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NIST
Smart Grid Interoperability Panel
Priority Action Plan 2:
Guidelines for Assessing Wireless Standards for Smart Grid Applications

Participants of the Priority Action Plan 2 working group

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U.S. Department of Commerce

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TABLE OF CONTENTS

PREFACE **1**

AUTHORS **2**

1 OVERVIEW OF THE PROCESS **3**

2 ACRONYMS AND DEFINITIONS **4**

2.1 ACRONYMS 4
2.2 DEFINITIONS 7

3 SMART GRID CONCEPTUAL MODEL AND BUSINESS FUNCTIONAL REQUIREMENTS **13**

3.1 SMART GRID CONCEPTUAL REFERENCE DIAGRAMS 13
3.2 LIST OF ACTORS 17
3.3 SMART GRID USE CASES 19
3.4 SMART GRID BUSINESS FUNCTIONAL AND VOLUMETRIC REQUIREMENTS 21
3.5 USE OF SMART GRID USER APPLICATIONS' QUANTITATIVE REQUIREMENTS FOR PAP02 TASKS 24
3.6 SECURITY 24

4 WIRELESS TECHNOLOGY **25**

4.1 TECHNOLOGY DESCRIPTOR HEADINGS 25
4.2 TECHNOLOGY DESCRIPTOR DETAILS 26
4.2.1 Descriptions of Groups 1-7 Submissions *26*
4.2.1.1 Group 1: Applicable Smart Grid Communications Sub-Network(s) 27
4.2.1.2 Group 2: Data / Media Type Supported 29
4.2.1.3 Group 3: Range Capability (or Coverage Area When Applicable) 29
4.2.1.4 Group 4: Mobility 30
4.2.1.5 Group 5: Channel / Sector Data Rates and Average Spectral Efficiency 30
4.2.1.6 Group 6: Spectrum Utilization 35
4.2.1.7 Group 7: Data Frames, Packetization, and Broadcast Support 36
4.2.2 Descriptions of Groups 8-12 Submissions *37*
4.2.2.1 Group 8: Link Quality Optimization 38
4.2.2.2 Group 9: Radio Performance Measurement and Management 39
4.2.2.3 Group 10: Power Management 39
4.2.2.4 Group 11: Connection Topologies 39
4.2.2.5 Group 12: Connection Management 40
4.2.3 Descriptions of Groups 13-17 Submissions *41*
4.2.3.1 Group 13: QoS and Traffic Prioritization 42
4.2.3.2 Group 14: Location Based Technologies 43
4.2.3.3 Group 15: Security and Security Management 43
4.2.3.4 Group 16: Unique Device Identification 43
4.2.3.5 Group 17: Technology Specification Source 43
4.2.4 Group 18: Wireless Functionality not Specified by Standards *43*
4.3 WIRELESS TECHNOLOGY / STANDARD SUBMISSIONS 45

5 MODELING AND EVALUATION APPROACH **47**

5.1 ASSESSMENT OF WIRELESS TECHNOLOGIES WITH RESPECT TO SMART GRID REQUIREMENTS 47
5.1.1 Initial Screening *47*
5.1.2 Refinements to Initial Screening *48*
5.1.2.1 Mathematical Models 48
5.1.2.2 Simulation Models 48
5.1.2.3 Testbeds 48
5.1.2.4 Network Design 48
5.2 MODELING FRAMEWORK 49

5.2.1 Channel Propagation or Path Loss Models ... 50
5.2.1.1 Generic Path Loss Model ... 51
5.2.1.2 Indoor Path Loss Models ... 52
5.2.1.2.1 ITU-R M.1225 Indoor Model ... 53
5.2.1.2.2 WINNER II Indoor Model ... 54
5.2.1.2.3 ITU-R M.2135-1 Indoor Model ... 55
5.2.1.2.4 NIST PAP02-Task 6 Model ... 55
5.2.1.2.5 Indoor Model Comparison ... 56
5.2.1.2.6 Modeling Floor-to-Floor Penetration Losses in Multilevel Buildings ... 57
5.2.1.2.7 Indoor Model Summary ... 58
5.2.1.3 Large Scale Outdoor Path Loss Models ... 59
5.2.1.3.1 Hata-Okumura Model ... 60
5.2.1.3.2 COST231-Hata aka Modified Hata Model ... 61
5.2.1.3.3 WINNER II Model ... 62
5.2.1.3.4 ITU-R M.2135-1 Model ... 63
5.2.1.3.5 Erceg-Stanford University Interim (SUI) Model ... 65
5.2.1.3.6 Comparing Large Scale Path Loss Models to Smart Grid Requirements ... 66
5.2.1.3.7 Path Loss Due to Foliage ... 67
5.2.1.3.8 Path Loss Due to Path Obstructions ... 69
5.2.1.3.9 Modified Erceg-SUI Model ... 71
5.2.1.3.10 Model Limitations with Respect to Meeting Smart Grid Deployment Requirements ... 73
5.2.1.3.11 Modeling Extreme Terrain Characteristics ... 74
5.2.1.4 Atmospheric Absorption ... 74
5.2.1.5 Line of Sight (LoS) and Fresnel Zone Clearance ... 75
5.2.2 Range and Coverage Analysis ... 77
5.2.2.1 Link Budget ... 77
5.2.2.1.1 Fade Margins ... 81
5.2.2.1.2 Interference Margin ... 84
5.2.2.1.3 Penetration Loss ... 85
5.2.2.2 Deployment Trade-offs ... 86
5.2.2.2.1 BS and SS Antenna Heights ... 86
5.2.2.2.2 Impact of Spectrum Choices ... 92
5.2.3 Estimating Channel and BS Sector Capacity ... 94
5.2.4 Physical Layer (PHY) Model ... 100
5.2.5 MAC Sublayer Model ... 101
5.2.6 Multi-Hop (or Multi-Link) Model ... 102
5.2.7 Modeling Latency ... 103
5.2.7.1 Binomial Distribution Model ... 104
5.2.7.2 M/D/1 and M/M/1 Queuing System Models ... 108
5.2.7.3 Comparing the Binomial Distribution Model with the M/M/1 Model ... 112
5.2.7.4 Additional Latency Considerations and Conclusions ... 113

6 PRACTICAL CONSIDERATIONS IN THE DEPLOYMENT OF WIRELESS NETWORKS FOR SG APPLICATIONS ... 116

6.1 COVERAGE, CAPACITY, LATENCY TRADE-OFFS ... 116
6.1.1 Demographic Breakdown ... 117
6.1.2 Dense Urban Regions ... 119
6.1.2.1 Dense Urban Latency Considerations ... 121
6.1.2.2 Relating Channel Capacity and Latency ... 121
6.1.3 Low Density Rural ... 123
6.1.4 Summary ... 126
6.2 ADVANCED ANTENNA SYSTEMS AND SPECTRUM CONSIDERATIONS ... 127
6.2.1 Multiple Input Multiple Output (MIMO) Antennas ... 127
6.2.2 Beamforming and Beam steering ... 128
6.2.3 Practical Considerations and Spectrum Trade-offs ... 129
6.3 MULTI-LINK / MULTI-HOP / MESH TOPOLOGIES ... 132

6.3.1 Network Topology Revisited *134*
6.3.2 The Neighborhood Area Network (NAN) in a Larger Context *136*
6.3.3 Other Neighbor Area Network (NAN) Topologies *138*
6.3.4 NAN Network Components *139*
6.3.5 Characteristics of NAN Multi-Hop Networks *140*
6.3.6 Additional Technical Characteristics of the NAN *140*
6.3.7 Further Considerations for NAN Design and Routing *142*
6.3.8 Smart Grid Neighborhood Area vs. Wide Area Networks *144*
6.4 ADDRESSING THE CHALLENGES WITH MULTI-TENANT HIGH RISE BUILDINGS 147
6.4.1 An Alternative Wireless Approach *147*
6.4.2 Conclusion *149*
6.5 SG FRAMEWORK AND WIRELESS MODELING TOOL 150
6.5.1 Modeling tool input parameters *151*
6.5.2 Modeling tool outputs *155*
6.5.3 Limitations of the modeling tool *156*
6.6 INTEROPERATING AND INTERWORKING WITH OTHER WIRELESS TECHNOLOGIES 158
6.6.1 Satellite Communication Networks *158*
6.6.2 Smart Grid Solutions in the 450 MHz to 470 MHz IG Band *160*
6.6.2.1 Frequency Usage and Capabilities 160
6.6.2.2 Implementation Using the IG Band 161
6.6.2.3 IG Band Summary 162
6.7 ASSESSMENT OF MODELING TOOL RESULTS 162
6.7.1 Impact of Packet Size *163*
6.7.2 Summary of Terrestrial-based Technology Submissions *166*
6.7.3 Baseline Parameter Choices for Modeling Tool Assessment *167*
6.7.4 Wireless Technology Assessment *170*
6.7.4.1 Meeting Highload Demand 171
6.7.4.2 Meeting Baseload Demand 175
6.7.4.3 Wireless Assessments for the ISM bands in a PMP Topology 176
6.7.4.4 Meeting Latency Requirements 177
6.7.4.5 Sensitivity Analysis 180
6.7.5 Assessment results summary *186*
6.8 CROSS WIRELESS TECHNOLOGY CONSIDERATIONS 191

7 CONCLUSIONS 195

8 BIBLIOGRAPHY 196

Preface
Wireless technologies for technical and business communications have been available for over a century and are widely used for many popular applications. The use of wireless technologies in the power system is also not new. Its use for system monitoring, metering and data gathering goes back several decades. However, the advanced applications and widespread use now foreseen for the smart grid require highly reliable, secure, well designed, and managed communication networks.

The decision to apply wireless technologies for any given set of applications is a local decision that must take into account several important elements including both technical and business considerations. Smart grid applications requirements must be defined with enough specification to quantitatively define communications traffic loads, levels of performance, and quality of service. Applications requirements must be combined with a complete set of management and security requirements for the life-cycle of the system. These requirements can then be used to assess the suitability of various wireless technologies to meet the requirements in the particular applications environment.

This report contains key tools and methods to assist smart grid system designers in making informed decisions about existing and emerging wireless technologies. An initial set of quantified requirements have been brought together for advanced metering infrastructure (AMI) and initial distribution automation (DA) communications. These two areas present technological challenges due to their scope and scale. These systems will span widely diverse geographic areas and operating environments and population densities ranging from urban to rural.

The wireless technologies presented here encompass different technologies that range in capabilities, cost, and ability to meet different requirements for advanced power systems applications. System designers are further assisted by the presentation of a set of wireless functionality and characteristics captured in a matrix for existing and emerging standards based wireless technologies. Details of the capabilities are presented in this report as a way for designers to initially sort through the available wireless technology options.

To further assist decision making, the report presents a set of tools in the form of models that can be used for parametric analyses of the various wireless technologies.

This report represents an initial set of guidelines to assist smart grid designers and developers in their independent evaluation of candidate wireless technologies. While wireless holds many promises for the future, it is not without limitations. In addition wireless technology continues to evolve. Priority Action Plan 2 (PAP02) fundamentally cuts across the entire landscape of the smart grid. Wireless is one of several communications options for the smart grid that must be approached with technical rigor to ensure communication systems investments are well suited to meet the needs of the smart grid both today, as well as in the future.

The scope and scale of wireless technology will represent a significant capital investment. In addition the smart grid will be supporting a wide diversity of applications including several functions that represent critical infrastructure for the operation of the nation's electric and energy services delivery systems.

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1 Overview of the Process

The main objectives for release 2 of the NISTIR 7761 were:

- Improve the intended interpretation and input of data from the Standards Development Organizations (SDOs) and alliances on the Wireless Functionality and Characteristic Matrix for the Identification of Smart Grid Domain Applications (section 4)
- Revise how the previously included technology appendix content is addressed in section 4 and section 5
- Provide more guidance to the reader on the use of various wireless standards and representative technologies for designers of the wireless telecommunication networks for smart grid deployments (see section 5 and section 6)
- Incorporate an extension to the modeling and evaluation approach via a framework (see section 6.5), that:
  - fully exploits the smart grid requirements from the UCA International Users Group (UCAIug) – Open Smart Grid User's Group (OpenSGug) - SG Communications Working Group - SG-Network Task Force via a modeled deployment scenario as input;
  - develops an Smart Grid (SG) framework and wireless modeling tool (spreadsheet) that incorporates inputs from section 4, Wireless Functionality and Characteristics Matrix and representative technology operating parameters;
  - outputs the quantities of network gear calculated across several spectrum bands and wireless end-point density and terrain and clutter categories.
- Provide sensitivity analysis and impacts around many of the input parameters and provide guidance (see section 5 and section 6)

These objectives were addressed by various tasks and working documents identified as release or version 2 artifacts located in the Smart Grip Interoperability Panel (SGIP) Priority Action Plan 2 (PAP02), first link below and SGIP 2.0 PAP02 the second link below:

- ❖ http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless
- ❖ http://members.sgip.org/apps/org/workgroup/sgip-pap02wg/

2 Acronyms and Definitions

The acronyms and definitions provided are used in this report and in some of its referenced supporting documentation.

2.1 Acronyms

AMI	Advanced Metering Infrastructure
AP	Access Point
ARQ	Automatic Repeat-reQuest
BE	Best Effort
BER	Bit Error Rate
BGAN	Broadband Global Area Network
BPSK	Binary Phase Shift Keying
BS	Base Station
BW	Bandwidth
CCI	Co-Channel Interference
CIA	Confidentiality, Integrity, and Availability
CIS	Customer Information Service
COST	CO-operative for Scientific and Technical research
DA	Distribution Automation
DAC	Distributed Application Controller
DAP	Data Aggregation Point
DB	Database
DER	Distributed Energy Resources
DL	Downlink
DMS	Distribution Management System
DRMS	Distribution Resource Management System
DSDR	Distribution Systems Demand Response
DSM	Demand Side Management
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
EMS	Energy Management System
EP	End-point
ESI	Energy Services Interface
EUMD	End Use Measurement Device
EV/PHEV	Electric Vehicle/Plug-in Hybrid Electric Vehicle
EVSE	Electric Vehicle Service Element
FAN	Field Area Network
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FEP	Front End Processor

FER	Frame Error Rate
FERC	Federal Energy Regulatory Commission[1]
FSK	Frequency Shift Keying
FTP	File Transfer Protocol
G&T	Generations and Transmission
GBR	Guaranteed Bit Rate
GIS	Geographic Information System
GL	General Ledger
GMR	Geo Mobile Radio
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HAN	Home Area Network
HARQ	Hybrid Automatic Repeat reQuest
HRPD	High Rate Packet Data
HSPA+	Evolved High-Speed Packet Access
HVAC	Heating, Ventilating, and Air Conditioning
H-FDD	Half-duplex Frequency Division Duplexing
IKB	Interoperability Knowledge Base
IP	Internet Protocol
ISM	Industrial Scientific and Medical
ISO	Independent System Operator
ITU	International Telecommunications Union
LB	Link Budget
LMS	Load Management System
LMS/DRMS	Load Management System/ Distribution Resource Management System
LoS	Line of Sight
LTE	Long Term Evolution
LV	Low Voltage
MAC	Medium Access Control
MBR	Maximum Bit Rate
MCS	Modulation and Coding Scheme
MDMS	Meter Data Management System
MIMO	Multiple-Input / Multiple-Output
MS	Mobile Station
MSS	Mobile Satellite Services
MU-MIMO	Multi-User Multiple Input Multiple Output (Antennas)
MV	Medium Voltage
NAN	Neighborhood Area Network
NISTIR	NIST Interagency Report
NMS	Network Management System

[1] Federal Energy Regulatory Commission - www.ferc.gov

ODW	Operational Data Warehouse
OFDMA	Orthogonal Frequency Division Multiple Access
OH	Overhead
OMS	Outage Management System
OSI	Open Systems Interconnection
OTA	Over-the-Air
PAP	Priority Action Plan
PCT	Programmable Communicating Thermostat
PHEV	Plug-in Hybrid Electric Vehicle
PHY	Physical Layer
PL	Path Loss
PMP	Point-to-Multipoint
PtP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
REP	Retail Electric Provider
RF	Radio Frequency
RTO	Regional Transmission Operator
RTU	Remote Terminal Unit
Rx	Receiver or receiving
SCADA	Supervisory Control and Data Acquisition
SDO	Standards Development Organization
SE	Spectral Efficiency
SER	Symbol Error Rate
SGIP	Smart Grid Interoperability Panel
SINR	Signal to Interference plus Noise Ratio
SM	Smart Meter
SNR	Signal to Noise Ratio
SRS	System Requirements Specification
SS	Subscriber Station
SUI	Stanford University Interim
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TF	Task Force
Tx	Transmitter or Transmitting
UL	Uplink
VAR	Volt-Amperes Reactive
VoIP	Voice over Internet Protocol
VVWS	Volt-VAR-Watt System
WAMS	Wide-Area Measurement System
WAN	Wide Area Network
WLAN	Wireless Local Area Network

2.2 Definitions[2]

Access Point	A stationary node, consisting of a transmitter and receiver, used to aggregate traffic in a wireless network. This term is most often used to describe this functionality for indoor wireless local area networks, but sometimes also used for outdoor terrestrial local area networks. Also see Base Station.
Actor	A generic name for devices, systems, or programs that make decisions and exchange information necessary for performing applications: smart meters, solar generators, and control systems represent examples of devices and systems.
Advanced Metering Infrastructure	A network system specifically designed to support two-way connectivity to Electric, Gas, and Water meters or more specifically for AMI meters and potentially the Energy Service Interface for the Utility (or ESI-Utility).
Aggregation	Practice of summarizing certain data and presenting it as a total without any personally identifiable information identifiers
Aggregator	SEE FERC OPERATION MODEL
Applications	Tasks performed by one or more actors within a domain.
Asset Management System	A system(s) of record for assets managed in the smart grid. management context may change (e.g., financial, network).
Backhaul	The portion of the network that comprises the intermediate links between the core network or backbone network and the sub-networks at the edge of a hierarchical network.
Base Station	A stationary node used to aggregate and backhaul traffic in a terrestrial multi-cellular wireless network. In an AMI network or NAN, the DAP serves the same function as a Base Station.
Capacitor Bank	This is a device used to add capacitance as needed at strategic points in a distribution grid to better control and manage volt-amperes reactive (VARs) and thus the power factor and they will also affect voltage levels.
Capacity-Limited (Deployment)	A wireless cellular-like deployment for which the number of base stations is determined by the capacity requirements of the geographic area. (may also be referred to as capacity-constrained)
Cell	Generally used to describe a base station and its surrounding coverage area.
Cell Site	Refers to the geographical position for a base station
Client Device	Used to describe customer or end user equipment. Device can be mobile, portable, or stationary (fixed).

[2] The definitions are specific to this report's context and intended usage. Even though other Standards Development Organizations have their own copyrighted definitions for some of these same terms, a specific effort to harmonize or obtain permission to reuse copyrighted definitions was not included in scope of this work.

Common Web Portal	Web interface for regional transmission operator, customers, retail electric providers and transmission distribution service provider to function as a clearing house for energy information. Commonly used in deregulated markets.
Data Aggregation Point	This device is a logical actor that represents a transition in most advanced metering infrastructure (AMI) networks between wide area networks and neighborhood area networks. (e.g., collector, cell relay, base station, access point, etc.)
Data Collector	See Substation controller
Demand Side Management	A system that co-ordinates demand response / load shedding messages indirectly to devices (e.g., set point adjustment)
Distribution Management System	A system that monitors, manages and controls the electric distribution system.
Distribution Systems Demand Response	A system used to reduce load during peak demand. Strictly used for distribution systems only.
Downlink (or Downstream)	Data traffic flow in the network from the Operations Center towards the end-point.
Electric Vehicle /Plug-in Hybrid Electric Vehicle	Cars or other vehicles that draw electricity from batteries to power an electric motor. PHEVs also contain an internal combustion engine.
End User (End-User Node)	Same as client device, terminal, etc.
End-Point	Term used to describe termination points in a NAN or AMI network.
Energy Services Interface	Provides the communications interface to the utility. It provides security and, often, coordination functions that enable secure interactions between relevant home area network devices and the utility. Permits applications such as remote load control, monitoring and control of distributed generation, in-home display of customer usage, reading of non-energy meters, and integration with building management systems. Also provides auditing / logging functions that record transactions to and from home area networking devices.
Enterprise Bus	The enterprise bus consists of a software architecture used to construct integration services for complex event-driven and standards-based messaging to exchange meter or grid data. The enterprise bus is not limited to a specific tool set; rather, it is a defined set of integration services.
Fault Detector	A device used to sense a fault condition and can be used to provide an indication of the fault.
Field Area Network	A network designed to provide connectivity to field DA devices. The FAN may provide a connectivity path back to the substation upstream of the field DA devices or connectivity that bypasses the Substations and links the field DA devices into a centralized management and control system (commonly called a SCADA system).
Field Force	Employee working in the service territory that may be working with smart grid devices.

Frame	A fixed length digital data transmission unit that includes synchronization at the link layer (layer 2). A frame will carry one or more packets of varied length. (also see packet)
Frequency Reuse Factor	A term to describe how often a channel is reused with a base station or cell. For example for a 3-sector cell, a Frequency Reuse Factor of 1 indicates the same channel is reused in each of the 3 sectors. Reuse 3 indicates that a different channel is used in each of the 3 sectors,
Goodput	Goodput is the application level throughput, i.e., the number of useful bits per unit of time forwarded by the network from a certain source to a certain destination, excluding protocol overhead, and excluding retransmitted data packets.
Header	The portion of a packet, before the data field that typically contains source and destination addresses, control fields and error check fields.
Home Area Network	A network of energy management devices, digital consumer electronics, signal-controlled or enabled appliances, and applications within a home environment that is on the home side of the electric meter.
Latency	As used in the OpenSG – SG Communications SG-Network TF's Requirement Table, is the summation of actor (including network nodes) processing time and network transport time measured from an actor sending or forwarding a payload to an actor, and that receiving actor processing (consuming) the payload. This latency is not the classic round trip response time, or the same as network link latency.
Latency-Limited (Deployment)	A wireless cellular-like deployment in which the number of base stations is determined by the number of end-points and payloads that can be supported by each base station while meeting a specific payload latency requirement.
Link Budget	Accounts for the attenuation of the transmitted signal due to antenna gains, propagation, and miscellaneous losses.
Load Management System	A system that controls load by sending messages directly to device (e.g., On / Off)
M/D/1 and M/M/1	M/D/1 describes a queuing system model with a Poisson arrival process, a deterministic service rate distribution, and a single server. In the notation, M = Markov or Markovian, D=Deterministic, and 1 indicates the number of servers. M/M/1 describes a queuing system model with a Poisson arrival process for which the service time is exponentially distributed rather than deterministic.
Macro-cell	A base station in a cellular architecture with a large coverage area, typically limited only by the propagation conditions and system gain.
Mega-cell	A point-to-multipoint cell designed to provide connectivity over an extremely large geographical area. Satellite coverage is typical.
Micro-cell	A base station in a cellular architecture with a coverage area greater than a pico-cell but less than a macro-cell
Mobile Station	See client device

Multi-Hop (Topology)	A group of interconnected nodes in a common network infrastructure where communication links can be established via node-to-node or hop-to-hop links, similar to relay functionality.
Multi-Link (Topology)	An interconnection of multiple discrete networks, such as linking a HAN with a NAN, then to a WAN.
Multi-User MIMO	A technique used with multiple antenna systems in which, transmissions from multiple end-users are aggregated on a single channel at the receiver by using multiple receive antennas.
Neighborhood Area Network	A network system intended to provide direct connectivity with Smart Grid end devices in a relatively small geographic area. In practice a NAN may encompass an area the size of a few blocks in an urban environment, or areas several miles across in a rural environment.
Net Spectral Efficiency	The channel spectral efficiency at the application layer taking into account all channel overhead factors including encryption. (= goodput ÷ channel BW)
Network Management System	A system that manages fault, configuration, auditing/accounting, performance and security of the communication. This system is exclusive from the electrical network.
Outage Management System	A system that receives out power system outage notifications and correlates where the power outage occurred
Packet	The unit of data that is routed from a source to a destination on a packet-switched network. The packet includes a header, footer, and other overhead bits along with the message ‘payload’. Packets do not generally have a fixed size.
Payload	The actual message data carried within a packet. From a business application payload perspective, application payload is the totality of the business data for an asymmetric message that the telecommunications standard and implementing technology may need to segment into multiple packets from which only a portion of the business application payload is included.
Pico-cell	A base station coverage area within a cellular network designed to cover a very small area for extending range in difficult coverage areas or to add capacity in a high density area.
Power Factor	A dimensionless quantity that relates to efficiency of the electrical delivery system for delivering real power to the load. Numerically, it is the cosine of the phase angle between the voltage and current waveforms. The closer the power factor is to unity the better the inductive and capacitive elements of the circuit are balanced and the more efficient the system is for delivering real power to the load(s).
Programmable Communicating Thermostat	A device within the premise that has communication capabilities and controls heating, ventilation and cooling systems.
Range-Limited (Deployment)	A wireless cellular-like deployment for which the number of base stations to cover the area of interest is determined strictly by the link-budget and path loss. (may also be referred to as range-constrained)

Rate Adaptation	The mechanism by which a modem adjusts its modulation scheme, encoding and/or speed in order to reliably transfer data across channel exhibiting different signal to noise ratio (SNR) characteristics.
Recloser	A device used to sense fault conditions on a distribution line and trip open to provide protection. It is typically programmed to automatically close (re-close) after a period of time to test if the fault has cleared. Two general types of reclosers are typically deployed e.g., non-teamed and teamed. • Non-Teamed – After several attempts of reclosing it can be programmed to trip open and stop trying to reclose until reset either locally or under remote control. • Teamed - A device that can sense fault conditions on a distribution line and to communicate with other related reclosers (the team) to sectionalize the fault and provide a coordinated open / close arrangement to minimize the effect of the fault.
Regional Transmission Operator	An organization that is established with the purpose of promoting efficiency and reliability in the operation and planning of the electric transmission grid and ensuring non-discrimination in the provision of electric transmission services based on the following required / demonstrable characteristics and functions.
Remote Terminal Unit	Aggregator of multiple serialized devices to a common communications interface
Smart Meter	Term applied to a Two-Way Meter (meter metrology plus a network interface component) with included energy services interface (ESI) in the meter component
Spatial Diversity	A technique employed with multiple antenna systems to increase link availability or link budget in which each uncorrelated Tx antenna transmits the same data stream.
Spatial Multiplexing	A technique employed with multiple antenna systems to increase peak and average channel capacity and spectral efficiency in which each uncorrelated Tx antenna transmits a different data stream.
Sub Meter	Premise based meter (e.g., used for Distributed Energy Resources and PHEV), which permits additional metering capabilities subordinate to a main meter.
Sub-Network	A self-contained wireless or wire-line domain, use case, or area-focused network within the overall SG Network System
Subscriber Station	See client device
Substation Controller	Distributed processing device that has supervisory control or coordinates information exchanges from devices within a substation from a head end system.
Switch	A device under remote control that can be used to open or close a circuit
Terminal	See client device
Throughput	The number of bits (regardless of purpose) moving over a communications link per unit of time. Throughput is most commonly expressed in bits per second (b/s).

Transformer (MV-to-LV)	A standard point of delivery transformer. In the smart grid context it is assumed there will be a need to measure some electrical or physical characteristics of this transformer such as voltage (high and/or low side) current, MV load, temperature, etc.
Universal Frequency Reuse	Same as Frequency Reuse factor of 1
Uplink (or Upstream)	Defines data traffic flowing in the SG network in the direction towards the Operation Center.
Use Case	A systems engineering tool for defining a system's behavior from the perspective of users. In effect, a use case is a story told in structure and detailed steps—scenarios for specifying required usages of a system, including how a component, subsystem, or system should respond to a request that originates elsewhere.
Voltage Regulator	This device is in effect an adjustable ratio transformer positioned at strategic points in a distribution grid and is utilized to better manage and control the voltage as it changes along the distribution feeder.
Voltage Sensor	A device used to measure and report electrical properties (such as voltage, current, phase angle or power factor, etc.) for specific voltage levels, e.g., low voltage customer delivery point, medium voltage distribution line points.
Volt-Amperes Reactive	In an alternating current power system the voltage and current measured at a point along the delivery system will often be out of phase with each other as a result the combined effects of the resistive and reactive (i.e., the capacitance and inductive) characteristics of the delivery system components and the load. The phase angle difference at a point along the delivery system is an indication of how well the inductive and capacitive effects are balanced at that point. The real power passing that point is the product of the magnitude of the voltage and current and the cosine of the angle between the two. The VAR parameter is the product of the magnitude of the voltage and current and the sine of the angle between the two. The magnitude of the VAR parameter is an indication of the phase imbalance between the voltage and current waveforms.
Web Portal	Interface between customers and their smart grid service provider (e.g., utility or third party or both).

3 Smart Grid Conceptual Model and Business Functional Requirements

This section provides an overview of the primary sets of information that UCAIug – OpenSG – SG Communications – SG-Network Task Force (SG-Network TF) prepared to address task 3 of PAP02, plus an explanation of how this information is intended to be interpreted and an example of how to consume the information as an input into other analysis tools (e.g., network traffic modeling).

3.1 Smart Grid Conceptual Reference Diagrams

SG-Network TF expanded upon the smart grid conceptual reference and framework diagrams that were introduced in the first release of NIST Special Publication 1108 - NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0 and other reference diagrams included in NISTIR 7628 - Guidelines for Smart Grid Cyber Security. The NIST Smart Grid Framework release diagram is shown in Figure 1, along with two views of SG-Network TF's conceptual domain actors and interfaces reference diagrams, one without (Figure 2) and one with (Figure 3) cross domain data flows. Alternative (optional) interfaces between actors and communication paths amongst actors are also contained in the diagrams. These reference diagrams are further explained in smart grid use case documentation and detailed business functional and volumetric requirements in the sections that follow. In these three figures the customer domain includes: residential customers or commercial or industrial customers.

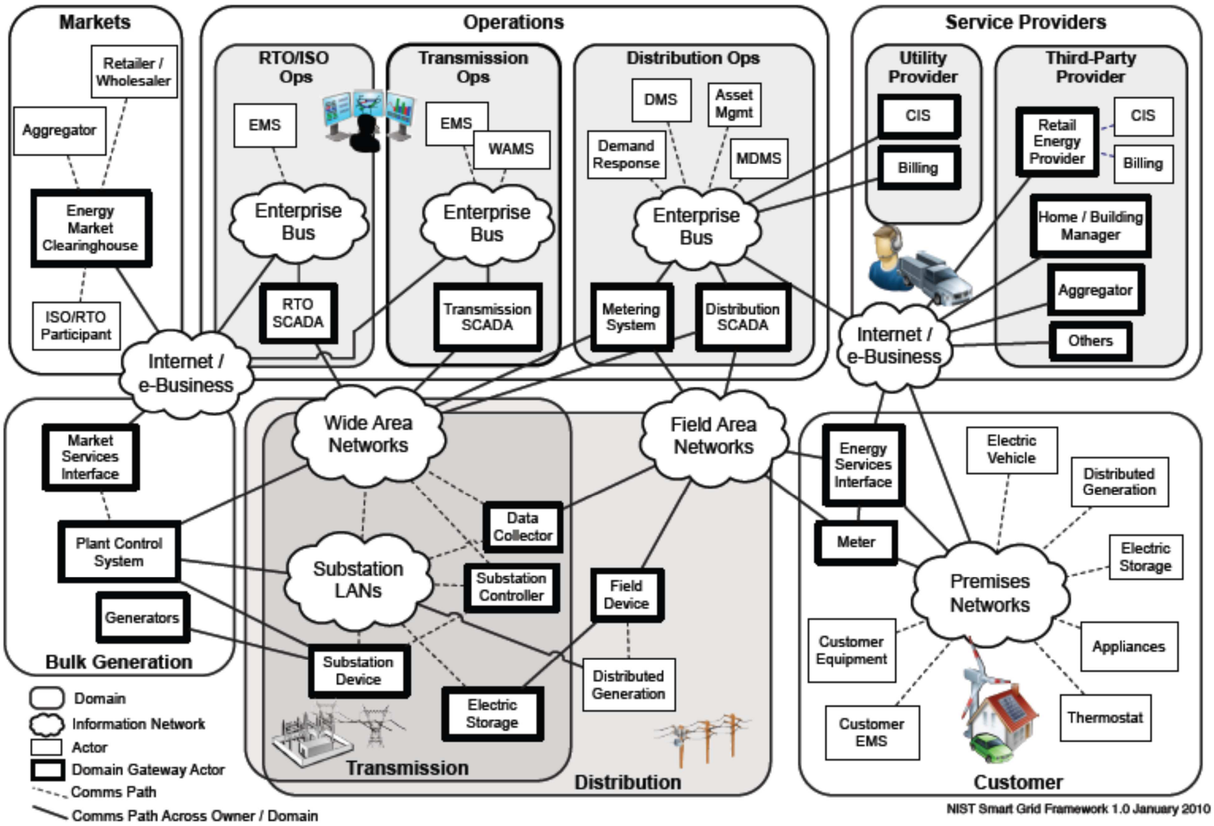


Figure 1 - Smart grid conceptual reference diagram – NIST Smart Grid Framework 1.0 January 2010

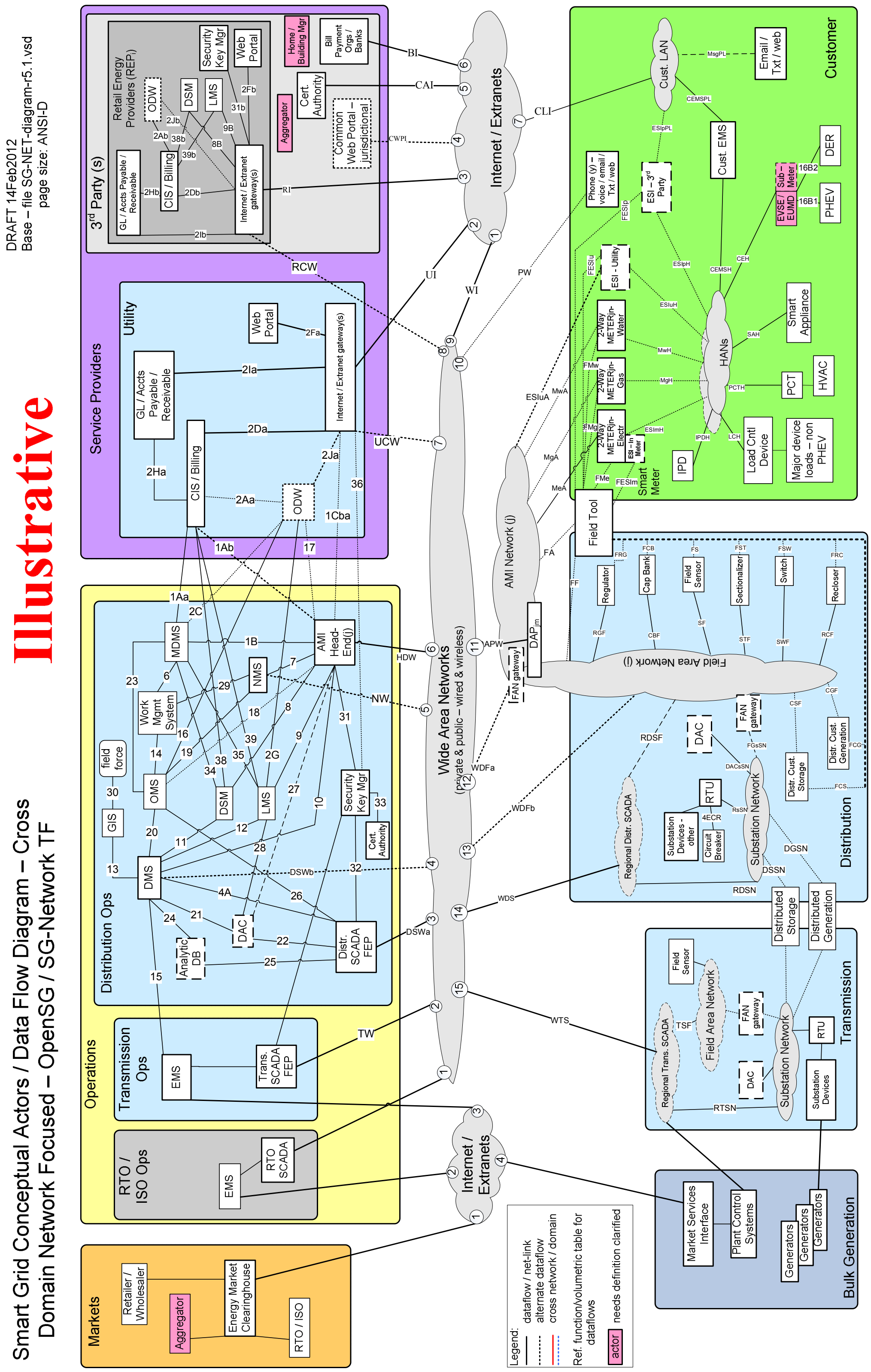


Figure 2 - OpenSG SG-Network TF smart grid conceptual reference diagram

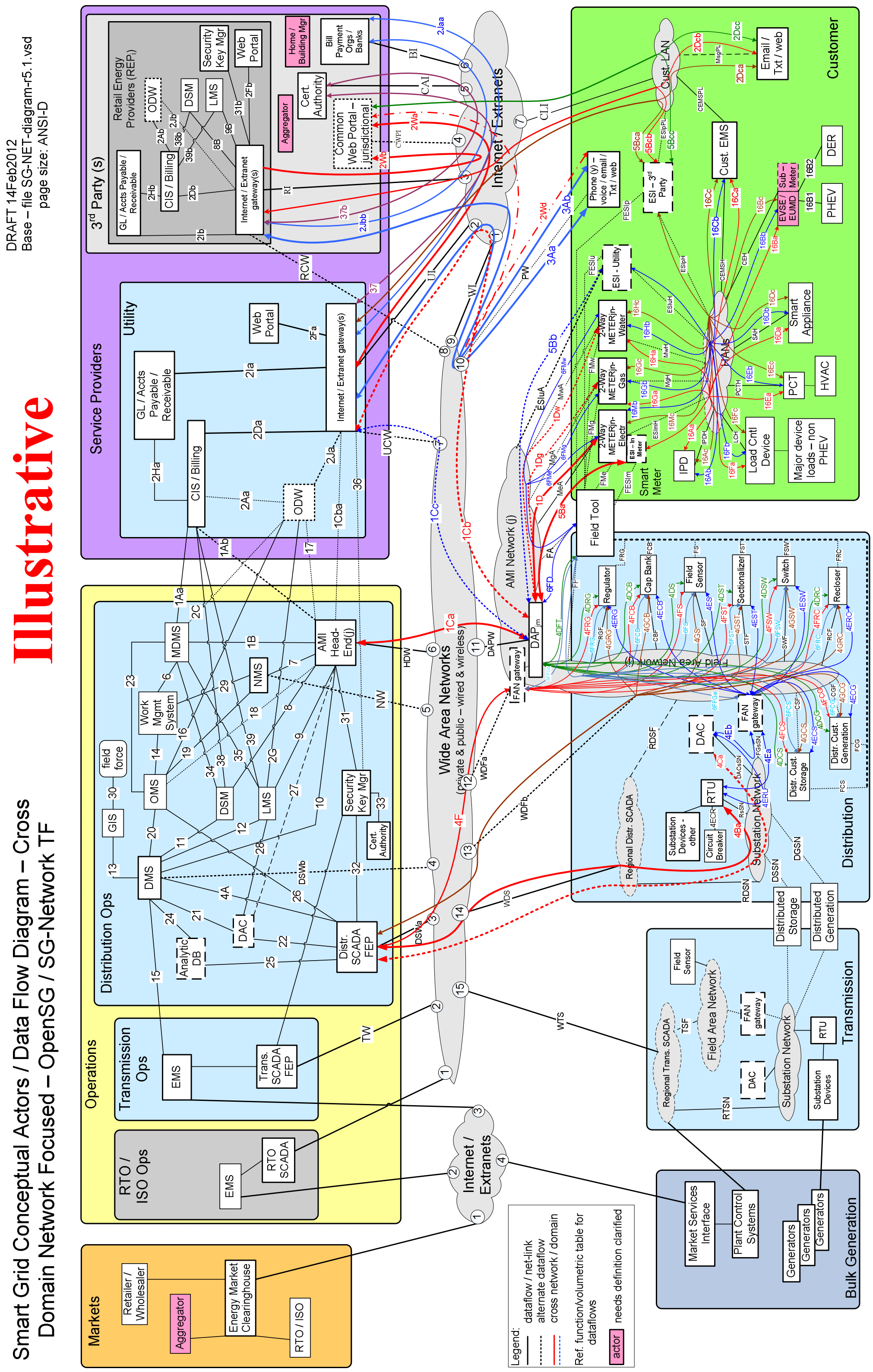


Figure 3 - OpenSG_SG-Network TF smart grid conceptual reference diagram with cross domain data flows

The latest set of SG-Network TF reference diagrams are located at

- http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/Diagrams/

3.2 List of Actors

Table 1 maps the actors included in the SG-Network TF smart grid conceptual reference diagram (Figure 3) and the NIST smart grid conceptual reference diagram (Figure 1). The SG-Network TF high level list of actors are further qualified by domain and sub-domain as used in documenting the smart grid business functional and volumetric requirements. Where there is no equivalent actor, a blank cell is used.

Table 1: Mapping of actors to domain names

SG-Network TF reference diagram descriptor (actor)	SG-Network TF reference diagram domain name	Related NIST release 1 diagram descriptor (actor)
Field Tools	Customer / Distribution	
Generators	Bulk Generation	Generators
Market Services Interface	Bulk Generation	Market Services Interface
Plant Control Systems	Bulk Generation	Plant Control Systems
	Customer	Electric Storage
Customer Energy Management System (EMS)	Customer	Customer EMS
DERs (Solar, Wind, premise generation sources)	Customer	Distributed Generation
ESI (3rd party)	Customer	Energy Services Interface
ESI (Utility)	Customer	Energy Services Interface
ESI (In meter)	Customer	Energy Services Interface
Electric Vehicle Service Element (EVSE) / End Use Measurement Device (EUMD)	Customer	Customer Equipment
Heating, Ventilating, and Air Conditioning (HVAC)	Customer	Customer Equipment
IPD (In Premise Device)	Customer	Customer Equipment
Load Control Device	Customer	Customer Equipment
PCT	Customer	Thermostat
PHEV	Customer	Electric Vehicle
Phone / Email / Text / Web	Customer	Customer Equipment
Smart Appliances	Customer	Appliances
Smart Meter	Customer	Meter
Sub-Meter	Customer	Customer Equipment
Two Way Meter - Electric	Customer	Meter
Two Way Meter - Gas	Customer	Meter
Two Way Meter - Water	Customer	Meter
Capacitor Bank	Distribution	Field Device
Circuit Breaker	Distribution	Field Device

SG-Network TF reference diagram descriptor (actor)	SG-Network TF reference diagram domain name	Related NIST release 1 diagram descriptor (actor)
Recloser	Distribution	Field Device
Distributed Customer Generation	Distribution	Distribution Generation
Distributed Customer Storage	Distribution	Storage System
Sectionalizer	Distribution	Field Device
Switch	Distribution	Field Device
Voltage Regulator	Distribution	Field Device
Distributed Application Controller (DAC)	Distribution / Transmission	Substation Controller
Distributed Generation	Distribution / Transmission	Distributed Generation
Distributed Storage	Distribution / Transmission	Storage System
Field Area Network (FAN) Gateway	Distribution / Transmission	
Field Sensors	Distribution / Transmission	Field Device
Remote Terminal Unit (RTU)	Distribution / Transmission	Data Collector
Substation Devices	Distribution / Transmission	Substation Device
Energy Market Clearinghouse	Markets	Energy Market Clearinghouse
Retailer / Wholesaler	Markets	Aggregator / Retail Energy Provider
Regional Transmission Operator (RTO) / Independent System Operator (ISO)	Markets	RTO / ISO
Aggregator	Markets / Service Providers	Aggregator
	Operations	Asset Mgmt
	Operations	WAMS
AMI Head-End	Operations	Metering System
Analytic Database	Operations	
Certificate Authority	Operations	
Distributed SCADA Front End Processor (FEP)	Operations	Distributed SCADA
Demand Side Management (DSM)	Operations	Demand Response
EMS	Operations	Utility EMS
OMS	Operations	

SG-Network TF reference diagram descriptor (actor)	SG-Network TF reference diagram domain name	Related NIST release 1 diagram descriptor (actor)
Geographic Information System (GIS)	Operations	
General Ledger (GL) / Accounts Payable / Receivable	Operations	
Load Management System (LMS)	Operations	
MDMS	Operations	MDMS
NMS	Operations	
RTO SCADA	Operations	RTO SCADA
Security Key Manager	Operations	
Transmission SCADA FEP	Operations	Transmission SCADA FEP
Utility Distribution Management System (DMS)	Operations	DMS
Utility EMS	Operations	EMS
Work Management System	Operations	
Bill Payment Organizations / Banks	Service Provider	Other
Certificate Authority	Service Provider	
Common Web Portal-Jurisdictional	Service Provider	Other
Demand Side Management (DSM)	Service Provider	
Home / Building Manager	Service Provider	Home / Building Manager
Internet / Extranet Gateway	Service Provider	
Load Management System (LMS)	Service Provider	
ODW	Service Provider	
REP CIS / Billing	Service Provider	Retail Energy Providers Billing
REP CIS / Billing	Service Provider	Retail Energy Providers CIS
Security Key Manager	Service Provider	
Utility CIS / Billing	Service Provider	Utility CIS
Utility CIS / Billing	Service Provider	Utility Billing
Web Portal	Service Provider	

3.3 Smart Grid Use Cases

From the Interoperability Knowledge Base (IKB),

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/InteroperabilityKnowledgeBase#Use_Cases

Use cases come in many shapes and sizes. With respect to the IKB, fairly comprehensive use case descriptions are used to expose functional requirements for applications of the smart grid. In order to provide this depth, these use cases contain the following information:

- Narrative: a description in prose of the application represented including all important details and participants described in the context of their activities
- Actors: identification of all the persons, devices, subsystems, software applications that collaborate to make the use case work
- Information Objects: defines the specific aggregates of information exchanged between actors to implement the use case
- Activities / Services: description of the activities and services this use case relies on or implements
- Contracts / Regulations: what contractual or regulatory constraints govern this use case
- Steps: the step by step sequence of activities and messaging exchanges required to implement the use case

For use cases following this description, see:

- ❖ http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/IKBUseCases

SG-Network TF performed an exercise to research and to identify all pertinent use cases (namely concerning Advanced Metering Infrastructure (AMI) and Distribution Automation (DA)) that involve network communication to help satisfy the OpenSG input requirements into the NIST PAP02 tasks. Use cases from several sources (Southern California Edison, Grid Wise Architecture Console, Electric Power Research Institute and others) were researched. Table 2 summarizes the use cases SG-Network TF has currently in scope for this work effort.

Table 2: OpenSG SG-Network TF use cases and status

Smart grid use case[3] – based on release V5.1.xls
Customer Information / Messaging
Demand Response – Direct Load Control (DR-DLC)
Distributed Storage – Dispatch ; Island
Distribution Systems Demand Response (DSDR) - Centralized Control
Fault Clear Isolation Reconfigure (FCIR) – Distributed DAC – Substations; DMS; Regional Distributed DAC
Field Distribution Automation Maintenance / Support – Centralized Control
Meter Events
Meter Read
Outage Restoration Management

[3] For several of the payloads that might be classified as associated to Accounting (Auditing), Fault Management, those payloads are included across several of the other listed use cases.

PHEV
Premise Network Administration
Pre-Pay Metering
Pricing: Time of Use (TOU) / Real Time Pricing (RTP) / Critical Peak Pricing (CPP)
Service Switch
System Updates (Firmware / Program Update)
Volt / VAR Management – Centralized Control
Smart grid use case[4] – potential for releases post V5.1.xls
Configuration Management
Distributed Generation
Field Force Tools
Performance Management
Security Management
Transmission automation support

Documentation and description of the in-scope smart grid use cases by the SG-Network TF is contained in the System Requirements Specification (SRS) document [5]. The SG-Network TF objective for the SRS is to provide sufficient information for the reader to understand the overall business requirements for a smart grid implementation and to summarize the business volumetric requirements at a use case payload level as focused on the communications networking requirements, without documenting the use cases to the full level of documentation detail as described by the IKB.

The scope of the SRS focuses on explaining the objectives; the approach to documenting the use cases; inclusion of summarization of the network and volumetric requirements and necessary definition of terms; and guidance upon how to interpret and consume the business functional and volumetric requirements. The latest released version of the SRS is located at

- http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/

with a file name syntax of "SG Network SRS Version vN Final.doc", where N represents the version number.

3.4 Smart Grid Business Functional and Volumetric Requirements

There are many smart grid user applications (use cases) collections of documentation. Many have text describing the user applications (see IKB), but few contain quantitative business functional and volumetric requirements, which are necessary to design communications protocols, to assess, or to plan communication networks. Documenting the detailed actor to actor payloads and volumetric requirements allows for:

[4] For the current status of what use cases and application payloads have been documented, see the latest Requirement Table (.xls) referenced in section 3.4.

- aggregation of the details to various levels (e.g., specific interface or network link, a specific network or actor and have the supporting details versus making assumptions about those details) and
- allows the consumer of the Requirements Table to scope and customize the smart grid deployment specific to their needs (e.g., which set of use cases, payloads, actors, communication path deployments).

OpenSG -SG Communications - SG-Network TF took on the task to document the smart grid business functional and volumetric requirements for input into the NIST PAP02 tasks and to help fill this requirements documentation void. The current SG-Network business functional and volumetric requirements are located at

- ❖ http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/

with a file name syntax of "SG Network System Requirements Specification vN.R.xls", where N represents the version number and R represents the revision number. This spreadsheet is referred to below as the Requirements Table. (as of this writing v5.1.xls)

Instructions for how to document the business functional and volumetric requirements were prepared for the requirement authors, but also can be used by the consumer of the Requirements Table to better understand what is and is not included, and how to interpret the requirements data. The requirements documentation instructions are located at:

- ❖ http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/

with a file name syntax of "rqmts-documentation-instructions-rN.R.doc", where N represents the version number and R represents the revision number.

The Requirements Table consists of several major sets of information for each use case. For example:

- Business functional requirement statements are documented as individual information flows (e.g., specific application payload requirement sets). This is comparable to what many use case tools capture as information flows and/or illustrated in sequence diagram flows.
- To the baseline business requirements are added:
    - the volumetric attributes (the when, how often, with what availability, latency, application payload size). Take note that the SG-Network TF Requirements Table definition for some terms (e.g., latency) is different than the classic network link latency usage. Please refer to the SG-Network TF Requirements Documentation Instructions and the Smart Grid Networks System Requirements Specification Release Version 5 for the detailed definitions for clarification.
    - an assignment of the security confidentiality, integrity, and availability low-medium-high risk values for that application payload.
- Payload requirement sets are grouped by rows in the table that contains all the detailed actor to actor passing of the same application payloads in a sequence that follows the main data flow from that payload's originating actor to primary consuming actor(s) across possible multiple communication paths that a

deployment might use. The payload requirements' sets will always contain a parent (main) actor to actor row and most will contain child (detailed) rows for that requirement set.

- Payload communication path (information or data flow) alternatives that a given smart grid deployment might use.

The process of requirements gathering and documentation has been evolutionary in nature as various combinations of additional attributes are documented; use cases added; payload requirement sets added; and alternative communication paths documented. The SG-Network TF has defined over 7,850 (as of release v5.1.xls; the basis of this work) functional and volumetric detailed requirements rows in the Requirements Table representing 204 different payloads for 19 use cases.

SG-Network TF intends to continue this incremental version release approach to manage the scope and focus on documenting the requirements for specific use cases and payloads, yet giving consumers of this information something to work with and provide feedback for consideration in the next incremental releases. It is expected that the number of requirements rows in the Requirements Table will more than double, if not triple, from the current size when completed.

To effectively use the business functional and volumetric requirements, the consumer of the Requirements Table must:

- select which use cases and payloads are to be included
- select which communication path scenario (alternative) is to be used for each of the main information / data flows from originating actor to target consuming actor
- specify the size (quantity and type of devices) of the smart grid deployment
- perform other tweaks to the payload volumetrics to match that smart grid deployment's needs over time.

The current Requirements Table (v5.1.xls) as a spreadsheet is not very conducive to performing these tasks. SG-Network TF is building a database that is synchronized with the latest release of the Requirements Table (spreadsheet). SG-Network TF will be adding capabilities to the database to:

- solicit answers to the questions summarized above;
- query the database; and
- format and aggregate the query results for either reporting or exporting into other tools.

The current SG-Network TF Requirements database and related user documentation are located at

- http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/Rqmts_Database/

Note: SG-Network_Rqmts_Database_r5.1 is the version available for the database as of this writing.

3.5 Use of Smart Grid User Applications' Quantitative Requirements for PAP02 Tasks

Release 5.1 (March 5, 2012) of the SG-Network TF Requirements Table contains numerous use cases, payloads (applications), communication path options, and associated non-functional volumetric requirements data sufficient for a variety of smart grid deployment scenarios as input to PAP02. The instructions for how to adapt the SG-Network TF's Requirements for use in the SG framework and wireless modeling tool is discussed in section 6.5 of that document.

As SG-Network TF continues to provide incremental Requirement Table releases and eventually completes that effort, that availability of quantified business functional and volumetric data will provide PAP02 and the reader of this report with a more complete set of smart grid business functional and volumetric requirement data for assessment of any given network standard and technology against. This is not a "do it once and it is completed" type of task.

3.6 Security

Security can be considered at every layer of the communication protocol stack, from the physical layer to the application layer. Security in the context of PAP02, which is mainly concerned with the physical and media access control layers, implies the inclusion of additional protocol and traffic events to achieve security signaling functionality as in the case of authentication and authorization, and additional bytes to existing payloads to achieve encryption. As a first step towards this goal, the SG-Network TF Requirements Table lists the security objectives of confidentiality, integrity, and availability (CIAs) for each event. As a second step, a mapping between these CIA levels (low / moderate / high) and the security protocols available at the various communication layers is needed in order to fully address security in the context of PAP02.

4 Wireless Technology

PAP02's task 5 calls for the collection of an inventory of wireless technologies. This inventory of wireless technologies is captured as a spreadsheet, "Wireless Functionality and Characteristic Matrix for the Identification of Smart Grid Domain Applications," which can be found on the PAP02 web site:

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless with a file name syntax of "Consolidated_Wireless_Characteristics_Matrix2_MM-DD-YY.xlsx", where MM represents the month, DD represents the day, and YY represents the last two digits of the year.
    - https://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PAP02Wireless/Consolidated_Wireless_Characteristics_Matrix2_09-03-13.xlsx

  OR
- http://members.sgip.org/apps/org/workgroup/sgip-pap02wg/download.php/1610/2013-09-17_sgip-pap02wg_00015_Consolidated_Wireless_Characteristics_Matrix2_09-03-13.xlsx

Disclaimer: The spreadsheet was created and populated by the Standards Setting Organizations, which proposed their wireless technologies as candidates for the smart grid. The parameters and metrics contained and values entered for each wireless technology were entered by the organizations representing those technologies.

The next subsections give a brief description of the parameters and metrics contained in the spreadsheet, "Wireless Functionality and Characteristic Matrix for the Identification of Smart Grid Domain Applications" and a listing of the technologies submitted (as of the 09-03-13.xlsx version). Note that this section is written with the assumption that the reader has a reasonable understanding of the wireless telecommunication terminology.

4.1 Technology Descriptor Headings

The spreadsheet identifies a set of characteristics and organizes these characteristics into logical groups. The group titles are listed below.

- Group 1: Applicable Smart Grid Communications Sub-Network(s)
- Group 2: Data / Media Type Supported
- Group 3: Range Capability (or Coverage Area When Applicable)
- Group 4: Mobility
- Group 5: Channel / Sector Data Rates and Average Spectral Efficiency
- Group 6: Spectrum Utilization
- Group 7: Data Frames, Packetization, and Broadcast Support
- Group 8: Link Quality Optimization
- Group 9: Radio Performance Measurement and Management
- Group 10: Power Management
- Group 11: Connection Topologies

- Group 12: Connection Management
- Group 13: QoS and Traffic Prioritization
- Group 14: Location Based Technologies
- Group 15: Security and Security Management
- Group 16: Unique Device Identification
- Group 17: Technology Specification Source
- Group 18: Wireless Functionality not Specified by Standards

4.2 Technology Descriptor Details

Each of these groups is composed of individual descriptive described in more detail below.

4.2.1 Descriptions of Groups 1-7 Submissions

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
Group 1: Applicable Smart Grid Communications Sub-Network(s)		
a:	Primary SG sub-network(s)	Select from HAN/FAN/NAN/WAN/etc.
b:	Secondary SG sub-network(s)	Select from HAN/FAN/NAN/WAN/etc.
Group 2: Data / Media Type Supported		
a:	Voice	Yes/No
b:	Data	Yes/No
c:	Video	Yes/No
Group 3: Range Capability (or Coverage Area When Applicable)		
a:	Theoretical range limitations at frequency	km, GHz
b:	Conditions for theoretical range estimate	PtP, PMP, LoS, non-LoS
Group 4: Mobility		
a:	Maximum relative movement rate	km/h
b:	Maximum tolerated Doppler shift	Hz
Group 5: Channel / Sector Data Rates and Average Spectral Efficiency (Layer 2, or Note Other Layer if Applicable)		
a:	Peak over-the-air uplink channel data rate	Mb/s
b:	Peak over-the-air downlink channel data rate	Mb/s
c:	Peak uplink channel data rate	Mb/s
d:	Peak downlink channel data rate	Mb/s
e:	Average uplink channel data rate	Mb/s
f:	Average downlink channel data rate	Mb/s
g:	Average uplink spectral efficiency	(Mb/s)/Hz
h:	Average downlink spectral efficiency	(Mb/s)/Hz

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
i:	Average uplink cell spectral efficiency	(Mb/s)/Hz
j:	Average downlink cell spectral efficiency	(Mb/s)/Hz
Group 6: Spectrum Utilization		
a:	Public radio standard operating in unlicensed bands (DL and UL)	GHz
b:	Public radio standard operating in licensed bands (DL and UL)	GHz
c:	Private radio standard operating in licensed bands (DL and UL)	GHz
d:	Duplex method	TDD / FDD / H-FDD
e:	If TDD supported – provide details	
f:	Channel bandwidth supported	kHz
g:	Channel separation	kHz
h:	Number of non-overlapping channels in band of operation	Integer value
i:	Is universal frequency reuse supported?	Yes/No
Group 7: Data Frames, Packetization, and Broadcast Support		
a:	Frame duration	ms
b:	Maximum packet size	bytes
c:	Segmentation support	Yes/No
d:	Is unicast, multicast, broadcast supported?	Yes/No

4.2.1.1 Group 1: Applicable Smart Grid Communications Sub-Network(s)

The Smart Grid communications network encompasses seven domains[5] (as shown in Figure 1, Figure 2, and Figure 3 and listed in Table 1) with multiple actors and use cases that define communication paths for connecting actors within and between the seven domains. Multiple wireless solutions may be required to optimally meet the challenge of interconnecting actors and domains given a range of demographics, data requirements (e.g., capacity and latency), and propagation characteristics. The sub-networks group is intended to provide an assessment from the standards organization's perspective as to where its specific wireless technology is best suited in the Smart Grid communications network.

a) Primary SG sub-network(s): Based on the technology's features and capabilities, for what SG sub-network is this technology best suited? Indoor Home Area Network (HAN), Field Area Network (FAN) or Neighborhood Area Network (NAN), Wide Area Network (WAN), Point-to-Point (PtP) backhaul, satellite, Any, etc.

b) Secondary SG sub-network(s): Same choices as for Primary SG sub-network(s)

[5] NIST Special Publication 1108 , NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0

For illustrative purposes Figure 4 shows an example of a Smart Grid communications network with sub-networks identified. Figure 5 provides additional detail to show the end-point (meter) connectivity in the AMI network.

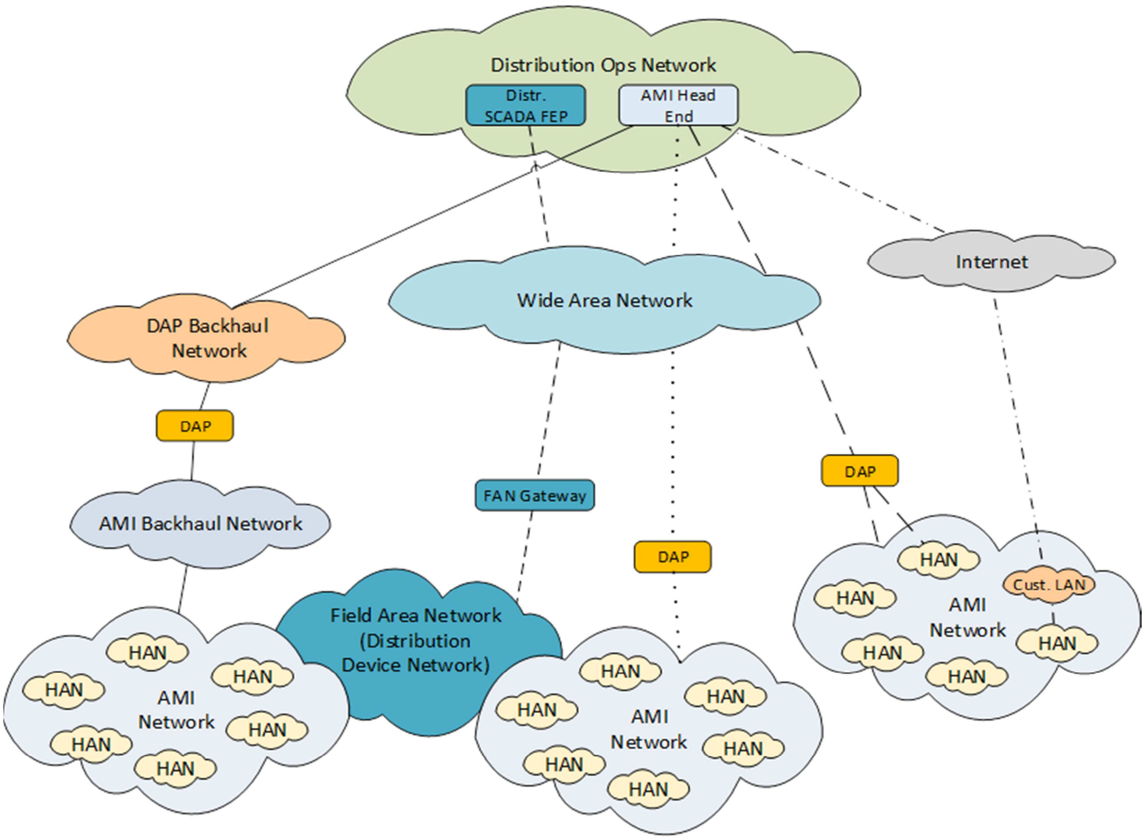


Figure 4 - Smart Grid communications sub-networks

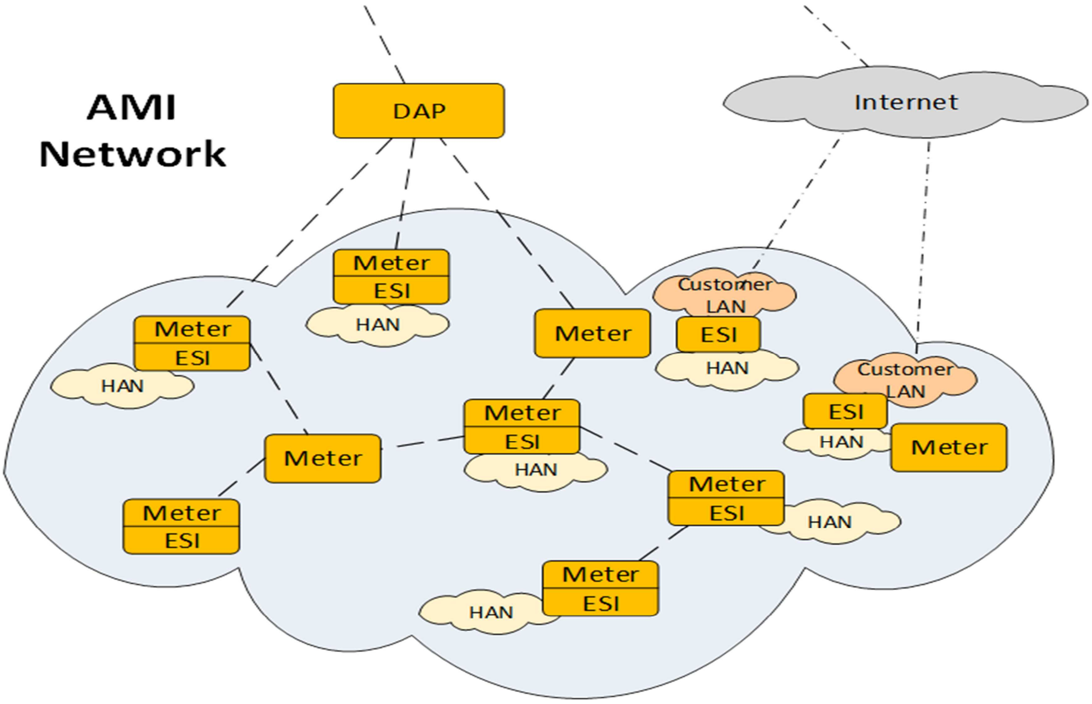


Figure 5 - Expanded view of the AMI network

4.2.1.2 Group 2: Data / Media Type Supported

The information to be transferred within the smart grid includes data, voice, and video information.

a) Voice: There is no specification of the codec being used but the assumption was that some form of packetized voice processing would be used and the connection would be two-way. Voice over Internet Protocol (VoIP) capacity should be derived assuming a 12.2 kb/s codec with a 50 % activity factor such that the percentage of users in outage is less than 2 % for a given bandwidth (please specify in simultaneous calls per MHz). If the VoIP's conditions are different, please specify those assumptions.
b) Data: is a generic term for information being transferred from machine to machine and can include information being displayed to a person for interpretation and further action. Please respond with yes/no. If yes, the details are provided in Group 5 and Group 13.
c) Video: in cases where there is an outage and the situation in the field needs to be displayed to others remote from the outage site, video is desirable. Video could be still pictures or motion pictures. Please respond with yes/no. If yes, the details are provided in Group 5 and Group 13.

4.2.1.3 Group 3: Range Capability (or Coverage Area When Applicable)

Land-based wireless systems are designed to service a wide variety of application scenarios. The intent of this group is to capture the expected range in a typical deployment. Some systems are optimized for very short ranges, perhaps 10 m or less, while others are intended for longer ranges, perhaps on the order of tens of kilometers (e.g., 30 km).

The intent of this group is to capture the expected range in a theoretical deployment and gain a perspective regarding the most applicable Smart grid network segment to which the technology is best suited.

A key deployment metric for satellite-based systems on the other hand, is the geographical size of the footprint covered. For these types of technologies the coverage area should be provided.

When comparing range predictions for land-based systems, it is important to take into account both the Uplink (UL) and Downlink (DL) system gains and the margins assumed for fading, penetration loss, and interference, etc. These margins together with the system gain determine the UL and DL link budgets used to predict the range. It is also important to indicate the path loss model used and the type environment assumed; indoor, outdoor Line of Sight (LoS) or non-LoS urban, outdoor suburban, Point-to-Point (PtP) or Point-to-multipoint (PMP), etc., since these factors will also influence the range prediction. Note that the greatest range achievable by a specific technology typically requires transmission at the maximum Effective Isotropic Radiated Power (EIRP) permitted in the frequency band of operation and assumes the most robust modulation index.

In some cases there may also be factors other than path loss and the link budget that place limits on the range. These factors may be latency-dependent features or other mechanisms built into the standard designed to optimize performance over a limited range of path lengths. If so, indicate if there is an inherent range over which the system is optimized, as well as a range for which the system is operational.

4.2.1.4 Group 4: Mobility

Some smart grid applications might require relative movement between a transmitter and receiver during the operation of the radio link. The inability of the radio link to operate successfully in situations of movement is due to many factors such as Doppler shift. This section covers Medium Access Control (MAC sublayer) and Physical layer (PHY). Higher layer mobility is covered in Group 12.

This metric is intended to display the mobility capability of the radio technology in one or both of the two ways commonly used:

a) Maximum relative movement rate (expressed in kilometers per hour)
b) The maximum tolerated Doppler shift (expressed in Hertz)

Mobile devices may not be able to communicate at the highest available data rates when moving at high speeds.

4.2.1.5 Group 5: Channel / Sector Data Rates and Average Spectral Efficiency

Channel data rates are a frequently used metric of radio link capability. The data rates for wireless technologies can span several orders of magnitude from a few bits per second up to several megabits per second, but so too can requirements for different smart grid applications. Unless the conditions under which the data rates are determined are fully described and understood, channel data rate values can be misleading when used for comparative analysis. Additional complications stem from the fact that the data payload of interest is surrounded with additional bits used to provide error correction, error detection, address information, and a variety of control information. Because of these added bits the data payload or goodput will be considerably less than the total number of over-the-air (OTA) bits transmitted and received by a channel. In this context goodput, as defined in section 2.2, is the term used to describe the successful delivery of user data bits per unit of time at the application level, excluding protocol overhead and retransmitted data packets.

Although goodput is the metric of most interest from a Smart Grid network application perspective, most wireless standards do not specify channel throughput or spectral efficiency at the application layer but instead focus on channel performance metrics at layer 1 and layer 2 (see Figure 6). For this group therefore, we ask for channel data throughput and spectral efficiency at the layer 2 - layer 3 interface. This is consistent with the evaluation methodology spelled out for International Mobile Telecommunications-Advanced (IMT-Advanced) in Report ITU-R M.2134[6]. In Figure 6 this is noted as the MAC rate. The data throughput and spectral efficiency at this layer includes the overhead factors introduced at the PHY and the Data Link layer including the MAC sublayer.

[6] Requirements related to technical performance for IMT-Advanced radio interfaces(s), see http://www.itu.int/pub/R-REP-M.2134-2008/en

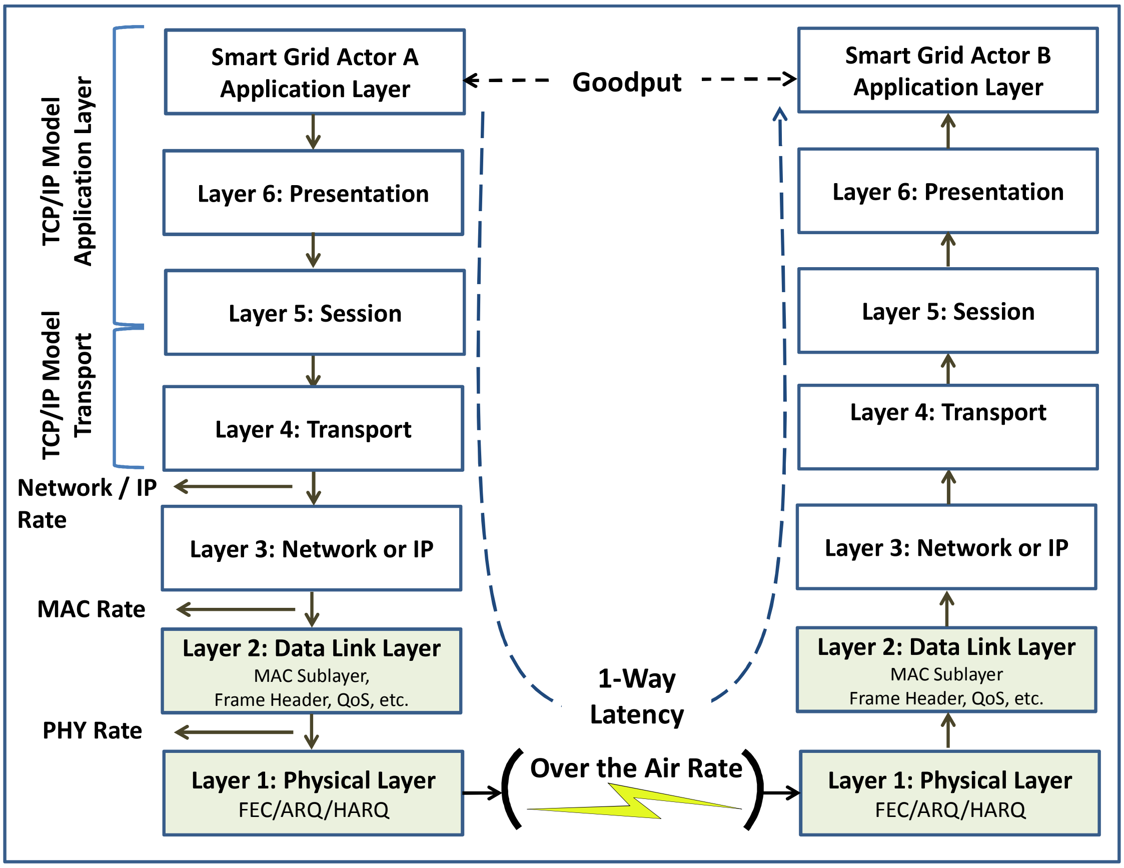


Figure 6 – Layers in accordance with OSI model

For the goodput it will be necessary to add the overhead introduced in the higher layers. These higher layer overhead factors would be quite similar for all technologies and include:

- Payload size
- Identity of the payload source
- Identity of the payload destination
- Security keys and encryption codes
- Error correction and detection codes
- Packet fragmentation codes
- Acknowledgements

There is also some overhead associated with establishing the data transmission channel (i.e., traffic channel) that is neither described above nor included in the goodput calculation. If this overhead value is available, it will be used in the framework and modeling tool. In addition there may be situations where packets are initially lost or corrupted and must be retransmitted. In these situations the data lost would further reduce the goodput delivery rate.

It is also important to differentiate between downlink and uplink. Some radio systems are designed with uplink and downlink data rates that are equal in both directions, whereas others support asymmetric rates. DL (also known as forward link or out-route) represents the data transmission from the central transmitter or base station (BS) to the client device receiver. UL (also known as return link or in-route) represents the data transmission from the client device transmitter to the central receiver. Typically the asymmetry is designed to provide a higher downlink rate than the uplink rate. This allows a central station or BS to take advantage of higher antenna height and transmit power that may not be practical on the client device.

There are several goals for the information submitted for this group. One is to get a measure of the peak OTA channel data rate in the UL and DL direction. A second goal is to get an assessment of the peak UL and DL channel data rates at layer 2. The latter value accounts for all of PHY and Data Link layer overhead including: error correction, control bits, packet headers, etc. The third goal is to gain a perspective for the average channel throughput and average channel spectral efficiency at the layer 1 - layer 2 interface for both the UL and DL channels.

Spectral efficiency is an important metric that measures how much data a given system can carry per unit of spectrum, and is typically given in units of bits/s/Hz. It is highly dependent on the channel modulation and coding scheme (MCS) being used. The average channel data capacity or average channel spectral efficiency is directly related to the average MCS over the channel or sector coverage area. Most, if not all, of today's access technologies make use of adaptive modulation and coding to account for differences in propagation path conditions on a link by link basis to individual user terminals. Terminals or client devices at or near the cell edge would be linked with the most robust MCS, which has relatively low spectral efficiency, whereas terminals close to the BS would generally experience a higher Signal to Noise Ratio (SNR) and thus support a higher efficiency MCS. The average MCS used by a terminal would lie somewhere between these two extremes. For comparative purposes, having an estimate for the average MCS and ultimately the average channel data rate is very desirable but, unfortunately, arriving at these values is not a straightforward process as it depends on a large number deployment-related factors. Most wireless access technologies have a specific evaluation methodology to simulate channel performance for typical deployment scenarios for either indoor or various outdoor venues. Although these evaluation methodologies have a lot of similarities they often cover a wide range of deployment scenarios and require a number of parameter inputs and assumptions to perform the simulations. Since reported results will often be based on different sets of assumptions, these simulations tend to be technology-specific. It is necessary therefore, to exercise care when using information derived from these simulations for comparative purposes.

To gain a better understanding for assessing the channel data rate and spectral efficiency at the layer 2 - layer 3 interface resulting from these simulations, this group provides the characteristics of the applicable evaluation methodology together with details regarding the input parameters used for the simulations.

The relationship between the net cell spectral efficiency and channel / sector spectral efficiency is dependent on the frequency reuse factor. For frequency reuse of 1 they will be the same whereas for a reuse factor of *n* the cell spectral efficiency will be 1/*n* times the sector spectral efficiency.

It is anticipated that the data rate and spectral efficiencies reported will typically apply to the layer 2 - layer 3 interface as described above. If for any wireless technology, these values are known for higher layers it should be noted.

Addendum to Group 5: Provide the characteristics of the evaluation methodology and the parameter assumptions for the simulations used to arrive at the average channel data rate and average spectral efficiency values in Group 5	
Note: If these parameters are not applicable to your specific technology, please provide a set of assumptions corresponding to your technology that were used in your simulation	
1) Base station cluster size	Integer value (e.g., 19)
2) Sectors per base station	Integer value (e.g., 3)
3) Frequency	GHz
4) Channel bandwidth	MHz
5) BS to BS spacing	km
6) BS antenna pattern	Omni or Azimuth in degrees and Front-to-Back Ratio in dB
7) Base station antenna height	m
8) Mobile terminal height	m
9) BS antenna gain	dBi
10) MS antenna gain	dBi
11) BS maximum Tx power	dBm
12) Mobile terminal maximum Tx power	dBm
13) Number of BS (Tx)×(Rx) antennas	Integer value (e.g., 2×2)
14) Number of MS (Tx)×(Rx) antenna	Integer value (e.g., 1×2, 2×2, etc.)
15) BS noise figure	dB
16) MS noise figure	dB
17) Frequency reuse factor	Integer value
18) Duplex	FDD / H-FDD / TDD
19) If TDD, what is UL to DL channel bandwidth ratio?	Ratio (e.g., 2 to 1)
20) Active users per sector or per BS	Integer value (e.g., 10 users per sector)
21) Path loss model (specify model or provide values for A in dB and n)	$PL = A_{dB} + 10n\log_{10}(d)$; where *d* is in km or COST231, WINNER II, etc.
22) Environment or terrain type	Indoor or Outdoor-urban / Outdoor-suburban, Urban-Micro-cell, etc.

23) Log-normal shadowing standard deviation	dB
24) Penetration loss (if applicable)	dB
25) Other link margins (if applicable) i.e., fast fading, interference, etc.	dB
26) Traffic type	FTP, VoIP, mixed, etc.
27) Multipath channel model and distribution	% Ped A, % Ped B, % Veh A, % Stationary, etc.
28) Number of paths	Integer value

4.2.1.6 Group 6: Spectrum Utilization

This group asks for display of information on radio spectrum use.

a) Public radio standard operating in unlicensed band
b) Public radio standard operating in licensed band
c) Private radio standard operating in licensed band

Some radio spectrum is license-exempt and is shared among a wide variety of devices. An example of this would be the 2.4 GHz Industrial Scientific and Medical (ISM) band which is generally available anywhere in the world but shared among diverse radio technologies, such as cordless phones, IEEE Std. 802.11 wireless local area networks (WLANs), IEEE Std. 802.15 personal area networks (including Bluetooth) devices, to name a few.

Some spectrum is sold and licensed to individual entities, such as a mobile phone service provider, and the designated spectrum (at least on a regional basis) is not expected to be used by any other radio type.

d) Duplex method - It is also generally assumed that smart grid radios will be both transmitting and receiving information. One method used to accomplish bi-directional transfer is time division duplexing (TDD) where uplink and downlink packets are alternated in time. Another method is frequency division duplexing (FDD) where uplink and downlink packets are carried on different frequencies. With FDD, DL and UL transmissions can take place simultaneously. A third duplexing approach is Half-duplex FDD (H-FDD). H-FDD also uses two separate channels but does not support simultaneous DL and UL transmissions. Some access technologies support both FDD for terminals which have a duplexing filter and H-FDD to support terminal designs which do not have a duplexing filter.

   When TDD is supported, technologies may also support adaptive or adjustable DL to UL traffic flow to improve channel spectral efficiency when traffic patterns are highly asymmetrical. For multi-cellular deployments adaptive TDD requires some form of sector-to-sector and cell-to-cell synchronization to mitigate interference.

e) If TDD is supported, provide details and characteristics. For example, Is adaptive or adjustable TDD supported and what synchronizations methods are employed?
f) Channel bandwidth - As with data rates, some radios use a very small amount of radio spectrum for their channel bandwidths (perhaps a few kilohertz (kHz)) while others may use a very large swath (perhaps several megahertz (MHz)).
g) Channel separation - This metric is intended to report the separation between channels.
h) Non-overlapping channels in the band

    To use an example, some IEEE Std. 802.11 radios operate in the 2.4 GHz unlicensed ISM band. Within the US there is 83.5 MHz of spectrum available; however, there are restrictions on out of band emissions (Described in Federal Communications Commission (FCC) Title 47). IEEE Std. 802.11 initially chose to use a spread spectrum technology that occupied 20 MHz of channel bandwidth. When the FCC rules and the technology choices are combined, the result is a technology that has 11 operating channels defined with center carrier frequencies separated by 5 MHz. Hence, in the 2.4 GHz band, the IEEE Std. 802.11 technology would be described as having 11 operating channels, separated by 5 MHz and three non-overlapping channels.

i) Support for universal frequency reuse - Most outdoor terrestrial deployments will use multi-sector BSs, with 3-sector BSs being the most common and the configuration most often assumed for simulations. Universal frequency reuse or a reuse factor of 1 indicates that the same channel can be reused in each of the three sectors. A reuse factor of three indicates that each sector is deployed with a unique channel. This deployment configuration requires three times as much spectrum as reuse 1 but will generally result in greater immunity to sector-to-sector and cell-to-cell interference. Although the channel or sector spectral efficiency will be higher for reuse three the increase is generally not sufficient to offset the fact that three times as much spectrum is required. The net cell spectral efficiency, therefore, will generally be higher with universal frequency reuse.

4.2.1.7 Group 7: Data Frames, Packetization, and Broadcast Support

This group asks for display of information on the packetization process.

A frame is defined as one unit of binary data that can be sent from one device to another device (or set of devices) sharing the same link. The term is used to refer to data transmitted at the Open Systems Interconnection (OSI) model’s Physical or Data Link layers (layer 1 and layer 2).

A packet is defined as one unit of binary data that can be routed through a computer network. The term is used to refer to data transmitted at the OSI model’s network layer (layer 3) and above.

a) What is the frame duration?

b) What is the maximum packet size that can be sent in one radio frame?
c) Does the radio system support layer 2 segmentation when the payload size exceeds the capacity of one radio frame?
d) Are unicast, multicast, and broadcast supported? (yes/no for each)

- Unicast: unicast is a form of message transmission where a message is sent from a single source to a single receiving node.
- Multicast: multicast is a form of message transmission where a message is sent from a single source to a subset of all potential receiving nodes. (The mechanism for selecting the members of the subset is not part of this definition.)
- Broadcast: broadcast is a form of message transmission where a message is sent from a single source to all potential receiving nodes.

4.2.2 Descriptions of Groups 8-12 Submissions

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
Group 8: Link Quality Optimization		
a:	Diversity technique	antenna, polarization, space, time
b:	Beam steering	Yes/No
c:	Retransmission	ARQ / HARQ / -
d:	Forward error correction technique	Yes/No (if Yes, please provide details)
e:	Interference management	Yes/No (if Yes, please provide details)
Group 9: Radio Performance Measurement and Management		
a:	RF frequency of operation	GHz
b:	Configurable retries?	Yes/No (if Yes, please provide details)
c:	Provision for received signal strength indication (RSSI)	Yes/No (if Yes, please provide details)
d:	Provision for packet error rate reporting	Yes/No (if Yes, please provide details)
Group 10: Power Management		
a:	Mechanisms to reduce power consumption	Yes/No (if Yes, please provide details)
b:	Low power state support	Yes/No (if Yes, please provide details)
Group 11: Connection Topologies		

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
a:	Point-to-point (single-hop)	Yes/No (if Yes, please provide details)
b:	Point-to-multipoint (star)	Yes/No (if Yes, please provide details)
c:	Multi-hop or multi-link	Yes/No (if Yes, please provide details)
d:	Statically configured or self-configuring multi-hop	Yes/No (if Yes, please provide details)
e:	Dynamic and self-configuring multi-hop network	Yes/No (if Yes, please provide details)
Group 12: Connection Management		
a:	Handover	Yes/No (if Yes, please provide details)
b:	Media access method (if applicable)	Specify (e.g., CSMA/CD, Token, etc.)
c:	Multiple access methods	Specify (e.g., CDMA, OFDMA, etc.)
d:	Discovery	Yes/No (if Yes, please provide details)
e:	Association	Yes/No (if Yes, please provide details)

4.2.2.1 Group 8: Link Quality Optimization

Radio systems can use a variety of techniques to improve the likelihood a transmitted packet will be successfully received. The most fundamental technique is to have the receiving radio send an acknowledgement back to the transmitting station. If the acknowledgement is not received, then the transmitter will try again (up to some limit of retries). This is called link layer Automatic Repeat-reQuest (ARQ). Other techniques seek to improve the SNR at the receiver. These techniques include diversity, advanced antenna systems such as beam steering, and forward error correction.

Interference can also impact link performance. Co-Channel Interference (CCI) can be caused by interference (Intra-operator interference) from adjacent sectors or other BSs in close proximity to the transmission link of interest. Adjacent channel interference may arise from systems operating in adjacent frequency bands (inter-operator interference). With shared spectrum, as would be the case in unlicensed bands, CCI can also arise from other wireless networks operating in the same geographical region. Some wireless systems have the capability of detecting and either avoiding or at least mitigating the impact of interfering signals to enhance Signal to Interference plus Noise Ratio (SINR).

4.2.2.2 Group 9: Radio Performance Measurement and Management

This group is used to indicate what the radio technology provides to an administrator to assist in link assessment. Most radio systems dynamically and autonomously assess their environment and adjust to optimize performance. Sometimes it is useful for a network administrator to monitor behavior to determine if problems exist that are impeding performance or perhaps make manual selections that might indeed improve radio performance beyond what might be achieved autonomously.

4.2.2.3 Group 10: Power Management

Radio devices may not be directly powered by mains power supply and may be required to “run off” a battery that is seldom, if ever, recharged. The intent is to capture information on techniques that the radio technology has defined that can be used to reduce power consumption.

4.2.2.4 Group 11: Connection Topologies

Radio systems may be designed and configured to use one or more connection topologies. A common topology is the star or point-to-multipoint topology as illustrated in Figure 7. This topology is common in today’s mobile (cellular) and fixed local area and wide area networks and can be expected to be a widely used topology in Smart Grid networks.

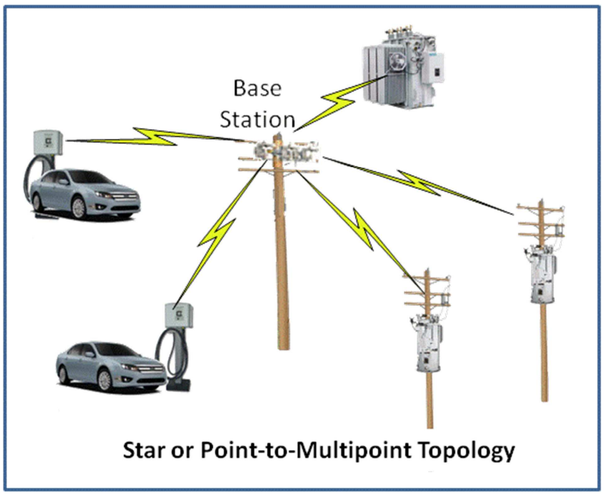


Figure 7 - Star or point-to-multipoint topology

Other wireless topologies that may be present in Smart Grid communication networks include the following:

a) Single-hop network: Also known as point-to-point, a single-hop network is one in which devices can only communicate with each other directly, e.g., over a single link (hop), and do not have the capability to forward traffic on each other’s behalf.
b) Multi-hop network: A multi-hop network is one in which devices have the capability to forward traffic on each other’s behalf and can thus communicate along paths composed of multiple links (hops).

A multi-hop network can take two forms. One form is a daisy chain of links (hops) that consists of a number of serial or tandem connected devices. This could serve to extend the reach of the network beyond the reach of an individual link. An example of this is illustrated on the left side of Figure 8. The other form of a multi-hop network is to form a tree or mesh topology. This could serve to provide connectivity to a number of devices located in a common geographic area, for example a number of AMI meters located in a neighborhood. An example of this is illustrated on the right of Figure 8. It should be noted in the example network diagram (Figure 8) that the two forms could be combined to extend the reach of the backhaul link to a mesh network.

i. Statically configured multi-hop network: A multi-hop network can be statically configured, such that each node's forwarding decisions are dictated by its pre-configured forwarding table.
ii. Dynamic and self-configuring multi-hop network: A multi-hop network can be dynamic and self-configuring, such that network devices have the ability to discover (multi-hop) forwarding paths in the network and make their own forwarding decisions based on various pre-configured constraints and requirements, e.g., lowest delay or highest throughput. This is a typical characteristic of current AMI mesh networks.

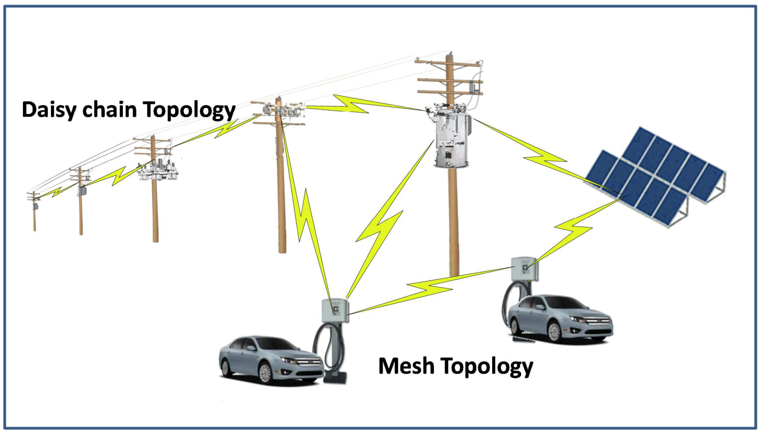


Figure 8 - Network diagram showing two types of multi-hop networks

4.2.2.5 Group 12: Connection Management

This group is intended to capture the capabilities provided to initiate and maintain radio connectivity.

a. Handover
b. Media access method, if applicable (e.g., CSMA/CD, Token, etc.)
c. Multiple access method (e.g., CDMA, OFDMA, etc.)
d. Discovery: The ability for the stations to discover available APs / routers / BSs in the area.
e. Association: Once authentication has completed, stations can associate (register) with an Access Point (AP) / router / BS to gain full access to the network. The

association is binding between the terminal or client and an AP such that all packets from and to the client are forwarded through that AP. Association typically involves the exchange of a small number of packets.

4.2.3 Descriptions of Groups 13-17 Submissions

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
Group 13: QoS and Traffic Prioritization		
a:	Radio queue priority	Yes/No (if Yes, please provide details)
b:	Pass-thru data tagging	Yes/No (if Yes, please provide details)
c:	Traffic priority	Yes/No (if Yes, please provide details)
Group 14: Location Based Technologies		
a:	Location awareness (x,y,z coordinates)	Yes/No (if Yes, please provide details)
b:	Ranging (distance reporting)	Yes/No (if Yes, please provide details)
Group 15: Security and Security Management		
a:	Encryption	Algorithms supported, AES Key length, etc.
b:	Authentication	Yes/No (if Yes, please provide details)
c:	Replay protection	Yes/No (if Yes, please provide details)
d:	Key exchange	Protocols supported
e:	Rogue node detection	Yes/No (if Yes, please provide details)
Group 16: Unique Device Identification		
a:	MAC address	Yes/No (if Yes, please provide details)

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
b:	Subscriber identity module (SIM) card	Yes/No (if Yes, please provide details)
c:	Other identity	Specify
Group 17: Technology Specification Source		
a:	Base standard SDO	SDO name
b:	Profiling and application organizations	Association / Forum Name

4.2.3.1 Group 13: QoS and Traffic Prioritization

Quality of Service (QoS) is a term that is used to describe a technology's ability to provide differentiated levels of performance to selected types of traffic. QoS can be viewed as an end-to-end requirement, but some radio systems assist in the process by supporting QoS between radio nodes. Generally this involves the ability to tag different data packets to establish a range of packet-priorities consistent with the type of information carried by the packet. QoS can be used to set priorities on data packets to ensure that there is sufficient bandwidth and that jitter, latency, and packet error rates are consistent with that required for satisfactory performance for the traffic type carried by the packet, whether it is voice, data, or streaming video.

Traffic categories fall into two generic types:

- real time - describing services that are sensitive to latency, jitter, and require a Guaranteed Bit Rate (GBR) for satisfactory performance; and
- non-real time - for services that are much more tolerant to variations in latency, jitter, and data rate.

Additionally, a Maximum Bit Rate (MBR) may also be imposed with any traffic type to prevent over-subscription by a single user or application.
Examples of real time or GBR services include:

- T1 / E1 leased line
- Voice with or without silence suppression
- Videoconferencing
- Real time gaming
- Streaming video or audio

Examples of non-real time or non-GBR services[7] include:

- IP Multimedia Subsystem (IMS) signaling and unicast polling
- Buffered video or audio
- Other services such as: web browsing, E-mail, file transfers (FTP), etc.,

This group is used to capture information regarding the capabilities for managing traffic priorities and supporting QoS. An important metric is the number of priority levels that are supported for either real time (or GBR) or non-real time (non-GBR) traffic.

[7] Best effort is a term often used to describe services in this category.

a. Radio queue priority refers to the ability of radio nodes to prioritize packets that are queued for transmission.
b. Pass-thru data tagging refers to the ability to transfer successfully packets that use a class of service priority tag, such as those defined by IEEE Std. 802.1p / 802.1Q
c. Traffic priority refers to the ability of radio systems to use high level priority.

4.2.3.2 Group 14: Location Based Technologies

Radio systems that provide information about their location can be helpful. One common form of location information would provide three-dimensional information regarding position, such as that provided via Global Positioning System (GPS) coordinates. Some technologies rebroadcast GPS ephemeris and almanac in an assisted GPS channel in order to reduce acquisition time for the GPS receiver. An alternate form would provide range information such that when the absolute location of every node is not known; if the location of one radio device was known, then at least the distance between the nodes could be provided.

4.2.3.3 Group 15: Security and Security Management

Ensuring that smart grid data is transferred securely is a high priority[8]. As with other entries such as QoS there are options to apply security measures at multiple layers in the communications OSI model. This group focuses on options provided by the radio system at layer 1 (PHY) and layer 2 (MAC).

4.2.3.4 Group 16: Unique Device Identification

It is desired that each radio node be directly identifiable and addressable. This requires that each device have a unique identification scheme. There is more than one way to accomplish this. The information provided will identify the unique identification scheme offered.

4.2.3.5 Group 17: Technology Specification Source

The intent is to provide information about the SDO that developed and maintains the radio technology, plus identify who provided the information contained in the matrix. Also, in some cases the base standard source is assisted by a compatriot organization that provides additional support including specifications or applications that operate above layer 2. The supporting organizations may also provide certification of specification compliance, interoperability and performance.

4.2.4 Group 18: Wireless Functionality not Specified by Standards

We asked the SDOs to provide ranges of values for these parameters which are generally not directly specified in the standard and will often be vendor-specific. Since these parameters play a key role in determining wireless performance, it is incumbent on the utility companies to work with their vendors to get more accurate values for these parameters.

The ranges provided are typical (not exhaustive) based on the experiences of the SDO community that has provided them.

[8] NISTIR 7628 Volumes 1 and 2

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Functionality / Characteristic		Measurement Unit
Typical wireless functionality NOT directly specified by a standard that is needed in quantifying operating metrics		
	Rx sensitivity	dBm
	Base station Tx peak power	dBm
	Subscriber station / user terminal Tx peak power	dBm
	Base station antenna gain	dBi
	Subscriber station / user terminal antenna gain	dBi
	Receiver thermal noise floor	dBm/Hz

Following is a list of additional characteristics that are needed to fully characterize the performance of the radio in a typical operating environment.

- Rx sensitivity - Receiver sensitivity may be specified as a minimum capability required by the SDO in the technology specification. Technology implementations may provide much greater sensitivity than the minimum, so the intent is to capture a typical value that is used for the operating point calculations.
- Base station Tx peak power – Transmission peak power to the antenna is needed for range calculations as well. Some technologies specify only a regulatory limit or allow for a number of options. The Tx power of the devices under consideration for the operating point calculations needs to be specified.
- Subscriber station (SS) / user terminal Tx peak power – Typical transmission peak powers delivered to the antenna for different user terminals are needed for range calculations as well.
- Base station antenna gain – BS antenna gain is rarely part of a technical radio standard, but is a critical component of link budget calculations.
- SS / user terminal antenna gain – Terminal antenna gains are rarely part of a radio standard and will also vary with the type of terminal. Where applicable provide typical antenna gains for different types of terminals.
- Thermal noise floor – Thermal noise floor is much like receiver sensitivity. There might be a minimal specification for noise floor required by the SDO in the technology specification. Technology implementations may provide a much lower noise floor than the minimum, so the intent is to capture a typical value that is used for the operating point calculations.

Although not specifically requested for in the capabilities matrix, the modulation and coding scheme is relevant for fully assessing the performance of the wireless technologies. We encourage the utility companies to work with their vendors to get the information regarding the modulation and coding schemes used by the corresponding technology.

Modulation is a method used to encode digital bits into a radio signal. There are dozens of different types of modulation technologies employed in wireless technologies. Modulation technologies are typically associated with an acronym. Acronyms that are commonly encountered include BPSK (binary phase shift key), FSK (frequency shift key), QAM (quadrature amplitude modulation) and dozens of variations on these themes. Simple modulation schemes convey one bit per time unit while high order modulation schemes can convey multiple bits per time unit. Transmission physics require that a relatively high signal to noise ratio exist at the receiver to enable low error decoding. Since entire books are dedicated to the topic, it is not appropriate for this guideline to try and identify or describe modulation options in detail.

Similarly, there are a wide variety of coding schemes for forward error correction (FEC), which are used to detect and correct errors incurred during transmission and reception. FEC adds bits to the transmitted data stream that are used by the receiver, in a carefully engineered algorithm, to determine if there were any errors in the reception and correct those errors if possible. There are numerous ways to construct the code and algorithms and a technical description of all the options is outside the scope of this guideline.

A transmission is comprised of a combination of modulation and coding. Each combination of a modulation and coding is referred to as a modulation and coding scheme (MCS). One wireless technology may have only a few such combinatorial options while another may have hundreds.

The reason for having options is to provide the wireless technology with a means to dynamically adapt the transmission in order optimize goodput under changing radio environments. This wireless dynamic is referred to as link adaptation or adaptive modulation and coding.

For example, high order modulation schemes such as 256 QAM require a significant signal to noise ratio in order to deliver packets at an acceptable packet error rate. If the signal strength falls, then the wireless system needs to choose a different combination of modulation and error correction to reduce packet errors and maintain the radio link.

4.3 Wireless Technology / Standard Submissions

Responses have been received for the following families of wireless access technologies / standards:

- ITU-T G.9959 (Z-Wave®)
- IG Band
- IEEE Std. 802.11™ family
- IEEE Std. 802.15.4™
- IEEE Std. 802.16™ family (WiMAX® / WiGRID™)
- GSM® Enhanced Data rates for GSM Evolution (EDGE)
- CDMA2000® 1x, High Rate Packet Data (HRPD) / EVDO and Extended Cell High Rate Packet Data (xHRPD)
- UTRAN (W-CDMA) and Evolved High-Speed Packet Access (HSPA+)
- E-UTRAN (Long Term Evolution (LTE™))
- Fixed Satellite Services (FSS) and Mobile Satellite Services (MSS)

Table 3 contains a more detailed listing of the submitted wireless technologies along with the sub-network for which it was designated for smart grid usage and the type of spectrum specified (i.e., licensed or unlicensed or both). Table 3 also indicates which technologies are assessed in section 6.7 for meeting SG network requirements. The framework and modeling tool used for this assessment is limited to terrestrially-based outdoor-located BSs with a PMP topology operating in frequency bands from 700 MHz to 6000 MHz.

Table 3: Listing of wireless technologies submitted

Wireless Technology	Sub-network (submitted)	Assessed in section 6.7	Licensed (L) or Unlicensed (UL) Spectrum
ITU-T G.9959 and Z-Wave wireless technologies	HAN		UL
IG Band (450 MHz - 470 MHz)	NAN, WAN		L
IEEE Std. 802.11	HAN, FAN	●	UL
IEEE Std. 802.11ah – Indoor / Outdoor	HAN, FAN, NAN	●	UL
IEEE Std. 802.11n	HAN, FAN	●	UL
IEEE Std. 802.11ac	HAN, FAN	●	UL
IEEE Std. 802.15.4	HAN, FAN, NAN	●	L, UL
IEEE Std. 802.16-2012 / WiMAX	WAN, FAN, NAN	●	L, UL
IEEE Std. 802.16.1-2012 / WiMAX 2	WAN, FAN, NAN	●	L, UL
IEEE Std. 802.161a-b / WiGRID	WAN, FAN, NAN	●	L, UL
GSM / EDGE Radio Access Network (GERAN)	WAN	●	L
cdma2000 1x	WAN	●	L
cdma2000 High Rate Packet Data (HRPD / EV-DO)	WAN	●	L
Extended High Rate Packet Data (xHRPD)	WAN	●	L
Universal Terrestrial Radio Access Network (UTRAN) (a.k.a. Wideband CDMA (W-CDMA))	WAN	●	L
Evolved High-Speed Packet Access (HSPA+)	WAN	●	L
Evolved Universal Terrestrial Radio Access Network (E-UTRAN) (a.k.a. Long Term Evolution (LTE))	WAN	●	L
Mobile Satellite Service (MSS) in L / S-Band	WAN		L
Fixed / Mobile Satellite Service (FSS / MSS) in Ku/Ka-band	WAN		L

5 Modeling and Evaluation Approach

Determining an assessment method for evaluating whether a wireless technology can satisfy the smart grid user applications' requirements is a daunting task, especially given that there are many possible physical deployment options for smart grid devices and facilities, many wireless technology standards, and uncertainty in anticipating future needs.

Some wireless technologies are a part of a larger system, while others are complete communication networks. For example, wireless technologies developed by many IEEE 802 working groups consider mostly the MAC sublayer and PHY. In many such cases, other non-IEEE specifications are used as the basis of a complete network specification. For example, the WiMAX Forum provides complete end-to-end specifications for fixed and mobile networks based on the IEEE Std. 802.16. Likewise, the Universal Mobile Telecommunications System (UMTS) is a complete mobile (and wireless) network system. For many reasons, including the differing scope of the basic specifications, comparing wireless technologies is a daunting task. PAP02 assesses different wireless technologies and provides tools and guidelines to help determine to what extent they can satisfy smart grid use case requirements but PAP02 will not attempt to rank the various wireless technologies relative to each other.

5.1 Assessment of Wireless Technologies with Respect to Smart Grid Requirements

The following assessment approach should be considered as an example, not the approach that must be used. Options are discussed on how the assessment can be refined by techniques further described and detailed in this section's subsections.

The two main tasks are:

1) Perform an initial screening of the wireless technologies against the smart grid business functional and volumetric requirements and
2) Perform refinements to the initial screening using one or a combination of the following:
    - Mathematical models
    - Simulation models
    - Testbeds (lab and in the field)

5.1.1 Initial Screening

The initial screening (technology assessment) is based on the smart grid user applications' requirements in section 3.4 and the wireless functionality and characteristics matrix in section 4. For example, a smart grid's application's requirement for reliability should be related to the wireless technology's availability to establish and maintain a communication link with an acceptable error rate. Likewise, smart grid requirements for range, data capacity, and latency must be considered when selecting technologies for further evaluation. One can use the results from the initial assessment provided in section 4 to determine whether a given wireless technology should be further considered for use in a particular network segment in a large scale smart grid communications network deployment. In making the wireless assessments it is very important to carefully consider the differences in baseline assumptions used for the different wireless technologies to arrive at the values entered into the matrix.

5.1.2 Refinements to Initial Screening

After the initial screening, the next step is to refine the assessment using other methods (i.e., mathematical models, simulations models, or testbeds).

5.1.2.1 Mathematical Models

These types of models require creating mathematical model representations that approximate the characteristics of the system in question (e.g., the smart grid). Mathematical models are often based on a combination of analytical and empirical techniques. These models can be simplistic in that event data volumetrics are aggregated to singular values, or events are treated as individual inputs into the models, or data volumetrics represented as inputs based on probabilities. Mathematical models usually take less time to produce results than simulation models, but there are some limitations to what some of the simpler mathematical models can adequately model.

5.1.2.2 Simulation Models

Simulation models attempt to account for more of the event occurrence variability than was described in the mathematical model discussion above. Since they take into account a greater number of variables, simulation models can provide more realistic results than mathematical models, which often require simplifying assumptions to make them tractable. As was shown in section 4, group 5, simulation models take into account a large number of deployment and equipment parameters resulting in results that are technology-specific making it difficult to make accurate comparisons. Although it would be desirable to have commonly accepted simulation model applicable to all of the wireless technologies, the development of such a model would be a complex and time-consuming process that is beyond the scope of this report.

5.1.2.3 Testbeds

Usually, neither mathematical or simulation model types are able to capture all of the details of a proposed network deployment (e.g., accurate channel models are difficult to obtain without direct measurement of the deployment environment). Using testbeds (in the lab and, preferably, in the field) can provide very accurate results; however, this method requires significant time, effort, and resources to produce results. Testbed results may also be provided as feedback to mathematical and simulation models to further validate or enhance the results.

5.1.2.4 Network Design

The key for network design is to understand and define the network's system design goals. Designing a network system to support the average data requirements is one design concept, which tends to result in under designed and built networks. Another concept is to design network systems that can handle the absolute worst case imaginable, which tends to result in over designed and built networks. Again the key is to establish a goal of the network and of the individual elements and threads of that network so that it will handle the heaviest expected (combined) burst rates with an acceptable level of failure. For example, in the old telephone trunk design days, one would specify the number of voice trunks necessary to carry the busy hour traffic with an acceptable level of failure (2 % failure, 5 % failure, etc.). This then leads to two questions that the network designers and implementers need to address, but are not answered in this guideline:

1) What is this highest level of traffic that must be accommodated over a specified burst period(s)?
    a. The methods for determining this will be highly dependent on the individual utility operational modes and the aggregated data that will flow through a particular network link or thread. As you can imagine, this will vary greatly from utility to utility and with the topology / technology used to construct the network threads.
2) What is an acceptable level of overloading these threads that will result in failure to deliver the data within the required latency and integrity constraints?
    a. This will depend on multiple factors, including the latency and integrity requirements of the system or application, buffering capabilities to buffer overflow traffic, and how error recovery is accomplished.

The utilities will need to implement systems that will satisfy the needs of that specific utility (i.e., one size does not fit all). So the network designers will need to find a way to project and predict the real temporal (and spatial) requirements of the data flows (for the utility, application, or operating mode in question) and then select and implement technologies and topologies that will provide the needed capacity, reliability, security, cost effectiveness, etc.

A general modeling framework was developed by the PAP02 working group and it is described in section 5.2.

5.2 Modeling Framework

The goal of the development process is to produce an analytical structure that is flexible enough to enable users to employ a variety of modeling techniques that can be used with virtually any proposed wireless technology. The framework's main components are a MAC sublayer model, a PHY model, a module that performs coverage analysis, a channel propagation model, and a model for multiple links (multi-link). The overall structure of the model is shown in Figure 9. The following subsections discuss each of these components and explain how they interact with each other and operate within the larger analytical framework.

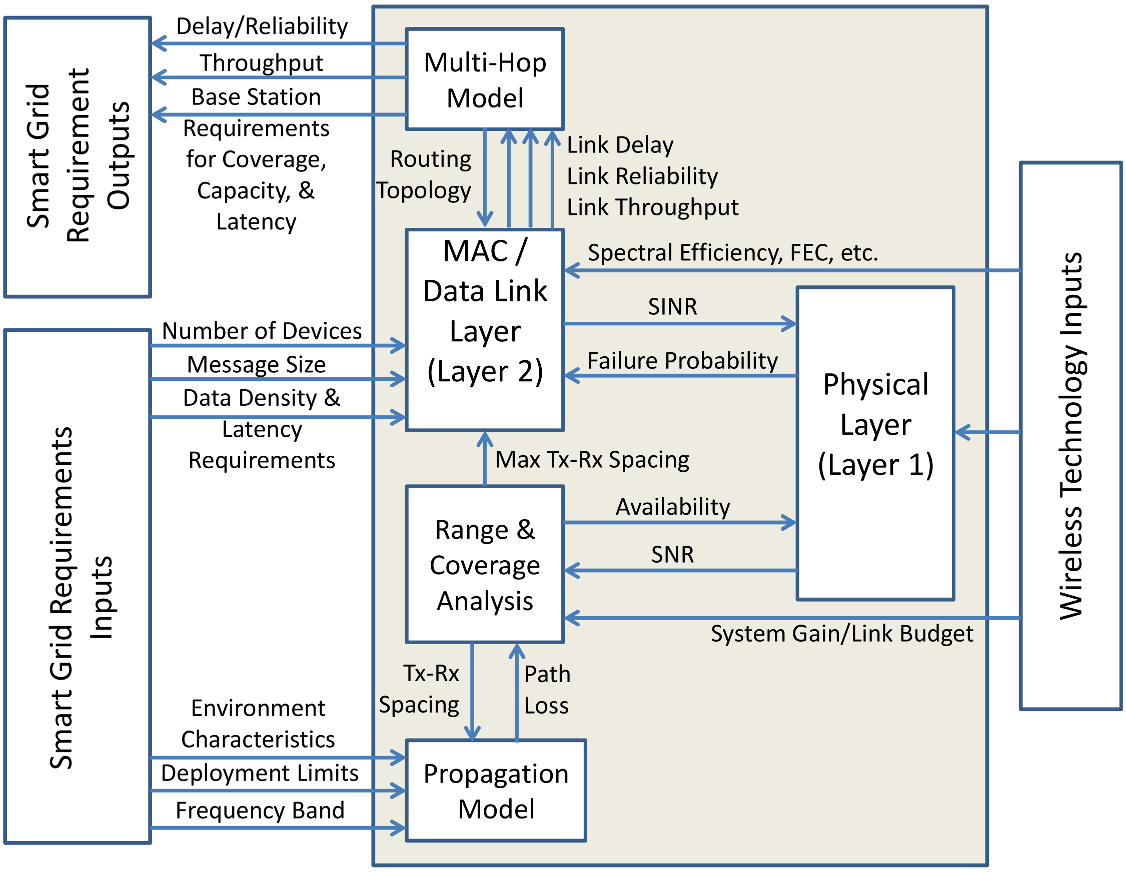


Figure 9 - Wireless modeling framework building blocks

5.2.1 Channel Propagation or Path Loss Models

Channel propagation or path loss models provide a means for characterizing how different wireless deployment environments impact a communications signal propagating along the wireless path between a transmitter and receiver. Since the attenuation of the transmitted signal directly impacts the signal to noise ratio at the receiver, it is the characteristic of greatest interest to the wireless communications designer. Other important characteristics are shadow fading, small-scale or fast fading, and penetration loss.

Signal attenuation is modeled through the quantity known as the path loss. It is important to recognize that a single path loss model cannot fully describe or predict path loss characteristics for all possible scenarios. Operating frequency and the characteristics of the deployment environment such as indoor, outdoor, urban, suburban, or rural; must be taken into consideration along with the location of the transmitter and receiver antennas relative to the obstacles that are likely to be encountered along the propagation path. In this section we look at various channel or path loss models that can be considered to predict path loss for terrestrial wireless networks.

5.2.1.1 Generic Path Loss Model

The path loss quantity, PL, models the attenuation of the signal in terms of the fraction of the received power to the transmitted power measured at the antennas. The deterministic component of the path loss, PL_d, is a function of the path distance, *d*, in meters between the transmitter and the receiver. The widely accepted model in the wireless propagation community predicts an exponential attenuation as a function of distance according to a path loss exponent, n_0. In non-line of sight environments, however, the degree of exponential fading increases to n_1 after a certain breakpoint distance, d_1. The breakpoint path loss model below (shown on a dB scale) captures this relationship:

$$PL_{d,dB}(d) = PL_{0,dB} + \begin{cases} 10n_0 \log_{10}(d/d_0), & d \le d_1 \\ 10n_0 \log_{10}(d_1/d_0) + 10n_1 \log_{10}(d/d_1), & d > d_1 \end{cases},$$

where d_1, in meters, is the breakpoint where the path loss exponent changes from n_0 to n_1, and $PL_{0,dB}$ is the reference path loss at $d_0 = 1$ m, given by the following equation:

$$PL_0 = 20\log_{10}(2\pi d_0/\lambda); \qquad \text{where } \lambda = \text{wavelength in meters}$$

The random component of the path loss ($PL_{r,dB} = X_{s,dB} + X_{f,dB}$) is composed from two terms. The first term, $X_{s,dB}$, is referred to as shadow fading. It represents the deviation of the signal from its predicted deterministic model due to the presence of large obstructions in the wireless path. Obstructions may be buildings or cars in the outdoor environment or partitions or furniture in indoor environments. These objects have varying size, shape, and material properties which affect the signal in different ways. $X_{s,dB}$ is modeled as a zero mean Gaussian random variable with standard deviation, σ, in dB, a log-normal distribution. The second term, $X_{f,dB}$, is referred to as small-scale or fast fading. It represents the deviation of the signal due to the presence of smaller obstructions in the path which cause scattering of the signal or multipath. These signals then constructively and destructively recombine at the receiver. X_f can be modeled as a unit-mean gamma-distributed random variable with variance $1/m$ (where m is the Nakagami fading parameter[9]) and $X_{f,dB} = 10 \log_{10}(X_f)$. The shadow fading and small-scale fading are assumed to be constant during the transmission of a frame, mutually independent, and independent of the fading occurring on other links. The complete path loss model, including both deterministic and random components, is given by:

$$PL_{dB} = PL_{d,dB} + X_{s,dB} + X_{f,dB} = PL_{d,dB} + PL_{r,dB}$$

Figure 10 shows an example of the path loss model extracted from actual measured data points. The deterministic component in red is fit to the blue data points collected in an indoor-to-indoor residential environment at a center frequency, f_c = 5000 MHz (5 GHz).

[9] Small-scale or fast fading is also often modeled as a Rayleigh distribution in non-line of sight environments or Rician when a dominant signal is present.

The deviation of the data points from the line reflects the contribution of the random component.

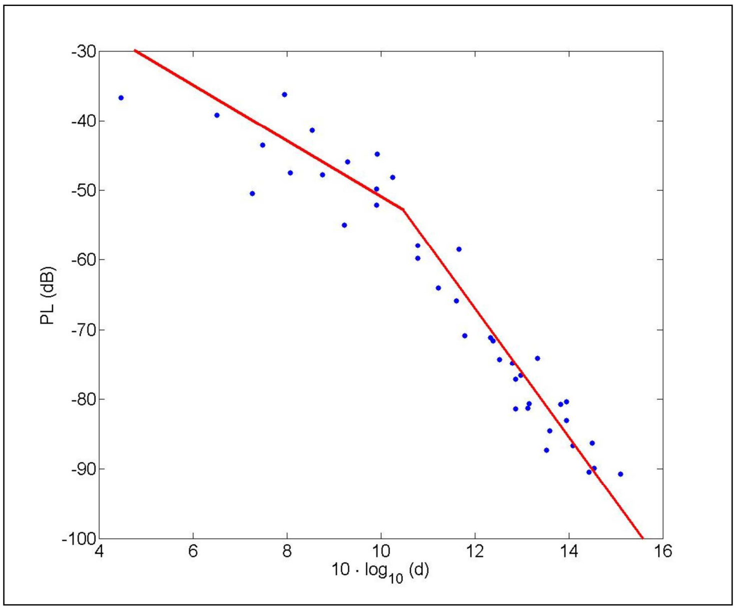


Figure 10 - Breakpoint path loss model for indoor-to-indoor residential environment at f_c = 5000 MHz

5.2.1.2 Indoor Path Loss Models

Assessing wireless performance in indoor environments is important for Smart Grid HANs which will generally operate in one or both of the license-exempt frequency bands at either 2400 MHz or 5000 MHz (2.4 GHz or 5 GHz). In addition to the HAN, a wireless solution may also be considered for aggregating data from basement or ground level meter clusters in multiple dwelling units and then via an indoor-to-indoor path, provide a means for connecting to individual HANs in a multi-story building to complete the end-to-end HAN-to-utility communication link.

As compared to outdoor networks, indoor networks for Smart Grid are characterized by:

- Shorter distances: Typically less than 100 meters
- Maximum BS or AP antenna heights constrained by ceiling heights: Typically 3 m to 5 m for office environments and 2.5 m to 3 m in residential environments.
- Lower antenna gains and lower transmit power to ensure EIRP is in compliance with FCC human exposure safety requirements[10] [6]: Must be < 1 mW/cm^2 for f > 1500 MHz and < f/1500 mW/cm^2 for 0.30 MHz < f < 1500 MHz (see Figure 11). For unlicensed spectrum, FCC Part 15.247 specifies a maximum EIRP of +30 dBm (1 watt)[11].

[10] RF exposure considerations are necessary when antenna locations are subject to accessibility by members of the public.

[11] Commercially available off-the-shelf APs have EIRPs that generally fall in the range of 200 mW to 300 mW well below the 1 watt allowed.

- The use of license-exempt ISM bands for indoor venues will be subject to interference from other applications in close proximity; microwave ovens, garage door openers, cordless phones, private WiFi networks, etc.

Smart Grid deployment requirements for indoor located BSs are:

- **Indoor BS or AP:** 0.5 meters to 5 meters above baseline
- **Indoor SSs / Terminals:** 0.5 meters to 5 meters above baseline
- **Special Situations:** Basement to customer connections (HANs) in multi-level residential and commercial buildings. This would require installations that favor upward directing antennas beams.

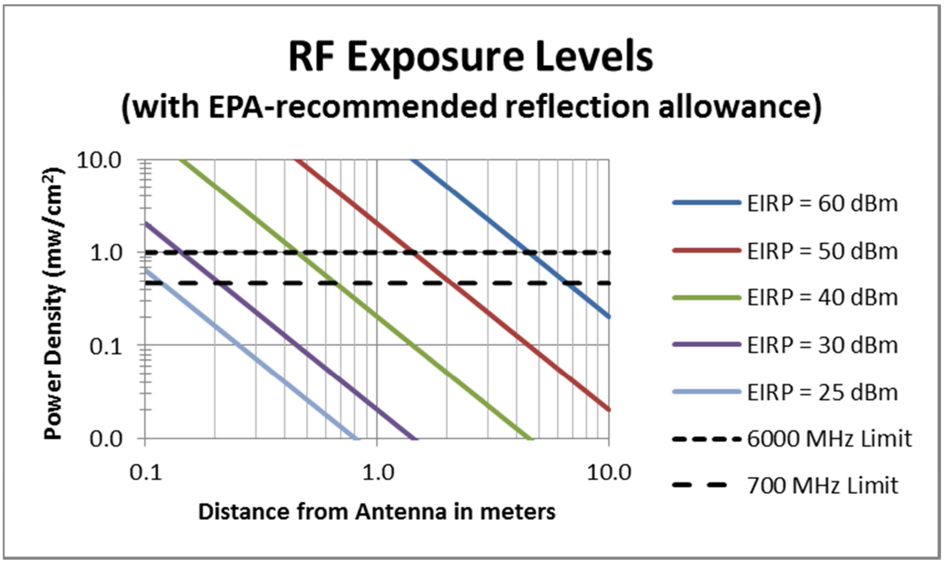


Figure 11 - RF exposure limits and EIRP

5.2.1.2.1 ITU-R M.1225 Indoor Model

The ITU-R M.1225 recommendation [7] was developed for the purposes of evaluating technologies for IMT-2000[12] in one of the 2000 MHz bands. The indoor model is based on the COST231 indoor model. The ITU-R M.1225 variant includes an unspecified number of walls or partitions in an office environment and a term to specifically account for floor loss. Since the formulation is designed for 2000 MHz, there is no frequency dependent term. The assumed antenna height for the SS is 1.5 m. The formulation for non-LoS indoor path loss is:

$$PL = 37 + 30\log_{10}(d) + 18.3 n_f^{[(n_f+2)/(n_f+1) - 0.46]}$$

where

d = path length in meters, $3 < d < 100$

[12] IMT (International Mobile Telecommunications) -2000 is the global standard for third generation (3G) wireless communications as defined by the International Telecommunications Union.

n_f = number of floors

In applying this model, the ITU-R M.1225 recommended allowance for shadow fading is 12 dB, a relatively large number.

The COST231 indoor model on which the ITU-R M.1225 model is based is more general and has the form:

$$PL = PL_{fs} + L_c + \sum n_w L_w + L_f n_f^{[(n_f+2)/(n_f+1)-b]}$$

where:
PL_{fs} = Free space loss
L_c = A constant, normally set to 37 dB
n_w = Number of penetrated walls
L_w = Loss per wall (3.4 dB for plasterboard internal walls and 6.9 dB for concrete or brick walls)
L_f = Loss between floors (18.3 dB assumed for typical office environment)
n_f = Number of penetrated floors
b = Empirically-derived parameter

The expression for the free space path loss is given by:

$$\mathbf{PL_{fs} = 20log_{10}(4\pi d/\lambda) = 20log_{10}(d) + 20log_{10}(f) - 27.56\ dB;}$$

where:
d is path length in meters and
f is frequency in MHz

5.2.1.2.2 WINNER II Indoor Model
The WINNER II Indoor Model is defined for an indoor office building environment in which the BSs or APs are installed in corridors. Transmissions from corridor to specific offices represent the non-LoS case. The model is based on measured data primarily at 2000 MHz and 5000 MHz. The formulation, which contains terms specifically for penetration through walls and floors, is:

$$PL = 43.8 + 36.8\log_{10}(d) + 20\log_{10}(f/5000) + X + [17 + 4(n_f - 1)]$$

where:
d = path length in meters, 3 m < d < 100 m, and
f = frequency in MHz from 2000 MHz to 6000 MHz
n_f > 0 is number of floors
n_w is number of walls the signal must pass through
$X = 5(n_w - 1)$ for light walls and $12(n_w - 1)$ for heavy walls.

At 2000 MHz the WINNER II expression becomes:

$$PL = 35.8 + 36.8\log_{10}(d) + X + [17 + 4(n_f - 1)]$$

The recommended allowance for shadow fading with the WINNER II indoor model is 4 dB.

WINNER II also provides a variation to the model for room-to-room transmissions. It is given by:

$$PL = PL_{fs} + X + [17 + 4(n_f - 1)]$$

where:
$X = 5n_w$ dB for light walls and $12n_w$ dB for heavy walls; and
n_w = the number of walls intersected by the signal.

This formulation does not have a specific term to account for excess loss due to clutter loss or shadowing, but recommended allowance for shadow fading is 6 dB for light walls and 8 dB for heavy walls.

5.2.1.2.3 ITU-R M.2135-1 Indoor Model

The test environment described for which the ITU-R M.2135-1 indoor model applies is a single floor in a building with 16 rooms and a long hall, 120 meters long and 20 meters wide. The formulation for the ITU-R M.2135-1 indoor model is:

$$\mathbf{PL = 11.5 + 43.3\log_{10}(\mathit{d}) + 20\log_{10}(\mathit{f}/1000)}$$

where:
d = path length in meters, 10 m < d < 150 m, and
f = frequency in MHz from 2000 MHz to 6000 MHz

The path loss formulation has a higher loss dependency on distance which can be explained by the number of wall penetrations called for in the described test environment. The expression is considered valid for AP antenna heights from 3 m to 6 m and SS heights from 1 m to 2.5 m. Shadow fading of 4 dB is recommended in the ITU-R M.2135-1 testing methodology.

5.2.1.2.4 NIST PAP02-Task 6 Model

NIST conducted studies for indoor-to-indoor, outdoor-to-outdoor, and outdoor-to-indoor propagation paths[13] [8][9]. In all cases the formulation presented in section 5.2.1.1 was fitted to the measured data, namely:

$$PL_d = PL_0 + 10n_0\log_{10}(d/d_0) \quad \text{for } d \le d_1$$
$$PL_d = PL_0 + 10n_0\log_{10}(d_1/d_0) + 10n_1\log_{10}(d/d_1) \quad \text{for } d > d_1$$

[13] See also http://www-x.antd.nist.gov/uwb for more measurement details

In the following non-LoS deployment scenarios for indoor-to-indoor, d_o is assumed to be 1 m and the remaining parameters are shown in the Table 4[14]. The results, using the above formulations, are plotted in Figure 12.

Table 4: Parameters for indoor-to-indoor non-LoS deployment scenarios

2400 MHz	PL_0 (dB)	n_0	d_1 (m)	n_1	σ (dB)
Residential	12.5	4.2	11.0	7.6	3.0
Office	26.8	4.2	10.0	8.7	3.7
Industrial	29.4	3.4	1.0	3.4	6.3
Cinder Block	9.1	6.9	1.0	6.9	6.7
5000 MHz	**PL_0 dB**	**n_0**	**d_1 (m)**	**n_1**	**σ (dB)**
Residential	20.2	4.4	11.0	7.4	3.3
Office	26.0	4.3	10.0	10.1	4.0
Industrial	27.5	3.7	1.0	3.7	6.7
Cinder Block	7.8	7.3	1.0	7.3	7.7

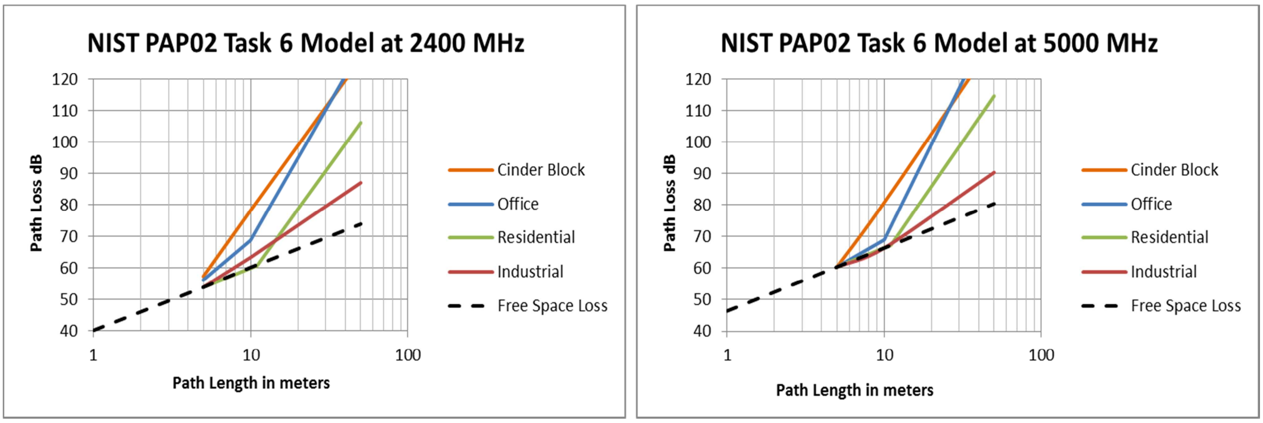


Figure 12 - Results for PAP02 Task 6 non-LoS indoor model

Many of the measurements for the PAP02 Task 6 model were taken with transmitters and receivers located in hallways with measurement distances ranging from 5 m to 45 m. The graphs in Figure 12, therefore, are limited to the 5 m to 45 m range and assume the greater of free space loss or model-predicted path loss to eliminate the impact of wave-guiding affects with hallway measurements.

5.2.1.2.5 Indoor Model Comparison

With the exception of the NIST PAP02 – Task 6 Model, the other three models are based on an office environment. The configurations used as the basis for the models differ thus

[14] The table in the cited reference only accounts for excess path loss, the value 2 is added to the path loss exponents in this case to provide a formulation for total path loss.

resulting in significant differences in the path loss predictions. The first difference to notice is the loss dependency relative to distance, ranging from 30 dB per decade for the ITU-R M.1225 model to 43.3 dB per decade for the ITU-R M.2135-1 model and up to 87 dB per decade for the PAP02-Task 6 Office Model for $d > 10$ m.

The WINNER II and ITU-R M.2135-1 indoor path loss models both assume that penetration losses between 2000 MHz and 6000 MHz are independent of frequency. Since these models are based on measurement data at 2000 MHz and 5000 MHz, this conclusion suggests that the indoor penetration losses are dominated by loss due to reflections as opposed to absorption losses in the wall material. Except for the residential case, the PAP02 – Task 6 model does predict an increase in excess loss with increased frequency as indicated by the increase in the parameter n_1 at 5000 MHz.

The four indoor models are compared at 2000 MHz in Figure 13. The plot for the WINNER II model is for corridor-to-room with a single light wall penetration. As a point of reference, the dashed line represents the free space path loss.

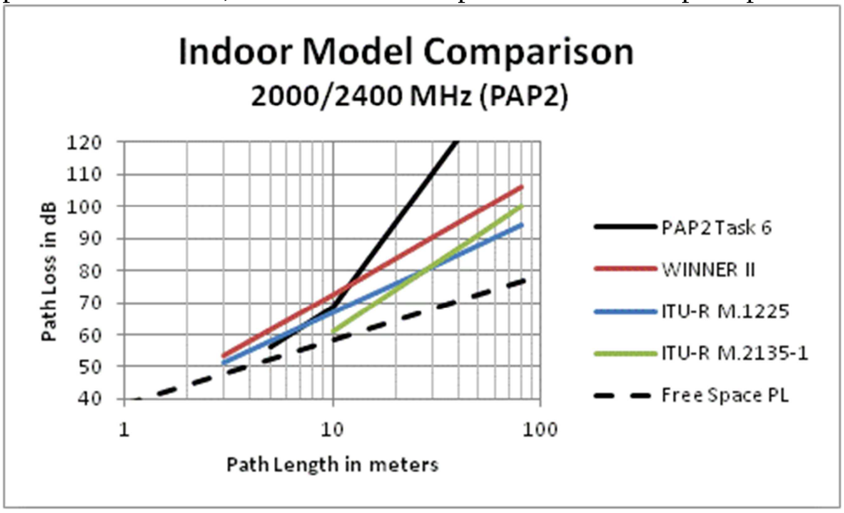


Figure 13 - Comparison of four indoor path loss models for office environment

Indoor path loss models will play a key role in coverage analysis for HANs and, although these models are based on office environments, they can be applied to residential environments using the predicted penetration loss for light walls: 3.9 dB (COST231) to 5.0 dB (WINNER II) per wall.

5.2.1.2.6 Modeling Floor-to-Floor Penetration Losses in Multilevel Buildings

Meeting the challenge of connecting basement-located meter clusters to individual households and businesses in multi-level apartment and office buildings is of great interest to utilities. Getting a reasonably accurate prediction for floor-to-floor penetration loss is essential for assessing the performance limitations for this use case.

Table 5 compares floor loss between the ITU and WINNER II indoor models and measurement data at 1900 MHz for three commercial office buildings [10][11]. The measured data includes, in parenthesis, the standard deviation for the multiple measurements done in conducting the tests. Although there are differences between these and other floor loss projections found in the literature, most likely attributable to the varied design and materials in the buildings used for the measurements, they all predict a higher attenuation for the first floor penetration and a lower attenuation for additional floors. The data for building #3 in fact showed virtually no change in loss after the first floor penetration. The measurement results shown in Table 5 also indicate a reduced spread in the collected data with increased floor penetrations. Unfortunately no measurement data could be found for buildings beyond five (5) stories.

The spread in the predictions between the two indoor path loss models for multiple floor penetrations is significant. Comparing the model predictions with the measured data at 1900 MHz suggests that a better estimate for penetration loss beyond the first few floors lies somewhere between what the two models predict.

Table 5: Comparison of floor loss between the ITU and WINNER II

Number of Floor Penetrations	Measured Path Loss at 1900 MHz [PL(σ)]			Predicted Path Loss	
	Building #1 in dB	Building #2 in dB	Building #3 in dB	ITU-R M.1225 Model (dB)	WINNER II Model (dB)
1	31.3 (4.6)	26.2 (10.5)	35.4 (6.4)	18.3	17.0
2	38.5 (4.0)	33.4 (9.9)	35.6 (5.9)	33.5	21.0
3		35.2 (5.9)	35.2 (3.9)	43.6	25.0
4		38.4 (3.4)		51.1	29.0
5		46.4 (3.9)		57.1	33.0
6				62.2	37.0

Table 6 summarizes the key differences between three of the indoor path loss models discussed in this section. None of the models predict a difference in excess path loss with frequency.

Table 6: Key differences in indoor models

Indoor Model	Frequency	Path Loss Exponent	Wall Loss	Floor Loss
ITU-R M.1225/COST231	2000 MHz	3.0	3.4 dB to 6.9 dB per wall	18.3 dB + 15 dB + 10 dB + 7.5 dB
WINNER II	2000 MHz to 6000 MHz	3.68	5 dB to 12 dB per wall	17 dB + 4 dB per floor
ITU-R M.2135-1	2000 MHz to 6000 MHz	4.33	Included in path loss exponent	Not specified

5.2.1.2.7 Indoor Model Summary

The differences in the predicted path loss for the four indoor models described in this section illustrate the limitations of the approach used to derive mathematical models. With indoor environments, it is especially difficult to identify a typical measurement environment from which to generate a mathematical model that would be generically applicable for either residential, office, or industrial environments. Factors such as building construction, types of materials, room layouts, along with the varied location, amount, and types of furnishings greatly impact the path loss data. At some frequencies, wave-guiding effects with transmitters and receivers located in hallways can also decrease path loss to values less than free space loss. Additionally, measurement data is often taken with tripod-mounted equipment with antenna heights that may not represent a permanent deployment which would generally have APs mounted at ceiling height. Indoor measurements can also be affected by structures and furnishings located within the near-field region of the transmitting antenna. The combination of these factors greatly complicates the data analysis and the subsequent derivation of a generic indoor path loss model.

Figure 13 can be used as a guide for judging which indoor model is most applicable for analysis and comparative purposes. The graph shows reasonably good correlation between the PAP02 Task 6, WINNER II, and ITU-M.1225 models for path lengths less than 15 meters whereas the two ITU models correlate quite closely for path lengths greater than 15 meters. Whichever indoor model is used it is important to be conservative in applying the predicted results for planning or estimating equipment requirements. In cases where unique environments are being considered, which may be the case for meter clusters in basement locations; it would be desirable to conduct on-site field tests to supplement the model predictions before committing to a permanent deployment.

5.2.1.3 Large Scale Outdoor Path Loss Models

In this section we look at a number of commonly used path loss models that can be considered for terrestrial “last mile” coverage analysis for assessing the suitability of wireless technologies for smart grid communications networks. All of these models have been derived from field measurements and, based on how and where the measurements were made, have some constraints that must be carefully considered before they are applied to any specific deployment scenario. The goal of this section is to provide a greater understanding of the benefits and limitations in using these models to predict total propagation path loss and ultimately provide an estimate for range and coverage for the wireless technology being considered for terrestrial wireless WAN, FAN, AMI, or backhaul deployments.

For Smart Grid wireless communication last mile network analysis, utilities require path loss models for outdoor terrestrial applications that are easy to apply and meet the following requirements for outdoor located BSs:

- **Frequency Range:** Path loss model must cover 700 MHz to 6000 MHz
- **BS Antenna Height Range:** 7 meters to 100 meters, below and above roof top levels
- **Terminal or SS Antenna Height Range:** Sub-grade to 2 meters above grade for exterior locations and 1.5 meters to 6.5 meters for interior locations for FANs and 1.5 meters to 10 meters for WANs.
- **Special Situations:** Terminals located in meter vaults, below grade, and in basement locations

- **Rural Regions:** Ranging from flat open areas to hilly or mountainous terrain with and without foliage
- **Suburban Regions:** 1- to 3-story residential with some commercial
- **Urban Regions:** Commercial and Industrial, large 1- to 4-story buildings, low foliage
- **Dense Urban Regions:** High rise residential and enterprise buildings

For outdoor located BSs several commonly used path loss models will be looked at in some detail and compared to the above requirements. Additionally, models developed specifically for predicting attenuation due to foliage and propagation path obstacles will be presented. This will lead to a suggested modification to one of the path loss models to provide a single path loss model that more closely fits the above utility requirements for suburban and rural areas over the frequency range of interest.

The large scale terrestrial models that will be reviewed are listed in Table 7.

Table 7: Terrestrial models

Path Loss Model	Applicable Frequency Range
Hata-Okumura	150 MHz to 1500 MHz
COST231-Hata	1500 MHz to 2000 MHz
WINNER II	2000 MHz to 6000 MHz
ITU-R M.2135-1	2000 MHz to 6000 MHz 450 MHz to 6000 MHz (for rural)
Erceg-SUI (Stanford University Interim)	1800 MHz to 2700 MHz

For simplicity in this discussion we will ignore the standard deviation that would apply to each of these models to account for the spread in the actual measured data as compared to the curve fit for the derived formulae. This zero-mean, log-normally distributed term can be taken into account when determining the link budget in the form of fade margin, a topic discussed later in this section. The fade margin will account for both slow log-normal shadow fading and fast fading with a value selected to meet a specific link availability goal.

For outdoor-to-indoor and indoor-to-outdoor propagation, building penetration loss must also be factored into the path loss or may be included in the link budget calculation. Both fading and penetration loss will be discussed further in following sections.

5.2.1.3.1 Hata-Okumura Model

Okumura's model is one of the first large scale models developed for wide area propagation and coverage analysis. The Okumura model is based on experimental data collected in the 1960s in the city of Tokyo, Japan [12] in the 900 MHz band. In 1980 M. Hata developed an expression to fit the path loss curves derived by Okumura [13]. The formulation for the Hata-Okumura model which is considered applicable from 150 MHz to 1500 MHz is:

For urban deployment the Path Loss in dB is given by:

$$PL_{urban\,dB} = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(T_h) - a(R_h) + [44.9 - 6.55\log_{10}(T_h)]\log_{10}(d)$$

$a(R_h) = 8.29[\log_{10}(1.54R_h)]^2 - 1.1$, **for 150 MHz < $f \le$ 200 MHz for large city**

$a(R_h) = 3.2[\log_{10}(11.75R_h)]^2 - 4.97$, **for 200 MHz < $f \le$ 1500 MHz for large city**

$a(R_h) = (1.1\log_{10}(f) - 0.7)R_h - (1.56\log_{10}(f) - 0.8)$, **for small to medium size city**

For suburban and open area deployments the path loss is given by $PL_{suburban\ dB}$ and $PL_{open\ dB}$, respectively.

$$PL_{suburban\,dB} = PL_{urban\,in\,dB} - 2\left[\log_{10}\left(\frac{f}{28}\right)\right]^2 - 5.4$$

$$PL_{open\,dB} = PL_{urban\,dB} - 4.78[\log_{10}(f)]^2 + 18.33\log_{10}(f) - 40.94$$

where:
d = path distance in km valid from 1 km to 20 km
f = frequency in MHz
T_h = BS antenna height valid from 30 m to 200 m (must be higher than average roof top or hill height)
R_h = SS or terminal antenna height from 1.0 m to 10 m.

In addition to the limited frequency coverage, a significant limitation for the Hata-Okumura model is the requirement that the BS antenna height must be higher than the average building height in the coverage area. Within these constraints, the model has proven to be an effective planning tool for cellular networks in the lower frequency bands.

5.2.1.3.2 COST231-Hata aka Modified Hata Model

The COST231-Hata model represents an extension of the Hata-Okumura model to cover frequencies higher than 1500 MHz [14]. The COST231 path loss model is considered valid from 1500 MHz to 2000 MHz and has been used extensively to analyze coverage for mobile communications in the 1900 MHz band.

The COST231-Hata model, with a slight modification[15], is specified in the 3GPP2 evaluation methodology for CDMA2000 [15]. The formulation for the COST231-Hata path loss model is given by:

$$PL_{dB} = A + B\log_{10}(f) - 13.82\log_{10}(T_h) - a(R_h) + [44.9 - 6.55\log_{10}(T_h)]\log_{10}(d) + 0.7R_h + C$$

where:
d = path length in km
f = frequency in MHz from 1500 MHz to 2000 MHz
A = 46.3
B = 33.9
T_h = BS antenna height from 30 m to 200 m (must be higher than average roof top height)
R_h = SS antenna height from 1.0 m to 10 m

For Urban Environments:

$$a(R_h) = 3.2[\log_{10}(11.75R_h)]^2 - 4.97$$

and C = 3 dB

For Suburban Environments:

$$a(R_h) = [1.1\log_{10}(f) - 0.7]R_h - [1.56\log_{10}(f) - 0.8]$$

and C = 0

The limitations of the COST231-Hata model are similar to the Hata-Okumura model, namely, limited frequency coverage and the requirement that BS antenna heights must be above surrounding roof tops.

5.2.1.3.3 WINNER II Model

The WINNER II project, initiated in 2006 as an extension to WINNER I, is a consortium focused on technologies for IMT-2000. One key output of this effort is the development of path loss models covering the frequency range from 2000 MHz to 6000 MHz using a combination of information available in the literature and applicable measurements contributed by the consortium members. The output is a collection of

[15] The path loss is reduced by 3 dB from the COST231-Hata prediction for the purposes of the 3GPP2 evaluation methodology

models for both LoS and non-LoS for both indoor and outdoor venues [16].

The following three variants of the WINNER II models are selected for description in this section.

C2 – Urban macro-cell, non-LoS:
$PL_{dB} = [44.9 - 6.55\log_{10}(T_h)]\log_{10}(1000d) + 34.46 + 5.83\log_{10}(T_h) + 23\log_{10}(f/5000)$

C1 – Suburban macro-cell, non-LoS:
$PL_{dB} = [44.9 - 6.55\log_{10}(T_h)]\log_{10}(1000d) + 31.46 + 5.83\log_{10}(T_h) + 23\log_{10}(f/5000)$

D1 – Rural macro-cell, non-LoS:
$PL_{dB} = 25.1 \log_{10}(d) + 55.4 - 0.13 \log_{10}(T_h\text{-}25) \log_{10}(d/100) - 0.9 \log_{10}(R_h\text{-}1.5) + 21.3 \log_{10}(f/5000)$

where:
d = path length in km
f = frequency in MHz from 2000 MHz to 6000 MHz
T_h = BS antenna height in meters from 25 m to 100 m (higher than roof top height)
R_h = terminal antenna height in meters for > 1.5 m

5.2.1.3.4 ITU-R M.2135-1 Model
ITU-R M.2135-1 provides recommendations for IMT-Advanced[16] and specifically lays out the guidelines for the IMT-Advanced technology evaluation methodology [17]. It has been adopted by both LTE and WiMAX / IEEE Std. 802.16 as an evaluation methodology. The path loss models adopted for ITU-R M.2135-1 are based on the WINNER II path loss models.

As with WINNER II several deployment scenarios are defined, each with specific recommendations for BS and terminal antenna heights. The ITU-R M.2135-1 formulation requires two additional parameters (average building height and average road width) thus making it somewhat more difficult for city to city comparisons. Average road width provides a means to indirectly infer building density.

Since the values for building height and average road width can be used to differentiate between urban, suburban, or rural macro-cells, a single formulation applies for all three demographic scenarios. Recommended values for building heights, road widths, and antenna heights for each geographic area are provided for the purposes of IMT-Advanced technology evaluations but the formulation is considered valid for a wide range of building heights and road widths. The ITU-R M.2135-1 formulation is:

[16] International Mobile Telecommunications - Advanced (IMT-Advanced), aka 4G, defines a global platform for mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000.

$$PL_{dB} = 161.04 - 7.1\log_{10}(W) + 7.5\log_{10}(H) - \left(24.37 - 3.7\left(\frac{H}{T_h}\right)^2\right)\log_{10}(T_h) + (43.42 - 3.1\log_{10}(T_h))(\log_{10}(1000d) - 3) + 20\log_{10}\left(\frac{f}{1000}\right) - (3.2(\log_{10}(11.75R_h))^2 - 4.97)$$

Where:
d = path length in km
f = frequency in MHz applicable from 2000 MHz to 6000 MHz for urban and suburban environments and 450 MHz to 6000 MHz for rural environments
W = average road width in meters from 5 m to 50 m
H = average building height in meters from 5 m to 50 m
T_h = BS antenna height in meters from 10 m to 150 m (must be above average building height)
R_h = terminal or SS height in meters from 1 m to 10 m

Although this model accommodates lower BS antenna heights, as with the previous models the BS antenna height must still be above the surrounding roof tops. There is another variant of the ITU-R M.2135-1 model however, that does support BS antenna heights below roof tops.

Described as Urban Micro-cell, this model is based on a Manhattan-like grid layout specifically for BS antenna heights well below the roof tops of surrounding buildings. The effective coverage area for this scenario is defined by signals propagating along streets on which the BS is located and diffracting around the corners of buildings along streets that are perpendicular as illustrated in Figure 14. Except for blockages due to passing vehicles, outdoor SSs along the street on which the BS is located will be mostly LoS while outdoor SSs on perpendicular streets will receive signals diffracted around the corners of buildings. These signals will typically be stronger than signal components penetrating through the buildings to reach the same end-point. This model also includes a formulation to cover outdoor-to-indoor paths which would be of greatest interest for Smart Grid FAN applications.

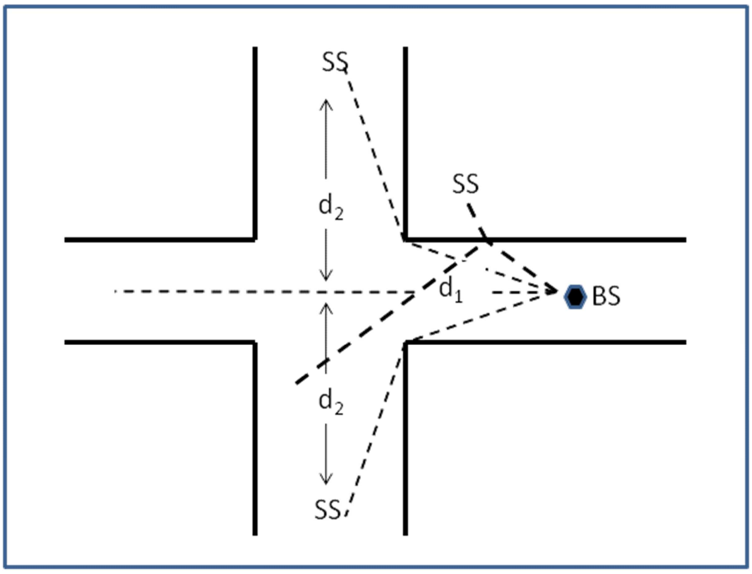


Figure 14 - Various transmission paths for urban micro-cell

For non-LoS outdoor, assuming a hexagonal cell layout, BS antenna height at 10 meters, SS antenna height from 1 m to 2.5 m, and a street width of 20 meters, the formulation is:

$$\mathbf{PL_{dB} = 36.7log_{10}(\mathit{d}) + 22.7 + 26log_{10}(\mathit{f})}$$

For: 10 m < *d* < 2000 m and 2000 MHz < *f* < 6000 MHz

For the outdoor-to-indoor scenario, the channel model comprises an outdoor component, an indoor component, and a value for penetration loss which, in general, is dependent on the angle of incidence to the building. For an unspecified angle of incidence, the building penetration loss is assumed to be 20 dB.

The formulation, assuming a hexagonal cell layout, BS antenna height of 10 m, and an SS antenna height between 1 m and 2.5 m is:

$$\mathbf{PL_{dB} = 20\ dB + PL_{out} + PL_{in}}$$

For the outdoor component the distance is defined as the distance from the BS to the wall next to the indoor terminal and the distance for the indoor calculation is assumed to be evenly distributed between 0 m and 25 m (i.e., 12.5 m).

5.2.1.3.5 Erceg-Stanford University Interim (SUI) Model

The Erceg model is a statistical path loss model based on propagation data collected in 95 different suburban environments throughout the United States at or close to a frequency of 1900 MHz [18][19]. To cover the range of encountered terrain and foliage characteristics for the data analysis, the environments were broken down into the following terrain categories.

- **Terrain Type A:** Hilly with moderate to heavy tree density.

- **Terrain Type B:** Hilly with light tree density or flat and moderate to heavy tree density.
- **Terrain Type C:** Flat with light tree density.

The time of year was such that in most of the test locations leaves were on the trees, thus representing a worse case path loss scenario. BS antenna heights were in the range of 12 m to 79 m.

This model is especially interesting for Smart Grid network applications in that it is based on measurements taken in areas throughout the United States representative of rural and suburban areas of interest to the utilities companies at BS antenna heights close to what utility requirements have specified.

The formulation for the Erceg-SUI model is:

$$PL_{dB} = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\left(a - bT_h + \frac{c}{T_h}\right)\log_{10}\left(\frac{d}{d_0}\right) + 6\log_{10}\left(\frac{f}{2000}\right) - X\log_{10}\left(\frac{R_h}{2}\right)$$

where:
T_h = BS antenna height in meters,
R_h = terminal or SS antenna height in meters,
d_0 = 100 meters,
λ = wavelength in meters,
f in MHz, and
d in meters.

The remaining parameters are terrain dependent and defined in Table 8.

Table 8: Parameters for terrain types

Parameter	Terrain Type A	Terrain Type B	Terrain Type C
a	4.6	4.0	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20
X	10.8	10.8	0

5.2.1.3.6 Comparing Large Scale Path Loss Models to Smart Grid Requirements

All of the large scale outdoor models discussed have limitations with respect to meeting the deployment requirements for Smart Grid applications that were outlined in section 5.2.1.3. No single model as described covers the entire frequency band of interest thus necessitating the need to apply at least three different path loss models to evaluate spectrum differences over the desired 700 MHz to 6000 MHz frequency range. This can be an issue for technology comparative purposes since it is not assured that any two models will produce a similar result at a frequency considered valid for the two models.

Other limitations of these models are summarized in Table 9.

Table 9: Path loss models' limitations

Path Loss Model	Limitations	Smart Grid Requirements
Hata-Okumura 150 MHz to 1500 MHz	-BS antenna height ≥ 30 m and above roof tops - Favors urban / suburban environments - Limited frequency coverage	-BS antenna height from 7 meters to 100 meters above and below roof top heights - Urban, suburban, rural (with foliage, hills, and valleys) - Applicable from 700 MHz to 6000 MHz
COST231-Hata 1500 MHz to 2000 MHz	-BS antenna height ≥ 30 m and above roof tops - Limited frequency coverage	
WINNER II 2000 MHz to 6000 MHz	-BS antenna height ≥ 25 m and above roof tops - Limited frequency coverage	
ITU-R M.2135-1 2000 MHz to 6000 MHz 450 MHz to 6000 MHz (For rural)	-BS antenna height must be above roof tops - Limited frequency coverage for urban and suburban	
ITU-R M.2135-1 Urban Micro-cell	-BS antenna height fixed at 10 meters - Limited range for SS antenna height - Manhattan-like grid structure - Limited frequency coverage	
Erceg-SUI 1800 MHz to 2700 MHz	-BS antenna height ≥ 10 m -Based on suburban / rural measurements - Limited frequency coverage	

To specify or recommend a model to meet Smart Grid requirements it will be necessary to develop a new model based on extensive field measurements in varied environments or consider modifications to one of the existing models to increase its applicability. For the latter approach we have to look at some additional path loss models.

5.2.1.3.7 Path Loss Due to Foliage

Accurately predicting propagation path excess loss due to foliage, as has been pointed out in numerous studies, is a complex process. Based on information reported several conclusions can be drawn with respect to path loss due to foliage.

- Vertically polarized signals experience higher attenuation than horizontally polarized signals in lower frequency bands

- Increases with frequency
- Does not increase linearly with depth of foliage
- There is a limiting value since signals will diffract around foliage
- Is dependent on type of tree or foliage; a 3:1 range in attenuation coefficient was found in a University of Texas study [20]
- Higher attenuation when trees are fully leaved
- Higher attenuation when trees are wet

Despite the above variations that complicate the adoption of a single universally applicable model, attempts have been made to derive closed form expressions to characterize excess path loss due to foliage [21].

Three easy to apply models for excess loss due to foliage (L_f in dB) are [22], [23]:

- Early ITU model: $\boldsymbol{L_f = 0.20f^{0.3} \times d_f^{\,0.6}}$
- Optimized or fitted ITU-R (FITU-R) Model for foliage in leaf:

$$\boldsymbol{L_f = 0.39f^{0.39} \times d_f^{\,0.25}}$$

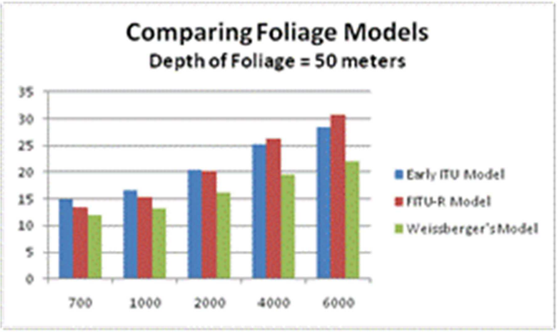
- Weissberger model [24]:

$\boldsymbol{L_f = 0.0633f^{0.284} \times d_f^{\,0.6}}$ for $d_f \leq 14$ m

$\boldsymbol{L_f = 0.187f^{0.284} \times d_f^{\,0.588}}$ for 14 m < $d_f \leq 400$ m

where:
f is in MHz and
d_f is the depth of foliage in meters.

Figure 15 provides some comparisons between these three models over the spectrum of interest and for foliage depths of 50 m and 150 m. Figure 16 shows the foliage loss predicted by Weissberger's model for foliage depths up to 400 m.



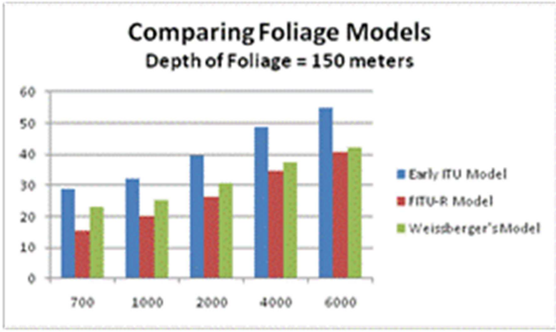


Figure 15 - Comparison of foliage models

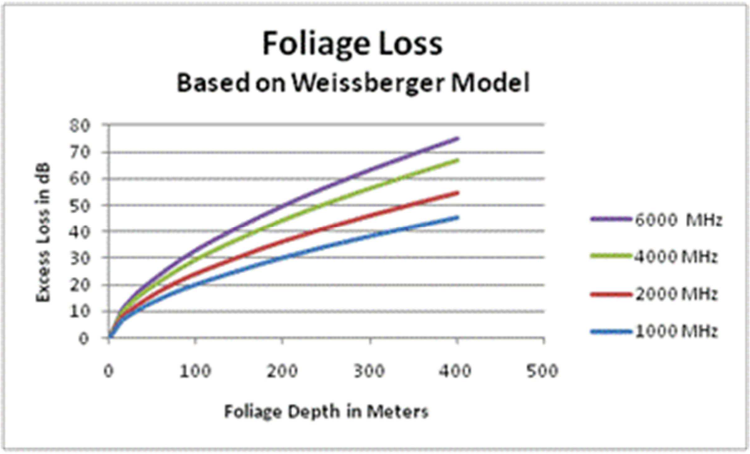


Figure 16 - Foliage loss predicted by Weissberger's model

5.2.1.3.8 Path Loss Due to Path Obstructions

Except for the Erceg-SUI Model, all of the large scale path loss models discussed above are based on scenarios for which the BS antenna height is at or above surrounding roof tops thus avoiding the possibility of obstacles blocking the signal path prior to diffracting over roof edges for coverage at street level as illustrated in Figure 17.

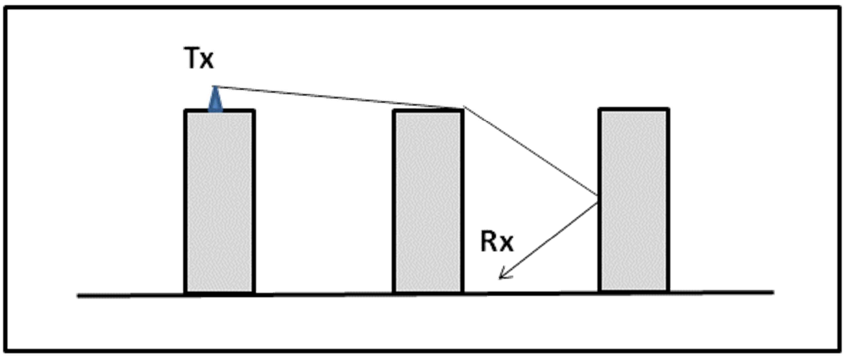


Figure 17 - Diffraction over roof tops for street level coverage

Over the years numerous models and algorithms have been developed with varied complexity to predict the path loss due to terrain obstacles. The Epstein-Peterson Diffraction Model, presented in this section, appears to be a reasonable compromise between prediction accuracy and ease of use [25].

The formulation for diffractive loss, (L_d in dB), due to an obstruction is as follows:

$$L_d \text{ (in dB)} = L(v,0) + L(0,p) + L(v,p)$$

Where:

$L(v,0) = 6.02 + 9.0v + 1.65v^2$; for $-0.8 \le v \le 0$
$L(v,0) = 6.02 + 9.11v - 1.27v^2$; for $0 < v \le 2$.
$L(v,0) = 12.953 + 20\log(v)$; for $v > 2$.

and

$L(0,p) = 6.02 + 5.556p + 3.418p^2 + 0.256p^3$

and

$L(v,p) = 11.45vp + 2.19(vp)^2 - 0.206(vp)^3 - 6.02;$ for $vp \le 3$
$L(v,p) = 13.47vp + 1.058(vp)^2 - 0.048(vp)^3 - 6.02;$ for $3 < vp \le 5$
$L(v,p) = 20vp - 18.2;$ for $vp > 5$

$$p = 0.676R^{0.333} \times f^{-0.1667}\sqrt{\frac{d}{(d_1 d_2)}}$$

where
R = obstacle radius in km,
f in MHz, and
$d = d_1 + d_2$

$v = h\,[2\,d/(\lambda d_1 d_2)]^{0.5} = h[fd/(150 d_1 d_2)^{0.5]}$;
where
f is in MHz,
h is the obstruction height in meters, and
d in meters

For $R = 0$ (denoting knife-edge); $L(0,p) = L(v,p) = 0$, and $L_d = L(v,0)$

Figure 18 for diffraction loss assumes a 500 m path length and path obstructions of 0.5m, 1.0 m, and 2.0 m.

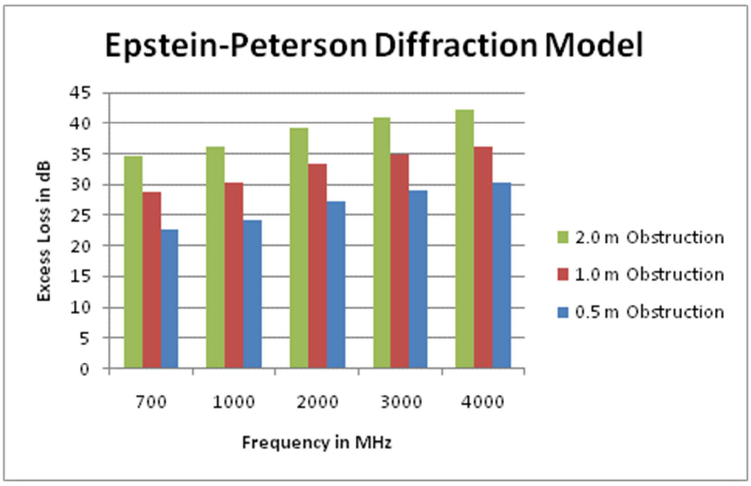


Figure 18 - The Epstein-Peterson diffraction model

For multiple path obstructions, each obstruction is treated separately and then added to yield the total path excess loss due to obstructions. This is illustrated in Figure 19.

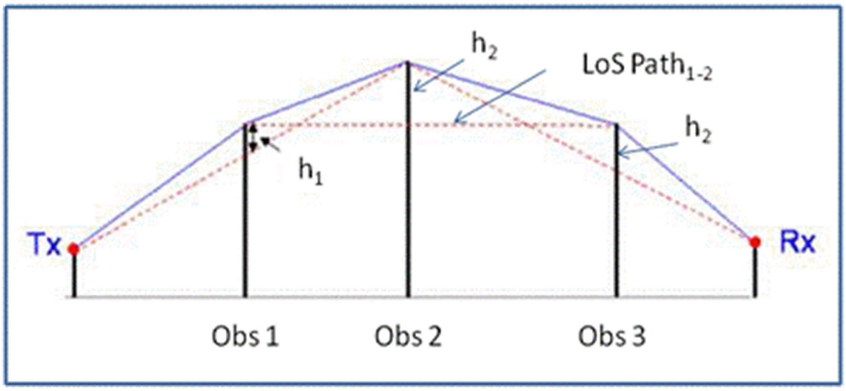


Figure 19 - Accounting for multiple terrain obstructions

5.2.1.3.9 Modified Erceg-SUI Model

Although any of the large scale path loss models described to this point may be selected and applied to a specific smart grid use case under conditions that fit the constraints of the model being used, the more extreme smart grid requirements cannot be met with the formulations as they are described. The Erceg-SUI model comes closest to meeting the stated goals at least for suburban and rural regions, since the testing environments did in fact include foliage and hilly terrain in conjunction with relatively low BS antenna heights. However, as is also the case for the other path loss models, the frequency range for which the Erceg-SUI is considered valid is limited to a small portion of the required 700 MHz to 6000 MHz range.

Further study of the Erceg-SUI path loss expression suggests that a simple modification to the term that determines the sensitivity of excess loss to frequency can increase the applicability of the Erceg-SUI model over a broader frequency range. The proposed modification is as follows:

- The term, $\mathbf{6\log_{10}(\mathit{f}/2000)}$, is modified[17] to: $\mathbf{6(1 + \mathit{ak}/\mathit{T_h})\log_{10}(\mathit{f}/2000)}$.

For $k > 0$ this will have the effect of increasing the excess loss frequency dependency without altering the path loss at 2000 MHz, the frequency at which the original data was collected. The modification also results in a frequency dependency that is greater with lower BS antenna heights as would be expected, since the impact of foliage and losses due to obstacles will be more significant with lower antenna heights. The resulting formulation for total path loss is then:

$$PL_{dB} = 20\log_{10}(4\pi\, d_0/\lambda) + 10(a - bT_h + c/T_h)\log_{10}(d/d_0) + 6(1 + ak/T_h)\log_{10}(f/2000) - X\log_{10}(R_h/2)$$

[17] This modification was arrived at after discussions with Vinko Erceg one of the principal investigators involved with the testing and derivation of the Erceg-SUI path loss model.

Table 10 shows the resulting excess loss frequency dependency, referenced to 2000 MHz, in dB per octave, for $k = 4$. The row with $k = 0$ represents the excess loss frequency dependency for the original Erceg-SUI formulation. The proposed modification results in an excess loss dependency on frequency, relative to 2000 MHz, that increases with lower BS antenna heights. This is consistent with the expectation that excess loss due to foliage and terrain obstacles would be more significant with lower antenna heights. For comparative purposes the following table includes the excess loss frequency dependency for the other large scale terrestrial path loss models discussed thus far.

Table 10: Model and its path loss dependence in dB per octave

Path Loss Model	k	T_h	PL Frequency Dependence in dB/octave		
			Type A	**Type B**	**Type C**
Erceg-SUI	0	Any	1.81 dB	1.81 dB	1.81 dB
Modified Erceg-SUI	4	80 m	2.22 dB	2.17 dB	2.13 dB
	4	50 m	2.47 dB	2.38 dB	2.33 dB
	4	30 m	2.91 dB	2.77 dB	2.67 dB
	4	10 m	5.13 dB	4.70 dB	4.41 dB
			Urban	**Suburban**	**Rural**
Hata-Okumura		30 m	1.85 dB	1.38 dB	
COST231-Hata		30 m	4.18 dB	3.71 dB	
WINNER II		25 m	0.9 dB	0.9 dB	
ITU-R M.2135-1		25 m	0.0 dB	0.0 dB	0.0 dB

To test the validity of this modification of the Erceg-SUI model over a wider range of frequencies, a comparison is made with the excess loss predicted by the modified Erceg-SUI model for a 1 km path length with excess loss predicted by the Weissberger foliage model and the Epstein-Peterson diffraction model for a 175 m foliage depth and single 2 m path obstruction, respectively.

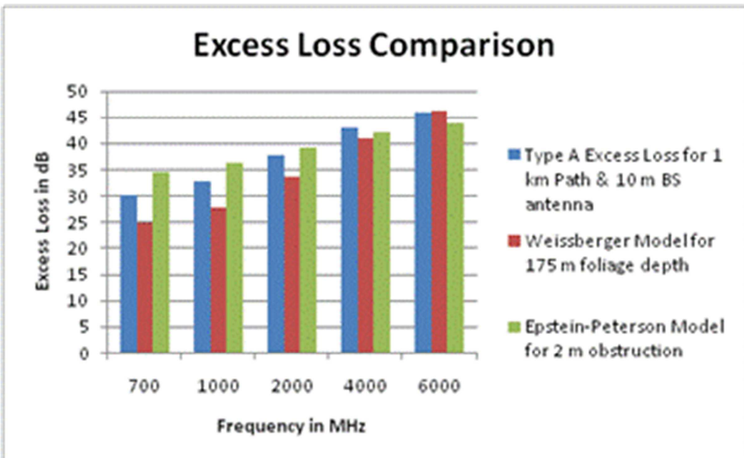


Figure 20 - Foliage and diffraction loss compared to modified Erceg-SUI model

As Figure 20 illustrates, this proposed modification to the Erceg-SUI path loss model provides a reasonably close match to what is predicted by foliage loss based on the

Weissberger model or obstruction loss based on the Epstein-Peterson model or, alternatively, a combination of the two.

5.2.1.3.10 Model Limitations with Respect to Meeting Smart Grid Deployment Requirements

In the previous sections several large scale path loss models for terrestrial applications have been discussed. It was shown that a modified version of the Erceg-SUI model could be applied for suburban and rural environments over the desired frequency range with a range of BS antenna heights consistent with Smart Grid deployment requirements. Identifying a suitable path loss model for urban areas proved far more challenging. Three different models are necessary to cover the spectrum requirements and no solution was found to be valid for BS antenna heights below the surrounding roof top heights in the 700 MHz to 2000 MHz band. Although there are multiple options that are considered valid for analyzing urban regions with BS antenna heights above neighboring building heights, care must be exercised when analyzing the data since, despite similar parameter assumptions, the range predictions will not be exactly the same. It is especially important when comparing multiple wireless technologies that the same path loss model be used with each of the technologies. For example, using the Hata-Okumura model at 1500 MHz for Technology A and COST231-Hata at 1500 MHz for Technology B will not be a fair comparison because the differences in the models will mask any differences that exist between the two wireless technologies.

Table 11 provides a summary for the large scale terrestrial path loss models discussed in the preceding sections.

Table 11: Summary of large scale terrestrial path loss models

<table>
<tr><th>Deployment Area</th><th>700 MHz to 1500 MHz</th><th>1500 MHz to 2000 MHz</th><th>2000 MHz to 6000 MHz</th></tr>
<tr><td rowspan="2">Urban Area with BS antenna above average roof top height</td><td>Hata-Okumura</td><td>COST231-Hata</td><td rowspan="2">WINNER II or ITU-R M.2135-1: Either model can be used. The ITU model provides a more conservative range estimate and takes building height and density into consideration.</td></tr>
<tr><td colspan="2">Both of these models have been used extensively over the years. Be aware however, the range predictions differ considerably at 1500 MHz, where they are both considered valid models. At 2000 MHz there is reasonably good correlation between COST231-Hata and the WINNER II and ITU-R M.2135-1 models.</td></tr>
</table>

Deployment Area	700 MHz to 1500 MHz	1500 MHz to 2000 MHz	2000 MHz to 6000 MHz
Urban Area with BS antenna at 10 m or less	There does not appear to be a proven solution in these frequency bands for BS antenna heights below surrounding building heights.		***ITU-R M.2135-1 Urban Micro-Cell***: Although specifically defined for a Manhattan-like grid structure and fixed BS antenna height of 10 m, this model should be applicable in most urban centers
Most Suburban or Rural areas with BS antenna heights from 7 m to 80 m	***Modified Erceg-SUI Model:*** This model was shown to be generally applicable to a wide range of suburban or rural deployments at BS antenna heights ranging from less than 10 m to 80 m over the entire 700 MHz to 6000 MHz frequency range.		
Extreme Rural Terrain	***Epstein-Peterson Diffraction Model*** or ***Weissberger Foliage Model:*** These models can be used together or individually in conjunction with ***free space path loss*** predictions for more extreme rural terrain conditions. Not an ideal approach for PMP but can be a very effective approach for PtP deployments.		

5.2.1.3.11 Modeling Extreme Terrain Characteristics

In the previous sections we have looked at five different, frequently used, large scale path loss models that have been developed for analysis of terrestrial wide area wireless networks in urban, suburban or rural areas. Additionally we have discussed specific models for excess loss due to foliage and diffractive loss due to terrain obstacles. Using the Erceg-SUI model as a basis, a modification to the formula has been proposed to improve the applicability of this model over a broader frequency range in suburban and rural environments with varied terrain and foliage characteristics.

From time to time it may be necessary, for rural areas, to estimate path loss for extreme propagation path conditions that do not appear to fall within the Erceg-SUI Type A terrain characteristics. An alternative approach for extreme conditions is to identify the worst case path conditions for a specific link within the desired coverage area and use GIS data, or equivalent, and apply the foliage model, terrain obstacle model, or both models to determine excess path loss for the specific path under consideration. Adding this value to the free space loss provides an estimate for the total path loss for the worse case link. Other models generally used for point-to-point links, such as the Egli [26] or Longley-Rice models [27], can also be considered.

5.2.1.4 Atmospheric Absorption

The question of atmospheric absorption is also often raised with respect to propagation. Fortunately for terrestrial WAN or FAN deployments in the frequency bands of interest and the typical path lengths encountered, atmospheric absorption is not significant. The anticipated losses are shown in Figure 21 derived from the formula developed in [28]. The plot for water absorption assumes 100 % humidity at 30 ^{o}C.

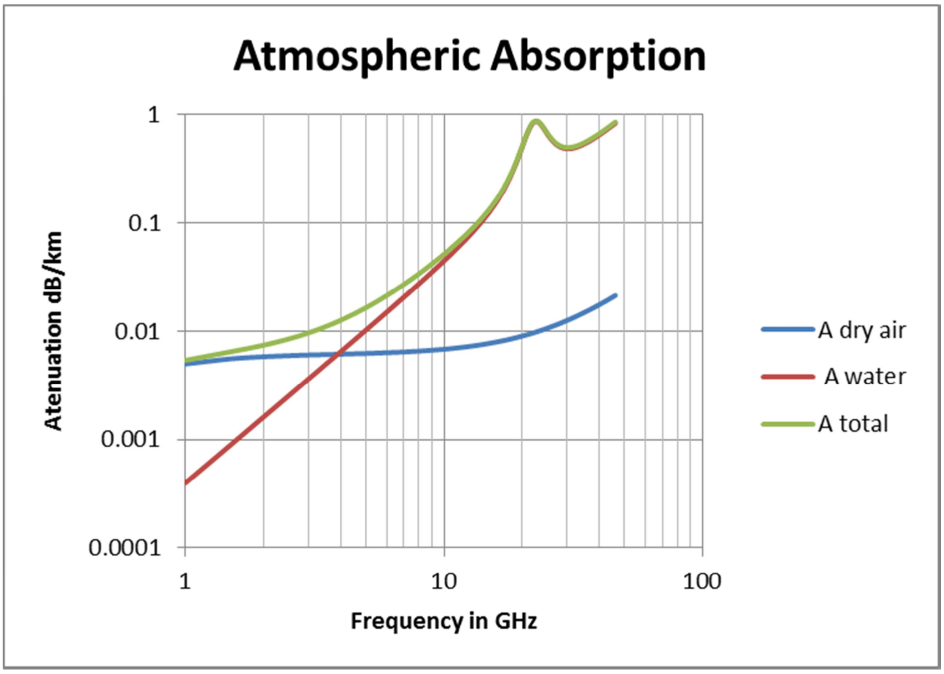


Figure 21 - Atmospheric absorption from 1 GHz to 100 GHz

Although atmospheric absorption can generally be ignored for terrestrial applications in the frequency bands below 6 GHz (6000 MHz), it can be a performance factor in frequency bands above 10 GHz and with the longer path lengths that would be typical when satellite technologies are being considered for smart grid communication solutions.

5.2.1.5 Line of Sight (LoS) and Fresnel Zone Clearance

Backhauling DAPs and other remotely located sites will often require the use of point-to-point links and in some cases multiple or daisy-chained links. Making use of existing utility poles can prove to be a cost-effective means for establishing point-to-point links. There are no right-of-way issues and foliage is generally cleared along these routes so as not to interfere with the power lines, LoS or near-LoS is therefore, assured. Relative antenna heights, however, are still important and can be a major factor in the path loss estimation. This is one application where the use of higher frequencies may prove to be an advantage.

For true LoS the propagation path must be clear of obstacles for a distance equal to or greater than the first Fresnel Zone[18] (see Figure 22). In practice a general guideline is to assure that at least 60 % of the first Fresnel Zone is clear of obstructions.

[18] The Fresnel Zone is an ellipsoid stretching between the transmit antenna and the receive antennas. The first Fresnel Zone is defined as the locus of points such that the indirect signal path is 180 degrees out of phase with the direct signal path.

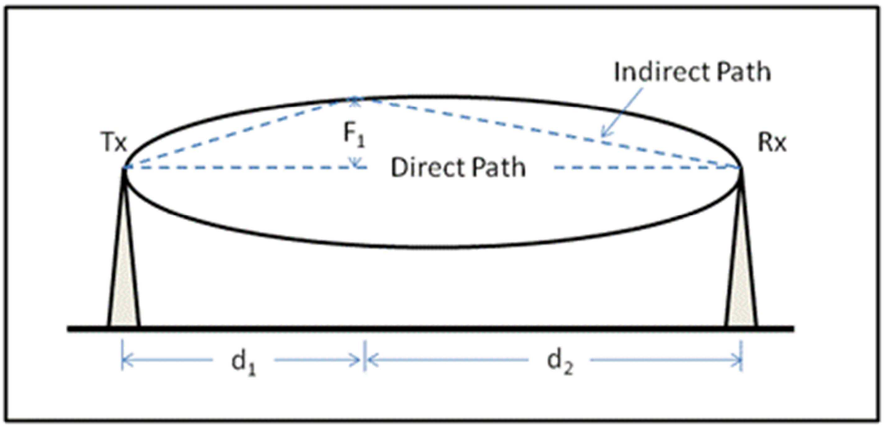


Figure 22 - 1st Fresnel zone for point-to-point link

An expression for the first Fresnel Zone, F_1, is given by:

$$F_1 = 17.3\sqrt{\frac{(d_1 d_2)}{(fD)}}$$

where
$d_1 + d_2 = D$, the path length and
f is frequency in GHz

As shown in Figure 23, for Tx and Rx antenna heights at 10 meters the earth represents an obstacle for well over 60 % of the first Fresnel Zone at 700 MHz. In this scenario transmitted vertically polarized[19] multipath reflections from the ground will arrive at the receive antenna in such a way so as to detract from the direct signal thus creating excess path loss. At the higher frequencies there is considerable clearance for the first Fresnel Zone and reduced likelihood of out-of-phase reflections. Note that at longer path lengths the Earth's curvature must also be taken into account when analyzing antenna height requirements for Fresnel Zone clearance.

[19] Horizontally polarized signals will reverse phase on reflection and actually add to the direct signal, this however is not something to be relied upon as ground reflections, except over water, are not predictable.

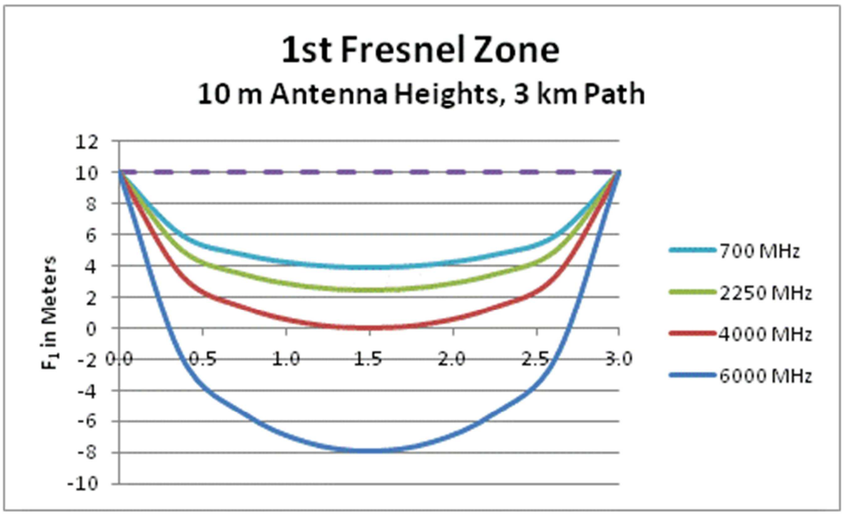


Figure 23 - Fresnel zone is wider at lower frequencies

5.2.2 Range and Coverage Analysis

The purpose of the coverage analysis is to predict the maximum range of a wireless technology for a given outage probability and a specified set of operating parameters.

The range capability of a wireless technology helps determine its suitability for linking a particular pair of actors and predicts its coverage area in a point-to-multipoint topology.

The outage criterion is the probability that the wireless transmitter-receiver link is not operational. It is expressed in terms of a probability due to the unpredictable behavior of RF propagation. It is often modeled as a stochastic process when accounting for the possible losses due to obstructions (shadowing) and reflections (multipath fading).

In the context of a point-to-multipoint wireless technology, coverage can be analyzed in terms of the maximum cell radius that a BS or AP can support. Within the cell coverage area, the outage probability varies, generally increasing for terminals / actors located at or near the cell edge. The outage criterion is expressed in terms of the average outage probability, averaged over all locations within the cell coverage area. A reported outage probability of 1 %, for example, means that a terminal located at a random point in the cell has a 1 % chance of being in outage. We define the outage probability as the probability that the received signal to interference plus noise ratio (SINR) is below the required SINR to operate the link. The required SINR depends on the wireless technology under consideration and serves as an input for the analysis. With a known transmit power the received SINR can be estimated by using the appropriate path loss model described in section 5.2.1 together with suitable margins for fading, interference, and when applicable, penetration loss.

5.2.2.1 Link Budget

A ***Link Budget*** analysis accounts for all of the relevant network parameters and thus serves as an essential tool in the analysis and design of a wireless network.

Control channels and data channels in wireless networks often use different features. Therefore the system gain and hence the link budget for control channels and data channels tend to be different. For example, during the network entry procedure when the bulk of the control messaging is exchanged in a wireless network, several features that enhance the link budget may not be used. These features are available however, for the data channels. These link budget enhancing features include: Hybrid Automatic Repeat Request (HARQ), MIMO, Beamforming, etc.

The system gain (SysGain) and link budget (LB) must be calculated for the data channels and the control channels for both uplink (UL) and downlink (DL) traffic. The applicable link budget for projecting the range is the minimum of: DL Control Channel LB, UL Control Channel LB, DL Data Channel LB, and the UL Data Channel LB.

To calculate the various link budgets, the following parameters are required:

a) Effective Isotropically Radiated Transmit Power in dBm (TxEIRP)
b) Receiver Sensitivity at lowest desired operating modulation and coding in dBm (RxSNS)
c) Combining Gains (HARQ gains, repetition gain, etc.) in dB (CombGain)
d) Receiver Antenna + Amplifier gain in dB (RxGain)
e) Receiver Cable Loss in dB (CablLoss)
f) Fade Margins (F_m) to account for fades due to Shadowing and Multipath
g) Interference Margin (I_m) must include margin for both self-interference and inter-operator interference
h) Penetration Loss (L_p) when applicable for indoor to outdoor or outdoor to indoor paths

The combination of items a) thru e) is generally referred to as the ***System Gain*** and is given by:

$$\mathbf{SysGain_{dB} = TxEIRP_{dBm} - RxSNS_{dBm} + CombGain_{dB} + RxGain_{dB} - CablLoss_{dB}}$$

When determining the receiver sensitivity, $\boldsymbol{RxSNS_{dBm}}$, in either the uplink or downlink direction, it is important to carefully consider the required throughput requirements for devices located on the cell edge. With knowledge of the PHY and media access control overhead, (PHY-OH + MAC-OH), for the specific technology being considered, the acceptable cell edge modulation efficiency and code rate can be determined to provide a required E_b/N_o and SNR to meet the desired cell edge performance.

The ***Link Budget (LB)*** represents the maximum allowable path loss for acceptable performance for a specific channel at the cell edge ($\mathbf{MaxPL_{CH}}$) and is given by the System Gain minus the margins allowed for fading, interference, and penetration loss.

$$\mathbf{LB = MaxPL_{CH} = SysGain_{dB} - F_m - I_m - L_p}$$

The maximum system allowable path loss is given by the minimum $MaxPL_{CH}$ for all channels

$MaxPL_{sys}$ = min ($MaxPL_{CH}$ over all channels in either UL or DL direction)

For an all-outdoor system, fading is generally the dominant variable for assessing probability of an outage. For a predefined system, the outage probability at a certain distance (*d*) from the BS or AP can be calculated as follows:

$$\textbf{Fade Margin} = MaxPL_{sys} - PL(d) - I_m$$

where
PL (*d*) is the path loss at a distance, *d*, as calculated by one of the path loss models in section 5.2.1.

Assuming a certain dominant fading profile for an environment, (Log-normal, Rayleigh, or Rician), the outage probability is given by:

Outage Probability = Probability (Random Fading > Fade Margin)

The above analysis can be done in reverse to calculate the maximum allowable range or, for ubiquitous coverage with a multi-cellular deployment, the maximum allowable BS to BS spacing to guarantee a specific outage probability.

Both the ***System Gain*** and ***Link Budget*** are closely linked to the smart grid use case that is being analyzed. Outdoor BS parameters for terrestrial wide area deployments are relatively independent of the Smart Grid use case. Typically these systems will be capable of transmitting at the maximum EIRP allowed by regulatory restrictions for the frequency band of operation and most solutions will support the many advanced antenna technologies supported by the applicable standard. There may be some exceptions for mixed deployment scenarios combining macro, micro, and pico-cells where BS EIRP limitations may be necessary to help manage inter-cell interference. For indoor deployments, as mentioned in section 5.2.1.2, BS EIRP limitations would generally be required to comply with human exposure safety requirements.

In contrast to the BS the terminal or SS characteristics will vary considerably depending on its role in the Smart Grid network. The terminal or actor location can also have a significant impact on the link budget and path loss. Since terminals will almost always be more limited in EIRP due to antenna and transmit power constraints and in some cases human exposure safety limitations, the UL system gain and link budget will generally be the limiting factor for range predictions.

Wireless terminals applicable to a variety of Smart Grid use cases can be described as follows:

- **Fixed Outdoor-Mounted Terminal:** This would be a typical installation for a DAP, substation, feeder line device, or other distribution or transmission facility. The terminal or SS can be mounted on an existing utility pole or transmission tower, on top of or on the side of an existing structure, or on an existing 3rd party tower. For this type of installation the terminal can be equipped with a high gain directional antenna that is aligned relative to the BS to maximize received signal strength. With easy access to an alternating current power system and an antenna location not easily accessible by the general public, the uplink transmit power (TxEIRP) can be set to any level up to the maximum allowed by regulation. In summary this application is characterized by:

- High Terminal Antenna Gain: Typically 12 dBi to 17 dBi dependent on operating frequency and antenna size
- High Transmit Amplifier Power: FCC regulatory EIRP limits range from 43 dBm to 85 dBm in licensed bands between 700 MHz and 6000 MHz
- Relatively High Antenna Height: Typically 8 m to 10 m or higher

- **Vehicular-Installed Mobile Terminal:** Equipping utility emergency vehicles with mobile wireless stations can provide a key communications link for disaster recovery, as well as routine grid maintenance activities. Compared to the Fixed Outdoor Terminal, these installations are characterized by:
    - Lower Antenna Gain: Must be omni-directional in azimuth, typically 6 dBi to 8 dBi
    - Lower Antenna Height: Typically 2 m to 3 m, if mounted on vehicle roof
    - Lower Transmit Power: Must comply with human exposure safety requirements

- **Fixed Indoor Self-Install Terminal:** In a Smart Grid network this would apply to a remote office, a temporary quick-to-install station, or possibly a work-at-home situation for a key utility employee. For this application the link budget is impacted by:
    - Antenna Gain: limited in size for convenience purposes, typically 6 dBi to 8 dBi
    - Antenna Height: Typically 1 m to 3 m
    - Lower Transmit power (EIRP): Must comply with human exposure safety requirements
    - Building / Wall Penetration Loss: This can vary from 3 dB to 4 dB for a window-placed terminal in the 700 MHz band to more than 15 dB to 20 dB for a location well inside an urban building in the higher frequency bands.

- **Wireless-Enabled Smart Meter:** Smart meter locations can be located on outside walls or in electronic vaults in below grade locations. Size limitation would limit the antenna size and gain.

  - Antenna Gain: Requires an omni-directional antenna, gain typically -1.0 dBi to +1.0 dBi
  - Antenna heights will typically be lower and locations can be indoor, below grade, or housed in a cabinet
  - Lower Transmit Power: Most locations will require limitations to meet human safety exposure limitations

- **Mobile Handheld Device:** This may not necessarily be a common application for Smart Grid since it can in most cases be covered with the use of public networks. Nevertheless for completeness it is worth including. Mobile handheld devices have limited antenna size and lower transmit power. The transmit power is constrained by the battery capability. For this usage model the link budget and path loss model must account for:
  - Lower Antenna Gain: Must be omni-directional, typically -1.0 dBi to 0 dBi
  - Antenna Height: Typically 1.5 meters
  - Lower Transmit Power: Typically 200 mW or less
  - Building / Vehicle Penetration Loss: To support indoor or in-vehicle operation
  - Loss due to absorption by the person holding the device

Taking all the above factors into account can result in significant differences in the system gain and link budget for various types of Smart Grid use cases. A fixed outdoor terminal for backhauling a DAP compared to a mobile handheld device or wireless-enabled smart meter can result in 30 dB or more difference in link budget and up to 50 dB for indoor basement-located smart meters.

5.2.2.1.1 Fade Margins

Fading in a propagation path is usually characterized as shadow fading which is slow or medium-term and fast fading. Shadow fading tends to be the dominant fading mechanism and is primarily due to obstructions in the propagation path. Shadow fading generally follows a Log-normal distribution and fast fading, which is primarily due to multipath, is Rician distributed when a dominant signal is present, as is the case for an LoS or near-LoS path, and is Rayleigh distributed when there is no dominant signal present. In the latter case it is simply the sum of Gaussian variables. Multipath fading has also been shown to follow a Nakagami distribution which is defined as the sum of multiple independent Rayleigh distributed signals. In any case fast fading due to scattering and multipath is generally not as significant as the deep fades caused by shadowing. Figure 24 shows a comparison of Log-normal shadow fading and multipath fast fading.

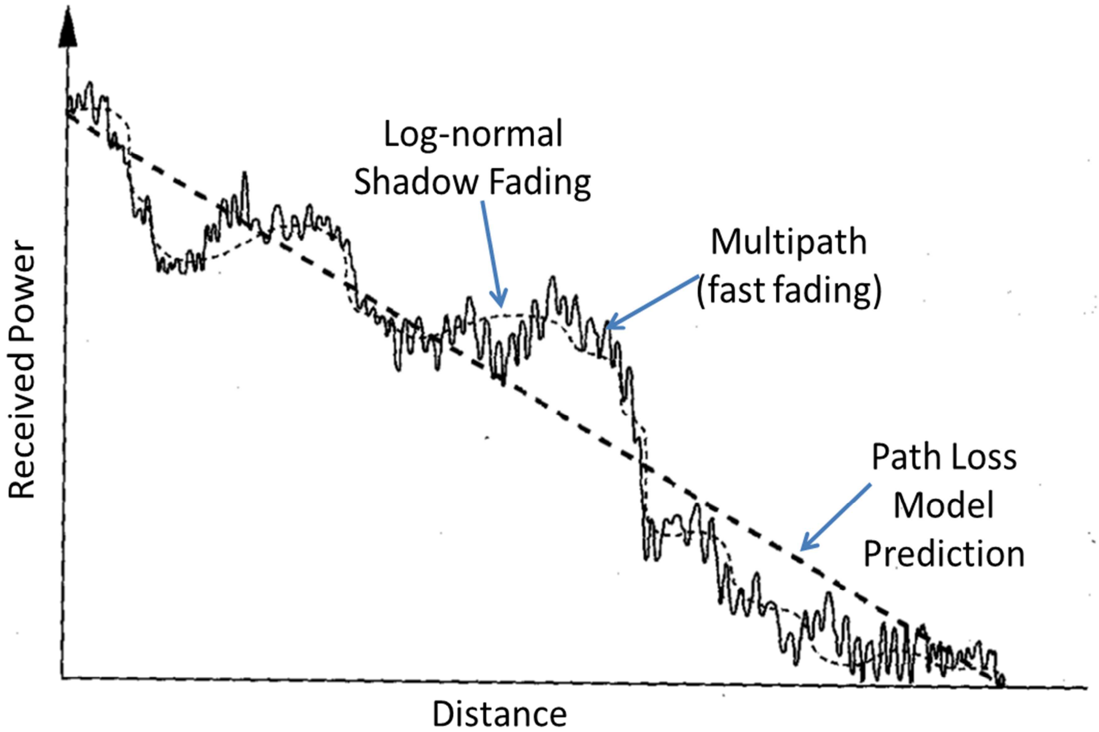


Figure 24 - Comparison of shadow fading and fast fading

In the link budget it is important to allow for sufficient fade margin to ensure sufficient link availability for terminals or actors at the cell edge. Since shadow fading, the dominant fading mechanism, is governed by a Log-normal distribution, it is a straightforward calculation to determine the probability that the signal level at the cell edge will be sufficient to maintain a specific level of performance. Figure 25 shows the relationship between fade margin, standard deviation, and cell edge availability.

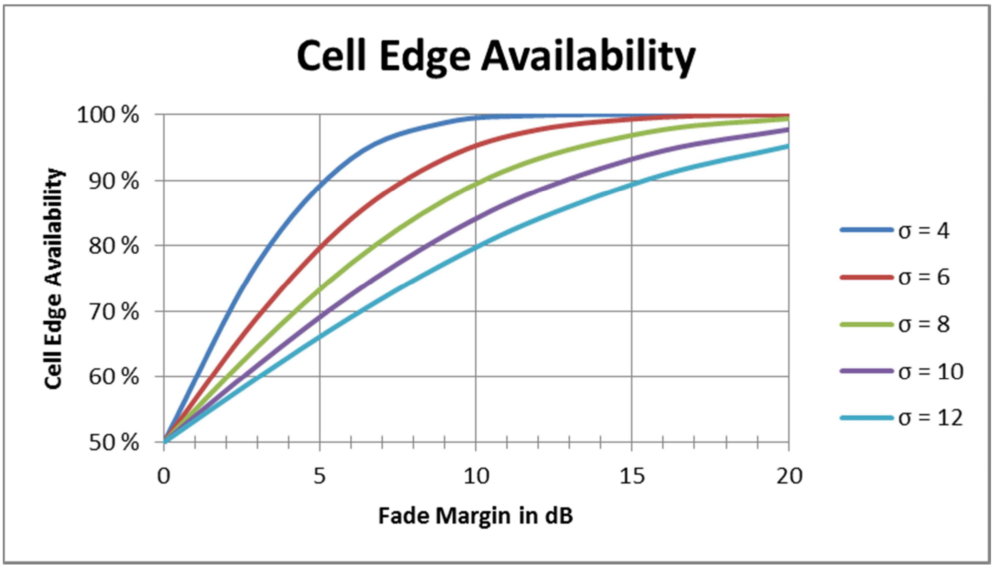


Figure 25 - Cell edge availability compared to fade margin and standard deviation

Typical fade margins for non-LoS propagation analysis are provided in Table 12. These values are expected to result in an availability of at least 90 % at the cell edge. It is important to emphasize that this does not necessarily mean there is 10 % likelihood that a complete outage will occur at the cell edge. Most well-planned deployments will specify a cell edge performance requirement that will be several dB above the absolute threshold required to maintain the link. If, for example, cell edge performance is based on operation with QPSK and ½ rate-coding, support for HARQ with 6 repetitions will provide approximately 8 dB of additional margin before a complete outage occurs. The availability with respect to a complete outage at the cell edge is therefore approximately 99 %.

Table 12: Typical fade margins

	Indoor (dB)	**Urban Outdoor (dB)**	**Urban Outdoor to Indoor (dB)**	**Suburban, Rural, Types A, B, C Outdoor (dB)**
Standard Deviation (σ)	4 to 8	6	7	8
Shadow Fade Margin (F_s)	5.2 to 10.3	7.8	9.1	10.3
Fast Fade Margin	2	2	2	2
Total Fade Margin (F_m)	7.2 to 12.3	9.8	11.1	12.3

For deployments in which higher availability is required or alternatively where lower availability may be acceptable, the curve in Figure 26 provides a simple relationship between cell edge availability and F_s/σ.

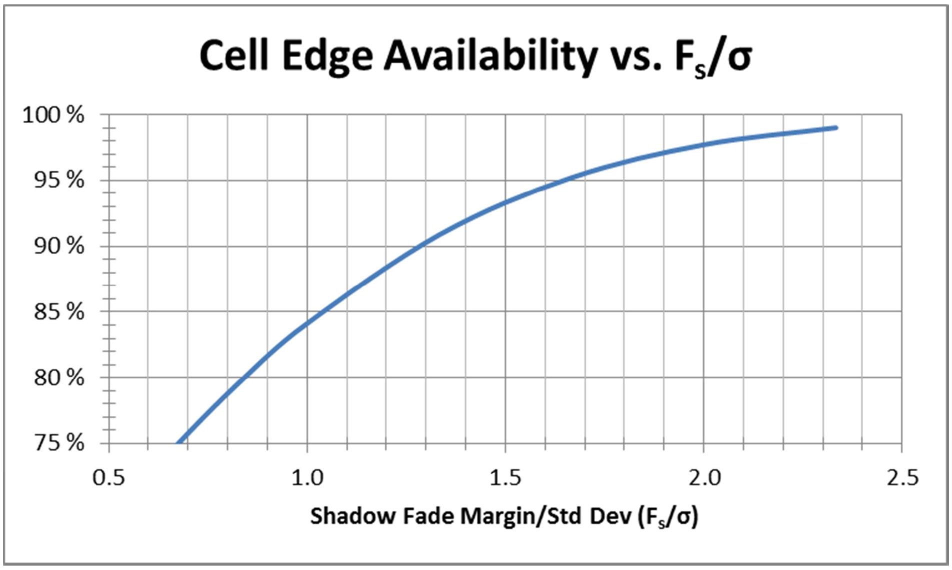


Figure 26 - Cell edge availability versus F_s/σ

5.2.2.1.2 Interference Margin

Both self-interference and interoperator interference must be considered. If one has dedicated access to a block of spectrum interoperator interference will generally not be an issue but the effects of self-interference or co-channel interference (CCI) must be taken into account. Using a 3-sector cell as an example, Figure 27 shows two frequency resuse schemes that can be employed. Reuse 1 requires less total spectrum for a given channel bandwdith but one must allow for sector to sector CCI and cell to cell CCI. Reuse 3 requires three times more spectrum but sector to sector CCI is replaced with adjacent channel interference which is considerably less. Cell to cell interference is greatly reduced as well. Typical values for interference margin (I_m) are:

- Reuse 1: I_m = 2.0 dB to 4.0 dB
- Reuse 3: I_m = 0.5 dB to 1.0 dB

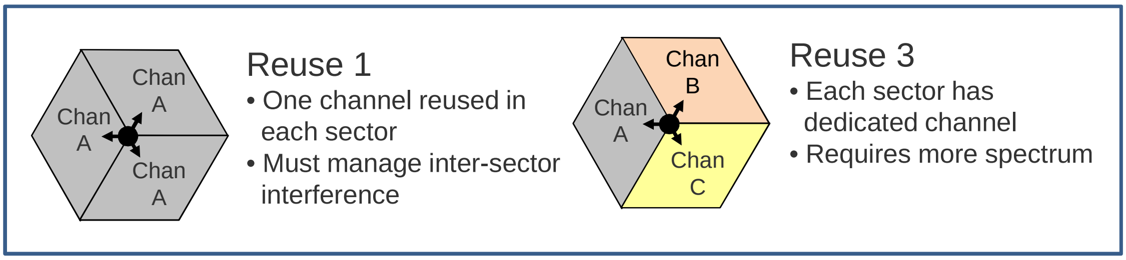


Figure 27 - Frequency reuse with 3-sector BS

Inter-operator interference can be a significant factor when the same block of spectrum is shared with other operators and applications. This situation will arise with operation in the unlicensed bands, sharing with municipalities in the US public safety bands, or when using the 3650 MHz to 3700 MHz lightly-licensed band. Typically, due to the higher incidence of network traffic, interference will be worse in higher density urban areas as opposed to what would be experienced in rural environments.

Some recommended margins for inter-operator interference are shown in Table 13.

Table 13: Inter-operator interference margins

	Urban	Suburban	Rural
Inter-Operator Interference	6 dB to 8 dB	4 dB to 6 dB	2 dB to 4 dB

5.2.2.1.3 Penetration Loss

For terminals or SSs located in indoor environments, it is necessary to account for the resulting signal loss as it passes through the medium separating the outdoor BS and the indoor terminal. When an RF signal hits an object, such as a wall, with dimensions larger than a wavelength a portion of the signal will be reflected and remainder will pass through the object with some additional loss before emerging on the other side. Arriving at a reasonably accurate estimate for the net penetration loss must take into consideration a range of factors including:

- Operating frequency
- Angle of incidence
- Wall or barrier material
- Wall or barrier thickness and surface texture
- Number of walls signal must pass through
- Existence and number of windows or openings in the wall

Many field tests have been conducted over the years at various frequencies. Some of these studies have investigated the impact of specific materials, such as plywood versus cinderblock walls while other studies have been conducted with various buildings with only a brief description of wall materials and other field studies included very limited or no information regarding the building type or wall materials. Most of these studies have been done at specific frequencies and in most cases there is a significant spread in the data. This makes it challenging to provide penetration loss predictions for the full frequency range of interest covering the many outdoor-to-indoor scenarios likely to be encountered in a Smart Grid network. Nevertheless it is of value to make this attempt with the limited data that is available. In Table 14, penetration loss data has been taken from various sources [29], [30], [31], [32] and shown in bold italics under the headings closely consistent with what was reported[20]. Other values have been inserted to fill out the table. The last row in Table 14 provides a suggested margin that should be included in the link budget to account for the spread in actual penetration loss that can be expected over a range of building types in a typical geographical area.

[20] It is important to mention that the WINNER II and ITU-R M.2135-1 indoor models suggested little or no difference in wall or floor penetration loss for measured data at 2 GHz and 5 GHz.

Table 14: Penetration loss (dB) by frequency and location

Frequency (MHz)	Inside Vehicle	Indoor Residential	Indoor Business, Industrial	Indoor Basement	Indoor Meter Vault
700	9.0	7.5	10	17	27
1000	***9.0***	***7.7***	***13***	***18***	***28***
2000	***9.0***	***11.6***	***20***	24	30
3000	***9.0***	13	24	28	32
4000	9.0	14	27	30	34
5000	9.0	15	29	31	35
6000	9.0	***16.2***	31	***31.5***	36
Suggested Margin (σ)	5	5	6	6	8

5.2.2.2 Deployment Trade-offs

In this section we look at some of the trade-offs that must be considered in any wireless deployment. Whether deploying in a high density urban area or a low density rural area achieving ubiquitous coverage with the minimum number of BSs is always a key planning goal. In addition to coverage, urban areas will also have capacity requirements to consider. In the following subsections we will look specifically at trade-offs with respect to range and coverage based on path loss predictions. While path loss is a primary factor for range predictions it is important to mention that it is not the only factor. A number of equipment and technology-related factors can also play a large role since, in many cases, wireless equipment designs are tailored to specific deployment scenarios. Path loss, however, is a factor common to all land-based wireless systems so it is the key metric used in the following analysis.

5.2.2.2.1 BS and SS Antenna Heights

All of the large scale propagation models have a term that describes the path loss dependency on the path length, *d*, for *d* well beyond the near-field distance from the transmit antenna. This distance-dependent term, which is applicable in either the DL or UL direction, can be expressed as:

$$\textbf{Total Path Loss (PL) vs Distance} = 10n\log_{10}(d)$$

where *n*, is generally referred to as the path loss exponent, is equal to 2 for free space, and is greater than 2 for obstructed or non-LoS paths.

The path loss exponent is dependent on parameters derived from the measurement data and, in most cases, has a direct dependence on BS antenna height. The value of *n* is plotted in Figure 28 for the different outdoor large scale models discussed in the previous sections. It is important to observe the rapidly increasing magnitude of *n* for BS antenna heights lower than 30 m as predicted by the Modified Erceg-SUI path loss model. It is also of interest to note that, other than the WINNER II rural case the other path loss models exhibit the same distance dependency for the different deployment regions. Since these models specify that BS antenna heights must be above average surrounding roof tops, this is a realistic expectation.

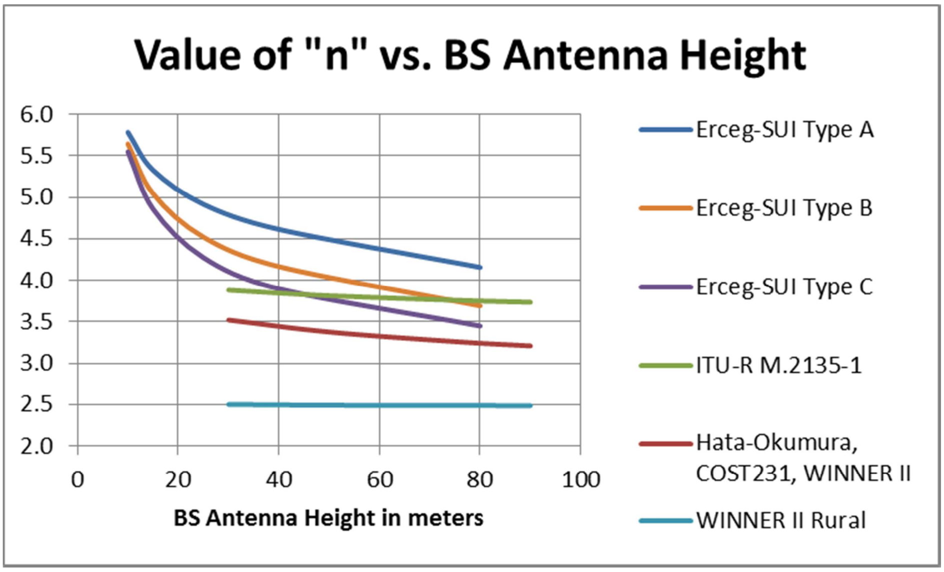


Figure 28 - Path loss exponent relative to BS antenna height

The potential impact of the additional path loss due to lower BS antenna heights is best analyzed by looking at the impact on cell range and coverage. In Figure 29 the relative range predicted by the Modified Erceg-SUI model for BS antenna heights from 7 m to 80 m is plotted.

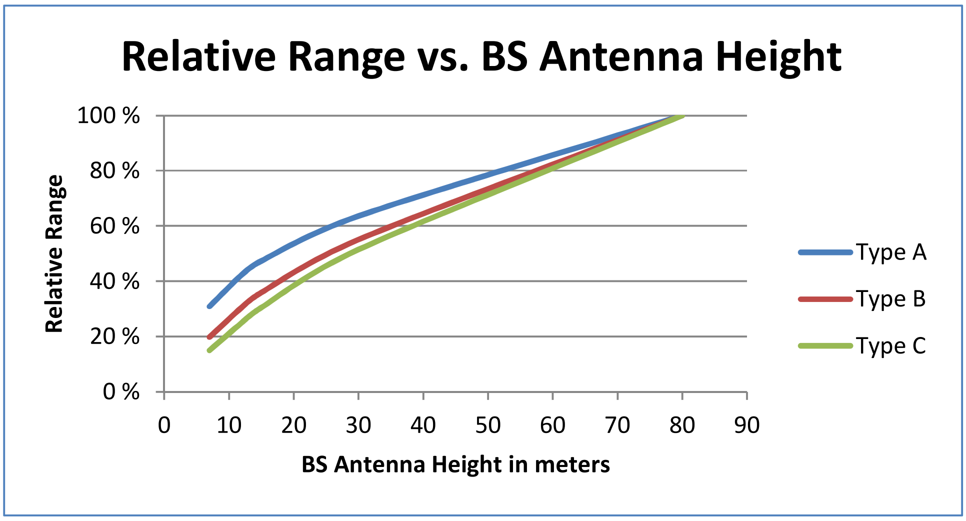


Figure 29 - BS antenna height impact on range prediction

The effective coverage area varies as the square of the range prediction. Being restricted to a BS antenna height of 7 m to 10 m can result in a need for 10 to 20 times as many BSs compared to having a 70 m to 80 m structure available for the BS to cover a specified geographical area. Since the relative BS antenna height has such a significant impact on range and coverage area it is worth looking at the alternative approaches in more detail to provide some insights to help evaluate the trade-offs based on several criteria including a qualitative cost comparison. In Table 15 we look at four possibilities for the BS deployment:

A) Use an existing utility pole
B) Use an available neighboring structure
C) Lease existing tower space
D) Build dedicated standalone tower

Table 15: Trade-offs for BS deployments

	A) Use an Existing Utility Pole	B) Use an Available Neighboring Structure	C) Lease Existing Tower Space	D) Build Dedicated Standalone Tower
Availability & Location	Large number of existing poles to select from for optimal coverage e.g., in utility easements or rights-of-way, as restricted by: • Available space on the pole • Utility pole usage standards	Lower availability as compared to utility poles • Further restrictions for: a) structure suitability for equipment attachment, b) property (non-utility) access privileges, c) electrical power agreements with structure owner (non-utility), d) required permitting	Considerable lease tower options exist but existing towers may not: • be optimally located for SG purposes • have space available for additional antennas	Locate suitable sites as restricted by: • Reaching agreement(s) with current property owner(s) • Gaining permits and jurisdiction approvals • Availability of backhaul and electric power options
Time to Deploy	Relatively short deployment times for existing poles • Slightly longer deployment durations for new or replacement poles • Some localities require additional permitting for higher than routine pole heights	More time than utility poles due to: • Time to find and negotiate terms with property owner other than the utility • To gain necessary permit(s) approval • Performing structural analysis as required	Considerable time investment, (but normally less than option D), to: • Negotiate terms with tower owner • Structural analysis for leased tower space • Gain permit(s) approvals e.g., National Environmental Policy Act (NEPA) requirements	Considerable time investment to: • Find suitable site • Conduct geographic survey • Negotiate terms with property owner • Structural analysis • Gain permits approvals e.g., NEPA requirements • Deal with potential environmental impact issues • Build new tower

	A) Use an Existing Utility Pole	B) Use an Available Neighboring Structure	C) Lease Existing Tower Space	D) Build Dedicated Standalone Tower
BS Height Limitations	• Typically 7 m to 15 m antenna heights for utility distribution poles. • Poles heights up to 30 m are also commonly used, for special utility electric grid or telecomm purposes • Permits frequently required for the higher pole heights especially in urban areas	• Multi-story buildings, power plant structures are generally available for higher antenna heights than option A • Unless the antenna heights are measurably higher than option A, the range impact may only be marginally better • Higher antenna heights may increase the observed RF noise floor in some areas and spectrum bands	• Height restricted to space available on tower • Restricted by capacity of tower to carry the additional antenna, mounting gear, cables, and antenna wind loading considerations • Higher antenna heights may increase the observed RF noise floor in some areas and spectrum bands	• Can erect as high as permits and local building restrictions allow, possibly 60 m to 110 m • Higher antenna heights may increase the observed RF noise floor in some areas and spectrum bands • FAA tower lighting requirements and registration for new towers

	A) Use an Existing Utility Pole	B) Use an Available Neighboring Structure	C) Lease Existing Tower Space	D) Build Dedicated Standalone Tower
Relative Costs	• Least expensive for both Capital Expense and Operating Expense[21] on a per BS basis, but requires greater number of BSs to provide coverage as compared to the other options • More backhaul points, but with potentially lower backhaul costs per BS due to reduced capacity needs than for the other options	• Generally greater Capital Expense than option A as driven by type and height of facility and the additional BS support structure requirements and facility structural analysis, and any addition permitting • Generally greater Operating Expense than option A as driven by property owner, lease, or rental fees • Generally fewer BSs needed to provide the same coverage as option A	• Lower Capital Expense for required equipment than option D, as offset by Operating Expense for tower space lease based on height placement on the tower. • Capital Expense requires tower loading / structural analysis. • Requires fewer BSs needed to provide coverage than option A and some option B locations-heights.	• Highest Capital Expense and Operating Expense costs per tower, but requires fewer BSs as compared to option A. • Tower owner has the option to lease out unused tower space • Major Capital Expense items include: acquisition of land property, tower design / build-erection / materials, electrical power • Fewer BSs needed to provide the same coverage as options A or B.

[21] For Table 15 Note: Capital Expense (or Expenditure) and Operating Expense (or Expenditure)

The impact of SS / terminal antenna height on range is shown in Figure 30. In the path loss models, for the valid range of antenna heights, this factor is accounted for as a fixed quantity independent of path length and independent of frequency. From a deployment standpoint, especially in a FAN, there is some control on the BS antenna heights but limited control on terminal antenna heights. Meter locations, for example, are already in place and must be dealt with wherever they are located.

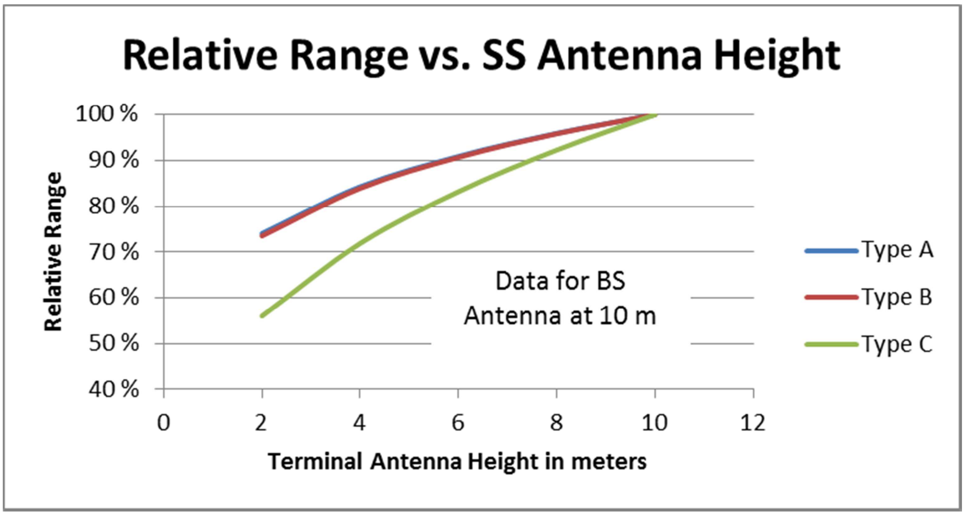


Figure 30 - Terminal antenna height impact on range

5.2.2.2.2 Impact of Spectrum Choices

When spectrum choices exist for the deployment of a wireless network it is important to quantifiably assess the trade-offs. Based on the previous discussions on path loss models it is clear that spectrum choice will be a key factor in determining cell range and coverage. Figure 31 shows the predicted range relative to 2000 MHz assuming the same link budget over the total frequency range from 700 MHz to 6000 MHz with a BS antenna height of 7 m and 30 m for terrain Type A. This analysis predicts almost a 4 to 1 difference in range which results in approximately 15 times difference in coverage area for a 700 MHz deployment versus a deployment at 6000 MHz. For an LoS PtP case, assuming sufficient clearance for the first Fresnel zone, greater than 8 to 1 range difference is predicted.

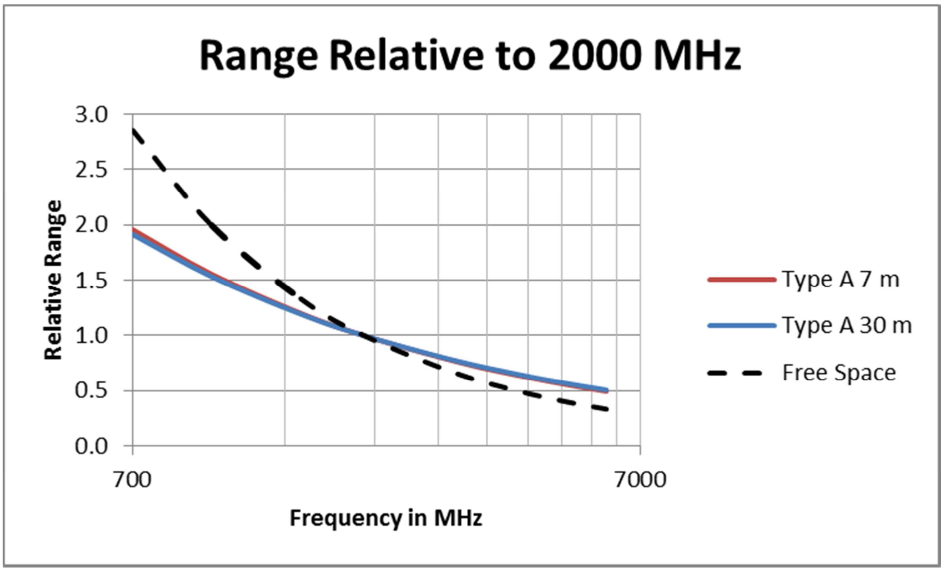


Figure 31 - Range dependency on frequency

To completely assess the frequency trade-offs other factors must also be considered. The above analysis assumes the same link budget for frequencies between 700 MHz and 6000 MHz. It is important to point out that some of the advanced antenna techniques that are currently available for wireless deployments may not be practical in the lower bands. This has the effect of narrowing the range gap.

Higher order MIMO systems for transmit and receive diversity are becoming more and more prevalent. For best results these techniques require a high degree of de-correlation between the antennas. For second order MIMO systems dual polarization can be used effectively in any of the frequency bands being considered without having to provide a large separation between the antennas to ensure the signals are uncorrelated [33]. For higher order MIMO antenna systems, however, the antenna separation would have to be on the order of 3 wavelengths to 5 wavelengths to maintain sufficient de-correlation between the antennas for good receive or transmit diversity performance. Since the wavelength at 700 MHz is almost 0.5 m, these antenna systems would not be practical in these lower frequency bands.

Beamforming is another approach that can be considered to improve the system gain in the higher frequency bands but would be impractical in the lower bands due to the size. These systems call for arrays of 4 antennas to 8 antennas spaced 0.5 wavelengths apart. A 4-antenna array in the 700 MHz band would be in the order of 3 m to 5 m in width.

Taking these factors into consideration plus higher antenna gains can result in a 6 dB to 8 dB higher link budget at 6000 MHz compared to 700 MHz thus reducing the range difference to less than 3:1. This is still a significant difference however, in that it requires almost 10 times as many BSs at 6000 MHz for ubiquitous non-LoS coverage for a given geographical area as compared to the BS requirements for a 700 MHz deployment.
To achieve true LoS with point-to-point links antenna heights must be selected to provide adequate Fresnal zone clearance as was discussed earlier. A good guideline is 60 %

clearance but in general one would like to plan for full clearance anticipating that propagation path changes occurring over time might eventually infringe on the first Fresnel zone. This requirement can also be somewhat more challenging in the lower frequency bands. If one end of a 700 MHz link is set at an antenna height of 10 m, as shown in Figure 32, the other end of the link would have to be above 32 m to provide first Fresnel zone clearance for a 3 km path length. On the other hand, any frequency above 2250 MHz would ensure clearance with antenna heights of 10 m. Alternatively, if the antenna heights at each end of the link were limited to 10 m, a 700 MHz link would be limited to a path length of less than 1 km to ensure first Fresnel zone clearance.

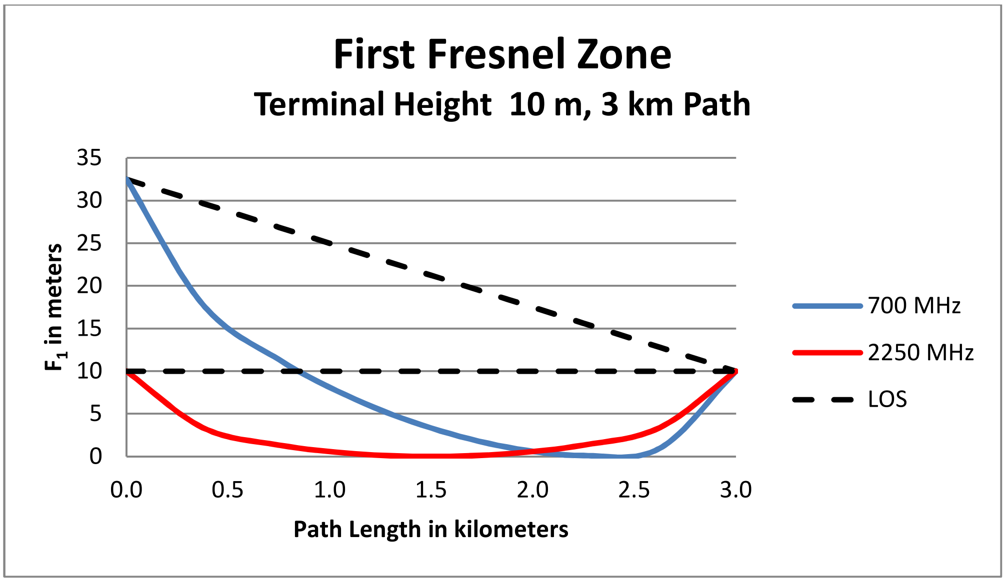


Figure 32 - Comparing 700 MHz and 2250 MHz for 1st Fresnel zone clearance

5.2.3 Estimating Channel and BS Sector Capacity

In the determination of the range capability for a specific wireless technology it is necessary to specify a threshold SNR to meet an acceptable throughput performance and link availability for SSs or actors located at the cell edge.

Many of the SSs or actors located randomly throughout the coverage area will experience significantly higher SNRs and thus be capable of higher throughput performance and higher availability.

Assuming a uniform distribution of SSs, the SNR relative to the cell edge performance can be determined based on the specific path loss model used and the BS antenna height. The plot in Figure 33 relates the percentage of coverage area for the SNR compared to the cell edge for different values of the path loss exponent.

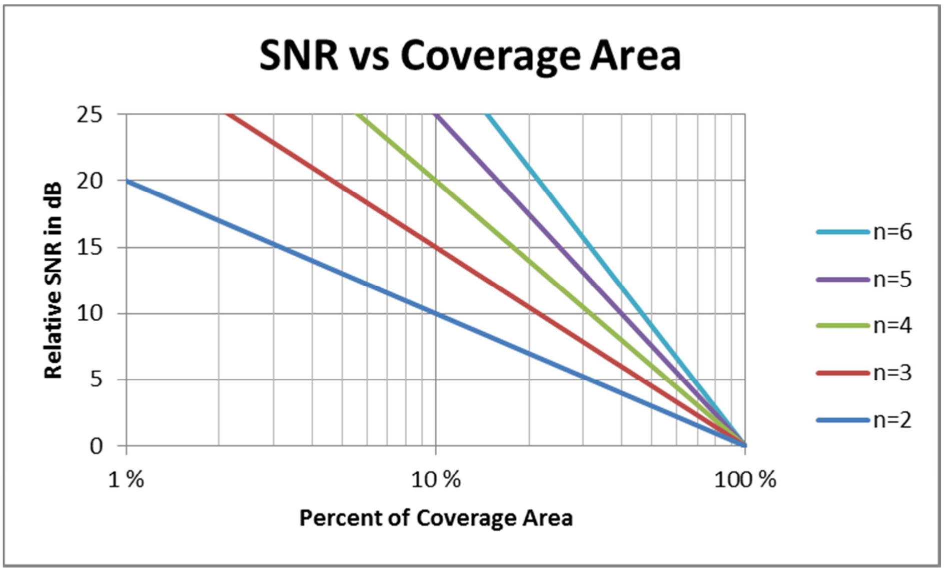


Figure 33 – Signal to noise ratio (SNR) and cell coverage area

The higher SNR that prevails over a large percentage of the coverage area results in a higher link availability, as well as enabling a percentage of subscriber terminals to operate at higher modulation efficiency.

As described earlier, the cell edge link availability is determined by the fade margin and can be predicted by assuming shadow fading is a log-normally distributed random variable. Figure 34 shows the relationship between the availability at the cell edge, in this case 90 %, and the predicted availability over the remainder of the coverage area. Note that this applies to a single cell or BS and a terminal located at the cell edge whose connection is restricted to that BS. For a typical multi-cellular deployment, terminals or actors at the cell edge with omni-directional antennas will generally have access to more than one additional BS. This scenario results in a significantly higher availability due to the very low probability that deep fades will occur simultaneously on multiple propagation paths.

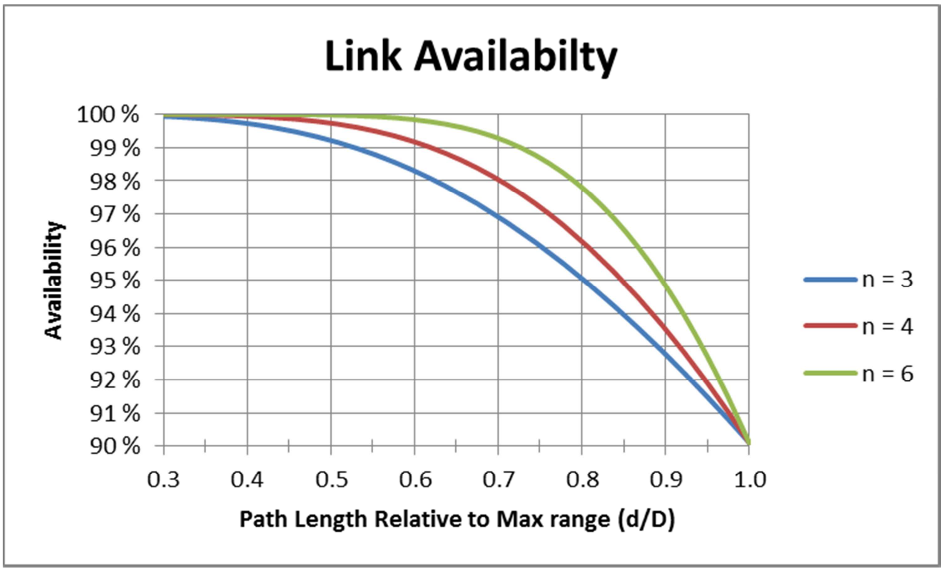


Figure 34 - Link availability relative to path length

Alternatively it may be of interest to look at the probability of an outage (see Figure 35), where in this case an outage is defined as not meeting a specified data rate. Whereas the probability of an outage is 10 % at the maximum range, it is considerably lower at a reduced path length.

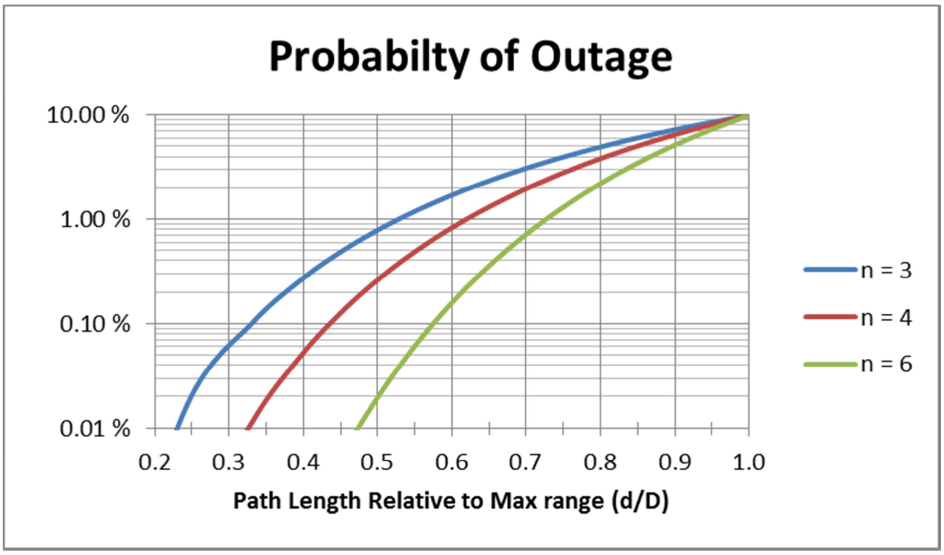


Figure 35 - Outage probability relative to range

The effective spectral efficiency also increases for actors or users closer to the BS, which translates directly to increased data throughput for those users. This is illustrated in Figure 36, which shows the relationship between signal to noise ratio (SNR) per symbol (E_s/N_o) and the Symbol Error Rate (SER). Note that the graph, for illustrative purposes, assumes no Forward Error Correction (FEC).

An increase in SNR of approximately 7.5 dB for a given SER will result in an increase of the modulation efficiency from QPSK to 16QAM, a 2:1 improvement. A further SNR increase of about 6 dB to 64QAM provides an additional 50 % increase in spectral efficiency while maintaining the same SER.

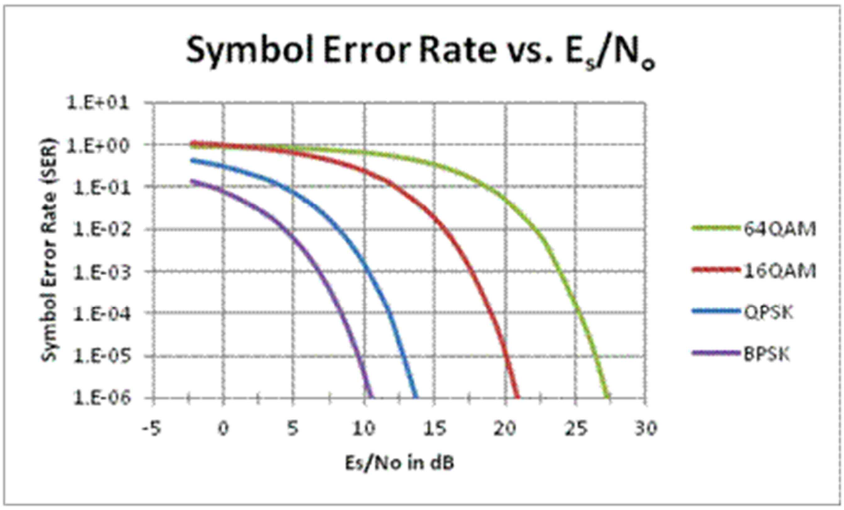


Figure 36 - Symbol error rate (SER) and *Es* over *No*

The addition of FEC can provide significant improvement in the SER or alternatively reduce the required threshold SNR for satisfactory performance. With respect to Figure 36 the addition of FEC would, in effect, move the plots to the left by an amount dictated by the type and amount of FEC. FEC, of course, adds redundant bits to the transmitted signal resulting in a lower effective data rate for the same overall channel bit rate.

Table 16 provides a view of what may typically be supported with any specific wireless technology with a single transmit and single receive antenna in either the DL or UL direction. Many of today's wireless technologies take advantage of advanced antenna systems including MIMO (Multiple Input Multiple Output). The use of multiple antennas with spatial multiplexing can increase both the DL and UL spectral efficiency. Although the following analysis assumes Single Input Single Output (SISO) the basic concept is applicable with multiple antenna systems as well.

An SNR for a specified SER or BER would be associated with each modulation efficiency and code rate. With the most robust modulation efficiency and several ARQ or HARQ repetitions a satisfactory error rate may be achieved with an SNR of less than zero whereas 64QAM with 5/6 rate-coding would require an SNR of 20 dB or more.

Table 16: Modulation and spectral efficiency

Modulation	Code Rate	Repetitions	Spectral Efficiency ((b/s)/Hz)
QPSK	1/2	6	0.166
QPSK	1/2	4	0.25
QPSK	1/2	2	0.5

Modulation	Code Rate	Repetitions	Spectral Efficiency ((b/s)/Hz)
QPSK	1/2	0	1.0
QPSK	3/4	n/a	1.5
16QAM	1/2	n/a	2.0
16QAM	3/4	n/a	3.0
64QAM	1/2	n/a	3.0
64QAM	2/3	n/a	4.0
64QAM	3/4	n/a	4.5
64QAM	5/6	n/a	5.0

Using a table similar to Table 16, along with the applicable SNR for each modulation and code rate, one can determine the channel spectral efficiency net of FEC relative to the range. This is shown in Figure 37 for different path loss exponents. The probability that the received signal level will be sufficient to support the SNR required for each modulation and code rate at different path lengths will be the same as that used to predict the maximum range. Since Figure 37 relates spectral efficiency to the relative path length the curves for different values of *n* start at the same point, namely the minimum spectral efficiency used to define the threshold SNR. With reduced distance the spectral efficiency increases to the value predicted for 64QAM with 5/6 rate-coding. The rate at which the spectral efficiency increases to its maximum value is a function of the path loss exponent, *n*.

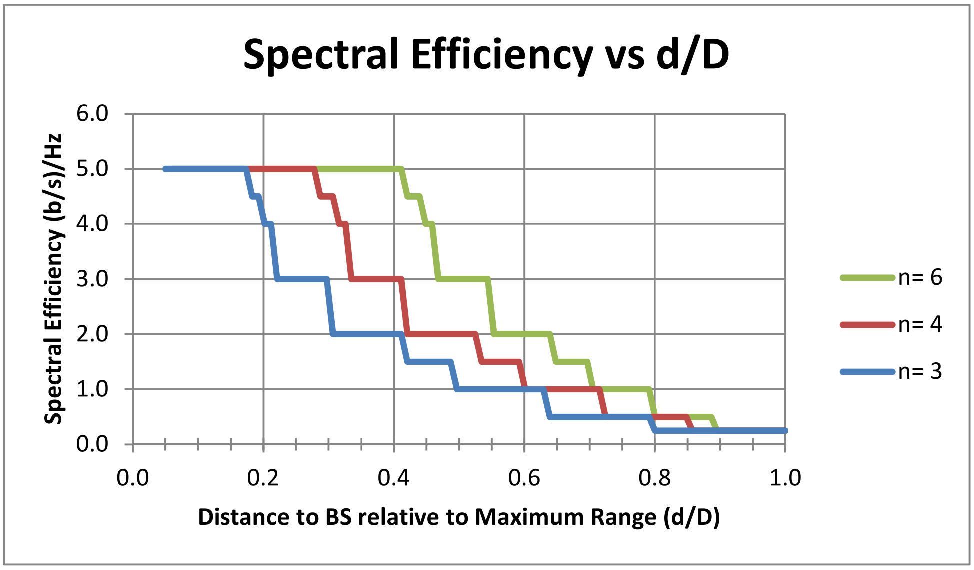


Figure 37 - Spectral efficiency (SE) increases with decreased range

In practice, whether it is due to the path loss model selected for the range analysis or the conditions under which the model is being applied, the higher path loss exponent will generally result in a lower range prediction but, as the curve shows, a greater percentage of the predicted cell coverage area will experience a higher channel spectral efficiency. This is shown more clearly in Figure 38 where the spectral efficiency is plotted versus the relative coverage area.

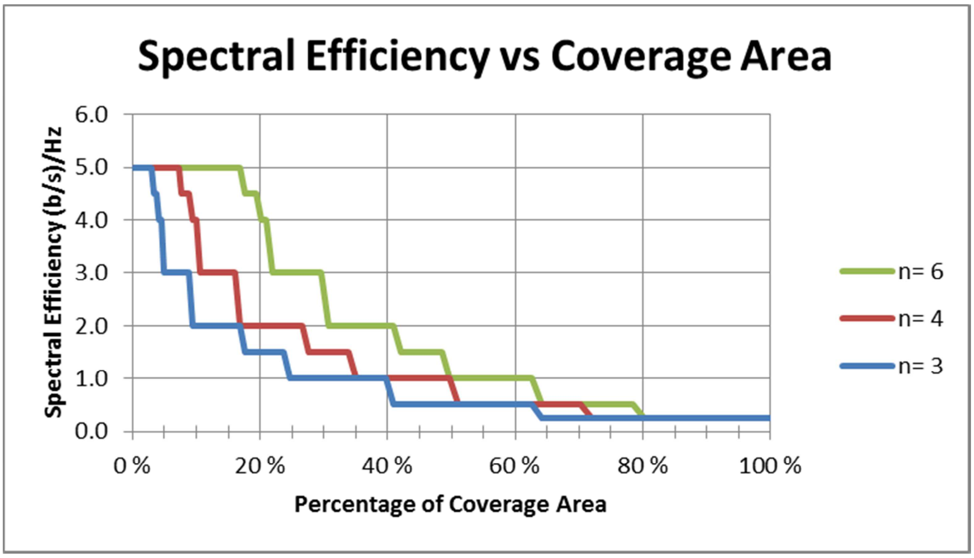


Figure 38 - Spectral efficiency (SE) relative to cell coverage area

Assuming the terminal devices are uniformly distributed over the cell coverage area, the average channel spectral efficiency can be found by estimating the area under the curve. This can be done by breaking the area into *m* segments and calculating the average of the spectral efficiencies over all of the segments.

$$AvgSE = \frac{1}{m}\sum_{i=0}^{m} SE_i$$

As an example for the path loss exponent, *n*= 6:

AvgSE = 2.0 (b/s)/Hz

Although average channel spectral efficiency is an important metric, of greater interest is the average channel capacity, and most importantly actual data throughput at the application layer or goodput. Multiplying the average spectral efficiency (AvgSE), as shown above, with the channel BW provides the average channel throughput. This however, only takes overhead due to FEC into account. For the net channel goodput**,** a number of additional channel overhead factors must also be taken into account. These include:

- Additional PHY overhead to account for control or pilot channels or sub-channels
- Layer 2 (MAC / Data Link) overhead
- Layer 3 to Application Layer overhead for additional protocols, headers, etc.
- Encryption overhead

Denoting this additional overhead as ChOH, the average channel goodput is easily calculated.

Avg Channel Goodput = AvgSE × ChanBW × (1 – ChOH)

It is useful to define the term net spectral efficiency (NetSE) given by:
NetSE = AvgSE × (1-ChOH)

It should be noted that overhead (OH) may be accounted for differently in how it is allocated between layer 1 and layer 2 with different technologies. What is important is that all of the OH factors must be taken into account.

In doing this analysis it is also important to consider the channel overhead (ChOH) in both the UL and DL channels as these may not always be the same. For most Smart Grid use cases the UL traffic will be greater than the DL traffic[22] so the UL channel data capacity or UL goodput will be the metric of interest for assessing BS capacity requirements.

If a higher data goodput is required to meet the data demand in high population density environments, BSs can be deployed with a closer spacing. When the range that each BS must cover is less than its maximum range capability the channel capacity is increased due to the higher average SNR over the entire coverage area. In the above example limiting the range to 0.7D results in an AvgSE = 3.05 (b/s)/Hz, a 70 % increase in throughput.

5.2.4 Physical Layer (PHY) Model

The purpose of the PHY model is to estimate the probability that a transmission attempt fails due to channel errors caused by noise or interference. The transmission failure probability takes into account factors affecting the link budget, including transmission power, antenna gains, channel attenuation, thermal noise, background interference, the number of contending stations (if the channel is shared), and the spread spectrum processing gain, if applicable. Depending on the level of modeling, the PHY model may also explicitly model the stages of the transceiver, such as channel equalization, demodulation, and forward error correction, resulting in a bit error rate, symbol error rate, or block error rate. Alternatively, the PHY model may abstract some of these functions and model them with an overall required E_s/N_0 or E_b/N_0 (ratio of energy per bit to noise power spectral density[23]), wherein the probability of transmission failure is reflected as the probability that the received SINR per bit exceeds the required E_b/N_0. As part of the modeling framework, the PHY model provides the MAC sublayer model with a conditional probability of transmission failure. For example, with a contention based MAC, the MAC model supplies the PHY model with the number of contending transmissions. Given the parameters of the link budget and channel statistics, the PHY model then returns the probability that the transmission of interest is unsuccessful conditioned on the number of contending transmissions.

[22] The exception would be when firmware is being updated. During these instances DL traffic can be more dominant.

[23] The energy per symbol to noise density can be found by the expression, $E_s/N_o = \log_2(M) \times E_b/N_o$, where M is the modulation index. Both E_s/N_o and E_b/N_o are directly related to SNR.

5.2.5 MAC Sublayer Model

The MAC sublayer model can be either analytical or simulation-based. The relative complexity is determined by the preferences and needs of the user. The MAC sublayer model receives inputs based on the application requirements and the wireless (or wired) technology that is being used to transport the data; the model interacts with both the PHY model and the coverage model. The MAC sublayer model is responsible for returning values for the following performance metrics for the communications system:

- Reliability
- Mean packet delay (latency)
- Layer 2 Throughput
- Encryption

Reliability is defined as the probability that a packet originating from a sending node's MAC sublayer is correctly received by the corresponding MAC sublayer at the receiving node. Thus the reliability is defined with respect to a single link, rather than on an end-to-end or edge-to-edge basis. For MAC sublayers with a shared channel, where there is contention for resources, the reliability is the probability that the packet does not collide with any packets that are transmitted by other senders and that the packet is not corrupted by channel errors. If the channel is dedicated to the sender (no contention), then the reliability is simply the probability that the packet does not experience any channel errors. The mean packet delay is the average time from the passage of the packet to the sender's MAC sublayer from the protocol layer immediately above to the delivery of the packet by the receiver's MAC sublayer to the protocol layer immediately above it. The mean packet delay includes the following:

- The time the packet spends in the sender's MAC sublayer's transmission buffer
- The processing time at the sender's MAC sublayer
- The time required to transmit the packet, which is the packet length in bits divided by the PHY channel data rate in bits per second
- The time spent waiting to retransmit the packet if it encounters collisions (in the case of a contention-based MAC protocol) or channel errors
- The propagation delay between the sender and the receiver
- The processing time at the receiver's MAC sublayer
- BS to BS handover delay (applicable for mobile terminals)

The throughput is a measure of how efficiently the channel is being used, and it is measured in units of application bits per second. The model computes two types of throughput.

- The first type is the average throughput, which is the product of the offered load at the application layer and the packet reliability. Note that this implies that the ratio of the throughput to the offered load is always a number between 0 and 1.
- The second type of throughput measured by the model is the instantaneous throughput, which is the ratio of the mean number of application data bits per packet to the mean packet delay. This gives the effective channel rate

experienced by a packet that is ultimately successfully sent across the link, even if it requires retransmissions.

The major external inputs that do not depend on the particular MAC technology are the number of devices accessing the channel, the mean packet generation rate of each device, and the mean packet size. The mean packet generation rate is typically given in units of packets per second; the actual packet generation process is arbitrary. Packets can arrive according to a deterministic process, in which case the mean generation rate is simply the actual generation rate, or they can arrive according to a random process (e.g., a Poisson arrival process). The size of the packet typically includes the size of the application data, as well as the combined size of all headers, including the MAC sublayer and PHY headers. The packet size can be deterministic or random, depending on the applications that are being modeled. There are additional inputs that are unique to the MAC technology that is being modeled. In the case of a contention-based MAC technology, these parameters can include the number of times the MAC sublayer will attempt to transmit a packet before giving up and dropping it, rules for handling packet collisions, such as the amount of time that the MAC sublayer must wait to retransmit a packet after it has collided with a packet from another transmitter, and the amount of time the sending MAC sublayer must wait for an acknowledgement of a transmitted packet before taking further action.

Non-contention MAC technologies will use different parameter sets. The PHY model exports the probability of transmission failure, P_{fail}, to the MAC sublayer model, which uses it to help compute the output metrics. For instance, if modeling a very simple MAC sublayer that uses dedicated resources (so no contention) and no retransmissions, it would be found that the reliability is equal to $(1 - P_{\text{fail}})$, and the mean delay of successfully received packets is the sum of the propagation delay and the transmission time. The coverage model exports the maximum Tx-Rx distance to the MAC sublayer model. With only a user population density, the maximum Tx-Rx distance can be used to compute the coverage area and size of the covered user population.

5.2.6 Multi-Hop (or Multi-Link)[24] Model

When the PHY parameters of a wireless link are such that the link is coverage limited, the effective coverage can be extended by routing through a sequence of multiple connections or links, denoted as a multi-hop, rather than through a single link alone. The MAC model generates performance metrics for single links; the multi-hop model, on the other hand, works interactively with the MAC model to generate end-to-end performance metrics for multiple hops or relays. As illustrated in Figure 9, the multi-hop model accepts single-link performance metrics as input from the MAC model. Subsequently, the multi-hop model generates the same classes of performance metrics for multiple hops. The actual sequence of links depends on the pair of source and destination nodes and the pair-wise link metric between the intermediate nodes. Common link metrics are minimum-hop and minimum-airtime. The resultant routing topology indicates the routes through which traffic is forwarded through the multiple hops. The routing topology

[24] Multi-hop is used to describe inter-technology BS to BS connections and multi-link to describe intra-technology BS to BS connections

affects links in a different manner. For example, if a link is forwarding traffic from multiple sources, it will have a heavier traffic load than otherwise. In particular, if the destination of all source nodes is a single BS or DAP, the backhaul links connected directly to the destination or DAP will be forwarding traffic from all other sources. This translates to a higher offered load for those links. The offered load of the source is an input to the MAC model from the application requirements. The MAC model also accepts the routing topology as input from the multi-hop model and in turn computes the offered load of all links accordingly. Source node facing links from the DAP to the other source nodes in this multi-hop network will similarly have higher traffic density dependent on the number of additional sources served the DAP.

5.2.7 Modeling Latency

When considering a Smart Grid application consisting of two-way transactions between two actors, one must consider the amount of time that can be tolerated for completing the two-way exchange of data between the actors involved in the transaction [5]. This is typically referred to as the maximum latency for this transaction. Multiple factors affect the total delay or latency of a transaction that usually includes: processing time in system servers, delays in database access, and communications or network delays to mention a few. Of these, the communication or network delay is considered and analyzed in further detail in this section. It must be noted that the network delay will consume only a fraction of the total maximum transaction latency. The remaining fractional portions of the total transaction latency will be allocated to other system components.

The analysis of the network delay is usually addressed by analyzing each link, hop, or segment of the network system forming the network path between two actors, A and B. The total network delay is then the sum of the individual delays contributed by each link, hop, or segment. The total two-way network delay would then include the network delay encountered in transmitting a transaction data payload from actor A to actor B plus the network delay encountered in transmitting the transaction's response data payload from actor B back to actor A.

As indicated above, a total network latency analysis must consider the discrete delays encountered in each segment or link through which transaction data payloads traverse. Therefore, even the fraction of the total transaction latency allocated for the network delay must be further sub-divided and allocated to the multiple segments in the network. In some of these network segments the actual delays may be insignificant while in others, the delays may be larger and must be analyzed more completely for a more accurate analysis. In general the delay encountered in a segment is related to the channel bandwidth and goodput (defined in section 5.2.3), the size of the data packet to be transmitted, and the congestion encountered at that network segment. If a network segment is idle when a data payload arrives, it is usually transmitted immediately and the only delay is the delay encountered in preparing the data for transmission plus the delay in actually transmitting the data payload at the goodput rate for the network segment of interest. For greater precision the propagation delay over the length of the segment path must also be included. However, for short path lengths, this delay is considered insignificant and, in most cases, ignored. If, on the other hand, a network segment is receiving multiple data payloads for transmission in a short period of time, there is a finite probability that some data payloads will encounter congestion from other data payloads waiting for access to the network segment or channel. When payloads compete for access to a congested channel queuing comes into play and results in additional delay.

Queuing theory, which is deeply rooted in probability theory, has been the subject of extensive research over the years for a wide range of applications that has resulted in many different mathematical models for predicting queuing-induced delay. The goal of this section is to provide an introduction to this subject and provide some insights as to how the channel goodput, message or payload size, and message or payload rate relate to the delay caused by queuing in a congested channel in a single network segment.

The first approach uses a binominal distribution technique to establish an estimation of the probability of meeting a specific latency value. The second approach uses a more traditional response time analysis technique based on M/D/1 [25] and M/M/1 [26] mathematical queuing models to derive the average response time for transactions transmitted over a network segment. Each model is intended to show the effects on latency when increasing the number of nodes or actors competing for access to a network segment of a given capacity or goodput.

5.2.7.1 Binomial Distribution Model

In this section we describe an approach based on a binomial distribution for determining the number of end-terminals or actors that can be supported by a specific channel while meeting a specific latency requirement. When a number of packets are competing for access to a limited resource, there is a probability at any instance of time that a specific packet carrying a message or data payload will or will not gain immediate access to the channel for transmission over the link. As indicated earlier, it must be noted that an individual network segment is not the only contributor to total network latency (or delay) but when a channel is operating at or near its capacity, it will often be the dominant contributor and thus an important one to model. The key parameters required for modeling this contribution to latency are:

- The average channel goodput (C_{GP})
- The average transmitted packet size (P_{AVG}) (note that large data payloads or messages may be segmented into smaller packets for transmission)
- The rate at which messages or packets are being transmitted (R_{MSG}) or alternatively, the average time between messages or packets (T_{MSG})
- The probability a packet is transmitted or received within a specified time window (P_{MSG})

The average channel goodput = C_{GP} = Net Spectral Efficiency multiplied by the Channel BW where the Net Spectral Efficiency is defined as the average spectral efficiency at the

[25] The notation follows Kendall’s notation where M stands for Markov (arrival times), D stands for deterministic (service times), and 1 stands for number of servers or in this case, transmission links.
[26] Another related model is the M/M/1 Queuing model where the service times are not constant but are also described by a Poisson process

application layer as described in section 5.2.3. This takes into account all of the channel overhead factors including the higher layer protocols, headers, and encoding overhead.

For any given actor in a Smart Grid network there can be hundreds of messages that must be transmitted within any 24 hour period. The message rates for different types of information can range from several messages per hour to one message per day, and the size of the message payload can vary from 25 bytes to several thousand bytes. From the detailed SG Network System Requirements Specification, the average message rate (R_{MSG}) per actor can be determined and the average message payload or packet size (P_{AVG}) can be calculated. The average time between messages is then given by:

$\boldsymbol{T_{MSG} = 1/R_{MSG}}$;
for T_{MSG} in seconds R_{MSG} must be expressed in messages per second.

The time in seconds it takes for the average packet to be carried over the channel is given by:

$\boldsymbol{T_{PKT} = 8 \times P_{AVG} / C_{GP}}$;
where C_{GP} is the channel goodput in b/s

By using a binomial distribution analysis mythology, we require two additional parameters: the number of trials and the packet probability. One way to do this is to assume that the number of trials is equal to the number of time slots that occur within a specified latency period. This value is $\boldsymbol{L/T_{PKT}}$ (rounded down to the nearest integer). Note that L must be greater than T_{PKT}. The probability that a message event falls within the time window defined by L is: $\boldsymbol{P_{MSG} = L/T_{MSG}}$. For the model, L is chosen to be the fraction of the overall latency at the application layer in seconds which has been apportioned to this network segment. Using these assumptions, the cumulative binomial distribution function is used to analyze the congestion that may occur during a time period defined by L.

It is important to visualize the relative value of each of these parameters in a typical Smart Grid network for a single actor. This is illustrated in Figure 39.

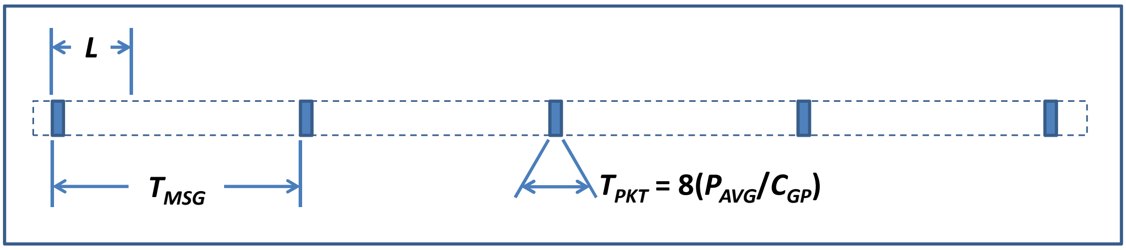


Figure 39 - Relationship between L, T_{MSG}, and T_{PKT}

As illustrated in Figure 39, $\boldsymbol{T_{PKT} < L < T_{MSG}}$. This relationship assures that $\boldsymbol{L/T_{MSG} < 1}$ and $\boldsymbol{L/T_{PKT} > 1}$.

The number of actors that can be supported by a channel can be estimated by using the Cumulative Binomial Distribution Function[27]. The probability that the offered load in a given time window, L, is less than the channel goodput is calculated as follows:

$$F(x; n, p) = Pr(X \leq x) = \sum_{i=0}^{\lfloor x \rfloor} \binom{n}{i} p^i (1-p)^{n-i}$$

Where
x = The maximum number of transmission events in a window = largest integer ≤ L/T_{PKT}
n = Number of actors
p = Probability of an actor transmitting in the window = $P_{MSG} = L/T_{MSG}$

It should be noted in this analysis we are calculating the probability that the offered load in the time period, L, does not exceed the goodput capacity of the channel or network segment. This does not mean that if this capacity is exceeded for a short period of time the overall transaction latency requirement or even the fraction of this latency allocated to this segment will be violated. It only indicates the probability that the offered load may exceed the goodput capacity of the network segment during the period, L. Even if the goodput capacity of the network segment is exceeded during time period, L, and packets start to queue up, there is still a finite probability that each packet may leave the queue and be transmitted through the network segment within its allocated latency allotment. However, this analysis is a good way to illustrate the probability of overloading the capacity of a network segment which may well result in a significant violation in the overall latency requirement for the transactions.

The results are shown in Figure 40 and Figure 41 for an average channel goodput of 1.0 Mb/s and 0.1 Mb/s (100 kb/s), respectively. For these two examples the message rate, R_{MSG}, is assumed to be 300 messages per hour which translates to an average time of 12 seconds between messages and the average packet size in both cases is assumed to be 250 bytes. In these figures the confidence values refer to the probability that the load offered by the number of nodes or actors will not exceed the goodput capacity of the network segment during a period defined by L, the allocated portion of the overall transaction latency requirement.

[27] In Excel® the expression is: BINOMDIST(L/T_{PKT}, # Actors, P_{MSG}, 1)

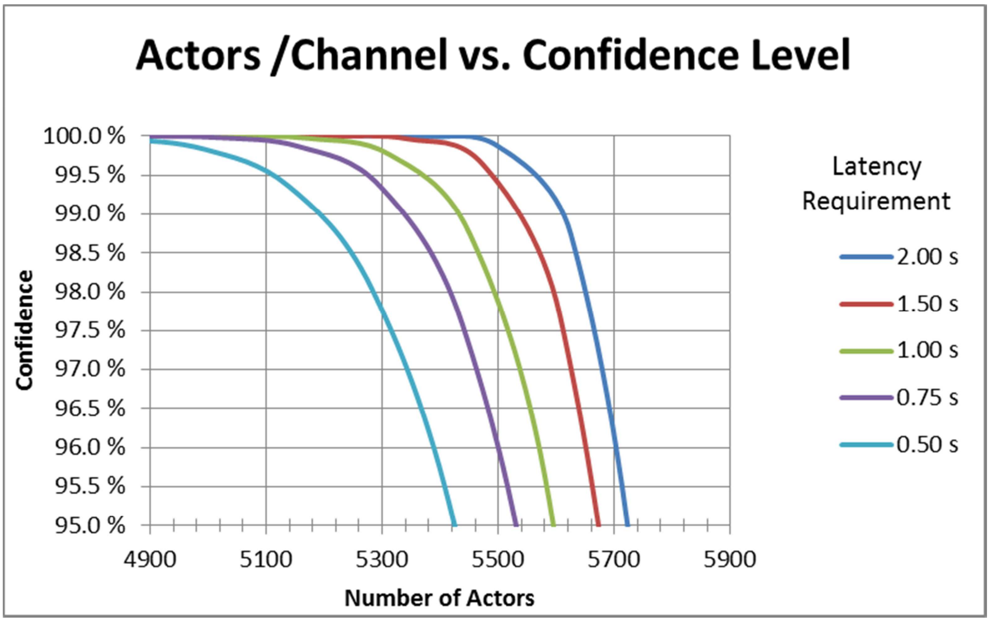


Figure 40 - Actors per channel for goodput = 1.0 Mb/s

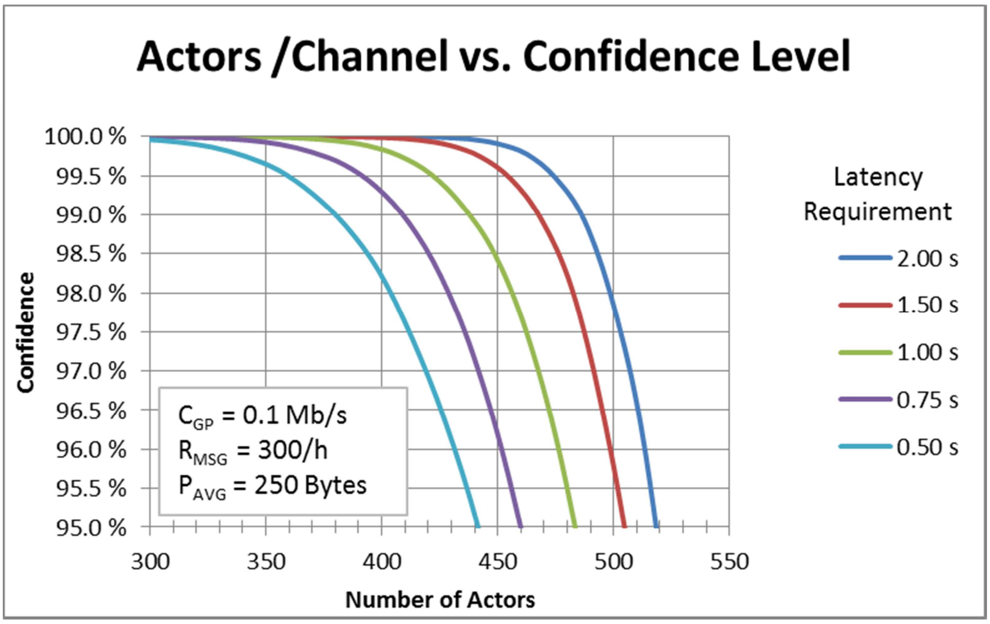


Figure 41 - Actors per channel for goodput = 0.1 Mb/s

Table 17 provides a summary of the expected change in the number of actors that can be supported per channel for variations in the relevant parameters. The desired confidence level in all cases is assumed to be 99.5 %.

Table 17: Summary of expected change

Parameter	Nominal Value	Parameter Change	Change in number of Actors
Latency (*L*)	1.0 second	- 50 %	- 5.5 %
Channel goodput (C_{GP})	1.0 Mb/s	- 20 %	- 22 %
Packet size (P_{AVG})	250 bytes	+ 20 %	- 17 %
Message rate (R_{MSG})	300 message per hour	+ 20 %	- 16 %

The number of actors that can be supported by a given channel is primarily dependent on the channel goodput which in turn is a function of the available bandwidth and the total channel overhead. A less obvious result is the fact that the value, *L*, used in this analysis has a relatively small effect on the number of actors that can be supported through a network segment. This is because the probability of a successful trial is more directly proportional to congestion of the network segment than to the time window size, *L*, used to calculate the binomial distribution values.

5.2.7.2 M/D/1 and M/M/1 Queuing System Models

Another approach for modeling the delay encountered in a network segment is based on the M/D/1 and M/M/1 mathematical models. These models have been used for general service time analysis and, when applied to networking systems, they are commonly used for response time and throughput analysis.

In the networking context considered here, the M/D/1 is referred to as a constant service model. It refers to a mathematical model where packet arrival rates are random, described by a Poisson process (sometimes also referred to as having negatively exponentially distributed inter-arrival times), and where service or transmission time through the network segment is constant. A further assumption is that there is only one network transmission path or segment through which all the payload packets will transit. These assumptions are reasonable for an analysis where each downstream node offers payload data packets at a fixed average rate, each packet is a constant fixed size, and the packets arrive from the multiple downstream nodes in an independent and random manner. This model requires two basic inputs; the average combined arrival rate of packets per unit time (λ)[28] and the number of packets that can be transmitted per unit time, which is also known as the service rate (μ). For a stable system λ, the arrival rate, must be less than μ, the service rate. If a sustained arrival rate is greater than the service rate, the queue will grow without limit. The arrival rate of packets is in-turn related to the average rate packets are generated by each node and the number of downstream nodes feeding into the network segment. It is calculated by simply multiplying the number of active downstream nodes by the average rate packets are generated by each node. The packet service rate is calculated by simply dividing the network segment goodput rate, C_{GP}, (in b/s) by the number of bits in each packet. This yields the service rate in packets per second. Since the size of the transmitted packets in these examples is considered

[28] λ is used here to be consistent with the terminology typically used in describing the M/D/1 or M/M/1 models. This is the same as R_{MSG} for the Binomial Distribution Model

constant (250 bytes each) and the goodput is also assumed constant for each example considered, the calculated service rate for each example is also constant, as required for the M/D/1 analysis.

In the forgoing M/D/1 and M/M/1 analysis two examples are considered. One considering the goodput of the network segment is 0.1 Mb/s, and the other for a goodput 1.0 Mb/s. This matches the assumptions in the previous analysis the Binomial Distribution Model, namely:

- Packet Size = 250 bytes (or 2,000 bits)
- Packet arrival rate per node = 300 packets per hour or equivalently 0.083333 packets per second per node
- For a goodput of 0.1 Mb/s the service rate (μ) is calculated by dividing 100,000 (b/s) by 2,000 bits per packet which equates to 50 packets per second.
- For a goodput of 1.0 Mb/s the service rate (μ) is calculated by dividing 1,000,000 (b/s) by 2,000 bits per packet which equates to 500 packets per second.

In considering the number of nodes or actors that can be supported by a network segment of a fixed capacity or goodput, we must consider the combined traffic load offered by these nodes. This can be easily calculated by multiplying the packet arrival rate from each node by the number of nodes. The result is the total offered load, λ, in packets per second.

The equation for calculating the expected average time (E_{rt}) a packet takes to be processed completely through the communications channel or network segment for the M/D/1 analysis is:

$$E_{rt} = (2-\rho)/((2\times\mu\times(1-\rho))$$

where
$\rho = \lambda/\mu$ = packet arrival rate per service rate.

In this example the combined average arrival rate (λ) is calculated by multiplying the number of nodes offering traffic (*N*) times the arrival rate from each node, or $N\times.083333$. The value of $\mu = 50$ for the 0.1 Mb/s goodput example, and $\mu = 500$ for the 1.0 Mb/s goodput example as pointed out above.

Thus the value ρ = arrival rate per service rate = *N* nodes × 0.083333/50 for 0.1 Mb/s goodput and the value ρ = arrival rate per service rate = *N* nodes × 0.083333/500 for 1.0 Mb/s goodput.

These calculations can be easily implemented in a spread sheet using, as input variables; the number of nodes or actors, the packet arrival rate from each node, and the service rate at which packets can be transmitted through the network segment at the given goodput rate. In a spread sheet analysis, the service rate would actually be calculated by dividing the size of the packets (in bits) into the goodput rate (in b/s).

In contrast to the M/D/1 model, the M/M/1 model is generally considered to be more conservative when estimating the effective capacity of a network segment which may, in-turn, lead to an underestimation of the number of nodes that can be effectively served through a network segment. In the M/M/1 model used in the forgoing examples, the assumed packet size is no longer considered a constant but instead its average size is considered to be 250 bytes but is expected to vary according to an exponential distribution. Thus the calculated service rate for these packets also follows an exponential distribution. When considering both an M/D/1 and M/M/1 analysis, they may together serve to bracket a more realistic number of nodes that can be effectively served by a network segment, with the M/D/1 over-estimating and the M/M/1 under-estimating the number of nodes that can be effectively served by a network segment of a given channel goodput. To illustrate, consider the M/M/1 model described here where all the variables used in the calculations remain the same as in the previous M/D/1 example, except the size of the packet is now assumed to vary according to an exponential distribution.

The equation for calculating the expected average time (E_{rt}) a packet takes to be processed completely through the communications channel or network segment for the M/M/1 analysis is:

$$E_{rt} = (1/\mu)/(1-\rho)$$

As before, for the M/D/1 analysis, the value $\rho = \lambda/\mu$ (packet arrival rate per service rate). In this example the combined average arrival rate (λ) is also calculated by multiplying the number of nodes offering traffic (N) times the arrival rate from each node, or $N \times 0.083333$. Thus the value of $\mu = 50$ for the 0.1 Mb/s goodput example, and $\mu = 500$ for the 1.0 Mb/s goodput example.

Therefore, the value ρ = arrival rate per service rate = N nodes× 0.083333/50 for 0.1 Mb/s goodput and the value ρ = arrival rate per service rate = N nodes× 0.083333/500 for 1.0 Mb/s goodput.

Using the stated input parameters, and the equation for E_{rt}, the following two charts, Figure 42 and Figure 43, of the expected average time for a packet to be transmitted through the network segment vs. the number of active actors offering packets to be transmitted, can be constructed for the M/D/1 (constant service time) and M/M/1 (exponential service time) models. The charts clearly show the more conservative estimate for the M/M/1 model compared to the M/D/1 model.

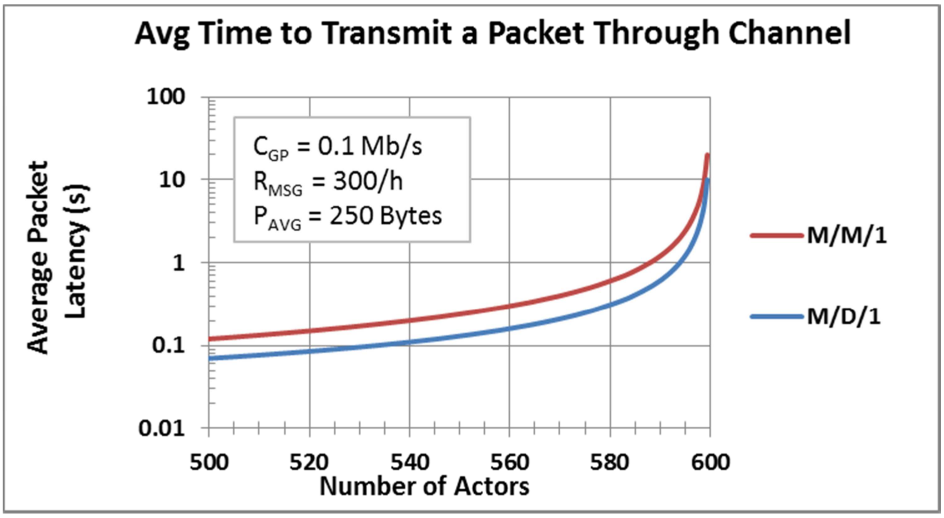


Figure 42 - Average packet latency for goodput = 0.1 Mb/s

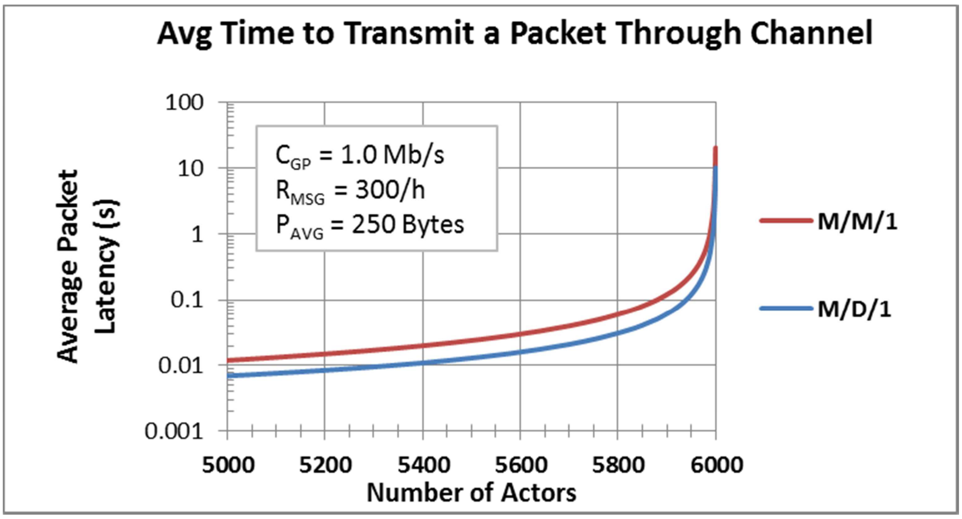


Figure 43 - Average packet latency for goodput = 1.0 Mb/s

In calculating the expected average time (E_{rt}) a packet takes to be processed completely through the communications channel or network segment, it is important to note the M/D/1 and M/M/1 analytical models used in this example take into account the probability that packets arriving at the network segment for transmission may not be immediately transmitted due to channel congestion. In that case they are placed in the queue of packets awaiting their turn to be transmitted. This additional queuing delay is obvious in Figure 42 and Figure 43 as the number of nodes increases such that the combined offered load approaches the total capacity or goodput of the network segment. These two charts show the analysis of capacity vs. latency in a different context than the Binomial Distribution Model described earlier, which calculated the probability distribution for the number of packets arriving within a given time window of size, *L*, that would exceed the maximum capacity for transmitting these packets in that same time window, *L*, where *L* was selected to be equal to the required latency. These latter charts (Figure 42 and Figure 43) however, dramatically show that as the number of nodes increases, the offered load to a network segment increases, the effects of congestion quickly cause the average delay for each packet to lengthen significantly as the offered load to the network segment approaches its maximum capacity.

Again, the reader is cautioned that the preceding M/D/1 analysis is based on average response time for a fixed set of parameters, namely in this case each message or packet is 250 bytes in size and the arrival rate is assumed constant over time at 300 packets per hour per node. In practice, the assumption of constant packet size and the resulting constant packet service rate is generally not realistic and may lead to over-estimating the number of nodes that can be effectively served through a network segment of a given goodput. The M/M/1 analysis on the other hand, can be considered as being a more representative model for simulating what would be encountered in practice.

One could use charts similar to Figure 42 and Figure 43 as a guide for estimating the maximum number of nodes or actors that can be effectively served by a network segment to ensure the average packet latency encountered in the network segment will lie between the two lines on the chart. By identifying the fractional portion of the overall transaction latency that can be apportioned to the network segment in question, using the charts illustrated here can provide guidance as to sizing the maximum number of nodes or actors that can be served by a network segment while ensuring the average packet latency will not exceed the allocated maximum value.

5.2.7.3 Comparing the Binomial Distribution Model with the M/M/1 Model

Two different approaches have been discussed for determining a network segment's ability to meet a desired latency. Both approaches are probability-based and thus will only provide an estimated value with some degree of confidence as to the number of supportable nodes or actors that can be supported as the network segment, or in this case a channel, approaches a congested state.

The use of either the binomial distribution analysis technique or the M/D/1 or M/M/1 analysis techniques will provide an estimate of the capacity of the link to meet the required latency for that segment. Using the binomial analysis technique described here will lead to an estimate of the probability for meeting the allocated latency, whereas the use of the M/D/1 and M/M/1 analysis techniques will provide an estimate of the average time to transmit a packet through the network segment. Both techniques are useful in evaluating the ability of the network segment to satisfy its latency requirement and how this ability is related to its goodput and the load to which it is being subjected.

To gain further perspective for the applicability of either of these models for predicting the latency performance in a Smart Grid network segment, it is informative to see how the two models compare.

The predictions for the number of supportable actors for the M/M/1 and Binomial Distribution models are shown in Figure 44 and Figure 45 for 97.5 % and 95 % probability respectively. As the charts illustrate, the Binomial Distribution approach provides a more conservative prediction than the M/M/1 approach which in turn, as discussed in the previous sections, provides a more conservative estimate than the M/D/1 model.

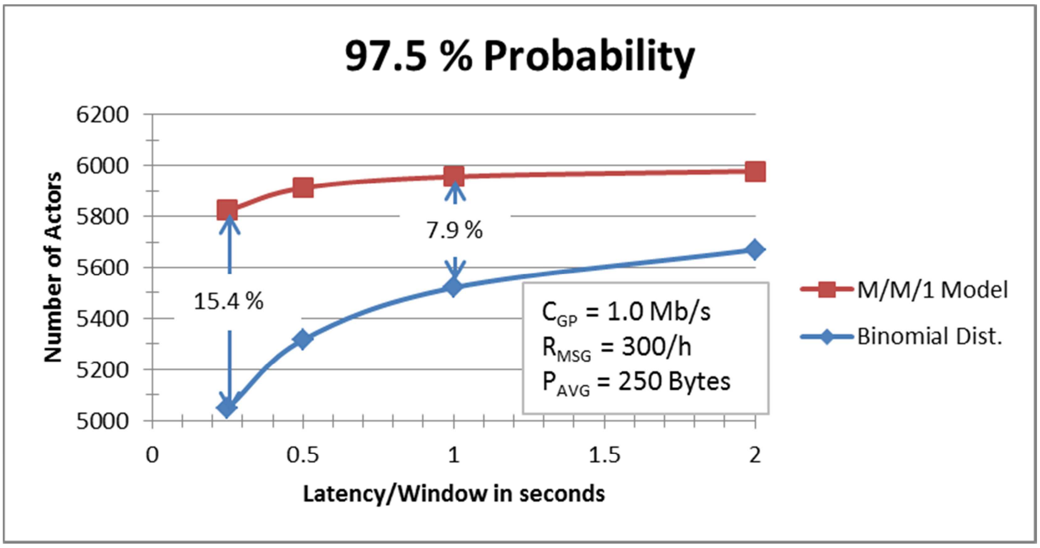


Figure 44 - Comparison for 97.5 % probability

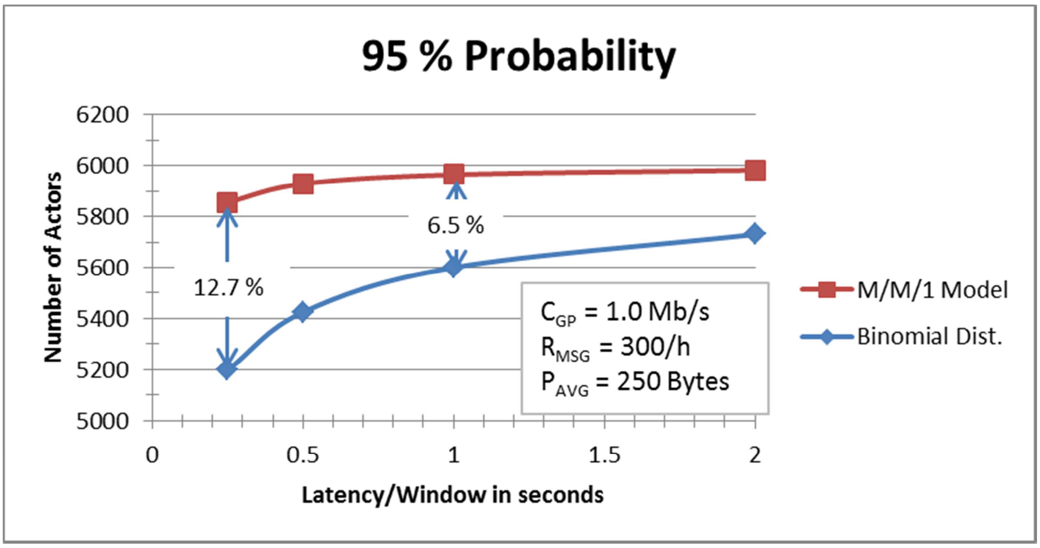


Figure 45 - Comparison for 95 % probability

5.2.7.4 Additional Latency Considerations and Conclusions

While the examples described in this section and their analysis may seem complex, unfortunately in the real world, one would expect the offered load to be even more complex than assumed in any of the preceding analysis. Transactions and packets transiting a network segment would likely consist of a mixture of transaction types, packet sizes, and the arrival rates and in this mixture is likely to vary dramatically over time, particularly for periodic events like meter reading. Other more complex mathematical models beyond those illustrated here may be employed to handle these more complex examples. While beyond the intent and scope of this rudimentary latency and response time analysis, an interested reader may wish to explore these more complex models further by exploring the subject of response time analysis on the Internet or by consulting a number of text written on the subject. However, the examples presented here illustrate the basic concepts and principals in analyzing the latency and capacity of a network segment and how these relate to the number of nodes that may be effectively served through that network segment.

For a more complete picture of the overall network delay, an analysis like this would need to be conducted on each network segment, and for each particular transaction type traversing it, and in each direction for the two-way or round trip application response time consideration. However, as each different network segment may have a different mixture of application transactions with each at different rates and then when combined will provide different congestion values, it can be seen a complete and comprehensive analysis would be a very complex problem indeed. Without the aid of a sophisticated computerized modeling system to provide a more comprehensive analysis, it is suggested one would look at the low bandwidth (or low goodput) network links and at the most congested links in a network and evaluate these further to determine if the congestion delay and the transmission delay through these links would be likely to cause the transaction latency values to be violated.

In conclusion, as stated earlier the models described in this section do not account for all of the contributors to network latency. A more complete analysis would include the delays required to initiate a session and fully process the data packets at each of the nodes in the transmission path and may also include, for longer physical path lengths, the propagation delay. To summarize, these additional contributors to latency are:

- Time to initiate a session from idle or sleep mode to active data session mode, this includes authentication and admission control
- Time required to process packet headers and determine where packets should be routed
- Time required to initiate a connection with an alternate BS that is within range (BS to BS handover) during periods of changing propagation conditions or for mobile applications
- Propagation (OTA) time

The propagation time is 3.3 μs / km and for any terrestrial network can be ignored. It may be a factor in satellite systems, however. The other three contributors are generally in the 10 ms to 100 ms range and may be ignored for most cases but could become significant when mission-critical data is transmitted over a multi-hop path. In those cases one could choose to simply add a reasonable value for each node; 25 ms to 50 ms would probably be sufficient to capture the average impact. Another scenario for which this contribution can be a factor is when the latency requirement for very large application payloads is apportioned to much smaller packets for transmission.

Another important factor not taken into consideration with any of the models is QoS. All of the wireless submissions for outdoor terrestrial networks have some support for setting packet priorities, an essential ingredient of QoS. This enables the prioritization of individual data packets with respect to their tolerance to latency.

Obviously, to account for all of these factors with a simple, easy to use, mathematical model for wireless network planning purposes would be a major undertaking. Despite the limitations, any of the models described in this section can prove useful in assessing a channel's ability to meet Smart Grid latency requirements when the channel is in a congested state, when queuing delays will tend to dominate. The latency performance based on the model will predict a conservative result since, when QoS features are taken into account, the performance will only improve for high priority latency-sensitive payloads.

6 Practical Considerations in the Deployment of Wireless Networks for SG Applications

Section 4 provided a detailed description of the various attributes and performance parameters that would be important in making an assessment of how different wireless access technologies would apply in a Smart Grid communications network. Section 4 also provides a link to the Wireless Functionality and Technology Matrix which provides a summary of performance details for several wireless access technologies as submitted by Standards Development Organizations.

In section 5, a number of propagation and path loss models were presented along with various graphs, tables, and other models and relevant information that would be applicable to a land-based wireless technology deployment. A special effort was made in this section to take into account the specific deployment requirements and trade-offs that are applicable to Smart Grid applications as opposed to traditional cellular networks.

The goal for this section is to build on what was presented in section 4 and section 5 and take into account some of the varied challenges and trade-offs that will likely be encountered in a typical Smart Grid communications network deployment. In section 6.5, an Excel®[29]-based tool is introduced. This tool is intended to provide a means for quantitatively assessing alternative terrestrial-based wireless solutions in deployment regions with varied demographic and propagation characteristics based on average Smart Grid network uplink and downlink payload requirements.

Specifically, this section is structured as follows:

- Section 6.1: Coverage, Capacity, Latency Trade-offs
- Section 6.2: Advanced Antenna Systems and Spectrum Considerations
- Section 6.3: Multi-Link / Multi-Hop / Mesh Topologies
- Section 6.4: Addressing the Challenges with Multi-Tenant High Rise Buildings
- Section 6.5: SG Framework and Wireless Modeling Tool
- Section 6.6: Interoperating and Interworking with Other Wireless Technologies
- Section 6.7: Assessment of Modeling Tool Results
- Section 6.8: Cross Wireless Technology Considerations

6.1 Coverage, Capacity, Latency Trade-offs

This section discusses key performance factors that are common to any smart grid wireless communication network deployment and how these factors relate to the demographics and characteristics of the area being considered for deployment. From an operational perspective key performance parameters are propagation range, UL and DL

[29] Any mention of commercial products within this report is for information only; it does not imply recommendation or endorsement by NIST.

channel capacity, and latency. In section 5 we discussed and provided generally accepted path loss models for indoor and outdoor land-based wireless networks. Additionally we described how link budgets can be derived and how range and channel capacity can be determined. In this section we bring in the other key deployment variable: demographics.

In a wireless network we can generally describe deployments as ***Range-Limited*** or ***Capacity-Limited***. Range-limited scenarios cover the case where each BS is deployed in a manner that fully utilizes its range capability determined solely by the applicable link budget and the path loss characteristics of the area being covered without regard to data capacity requirements. Capacity-limited describes scenarios for which data traffic requirements are high and BSs or APs have to be spaced closer together to limit the number of actors per BS so as not to exceed the BS capacity capability.

Latency is another key SG performance requirement and depending on; channel goodput, average message size and rate, and number of actors, could result in a deployment that is limited in its ability to meet latency requirements in accordance with the model that was described in section 5.2.7. In addition to the channel access delay predicted by the model, it may, in some cases, be necessary to account for node processing delays. These would account for encryption / de-encryption, error detection and correction, etc. Generally these are small enough to be neglected but may come into play with large latency-critical payloads. The remaining contributor to delay is propagation (OTA) delay, 3.33 μs / km. This can be ignored for terrestrial wireless networks but can be a factor with satellite links.

6.1.1 Demographic Breakdown

From a demographics perspective it is informative to group deployment regions into the five categories described in Table 18 which includes area breakdowns based on US census data[30].

Table 18: Demographic breakdown

Demographic Region	Housing Unit (HU) Density (housing unit per square mile)	% of US Population	% of US Land Area	Typical Characteristics
Dense Urban	≥ 4,000 (≥1545 housing unit per square kilometer)	11.0	0.05	Large number of high rise multi-tenant buildings large number of businesses
Urban	1,000 to 3,999	34.7	0.6	Densely packed 4-6 story buildings, residential and industrial
Suburban	100 to 999	30.7	3.2	Mix of 1 and 2-family homes, low rise apartment buildings, shopping centers, more trees, parks, etc.
Rural	10 to 99	17.0	22.7	Larger parcels, low rise buildings, more trees and terrain obstacles

[30] The data for area breakdowns are from the US 2010 Census data which is based on square miles

Demographic Region	Housing Unit (HU) Density (housing unit per square mile)	% of US Population	% of US Land Area	Typical Characteristics
Low Density Rural	< 10 (<4 housing unit per square kilometer)	4.2	72.3	More extreme terrain characteristics, HU densities vary from clusters to individual HU miles apart

In addition to the typical area characteristics included in the table there are some additional generalizations that can be made related to population and housing unit (HU) densities that relate directly to terrestrial wireless SG network deployments.

In deployment regions with very high population densities one can expect:

- Limited spectrum options: Spectrum congestion will always be a limiting factor in areas with high population density. These are prime markets for other wireless operators and if any excess network capacity does exist, it will very likely be quickly consumed to keep up with the growing demand. That said, any spectrum that is available for Smart Grid networks may be in limited amounts and may not always be in a favorable frequency band for best range and coverage. This may require the use of smaller channel BWs, subsequently leading to lower channel capacity.
- Higher interference: With higher traffic densities and smaller cell sizes the potential for interference will be higher in these regions. This will be especially true in the unlicensed bands but can also play a role in licensed bands unless generous guard-bands are used. Limited spectrum dictates more aggressive frequency reuse, giving rise to greater sector to sector and cell to cell interference. The need for greater margins to account for interference will lower the link budget.
- Most deployments will be capacity-limited or limited in the number of actors per channel to meet latency requirements. Limited spectrum and high HU densities will lead to deployments that will have to be sized to meet capacity and latency requirements for most SG network segments.

In contrast, for areas with very low population densities it is reasonable to expect:

- Spectrum availability: Spectrum is more likely to be available. Existing license holders in some cases will be willing to lease portions of underutilized blocks of spectrum. Sharing the Public Safety bands with local municipalities is a realistic expectation and the use of license-exempt spectrum can be considered without the concern for large amounts of interference.
- Most deployments will be range-limited: With the ability to deploy a wireless network with a reasonable channel BW, deployments in rural areas will most

always be limited by the range capability. The exception would be in the unlicensed bands where regulators impose EIRP restrictions.

It is informative to delve deeper into the two extreme demographic categories, Dense Urban and Low Density Rural, to gain a better understanding of the challenges associated with each with respect to an SG wireless network.

6.1.2 Dense Urban Regions

In addition to the high density of meters and other utilities infrastructure that must be connected in a Dense Urban area wireless network, the deployment must also deal with significant propagation challenges. With the prevalence of underground utilities in metropolitan areas, meter banks will often be located in grade-level weatherized enclosures or below ground level in the basements of high-rise multi-tenant buildings. In either case the penetration losses will be significant. Additionally, as was discussed in section 5, all of the relevant path loss models predict a higher path loss for urban deployments as compared to average suburban and rural areas due to building blockage. The range capability is further impacted when BS antennas are located below the roof tops of the surrounding buildings. This is clearly illustrated in Figure 46, where range projections are shown for an AMI network under the following conditions:

- Outdoor pole-mounted DAP (BS) with an antenna height of 10 m (denoted as OD Pole)
- Basement located or cabinet-enclosed meter banks (denoted as ID Basement)
- Above ground located meter banks in indoor locations (denoted as ID Other)

The range projections are based on the ITU-R M.2135-1 Urban Micro-cell path loss model described in section 5.2.1.3.4. This model is considered valid for the 2000 MHz to 6000 MHz frequency range. The dotted lines extending the data to 700 MHz are simply estimated projections for illustrative purposes.

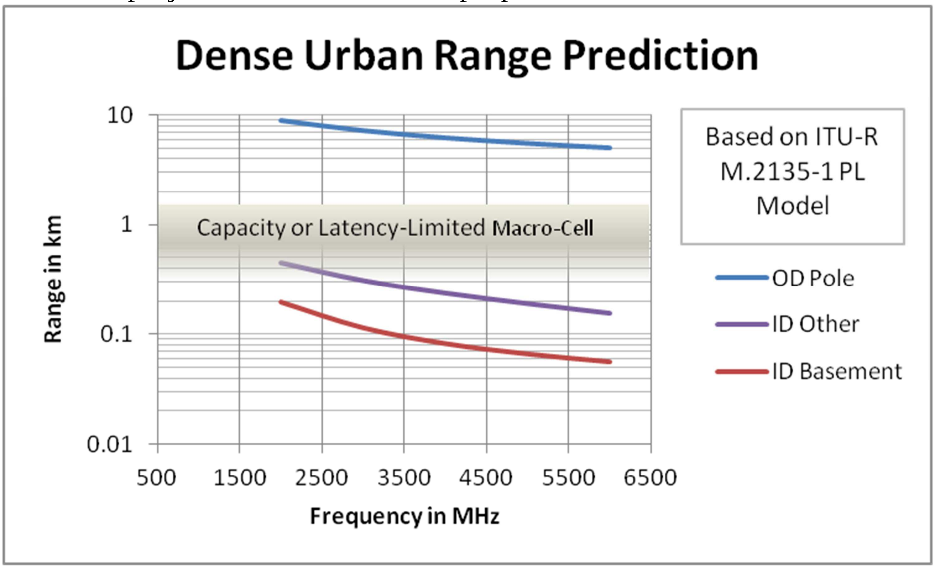


Figure 46 - Dense urban range projections

The third plot in Figure 46 is based on the ITU-R M.2135-1 Large City Urban path loss model and assumes:

- An outdoor roof mounted BS (30 m height)
- Terminals consisting of outdoor pole-mounted DAPs (10 m height)

What can be surmised by this is that for AMI deployments in Dense Urban and probably many Urban area deployments, the deployment will very often be range-limited and not capacity-limited since the coverage area will be severely limited by the high penetration loss to reach installed meter banks and the higher urban area path loss with DAPs mounted below adjacent roof tops. With the small coverage area the number of meters per DAP will generally be well within the capacity capability of the BS. At 3500 MHz, based on 4000 housing units per square mile, the traffic load for each sector would be about 300 smart meters per channel. It is important to mention that mounting the DAPs above the prevailing roof height in a dense urban area would not yield a significant benefit. Since the DAP antennas, with a fan-shaped beam, would be pointed downward to reach the grade or below grade located meters, the effective area coverage would not be increased enough to offset the added complexity and cost of acquiring roof-rights.

The above analysis suggests a layered architecture for dense urban areas as shown in Figure 47. The pico-cells and micro-cells represent DAPs with a nominal antenna height of 10 m. The pico-cells access basement-located and vault-enclosed smart meters while the micro-cells have access to smart meters in more favorable locations from a path loss perspective and, with lower penetration loss, cover a wider area. The macro-cell provides an aggregation node for the DAPs and may also pick up additional smart meters within its wider coverage area. The macro-cell would have to handle the combined data traffic and in most cases will be capacity-limited.

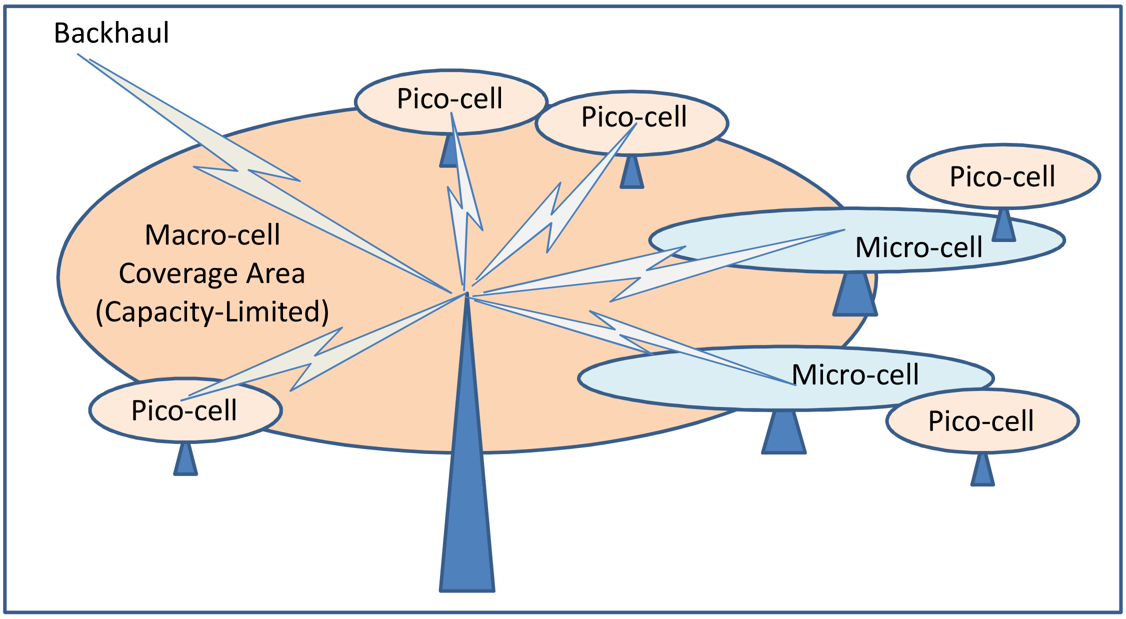


Figure 47 - Layered architecture for dense urban

6.1.2.1 Dense Urban Latency Considerations

As mentioned earlier, a model for assessing the network's ability to meet latency requirements was described in section 5.2.7. The model applies to a single link with a known average channel goodput. The same model can be used for a layered network architecture provided the latency allocated for the network is properly apportioned to the link being analyzed. For an end-to-end latency requirement of L_N and the data path illustrated in Figure 48, each link must be designed to meet a latency of $L_N/4$. The probability (or confidence) factor must also be apportioned between the multiple links. For an end-to-end requirement of 99 % and four links, each link would be required to meet $0.99^{1/4} = 0.9975$ (99.75 %).

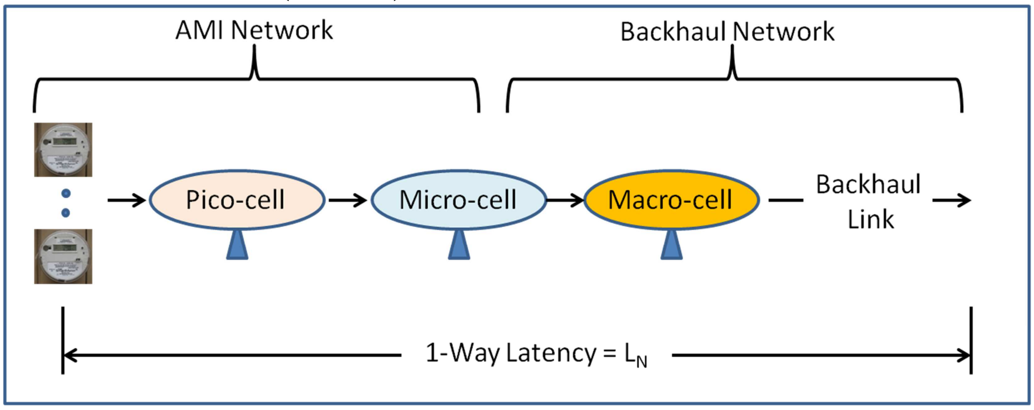


Figure 48 - Latency with layered architecture

The AMI network will have a greater number of actors with small data packets. The DAP backhaul network, on the other hand, will be supporting fewer actors but data payloads will be larger. Even with the same channel BW, the average channel goodput will typically be higher for the macro-cell since, in most cases, it will be capacity-limited or limited in its ability to meet latency requirements.

6.1.2.2 Relating Channel Capacity and Latency

In the design of any communications network the decision that must always be addressed is whether to design to meet average or peak busy-hour demand. Sizing the network for average demand reduces network cost but means that reduced performance will have to be tolerated during periods of peak demand. For a telephony network it generally translates to a higher probability of a 'busy signal', for a Smart Grid network it may result in higher average latency. Designing the network to meet peak demand increases network cost and may result in a network that has excess capacity for a large percentage of time. For a Smart Grid network highload, driven by large payload firmware upgrades and other special events, can be orders of magnitude greater than baseload.
Even though the pico-cell deployment in the AMI network will, in most cases, be range-limited due to the high penetration losses, highload traffic conditions, especially in dense urban areas, may approach the channel capacity limit.

Since the AMI network is likely to be operating with limited spectrum and link latency, requirements may be quite stringent due to the multiple links or hops in the end-to-end communications path. It is important to understand the relationship between the channel data capacity and the link latency. As was described in section 5.2.7, the latency prediction is based on the channel goodput (C_{GP}), the average packet size (P_{AVG}), and the message (or packet) rate R_{MSG}.

If, as an example, we assume a C_{GP} of 1.0 Mb/s and a peak data rate per actor or end-point of 100 b/s (approximately 12 bytes per second), the channel capacity at peakload would be 10,000 actors per channel. The actor message rate, R_{MSG}, under these conditions is 0.05/s or 180/h.

Figure 49 shows the probability of meeting a particular link latency requirement as a function of the actor load on the channel using the Binomial Distribution Model described in section 5.2.7. With 8500 actors (85 % of the channel actor capacity) there is a 99.5 % probability that a packet will meet a 0.5 second latency requirement or, alternatively, less than 0.5 % of the packets will exceed a latency of 0.5 seconds. This value is about 10 % at 92.5 % of the channel capacity and grows to over 30 % when the channel is loaded to more than 97.5 % of capacity. If the channel were operating at full capacity the latency would be about 20 seconds.

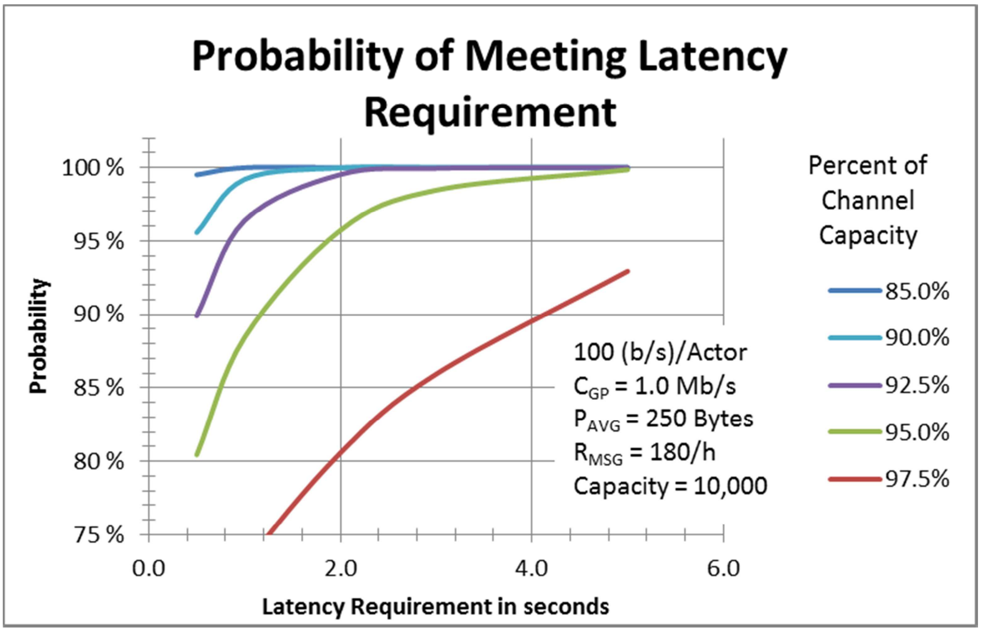


Figure 49 - Probability of meeting latency requirement

Another way to present this data is shown in Figure 50, where the channel load as a percentage of channel capacity is plotted versus the latency prediction for different probabilities. This representation may prove more useful as a network design or planning tool when one is faced with the decision of dimensioning the network capacity to meet baseload, average load, or highload requirements.

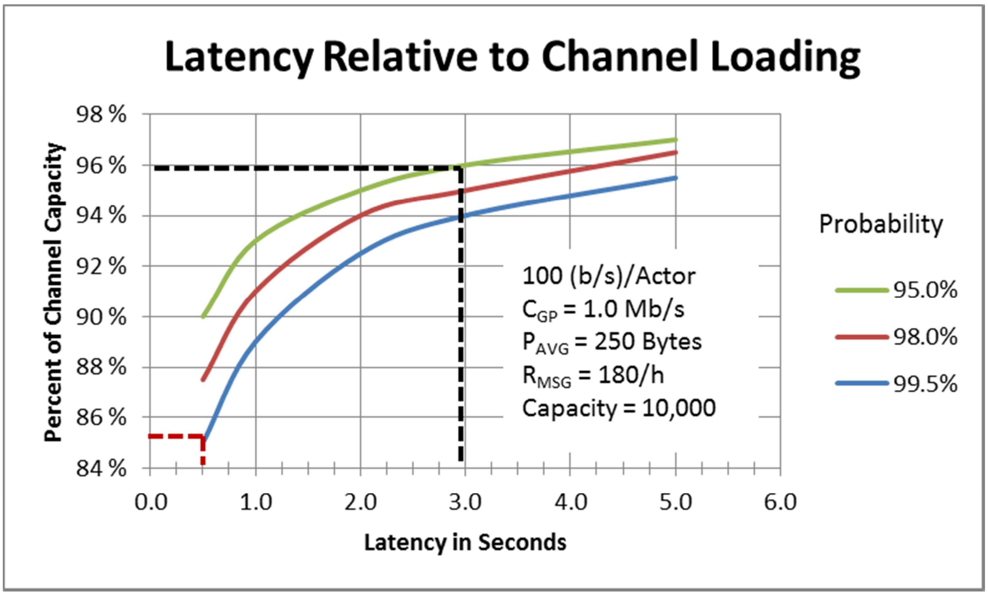


Figure 50 - Latency relative to channel loading

For this particular example, if one wanted to maintain a latency of 0.5 seconds with a probability of 99.5 % during periods of highload, it would be necessary to design for a channel capacity 15 % higher. If, on the1 other hand, a latency of 3.0 seconds with a probability of 95 % could be tolerated during peakloads, one could operate up to 96 % of the channel capacity.

Figure 50 is applicable for this particular example and would have to be re-plotted for different parameter assumptions. Generally a reduced packet size would support higher channel loading for a given latency. Although a smaller packet size increases the message rate (R_{MSG}), the probability that a packet falls within the specified latency window increases. Bear in mind that smaller packet sizes will also increase the channel OH so one can also expect a slight reduction in channel goodput.

This analysis does not take into account any of the QoS features that are supported by most wireless technologies. The analysis assumes all packets are treated with equal priority. With QoS support it would be possible to assign higher priorities to packets that are more latency-sensitive while relegating latency-tolerant packets to a best effort status. From the standpoint of evaluating the channel's ability to meet latency requirements, with QoS, the best effort packets would be ignored.

6.1.3 Low Density Rural

The opposite extreme to Dense Urban is the area designated as Low Density Rural. According to the United States census data over 4 % of the US population lives in over 70 % of US land area. With housing unit densities less than 10 HU per mi^2 (< 4 HU/km^2), deployments in these regions will always be range-limited with any reasonable amount of spectrum. The key challenge for a terrestrial wireless network deployment is to optimize the coverage so as to reach all housing units and enterprise units that are connected to the electrical grid. Special attention has to be paid to:

- **Terrain characteristics** that can vary from flat wide-open spaces to rugged mountainous terrain with high tree density.
- **Long distance wireless backhauls** that may require daisy-chained point-to-point (PtP) links or a satellite link for connectivity to the command center.

Path loss models for foliage (5.2.1.3.7) and path obstructions (5.2.1.3.8) were presented in section 5.2.1.3 and a modified version of the Erceg-SUI path loss model was shown to be an effective path loss predictor for various terrain categories in rural and suburban areas over the full 700 MHz to 6000 MHz frequency range. A description of the three terrain categories are repeated here for convenience:

- **Terrain Type A:** Hilly with moderate to heavy tree density
- **Terrain Type B:** Hilly with light tree density or flat with moderate to heavy tree density
- **Terrain Type C:** Flat with light tree density

Although not all terrain types that are likely to be encountered throughout North America can be fit into one of the above types, it is believed that these three terrain types can be used to describe a large majority of Low Density Rural deployment scenarios. For extreme terrain conditions other approaches, as noted in section 5.2.1.3.11, may have to be employed to provide a more accurate estimate.

Figure 51 provides the coverage area projections for the three terrain types for an AMI network for the 700 MHz to 6000 MHz frequency range. The link budget of 143 dB[31] in the UL direction is the limiting factor for the range determination due to the lower EIRP and antenna gain for the wireless enabled smart meter. The DAP antenna height is assumed to be 20 m with a gain of 15 dBi. This height should not be unreasonable in rural areas where existing transmission towers would be logical candidates for BS locations.

[31] Assumes 14 dB fade and interference margin and outdoor-located smart meters with 0 dBi antenna gain

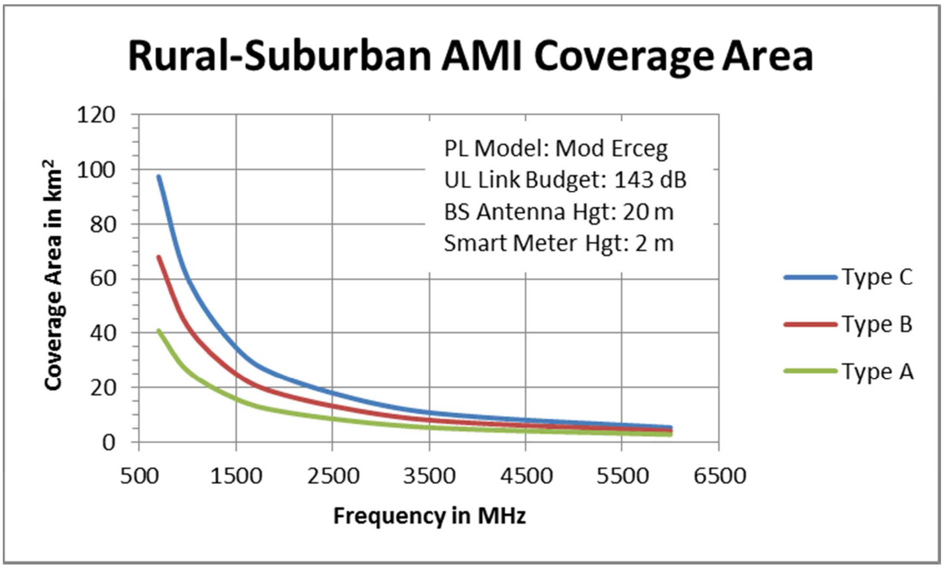


Figure 51 - AMI coverage area projections

In Figure 52 the sensitivity of the coverage area is plotted for different antenna heights for those locations where a 20 m height is impractical. The chart also shows the benefit of higher heights for situations where suitable structures or standalone towers are available. This data is plotted for a frequency of 2000 MHz but the results are not significantly different at either 700 MHz or 6000 MHz. With its large impact on coverage area, BS antenna height will play an especially big role in determining equipment requirements for SG networks in low density rural areas.

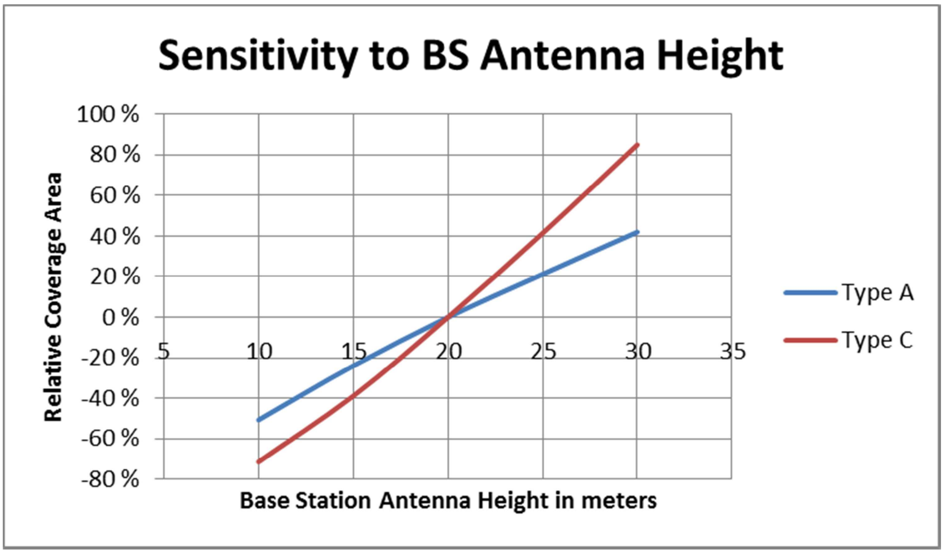


Figure 52 - Sensitivity to BS antenna height

The second key challenge in low density rural areas is the backhaul connection which may require multiple PtP links for a land-based solution or the possible use of a satellite link or some combination of the two. A typical Low Density Rural or Rural wireless network architecture may resemble what is shown in Figure 53.

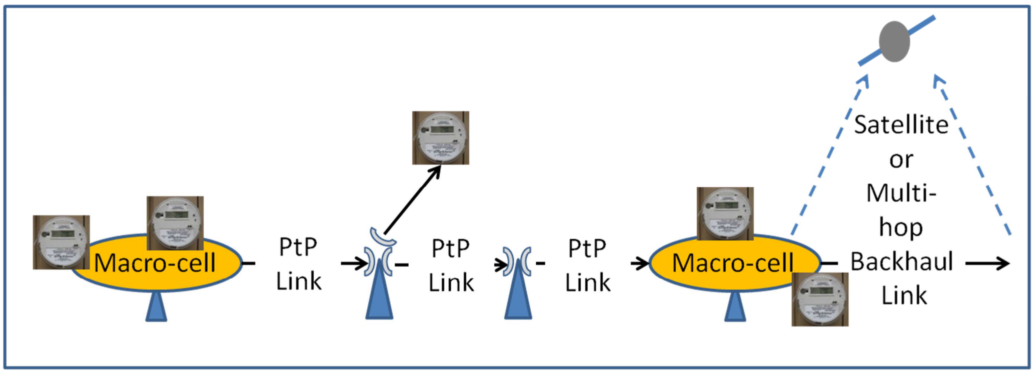


Figure 53 - Typical network architecture for low density rural

As shown in Figure 53 the end-to-end data path will very often encompass multiple links or hops, each with very different characteristics. As was the case with dense urban, the network latency budget should be properly apportioned to each individual link before applying the latency model described in section 5.2.7. If a satellite link is employed, the propagation (OTA) delay should also be considered. When end-to-end latency is the limiting performance factor, fewer terrestrial long links will be preferable to a higher number of short links for reducing latency. This replaces node processing delay with propagation delay. Longer links, of course, will generally require increased antenna heights and higher EIRPs.

6.1.4 Summary

Urban area path loss and high penetration losses will significantly limit the range and coverage for a wireless AMI network. In most cases these deployments will be range-limited pico- and micro-cells. With roof mounted BS antennas to provide a backhaul connection for the DAPs, the coverage potential will be much greater but capacity requirements to handle the aggregated traffic will ultimately determine the coverage not the range.

Low density rural area deployments will be primarily range-limited. The use of the lower frequency bands and deploying BS heights of 20 m or more will greatly reduce equipment requirements. A combination of PtP links and satellite links may prove to be the best choice to fulfill backhaul requirements in remote areas but with an increasing number of links, latency could become a limiting factor.

The various trade-offs and considerations for deployments in Dense Urban and Low Density Rural areas should provide some insights into the factors that must be considered in the other three demographic regions described earlier; Urban, Suburban, and Rural. Urban areas would still have the building clutter to deal with but, with lower average building heights, slightly better propagation characteristics. Deployments, however, will still tend to be capacity-limited.

Residential suburban and rural areas will not generally be able to accommodate the higher BS antenna heights due to visual impact and the limited height of utility poles that would often be the preferred choice for BS locations. Depending on channel BW limitations imposed by limited spectrum availability and HU density, suburban areas may be either range-limited or capacity-limited.

6.2 Advanced Antenna Systems and Spectrum Considerations

Advanced antenna systems have become commonplace in today's wireless networks; even indoor WiFi APs are often equipped with multiple antennas. These advanced antenna systems can be grouped into two generic categories designated as Multiple Input Multiple Output (MIMO) and Beamforming (aka Phased Arrays). Each of these generic categories has different attributes that translate to improved range and coverage, improved channel capacity, higher availability, or a combination of the three.

6.2.1 Multiple Input Multiple Output (MIMO) Antennas

MIMO systems are described as illustrated in Figure 54, where transmit antennas are designated as inputs to the OTA channel and receive antennas are receptors of multiple input paths. A BS equipped with N_T transmit (Tx) antennas and N_R receive (Rx) antennas would therefore be described as having a ($N_T \times N_R$) MIMO antenna configuration. A configuration with 1 Tx antenna and 2 Rx antennas would be designated as having a (1×2) Single Input Multiple Output (SIMO) antenna configuration.

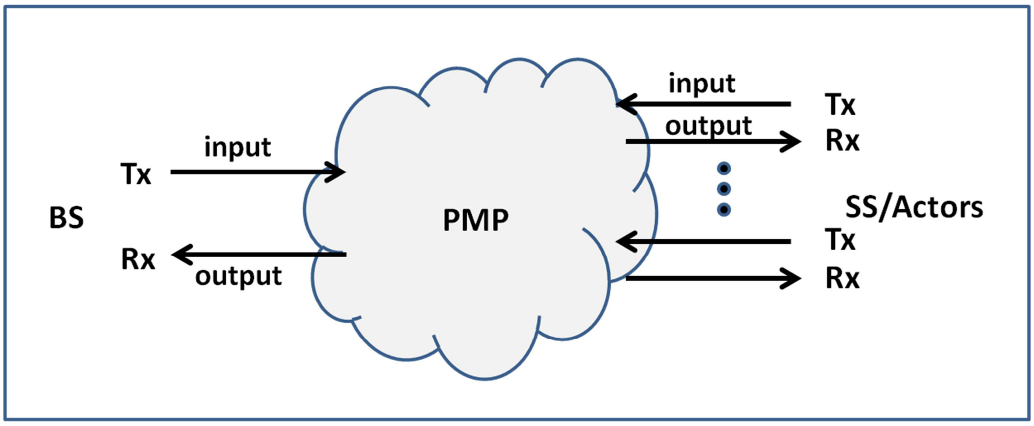


Figure 54 - Antenna nomenclature

To take maximum advantage of the performance attributes that MIMO antenna systems can support, it is necessary to minimize correlation between antennas. This can be accomplished through spatial separation, typically 3 wavelengths to 5 wavelengths or more. With only two antennas, cross polarization can be used.

With multiple Tx antennas, MIMO systems can generally operate in one of two transmit modes and in most cases can auto-adapt to the mode most applicable to existing channel conditions at any given time. These transmit modes are called:

- Transmit Diversity
- Spatial Multiplexing

Transmit diversity describes a scenario whereby the same data stream is transmitted over each of the transmit antennas. This provides multiple independent transmit paths thus increasing the probability of a satisfactory reception at a distant terminal. This feature translates to an increase in system gain resulting in either an increase in range or an increase in availability. Assuming there is no correlation between antennas, a system with 2 Tx antennas will result in a 3 dB system gain increase and a 4 Tx antenna system will result in a 6 dB increase.

With ***spatial multiplexing*** each Tx antenna transmits a different data stream to effectively increase the channel capacity. This can provide up to a two-fold increase with two Tx antennas and up to a four-fold increase with four Tx antennas.

As a practical matter the performance gains for Transmit Diversity or Spatial Multiplexing will be somewhat less than theoretically predicted due to variations in multipath, antenna patterns, and mounting limitations.

Multiple Rx antennas in MIMO systems generally support:

- Receive Diversity with or without Maximal Ratio Combining (MRC)
- Multi-User MIMO (MU-MIMO)

Receive Diversity enhances link reliability by providing multiple independent receive paths. In its simplest implementation the receiver simply selects the highest signal level from one of the multiple antennas. Since a deep fade is unlikely to occur simultaneously on each path the probability of receiving a signal above the threshold level is increased. With Maximal Ratio Combining (MRC) the received signals are combined to provide a received signal level higher than any of the antennas receive individually.

Multi-User MIMO (MU-MIMO) is a technique typically employed on the receive side at the BS. With multiple Rx antennas, this approach combines transmissions from multiple terminals to increase the BS UL channel throughput.

6.2.2 Beamforming and Beam steering

Beamforming is another advanced multiple antenna option that is available with many terrestrial-based wireless systems. This approach requires each BS antenna in the array to be spaced one-half wavelength apart. With proper phasing and amplitude control the resulting antenna pattern is formed into a narrow beam that can be steered (beam steering) to direct the beam to different areas within a sector coverage area as illustrated in Figure 55. The beamwidth is indirectly proportional to the number of antennas in the array. Typically from 4 antennas to 8 antennas are used to achieve the desired beamwidth. The resulting increase in antenna gain increases the link margin in both the DL and UL directions and significantly reduces the potential for interference in UL.

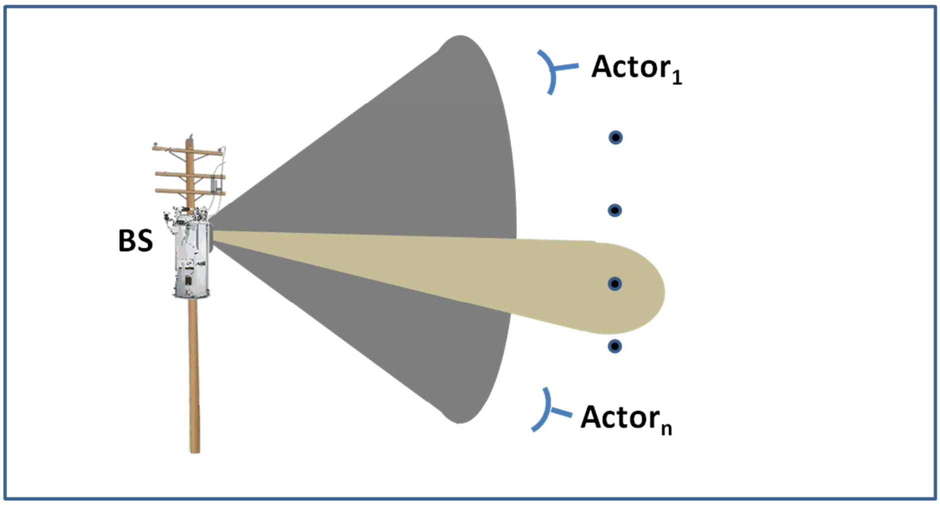


Figure 55 - Beamforming

Since all of the terminals must maintain a connection with the BS at all times, the range is determined by the control channels which are generally linked in a sector-wide broadcast mode. The added link budget in a beamforming system therefore does not translate to a significant increase in range or coverage but does enable a higher throughput and higher link availability.

6.2.3 Practical Considerations and Spectrum Trade-offs

Advanced antenna systems can definitely provide significant performance advantages for terrestrially-based wireless access systems, however one must also consider the deployment implications, especially in the lower frequency bands. The impact on spectrum choices with respect to multiple antenna systems was briefly mentioned in section 5.2.2.2.2.

As described above, antenna spacing is an important consideration for these systems to be effective. This can be especially challenging for higher order MIMO systems in the lower frequency bands. The Figure 56 shows the spacing for a (4×4) MIMO array assuming, for illustrative purposes, an antenna to antenna spacing of three wavelengths. Note that this is a minimum requirement which will result in reduced performance due to the potential for antenna to antenna correlation as compared to a spacing of five or more wavelengths.

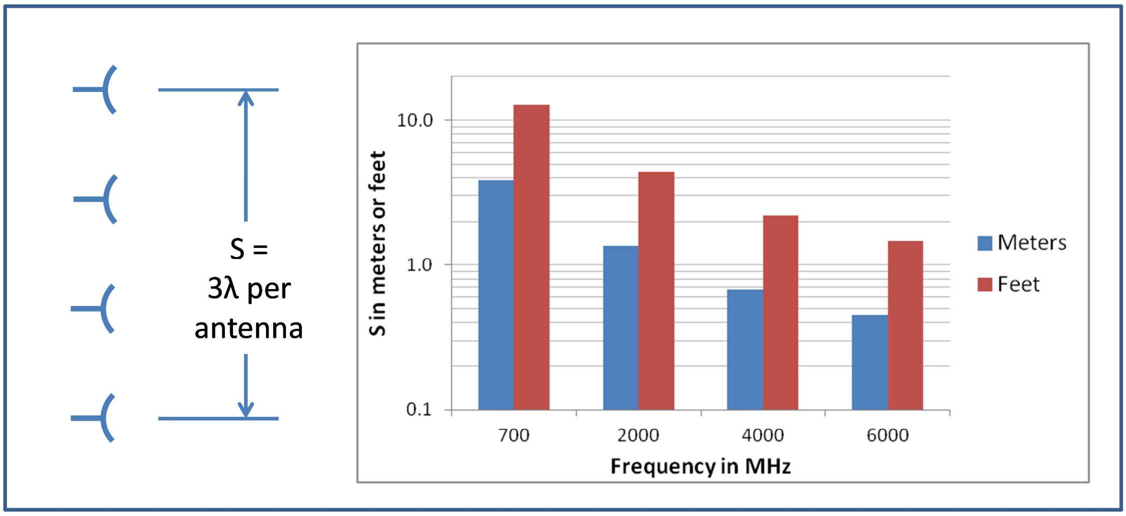


Figure 56 - (4×4) MIMO array with 3 wavelength spacing

Only taking into account the antenna spacing, at frequencies below 1000 MHz the size of a (4×4) MIMO array will exceed 4 m with a 3-wavelength antenna separation.

The dimensional requirements for beamforming arrays are somewhat better since the antennas are spaced at one-half wavelength apart rather than several wavelengths. Nevertheless, since beamforming arrays generally require more elements to be effective, the arrays still get quite large in the lower frequency bands as shown in Figure 57 for an 8-element beamforming array.

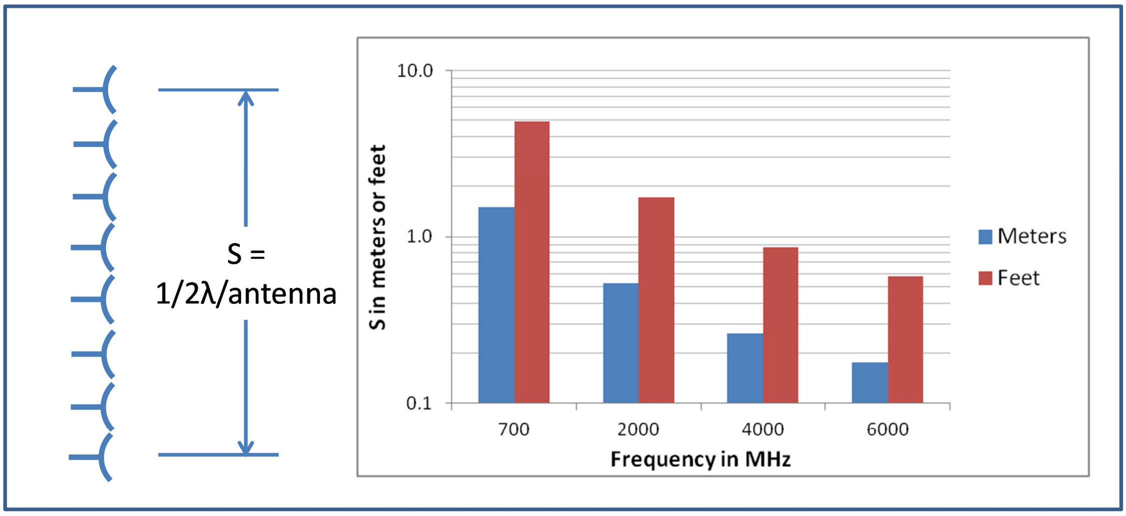


Figure 57 - An 8-element beamforming array

In addition to antenna spacing the relative size of the antenna itself must also be considered. The gain of an antenna can be expressed as:

$$\text{Antenna Gain in dBi} = 10 \text{ Log}_{10} (4\pi\eta A/\lambda^2),$$

where
A = the size of the antenna aperture,
η = the efficiency (generally a value between 30 % and 50 % depending on the antenna type design), and
λ = wavelength.

As the equation indicates the antenna gain varies inversely as the square of the wavelength thus providing a significant variation in gain for a fixed antenna aperture over the frequency range 700 MHz to 6000 MHz.

BS antennas for wide area networks are typically designed to provide a fan-shaped pattern with a gain in the order of 12 dBi to 16 dBi. Figure 58 shows the gain for a BS antenna with an aperture to height ratio of 10 to 1 and an aperture height of 0.67 m. This provides a gain of about 15 dBi at 3000 MHz assuming an aperture efficiency of 50 %.

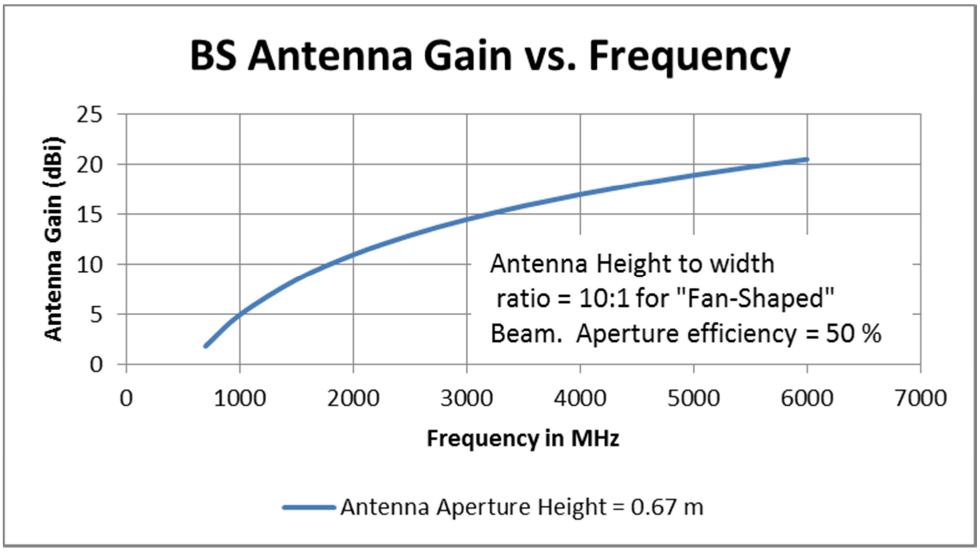


Figure 58 - Antenna gain variation with frequency

In Figure 59 the antenna aperture height required to maintain a 15 dBi gain over the 700 MHz to 6000 MHz is plotted. This, of course, is a simplistic analysis since it does not consider alternative antenna designs that can potentially improve the aperture efficiency in the lower bands. Although the curves in Figure 58 and Figure 59 may present a more pessimistic prediction for the lower frequency bands the general trend is the same; antennas in the lower bands will be larger and have lower gain.

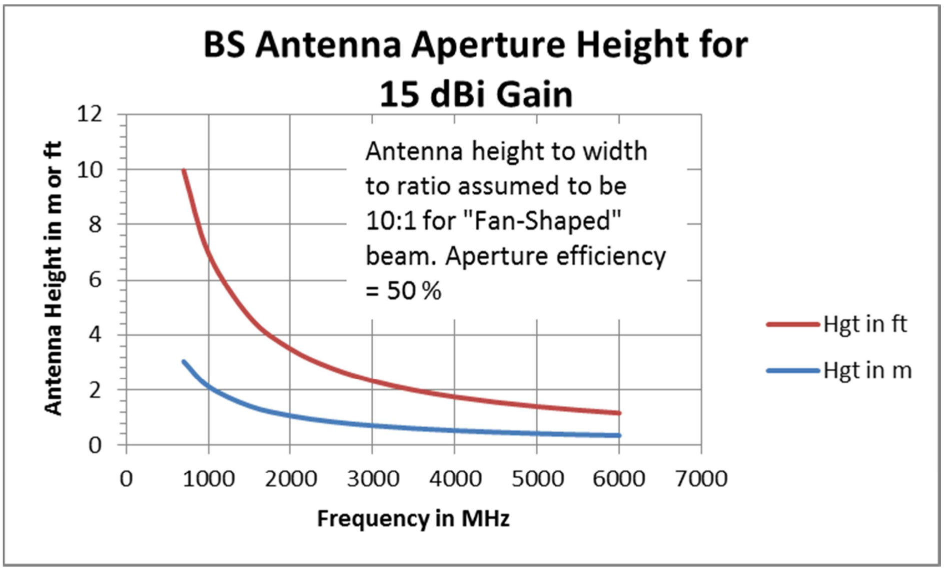


Figure 59 - Estimated aperture height for 15 dBi BS sector antenna

When deploying MIMO or Beamforming arrays, taking into account the required antenna spacing and antenna size, one must carefully consider the following factors:

- Visual impact
- Space requirements on existing utility infrastructure (utility poles, transmission towers, etc)
- Structural requirements for wind-loading forces.

As described above the challenges with respect to these deployment factors are greater in the lower frequency bands. Since some of the commercially available advanced antenna systems may prove impractical in the lower frequency bands due to the antenna and array size, the path loss advantage is mitigated somewhat. Analysis will indicate that there is still a significant coverage advantage in the lower frequency bands, but the point to be made is that the projected path loss difference should not be the sole criteria for selecting these bands.

6.3 Multi-Link / Multi-Hop / Mesh Topologies

Several networking topologies were briefly discussed in section 4.2.2.4. This section will provide additional discussion of some of these topologies and specifically, those more commonly used in the Neighborhood Area Networks (NAN). One definition of a NAN is a common network infrastructure that links multiple intelligent devices in a relatively small or neighborhood sized geographic area. This section will provide a general overview of the NAN and several important considerations for its use in a Smart Grid environment. Many of the considerations described with respect to NANs also apply to mesh topologies in Wide Area Networks (WAN) and Field Area Networks (FAN).

Figure 2 of section 3 describes the Smart Grid Conceptual Reference Diagram illustrating the multiple Domains and the network infrastructures interconnecting those domains. Shown are two holistic NAN infrastructures; one identified as a Field Area Network

(FAN), and the other identified as an AMI Network. Although the FAN and AMI could be the same network they are each shown as composite but separate networks in this diagram in order to show their relationship and support for two of the Smart Grid Reference Domains. More specifically, the FAN is depicted as supporting and serving the Distribution Domain, and the AMI Network supporting and servicing the Customer Domain. While this depiction is appropriate for the conceptual or high level Domain view of the SG, it is somewhat misleading from the physical network implementation perspective. In actual practice both the FAN and the AMI Networks can and usually are composed of multiple smaller geographically based networks or NANs, each with one or more Data Aggregation Points (DAPs) as will be described in greater detail below. Also depicted in Figure 2 of section 3, the communication network end-points for the AMI Network NANs include the two-way AMI Meters and ESI – Utility. The end-points for the FAN and NANs include distribution feeder devices and may also include a FAN gateway linking with a Substation Network. While the conceptual reference diagram illustrates the domain view of the SG systems, it should be noted that both the Distribution Domain and Customer Domain will have significant geographic overlap, and thus the network infrastructures serving them likewise will have significant geographic overlap. This overlap leads to the potential for integrating the FAN and AMI Network NANs in these common geographic areas into a common network infrastructure. Thus in these areas, a single composite NAN may be implemented to provide connectivity for the end-points from both the AMI Network (i.e., the AMI meters) and FAN end-point devices (i.e., field Distribution Automation devices). Throughout the rest of this section the distinction of the Domains served will be considered only insomuch as the end-point devices for the Domains will bring different use cases and thereby bring different network requirements. However, the primary focus of this section will be on the underlying NAN infrastructure and considerations for supporting the uses cases for the various end devices it serves. The subsections below will cover the components of the NAN in greater detail but a common network element of the NAN is the Data Aggregation Point (DAP), as mentioned above. While the different AMI and NAN vendors typically identify the DAP using their own specific product names, the primary purpose of the DAP is to serve as a gateway from the NAN to other networks to ultimately link back to one or more common application system and services. In some cases more sophisticated NANs allow more than one DAP for an individual NAN that may allow segregation of traffic types and may allow linking with different upstream application systems. Other commonalities and distinctions will be discussed further in the following subsections considering the technology and topology of the NAN.

Furthermore, for the current Smart Grid implementations the dominate use of the NAN is for AMI. In these implementations the NAN provides connectivity between AMI meters and a DAP, with the DAP having a backhaul path via a WAN to the host AMI System or AMI Head-End. For these dedicated AMI system there are specific requirements for information flow between the back-office metering systems, through the NAN, and to the individual AMI meters. For these AMI systems, there is no need for the meters to share their metering information amongst themselves, but only to share this information with the AMI Head-End and the centralized metering system. Therefore meter to meter (i.e., peer-to-peer) information sharing in the NAN is not required. However, in a Multi-Hop

AMI NAN the meter communication modules may be called on to relay messages between the DAP and other meters too far removed from the DAP to directly link with it and they may also exchange network housekeeping messages between the communication modules of neighboring AMI meters. As these AMI NAN networks are expanded to include DA devices there may be additional requirements for the NAN to support direct peer-to-peer information exchanges between these DA devices leading to additional requirements for the NAN to support these peer-to-peer routes along with effectively managing message priorities. Both the current and potential future requirements of the NAN should be fully considered when choosing a technology and topology for NAN connectivity.

6.3.1 Network Topology Revisited

In order to better identify the common NAN infrastructure a brief digression further into network topology is in order. Multiple terms are often used in conjunction with the NAN; Point-to-Multipoint (PMP), Multi-Link, Multi-Hop, and Mesh. However, these terms may be misleading and it can be said may inaccurately describe the commonly deployed NAN topologies.

The term, Multi-Link network, can be defined as interconnecting multiple discrete networks, such as linking a HAN with a NAN, then to a WAN. The obvious reason for interconnecting these networks is to allow data exchanges between the devices connected to these discrete networks. That is, a Multi-Link network path can be established through the linked HAN, NAN, and WAN Multi-Linked networks.

The term, Multi-Hop network, can be defined as group of interconnected nodes in a common network infrastructure where links to traverse this network can be established by using node-to-node or hop-to-hop links, thus the term Multi-Hop.

The term, Mesh, is used to describe a family of interconnected nodes in a common network infrastructure. There are several forms of mesh topologies which are well documented in multiple books and other technical papers on network systems. However, briefly here, the term full mesh is commonly used to describe a mesh where each node is directly connected to each other node, which can lead to an inordinately large number of links in large networks but also provides the largest number of direct communication paths. With a larger set of links, a full mesh has more choices to dynamically adapt to faults or traffic loads in any given communication link. A partial mesh is a subset of a full mesh where not all nodes are directly linked to all other nodes, and traversing the network may involve relaying or routing through multiple nodes or in essence forming a Multi-Hop link.

The goal of a classical mesh network is to provide connectivity from any node to any other node. However, in an AMI NAN, the application level or use case data is usually limited to exchanges between the DAP and the AMI meter. Stated another way, within the AMI NAN the community of interest is between the DAP and the individual AMI meters with one being considered the source and the other being considered the destination or sink of the data. Thus for an AMI NAN, the goal is to provide links from a

DAP to the AMI meters. A potential exception to this DAP to end device community of interest within a NAN may be if DA devices are linked via the NAN and the DA applications or use cases require some peer-to-peer data exchanges between the DA devices. Node-to-node data exchanges for AMI NANs are otherwise generally limited to network housekeeping messages where the AMI meter communication modules share information amongst themselves on link and network status and best routes. However, it should be obvious in Multi-hop AMI NANs the meter communication modules will often be used as relay points to relay messages between the DAP and other AMI meters further downstream.

As indicated in section 4.2.2.4 the nodes in a Multi-Hop NAN are typically intelligent devices (end-points), that have the ability to discover (multi-hop) forwarding paths in the network and make their own forwarding decisions based on various pre-configured constraints and requirements. Using this dynamic routing capability, the end-points first determine which neighbor nodes are within radio range, assess potential links with these neighbors and dynamically choose the best or most appropriate path as their primary route through the NAN to an DAP. Depending on the routing algorithms implemented in the end-point nodes, this best route determination may be based on RF signal strength, ability to exchange messages with neighbor nodes with minimal errors, using neighbors that provide the minimum number of hops back to an DAP, the geographic coordinates of the nodes, or a combination of these. The subject of routing and route determination algorithms for wireless Multi-Hop networks has been the subject of study for many years and multiple books and other publications are available on this subject. Suffice it to say here that the meter nodes will use their programmed algorithms to select what they have determined as the best route back to a DAP at that particular point in time. It has been noted that some of the dynamic self-configuration algorithms implemented in currently deployed NAN networks may occasionally lead to unstable or otherwise infeasible routes and may need some external oversight to force a usable route or the additional of other NAN network devices to establish useful routes.

In addition to selecting a primary path and route to a DAP, an AMI meter node will typically also preselect other (second best) routes to be used should its primary route become degraded or unavailable. Normally all AMI meter traffic to and from a DAP will use only their currently established primary path. The secondary path would be used if and when it is promoted to be the primary path because the previous primary path had degraded or become unserviceable.

An interesting side note is that while the NAN AMI meter nodes have the ability to link with any of their neighboring nodes (within RF range) and potentially route through them, in practice as the routes are established between the DAP and the AMI meters, the routes usually form a tree network structure as shown in Figure 60. For an AMI NAN this is a consequence of the need and requirement that the AMI meters exchange information only with their selected DAP, using the Multi-Hop links through other AMI meter nodes merely as relay or routing points. In this tree structure the primary branches or links extend from the DAP to a first layer of nodes and from this first layer of nodes additional branches or links extend to secondary nodes, and so on until all nodes have established a path between themselves and the DAP. The distribution of the number of hops from the end nodes to the DAP is then a general index of how effective the NAN may be in providing connectivity to the devices in that NAN. The nodes further removed from the DAP having a greater number of hops to traverse will also have greater latency and are generally more susceptible to having their path to the DAP interrupted as propagation conditions in the NAN may change.

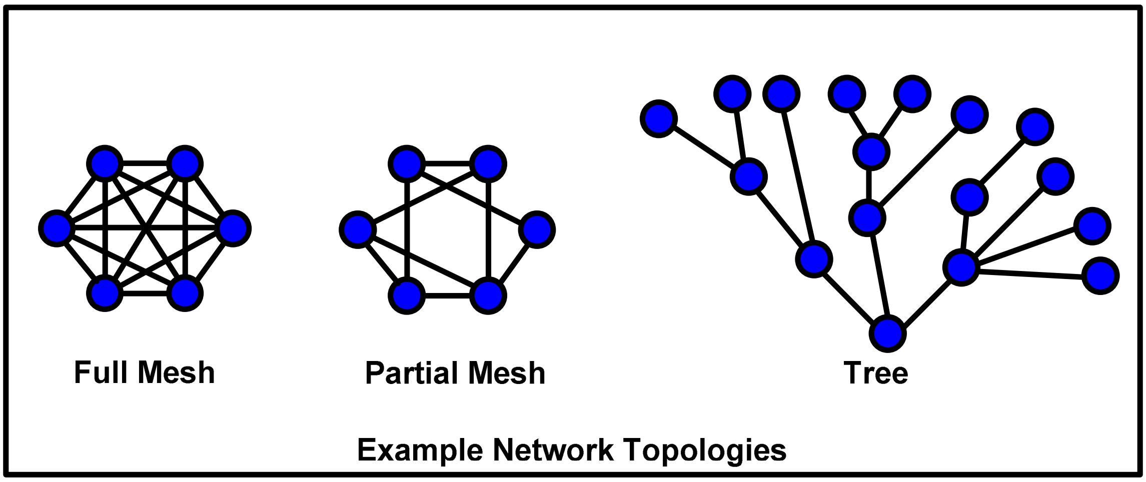


Figure 60 - Full mesh, partial mesh, and tree topologies

6.3.2 The Neighborhood Area Network (NAN) in a Larger Context

Another concept is the use of the term, AMI Network, to describe a single monolithic network spanning large geographic areas. However, an individual NAN infrastructure will consist of at least one DAP and a number of end-point nodes or meters linked to it, and potentially other relaying / routing devices to extend the reach of the NAN or to provide additional reliability. Thus the term, AMI Network, while generally used to denote a single monolithic network, is in reality an aggregation of multiple individual NANs, each consisting of a DAP and the end nodes connected to and through it. These multiple individual NANs collectively provide coverage and connectivity to the end nodes in larger geographic area. However, this is not to say that the individual NANs operate totally autonomously.

For the example where the AMI NANs use mesh technologies, as several DAPs are deployed in a geographic area, the AMI meters (end-points) in this area typically use dynamic routing to establish the best route to a DAP, which in some cases may not be the geographically closest DAP. In reviewing the links established in working AMI NANs, it is often observed there are significant areas where individual meters in common geographical areas establish links to different DAPs. One of the obvious advantages to this is the potential redundancy offered in areas with multiple DAPs. If one DAP fails, or the backhaul link serving it fails, the meters normally served by that failed DAP typically will dynamically reroute to link with other meters connected to other working DAPs. An example of this is shown in Figure 61.

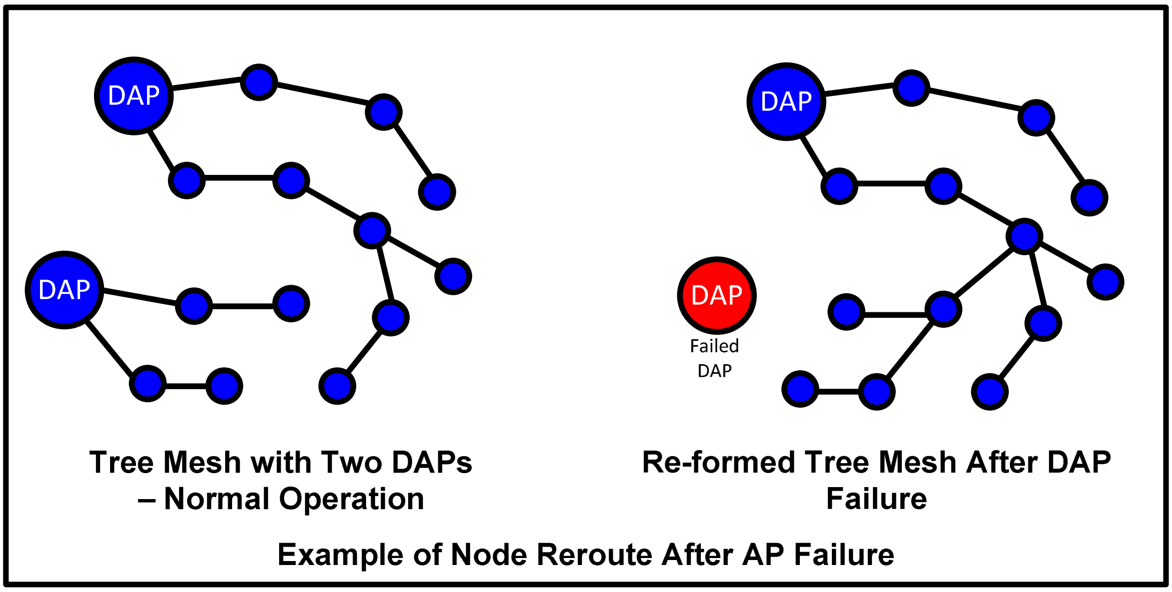


Figure 61 - Node reroute example – failed DAP

In addition to rerouting to bypass a failed DAP the individual nodes have the ability to dynamically reroute within the NAN should the path currently chosen as their primary route to the DAP become unavailable or unreliable. In this case, the node will typically try to route through its preselected second best route, or if that also fails, the node will continue to evaluate neighbor links to find the best route back to an DAP. An example of this is shown in Figure 62.

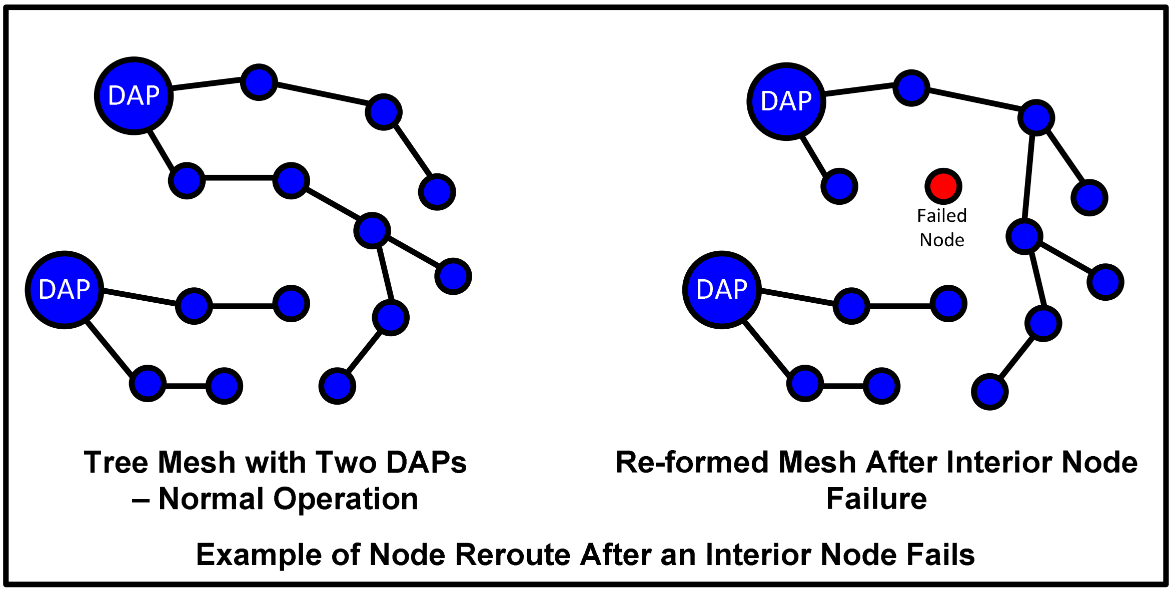


Figure 62 - Node reroute example – failed node

Similarly if an intra-NAN link fails, the nodes that were supported through that failed link will reroute to establish a new path to a DAP. An example of this is shown in Figure

63. However, in this example note the new route chosen is to a different DAP only because that new route may have been determined as the best route to a DAP during the route recovery process.

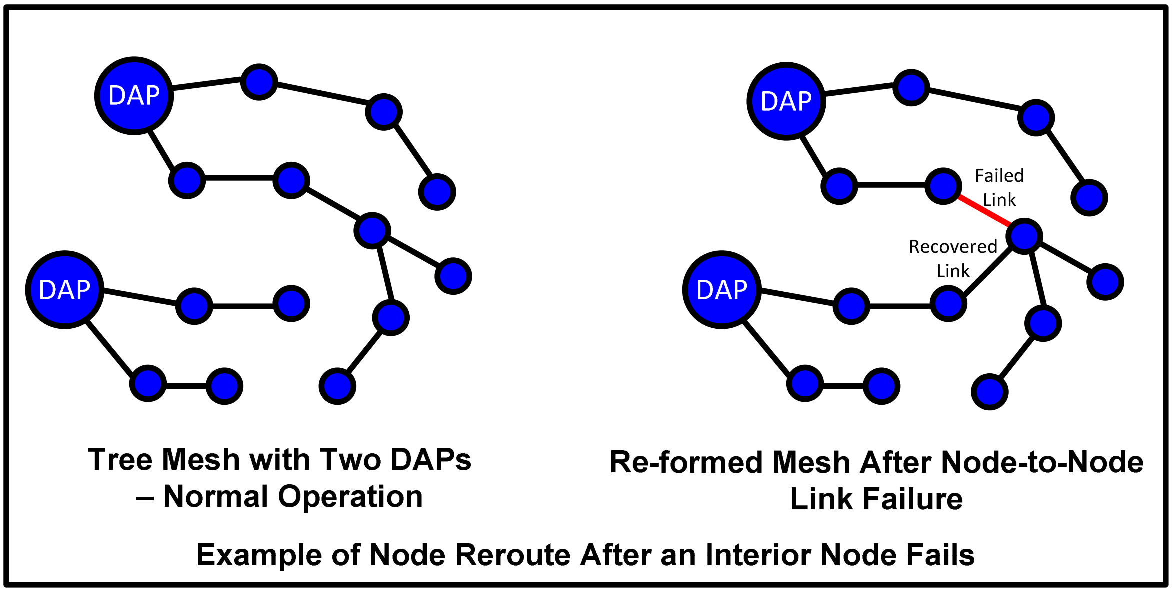


Figure 63 - Node reroute example – after failed link

6.3.3 Other Neighbor Area Network (NAN) Topologies

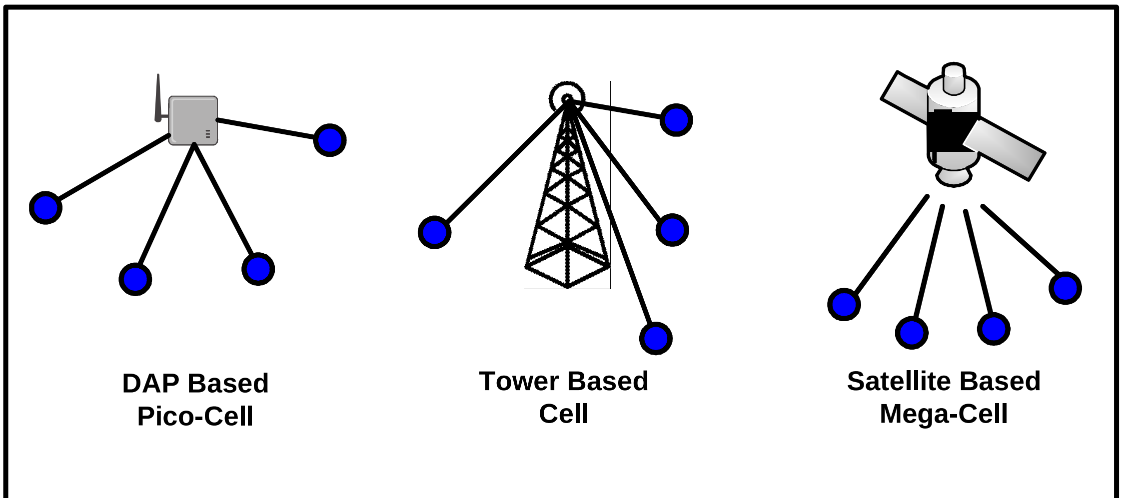
While the focus of this section is on the AMI Multi-Hop network topologies it is of value to mention other alternatives commonly used to provide connectivity between AMI meters and the AMI host or AMI Head-End system.

One example is the use of commercial or private cellular-like networks to establish point-to-multipoint links from a master radio site or BS to the end-point devices. While commercial cellular networks are designed and deployed primarily to support mobile devices moving from cell to cell, they can and do also serve fixed devices like AMI meters. In these networks, each BS typically serves a limited geographic area and when covering large geographic areas, multiple BSs are deployed to provide overlapping coverage to help ensure ubiquitous coverage. Utilizing commercial cellular services for linking with AMI meters may be appropriate in areas where implementing private or purposely built wireless networks are not feasible or are not cost-effective.

Other AMI systems may use purposely built point-to-multipoint wireless networks designed specifically to support fixed locations. As such they can be implemented without the additional complication of tracking and handing off mobile devices as they move from cell to cell. These are generally tower-based systems and are typically designed to provide connectivity extending multiple miles to remote AMI meters. A single master radio or BS therefore, may be able to provide coverage over a large geographic area.

In both point-to-multipoint networks described above, the master radio or BS would then be linked through an appropriate backhaul network to a centralized AMI system or host.

Point-to-multipoint networks may be implemented to cover different geographic areas ranging from pico-cells covering tens to hundreds of feet across to mega-cells covering areas hundreds of miles across. Pico-cells might be appropriate in small geographic areas like meter closets in multiple dwelling units, whereas satellite-based mega-cells might be appropriate for linking multiple remote meters spread over large geographic areas covering thousands of square miles. Use of these technologies should be considered when the use of other primary technologies may not provide effective coverage for all meters in a service territory. These examples are illustrated in Figure 64.



Example Implementations of Point to Multipoint Topologies

Figure 64 - Point-to-multipoint implementations

6.3.4 NAN Network Components

This section identifies some of the network elements commonly used in implementing NAN systems. One of the original purposes of the NAN was to provide network connectivity from a centralized metering system to remote AMI meters, thus the original name AMI NAN. Using the network connections, the centralized metering system was able to retrieve energy usage and other information from the AMI meters and to send configuration and other command and control functions to them.

Typical AMI NAN implementations also included a centralized AMI Head-End management system linked to the NAN through a backhaul network to provide network management and control of the NAN elements themselves. This AMI Head-End system is depicted in network diagram Figure 2 of section 3.

As for the NAN nodes themselves, to some extent the type and function of these nodes are dependent on the technology and topology used to implement the NAN. However, there are some elemental components commonly used in these nodes. For wireless NANs, one of the elemental components of a node is a NAN radio. The NAN radio is typically modularized and will consist of an RF transmitter and receiver, antenna, and the control electronics which allow the radio (and thus the node) to actively participate in the NAN. NAN radios are mated with end devices, for example, AMI meters, DA devices, etc., typically in a composite package provided by the Original Equipment Manufacturer (OEM) or end device manufacturer. For AMI meters, this package is almost always in the meter housing itself or under cover. In any case, the NAN radio provides a data interface used to interconnect with the meter or other end device. Other NAN radios may be implemented as standalone repeaters, relays, or routers used to strengthen and/or extend the reach of the NAN. Also common to wireless NAN systems are the DAPs. The DAP serves as the centralized connection point for its supported NAN nodes and thus will include one or more NAN radios to link with these nodes. The DAP will also contain a backhaul network interface and necessary controlling electronics to allow it to be linked with the NAN Head-End through a backhaul network.

Depending on the vendor and NAN networking technology used, the NAN radio module may also be capable of supporting additional data processing functions as may be required to properly interface with its connected end device. This data processing capability may be necessary to aggregate end device data for more efficient network transmission through the NAN or to accommodate specific application level or native protocols utilized by that end device.

6.3.5 Characteristics of NAN Multi-Hop Networks

When employing a Multi-Hop network topology, there are additional network considerations that must be taken into account. These considerations include:

- Mesh Multi-Hop Latency: Each application and use case may bring additional latency requirements. In a Multi-Hop NAN, latency can be significantly impacted by several factors including the node-to-node effective data throughput rate (which, in turn, is related to RF bandwidth, RF modulation efficiency, and error rates) and the internal processing delay introduced by intermediate nodes in relaying data packets. Consideration should be given to the distribution of the number of intervening nodes or hops that may exist between the DAP and nodes in that NAN. The cumulative or combined latency of multiple hops encountered in reaching end nodes further removed from the DAP may be significant.
- Incremental expansion of the mesh topology: Both in number of devices and functionality without risk to the existing topology.
- Resiliency and Redundancy: Requirements for recovery of failed network elements along with the techniques employed to provide redundancy

6.3.6 Additional Technical Characteristics of the NAN

Several vendors offer NAN systems designed to support AMI and other SG data requirements. While most of these employ the use of Mesh or Multi-Hop networks as described in this section, they can vary significantly with respect to their implementation.

Several technical issues to consider when selecting a technology, topology, and vendor include the following:

- Spectrum Used – Many commercial AMI NAN systems use the 900 MHz (902 MHz to 928 MHz) ISM band. Others use the 2.4 GHz ISM bands. These bands are unlicensed, and with some technical restrictions on their use, they are shared by multiple users. Other systems use private licensed frequencies, thus minimizing potential interference with shared users. Still others may use the registered but non-exclusive 3.65 GHz band. Regardless of the spectrum used, the capabilities and limitations inherent with this spectrum should be considered in choosing a NAN technology and topology. A number of other sections provide much more information on the capabilities and restrictions of the spectrum choice.
- Route Forming and Maintenance – As a NAN (i.e., a DAP and associated end devices) forms a PtP, PMP, mesh, or Multi-Hop network; a set of data paths or routes will be established from the end devices to the DAP. These routes will form as a result of the dynamic self-routing ability inherent in the nodes of the NAN. As indicated in section 4.2.2.4 the nodes in a Multi-Hop NAN are typically intelligent devices that have the ability to discover (multi-hop) forwarding paths in the network and make their own forwarding decisions based on various pre-configured constraints and requirements.

  Consideration should be given to the length of time it takes to initially form and stabilize the routes, how often and under what conditions automatic route maintenance (i.e., the process of analyzing network performance data and automatically performing node-to-node incremental network tuning) is performed, as well as routing recovery time for internal NAN node failures.

  Another important consideration is the ability of the NAN nodes to route to an alternate DAP should a node's primary DAP fail. Yet another important consideration is the ability of a NAN to recover after a significant widespread power outage. The ability of the nodes to hold their current configuration and routes in non-volatile memory would offer a significant advantage for quickly restoring operation after power is restored, although some network churn may be expected as the nodes are repowered and begin to return to normal operation.

  Related to these automatic routine process is the possibility that due to the long lasting loss of end device nodes or any long lasting changes in the RF environment in an area may necessitate a manual redesign process including the relocation or addition of the DAPs, repeaters, relays, or routers.

- NAN Throughput – This measures the capability to support the volume and latency requirements for data exchanges from the DAP to the end nodes. This is, in turn, related to multiple technical aspects and operational processes used by the DAP and other NAN nodes. The DAP must support the interconnection with the

WAN network, maintain the links with its internal NAN nodes, and process and relay all data to and from all of the DAP's attached NAN nodes. The internal NAN nodes must relay data for its supported downstream nodes and also process all data exchanges between themselves and the DAP. Considerations should be given to the following technical aspects:

- The processing power of the DAP
- Number of discrete radios in a DAP
- Processing power of the internal NAN nodes
- The bandwidth of the NAN radio links
- The RF modulation scheme used
- The point-to-point latency
- Data fidelity checks and recovery processes used in the NAN

Equally important to these technical aspects is the degree to which the NAN technology is conforming or adhering to the standards being fostered and promulgated by the SGIP in the Catalog of Standards (CoS). For greater detail of the technical aspects, multiple books and technical papers have been written on these subjects. Suffice it to say here, these are important items to be fully considered in selecting a NAN infrastructure.

6.3.7 Further Considerations for NAN Design and Routing

This subsection addresses some of the complications that would be encountered in designing Multi-Hop NANs.

As indicated in this section, a Multi-Hop NAN generally will be self-forming by the nodes themselves using dynamic routing algorithms. To use standard RF modeling techniques to predict the optimal routes that would be formed in a NAN and then predict the operation characteristics of the combined links and routes for each NAN node would be a formidable task. Consider that the number of nodes or AMI meters in a NAN and linked through a single DAP may be on the order of thousands, and as a result, there may tens of thousands of candidate RF links that would need to be modeled and evaluated to determine an optimal connectivity path or route from each internal NAN node to the DAP. Further complicating this exercise would be the recognition that a NAN will be in a dynamic RF environment. Considering that nodes are subject to being added or removed, obstructions such as vehicles changing locations, changing weather conditions, vegetation changes throughout the year, etc.; the NAN will always be in some state of flux as it dynamically adapts to the changing environment. To model this environment would be an extremely difficult task when using discrete RF modeling techniques as may be used in modeling point-to-multipoint network links as described in section 5. Considering the sheer number of point-to-point links possible in a Multi-Hop NAN network consisting of thousands of relatively closely located end nodes makes this an almost impossible task. In summary, each individual link has associated with it a specific probability, at any given time, a satisfactory connection will be achieved (i.e., having a received signal above threshold) it is a daunting task to come up with an easy-to-use mathematical model to analyze and accurately predict the routing within a NAN.

Even with the difficulties identified above, most vendors supplying AMI meters and/or the Multi-Hop networks to support them have typically developed a set of internal tools and capabilities to assist them in developing effective and efficient Multi-Hop NANs. Given the number and location of the AMI meters or other end-points to be covered, they use these internal tools along with knowledge of the terrain, clutter, and other characteristics for a particular geographic area, combined with rules-of-thumb they have developed while implementing previous NAN systems to produce the infrastructure designs. Using techniques and processes they have found to be successful allows them to predict with some degree of accuracy the number and placement of the DAPs and RF repeaters or relays or routers required to effectively service the specified number and location of the AMI meters or other end nodes. It is worth noting that these vendors may also have internal simulation tools to validate their designs prior to implementation. However, it would be prudent and indeed necessary to validate expected performance of the NAN after implementation in the field and to augment or adjust infrastructure if necessary to achieve required performance.

Finally, there are evolving commercially available RF software modeling tools specifically designed for designing and analyzing Multi-Hop NANs. These tools use the proposed number and location of the AMI meters or end-point devices to be included in the NAN, along with some NAN design constraints (for example the maximum number of hops allowed from an end node to the DAP) to develop an infrastructure design. These tools take into account the combined RF coverage that would be provided by the proposed infrastructure devices (DAPs, relays, repeaters, and routers) along with the additional RF coverage that will be provided by the end nodes themselves to propose an infrastructure design which would include the predicted routes the AMI meters or other end nodes will form when linking back to the DAP. These tools allow a designer to specify design constraints like load and maximum hop counts allowed within the NAN. However, the routes formed within a NAN when deployed in the field will likely not exactly match the predicted configuration for the same reasons mentioned above relating to the dynamics of the RF environment in a given area. Nevertheless, the proposed infrastructure design should enable the formation of a Multi-Hop NAN suitable for providing effective and reliable connections of the NAN end nodes with the DAP. As one might expect, these tools are extremely process intensive and may require multiprocessor computing power to develop designs within a reasonable amount of time for large numbers of end devices covering large geographic areas. An example of several relatively small NAN designs and their predicted links or routes is shown in Figure 65.

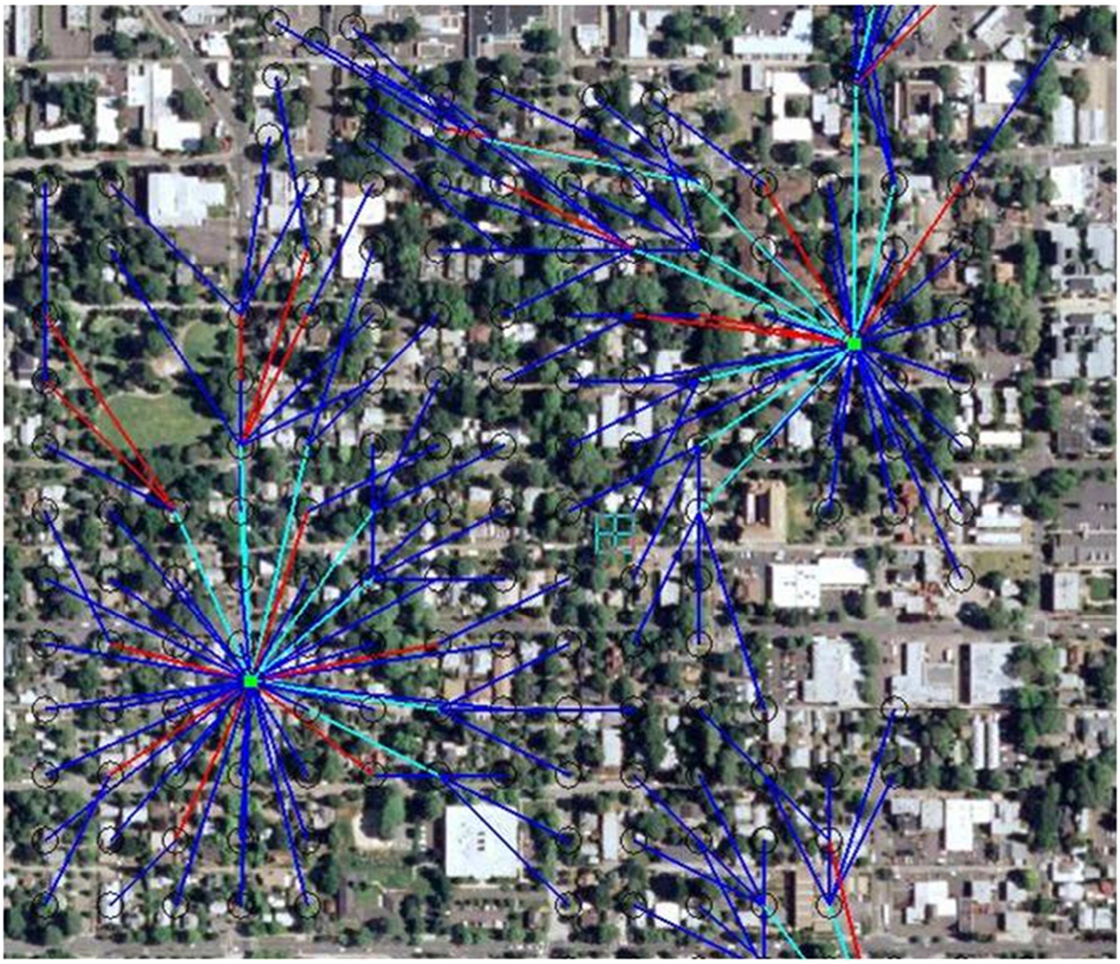


Figure 65 - Example of NAN design from software design tool

6.3.8 Smart Grid Neighborhood Area vs. Wide Area Networks

The preceding sections have provided considerable detail concerning Multi-Hop networks with a specific focus on the smart grid NAN networks utilized to provide connectivity to multiple end-points such as meters and/or DA devices. However, the Multi-Hop topology may be utilized in other Smart Grid network systems as well. More specifically Wide Area Networks (WANs) may be implemented utilizing PMP, Mesh, or Multi-Hop techniques and topology. This section briefly considers these WAN implementations in the context of the Smart Grid network. In general a NAN PMP, Multi-Hop, or mesh network may have a number of similarities with a WAN. However, due to differences in the intended uses, specific use cases, capacity, and reliability requirements for which these networks are designed to support, will often lead to significant differences in implementation technology and operational characteristics. A brief comparison of some general requirements and operational characteristics will help illustrate these differences as listed in Table 19.

Table 19: Differences between NANs and WANs

Requirement / Characteristic	NAN	WAN
Geographic coverage	Neighborhood area size – ranging from several hundred square yards to a small number of square miles or square kilometers	Larger geographic areas – ranging from multiples of square miles up to hundreds of square miles or square kilometers – or even larger.
Technology used	Usually a single technology – usually wireless with a common physical interface.	Can be made up of multiple technologies (wireless and wire-line / fiber optics) with bridging devices or routers used to connect disparate technologies.
Node-to-Node physical spans or links	Usually established and changed dynamically as needed by the nodes	Usually established statically and may or may not be dynamically changed by the nodes
Ability to route data through the network	Dynamic routes can be established by the connected nodes through the dynamic links and can automatically update as needed by network topology changes.	Dynamic routes can be established by the connected nodes through the static links and can automatically update as the state of the nodes or static links change.
Number of connected nodes	Ranging from tens to multiple thousands of nodes per individual NAN	Typically ranging 10 to 100 nodes – except for very large WANs (i.e., the Internet).
Capacity per node-to-node link	Ranging from tens of kb/s to several hundred kb/s (e.g., IEEE 802.15.4g)	Typically several Mb/s to several Gb/s
Node-to-Node distance	Typically several hundred feet to several thousand yards or meters	Typically multiple miles to hundreds of miles or kilometers.
Example networks	AMI NAN encompassing 10 to 20 city blocks in an urban or dense urban environment	A composite network spanning a city, county, or state – or even a global network.

Another significant difference in the NAN and WAN may be in the source and ownership of the equipment used to implement the network. A WAN may be provided by a network service provider as a virtual private network and will appear to the user or customer as a cloud that provides connectivity between nodes as required and as negotiated in the service contract with the network service provider. In that case the topology and technology of the physical network is less important than the service level agreement contracted by the customer. Alternatively a user may elect to construct and build a private network infrastructure. The user may plan and develop the network by using internal network design talent or relying on a service provider or other contract services to design and implement the network. In this case the user is free and indeed obligated to specify the topology and technology utilized to implement the network. For a private

WAN the owner can specify and design a PMP or Multi-Hop network or other topology to best suit their requirements and budgetary and operational constraints.

Just like for a NAN, for a WAN Multi-Hop or mesh network, considerations and evaluation must be given to the intended use and operational characteristics of the WAN before committing to a specific topology and technology. This is particularly true for a private WAN where the cost to implement the WAN may be substantial and mistakes in choosing the proper technology and topology caused by not properly evaluating the current and potential future requirements can lead to an untenable situation that can result in costly redesign and rework.

In contrast, for an SG NAN, the network infrastructure and the end nodes (i.e., meters) are commonly owned by the utility. A notable exception to this is if the utility subscribes to a service provider to provide discrete links or lines of service to each end node. However, in this case it is not a question of the use of a Multi-Hop, or even if it is a NAN or a WAN but instead the significant element of concern to the utility is the service level agreement contracted with the service provider.

In most cases the utility contracts with a NAN system vendor to develop and provide a customer owned network consisting of the necessary NAN infrastructure and head end services to provide connectivity to meters and other end devices required by that utility.

Another distinction between a WAN and a NAN is that a NAN almost by definition is much smaller and less costly on an individual NAN instantiation basis. Mistakes in evaluating the capacity requirements for a particular isolated NAN can usually be corrected with minimal cost by adding another Access Point or forcing traffic through an alternate takeout point. However, all the caveats mentioned earlier should be carefully considered when specifying the operational characteristics of the NAN system to serve an enterprise. It must be remembered that the enterprise NAN system will be composed of multiple individual NANs to provide the required enterprise coverage. Mistakes at the system or enterprise level can also be very costly to remedy or correct.

Although this section describes NANs and WANs as separate entities, in practice a WAN may be used to provide connectivity for SG end devices if this connection mechanism is more effective than implementing a NAN to provide this connectivity. The intent of this section is to acknowledge that there are a number of similarities in Multi-Hop NANs and Multi-Hop WANs, but there are also a number of differences in the purposes of these networks and the operational characteristics of each.

This concludes a brief coverage of the WAN Multi-Hop network. This description is not intended to be a comprehensive treatise on all aspects of network theory, design, or operations. It is merely to acknowledge that there are multiple network types and classifications and the choice of technology, topology, and whether to build or buy services is going to be highly dependent on the utility and their business and regulatory environment, requirements, and obligations.

Finally, and again, this section is not intended to be the definitive guide for a utility in selecting their SG network technology or topology. Further information is available in other sections in this report and information in much greater depth can be obtained from a number of books and technical papers devoted to the theory of network design.

6.4 Addressing the Challenges with Multi-Tenant High Rise Buildings

A major challenge faced by utilities in Dense Urban and Urban centers is establishing a reliable communications link between the Smart Meter and the HAN in high-rise, multi-tenant buildings. With the utilities' infrastructure generally underground, meter banks are often located at ground level in weatherized enclosures or below ground in basement locations. To consider an all-indoor wireless solution for this application, one must take into account the excess path loss caused by successive floor penetrations.

A number of indoor path loss models were described in section 5.2.1.2. Two of the models, ITU-R M.1225 and WINNER II, include a parameter for predicting floor-to-floor penetration losses. Although the two models diverge considerably with an increased number of floor penetrations, both predict a higher penetration loss for the first floor with a diminishing loss per floor for successive floors. For three floor penetrations the ITU model predicts 25 dB excess path loss at 1900 MHz and the WINNER II model predicts 44 dB. Another field study cited in section 5.2.1.2 predicts about 35 dB for three floor penetrations, which coincidentally, is close to the average loss predicted by the two path loss models.

Whichever model is used to project floor-to-floor penetration loss, it is clear that propagation paths that go beyond 4 or 5 levels will create a major deployment challenge for an all-indoor wireless meter to HAN connection. In addition to the high total path loss, EIRP limitations to comply with human safety exposure limits further reduces the range potential for an indoor wireless link. One potential deployment solution is to position relays every 2 to 4 floors. This approach might be suitable for buildings under 9 or 10 stories but probably not cost-effective for taller buildings.

6.4.1 An Alternative Wireless Approach

An alternative deployment approach for a wireless solution that can be considered for this scenario is one in which a basement-located DAP communicates with an outdoor pole-mounted[32] BS acting as a relay to connect to apartment HANs on higher floors as illustrated in Figure 66. In addition to reducing the total penetration loss compared to the all-indoor wireless solution, this approach can take advantage of higher gain antennas and higher EIRPs on the outdoor pole-mounted BS labeled as relay node in Figure 66.

[32] Pole is used generically to indicate any suitable existing mounting location, such as a street light, traffic light structure, or the side of a building across the street.

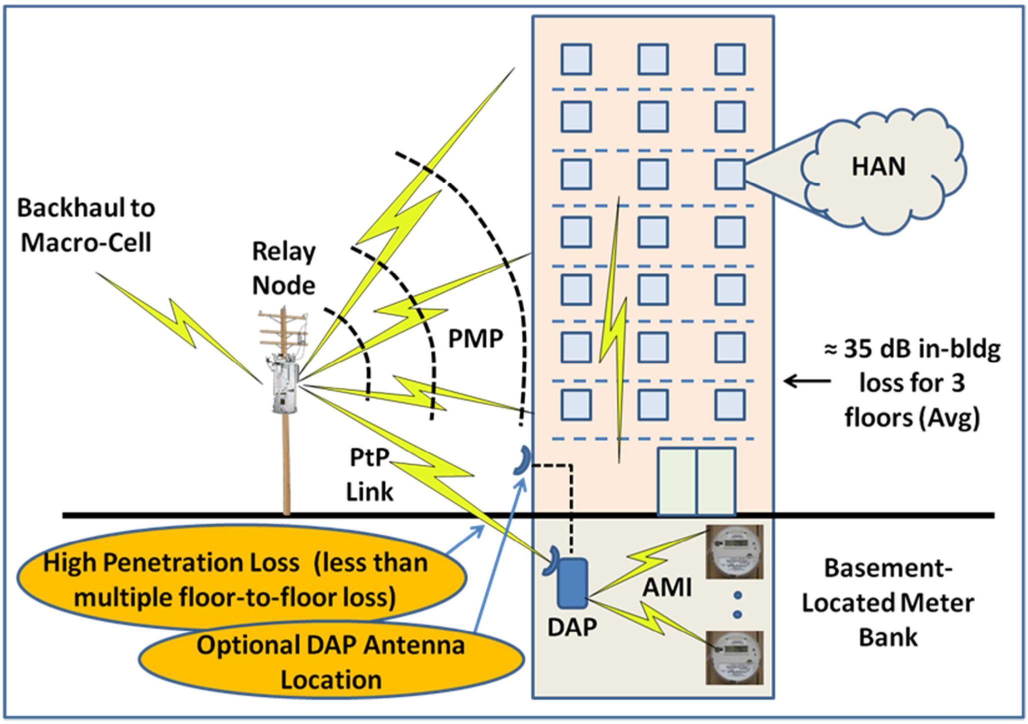


Figure 66 - Approach for basement to HAN connections in multi-story buildings

The Relay Node serves multiple functions. It provides a PtP link to the basement-located DAP, a PMP link to the HANs in the multi-tenant building, and a backhaul link to a macro-cell in the NAN or WAN.

To better understand the attributes for this approach, it is informative to look at the characteristics of each communications link individually.

Basement-located AMI Network: This is a totally indoor PMP link probably comprising a single sector in a license-exempt band to aggregate the data traffic to and from the smart meters. The meters are typically tightly clustered and the distances to the DAP will be relatively short. The DAP can be strategically positioned for the most optimal favorable propagation path to the outdoor pole-mounted Relay Node. Where very high penetration losses are anticipated one can consider running a line to an outdoor mounted antenna. The cable losses will be far less than the basement to outdoor penetration loss thus greatly increasing the link margin.

DAP to / from Relay Node: Both the DAP and the Relay Node would employ a high gain, narrow beamwidth antenna to provide a PtP connection between the two sites. Although the DAP EIRP, depending on how and where it is mounted, may still be limited for compliance to human safety exposure limits, the narrow beamwidth will help mitigate the potential for interference in a license-exempt band. Even with dedicated spectrum, the narrow beamwidth will help protect against interference from a similar deployment in the adjacent building or the next block. With careful antenna positioning and alignment at each end of the link and the relatively short path length, the 20 dB to 30 dB penetration loss will be easily accommodated. With the lower EIRP at the DAP the link budget in the UL will be the dominant determinant for the link budget and link availability.

Relay Node to / from HAN: At the Relay Node this would be a single sector PMP link in an unlicensed band consistent with the operating frequency of the HANs. Rather than being optimized for surface area coverage, the PMP antenna would be positioned to have wide elevation angle and relatively narrow azimuth consistent with the building height to width ratio. The link budget would have to take into account at least one external wall and in some cases multiple internal walls to access individual HANs. The relatively shallow angle of incidence for the upper floors in a very high building will result in a higher penetration loss than that encountered with the lower floors. As in the last case, the link budget in the UL will be the major determinant for the link performance due to the lower EIRP and lower antenna gain for the HAN.

Relay Node Backhaul to / from macro-cell: The backhaul connection for the Relay Node would employ a high gain fixed antenna that is aligned to optimize the link between it and the macro-cell BS which would typically be mounted on one of the adjacent building roof tops for maximum coverage. The macro-cell BS would employ a typical PMP sector antenna to provide a backhaul for several Relay Nodes or other pico-cells (DAPs) within its coverage area. Since the Relay Node would be mounted on a pole about 8 m to 10 m above ground, accessible only by trained personnel, it would be able to operate at a higher EIRP. The narrow antenna beamwidth would also help to mitigate the potential for interference to the relay node. For this link the DL and UL link budgets would be quite comparable due to the higher antenna gain at the relay node.

A schematic view of this proposed solution is shown in Figure 67. As was stated in previous sections, when considering end-to-end payload latency requirements it is necessary to apportion the latency requirement on a per-link basis.

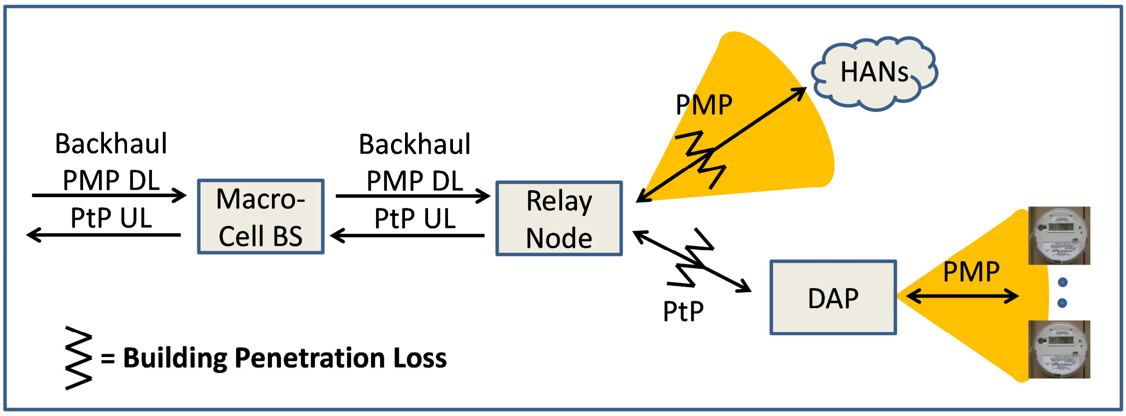


Figure 67 - Schematic view of the network architecture

6.4.2 Conclusion

Implementation of the alternative to an all-indoor wireless solution described above depends on having access to a conveniently located structure for mounting the relay node equipment and associated antennas. The location must provide a good propagation path to the antenna for the basement-located DAP, as well as to the HANs on the highest floors. In some situations it may pay to take advantage of the roof mounted macro-cell

BS site. This site may have a better propagation path to HANs on the highest floors of the building while the Relay Node can be used for connectivity to the lower floors in the building.

6.5 SG Framework and Wireless Modeling Tool

The modeling framework discussed in section 5.2 was extended both on the input parameters and the outputs of a wireless model. This section describes this extended framework and a wireless modeling tool that has been developed to exercise the framework to provide more information to help assess wireless standards, representative technologies, and spectrum band usage specific to terrestrial wireless Smart Grid networks. The SG framework and wireless modeling tool is a merger of the 'SG Networks Deployment Modeling Framework' developed by the OpenSG Networks Working Group and the 'Wireless Modeling Engine' developed by SGIP PAP02.

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless with a file name syntax of "SG_Framework_and_Wireless_Modeling_Tool_V0.xlsx", where N represents the number of the version.
    - https://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PAP02Wireless/SG_Framework_and_Wireless_Modeling_Tool_V0.xlsx

  OR
- http://members.sgip.org/apps/org/workgroup/sgip-pap02wg/download.php/1609/2013-09-17_sgip-pap02wg_00014_SG_Framework_and_Wireless_Modeling_Tool_V0.xlsx

The SG framework and wireless modeling tool (see Figure 68), is structured to provide an estimate for the number of BSs[33] required to provide ubiquitous coverage and the required BS to BS spacing to meet data throughput, payload latency, and reliability requirements called for by the demographics for the specific geographical area under consideration.

[33] The term, base station, as used in the context of the modeling tool, describes an aggregation point for a point-to-multipoint topology. Other terminology may be encountered with different land-based wireless technologies to describe similar functionality e.g., Central Station, AP, Cell-Site, and specifically for SG Network Requirements: for AMI networks, Data Aggregation Point (DAP); for Field Area Networks, FAN Gateway.

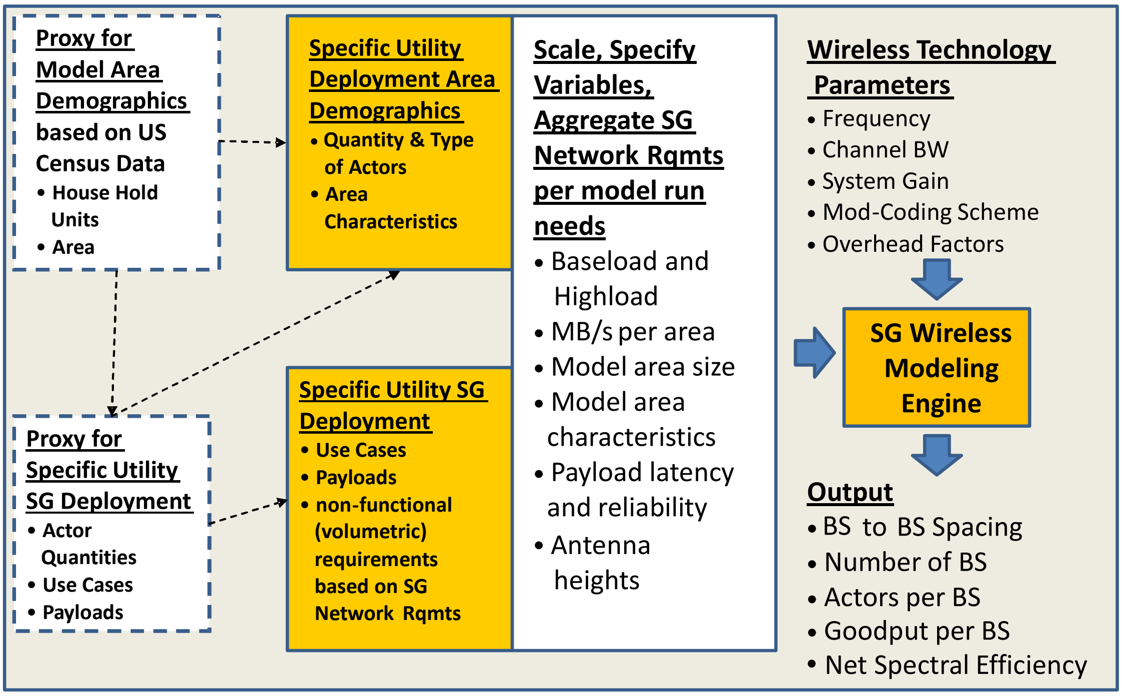


Figure 68 – SG framework and wireless modeling tool

The smart grid requirements section of the tool accommodates several approaches for adaptation of SG requirements data for input into the SG Wireless Modeling Engine. Normally the utility or other organization wanting to use this tool would base the inputs on their specific SG Deployment area specifics. The tool framework also allows use of data proxies in the absence of specific SG Deployment details. The details of preparation and use of proxied input data as based on the SG-Network TF's Requirements data is described in section 6.5.1.

The wireless section of the tool utilizes five large scale terrestrial path loss models, the latency model, and other relationships developed and discussed in section 5 for outdoor-located BSs. Whereas the modeling tool assumes outdoor-located BSs, terminal or end-point locations can be specified as being indoors or outdoors. Recognizing the fact that no mathematical model is an ideal choice for all deployment scenarios, the modeling tool makes use of the five terrestrial models where appropriate. That said, depending on the range of requirement parameters that are inputted to the model, there will be cases for which multiple solutions result. It is left to the user to decide which is most appropriate for the specific case being analyzed considering the terrain characteristics and demographics for the region being analyzed.

6.5.1 Modeling tool input parameters

As shown in Figure 68, required inputs to the modeling tool fall into three categories:

1. **Deployment Area Demographic Requirements:** This information would generally originate from the utility specific to the SG deployment area of interest. Alternatively readily available census data combined with local utility information can be used as a reasonable proxy. End-point actors quantities (or

densities), combined with substation and feeder circuit information can be converted into a data density requirement over the specific geographical area under consideration. The model supports inputs in square miles, consistent with US census data information, or km^2 for those preferring the metric system. Another input in this category is the terrain and area characteristics.

2. **Smart Grid Deployment Requirements:** These inputs are specific to the Smart Grid use cases, payloads, and actors for the specific deployment profiles being studied. These inputs also include the payload volumetric (architectural non-functional) requirements. The OpenSG SG-Network Task Force System Requirements Specification [5] describes a methodology for adapting the SG-Network TF Requirements Table data for input into the SG framework and wireless modeling tool. The SG framework and wireless modeling tool spreadsheet includes a tab that contains these same detailed steps. The following provides an overview of these steps.

- ***Adaptation of SG-Network TF's Requirements Table Data for Use in Network Modeling Tools***

General Steps - Regardless of study analysis intent:

Step 1) Select the Study / Analysis Deployment Profile (including end-points, use cases, payload requirement sets.

Step 2) Identify which business application payload requirement sets (parent rows and selected comm-paths) are in play based on selections and restrictions from step 1 above.

a) Flag the Deployment Profile parent rows
b) Flag the Deployment Profile child rows, if any associated with the parent rows selected in Step 2) a)
c) Optionally, identify the child's parent Rqmt Ref (used for back reference and audit purposes)
d) Extract the Deployment Profile Requirements to a separate workspace

Step 3) Select one value for the documented non-functional metrics where ranges or unspecified parameters (variables) are identified in the Requirements tab, specific to your business requirements. Optionally, modify the other fixed / specified metrics to your business requirements.

a) How Often
b) Business App Payload Latency
c) App Payload Size
d) Daily Clock Period Factor for Specific Hour

Step 4) Scale the non-functional app payload metrics in the Requirements tab specific to the study / analysis deployment characteristics. This step is where, optionally, the type and quantities of the actors can use the census and model-area parameters and relationships between some of the deployment characteristics can be used as proxies for the specific utility deployment study / analysis area actor quantities.

a) Multiple actor payloads multiplier for shared child row data flows / interfaces
b) How Often Actor Quantity conditional / qualified and root actor names
c) Summarized Table of Actor Quantities
d) Payload Frequency metric per unit of time per How Often conditional / qualified Actor
e) Conditional / Qualified Actor Quantities

Additional Steps for:

General Telecomm Traffic Modeling

Step 5) Specify which application payload data flow and/or interfaces are to be studied / analyzed.

Step 6) Specify the wireless uplink and downlink designation for the requirement rows.

Step 7) Specify the use case payloads requirement as being baseload or highload traffic and Specify the associated payload frequency:

a) tag the requirements as baseload and/or highload
b) specify those qualified actor where their quantities vary from baseload to highload
c) create baseload and highload payload frequency metric calculations for each payload as appropriate

Step 8) Specify the application payload and application packet size and latency values:

a) Specify a variable for telecomm application packet size (e.g., the payload portion of a transmitted packet that also includes protocol overheads)
b) Calculate the number of packets to accommodate the application payload
c) Adjust the payload latency metric to account for the adjustment made in step 6 for wireless technologies that require the use of a DAP or BS for end-point to end-point communication versus peer-to-peer
d) Calculate the packet latency for each requirement row

SGIP PAP02 Wireless Modeling

Step 9) Seed the DAP quantities and refresh after initial model runs.

Step 10) Specifying the calculations – Part 1 of the Non-functional application payload requirement metrics. Note: these are the raw calculations by each requirement row that are then further processed in step 11 to create the inputs into the SG framework and wireless modeling tool. For the various combinations of uplink / downlink and baseload / highload calculate the following:

a) Payload and packet rates (quantity per second)
b) (MB/s) / mi^2
c) Payload and packet size
d) Payload and packet latency

Step 11) Specifying the calculations – Part 2 of the non-functional application payload requirement metrics and consolidating for input into the wireless model. The SG framework and wireless modeling tool inputs from the SG-Network Task Force Requirements are categorized as follows for each modeling area density category (e.g., high density urban, urban, suburban, rural, low density rural):

• RF Propagation Path Loss - Calculating the number of DAPs required to provide coverage for the data volume across the geographic area that contain the end-points:

- (MB/s) per square-mile [(baseload or highload) and (uplink or downlink) traffic]
- Study / analysis area (square mile)
- number of end-points in the study / analysis area

• Payload Latency Rqmts - Calculating the number of end-points that a DAP can support at a specific probability of satisfying the latency requirements [(baseload or highload) and (uplink or downlink) traffic]:

- Message Rate # per second (R_{MSG})
- Average time between Message in seconds ($T_{MSG} = 1/R_{MSG}$)
- Average application packet (without overheads) size in bytes (P_{AVG})
- Single Network Link Latency seconds (L) from [average or manual input or minimum] application packet latency
- Probability that message event falls within latency window ($P_{MSG} = L/T_{MSG}$) from [average or manual input or minimum] application packet latency

3. **Wireless Technology Parameters:** Required information about the specific wireless technology under consideration will not only be technology-specific but in most cases will also be vendor-specific. System gain information for both UL and DL transmission is essential for estimating range and coverage. Channel bandwidth, modulation and coding schemes, and channel overhead factors are required to provide an estimate for the average channel or sector and BS goodput and net spectral efficiency. If the overhead factors available do not account for all higher level protocols, headers, encryption, etc., there is provision for the user to add to the OH to take these factors into account. In assessing different technologies in different frequency bands (and possibly different countries) local regulatory rules must also be considered. These rules will generally place

limitations on antenna gain and EIRP, two parameters essential for calculating the system gain, and may also impose restrictions on occupied spectrum or allowable channel BW. To facilitate the comparative assessment of different wireless access solutions, there is provision for 16 sets of wireless parameters, 14 of which are preloaded with information provided in the Wireless Capabilities Matrix described in section 4.

6.5.2 Modeling tool outputs

The modeling tool provides an estimate for the BS to BS spacing necessary to meet the data density and latency requirements while, at the same time, achieving ubiquitous coverage over the specified geographic area. In some cases, based on frequency, antenna heights, and region type, there may be more than one applicable path loss model thus resulting in two or more output results that may or may not be similar. When results differ, it is left to the user, based on more specific knowledge of the terrain characteristics, to decide on which result to use. Alternatively, one could simply rely on the more conservative result, which for planning purposes may be adequate.

Figure 69 illustrates how the output information would apply to a specific area that is being studied. Since the BS requirements are rounded up to the next highest whole number, the combined BS coverage will meet or exceed the area coverage requirements. The tool also takes into account the fact that end-points at the cell edge in a multi-cellular deployment will generally have connectivity access to more than one BS as shown in the figure. This reduces the fade margin requirement thus enhancing the link budget and the effective BS range.

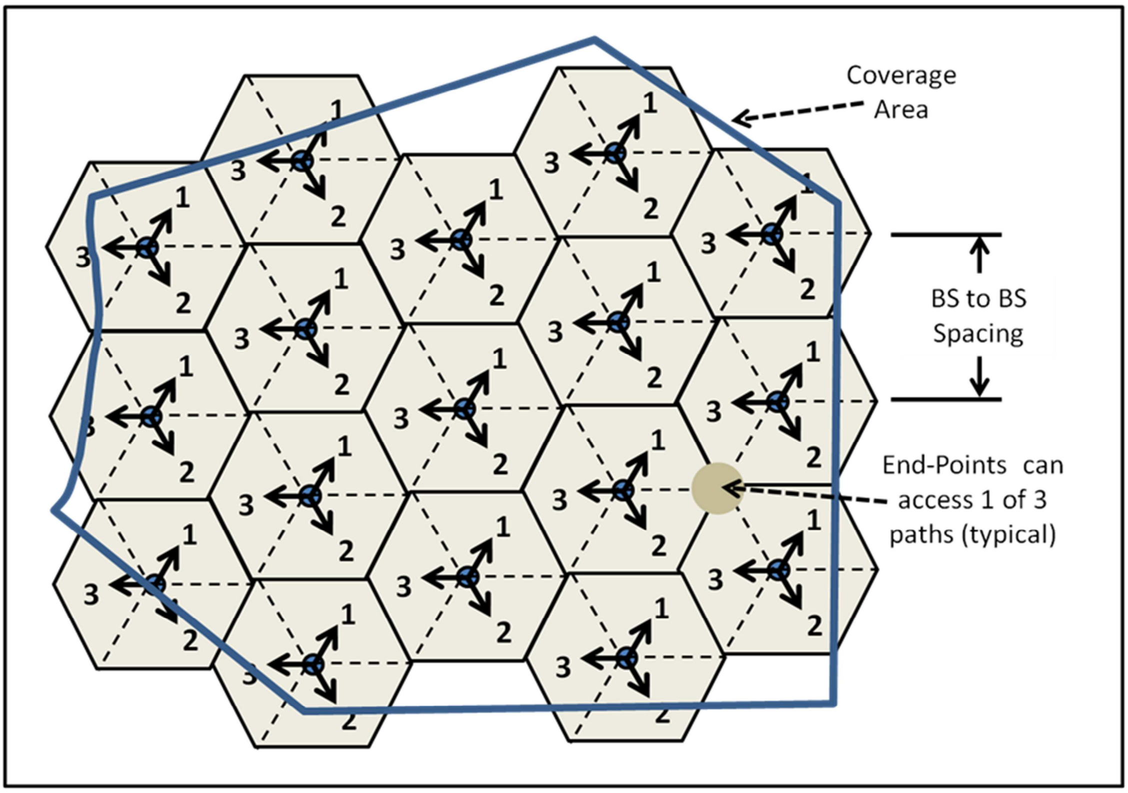


Figure 69 - Modeling engine assumes a uniform (hexagonal) BS to BS spacing

6.5.3 Limitations of the modeling tool

The modeling tool has been developed specifically to facilitate terrestrially-based wireless network planning with outdoor-installed BSs and terminals located indoors or outdoors in a Point-to-Multipoint (PMP) cellular-like architecture. The tool is not suitable for analyzing a mesh topology, which by its nature has the potential to provide coverage beyond that predicted for the BS itself. As currently configured the tool is also not intended to address indoor Home Area Networks (HANs). Although a similar approach can be used for HANs, additional study would be required to arrive at better mathematically-based path loss models for wall and floor penetrations, covering the frequency range of interest for residential and enterprise environments. The current tool is also not intended for analyzing satellite networks, as these would require a different set of path loss models.

To estimate propagation path loss, the modeling tool is based on large-scale mathematical models, each derived from field measurements in selected environments as described in section 5. These models are convenient and easy to apply but have limitations as there is no practical way to develop a mathematical model that would cover all possible deployment scenarios over the unlimited range of terrain characteristics and building densities that are likely to be encountered over a large geographical area.

The latency model that is embedded in the modeling tool is based on the binomial distribution methodology described in section 5.2.7. This approach provides a more conservative estimate for supportable end-points than the M/M/1 or M/D/1 approaches, also described in section 5.2.7. The latency model assumes the average packet time for the end-points of interest is less than the required latency. This is a reasonable assumption for most Smart Grid network segments with channel data throughputs that are likely to be encountered with any of the wireless technologies being considered. An error message will indicate when the desired latency requirement cannot be met and there is provision in those cases to select a different latency, labeled as 'Acceptable', so as to determine the latency that can be met. For the latency predictions, the modeling tool also assumes all packets have equal priority. QoS, which provides a means for prioritizing latency-critical packets, is not taken into account. Therefore, in assessing the results with respect to latency for a specific wireless technology, it is important to also consider the QoS that is supported by the technology of interest.

To estimate average channel data density and average channel throughput, the modeling tool assumes a uniform distribution of terminals (actors) over the area of interest. This may be a reasonable assumption in many suburban and most urban and dense urban areas where BS coverage areas are relatively small and households are close to being distributed uniformly over the coverage area of interest. It may not be an accurate assumption, however, in rural areas where clusters of closely spaced housing units can be separated by several miles or kilometers from other clusters with scattered individual housing units in between thus resulting in a very non-uniform distribution of terminal locations as illustrated in Figure 70.

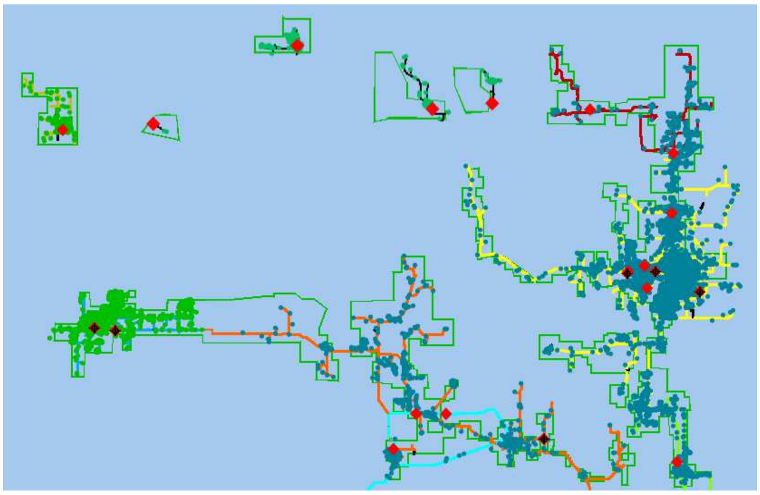


Figure 70 - Typical rural area demographics

Typically in this type of environment, BSs would be deployed close to or within areas where housing or end-point clusters are concentrated, or where placement is needed to satisfy the application latency requirements. For this deployment scenario, channel or BS capacity will be under-estimated rather than over-estimated since a higher percentage of terminals will be closer to the BS than what would be predicted assuming a uniform distribution of housing units. It can also be argued that, for most land-based wireless technologies under consideration, the most important metric for rural area deployments will be range capability whereas average channel capacity will only be of secondary interest. Average channel and BS throughput will play a larger role in the more heavily populated urban and dense urban areas. In these high density environments, it is quite reasonable, for planning purposes, to assume utility customers are uniformly distributed over the area of interest.

The SG framework and wireless modeling tool can be an effective tool for comparing the relative performance of different terrestrial wireless technologies and to provide initial estimates of network BS requirements to meet coverage, data density, and latency requirements in a wide range of deployment venues. Since the tool does have limitations, it is strongly recommended, before actual deployments are undertaken that the results be supplemented with more detailed network planning and, in some cases, on-site field testing or RF surveying. This is especially important for extreme terrain characteristics and unique deployment situations as might be encountered with below grade, indoor, or vault-located smart meters in an AMI network.

6.6 Interoperating and Interworking with Other Wireless Technologies

Section 5 and most of what has been presented in section 6 so far has been focused on terrestrial-based wireless technologies in the 700 MHz to 6000 MHz frequency range. Although these technologies, which are all cellular-like, can and will play a significant role in any of the demographic areas of interest for Smart Grid networks, it must be recognized that they may not provide an optimum solution for all possible scenarios that are likely to be encountered. In this section we discuss some of the other technologies that are included in the Wireless Characteristics Matrix discussed in section 4 and, additionally where these different technologies should be considered for application in the Smart Grid communication network.

6.6.1 Satellite Communication Networks

Satellite communications is another wireless solution that can play a vital role in a Smart Grid network. It was already pointed out in section 6.1 how a satellite link could be used to provide or augment a backhaul connection in a rural Smart Grid network. In other rural or low density rural regions with extreme terrain characteristics, a satellite solution may prove to be the only cost-effective approach to reach all of the desired utility end-points. The intent of this subsection is to provide additional insights as to the attributes and trade-offs for satellite-based networks.

Satellite communications technologies have features which can be used for many of the use cases identified for the Smart Grid. For example, satellite services are available throughout North America and cover 100 % of the conterminous United States. This means that the same user terminal can work anywhere in any rural or urban location.

Furthermore, since satellite communications is independent of any local infrastructure it is ideal for emergency response and restoration, as well as for a redundant path to support highly reliable communications.

Satellite communications systems all operate in licensed-band spectrum. Mobile Satellite Services (MSS) spectrum is available in L-band and S-band and includes both

Geostationary Earth Orbit (GEO) constellations, as well as Low Earth Orbit constellations. Fixed Satellite Services (FSS) spectrum includes C-Band, Ku-Band, and Ka-Band. Fixed satellites are generally in the GEO. FSS is becoming a misnomer as portable, transportable and fully mobile terminals are routinely supported.

The one-way path delay between a user terminal and a GEO satellite is between 117 ms and 135 ms. The round trip latency due to propagation between a remote terminal and a gateway hub station is between 468 ms and 540 ms. In addition to propagation there are processing and queuing delays which are dependent on the specific implementation. This delay is acceptable for most Smart Grid applications. While some latency is tolerable, certain events have to be logged with an accurate time stamp. The mobile satellite technologies are completely integrated with the GPS system for routine functions like spot beam selection and paging area location and many terminals are required to have GPS receivers. The fixed satellite technologies are not required to have a GPS receiver but are routinely integrated with GPS depending on the application. Therefore, accurate GPS time is available for a time stamp.

The ubiquitous capability of satellite communications gives repair crews the opportunity to use satellite terminals or handsets anywhere in the United States where they may be dispatched in the event of emergencies. Mobile terminals in both MSS and FSS bands can be used at speeds up to 1,200 km/h with Doppler compensation but are more routinely used below 160 km/h (100 miles per hour).

In order to close the link and provide adequate margin, MSS satellites all deploy on the order of hundreds of spot beams throughout their coverage areas. Not only do spot beams provide improved satellite EIRP and Gain to System Noise Temperature ratio (G/T) but also increased capacity with frequency reuse. New fixed satellites feature similar numbers of spot beams.

Several MSS terminal types are small handheld devices similar to a cell phone having low antenna directivity. These are ideal for emergency crew dispatch. Both data and voice are supported, though the available bandwidths are commensurate with the antenna gain performance and terminal type.

Satellite communications typically rely on line of sight propagation. Fading from foliage and imperfect terminal orientation is tolerated in low directivity handheld terminals used in MSS. Some MSS terminals have several dB of directivity and operate best when oriented properly and may really be considered transportable. These terminals can support up to 590 kb/s of data in the forward direction or downlink direction from satellite to terminal and 186 kb/s in the return or uplink direction from the terminal to the satellite. These data rates exceed the required rates.

Many MSS networks employ the 3GPP Iu-interface between the radio access stratum and the core network non-access stratum. The physical and media access control layers are optimized for the satellite radio propagation characteristics but the higher layers are integrated. MSS terminals can be dual-mode satellite / terrestrial and have a single shared protocol stack above the radio resource control layer so that mobility management and session management are the same for both modes. Core networks can also be fully integrated sharing the same 3GPP Serving GPRS Support Node (SGSN).

FSS terminals use highly directive offset parabolic dish antennas, between 0.5 m and 1 m in diameter. They support data rates up to 440 Mb/s in the forward link and 16 Mb/s in the return link. These terminals are intended for fixed transportable and mobile applications.

6.6.2 Smart Grid Solutions in the 450 MHz to 470 MHz IG Band

Relevant regulatory information for the IG Band (Industrial / Business Band) can be found at [34]. Note that the 450 MHz to 470 MHz band is a sub-band of the entire IG Band which, in addition, includes several other blocks of spectrum between 150 MHz and 512 MHz.

6.6.2.1 Frequency Usage and Capabilities

This band is one of the oldest bands for industrial group use. It requires FCC licensing and usually requires a Frequency Coordinator[34] when obtaining licenses in this band. When licensed, operators in this band are, in effect, operating a private network and generally have protection against interference and less restrictive operating conditions compared to operating in any of the unlicensed ISM bands. Compared to higher frequencies, this band is notable for its longer communication range, typically 5 km to 7 km with an outside end-point antenna at a 1.5 m elevation, level ground, and a transmit power of 2 watts[35] (33 dBm) [35]. There is also lower penetration loss for end-points in buildings or other highly obstructed areas. For in-building communications, lower transmit powers can be used. Transmitters generally use some form of Frequency Shift Keying (FSK) transmission and AM and FM usage is permitted. The channel bandwidth (as of January 1, 2013 in this band) is now all narrowband (± 12.5 kHz) around channel center frequency. Licenses are typically good for a 32 km radius from the BS although with appropriate licensing it is possible to string additional licenses on the same channel to daisy chain the use of the channel over greater areas. Due to the popularity of this band, spectrum availability in large metropolitan areas such as New York city may be limited. Simplex or half duplex communication is the usual method of radio to radio communication although limited paired channels are available for full duplex operations. This means that small short messages (less than a Twitter™ message) are the preferred messaging strategy in this band. These frequencies are particularly useful both in NAN and WAN designs. To prevent congestion in a given area of dense coverage such as an urban environment reducing transmitting power to limit range and using frequency diversity to prevent saturation and message collision issues are common design elements of these NAN's and WAN's. This band is particularly suited to longer distance and

[34] Frequency Coordinators are FCC certified private organizations that recommend specific channel frequencies most appropriate for the applicant.
[35] Human safety exposure limits are not applicable at these lower frequencies.

sparse transceiver network trees. So it would be an ideal candidate for rural and suburban applications. Commercial and Industrial (C&I) and irrigation type monitoring and control applications where there may be increased distances between complexes or fields are also good candidates for this frequency band.

There are approximately 2,180 individual channels in this part of the IG Band available for licensing. While these channels are generally available nationwide, it is unlikely that any given licensee would have universal nationwide access to any given channel in this band. This means Smart Grid applications must be able to handle multiple channels in their data backhaul designs when using this frequency band.

6.6.2.2 Implementation Using the IG Band

The Hata-Okumura Model can be used to evaluate coverage potential in this band (see section 5.2.1.3.1). This model generally assumes that roof top antennas are being used so this model should be used as a maximum or ideal usage model. For rural areas the ITU-R M2135-1 path loss model is also valid in the 450 MHz band. This model also requires BS antennas higher than neighboring roof tops but has entries for actual building heights and road-widths (see section 5.2.1.3.4). Use inside of buildings, even with the greater penetration capability of this frequency band, will limit a given transmitter's effective range. This band is very useful in retrieving meter items such as pulse counts (odometers) data and is used in real time demand response and time of use applications where the age of the data is a critical component for implementing reductions or increases in energy or water usage in response to outside triggers or predetermined usage or pricing points. Usually a Smart Grid application will use a partial mesh network with a tree and multiple DAPs design. Repeaters can be used in difficult communication areas to assure that messages are delivered in a timely manner to the BS or DAP. Because of the risk of having messages continually passed back and forth between mesh elements in a message hopping technique, most systems have a limit to the number of hops a message can make before it is discarded. This limitation will define the maximum depth of a given tree. So as not to lose data most end-points will have a data-logger or equivalent device from which to independently recover missing data points when the RF and network conditions permit retransmission of the missing data.

As important as the transmitting power is to these solutions, the receiver sensitivity is also an important factor when selecting a transceiver as the increased distances capable in this band are maximized with a high receiver sensitivity. Current models will typically detect signal strengths as low as -123 dBm to -118 dBm, or lower depending on the RF Baud rate.

Antenna tuning, placement, and gain are also key factors in the success of communications networks in this band [36]. Typically the mobile units (or end-points) will use omnidirectional antennas. BSs (DAPs) depending on terrain may use beam antennas in their solutions, but the transmission signal range must remain within the licensed area so as to minimize interference issues and conform to FCC requirements. Maximum antenna heights are also a part of the FCC license. (Typically 12.2 m above the structure to which it is mounted)

6.6.2.3 IG Band Summary

Wireless solutions for Smart Grid in the 450 MHz to 470 MHz IG Band offer the potential for increased range and coverage and reduced penetration loss for indoor located end-points. Additionally, since it is licensed spectrum, there is protection against inter-operator interference throughout the geographical area covered by the license and less restrictive operating rules as compared to wireless solutions in the unlicensed ISM bands.

When considering solutions in the IG band, however, one must also take into account the trade-offs imposed by the FCC-mandated channel BW limitations. As stated above, high density regions with high data density requirements will require a pico- or micro-cellular deployment topology to compensate for the limited channel capacity and in the lower density demographic regions cell edge data rate performance requirements will play a big role and may very likely mitigate much of the range benefit. Nevertheless, with careful RF planning and frequency reuse, it is in rural and low density rural regions where the IG Band is likely to have the greatest benefit in the Smart Grid network.

6.7 Assessment of Modeling Tool Results

In this section the SG framework and wireless modeling tool described in section 6.5 is applied to various terrestrial cellular-like wireless deployment scenarios. This analysis will provide some insights as to the wireless BS equipment required to meet specific network requirements under varied terrain and demographic characteristics and wireless technology choices. The focus of this analysis is on the AMI / FAN or NAN with the key output being the number of DAPs required for deployment to meet the Smart Grid network coverage, capacity, and latency requirements.

As described in section 6.1, a wireless deployment can be described as being either range-limited, capacity-limited, or limited in its ability to meet latency requirements.

From a wireless technology perspective, whether a deployment will be range-limited or limited by capacity or the ability to meet latency requirements depends on the following key metrics:

- Wireless channel goodput which in turn is a function of the channel BW, the modulation and coding scheme (MCS), and the total channel OH (including OH contributions from lower and higher layers). The modeling tool estimates the channel goodput using the methodology described in section 5.2.3.
- Wireless range which is a function of the system gain, link margins for fading, interference, and penetration losses, and the path loss predicted by one or more of the wide area outdoor path loss models described in section 5.
- Packet size and whether it is fixed or variable: As we will see later, this can have a major impact on the network's ability to meet latency requirements and, to some degree, can also influence goodput and range.

From an SG network perspective, key metrics are:

- Density of Actors (or End-Points)

- Data payload requirements for baseload and highload in both the DL and UL direction
- Average and maximum payload size in bytes
- End-to-end latency requirement per payload

In the SG framework and wireless modeling tool average data capacity requirements, expressed as a data density in bytes per square mile, are provided for five (5) demographic regions as shown in Table 20.

Table 20: Density requirements for five demographic regions

	Dense Urban	Urban	Suburban	Rural	Low Density Rural
Average Housing Units per square mile	7483	1794	303	26	2.2
Average Commercial & Industrial per square mile	1320	317	54	4.6	0.4
Average End-Points/mile^2	14212	3447	1111	65	4
Average Baseload Requirements					
UL bytes/mile^2	1234	449	5239	10.4	1.4
Average UL Payload (bytes)	1020	344	189	274	190
DL bytes/mile^2	5.2	102	124	3.3	0.7
Average DL Payload (bytes)	90	99	89	99	100
Average Highload Requirements					
UL bytes/mile^2	16129	2314	51283	66	25.7
Average UL Payload (bytes)	8116	1517	911	1538	3178
DL bytes/mile^2	29327	5472	116023	108	9
Average DL Payload (bytes)	65649	4806	2538	3003	1189

From a wireless technology perspective, both channel goodput and packet size will influence how well latency requirements are met for a given number of end-points. The effect that packet size has on performance with respect to range, capacity, and meeting latency requirements deserves further discussion.

6.7.1 Impact of Packet Size

The submissions made to fill out the Wireless Capabilities Matrix in section 4 indicate maximum packet sizes that vary from 96 bytes to 14,400 bytes for the UL and from 640 bytes to 14,400 bytes in the DL. Channel BWs range from 0.208 MHz (208 kHz) to 20 MHz in the frequency bands between 700 MHz and 5800 MHz and for the 450 MHz band, the submitted channel BW is 0.0125 MHz (12.5 kHz)

The relative trade-offs between small and large packet sizes are summarized in Table 21, Table 22, and Table 23.

Table 21: Small packet size trade-offs

Pros	Cons
• A higher probability of falling within the latency window • Reduced requirements for cell edge goodput	• Higher Channel OH since each packet must contain some OH bits • Payloads larger than the maximum packet size must be divided into smaller packets and the payload latency requirement must then be divided by the number of packets to arrive at a latency requirement per packet.

Table 22: Large packet size trade-offs

Pros	Cons
• Better OH efficiency. • A greater number of payloads can be accommodated without breaking it into smaller packets • Very large payloads can be transmitted with less segmentation	• Lower probability of falling within the latency 'window' • Larger packet size places greater demands on cell edge performance which in turn will impact the receive sensitivity at the cell edge • Higher probability of a packet error due to a bit error • For some combinations of channel bit rate and packet size, the packet time will exceed the packet latency requirement

Table 23: Summary of end-to-end packet payload minimum latency requirements for a Suburban Region

Maximum UL Packet Size[a]	**96 bytes**	**2042 bytes**	**14400 bytes**
Baseload UL	0.080 s[b]	1.33 s	2.40 s
Highload UL	0.006 s[b]	0.125 s[c]	0.879 s
Maximum DL Packet Size[a]	**640 bytes**	**2042 bytes**	**14400 bytes**
Baseload DL	1.20 s	2.40 s	2.40 s
Highload DL	0.039 s[b]	0.125 s[c]	0.879 s

a) UL OH is assumed to be 31 % and DL OH is assumed to be 29 %
b) Indicates packet latency requirements that will very likely be exceeded by node processing and other higher layer latency contributions, i.e., 'Latency OH'
c) Indicates packet latency requirements that may be exceeded by node processing and other higher layer latency contributions

Figure 71 shows the requirements for cell edge goodput to meet a specific packet time for different packet sizes. Obviously a larger packet size requires a higher cell edge goodput which will affect the threshold sensitivity and subsequently, the system gain and propagation range. Channel BW, channel OH, and MCS also come into play, thus for the same cell edge goodput, there will be differences in threshold sensitivity from technology to technology.

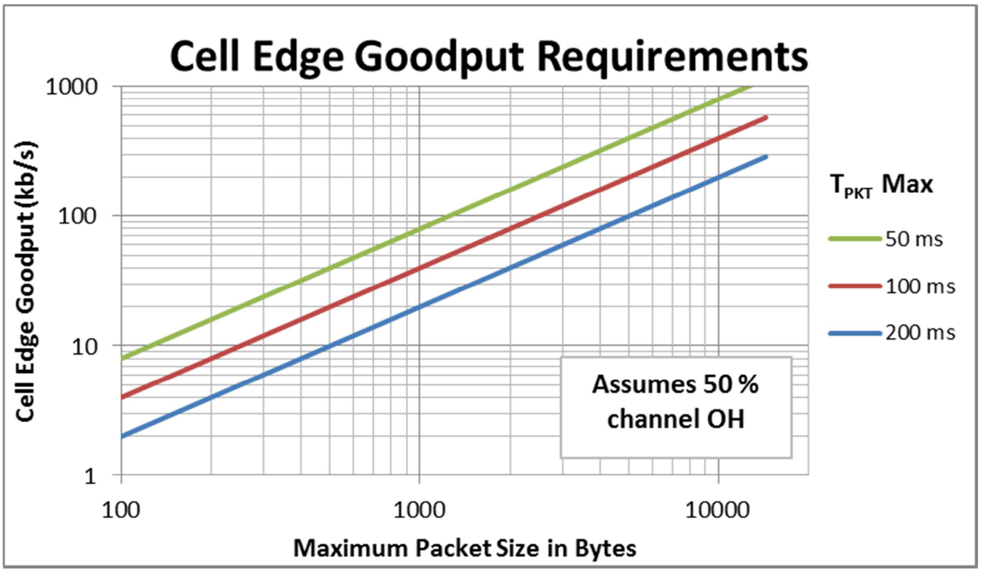


Figure 71 - Cell edge goodput vs. maximum packet size

Even with a modest channel BW and low peak spectral efficiency, most wireless technologies of interest will be able to meet capacity requirements for rural and low density rural AMI / FAN deployments due to the very low density of end-points or actors and the resulting low data rate requirements.

In urban and dense urban areas the range is severely limited due to deployments requiring relatively low BS antenna heights in the presence of multi-story buildings and high penetration losses associated with basement-located end-points. The limited range in these cases will result in fairly modest capacity requirements for each BS.

The range in suburban areas will generally be greater than in urban areas due to reduced building clutter and more favorable outdoor end-point locations. Additionally, as shown in Table 20, even though the average end-point density is lower than in urban areas, the SG data requirement per end-point is higher.

Predicting the network's ability to meet latency requirements is not as straightforward as it is for range and capacity predictions. As one would expect, as the traffic transmitted on any given channel approaches the channel capacity there will be a diminishing number of time slots for packets queued for transmission. This channel congestion leads to longer packet delays and typically creates a situation in which latency becomes the limiting performance factor long before data traffic levels reach the channel capacity limit. In practice, QoS would come into play to help alleviate issues with high priority, latency-sensitive payloads. One of the limitations of the modeling tool, however, is that it does not take QoS into account. With respect to meeting SG latency requirements, this limitation should be kept in mind when evaluating the results that follow in later sections.

6.7.2 Summary of Terrestrial-based Technology Submissions

There are a great number of demographic and wireless technology-related parameters that can be adjusted or selected when using the modeling tool. Although many of the wireless technology parameters are specified by an applicable standard, some parameters will be vendor-specific. At this point it is informative to look at a summary of the terrestrial-based wireless submissions provided by the SDOs in response to the requests made in section 4 with a focus on the performance parameters that directly influence the output of the framework and modeling tool.

Table 24 summarizes the submissions for coverage in licensed bands in the frequency range of primary interest, 700 MHz to 6000 MHz. A number of submissions also offered solutions in licensed bands below 700 MHz, including the 450 MHz to 470 MHz IG Band. There were nine submissions covering frequencies from 700 MHz to 1000 MHz and 1400 MHz to 1900 MHz, respectively, but no wireless submissions to cover licensed frequency bands from: 1000 MHz to 1400 MHz, 2700 MHz to 3300 MHz, or 3700 MHz to 6000 MHz.

Table 24: Summary of submitted wireless technologies coverage in license bands

< 700 MHz	**700 MHz to 1000 MHz**	**1400 MHz to 1900 MHz**	**2000 MHz to 2700 MHz**	**3300 MHz to 3700 MHz**
4	**9**	**9**	**4**	**4**
xHRPD HRPD EV-DO CDMA2000 IEEE 802.15.4g-e	LTE WiMAX HSPA+ WCDMA GSM-EDGE xHRPD HRPD EV-DO CDMA2000 IEEE 802.15.4g-e	LTE WiMAX HSPA+ WCDMA GSM-EDGE xHRPD HRPD EV-DO CDMA2000 IEEE 802.15.4g-e	LTE WiMAX / WiGRID HSPA+ WCDMA	LTE WiMAX / WiGRID HSPA+ WCDMA

In addition to coverage in the licensed bands, there were submissions for the three unlicensed ISM bands in the US. These are summarized in Table 25.

Table 25: Submissions for the ISM bands (unlicensed spectrum)

902 MHz - 928 MHz	**2400 MHz - 2483.5 MHz**	**5725 MHz – 5875 MHz**
IEEE 802.15.4g-e IEEE 802.11ah	IEEE 802.15.4g-e IEEE 802.11n	WiGRID IEEE 802.11ac

With respect to channel bandwidth for the licensed bands, three of the submissions provided a wide range of choices, whereas, five of the technologies offer only one choice (as shown in Table 26).

Table 26: Channel bandwidth options

0.208 MHz	1.25 MHz	5.0 MHz (3.84 MHz)	≤ 3 MHz to ≥ 10 MHz
1	**2**	**2**	**3**
GSM EDGE	xHRPD CDMA2000	HSPA+ WCDMA	LTE WiMAX / WiGRID HRPD EV-DO

As listed in Table 27 for duplex choices, four of the technologies offer only FDD and four have solutions for both FDD and TDD. Adaptive TDD when available can provide improved spectral efficiency for traffic that is highly asymmetric.

Table 27: Duplex options

FDD Only	TDD or FDD	Adaptive TDD
4	**4**	**1**
xHRPD HRPD EV-DO CDMA2000 GSM EDGE	HSPA+ WCDMA LTE WiMAX	WiMAX / WiGRID

In addition to the channel BW, key parameters for estimating channel and BS capacity is the peak UL and peak DL modulation index. Although this information was not requested specifically in section 4, it can be derived from the OTA submissions for peak DL and UL data rates or from the references cited for the technologies in the wireless capabilities matrix. Table 28 lists some wireless technologies and their UL and DL modulations.

Table 28: Peak UL and DL modulation

DL					
64QAM		LTE WiMAX HSPA+ HRPD EV-DO		WiGRID WiMAX (UL Optional)	
32QAM			GSM EDGE		
16QAM	WCDMA CDMA2000	xHRPD			
QPSK	802.15.4g-e				
	QPSK	**16QAM**	**32QAM**	**64QAM**	**UL**

6.7.3 Baseline Parameter Choices for Modeling Tool Assessment

To maximize its utility, the SG framework and wireless modeling tool has a number of parameters that can be inputted or selected by the user. To enable a fair analysis for the purposes of this report a number of parameter choices have been made to ensure relative consistency with technology to technology comparisons. For the five different demographic regions the deployment related parameter choices are shown in Table 29. The notes in the bottom row of the table provide the reasoning for some of the choices that were made.

Table 29: Parameter choices for demographic regions

	Dense Urban	Urban	Suburban	Rural	Low Density Rural
Coverage Area	5 mi^2	20 mi^2	100 mi^2	1,000 mi^2	3,000 mi^2
BS Antenna Height[1]	10 m	10 m	10 m	25 m	30 m
End-Point Antenna Height	n/a	2 m	2 m	2 m	2 m
End-Point Location[2]	Indoor Basement	Indoor Business	Outdoor	Outdoor	Outdoor
Number of Alternate (Parallel) Propagation Paths[3]	2	3	3	1	1
Terrain Type[4]	n/a	n/a	Type A		
BS MIMO[5]	(1×1)	(1×1)	(1×1)	≤ 1800 MHz (1×1) > 1800 MHz (2×2) > 3500 MHz (4×4)	
Number of Serial Links[6]	1	1	1	2	3
Frequency Range[7]	1900 MHz to 6000 MHz	700 MHz to 6000 MHz		700 MHz to 6000 MHz	

Notes

1 *Higher average heights are anticipated in rural and low density rural, taking advantage of existing transmission towers. Heights in other regions consistent with typical utility pole heights.*

2 *Dense Urban meter banks are typically basement-located consistent with underground utilities. Meter banks in urban areas are more likely to be at grade in alleys outdoors or in an indoor enclosure.*

3 *Less likely to have access to multiple BS in rural areas due to wider BS to BS spacing and less requirement for ubiquitous coverage. Limited access in Dense Urban regions due to building blockage with low BS antenna heights*

4 *Terrain type is only applicable for Erceg-SUI path loss model used for suburban and rural environments. Type A defines terrain that is 'hilly with moderate to heavy tree density'.*

5 *Multiple antenna options in the higher frequency bands will be more practical in rural areas where there is less objectionable visual impact and existing towers that can handle the increased wind loading*

6 *Rural regions will more likely require multiple hops or links to complete an end-to-end connection*

7 *Frequency limitations due to lack of valid path loss model for selected antenna heights*

Technology and network related parameter choices for the analysis are as follows:

- Latency Overhead (L_{OH}): Inherent with any deployment will be a baseline latency due to node processing times at Layer 1 / Layer 2 and further processing delays in the higher levels. These are assumed to be: 25 millisecond per node (2 nodes per link) plus 50 millisecond per link. The assumed L_{OH} is then: for 1 hop, 100 ms; for 2 hops, 125 ms; and for 3 hops, 150 ms.
- Channel OH: This is an especially important performance parameter for technology comparative purposes but, unfortunately, a difficult metric to quantify since it is dependent on many different factors, including the average packet size, traffic type, number of end-points, etc. Most wireless technologies use a simulation approach to arrive at an estimate for average layer 2 data throughput (see Group 5 in section 4) but since the simulation parameters and assumptions differ between technologies and, additionally, the deployment assumptions used for the simulations will not typically reflect what is called for in an SG Network, the channel throughput and OH arrived at with this approach can only be considered a guideline. For the purposes of this section the following assumptions are made for channel OH for each of the wireless technologies that are analyzed:

  Nominal layer 2 DL Channel OH = 29 % and layer 2 UL Channel OH = 31 % (total OH including higher layers is 49 % and 51 % for DL and UL, respectively and no adjustment is made for different packet or frame sizes).

  For range-limited deployments any errors in the channel OH estimate will have little or no effect on the resulting number of required BSs or DAPs. Channel OH will play a role only in deployments that are latency- or capacity-limited. In those cases, solutions will be shown with a plus and minus channel OH variation so as to illustrate the sensitivity to that parameter.
- Cell edge goodput: This is calculated to ensure a maximum time of 1 s for the average highload payload size for each demographic region in the DL and for an average packet size of 8116 bytes in the UL or a modulation-coding index of QPSK-1/4, whichever results in a higher cell edge goodput.
- Packet Size: The packet size is assumed to be the maximum submitted by each of the technologies. For the four technologies that submitted different packet sizes for the DL and UL, the DL packet size is assumed for the highload assessment and the UL packet size for the baseload assessment. Since the modeling tool does not account for the packet size impact on channel OH, this impacts only the latency and the ability to meet the latency requirement.
- Link availability: This is assumed to be 96 % at the cell edge, which, in turn, determines the value for fade margin.

- BS configuration and frequency reuse: 3-sector BSs are assumed with one channel per sector and a reuse factor of 1 with dedicated as opposed to shared spectrum (no additional margin for inter-operator interference)
- Smart Meter Antenna Gain and Tx Power: 0 dBi and 0.5 W (+27 dBm), respectively
- BS Noise Figure: <3000 MHz = 4 dB, ≥3000 MHz = 5 dB

BS Antenna Gain: There will generally be size constraints, especially with low BS heights. For the same size antenna the higher frequency bands have an advantage. The BS / DAP antenna gains assumed for the modeling tool assessment are shown in Figure 72.

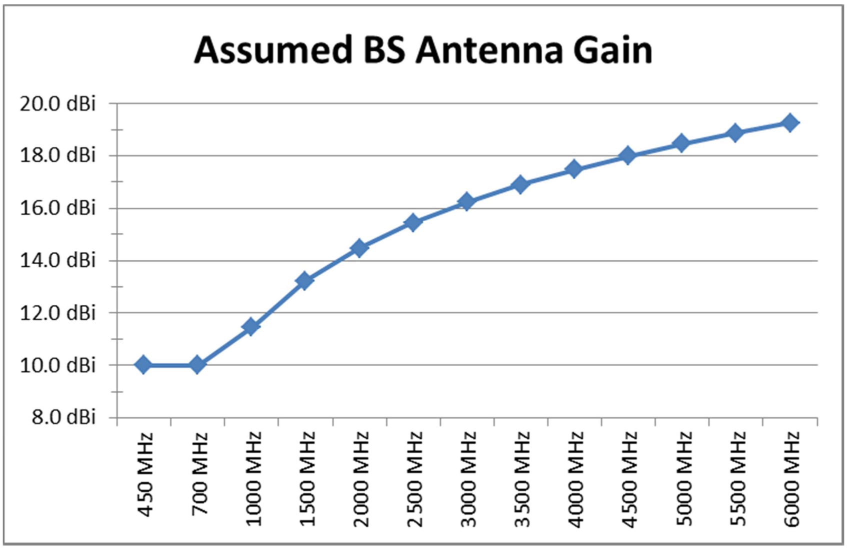


Figure 72 - Base station (DAP) antenna gain

- BS Tx Power and EIRP: For the unlicensed ISM bands the BS EIRP is set to +36 dBm (4 watts) to comply with FCC regulations. In the licensed bands the BS power is assumed to be 10 watts, resulting in an EIRP ranging from +50 dBm at 700 MHz to +57 dBm at 3700 MHz, well below the regulatory maximum for these bands.

6.7.4 Wireless Technology Assessment

As discussed in section 6.5, the modeling tool makes use of five different path loss models to address different frequencies, deployment venues, and antenna heights. In some cases, there may be more than one valid model applicable for the parameter choices summarized above and for other cases there may not be a valid model for the selected parameters or deployment venue. In reviewing the results of the assessment, it is important to understand the basis for the path loss models assumed for the different scenarios that are being analyzed.

Dense Urban: The ITU M.2135-1 model is the only valid model for a 10 m BS antenna height in a deployment region surrounded by higher multi-story buildings. It is considered valid over the 2000 MHz to 6000 MHz frequency range. For the purposes of this assessment it has been extended to 1900 MHz, since that represents the upper end of many of the technologies submitted. Due to the lack of a valid model, no dense urban data is shown for 700 MHz.
Urban: We do not have a generally accepted path loss model for BS antenna heights lower than surrounding roof tops (i.e., 10 m) for small city urban regions. For the purposes of this assessment, the Modified Erceg-SUI for terrain Type A is assumed. This is considered a reasonable assumption since, to a first order, the excess path loss due to small city urban building clutter, can be considered similar to the excess path loss resulting from the presence of hills and trees.
Suburban: The Erceg-SUI model takes into account varied terrain types and low BS antenna heights and as was shown in section 5.2.1.3.9, the modified version of the model provides a good correlation with generally accepted foliage and diffraction models with respect to frequency dependence. Since the ITU M.2135-1 path loss model includes parameters for building heights, inserting building heights below 10 m would validate this model over the 2000 MHz to 6000 MHz frequency range. For the assessment results the Modified Erceg-SUI Model was felt to be the best choice.
Rural and Low Density Rural: For the higher BS antenna heights assumed for the rural venues, the ITU M.2135-1 or the Modifies Erceg-SUI could be considered valid over the 700 MHz to 6000 MHz frequency range. For the same reasons cited above, the Modified Erceg-SUI Model was used for the rural area assessments.

The differences in the frequency dependency for predicted excess path loss can be seen by comparing the ITU model with the Modified Erceg-SUI model for Type A terrain. Compared to the Modified Erceg-SUI model, the ITU model predicts a higher excess pass loss at 700 MHz, comparable excess path loss at 2000 MHz and lower excess path loss at 6000 MHz.

6.7.4.1 Meeting Highload Demand

Tables are provided for three frequency bands: 700 MHz (Table 30), 1900 MHz (Table 31), and 3550 MHz to 3700 MHz (Table 32). These tables make use of the following notations to display the results.

- Number of BS / DAPs: BS = Total number of BS followed by letter; R = Range-limited, C = Capacity-limited, and L = Latency limited. When used in this context latency limited means the BS / DAP is limited in the number of end-points that can be supported to meet either the minimum latency required or a latency specified in the model as ‘acceptable’.
- End-points: EP = Total number of End-points per BS. Divide by 3 to get the number of end-points per channel (or sector).
- Latency requirement, in seconds (L): If the minimum latency requirement, L, is met; L= -/L, if not met; L = ‘latency value that can be met in seconds’/L. In some cases L_{OH} the will be greater than the required latency, L, these cases will have the notation, ‘$L_{OH} > L$’.

The number of supportable end-points is determined by the binomial distribution approach discussed in section 5.2.7 and, as previously described, this approach results in a more lower estimate for the number of supportable end-points as compared to the approach using the M/M/D queuing model.

Percentage of BS capacity for SG: For range-limited deployments there will be excess BS capacity, SGL (Smart Grid Load) = % will indicate what percentage of the total 3-sector BS capacity is for the SG AMI / NAN.

Table 30: Highload 700 MHz

700 MHz Highload **Coverage Area**	**Dense Urban** **5 mi^2**	**Urban** **20 mi^2**	**Suburban** **Type A** **100 mi^2**	**Rural** **Type A** **1,000 mi^2**	**Low Density Rural** **Type A** **3,000 mi^2**
GSM EDGE ● FDD ● BW=208 kHz ● Pkt=1560	n/a	BS = 11 L EP = 6267 L = -/0.12 BS = 10 R	BS = 391 L EP = 284 L = -/0.12 BS = 59 C BS = 12 R	BS = 133 R EP = 488 L=0.15/0.06 L_{OH} > L SGL=0.72 %	BS = 348 R EP = 32 L = 0.2/0.04 L_{OH} > L SGL=0.33 %
802.15.4g-e ● TDD ● BW=1.2 MHz ● Pkt=2047	n/a	BS = 8 R EP = 8617 L = -/0.16 SGL=8.9 %	BS = 281 L EP = 396 L = -/0.16 BS = 63 C BS = 11 R	BS = 110 R EP = 590 L=0.15/0.08 L_{OH} > L SGL=0.49 %	BS = 286 R EP = 39 L = 0.2/0.05 L_{OH} > L SGL=0.23 %
WCDMA ● FDD ● BW=3.84 MHz ● Pkt=12750	n/a	BS = 8 R EP = 8617 L = -/0.97 SGL=0.62 %	BS = 11 R EP = 10095 L = -/0.97 SGL=47.9 %	BS = 110 R EP = 590 L = -/0.47 SGL<0.1 %	BS = 286 R EP = 39 L = -/0.31 SGL<0.1 %
HSPA+ ● FDD ● BW=3.84 MHz ● Pkt=5274	n/a	BS = 8 R EP = 8617 L = -/0.40 SGL=.71 %	BS = 11 R EP = 10095 L = -/0.40 SGL=65.2 %	BS = 110 R EP = 590 L = -/0.20 SGL<0.1 %	BS = 286 R EP = 39 L = 0.2/0.13 L_{OH} > L SGL<0.1 %
CDMA2000 ● FDD ● BW=1.25 MHz ● Pkt=480	n/a	BS = 8 R EP = 8617 L=0.15/0.04 L_{OH} > L SGL=1.90 %	BS = 24 L EP = 4627 L=0.15/0.04 L_{OH} > L BS = 16 C BS = 11 R	BS = 110 R EP = 590 L=0.15/0.02 L_{OH} > L SGL=0.17 %	BS = 286 R EP = 39 L=0.20/0.01 L_{OH} > L SGL<0.1 %
HRPD EV-DO ● FDD ● BW=1.25 MHz ● Pkt=1024	n/a	BS = 8 R EP = 8617 L=0.15/0.08 L_{OH} > L SGL=1.34 %	BS = 17 L EP = 6532 L=0.15/0.08 L_{OH} > L BS = 11 RC	BS = 110 R EP = 590 L=0.15/0.04 L_{OH} > L SGL<0.1 %	BS = 286 R EP = 39 L=0.2/0.03 L_{OH} > L SGL<0.1 %

700 MHz Highload **Coverage Area**	**Dense Urban** **5 mi^2**	**Urban** **20 mi^2**	**Suburban** **Type A** **100 mi^2**	**Rural** **Type A** **1,000 mi^2**	**Low Density Rural** **Type A** **3,000 mi^2**
xHRPD ● FDD ● BW=1.25 MHz ● Pkt=640	n/a	BS = 8 R EP = 8617 L=0.15/0.05 L_{OH} > L SGL=1.90 %	BS = 25 L EP = 4442 L=0.15/0.05 L_{OH} > L BS = 16 C BS = 11 R	BS = 110 R EP = 590 L=0.15/0.02 L_{OH} > L SGL=0.17 %	BS = 286 R EP = 39 L=0.20/0.01 L_{OH} > L SGL<0.1 %
LTE ● FDD ● BW=5 MHz ● Pkt=8188	n/a	BS = 8 R EP = 8617 L = -/0.60 SGL=0.37 %	BS = 11 R EP = 10095 L = -/0.6 SGL=30.0 %	BS = 110 R EP = 590 L = -/0.3 SGL<0.1 %	BS = 286 R EP = 39 L = -/0.2 SGL<0.1 %
WiMAX ● FDD ● BW=5 MHz ● Pkt=2042	n/a	BS = 8 R EP = 8617 L = -/0.15 SGL=0.37 %	BS = 11 R EP = 10095 L = -/0.15 SGL=30.0 %	BS = 110 R EP = 590 L=0.15/0.08 L_{OH} > L SGL<0.1 %	BS = 286 R EP = 39 L = 0.2/0.05 L_{OH} > L SGL<0.1 %
700 MHz Summary ● BS for Range ● BS for Capacity ● BS for Latency	n/a	8 to 10 8 to 11	11 to 12 11 to 63 11 to 391	110 to 133	286 to 348

Table 31: Highload 1900 MHz

1900 MHz Highload **Coverage Area**	**Dense Urban** **5 mi^2**	**Urban** **20 mi^2**	**Suburban** **Type A** **100 mi^2**	**Rural** **Type A** **1,000 mi^2**	**Low Density Rural Type A** **3,000 mi^2**
GSM EDGE ● FDD ● BW=208 kHz ● Pkt =1560	BS = 64 R EP = 1111 L =0.15/.12 T_{PKT} > L SGL=1.94 %	BS = 41 R EP = 1682 L = -/0.12 SGL=1.88 %	BS= 1158 L EP = 96 L = -/0.12 BS = 69 C BS = 28 R	BS = 232 R EP = 280 L = 0.15/.06 L_{OH} > L SGL=0.17%	BS = 597 R EP = 19 L = 0.2/.04 L_{OH} > L SGL<0.1 %
WCDMA ● FDD ● BW=3.84 MHz ● Pkt=12750	BS = 49 R EP = 1451 L = -/0.97 SGL=0.24 %	BS = 35 R EP = 1970 L = -/0.97 SGL=0.15 %	BS = 26 R EP = 4271 L = -/0.97 SGL=20.8 %	BS = 192 R EP = 338 L = -/0.47 SGL<0.1 %	BS = 491 R EP = 23 L = -/0.31 SGL<0.1 %
HSPA+ ● FDD ● BW=3.84 MHz ● Pkt=5274	BS = 49 R EP = 1451 L = -/0.40 SGL=0.13 %	BS = 35 R EP = 1970 L = -/0.40 SGL<0.1 %	BS = 26 R EP = 4271 L = -/0.40 SGL=14.9 %	BS = 192 R EP = 338 L = -/0.20 SGL<0.1 %	BS =491 R EP = 23 L=0.2/0.13 L_{OH} > L SGL<0.1 %

1900 MHz Highload Coverage Area	Dense Urban 5 mi^2	Urban 20 mi^2	Suburban Type A 100 mi^2	Rural Type A 1,000 mi^2	Low Density Rural Type A 3,000 mi^2
CDMA2000 ● FDD ● BW=1.25 MHz ● Pkt=480	BS = 49 R EP = 1451 L=0.15/0.04 L_{OH} > L SGL=0.73 %	BS = 35 R EP = 1970 L=0.15/0.04 L_{OH} > L SGL=0.51 %	BS = 26 R EP = 4271 L=0.15/0.04 L_{OH} > L SGL=63.9 %	BS = 192 R EP = 338 L=0.15/0.02 L_{OH} > L SGL<0.1 %	BS = 491 R EP = 23 L=0.2/0.01 L_{OH} > L SGL<0.1 %
HRPD EV-DO ● FDD ● BW=1.25 MHz ● Pkt=1024	BS = 49 R EP = 1451 L = 0.15/.08 L_{OH} > L SGL=0.65 %	BS = 35 R EP = 1970 L = 0.15/.08 L_{OH} > L SGL=0.32 %	BS = 26 R EP = 2023 L =0.15/.08 L_{OH} > L SGL=45.8 %	BS = 192 R EP = 338 L =0.15/.04 L_{OH} > L SGL<0.1 %	BS = 491 R EP = 23 L = 0.2/.03 L_{OH} > L SGL<0.1 %
xHRPD ● FDD ● BW=1.25 MHz ● Pkt=640	BS = 49 R EP = 1451 L=0.15/0.05 L_{OH} > L SGL=0.73 %	BS = 35 R EP = 1970 L=0.15/0.05 L_{OH} > L SGL=0.45 %	BS = 26 R EP = 4271 L=0.15/0.05 L_{OH} > L SGL=63.9 %	BS = 192 R EP = 338 L=0.15/0.02 L_{OH} > L SGL<0.1 %	BS = 491 R EP = 23 L=0.2/0.01 L_{OH} > L SGL<0.1 %
LTE ● FDD ● BW=3 MHz ● Pkt=8188	BS = 49 R EP = 1451 L = -/0.60 SGL=0.28 %	BS = 35 R EP = 1970 L = -/0.60 SGL=0.17 %	BS = 26 R EP = 4271 L = -/0.6 SGL=21.4 %	BS = 192 R EP = 338 L = -/0.3 SGL<0.1 %	BS = 491 R EP = 23 L = -/0.2 SGL<0.1 %
WiGRID ● A-TDD ● BW=5 MHz ● Pkt=14400	BS = 49 R EP = 1451 L = -/1.1 SGL=0.25 %	BS = 35 R EP =1970 L = -/1.1 SGL=0.13 %	BS = 26 R EP = 4271 L = -/1.1 SGL=18.3 %	BS = 192 R EP = 338 L = -/0.55 SGL<0.1 %	BS = 491 R EP = 23 L = -/0.35 SGL<0.1 %
1900 MHz Summary ● BS for Range ● BS for Capacity ● BS for Latency	49 to 64	35 to 41	26 to 28 26 to 69 26 to 1158	192 to 232	491 to 597

Table 32: Highload 3550 MHz to 3700 MHz

3550 MHz to 3700 MHz Highload Coverage Area	Dense Urban 5 mi^2	Urban 20 mi^2	Suburban Type A 100 mi^2	Rural Type A 1,000 mi^2	Low Density Rural Type A 3,000 mi^2
WCDMA (3550 MHz) ● FDD - 3550 ● BW=3.84 MHz ● Pkt=12750	BS = 200 R EP = 356 L = -/0.97 SGL<0.1 %	BS = 116 R EP = 595 L = -/0.97 SGL<0.1 %	BS = 50 R EP = 2221 L = -/0.94 SGL=10.4 %	BS = 267 R EP = 243 L = -/0.47 SGL<0.1 %	BS =676 R EP = 17 L = -/0.31 SGL<0.1 %

3550 MHz to 3700 MHz Highload Coverage Area	Dense Urban 5 mi²	Urban 20 mi²	Suburban Type A 100 mi²	Rural Type A 1,000 mi²	Low Density Rural Type A 3,000 mi²
HSPA+ (3550 MHz) ● FDD – 3550 ● BW=3.84 MHz ● Pkt=2874	BS = 200 R EP = 356 L = -/0.40 SGL<0.1 %	BS = 116 R EP = 595 L = -/0.40 SGL<0.1 %	BS = 50 R EP = 2221 L = -/0.40 SGL=12.1 %	BS = 267 R EP = 243 L = -/0.22 SGL<0.1 %	BS =676 R EP = 17 L=0.20/0.13 L_{OH} > L SGL<0.1 %
LTE (3700 MHz) ● TDD – 3700 ● BW=5 MHz ● Pkt=8188	BS = 217 R EP = 328 L = -/0.60 SGL<0.1 %	BS = 125 R EP = 552 L = -/0.60 SGL<0.1 %	BS = 52 R EP = 2136 L = -/0.60 SGL=12.7 %	BS = 276 R EP = 235 L = -/0.30 SGL<0.1 %	BS= 700 R EP = 16 L = -/0.20 SGL<0.1 %
WiGRID (3700 MHz) ● A-TDD – 3700 ● BW=5 MHz ● Pkt=14400	BS = 217 R EP = 328 L = -/1.10 SGL<0.1 %	BS = 125 R EP = 552 L = -/1.10 SGL<0.1 %	BS = 52 R EP = 2136 L = -/1.10 SGL=9.1 %	BS = 276 R EP = 235 L = -/0.55 SGL<0.1 %	BS = 700 R EP = 16 L = -/0.35 SGL<0.1 %
3700 MHz Summary ● BS for Range ● BS for Capacity ● BS for Latency	200 to 217	125 to 143	50 to 52	267 to 276	676 to 700

The difference in results for the frequency band assessment in the table above is directly attributable to the difference in path loss between 3550 MHz and 3700 MHz.

6.7.4.2 Meeting Baseload Demand

Of the nine wireless technologies analyzed with the SG framework and wireless modeling tool in the 700 MHz band, the five with channel BWs of 1.25 MHz and below were capacity- or latency-limited for a suburban deployment. The same five technologies however, did have sufficient capacity for the other four demographic regions. GSM EDGE with a 0.208 MHz channel BW was also capacity-limited in the 1900 MHz band for suburban deployments.

Table 33 provides a summary of those five technologies at baseload demand. For this case they all meet capacity requirements for demographic regions and four out of the five meet the latency requirements. As expected, xHRPD, with a 96 byte maximum packet size limitation, results in a minimum latency requirement that is less than L_{OH} in all of the demographic regions.

Table 33: Summary of five technologies in 700 MHz at baseload

700 MHz Baseload Coverage Area	Dense Urban 5 mi^2	Urban 20 mi^2	Suburban 100 mi^2	Rural Type A 1,000 mi^2	Low Density Rural Type A 3,000 mi^2
GSM EDGE • FDD • BW=208 kHz • Pkt=1560	n/a	BS = 10 R EP = 6894 L = -/1.25 SGL=1.20 %	BS = 12 R EP = 9254 L = -/1.25 SGL=58.2 %	BS = 133 R EP = 488 L=-/0.63 SGL=0.11 %	BS = 348 R EP = 39 L = -/0.4 SGL<0.1 %
802.15.4g-e • TDD • BW=1.2 MHz • Pkt=2047	n/a	BS = 8 R EP = 8617 L = -/1.67 SGL=0.88 %	BS = 11 R EP = 10095 L = -/1.67 SGL=37.6 %	BS = 110 R EP = 590 L= -/0.83 SGL<0.1 %	BS = 286 R EP = 39 L = -/0.56 SGL<0.1 %
CDMA2000 • FDD • BW=1.25 MHz • Pkt=1536	n/a	BS = 8 R EP = 8617 L = -/1.25 SGL=0.29 %	BS = 11 R EP = 10095 L = -/1.25 SGL=12.3 %	BS = 110 R EP = 590 L= -/0.63 SGL<0.1 %	BS = 286 R EP = 39 L = -/0.40 SGL<0.1 %
HRPD EV-DO • FDD • BW=1.25 MHz • Pkt=4608	n/a	BS = 8 R EP = 8617 L = -/2.50 SGL=0.23 %	BS = 11 R EP = 10095 L = -/2.50 SGL=9.8 %	BS = 110 R EP = 590 L = -/1.25 SGL<0.1 %	BS = 286 R EP = 39 L = -/0.83 SGL<0.1 %
xHRPD • FDD • BW=1.25 MHz • Pkt=96	n/a	BS = 8 R EP = 8617 L = 0.12/0.1 $L_{OH} > L$ SGL=0.29 %	BS = 11 R EP = 10095 L=0.12/0.10 $L_{OH} > L$ SGL=12.3 %	BS = 110 R EP = 590 L=0.15/0.05 $L_{OH} > L$ SGL<0.1 %	BS = 286 R EP = 39 L =0.2/0.03 $L_{OH} > L$ SGL<0.1 %

6.7.4.3 Wireless Assessments for the ISM bands in a PMP Topology

The IEEE 802.11, IEEE 802.15.4g-e, and WiGRID solutions for the ISM bands all support a mesh topology, a topology that is beyond the capability of the SG framework and wireless modeling tool. Nevertheless, it can be informative to assess these technologies assuming a PMP topology as long as the results are not used to draw direct comparisons to the wireless solutions in the licensed bands summarized above. Although the EIRP regulatory limit in the ISM bands significantly reduces the range and coverage capability for a PMP topology, the support for mesh will increase the effective coverage area well beyond what is predicted for PMP. What the PMP analysis does provide for ISM band solutions is, at least, a qualitative assessment for relative variations in coverage due to frequency and demographic differences due to end-point locations and varied BS antenna heights. Additionally, the analysis shows that unless mesh can be supported, the ISM solutions would not be a practical solution in a dense urban deployment in the higher frequency bands unless an intermediate AP were used to aggregate the basement-located end-points as described in section 6.4.

Table 34 shows the summary of these three technologies at highload demand assuming PMP.

Table 34: Highload ISM bands

ISM Bands BS EIRP = 36 dBm Highload Coverage Area	Dense Urban 5 mi^2	Urban 20 mi^2	Suburban Type A 100 mi^2	Rural Type A 1000 mi^2	Low Density Rural Type A 3000 mi^2
802.15.4g-e 915 MHz • TDD • BW=1.2 MHz • Pkt=2047	No valid path loss model	BS = 14 R EP = 4924 L = -/0.16 SGL=6.03 %	BS = 281 L EP = 396 L = -/0.16 BS = 64 C BS = 16 R	BS = 168 R EP = 386 L=0.15/0.08 $L_{OH} > L$ SGL=0.5 %	BS = 438 R EP = 25 L=0.2/0.05 $L_{OH} > L$ SGL=0.15 %
802.11ah 915 MHz • TDD • BW=5 MHz • Pkt=1500	No valid path loss model	BS = 14 R EP = 4924 L = -/0.12 SGL=3.62 %	BS = 309 L EP = 360 L = -/0.12 BS = 39 C BS = 16 R	BS = 168 R EP = 386 L=0.15/0.06 $L_{OH} > L$ SGL<0.1 %	BS = 438 R EP = 25 L=0.2/0.04 $L_{OH} > L$ SGL<0.1 %
802.15.4g-e 2450 MHz • TDD • BW=1.2 MHz • Pkt=2047	BS = 641 R EP = 111 L = -/0/16 SGL=0.25 %	BS = 97 R EP = 111 L = -/0/16 SGL=0.87 %	BS = 464 L EP = 240 L = -/0.16 BS = 74 C BS = 59 R	BS =470 R EP = 138 L=0.15/0.08 $L_{OH} > L$ SGL<0.1 %	BS=1223 R EP = 9 L=0.2/0.05 $L_{OH} > L$ SGL<0.1 %
802.11n 2450 MHz • TDD • BW=5 MHz • Pkt=1500	BS = 641 R EP = 111 L = -/0/12 SGL<0.1 %	BS = 97 R EP = 111 L = -/0/12 SGL<0.1 %	BS = 59 R EP = 883 L = -/0.12 SGL=4.31 %	BS =470 R EP = 138 L=0.15/0.06 $L_{OH} > L$ SGL<0.1 %	BS=1223 R EP = 9 L=0.2/0.04 $L_{OH} > L$ SGL<0.1 %
801.11ac 5800 MHz • TDD • BW=5 MHz • Pkt=1500	Range < 20 m	BS = 980 R EP = 71 L = -/0.12 SGL<0.1 %	BS = 263 R EP = 423 L = -/0.12 SGL = 1.0 %	BS =1646 R EP = 40 L=0.15/0.06 $L_{OH} > L$ SGL<0.1 %	BS=4306 R EP = 3 L= 0.2/0.04 $L_{OH} > L$ SGL<0.1 %
WiGRID 5800 MHz • A-TDD • BW=5 MHz • Pkt=14400	Range < 20 m	BS = 980 R EP = 71 L = -/1.10 SGL<0.1 %	BS = 263 R EP = 423 L = -/1.10 SGL=1.52 %	BS =1646 R EP = 40 L = -/0.55 SGL<0.1 %	BS=4306 R EP = 40 L = -/0.35 SGL<0.1 %

Support for mesh can offer considerable coverage and availability benefits but one must also take care to assess the potential latency issues that may arise when a large number of hops are required to maintain an end-to-end communications path.

6.7.4.4 Meeting Latency Requirements

What stands out in the PMP technology assessments, for both highload and baseload demand, is the number of scenarios for which the latency requirement is less than the node processing time ($L_{OH} > L$) used in the binomial distribution latency model. It is informative to look at a few of the key SG-Network Task Force Smart Grid application payloads that are driving these low latency requirements and how the per link latency requirement is impacted by actor-to-actor latency requirements and the maximum packet size supported by the technology that is being assessed.

The maximum packet sizes supported by the terrestrial-based wireless technologies submitted, range from 96 bytes to 14,400 bytes and are summarized in Table 35.

Table 35: Number of technologies supporting packet size ranges

14400 bytes to 12750 bytes	**8188 bytes to 4608 bytes**	**2874 bytes to 1024 bytes**	**640 bytes to 96 bytes**
2	**3**	**7**	**2**
WiGRID WCDMA	LTE HSPA+ (DL) HRPD EV-DO (UL)	HSPA+ (UL) WiMAX CDMA2000 (UL) GSM-EDGE IEEE 802.11 IEEE 802.15.4g-e HRPD EV-DO (DL)	xHRPD (UL & DL) CDMA2000 (DL)

In the AMI, FAN, or NAN network there will be actor-to-actor data-flows that are peer-to-peer data flows or use a DAP as an intermediate actor bridge between the actors. For the peer-to-peer actor data flows, they were specifically changed to an actor to DAP and DAP to the other actor data flow to accommodate the Wireless Model, thus requiring that the total business application peer-to-peer actor-to-actor latency requirement be divided by two to get the per actor to DAP or DAP to actor link latency. These data paths generally involve the field tool.

Another general observation is that the majority of the latency-sensitive application payloads are associated with firmware and program use cases for which larger sized payloads are necessary. These use cases are the key drivers for the highload demand and even though the payload latency requirement for these cases is quite modest, the larger payloads must be divided into packet sizes to comply with the maximum packet size supported by the wireless technology of interest. The per-link latency is then divided by the total number of packets required to carry the entire payload plus the overhead bits. For a business payload latency requirement of several minutes the resulting packet latency requirement will be significantly less than 1 s and in some cases, in the millisecond range, with smaller sized packets.

Table 36 provides a summary of the per packet latency requirement per link in seconds for some representative data-flows taken from the SG-Network Task Force Requirements for business application payloads that result in a per packet latency requirement less than 1 second. The field tool case assume an Actor-to-DAP-to-Actor data –flow, whereas the DAP and FAN gateway (GW) cases assume an Actor-to-DAP or DAP-to-Actor data flow. The packet overhead for all scenarios is assumed to be 50 %.

Table 36: Summary of per packet latency requirement per link

Payload Description	Latency	Payload Size in bytes	Baseload or Highload	To-From Actor	Maximum Packet Size: >12750 bytes	8188 bytes to 4608 bytes	2874bytes to 1024 bytes	640 bytes to 480 bytes	96 bytes
					Latency per Packet per Link in seconds				
Fdr-dev_cntl_ firmware_update_ cmd	<10 min	400k-2000k	High	Field Tool	>0.96	0.61 - 0.35	0.22-0.08	0.05-0.04	0.007
DAP_firmware_ update_cmd	<5 min	400k-750k	High	Field Tool		0.82-0.45	0.29-0.10	0.06-0.05	0.010
Metrology_ program_update_ cmd	<1 min	25k-50k	High	Field Tool			0.86-0.31	0.19-0.14	0.029
FeederFault_Detect or_sensor_data_ resp-data	< 3 s	1000	Both	DAP				0.75-0.60	0.136
FeederCapBank_ne w_confg_cmd	< 3 s	500	Both	DAP					0.25
FeederCapBank_op en_cmd	< 3 s	150	Both	DAP					0.75
Dstr_cust_storage_ status_resp-data	< 2 s	50	Both	FAN GW					0.50

As Table 36 shows the large payloads associated with firmware updates can result in packet latency requirements less than 100 ms for smaller sized packets. This is in the range of expected node processing times and will result in a situation where the latency requirement, L, will be less than the latency overhead, L_{OH}.

It is also important to note that the SG-Network Task Force Requirements for application payload sizes do not take into account any type of data encoding schemes that might reduce the size of the actual payloads that are transmitted across various networks segments. Another factor not accounted for is the additional overhead that would occur with smaller packet sizes. Since each packet would typically require a fixed number of overhead bits, the percent OH would increase with smaller packet sizes. Since these two factors will offset each other, the net impact is not clear without having additional information.

6.7.4.5 Sensitivity Analysis

To facilitate the assessment of the nine terrestrial-based wireless technologies, assumptions were made for some key wireless parameters. In the next few paragraphs we will look at the relative sensitivity of some of these parameters and other factors that influence the number of BSs (or DAPs) necessary to meet Smart Grid requirements for an AMI / NAN deployment.

Specifically we look at the relative impact of:

- Channel OH
- Packet Size versus Latency Requirement
- Channel Bandwidth
- Terrain Type
- Link Budget and System Gain

Channel OH: As mentioned earlier, getting an accurate estimate for total channel OH can be a daunting task. That said, for the purposes of the assessment, we assumed 49 % for the DL channel OH and 51 % for the UL channel OH. For suburban deployments in the 700 MHz band five of the technologies with channel BWs of 1.25 MHz or less did not meet the highload minimum latency requirement. With a relaxed latency requirement four of these technologies were still capacity-limited. The technologies with larger channel BWs, on the other hand, easily met capacity requirements in all five demographic regions. With respect to latency, however, some were impacted by the maximum supportable packet size in the rural and low density rural deployments where we assumed 2 and 3 links, respectively. Based on the model it would take a maximum packet size greater than approximately 6000 bytes to meet the latency requirements in these areas.

The sensitivity to either a lower or higher channel OH is illustrated in Figure 73. The graph provides a view of the DAP and End-point count for a range of UL channel OH values for CDMA2000 in the 700 MHz band for a suburban Type A deployment. A fixed latency requirement of 200 ms (0.2 seconds) is assumed to determine the number of supportable end-points per channel.

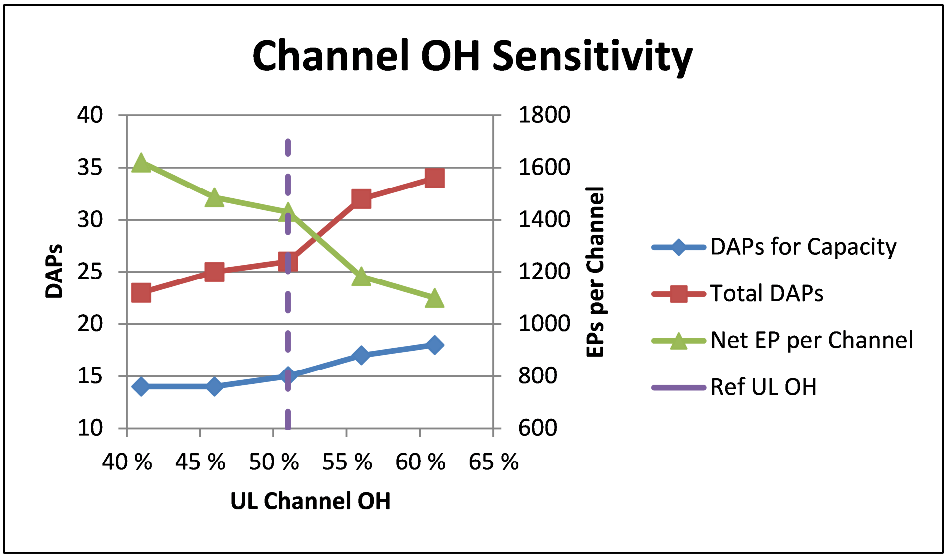


Figure 73 - CDMA2000, 700 MHz, suburban highload, 0.2 second latency

Packet Size and Latency Requirements: Both packet size and channel goodput play a role in determining latency performance. It is important to mention again that QoS is not taken into account in this technology assessment. Whereas QoS enables the assignment of higher priorities to more latency-sensitive payloads and packets, the model assumes all packets have the same priority. Despite this limitation, the model is useful in providing some insights as to how the different wireless parameters relate to the technology's ability to meet latency requirements.

As the assessment results indicate, with a constrained channel BW meeting the minimum latency requirement may require a substantial increase in the number of BSs. With a 0.208 MHz channel BW limitation, GSM EDGE is limited to 284 end-points per BS (95 per channel) to meet a 0.12 s minimum latency requirement. As illustrated in Figure 74, a modest relaxation in the latency requirement would greatly enhance the supportable end-points per channel and reduce the number of BSs required. With a latency of 2 or more seconds, the number of BS approaches 59, the number required to meet capacity requirements.

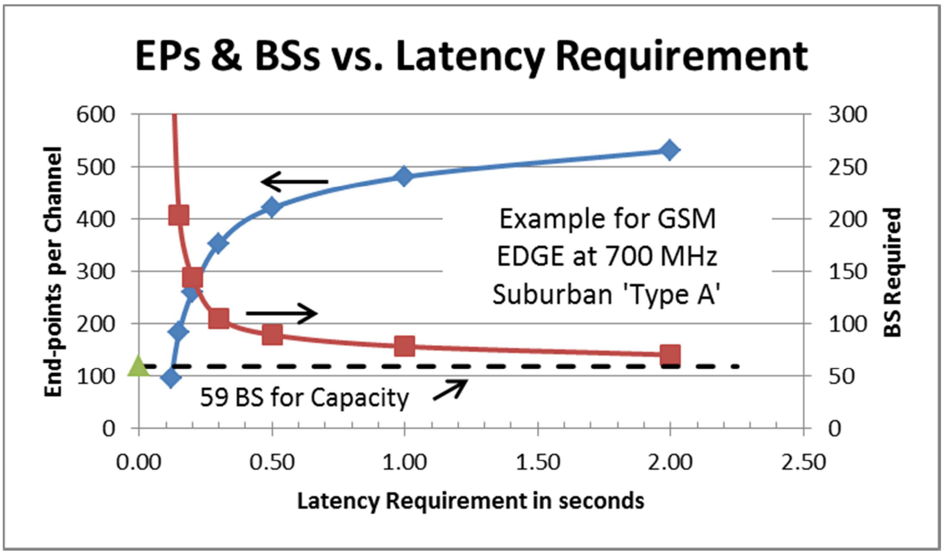


Figure 74 - GSM EDGE at 700 MHz, suburban Type A, highload demand

The minimum latency requirement is inversely proportional to the maximum packet size, so it is also of interest to look at how the maximum packet size impacts BS requirements. Using GSM EDGE as an example again, Figure 75 shows the end-points per channel and BS requirements for packet sizes larger than the 1560 bytes listed in the wireless capabilities matrix for GSM EDGE. It is not clear how much flexibility there is with this parameter but as the chart indicates, an increased packet size results in a dramatic decrease in the number of required BSs.

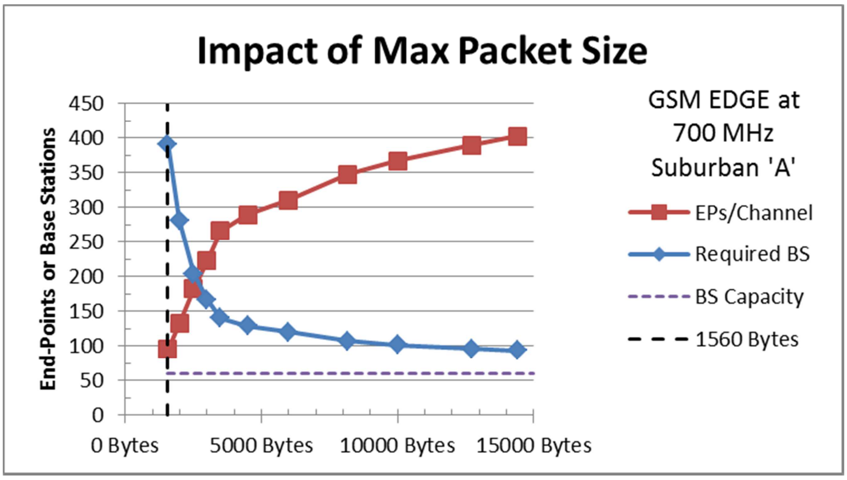


Figure 75 - Increasing the maximum packet size for GSM EDGE

Another example that is interesting to look at in more detail is xHRPD. This technology has the lowest maximum packet size, 96 bytes for the UL, of the nine technologies reviewed. At 96 bytes, the minimum latency requirement is less than the latency overhead for all demographic regions at all frequencies supported by xHRPD. For a suburban deployment and highload demand, the 96 byte packet size reduced the minimum latency requirement to 7 ms. The latency that can be achieved with 19 BS is

0.15 s. As described earlier, one of the benefits of a smaller packet size is an increased probability the packet will fall within a specified latency period, in this case, 0.15 s. As shown in Figure 76, with an increase in packet size the BS count goes up due to the drop in probability until the packet size gets to about 2000 bytes. Although more BSs are required, the minimum latency requirement can be met at that point. Beyond 2000 bytes the minimum latency requirement increases more quickly than the packet size resulting in an increasing probability and a decreasing BS count. At about 13000 bytes, the BS count is at the same level it was at 96 bytes, but instead of missing the minimum latency requirement by more than 20 times, the latency requirement can be met with the larger packet size.

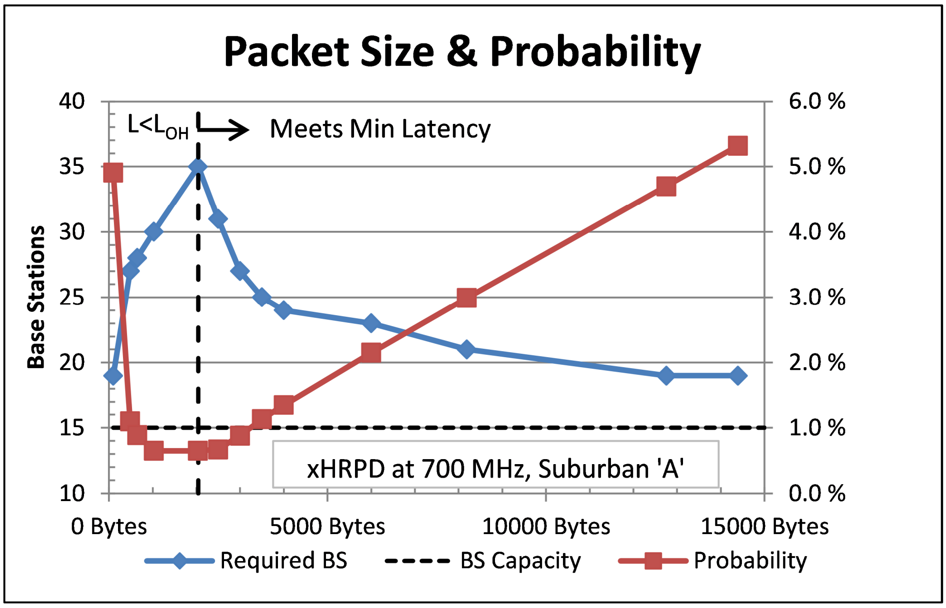


Figure 76 - Relationship between packet size and BS requirements

Channel BW: Figure 77 illustrates how channel BW affects the BS requirements necessary to meet capacity requirements for a suburban deployment. At approximately 135 kHz for baseload and 2.5 MHz for highload, the deployment transitions from capacity-limited to range-limited.

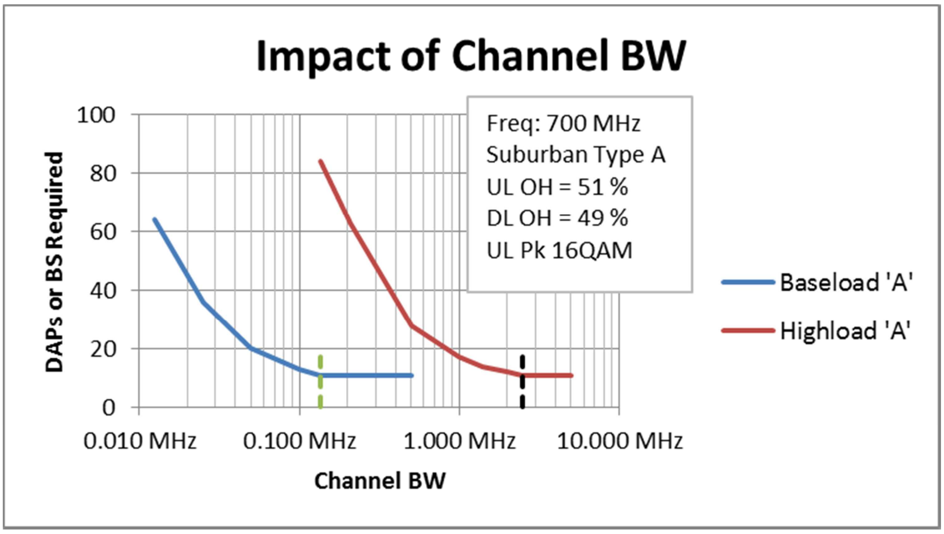


Figure 77 - Channel BW for meeting capacity requirements

To account for latency, as well as capacity, it would be necessary to plan for excess channel capacity by an amount inversely related to the maximum packet size. Typical numbers for highload are as presented in Table 37.

Table 37: Packet size, channel BW, meets

Approx. Packet Size	Channel BW	Meets
-	≥ 2.5 MHz	Capacity only
< 1500 bytes	5.0 MHz	Capacity, Latency = 0.15 s (L_{OH} > L)
1500 bytes to 2000 bytes	~ 4.5 MHz (+80 %)	Capacity and Latency
2000 bytes to 3000 bytes	~ 4.0 MHz (+60 %)	Capacity and Latency
≥ 3000 bytes	~ 3.5 MHz (+40 %)	Capacity and Latency

Terrain Type: From a propagation perspective the wireless assessments summarized in the preceding tables (Table 30 through Table 34) assume a worst case scenario for suburban, rural, and low density rural regions by assuming terrain 'Type A'. This terrain type is defined as 'hilly with moderate to heavy tree density'. Although there will be more extreme cases than this, Type A represents the most extreme case for which we have a valid path loss model. Terrain types that are more propagation friendly are Types B and C. Figure 78 shows the reduced BS requirements for deployments in terrain Types B and C relative to Type A. The propagation benefits of more favorable terrain are less significant in suburban areas where a lower BS antenna height (10 m vs. 30 m) is assumed.

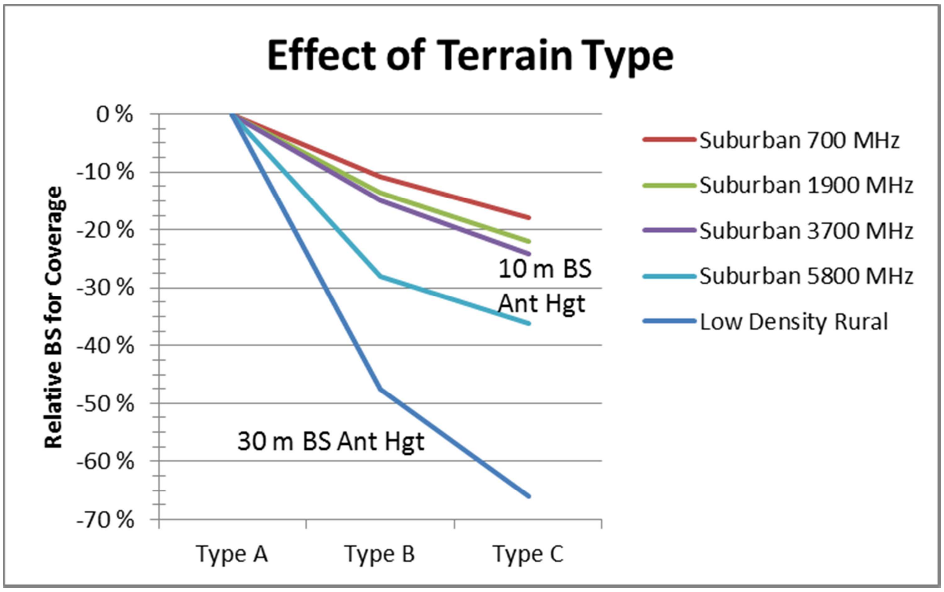


Figure 78 - Relative number of BSs vs. terrain type

Link Budget and System Gain: System gain, which is the major component of the link budget, is not generally defined by wireless standards organizations. Although the wireless standard may set some guidelines, there is usually considerable latitude left to equipment vendors for the parameters that comprise system gain. That said, one can expect some variations from the system gain parameters assumed for this assessment. The other terms used to determine the link budget include fade margin, penetration loss, and interference margin. The same values have been applied to all of the technologies for this assessment. Of these, interference margin may differ somewhat between technologies, but probably not more than 1 dB or 2 dB.

Figure 79 shows the difference in BS requirements for coverage for a link budget range from -3 dB to +3 dB. As the chart indicates, a couple of dB can make a significant difference.

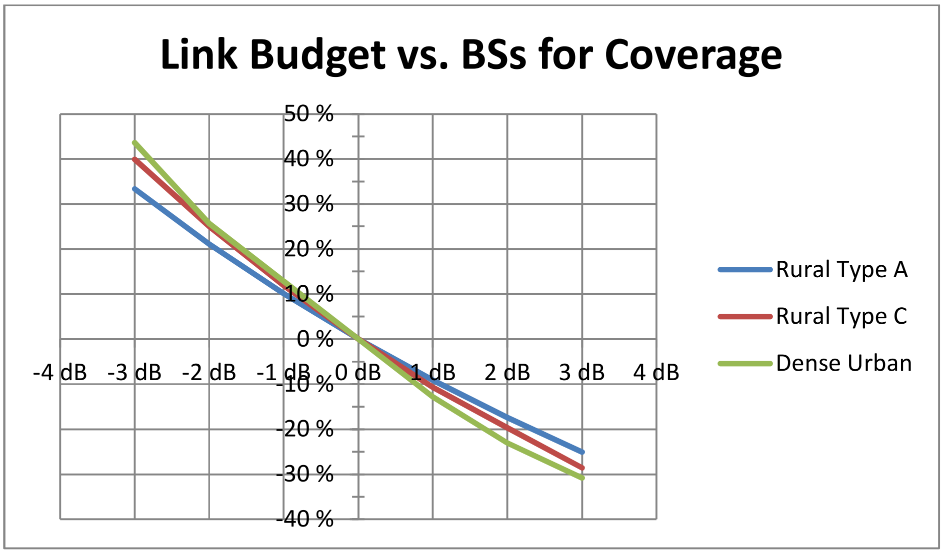


Figure 79 - Link budget impact on BS requirements

6.7.5 Assessment results summary

The SG framework and wireless modeling tool has been used to assess nine terrestrially based wireless technologies using parameters submitted for the Wireless Capabilities Matrix described in section 4 with other assumed deployment and wireless variables described earlier in this section. The Smart Grid requirements for this analysis is based on a FAN or NAN network with end-points estimates based on US census data and generalized parsing of the house-holds to specific categories / types of smart grid end-points.

Some general observations are:

- **Suburban:** This demographic SG deployment area represents the greatest challenge from a capacity and latency perspective, especially in the lower frequency bands. For solutions with Channel BW constraints either additional channels or more BSs are necessary. Even when range-limited, SG requirements consumed a significant portion of the BS capacity. This could limit the use of existing public or other shared networks.
- **Dense Urban and Urban:** With the range limited by less favorable end-point locations, capacity requirements for SG typically consumed less than 1 % of the available BS capacity with the exception of GSM EDGE for urban deployment in the 700 MHz band due its limited channel BW.
- **Rural and Low Density Rural:** Capacity requirements were typically at about 0.1 % or below of the available BS capacity for all technologies. Latency was an issue with many of the technologies where we assumed 2 and 3 serial links, respectively for Rural and Low Density Rural. This was alleviated with larger packet sizes and of course QoS can also play a role. On the other hand, there will be many cases where a greater number of links will be required and in some cases a satellite link might have to be included for these regions. Meeting latency

requirements for large latency-sensitive payloads are likely to be an on-going challenge in these areas.

Table 38 provides a perspective on deployment requirements with respect to: Technology, Frequency, and Demographic Region. The entries in the table show the requirements for each technology for an average US state as a proxy for a specific SG deployment area that includes some combination of the end-point density categories, arrived at by estimating the number of BSs or DAPs necessary to cover 2 % of the total US land area for each demographic region. It is informative to summarize requirements solely on the basis of coverage, even though some of the suburban area deployments are latency- or capacity-limited, since in many of those cases the limitations can be addressed by adding more channels rather than adding more BSs. Additionally, QoS, supported by most[36] of the assessed technologies, can address many of the latency limitations.

There is no data for Dense Urban in the 700 MHz band, since we have not found a suitable path loss model for BS antenna heights below surrounding roof tops.

Table 38: Summary of assessment results assuming range-limited deployments

Demographic Region	**Dense Urban**	**Urban**	**Sub-urban**	**Rural**	**Low Density Rural**	**Totals**
1/50 US Land Area	**36.1**	**449**	**2,306**	**16,127**	**51,310**	**70,228**
Total End-Points	**512,627**	**1,547,290**	**2,562,144**	**1,048,285**	**205,240**	**5,875,586**
			Type A	**Type A**	**Type A**	
700 MHz			**Totals for 700 MHz exclude dense urban**			
802.15.4g-e[1], CDMA2000[1], HRPD EV-DO[1], xHRPD[1], WCDMA, HSPA+, LTE, WiMAX	n/a	180	254	1,775	4,892	**7,101**
GSM EDGE[1]	n/a	225	277	2,145	5,952	**8,599**
1900 MHz						
CDMA2000[2], HRPD EV-DO[2], xHRPD, WCDMA, HSPA+, LTE, WiGRID	354	786	600	3,097	8,398	**13,235**
GSM EDGE[2]	462	921	646	3,742	10,211	**15,982**
3550 MHz						
WCDMA, HSPA+	1,443	2,604	1,154	4,307	11,562	**21,070**
3700 MHz						
LTE, WiGRID	1,566	2,806	1,200	4,452	11,973	**21,997**

[36] IEEE 802.15.4g-e is a data only solution and does not support traffic priorities.

Demographic Region	Dense Urban	Urban	Sub-urban	Rural	Low Density Rural	Totals
1/50 US Land Area	**36.1**	**449**	**2,306**	**16,127**	**51,310**	**70,228**
Total End-Points	**512,627**	**1,547,290**	**2,562,144**	**1,048,285**	**205,240**	**5,875,586**
			Type B	**Type B**	**Type B**	
700 MHz			**Totals for 700 MHz exclude dense urban**			
802.15.4g-e[1], CDMA2000[1], HRPD EV-DO[1], xHRPD[1], WCDMA, HSPA+, LTE, WiMAX	n/a	180	227	930	2,561	**3.898**
GSM EDGE[1]	n/a	225	247	1,123	3,116	**4.711**
1900 MHz						
CDMA2000[2], HRPD EV-DO[2], xHRPD, WCDMA, HSPA+, LTE, WiGRID	354	786	519	1,622	4,396	**7,677**
GSM EDGE[2]	462	921	559	1,959	5,345	**9,246**
3550 MHz						
WCDMA, HSPA+	1,443	2,604	981	2,255	6,052	**13,335**
3700 MHz						
LTE, WiGRID	1,566	2,806	1,020	2,331	6,268	**13,991**
			Type C	**Type C**	**Type C**	
700 MHz			**Totals for 700 MHz exclude dense urban**			
802.15.4g-e[1], CDMA2000[1], HRPD EV-DO[1], xHRPD[1], WCDMA, HSPA+, LTE, WiMAX	n/a	180	209	604	1,665	**2,658**
GSM EDGE[1]	n/a	225	228	730	2,026	**3,209**
1900 MHz						
CDMA2000[2], HRPD EV-DO[2], xHRPD, WCDMA, HSPA+, LTE, WiGRID	354	786	468	1,054	2,858	**5,520**
GSM EDGE[2]	462	921	504	1,274	3,475	**6,636**
3550 MHz						
WCDMA, HSPA+	2,020	2604	875	1,466	3,934	**10,322**
3700 MHz						
LTE, WiGRID	1,566	2806	910	1,515	4,074	**10,871**

Demographic Region	Dense Urban	Urban	Sub-urban	Rural	Low Density Rural	Totals
1/50 US Land Area	**36.1**	**449**	**2,306**	**16,127**	**51,310**	**70,228**
Total End-Points	**512,627**	**1,547,290**	**2,562,144**	**1,048,285**	**205,240**	**5,875,586**
Composite View			**A=16.4 % B=32.0 % C=51.6 %**	**A=25.4 % B=34.6 % C=40.0 %**	**A=26.4 % B=28.0 % C=45.6 %**	
700 MHz			**Totals for 700 MHz exclude dense urban**			
802.15.4g-e[1], CDMA2000[1], HRPD EV-DO[1], xHRPD[1], WCDMA, HSPA+, LTE, WiMAX	n/a	180	222	1,014	2,767	**4,183**
GSM EDGE[1]	n/a	225	242	1,225	3,366	**5,059**
1900 MHz						
CDMA2000[1], HRPD EV-DO[1], xHRPD[1], WCDMA, HSPA+, LTE, WiMAX	354	786	506	1,770	4,749	**8,165**
GSM EDGE[2]	462	921	545	2,138	5,774	**9,840**
3550 MHz						
WCDMA, HSPA+	1,443	2,604	955	2,461	6,538	**14,000**
3700 MHz						
LTE, WiGRID	1,566	2,806	993	2,543	6,771	**14,679**
Note 1	*Additional channels or BSs will be required for 700 MHz suburban deployments to meet capacity and/or latency requirements*					
Note 2	*Additional channels or BSs will be required for 1900 MHz suburban deployments to meet capacity and/or latency requirements*					

The assessment results are included for terrain Types A, B, and C for suburban, rural, and low density rural areas. It is up to the reader to decide which terrain type is more applicable for the geographic characteristics of the area being analyzed or more specifically, what percentage breakdown between terrain types is most applicable. For illustrative purposes, a worksheet (Tab 1a) in the SG framework and wireless modeling tool provides an approximate breakdown, with respect to terrain, for each of the states and the District of Columbia[37]. This information is summarized in Table 39 and Figure

[37] It is important to emphasize that this terrain information is only a rough approximation based on information collected from many different sources. It is provided for illustrative purposes and should not be used as a substitute for more detailed statewide GIS information, other 3D mapping techniques, or local observations.

80. The spread in land area percentage breakdowns for each of the terrain types emphasizes the need to have specific terrain information about the particular state and geographic area of interest. Although a majority of states appear to have a significant amount of the land area (Terrain Type C) that is generally favorable for terrestrial-based wireless coverage, it must also be noted that much of this land area is also very sparsely populated.

In addition to showing the assessment results for Types A, B, and C respectively, the SG Model-Area average demographic breakdowns for Types A, B, and C are used, for illustrative purposes, to show a composite view for the SG Model-Area.

Table 39: Approximate terrain type breakdown for combined suburban, rural, and low density rural in 50 US states plus the District of Columbia

	Type A	Type B	Type C
State by state minimum	0.0 %	10.8 %	18.9 %
State by state maximum	49.6 % 3 States ≥40 %	59.0 % 3 States ≥45 %	80.8 % 8 States ≥60 %
Average for all states	25.0 %	31.8 %	43.2 %
USA average	25.8 %	29.7 %	44.5 %

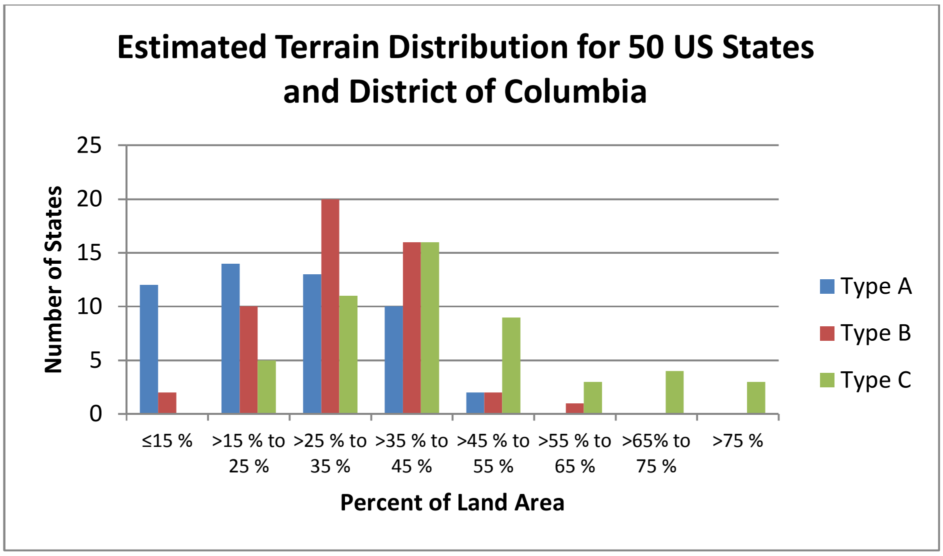


Figure 80 - Estimated US terrain type distribution

In making use of this assessment data from a spectrum point of view, it should be noted that it may not be realistic to assume the same spectrum availability over a very large geographic area. Geographic boundaries for spectrum licenses in the US may or may not coincide with specific utility regions nor will they necessarily coincide with state boundaries. Additionally, with respect to spectrum, the different wireless solutions are grouped into four categories to simplify the presentation of the data. There are numerous frequency allocations between 1400 MHz and 2700 MHz covered by one or more of the wireless technologies. While 1900 MHz is a reasonable choice for purposes of this comparative assessment, it should be obvious, based on link budget and path loss differences alone, that a solution in the 2300 MHz band with one wireless technology would yield quite different results in the 1800 MHz or 1900 MHz band even though the wireless attributes are similar.

The intent of this analysis has been to provide some insights as to how the SG framework and wireless modeling tool can be used to assess the different terrestrial-based wireless technologies in a PMP topology based on the mathematical path loss models described in section 5 and the wireless technology attributes presented in section 4. In this analysis, the Smart Grid AMI / NAN average data throughput and latency requirements were derived from the end-point densities based on SG Model-Area data.

Despite the limitations stated earlier, Table 38 should prove useful for early planning purposes to assess how the different terrestrial-based wireless technologies are likely to perform with respect to frequency, demographics, and relative propagation conditions. The above assessment should also provide a perspective on the role that different wireless parameters play in determining the number of BSs and equipment necessary to meet SG AMI / NAN requirements for coverage, latency, and capacity.

6.8 Cross Wireless Technology Considerations

In considering a Smart Grid network, it should be recognized that the network quite likely will not be a single homogeneous network, but will in fact likely be a network consisting of multiple disparate sub-networks interconnected to form an overall Smart Grid network system. These sub-networks could include both non shared private networks and shared commercial networks. Technologies will likely include both wire-line and wireless networks. In addition they could utilize both standards based and proprietary network technologies and protocols. However, regardless of the number and type of sub-networks used to implement the enterprise Smart Grid network system, it is critical that proper attention and consideration be given to the operational and load characteristics of each of the sub-networks individually and collectively to ensure that the composite Smart Grid network system will satisfy the overall Smart Grid Systems requirements.

While the overall Smart Grid System requirements will likely vary from one implementation to the next, they will, in general, include elements of and be driven by the following considerations:

- Business Goals and Requirements
- Regulatory Requirements
- Security Requirements
- System Functionality
- System and Operational Characteristics
    - Coverage
    - Capacity and Latency

- Responsiveness
- Availability and Reliability
- Resiliency to failure modes and redundancy to overcome failed network links
- Flexibility to accommodate system growth, changing requirements, and changes in technology

The following characteristics should be carefully considered and can be used as a guide in formulating the requirements for the overall SG network system and each of the constituent sub-networks. In addition and very importantly, a Smart Grid network system should be implemented to support the current requirements and yet be flexible enough to gracefully grow and evolve to accommodate expected future requirements and technology enhancements.

Important Network Characteristics

- Intended use of the Network – What is the intended use of the network system? It is important to understand the intended and potential future use of the network, which could be exclusively for AMI, or for DA, or for HAN interconnectivity, or for Direct Load Control, or for a combination of these. Often an enterprise may focus narrowly on a particular application without fully considering future applications that may also be able to leverage and effectively utilize the proposed network infrastructure. The applications and use cases, both current and those projected for the future, should be considered carefully when establishing requirements for the SG Network and in evaluating the network capabilities in this overall context. Even after fully considering potential future applications, it is very possible that some SG sub-networks may be implemented to serve specific use cases where other sub-networks may serve other use cases (for example, a sub-network specifically implemented for DA and a separate sub-network implemented specifically for direct load control). However, it is also likely that all sub-networks will interconnect with other shared network facilities and a common backbone network infrastructure linking them to one or more centralized service facilities. Thus while each sub-network should be evaluated for its intended specific use, the common and shared network infrastructure should be evaluated for its intended composite use.
- Size of the Network – Consideration must be given to the number of end-points, their function, their location, their density, and the variability of their density. This is particularly important for a NAN network directly linking with the end-points. The density of the end-points in a geographic area or region along with their expected traffic load characteristics will directly drive the requirements for the capacity and latency of the network in that area.
- Network Capacity Requirements – Consideration for the expected traffic load, both deterministic and non-deterministic traffic, average and bursty traffic

patterns, and the relationship of the combined traffic patterns with the use case latency requirements are all critical elements when considering capacity. Often, while it may not be known apriori what the ultimate traffic capacity requirements will be, especially with periodic bursty payloads, it is critical that proper analysis and planning of capacity requirements are conducted for all network segments and facilities. Insufficient planning can result in overbuilding the network, resulting in higher costs for no appreciable gain, or under building the network, potentially less costly but negatively impacting responsiveness.

- Latency Requirements – Each application and use case will have different latency requirements. End-to-end latency can be significantly impacted by several factors including node-to-node effective data goodput (which in turn is related to: the application design; security risk mitigation techniques employed; the bandwidth capacity between the nodes; error rates; protocol efficiency; and network load), as well as the internal processing delays and queues introduced by intermediate nodes in the data path. Careful consideration must be given to the latency characteristics of any and all network segments utilized to establish the path between the source and sync nodes for all applicable use cases. The cumulative or combined latency of multiple network segments encountered in linking source and sink nodes can be significant. Equally important is consideration for any potential concurrent execution of multiple use cases as may occur in the SG system, and the impact this would have on any potential network congestion points. Network congestion at critical points that may occur as a result of concurrent use case execution may in turn introduce unexpected but significant additional latency that could negatively impact latency sensitive applications and use cases.
- Router and Node Throughput – In addition to the throughput of the individual network links, consideration must be given to the processing power, packet throughput capacity, and internal latency of the routers, relays, or repeaters and other transient network nodes used to implement connectivity between the various network segments.
- Spectrum and Bandwidth Requirements – For private wireless network components, consideration should be given for spectrum availability and the bandwidth that may be needed to satisfy the transport capacity requirements.
- Geographic location and RF morphology – The terrain and other RF environmental and existing RF interference factors will significantly impact the coverage, capacity, and reliability of any wireless network. These characteristics should be fully considered in any areas intended to be served by wireless technologies. The SG framework and wireless modeling tool described in section 6.5 and used in section 6.7 to assess various terrestrial wireless technologies provides a means to gain initial insights in this regard.

- Availability and Reliability – Adequate link margins for wireless networks should be part of the planning process to ensure satisfactory link connectivity under highly variable propagation conditions.
- Resiliency and Redundancy – Requirements for network resiliency, or the ability of the network to tolerate failures and the requirements for network redundancy to route around failures should be fully considered to insure the Availability and Reliability requirements are met.
- Backhaul requirements and availability – The requirements of the backhaul links from the NAN DAPs to the centralized systems, and the availability and reliability of these backhaul links. Of particular importance here is the additional latency or any capacity constraints that may be introduced by the backhaul component of the network.
- Flexibility for Growth and other Changes – The ability to accommodate growth and changes in the number of Smart Grid applications, the number and type of end-points, and any likely or potential changes in functionality of those end-points are key considerations when selecting a network system and in selecting the technology and topology of the sub-networks.
- Security – Security requirements are particularly important for an SG system and the networks supporting them. Important and significant elements of network security include requirements for:
    - Policies and procedures for nodes and devices joining the network
    - Protecting confidentiality of the data on the network
    - Safeguards to prevent modification or destruction of the information and data being transmitted over the network
    - Preventing unauthorized attachment or connections to the network
    - Authorizing and permitting data exchanges only between nodes authorized to do so

  Failure to recognize and properly plan for adequate network security could be very costly both in potential fines for regulatory violations and in the cost of any retrofits as may be required by governmental mandates. Additionally, corrupted or lost data payloads can lead to costly service disruptions, organizational disruptions, billing errors, etc.
- Ease of Deployment – How capable or flexible does the network have to be to adapt to changes in the deployment planning, processes, and physical environments.
- Ease of Monitoring and Managing the Network – The ability to provide comprehensive monitoring and management of the individual sub-networks, as well as the overall SG network system is a critical element for the ongoing effective operation of an SG system.

- Incremental Cost to Achieve 100 % Coverage – Typical Smart Grid applications require 100 % fixed node coverage; different topologies have different incremental costs to go from a nominal coverage to 100 % coverage.
- Scalability – Expansion of the network as needed to adjust to the deployment planning, processes, and physical environments.

The above list provides some of the key characteristics that must be carefully considered when establishing the requirements for the SG network system. Particular care must be taken when considering sub-networks (like the SG NAN systems that directly connect to the SG end-points), both for their intended initial use and for any expected expansion beyond their initial use cases which may include both new use cases and additional numbers of end-point devices. Proper network planning prior to deployment can lead to a more efficient SG network and mitigate the need for significant and costly network re-engineering in the future.

7 Conclusions

The goals of PAP02 are to develop guidelines for the use of wireless communications in a smart grid environment. To date several milestones have been achieved towards these goals and are described in this report.

The first significant milestone is the development of smart grid application communication requirements. While many use cases and scenarios have been described in the past, the task undertaken by OpenSG provides comprehensive and detailed sets of quantitative user communication requirements capturing different use cases and environments. These requirements are tremendously valuable to both the user and network technology communities in order to better understand the smart grid landscape. The use of these requirements is not limited to wireless technologies; but they can also be used for evaluating any communication technology, be it wireless or wired.

Another milestone described in this report is a framework to evaluate wireless communication technologies. This is a general methodology that helps users and network technologists provide answers to the question: how well does wireless technology, X, support application requirements, Y? Rather than provide a single answer to this question, a framework and a set of tools are provided for users and network technologists to help them formulate answers that apply to their own environment. Recognizing that every environment is different and every user requirement may pose additional constraints and challenges to the network designer, this approach is more useful because it is universal. Proof of concept examples are also included in this report in order to further illustrate the concepts described and make it easier for users to develop their own evaluations. Additional tools and evaluation models developed by different contributors are referenced in this report and are available on the NIST PAP02 collaborative site:

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

Also included in this report are key performance findings that are applicable to most environments and wireless technologies. These represent key factors to consider in the assessment of wireless technologies such as interference, environment, coverage range, and deployment range extension.

Going forward, this report may be revised as needed in order to include additional material contributed by PAP02 members. Additional material may include examples on how to combine security and communication requirements and their implications on performance, and additional communication requirements and wireless technology evaluation examples and models.

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