NIST Priority Action Plan 2

Guidelines for Assessing Wireless Standards for Smart Grid Applications

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Revision History

Revision Number	Revision Date	Revision By	Summary of Changes
.01	3/31/2010	Matt Gillmore	Initial take on the outline, TOC, ,authors, definitions, acronyms, reference architecture
.02	4/28/2010	David Cypher	Added outline numbering for cross reference purposes, added text for 1, 3.3 and 5
.03	5/3/2010	David Cypher	Edits and additional material for 3.2, 5 and 6
.04	5/4/2010	Nada Golmie	Edits to section 5
.05	7/28/2010	NIST & PAP2 Team	Updated most of the document
.06	9/30/10	NIST & PAP2 Team	Updated most of the existing sections and provided material for empty sections.
.06a	10/25/10	NIST	Included material presented at St.Louis, MO meeting (and formatting)
1.0	12/31/10	NIST	Included material from call for comments on .06

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 as complete a 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 is a draft of 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 document presents a set of tools in the form of models that can be used for parametric analyses of the various wireless technologies.

This document 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 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.

Feedback and critical review of this document are welcome. Individuals interested in directly participating in follow on work are encouraged to join in assisting with tasks defined within PAP 2 on the SGIP twiki page at

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless.

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1 Overview of the Process

The process by which this document was generated is based on the six tasks for Priority Action Plan 2 (PAP 2).

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

Task 1: Segment the smart grid and wireless environments into a minimal set of categories for which individual wireless requirements can be identified. This was accomplished by the creation of a template (app_matrix_pap.xls) for input to application communication requirements. This template contained two main sheets: one for characterizing the user application and the other for characterizing the physical devices that would be used for the user applications. With this template as a basis, OpenSG[1] submitted a subset of user application quantitative information (SG Network System Requirements Specification v4.0.xls). See section 3.4.

Task 2: Develop Terminology and definitions. This was accomplished by combining the terms and definitions from the various input documents to other tasks of PAP 2, as well as using those from the base Smart grid documents (NIST IR 7628 Guidelines for Smart Grid Cyber Security: Vol. 1, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements). For Acronyms see 2.1 and definitions see 2.2.

Task 3: Compile and communicate use cases and develop requirements for all smart grid domains in terms that all parties can understand. This task is in progress and has been partially completed for the submitted user applications (see 3.3) and the smart grid domains that are applicable to the user requirements.

Task 4: Compile and communicate a list of capabilities, performance metrics, etc. in a way that all parties can understand. - Not quantifying any standard, just defining the set of metrics. This was accomplished by default with the submission for task 5.

Task 5: Create an inventory of wireless standards and their associated characteristics (defined in task 4) for the environments identified in task 1. The Wireless Functionality and Characteristics Matrix for the identification of smart grid domain application (Consolidated_NIST_Wireless_Characteristics_Matrix-V5.xls.) excel spreadsheet captures a list of wireless standards and their associated characteristics. (See section 4)

Task 6: Perform the mapping and conduct an evaluation of the wireless technologies based on the criteria and metrics developed in task 4. This is the subject of sections 5 – 6 of this document (Modeling and Evaluation Approach (5), Factors to Consider in Determining Performance (6)) and the Conclusions (7).

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[1] The full description of the procedures used in this document requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

2 Acronyms and Definitions

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

2.1 Acronyms

3G	Third Generation
AC	Alternating Current
ACK	Acknowledgement
AICPA	American Institute of Certified Public Accountants[2]
AMI	Advanced Metering Infrastructure
AMS	Asset Management System
ARQ	Automatic Repeat-reQuest
ASAP-SG	Advanced Security Acceleration Project-Smart Grid
AWGN	Additive White Gaussian Noise
B2B	Business to Business
BAN	Business Area Network
BER	Bit Error Rate
BGAN	Broadband Global Area Network
BPSK	Binary Phase Shift Keying
CIM	Common Information Model
CIP	Critical Infrastructure Protection
CPP	Critical Peak Pricing
CRC	Cyclic Redundancy Check
CSWG	Cyber Security Working Group
DA	Distribution Automation
DAC	Distributed Application Controller
DAP	Data Aggregation Point
DCF	Distributed Coordination Function
DER	Distributed Energy Resources
DHS	Department of Homeland Security[3]
DIFS	Distributed InterFrame Space
DMS	Distribution Management System
DNP	Distributed Network Protocol
DO	Downlink Only
DOE	Department of Energy
DOMA	Distribution Operations Model and Analysis
DR	Demand Response
DRMS	Distribution Resource Management System
DSDR	Distribution Systems Demand Response

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[2] AICPA, 1211 Avenue of the Americas, New York, NY 10036; www.aicpa.org

[3] Department of Homeland Security – www.dhs.gov

DSM	Demand Side Management
DVB	Digital Video Broadcast
EDGE	Enhanced Data Rates for GSM Evolution
EIFS	Extended InterFrame Space
EIRP	Effective Isotropic Radiated Power
EMS	Energy Management System
EPRI	Electric Power Research Institute[4]
ES	Electric Storage
ESB	Enterprise Service Bus
ESI	Energy Services Interface
ET	Electric Transportation
EUMD	End Use Measurement Device
EV/PHEV	Electric Vehicle/Plug-in Hybrid Electric Vehicles
EVSE	Electric Vehicle Service Element
FAN	Field Area Network
FDD	Frequency Division Duplexing
FEP	Front End Processor
FER	Frame Error Rate
FERC	Federal Energy Regulatory Commission[5]
FIPS	Federal Information Processing Standard Document
FLIR	Fault Location, Isolation, Restoration
G&T	Generations and Transmission
GAPP	Generally Accepted Privacy Principles
GFSK	Gaussian Frequency-Shift Keying
GIS	Geographic Information System
GL	General Ledger
GMR	Geo Mobile Radio
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
HAN	Home Area Network
HARQ	Hybrid Automatic Repeat reQuest
HMI	Human-Machine Interface
HRPD	High Rate Packet Data
HSPA+	Evolved High-Speed Packet Access
HVAC	Heating, Ventilating, and Air Conditioning
I2G	Industry to Grid
IEC	International Electrotechnical Commission[6]
IED	Intelligent Electronic Device
IETF	Internet Engineering Task Force

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[4] Electric Power Research Institute, Inc. (EPRI) 3420 Hillview Avenue, Palo Alto, California 94304

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

[6] International Electrotechnical Commission – www.iec.ch

IHD	In-Home Display / In-Home Device
IKB	Interoperability Knowledge Base
IPoS	Internet Protocol over Satellite
ISA	International Society of Automation[7]
ISO	Independent System Operator
	International Organization for Standardization
IT	Information Technology
LAN	Local Area Network
LMS	Load Management System
LMS/DRMS	Load Management System/ Distribution Resource Management System
LTE	Long Term Evolution
LV	Low Voltage
MAC	Medium Access Control
MDMS	Meter Data Management System
MFR	Multi-Feeder Reconnection
MIMO	Multiple-Input / Multiple-Output
MSW	Meter Service Switch
MV	Medium Voltage
NAN	Neighborhood Area Network
NERC	North American Electric Reliability Corporation[8]
NIPP	National Infrastructure Protection Plan
NISTIR	NIST Interagency Report
NLOS	Non Line of Sight
NMS	Network Management System
ODW	Operational Data Warehouse
OFDM	Orthogonal Frequency Division Multiplexing
OMS	Outage Management System
OSI	Open Systems Interconnection
OWASP	Open Web Application Security Project
PAP	Priority Action Plan
PCT	Programmable Communicating Thermostat
PEV	Plug-In Electric Vehicle
PGF	Probability Generating Function
PHEV	Plug-in Hybrid Electric Vehicle
PHY	Physical Layer
PI	Process Information
PIA	Privacy Impact Assessment
PII	Personally Identifying Information
QAM	Quadrature Amplitude Modulation

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[7] ISA, 67 Alexander Drive, Research Triangle Park, NC 27709 USA - www.isa.org

[8] www.nerc.com

QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R&D	Research and Development
REP	Retail Electric Provider
RF	Radio Frequency
RFC	Request for Comments
RSM	Regenerative Satellite Mesh
RSSI	Received Signal Strength Indication
RTO	Regional Transmission Operator
RTP	Real Time Pricing
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison[9]
SDO	Standards Development Organization
SGIP	Smart Grid Interoperability Panel
SGIP-CSWG	SGIP – Cyber Security Working Group
SIFS	Short InterFrame Space
SIM	Subscriber Identity Module
SIMO	Single-input / Multiple-output
SINR	Signal to Interference plus Noise Ratio
SISO	Single-input / Single-output
SM	Smart Meter
SNR	Signal to Noise Ratio
SP	Special Publication
SSP	Sector-Specific Plans
T/FLA	Three/Four Letter Acronym
TDD	Time Division Duplexing
TOU	Time Of Use
UMTS	Universal Mobile Telecommunications System
VAR	Volt-Amperes Reactive
VVWS	Volt-VAR-Watt System
WAMS	Wide-Area Measurement System
WAN	Wide Area Network
WASA	Wide Area Situational Awareness
WLAN	Wireless Local Area Network
WMS	Work Management System
WWAN	Wireless Wide Area Network

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[9] www.sce.com

2.2 Definitions[10]

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.
Anonymize	A process of transformation or elimination of personally identifiable information (PII) for purposes of sharing data
Aggregation	Practice of summarizing certain data and presenting it as a total without any personally identifiable information (PII) 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).
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 reactives (VARs) and thus the power factor and they will also affect voltage levels.
Common Information Model	A structured set of definitions that allows different smart grid domain representatives to communicate important concepts and exchange information easily and effectively.
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 Collector	See Substation controller
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.)
De-identify	A form of anonymization that does not attempt to control the data once it has had personally identifiable information (PII) identifiers removed, so it is at risk of re-identification.
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.

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[10] The definitions are specific to this document'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.

Electric Vehicle (EV) /Plug-in Hybrid Electric Vehicles (PHEV)	Cars or other vehicles that draw electricity from batteries to power an electric motor. PHEVs also contain an internal combustion engine.
Energy Services Interface (ESI)	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 Service Bus (ESB)	The enterprise service 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 service bus (ESB) 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 Force	Employee working in the service territory that may be working with smart grid devices.
Generally Accepted Privacy Principles	Privacy principles and criteria developed and updated by the American Institute of Certified Public Accountants (AICPA) and Canadian Institute of Chartered Accountants to assist organizations in the design and implementation of sound privacy practices and policies.
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 address 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.
Intelligent Fault Detector	A device that can sense a fault and can provide more detailed information on the nature of the fault, such as capturing an oscillography trace.
ISO/IEC27001	Provides an auditable international standard that specifies the requirements for establishing, implementing, operating, monitoring, reviewing, maintaining and improving a documented Information Security Management System within the context of the organization's overall business risks. It uses a process approach for protection of critical information
Last Gasp	Refers to the capability of a device to emit one last message when it loses power. Concept of an energized device within the smart grid detecting power loss and sending a broadcast message of the event

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."
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)
Low Voltage Sensor	A device used to measure and report electrical properties (such as voltage, current, phase angle or power factor, etc.) at a low voltage customer delivery point.
Medium Voltage Sensor	A device used to measure and report electrical properties (such as voltage, current, phase angle or power factor, etc.) on a medium voltage distribution line.
Motorized Switch	A device under remote control that can be used to open or close a circuit
Neighborhood Area Network	A network comprised of all communicating components within a distribution domain.
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	A formatted unit of data sent across a network.
Personal Information	Information that reveals details, either explicitly or implicitly, about a specific individual's household dwelling or other type of premises. This is expanded beyond the normal "individual" component because there are serious privacy impacts for all individuals living in one dwelling or premise. This can include items such as energy use patterns or other types of activities. The pattern can become unique to a household or premises just as a fingerprint or DNA is unique to an individual.
Phase Measuring Unit	A device capable of measuring the phase of the voltage or current waveform relative to a reference.
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).
Privacy Impact Assessment	A process used to evaluate the possible privacy risks to personal information, in all forms, collected, transmitted, shared, stored, disposed of, and accessed in any other way, along with the mitigation of those risks at the beginning of and throughout the life cycle of the associated process, program or system.

Programmable Communicating Thermostat	A device within the premise that has communication capabilities and controls heating, ventilation and cooling systems.
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 (non-Team)	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. 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.
Recloser (Team)	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 2-Way Meter (meter metrology plus a network interface component) with included energy services interface (ESI) in the meter component
Sub Meter	Premise based meter (e.g., used for Distributed Energy Resources and PHEV), which permits additional metering capabilities subordinate to a main meter.
Substation Controller	Distributed processing device that has supervisory control or coordinates information exchanges from devices within a substation from a head end system.
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.
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.
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.

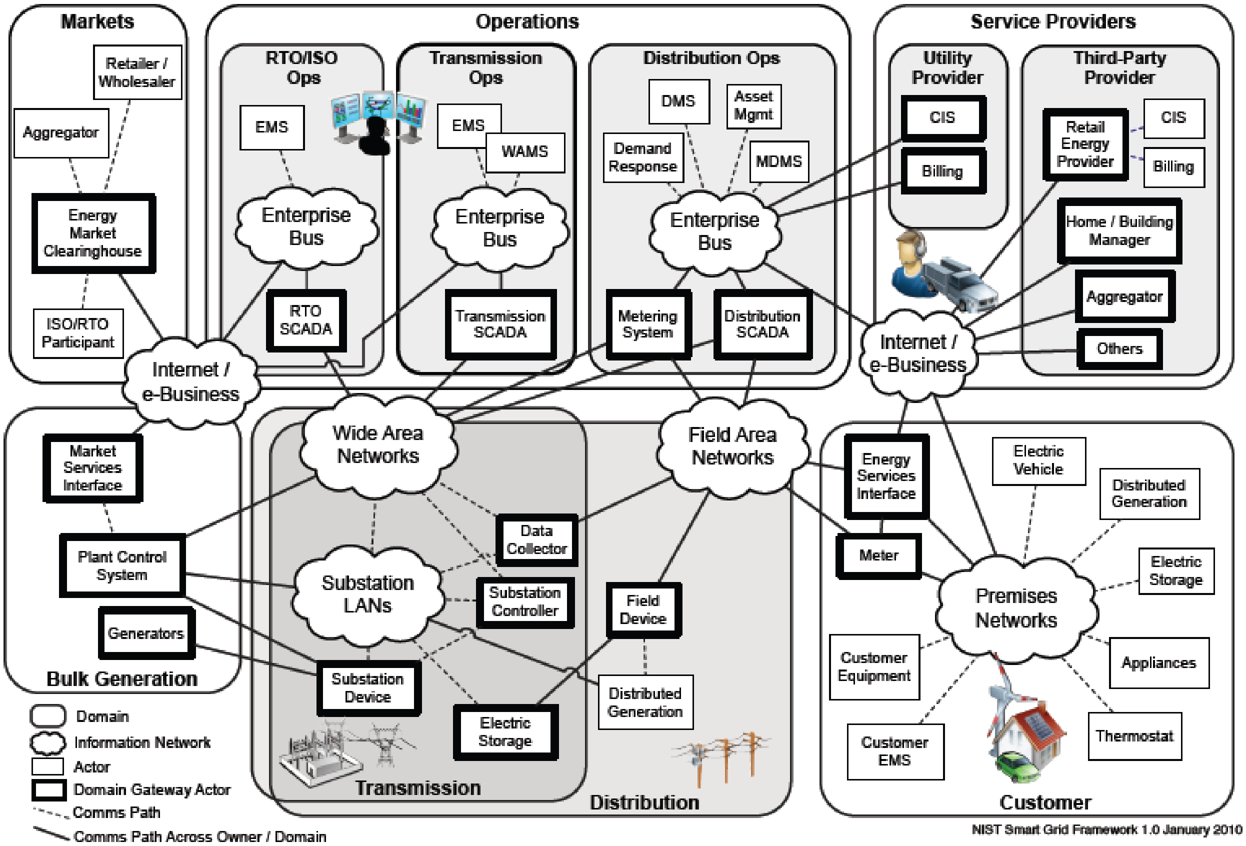
Voltage Regulator	This device is in effect an adjustable ratio transformer positioned at strategic points in a distribution grid and is utilized to better manage and control the voltage as it changes along the distribution feeder.
Volt-Amperes Reactive;	In an alternating current (AC) power system the 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 PAP 2, 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 diagram that was introduced in 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 smart grid conceptual reference diagram is included below, along with two views of SG Network TF's conceptual reference diagrams, one without and one with 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 figures the customer domain is focused on the residential customer.



NIST Smart Grid Framework 1.0 January 2010

Figure 1 - Smart grid conceptual reference diagram

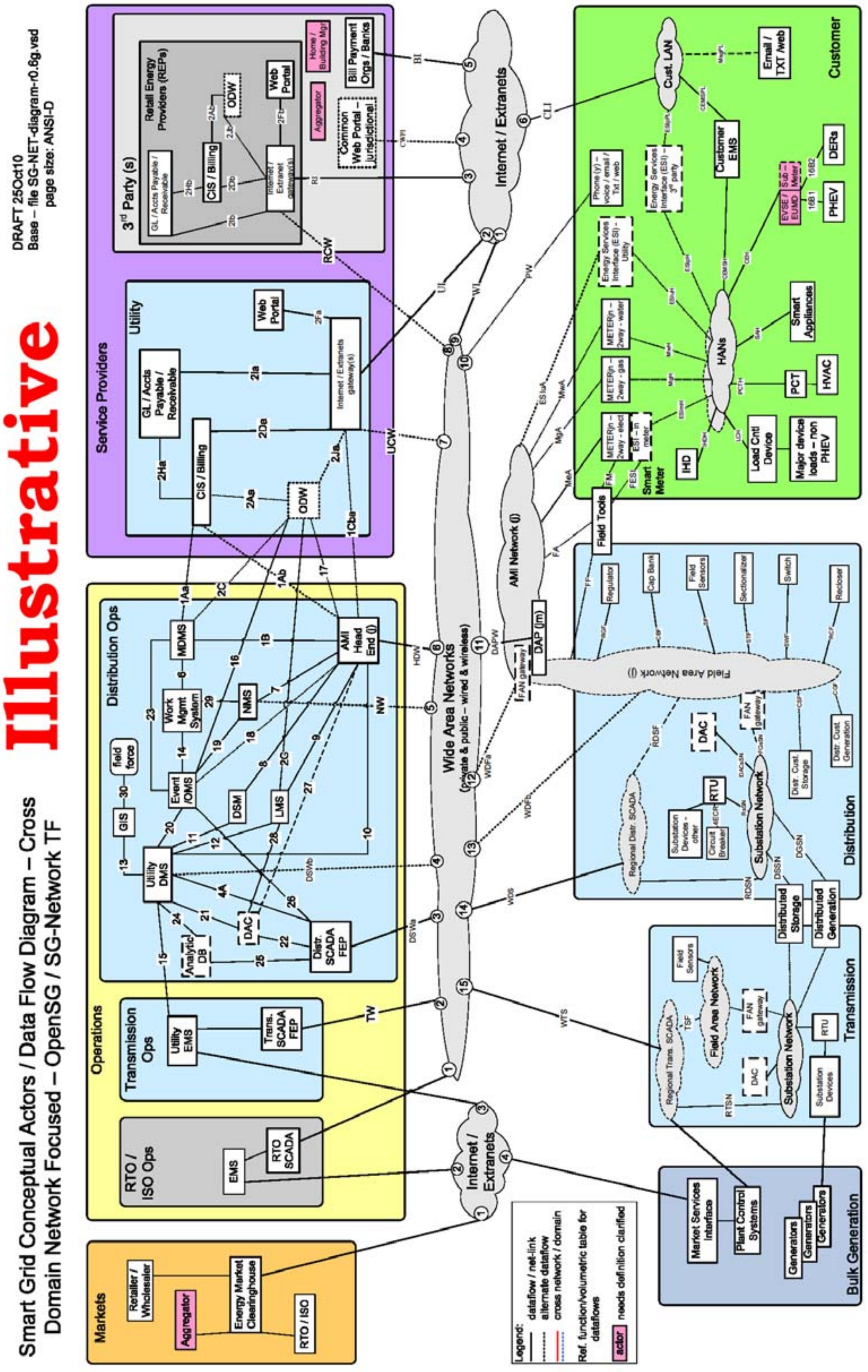


Figure 2 - OpenSG SG Network TF smart grid conceptual reference diagram

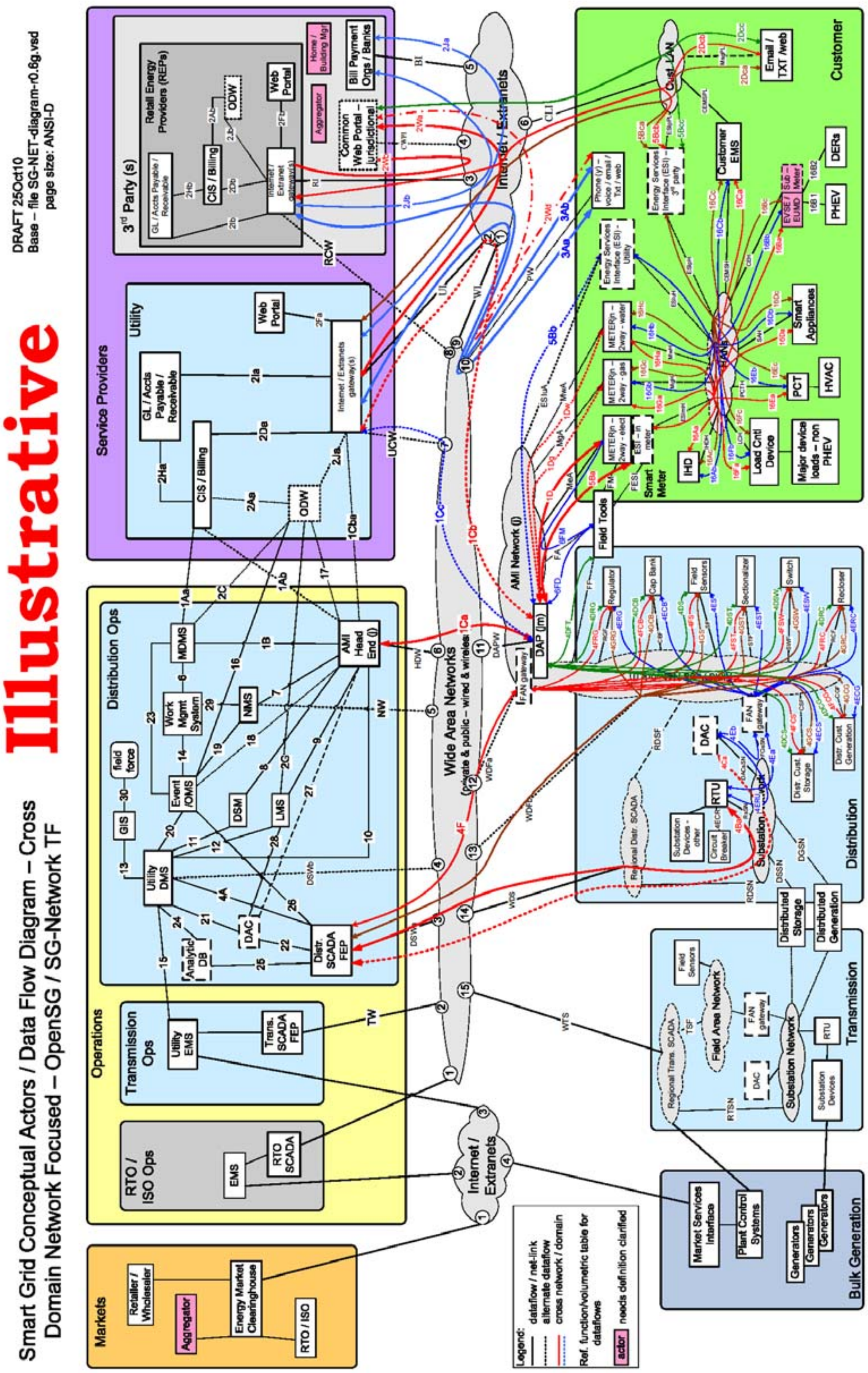


Figure 3 - OpenSG_SG Network TF smart grid conceptual reference diagram with cross domain data flows

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.

Table 1: Mapping of actors to domain names

SG Network TF reference diagram descriptor (actor)	**SG Network TF reference diagram domain name**	**Related NIST 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
IHD (In Home 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 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	
Distributed SCADA Front End Processor (FEP)	Operations	Distributed SCADA
Demand Side Management (DSM)	Operations	Demand Response
EMS	Operations	Utility EMS
Event/OMS	Operations	
Geographic Information System (GIS)	Operations	

SG Network TF reference diagram descriptor (actor)	SG Network TF reference diagram domain name	Related NIST diagram descriptor (actor)
General Ledger (GL) / Accounts Payable / Receivable	Operations	
Load Management System (LMS)	Operations	
MDMS	Operations	MDMS
NMS	Operations	
RTO SCADA	Operations	RTO SCADA
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
Common Web Portal-Jurisdictional	Service Provider	Other
Home/Building Manager	Service Provider	Home/Building Manager
Internet/Extranet Gateway	Service Provider	
ODW	Service Provider	
REP CIS/Billing	Service Provider	Retail Energy Providers Billing
REP CIS/Billing	Service Provider	Retail Energy Providers CIS
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 AMI and DA) that involve network communication to help satisfy the OpenSG input requirements into the NIST PAP 2 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[11] – based on release V4.0.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
PHEV
Premise Network Administration
Pre-Pay Metering
Service Switch
System Updates (Firmware / Program Update)
Volt/VAR Management – Centralized Control
Smart grid use case[12] – potential for releases post V4.0.xls
Configuration Management

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[11] 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.

[12] For the current status of what use cases and application payloads have been documented, see the latest Requirement Table.

Distributed Generation
Field Force Tools
Performance Management
Pricing: Time of Use (TOU) / Real Time Pricing (RTP)/ Critical Peak Pricing (CPP)
Security Management
Transmission automation support

Documenting and describing the in-scope smart grid use cases by SG Network TF is contained in the System Requirements Specification (SRS) document. 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, 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 System Requirements Specification vN.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:

- 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 PAP 2 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 v4.0.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 or section 2.2 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 1400 (as of release v4.0.xls; the basis of this work) functional and volumetric detailed requirements rows in the Requirements Table representing 165 different payloads for 18 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 (v4.0.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_r4.0 is the version available for the database as of this writing.

3.5 Use of Smart Grid User Applications' Quantitative Requirements for PAP 2 Tasks

Release 4.0 (June 15, 2010) of the SG Network TF Requirements Table contains numerous use cases, payloads (applications), communication path options, and associated volumetric requirements data sufficient for a variety of smart grid deployment scenarios as input to PAP 2. 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 PAP 2 and the reader of this document 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 Adaptation of SG Network TF's Requirements Table Data for Use in Network Modeling Tools

When examining the detailed records of the Requirements Table and as noted in section 3.4, there are several decisions and selections the consumer of the Requirements Table must make. This section identifies a method for making most of those decisions and selections, and how to adapt the detailed quantified requirements into a form that can be loaded into the wireless model in section 5.2 or into any other traffic modeling or assessment tool.

Method:

Step 1 - Determine which use cases (applications) to use.
Step 2 - Select which actor to actor interface is to be investigated:
  a) which communication path
  b) which network link(s).
Step 3 - Identify the applications' events (payloads) that are to be used.
Step 4 - Select one value for metrics where ranges are provided.
Step 5 - Assume (and document) values for missing information.
Step 6 - Select which type of data analysis method is to be used:
  a) aggregation of data volumetrics based on values per a specified time period for input into a static system model
  b) simulation of multiple discrete transactions (payloads) retaining each events unique data volumetrics and profiles
Step 7 - Finalize the data preparation tasks based on the selections and assumptions from steps 1-6.

The remainder of this section provides an example of using the steps above on the Requirements Table (release v4.0.xls). As the seven steps are exercised, a very limited and focused amount of requirements from the Requirements Table will be selected for analysis. The user of the Requirements Table and this method needs to perform the steps as driven by the specific objectives and scope of their assessment.

Example use of the method

Step 1 - Determine which use cases (applications) to use

The spreadsheet filter feature can be used on the "Use Case Ref" column to identify and select which uses cases are of interest. For this example exercising of the steps above, two applications (meter reading and service switch) of the available use cases will be used.

Step 2 - Select which actor to actor interface is to be investigated:

  a) which communication path

Using a combination of "pivot tables or data pilots" and additional queries of the Requirements Table for the two selected applications and reviewing the distinct two-way communications between the "From" and "To" actors indicates that there are 41 unique actor to actor pairings.

Let us focus on the Data Aggregation Point (DAP) from/to 2-Way Meter actor to actor pairing.

b) which network link

The SG Network TF conceptual reference diagrams (Figure 2 and Figure 3), indicates that there are three network interfaces "MeA", "MgA", :MwA" between the DAP and the 2-Way Meter[13]. Note the term, smart meter, includes both the 2-Way Meter and the ESI – in meter components. There are two independent data flows identified between the DAP to the electric Smart Meter: "1D'" which is intended to deal with that traffic terminating with the meter metrology, and "5Ba" which is terminating with the ESI module in meters that have ESI modules, plus "1Dg" and "1Dw" for the other two 2-Way Meters. Without getting too technology specific, many technologies for communicating with 2-way meters use one network interface module that "MeA" interfaces to. Consequently, both the "1D" and "5Ba" data flows would traverse across the "MeA" interface.

The vast majority of the communication interfaces included in the Requirements Table are documented as data flows, which are further decomposed to specific network actor to actor or actor to network or network to network links. If the modeling effort is intended to focus on ALL traffic that passes across a network link (e.g. "MeA), for a specific smart grid deployment, then all business requirements in the Requirements Table that have data flows that traverse this interface for the specific selection of use cases, payloads, and communication paths (deployment topologies), must be used in selecting the requirements data for analysis.

For this simple example, let us focus on just the payloads that use the 2-Way Meter – Electric actor metrology to/from the DAP (i.e., "1D") data flow and NOT the traffic with the ESI – In meter component via "5Ba" or the gas "1Dg" or water "1Dw" data flows.

Step 3 – Identify the applications' events (payloads) that are to be used
Using the Requirements Table (v4.0.xls) filter capabilities against the previous two application filters and applying the following two column filters:

- "Data Flow Ref" contains "1D"
- "Data Flow from Actor" equals "DAP"

  would include those events coming from three actors:
  - CIS/Billing – Utility
  - IHD if the communications option via ESI –Utility actor "1D + 5Bb + 16Ab" is selected
  - Customer EMS if the communications option – ESI – Utility actor "1D + 5Bb + 16Cb" is selected.

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[13] Smart grid architectures include the use of AMI technologies which specifies telecommunication capabilities with the meters as being 2-way. Consequently this excludes 1-way meters and meters without any remote communication capabilities. If the user of the Requirements Table wants to include 1-way meters into their analysis, then the requirements specific to those 1-way meters will need to be created by the user specific to their needs.

For this example let us restrict the events to those only coming from the CIS/Billing – Utility actor, which results in five events present in the DAP to 2-Way Meter – Electric metrology direction

- two for the meter reading application,
    - multiple interval meter reading request and
    - on-demand meter read request.
- three for service switch application
    - cancel service switch operate request,
    - service switch operate request, and
    - service switch state request.

After resetting the previous filters and applying the following two column filters:

- "Data Flow Ref" contains "1D"
- "Data Flow to Actor" equals "DAP"

  would include those events going to three actors:
    - CIS/Billing – Utility
    - IHD if the communications option via ESI –Utility actor "16Ab + 5Bb + 1D" is selected
    - Cust. EMS if the communications option – ESI – Utility actor "16Cb + 5Bb + 1D" is selected .

For this example let us restrict the events to those only going to the CIS/Billing – Utility actor, which results in eight events present in the 2-Way Meter –Electric metrology to DAP direction

- four for meter reading application,
    - multiple interval meter read data
        - Commercial / industrial electric meters,
        - Residential electric smart meters.
    - on-demand read request application errors, and
    - on-demand meter read data.
- four for service switch application
    - send service switch operate acknowledgment,
    - send service switch operate failure,
    - send metrology information after a successful service switch operate, and
    - send service switch state data.

Step 4 – Select one value for metrics where ranges are provided.
Use the information from these events (and perhaps others) to calculate the individual contribution of each event in terms of its frequency (Requirements Table: "How Often" values) and its application payload size. Please note that the Requirements Table "Daily Clock Periods" values directly impacts the frequency calculations when the frequency is taken down from say a daily value to an hourly value for specific time blocks in the day, refer to the hourly columns in Table 3 and Table 4 below. Also if the hour of consideration is shifted to an evening hour, the values may or may not change depending upon the "Daily Clock Periods" for that payload (event).

These metrics have either ranges of values or scalar values. An example of a range of values is the multiple interval meter read data (Commercial / Industrial Electric smart meters) where the frequency is 12 – 24 transactions per day and the size of the data is 200 bytes – 1600 bytes. An example of a scalar value is the send service switch operate failure to DAP where the frequency is 1 trans per 1000 switch operate per day. Since this is an error based on the original number of switch operate commands, that event's frequency information, which is 1 - 50 transactions per 1000 meters per day, must be obtained.

For each of the possible ranges of values, select a value that is meaningful to your particular deployment scenario. The Table 3 and Table 4 contain example selections of values.

Table 3: Selected values for DAP to smart meter direction

Event	**How often (events/meter/day)**	**How often (events/meter/midday hour)**	**Size (bytes)**
multiple interval meter reading request	25 events / 1000 meters / day	Daily value/11	25
on-demand meter read requests	25/1000	Daily value/15	25
cancel service switch operate request	2/1000	Daily value/8	25
service switch operate request	50/1000	Daily value/8	25
service switch state request	50/1000	Daily value/8	25

Table 4: Selected values for smart meter to DAP direction

Event	**How often (events/meter/day)**	**How often (events/meter/midday hour)**	**Size (bytes)**
multiple interval meter read data (Commercial / Industrial Electric meters)	24[14]	If randomized then daily value/24, otherwise depends on fixed hourly periods	1600
multiple interval meter read data (Residential electric smart meters)	6	If randomized then daily value/24, otherwise depends on fixed hourly periods	2400

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[14] There is an inverse relationship between one value of the "How Often" range to that of some of the associated "Payload Size" range values. The intended interpretation of the stated payload size of 1600 is associated with a "How Often" value of 12 which ties with 15 minute interval data and 20 data points per interval. This misinterpretation of the Requirements Table should not take away from the example of using the method and steps. SG Network TF will address how to better document the intended interpretation and use of these range of values in the next release (i.e., after v4.0) of the Requirements Table.

Event	**How often (events/meter/day)**	**How often (events/meter/midday hour)**	**Size (bytes)**
on-demand read request app errors	25/1000 *1/1000	Daily value/15	50
on-demand meter read data	25/1000	Daily value/15	100
send service switch operate acknowledgment	2/1000	Daily value/8	25
send service switch operate failure	1/1000 * 50/1000	Daily value/8	50
send metrology information after a successful service switch operate	2/1000	Daily value/8	100
send service switch state data	50/1000	Daily value/8	100

Step 5 - Assume (and document) values for missing information.
There is still some information not available from the user applications matrix. For example to calculate the aggregate traffic from a single 2-Way meter to a DAP, the type of 2-way meter is needed; also the number of 2-way meters that will be sending their data to a single DAP is needed.

- How many 2-way Meters?
    - What proportion of types (deployment classifications using the same network technology) of smart meters?
        - Commercial / industrial gas smart meters,
        - Commercial / industrial electric meters,
        - Commercial / industrial water meters,
        - Residential gas smart meters,
        - Residential electric smart meters, and
        - Residential water smart meters.

Assume the following proportions of types of 2-way meters using scenario 2 in Table 5 as this example has been filtered to just the electric meters:

Table 5: Example 2-way meter deployment classifications and example apportionments

2-Way meter deployment classifications	**Scenario 1 – meter (%)**	**Scenario 2 – meter (%)**	**Scenario 3 – meter (%)**
Commercial / industrial gas smart meters	6.5		2.5
Commercial / industrial electric meters	17.4	10	5.0
Commercial / industrial water meters			2.5
Residential gas smart meters	6.5		20
Residential electric smart meters	69.6	90	45
Residential water smart meters			25
Total	100	100	100

- Quantity of endpoints (meters) per the same technology DAP in a specific deployment geographic area.

Current AMI networks have design maximum number of endpoints per DAP that typically range from 1,000 – 50,000. Actual deployment quantity of endpoints per DAP will be less than the technology's maximums based on:

- the endpoint density
- design limits' thresholds imposed by the network designers to address application latency requirements and providing "headroom" in the network.

For deployments of 100,000 endpoints, multiple DAPs will be required, with the actual quantity of endpoints (e.g., meters) per DAP varying significantly across that 100,000 deployment. When the assessment is focused on the ability of a technology to handle the deployment, two areas of concern arise (i.e., the high density urban areas and the low endpoint density rural areas). One is focused on the handling of all the traffic and the other is being able to extend the reach between the DAP and the endpoints and still provide acceptable application latency and reliability at acceptable cost points.

For example purposes only, let us assume a 1000 endpoints per DAP assessment.

Step 6 - Select which type of data analysis method is to be used:
There are at least two common approaches to data analysis that deal with events that occur in time displaying deterministic timings and those with probabilistic distributions:

a) aggregation of data volumetrics based on values per a specified time period for input into a static system model
b) simulation of multiple discrete transactions (payloads) retaining each event's unique data volumetrics and profiles

The aggregation of data volumes based on values per specified time periods will be discussed in this step. The simulation approach is further discussed in section 5.

Aggregation of data volumes based on values per specified time periods, carries with it no indication of when those events occur during the time period. Many readers may make the assumption that the events occur evenly across the time period, but it is just that, an assumption. All that can be stated is that during that time period the events are expected to occur at the stated quantity per total period.

When using the "Daily Clock Periods" a better understanding of the quantity of events occurring in that shorter time period is possible, though as in illustrated in Table 3 and Table 4 above, interpolating that value to an hourly value for a specific hour of the day is possible, but carries the same limits to that usage as mentioned above.

An alternative to just these simple "How Often" values is to consider what those values would be for different operating modes that a smart grid deployment might encounter. This might be represented as three different values to account for: normal; medium; and high periods of event occurrence. For the meter reading and service switch use cases, this might entail:

- after new rate structures have been imposed
- high energy usage billing periods
- college move ins / move outs or entry or exodus of customers
- storm events

Whether or not SG Network TF adds this additional level of detail to the Requirements Table, the user of the Requirements Table can modify the requirement data themselves to match their analysis needs and assumptions, but it must be documented.

For simplicity, let us disregard the "Daily Clock Periods" and keep the frequency (How Often) based on a 24 hour period, daily values.

Step 7 – Finalize the data preparation tasks based on the selections and assumptions from steps 1-6.

Using the selected values from step 4 and the assumed values from step 5, and assuming that a data analysis method is selected using the aggregation of data volumetrics to simple per period metrics, the aggregate traffic for each direction is calculated in Table 6 and Table 7.

Table 6: DAP to smart meter direction

Event	**How often (events/meter/day)**	**Size (bytes/event)**	**Average traffic load (bytes/meter/day)**
multiple interval meter reading request	25/1000	25	0.625
on-demand meter read requests	25/1000	25	0.625
cancel service switch operate request	2/1000	25	0.05
service switch operate request	50/1000	25	1.25
service switch state request	50/1000	25	1.25
Total	0.152	N/A	3.8

Mean message size (bytes) per event = 3.8 / 0.152 = 25 bytes/event
Number of events per meter per second = 0.152 / 86400 = 1.76 x 10^{-6} events/meter/s

Table 7: Smart meter to DAP direction

Event	**How often (events/ meter/ day)**	**proportion**	**Size (bytes/ event)**	**Average traffic load (bytes/ meter/day)**
multiple interval meter read data (Commercial / industrial electric meters)	24	0.10	1600	3840

multiple interval meter read data (Residential electric smart meters)	6	0.90	2400	12960
Subtotal	Frequency * proportion =	7.8 events/ meter/day	Frequency * Size * proportion =	16800 bytes/ meter/day
on-demand read request app errors	25/1000 * 1/1000		50	0.000025
on-demand meter read data	25/1000		100	2.5
send service switch operate acknowledgment	2/1000		25	0.05
send service switch operate failure	1/1000 * 50/1000		50	0.0025
send metrology information after a successful service switch operate	2/1000		100	0.2
send service switch state data	50/1000		100	5
Subtotal	0.079		N/A	7.75375
Total	7.879 events/meter/day		N/A	16808 bytes/ meter/day

Mean message size (bytes) per event = 16808 / 7.879 = 2133 bytes/event
Number of events per meter per second = 7.879 / 86400 = 9.12 x 10^{-5} events/meter/s

3.7 Security

Security can be considered at every layer of the communication protocol stack, from the physical layer to the application layer. To consider security in the context of PAP 2, 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 (CIA's) 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 PAP 2.

4 Wireless Technology

PAP 2'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 PAP 2 web site:

- ❖ http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

with a file name syntax of "Consolidated_NIST_Wireless_Characteristics_Matrix-VN.xls", where N represents the version number.

Disclaimer: The spreadsheet was created and populated by the Standards Setting Organizations (SSO), which proposed their wireless technologies as candidates for the smart grid. The parameters and metrics contained and values entered for each wireless technology were done by proponents for that technology. The values were not verified by PAP 2.

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 V5.xls).

4.1 Technology Descriptor Headings

To be able to describe wireless technology a set of characteristics were identified and organized into logical groups. The group titles are listed below.

- 1. Link Availability
- 2. Data/Media Type Supported
- 3. Coverage Area
- 4. Mobility
- 5. Data Rates
- 6. RF Utilization
- 7. Data Frames & Packets
- 8. Link Quality Optimization
- 9. Radio Performance Measurement & Management
- 10. Power Management
- 11. Connection Topologies
- 12. Connection Management
- 13. QoS & Traffic Prioritization
- 14. Location Characterization
- 15. Security & Security Management
- 16. Radio Environment
- 17. Intra-technology Coexistence
- 18. Inter-technology Coexistence
- 19. Unique Device Identification
- 20. Technology Specification Source
- 21. Deployment Domain Characterization

- 22. Exclusions

4.2 Technology Descriptor Details

Each of these groups was composed of individual descriptive components for which an entry for each technology was requested. The rows are 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: Link Availability		
a:	Ability to reliably establish an appropriate device link	% of time
b:	Ability to maintain an appropriate connection	failure rate per 1000 sessions
Group 2: Data/Media Type Supported		
a:	Voice	
b:	Data	Max user data rate per user in Mb/s
c:	Video	Max resolution in pixels @ x fps
Group 3: Coverage Area		
a:	Geographic coverage area	km^2
b:	Link budget	dB
Group 4: Mobility		
a:	Maximum relative movement rate	m/s
b:	Maximum Doppler	Hz
Group 5: Data Rates		
a:	Peak over the air uplink data rate	Mb/s
b:	Peak over the air downlink data rate	Mb/s
c:	Peak goodput uplink data rate	Mb/s
d:	Peak goodput downlink data rate	Mb/s
Group 6: RF Utilization		
a:	Public radio standard operating in unlicensed bands	GHz L/UL
b:	Public radio standard operating in licensed bands	GHz L/UL
c:	Private radio standard operating in licensed bands	GHz L/UL
d:	Duplex method	TDD/FDD
e:	Bandwidth	kHz
f:	Channel separation	kHz
g:	Number of non overlapping channels in band of operation	
h:	Spectral Efficiency	bits/s/Hz
i:	Cell Spectral Efficiency	bits/s/Hz/cell

Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application		
Group 7: Data Frames and Packets		
a:	Frame duration	ms
b:	Maximum packet size	bytes
c:	Segmentation support	Yes/No

4.2.1.1 Group 1: Link Availability

The desire is to be able to use the radio link whenever it is needed by the application. There is an expectation that the radio link will not be continuously maintained and that some devices will be "put to sleep" for periods of time and then, upon "wake up," be required to connect to another device on the network to transfer control information or data. Since there is no absolute certainty that a link will be fully operational, there is a probability associated with the connection. The technology "Operating Point" chosen is presumably chosen recognizing that a high % availability is desired.

During the period when a radio link is active there is, again, no guarantee that the link will be flawlessly maintained. The failure source is not defined but is presumed to be associated with the failure of the radio to decode properly the radio symbols causing a packet error. Failure could also be caused by interference from other radio sources or perhaps deep fading due to shadowing, but these effects are not explicitly included in the failure calculations. Rate is another way to represent the statistical nature of a radio link. The technology "Operating Point" chosen is presumably chosen recognizing that achieving a low failure rate is desirable.

4.2.1.2 Group 2: Data/Media Type Supported

Information transferred within the smart grid is usually associated with data. However, it was noted that there would be value in transferring both 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.
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.
c) Video: Especially 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. The request is that the best case capabilities be reported.

4.2.1.3 Group 3: Coverage Area

Wireless systems are designed to service a wide variety of application scenarios. The intent of this group is to capture the expected coverage area in a typical deployment. Some systems are optimized for very short ranges, perhaps 10 meters or less, while others are intended for longer ranges, perhaps on the order of 30 km.
The intent of this group is to capture the expected coverage area in a typical deployment.

When comparing coverage areas, it is important to take into account the link budgets used in the coverage computation. Note that the largest coverage area achievable by a specific technology typically requires transmission at the lowest data rate used by that technology.

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 Doppler shift.

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 meters/second)
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: Data Rates

Data rates are a very frequently used metric of radio link capability. The data rates for wireless technologies can span three decades of range starting at a few kilo bits per second up to several mega bits per second. However, data rate can be considered to be an ambiguous term unless the terms of use are fully described. An additional complication comes 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 pieces of control information. Because of these added bits the data payload may be a small portion of the total number of bits transmitted and received. The metrics used for this group are therefore in two subsets.

a) Peak over the air data rates are intended to display the data rates of the PHY when sending bits through the air from transmitter to receiver.
b) Peak goodput is intended to display the rate at which “application data” is being transferred.

Peak goodput rate calculations remove such items as PHY and MAC preamble, address and error correction from the calculation. A Goodput data rate will always be less than the over the air rate used to send data.

Additionally, some radio systems are designed with uplink and downlink data rates that are equal in both directions, as well as others that allow asymmetric rates. Downlink represents the data transmission from the “central” transmitter to the client device receiver. Uplink 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 uplink. This allows a “central” station or base station to take advantage of antenna height and transmit power that may not be available on the client device.

4.2.1.6 Group 6: RF 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 ISM band which is generally available anywhere in the world but shared among diverse radio technologies, such as cordless phones, 802.11 Wireless Local Area Networks (WLANs), 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.
e) Channel bandwidth - As with data rates, some radios use a very small amount of radio spectrum for their channel bandwidths (perhaps a few kilohertz) while others may use a very large swath (perhaps several MHz).
f) Channel separation - This metric is intended to report the separation between channels.
g) Non-overlapping channels in the band

> To use an example, some 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 FCC Title 47). 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, 802.11 technology would be described as having 11 operating channels, separated by 5 MHz and three non-overlapping channels.

h) Spectral efficiency (bits/second/Hz) - This is a measure of the efficiency of use of the spectrum. It is highly dependent on the modulation scheme being used. Although the differences between over-the-air and usable data described under "Group 5 - data rate" could be repeated here, the intent for this study is only to represent over-the air information. As an example, a radio system operates at a nominal 1800 MHz with a signal that uses 10 kHz of spectrum (Channel bandwidth) to transfer 10 kb/s of signal information, plus has a spectral efficiency of 1 bit per second per Hertz.
i) Spectral efficiency (bits/second/Hz/cell) - By default a simple monopole antenna generates an isotropic pattern with equal transmit and receive gain equal in all directions. Some systems employ narrow band antenna technology to allow the otherwise circular coverage area to be subdivided into "sectors". Each sector then services its own group of radios independently. Although the "central" station

requires a separate antenna for each sector the scheme allows for a greater number of client devices per area of coverage.

4.2.1.7 Group 7: Data Frames and Packets

This group asks for display of information on packetization process.

a) What is the maximum frame duration?
b) What is the maximum packet size that can be sent in one radio frame?
c) Does the radio system support segmentation when the payload size exceeds the capacity of one radio frame?

4.2.2 Descriptions of Groups 8-12 Submissions

Group 8: Link Quality Optimization		
a:	Diversity technique	antenna, polarization, space, time
b:	Beam steering	Yes/No
c:	Retransmission	ARQ/HARQ/-
d:	Error correction technique	
e:	Interference cancellation	
Group 9: Radio Performance Measurement & Management		
a:	RF frequency of operation	
b:	Retries	
c:	RSSI	
d:	Lost packets	
Group 10: Power Management		
a:	Mechanisms to reduce power consumption	
b:	Low power state support	
Group 11: Connection Topologies		
a:	Point to point	
b:	Point to Multipoint	
c:	Broadcast	
d:	MESH	
Group 12: Connection Management		
a:	Handover	
b:	Media Access Method	
c:	Discovery	
d:	Association	

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 (ACK) back to the transmitting station. If the ACK is not received, then the transmitter will try again (up to some limit of retries). Other techniques seek to improve the signal to noise ratio (SNR) at the receiver. The techniques include polarization, beam steering, etc. The intent here is to capture the techniques employed by the candidate systems.

4.2.2.2 Group 9: Radio Performance Measurement & Management

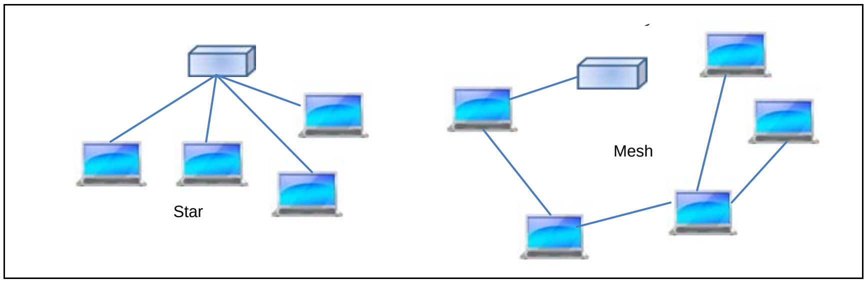
This group is used to indicate what the radio technology provides to an administrator to assist in link assessment. Most radio systems dynamically and autonomously assess their environment and adjust to optimize performance. Sometimes it is useful for a network administrator to monitor behavior to determine 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 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 to use one or more connection topologies. One form that is often used is the star topology.



4.2.2.5 Group 12: Connection Management

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

4.2.3 Descriptions of Groups 13-20 Submissions

Group 13: QoS and Traffic Prioritization		
a:	Traffic priority	diffserv, resserv
b:	Pass-thru Data Tagging	
c:	Radio queue priority	
Group 14: Location characterization		
a:	Location awareness (x,y,z coordinates)	
b:	Ranging (distance reporting)	
Group 15: Security and Security Management		
a:	Encryption	Algorithms supported
b:	Authentication	
c:	Replay protection	

d:	Key exchange	Protocols supported
e:	Rogue node detection	
Group 16: Radio Environment		
	Channel model	
	Interference sources	
Group 17: Intra-technology Coexistence		
a:	Co-channel interference	
b:	Adjacent channel interference	
c:	Alternate channel interference	
d:	Collision avoidance	
e:	Protection mechanisms	
Group 18: Inter-technology Coexistence		
a:	Sensitivity to other interfering radio technologies	
b:	Degree of interference caused to other radio technologies	
c:	Sensitivity to power line RF emissions	
Group 19: Unique Device Identification		
a:	MAC address	
b:	SIM card	
c:	Other identity	
d:	Rogue detection	
Group 20: 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 can be viewed as an end-to-end requirement, but some radio systems assist in the process by providing QoS between radio nodes. This group is used to capture information regarding the capabilities to manage traffic priority.

a) Traffic priority refers to the ability of radio systems to use high level priority schemes such as diffserv (defined by Internet Engineering Task Force (IETF) RFCs 2472 & 2475) & intserv (defined by IETF RFCs 1633 & 2205).
b) Pass-thru data tagging refers to the ability to transfer successfully packets that use a class of service priority tags, such as those defined by IEEE 802.1p
c) Radio queue priority refers to the ability of radio nodes to prioritize packets that are queued for transmission.

4.2.3.2 Group 14: Location Characterization

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 GPS coordinates. 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. As with others such as QoS there are options to apply security at multiple different layers in the communications OSI model. This group focuses on options provided and by the radio system at layer 1 and layer 2.

4.2.3.4 Group 16: Radio Environment

When a wireless technology is designed, the radio environment is considered for effects that it might have on the quality of the radio link. A channel model is usually chosen to represent a typical (or expected) radio environment where the wireless technology is to be deployed. A channel model may consider various forms of signal degradation due to propagation losses and system losses, and it may include environmental effects such as fading and shadowing.

Interference sources generate electromagnetic energy that impinges on the receiver, and which can make receiving the intended transmitted signal difficult. Interference can arise from a variety of natural and human-made sources. Interference can be unintentional (e.g. sources such as rotating machinery or other wireless communications networks that share the same frequency band) or it can be intentional (e.g. jamming).

When the details are provided for both the channel model and the interference sources, the expected performance and quality of service for a given wireless technology can be studied and verified. Without such details, the behavior of a wireless technology in a radio environment for which it was not designed would be unpredictable. In the absence of testing, wireless technologies should not be assumed to operate in environments for which they were not designed.

4.2.3.5 Group 17: Intra-technology Coexistence

Some radio technologies provide mechanisms for avoiding or detecting interference caused by other radios of the same type within receiving range. The intent is to determine if a system has such capabilities that can be used to reduce detrimental interference and thereby improve SINR, and thus allow the radio to maintain a low error rate link.

4.2.3.6 Group 18: Inter-technology Coexistence

As with the previous group, some radio technologies provide mechanisms for avoiding or detecting interference caused by other radios of a different type that are operating in the same spectrum and are within receiving range. The intent is to determine if a system has such capabilities that can be used to reduce detrimental interference and thereby improve SINR, and thus allow the radio to maintain a low error rate link.

4.2.3.7 Group 19: 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.

4.2.3.8 Group 20: 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 support organizations may also provide certification of specification compliance, interoperability and performance.

4.2.4 Descriptions of Group 21 Submission

Wireless Functionality NOT directly specified by a standard that is needed in quantifying operating metrics		
	Rx sensitivity	dBm
	Tx power peak	dBm
	Antenna gain	dBi
	Noise floor	dBm
	Modulation	GFSK, OFDM, BPSK, GMSK
	Forward error coding	Coding rate

4.2.4.1 Group 21 Description

Although these items are vital components of a radio technology description, they do not directly affect the suitability of a technology to a smart grid application.

They are a few additional characteristics that are needed to characterize the operation of the radio for the chosen operating point.

- 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.
- Tx power peak – Transmission peak power is needed for the calculations as well. Some technologies specify only a regulatory limit or allow for a wide variety of options. The Tx power of the devices under consideration for the operating point calculations needs to be specified.
- Antenna gain - Antenna gain is rarely part of a technical radio standard, but is a critical component of link budget calculations.
- Noise floor - 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.
- Modulation - The modulation scheme is not directly part of any calculation but needs to be indentified to aid in other technologists verifying the operating point calculations were correct.

- Forward error coding - The methods used by the technology are not of direct interest but the coding rate is when trying to understand the difference between over-the-air data rates and goodput rates.

4.3 Technology Submission Titles

Responses have currently been received for the following technologies:

- Cdma2000 1x and cdma2000 High Rate Packet Data (HRPD)
- Cdma2000 xHRDP
- Geo Mobile Radio 1 (GMR-1) Third Generation (3G)
- Internet Protocol over Satellite (IPOS) /Digital Video Broadcast (DVB)-S2
- Regenerative Satellite Mesh - A (RSM-A)
- IEEE 802.16 e,m
- IEEE 802.11
- IEEE 802.15.4
- Inmarsat Broadband Global Area Network (BGAN)
- Long Term Evolution (LTE)
- Evolved High-Speed Packet Access (HSPA+)
- Universal Mobile Telecommunications Systems (UMTS)
- Enhanced Data rates for GSM Evolution (EDGE)
- Bluetooth

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 planning for 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 Media Access Control (MAC) sublayer and Physical Layer (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 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 impractical. PAP 2 assesses each wireless technology on whether it can satisfy the smart grid user applications' requirements; PAP 2 will not rank the various wireless technologies relative to each other.

5.1 Assessment of Wireless Technologies Against Smart Grid Business Application Requirements

The assessment approach described below should be considered as an example, not the approach that must be used. Options are discussed on how the assessment can be refined with one method 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 user application's requirement for reliability should be related to the wireless technology's link availability (i.e. the ability to reliably establish an appropriate device link and the ability to maintain an appropriate connection). One can use the results from the initial assessment to determine whether a given wireless technology should be further considered for use with a particular application in a particular deployment.

5.1.2 Perform 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). 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 and input based on probabilities. Mathematical models usually take less time to produce results than simulation models. There are some limitations to what some of the simpler mathematical models can adequately model.

5.1.2.2 Simulation Models

These types of models, attempt to account for more of the event occurrence variability as noted in the mathematical model discussion above. Simulation models can provide more realistic results than mathematical models, which often require simplifying assumptions to make them tractable.

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, actual in the field), can provide very accurate results; however, this method requires significant time, effort, and resources to produce results.

These results may also be provided as feedback to the other types of models to improve their 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 the 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 fidelity constraints?
    a. This will depend on multiple factors, including the latency and fidelity 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. Translation – one size does not fit all. So the network designers 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 to 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 PAP2 working group and it is described in section 5.2.

5.2 Modeling Framework

The goal of the development process was to produce an analytical structure that was flexible so that it allows 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 (multilink). The overall design of the model is shown in Figure 4. The following subsection discuss each of these components and explain how they interact with each other and operate within the larger analytical framework.

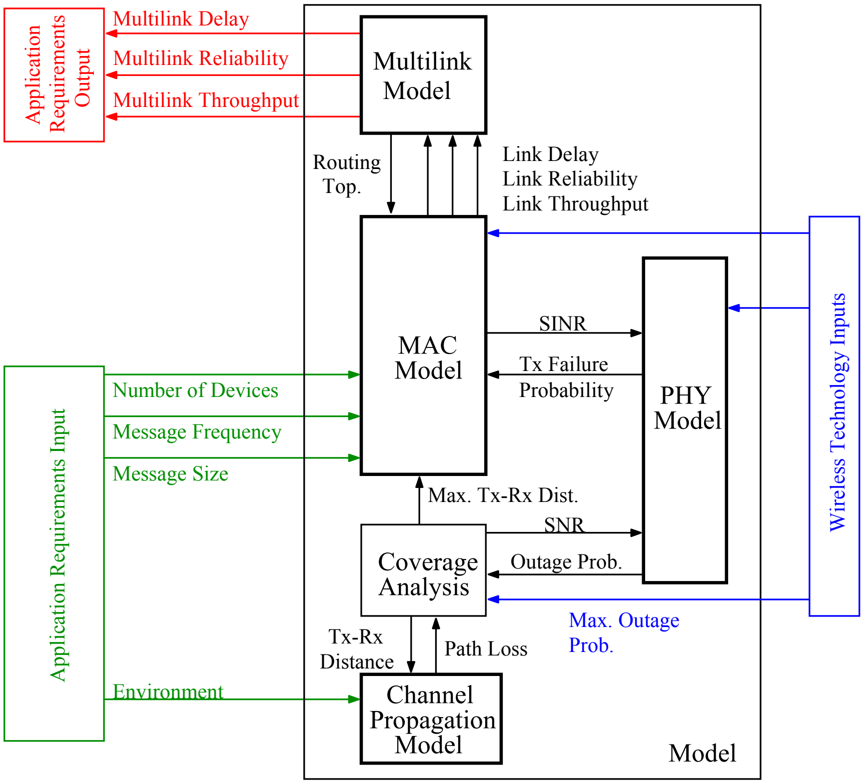


Figure 4 – Modeling Framework Building Blocks

5.2.1 Channel Propagation Models

Channel propagation models characterize how different electromagnetic environments alter a communications signal propagating along the wireless path between a transmitter and receiver. Because it affects the receiver signal-to-noise ratio, the characteristic of greatest interest to the wireless communications designer is signal attenuation. Other important characteristics are shadow fading and small-scale fading.

Signal attenuation is modeled through the quantity known as the path loss. It is important to recognize that a single model cannot fully describe or predict path loss characteristics for all possible scenarios. Operating frequency and deployment environment such as indoor, outdoor, urban, suburban, or rural; must also be considered. Following are some well-known narrowband channel models that can used to predict the path loss for ground-to-ground and tower-to-ground systems.

5.2.1.1 Generic 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 pair. The widely accepted model in the wireless propagation community is exponential attenuation in function of distance according to a path loss exponent, n_0. However, in particular in non-line-of-sight environments, the degree of exponential fading increases to n_1 after a certain breakpoint distance, d_1. The breakpoint path loss model below (equivalently shown on a dB scale) is more general to capture this phenomenon:

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

where $PL_{0,dB}$ is the reference path loss at $d_0 = 1$ meter. All the model parameters are frequency-specific.

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 on the wireless path. Obstructions may be buildings or cars in the outdoor environment or walls or furniture in the 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. The second term, $X_{f,dB}$, is referred to as small-scale fading. It represents the deviation of the signal due to the presence of smaller obstructions on the path which cause scattering of the signal. The signals then constructively and destructively recombine at the receiver. X_f is modeled as a unit-mean gamma-distributed random variable with variance 1/m (where m is the Nakagami fading parameter) 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 those on other links.

The complete path loss model, including both deterministic and random components, is

$$PL_{dB} = PL_{d,dB}(d) + PL_{r,dB}$$

Figure 5 shows 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-indoor residential environment at $f_c = 5$ GHz. The deviation of the data points from the line reflects the random component.

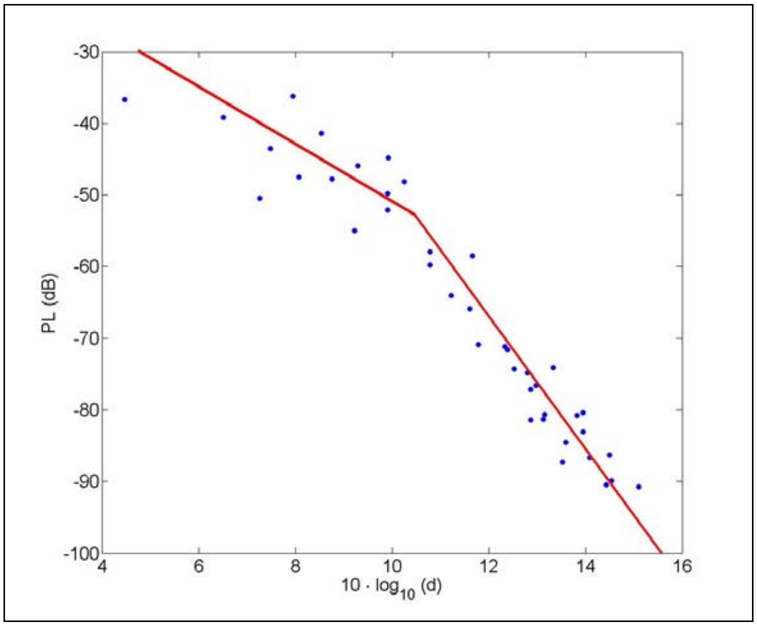


Figure 5 - The breakpoint path loss model in an indoor-indoor residential environment at $f_c = 5$ GHz

5.2.1.2 Outdoor Channel Models

5.2.1.2.1 The Hata Model:

The Hata model for the deterministic component of the path loss $PL_{d,dB}$, based on empirical data, is applicable over a frequency range from 700 MHz to 1500 MHz.

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

where:

d = path distance in km from 1 – 20
f = frequency in MHz
T_h = base station antenna height from 30 to 200 meters
R_h = subscriber station antenna height from 1.0 to 10 meters

and

for Urban environments:

$a(R_h) = 3.2[\mathrm{Log}_{10}(11.75*R_h)]^2 - 4.97$
$D = 0$

for Suburban environments:

$a(R_h) = [1.1*\mathrm{Log}_{10}(f)-0.7]*R_h - [1.56*\mathrm{Log}_{10}(f)-0.8]$
$D = - 2[\mathrm{Log}_{10}(f/28)]^2 - 5.4.$

5.2.1.2.2 Modified Hata (aka COST 231 Model):

The modified Hata model, also for the deterministic component of the path loss $PL_{d,dB}$, is applicable from 1500 MHz to 2000 MHz and with a frequency correction factor f_c can be extended to higher frequencies.

$$PL_{d,dB} = 46.2 + 33.9\log_{10}(f) - 13.82\log_{10}(T_h) - a(R_h) + [44.9-6.55\log(T_h)]\log_{10}(d) + 0.7*R_h + C + f_c$$

where:

d = path distance in km from 1 – 20
f = frequency in MHz
T_h = base station antenna height from 30 to 200 meters
R_h = Subscriber Station Antenna Height from 1.0 to 10 meters
$f_c = 26*\mathrm{Log}_{10}(f/2000)$ for $f > 2000$ MHz, 0 for $f < 2000$ MHz

and

for Urban environments:

$a(R_h) = 3.2*[\log_{10}(11.75*R_h)]^2 - 4.97$ and $C = 3$ dB

for Suburban environments:

$a(R_h) = [1.1*\log_{10}(f)-0.7]*R_h - [1.56*\mathrm{Log}_{10}(f)-0.8]$ and $C = 0$.

5.2.1.2.3 Erceg Model:

Another channel model that has proven effective for projecting path loss for fixed rural area deployments is the Erceg Model. For this model, which is considered applicable from 1800 to 2700 MHz, three terrain types are defined as follows:

- 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 path loss is given by the following expression:

$$PL_{d,dB} = 20\log_{10}(4\pi\, d_0/\lambda) + 10(a-b*T_h + c/T_h)\log_{10}(d/d_0) + 6\log_{10}(f/2000) - X\mathrm{Log}_{10}(R_h/2)$$

where:

d = distance of path distance in meters
f = frequency in MHz
T_h = base station antenna height in meters
R_h = subscriber station antenna height in meters

d_0 = 100 meters
λ = wavelength in meters

The remaining parameters are provided in the following table:

Parameter	Type A	Type B	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	20

The following figures (Figure 6, Figure 7, and Figure 8) provide a view of the path loss predicted based on the above models for frequencies ranging from 700 MHz to 3650 MHz. In all cases, the base station antenna height is assumed to be 30 meters and the subscriber station antenna is assumed to be 10 meters. The subscriber station antenna height assumption is considered reasonable for a DAP.

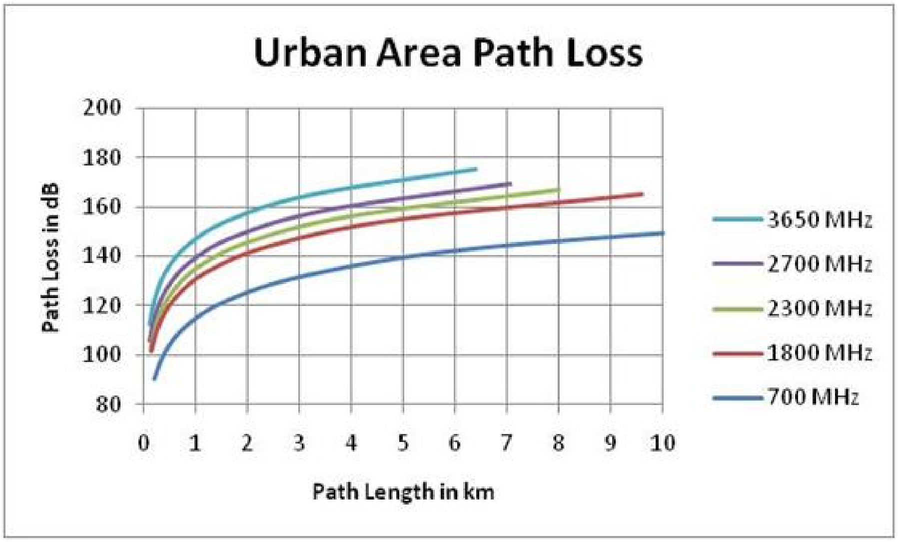


Figure 6 - Path loss as a function of path length for an urban area

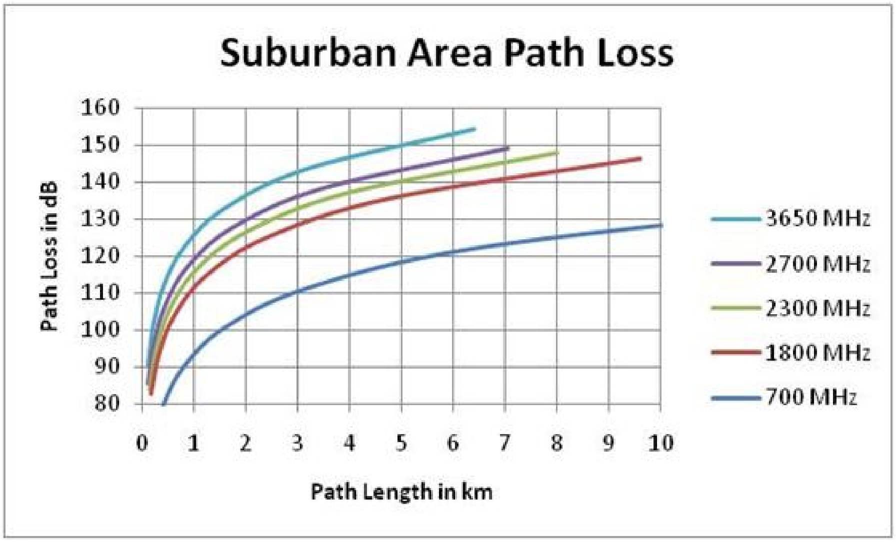


Figure 7 - Path loss as a function of path length for a suburban area

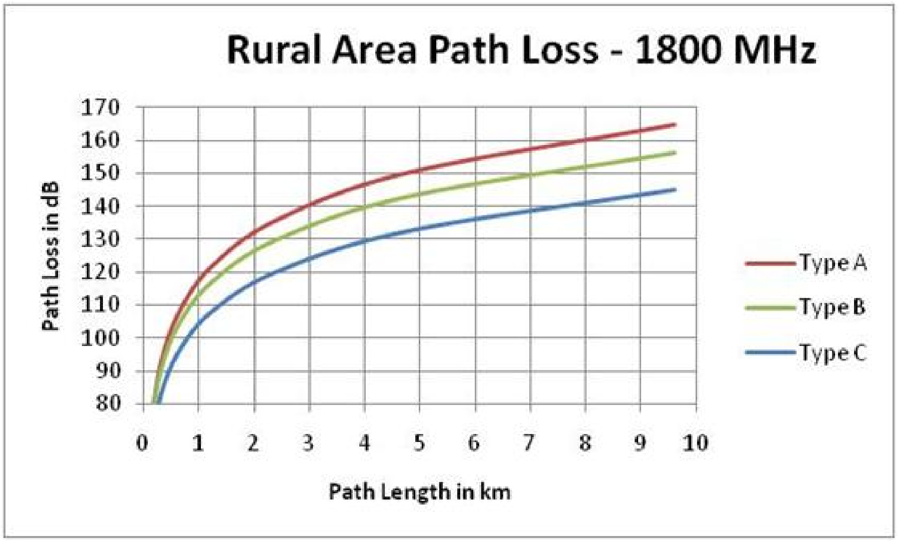


Figure 8 - Path loss as a function of path length for a rural area

Another parameter that is of interest in assessing the path loss is the sensitivity to the relative antenna heights. Each of the three channel models described above has a dependency on both the base station and subscriber antenna height. In most deployments the base station will be mounted on a tower or on a building rooftop to achieve an antenna height of 30 meters or more. The subscriber station antenna height, however, will be more variable as it is strongly tied to the usage model.

Figure 9 and Figure 10 show the effect of varied subscriber station antenna heights on path loss as predicted by the Hata and modified Hata models. Note that for urban areas the impact of the subscriber station antenna height on path loss is independent of frequency.

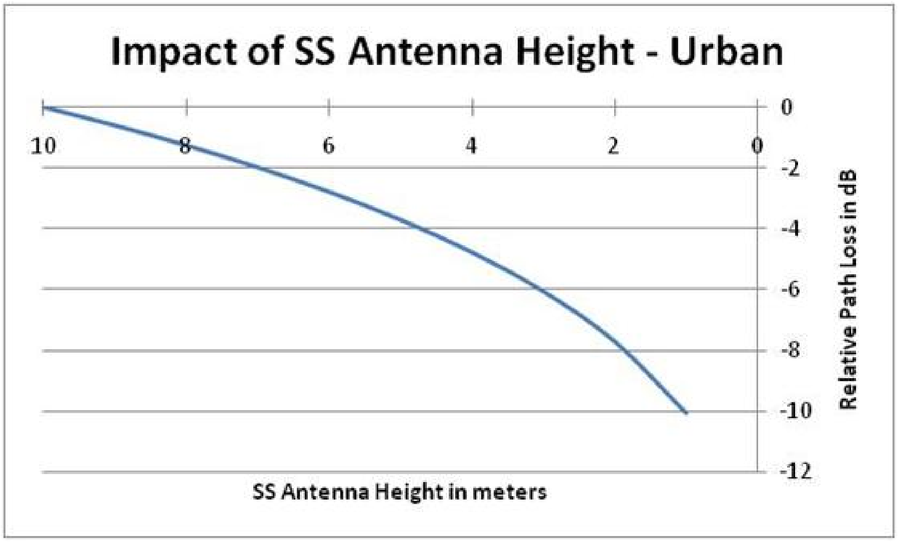


Figure 9 - Effects of SS antenna height on relative path loss in an urban area

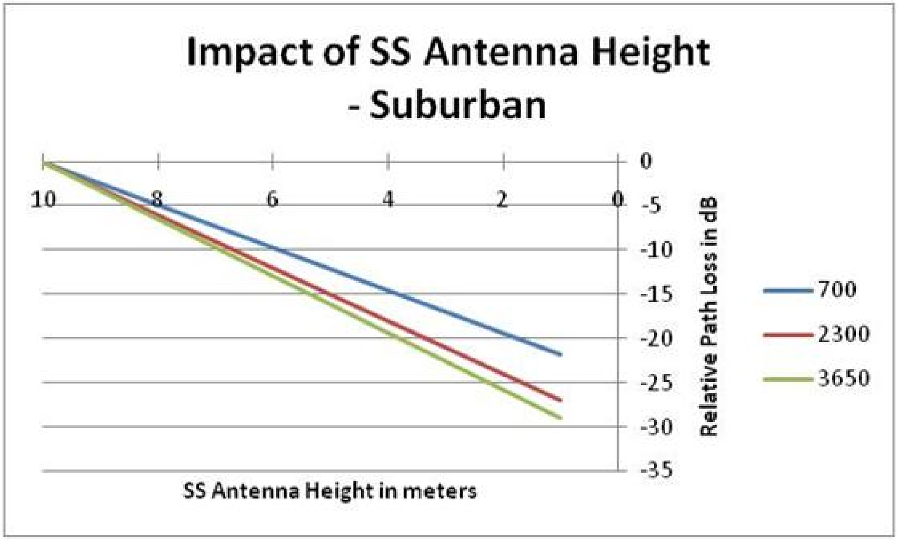


Figure 10 - Effects of SS antenna height on relative path loss in a suburban area

5.2.2 Coverage and Range 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 maximum range is useful in determining the suitability of a technology for linking a particular pair of smart grid 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. Outage 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 point-to-multipoint wireless technology, coverage can be analyzed in terms of the maximum cell radius that a base station or an access point can support. In this spirit, the link budget of the wireless link is examined in conjunction with the appropriate path loss models described in section 5.2.1.

A ***Link Budget*** analysis considers all of the relevant network parameters and thus serves as an essential tool in the design of point-to-multipoint wireless networks.

Control channels and data channels in wireless networks often use different features. Therefore 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 are not used. These features are available however, for the data channels. These link budget enhancing features include: Hybrid Automatic Repeat Request (HARQ), multiple-input / multiple-output (MIMO), etc.

The link budget 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 link budget, UL Control Channel link budget, DL Data Channel link budget, and the UL Data Channel link budget.

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

- Effective isotropically radiated transmit power (EIRP) in dBm (TxEIRP)
- Receiver sensitivity at lowest operating MCS in dBm (RxSNS)
- Combining gains (HARQ gains, repetition gain, etc…) in dB (CombGain)
- Receiver antenna + amplifier gain in dB (RxGain)
- Receiver cable loss in dB (CablLoss)
- Wall penetration loss in dB (PenLoss)

The maximum allowable path loss for a specific channel is given by:

$$\text{MaxPL}_{\mathbb{CH}} = \text{TxEIRP} - \text{RxSNS} + \text{CombGain} + \text{RxGain} - \text{CablLoss} - \text{PenLoss} \qquad (1)$$

The maximum system allowable path loss is given by the minimum $\text{MaxPL}_{\mathbb{CH}}$ for all channels

$$\text{MaxPL}_{\text{sys}} = \min\left(\text{MaxPL}_{\mathbb{CH}} \text{ over all channels in either UL or DL direction}\right) \qquad (2)$$

For a predefined system, the outage probability at a certain distance, d, from a base station or an access point can be calculated as follows:

$$\text{Fade Margin} = \text{MaxPL}_{\text{sys}} - \text{PL}_{\text{d,dB}}\ , \qquad (3)$$

where $\text{PL}_{\text{d,dB}}$ is the path loss at d as calculated by one of the path loss models in section 5.2.1.

In addition, given the stochastic models for various categories of fading (shadow, small-scale), the outage probability can be expressed as:

Outage Probability = Probability (Random Fading > Fade Margin) (4)

The above analysis can be done in reverse to calculate the maximum range or, for ubiquitous coverage, the maximum allowable base station–to-base station spacing to guarantee a specific outage probability.

Both the ***Link Budget*** and the ***Path Loss*** are also linked to the usage model of interest. While the base station parameters are relatively independent of the usage model, the terminal or subscriber station parameters will vary considerably depending on the application.

Usage models for smart grid applications can be described as follows:

- **Fixed Outdoor-Mounted Subscriber Station:** This would be a typical installation for a DAP, substation, or other distribution facility. The terminal or subscriber station can be mounted on an existing utility pole, on top of, or on the side of an existing structure. For this usage model the subscriber station is equipped with a high gain directional antenna that is aligned to maximize received signal strength. With easy access to AC power, the uplink transmit power (TxEIRP) can be set to the maximum allowed by regulation. In summary, this usage model is characterized by:
  - High subscriber station antenna gain: typically 12 dBi to 17 dBi dependent on operating frequency and antenna size
  - Higher transmit amplifier power
  - Relatively high antenna height: typically 8 meters -10 meters (or higher)

- **Vehicular-Installed Mobile Station:** 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 Subscriber Station, these installations are characterized by:
  - Lower antenna gain: must be omnidirectional in azimuth, typically 6 dBi - 8 dBi
  - Lower antenna height: typically two meters to three meters, if mounted on vehicle roof

- **Fixed Indoor Subscriber Station:** For smart grid applications, this usage model would apply to a smart meter, remote office, a temporary quick-to-install station, or possibly a work-at-home situation for a key utility worker. For this usage model, the link budget is impacted by:
  - Antenna gain: limited in size for convenience purposes, typically 6 dBi - 8 dBi
  - Antenna height: typically 1 meter to 3 meters
  - Building/wall penetration loss: this can vary from 3 dB to 4 dB for a window-placed station 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.

- **Mobile Hand-Held Subscriber Station:** This may not necessarily be a common usage model for smart grid applications, since it can in most cases be covered with the use of public networks. Nevertheless, for completeness, it is worth mentioning here. The link budget for the mobile usage model is almost always limited by the uplink control channel; this is due to the limited antenna size and the lower transmit power of the hand-held device. The transmit power is constrained by the battery capability. For this usage model, the link budget must account for:
    - Lower antenna gain: must be omnidirectional, typically -1 dBi to 0 dBi
    - Antenna height: typically 1.5 meters
    - Lower transmit power: typically 200 mW
    - Building/wall penetration loss: to support indoor operation

Taking these factors into account, the difference in link budget for a fixed outdoor subscriber station compared to a mobile hand-held subscriber station can range from as much as 20 dB in the 700 MHz band to more than 30 dB in the 3650 MHz band. Deciding on which usage models are most important for smart grid applications is a key consideration in determining the base station requirements for ubiquitous wireless coverage.

5.2.3 Physical Layer Model

The purpose of the PHY layer model is to estimate the probability that a transmission attempt fails due to channel errors caused by noise and 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 layer 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 or block error rate. Alternatively, the PHY model may abstract some of these functions and model them with an overall required E_b/N_0 (energy per bit to noise power spectral density ratio), wherein the probability of transmission failure is reflected as the probability that the received signal-to-noise-and-interference ratio (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.

5.2.4 MAC Sublayer Model

The MAC sublayer model can be either analytical or simulation-based, and its 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
- Throughput

Reliability, R, is defined to be 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, D, 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 that 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 rate in bits/s
- 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

The throughput, S, 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, λ, and the packet reliability, R. Note that this means 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 layer 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 layer that uses dedicated resources (so no contention) and no retransmissions, it would be found that the reliability is equal to ($1 - P_{fail}$), 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 size of the user population.

5.2.5 Multilink 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 links, denoted as a multilink, rather than through a single link alone. The MAC model generates performance metrics for single links; the multilink model, on the other hand, works interactively with the MAC model to generate end-to-end performance metrics for multilinks.

As illustrated in Figure 4, the multilink model accepts single-link performance metrics as input from the MAC model. From them, the multilink model generates the same classes of performance metrics for multilinks. 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 multilinks.

The routing topology 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 sources nodes is a single base station or access point, links connected directly to the destination will be forwarding traffic from all other sources. This translates to a higher offered load λ for these 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 multilink model and in turn computes the offered load of all links accordingly.

6 Factors to Consider in Determining Performance

This section identifies key performance trends and factors that are common to many smart grid wireless communication deployments. Among these factors are coverage, capacity, interference, and the wireless environment.[15] Though these factors by no means represent an exhaustive list, they are a subset that will have to be considered in almost any deployment.

Rather than consider every candidate wireless technology in the context of every environment and smart grid application that has been catalogued, and given the need to produce this report in a timely fashion, examples drawn from the models contributed in the Annexes are used to illustrate how these factors can affect whether the application requirements of certain use cases can or cannot be met. While these examples are based on models of specific technologies and environments, the trends observed and the conclusions drawn generally apply to many other wireless technologies and deployment scenarios.

The main conclusions are summarized as follows.

- There is an inherent tradeoff between wireless coverage and capacity. For example, reducing the coverage range of a DAP increases the maximum sustainable load per smart meter. However, if interference is severe enough to cause performance loss even at low loads, then reducing coverage will not bring any benefit. Also, there is a cost associated with reducing coverage, namely a greater number of base stations or access points. Conversely, in coverage-limited cases where wireless capacity is underutilized, one model is used to illustrate the benefits and limits of extending coverage through multi-hop communication.

- Whether a link is coverage-limited or capacity-limited depends not only on the offered load, but also on environmental conditions. In one example using representative urban, suburban, and rural environments, the wireless link is shown to be coverage-limited in all three environments under average offered load per smart meter. However, at peak offered load, the link is capacity-limited in urban and

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[15] One recognizes that these factors are interdependent. For example, there is a tradeoff between coverage and capacity, and both are affected by interference and the propagation environment.

suburban environments, but remains coverage-limited in a rural environment. Thus, the network designer may have to consider the environment carefully, especially when designing the link to handle the more infrequent high-load cases.

- Interference lowers the maximum load per smart meter that can be sustained while still satisfying reliability and delay requirements. Furthermore, associated with each wireless technology deployment is a maximum tolerable level of interference beyond which reliability suffers even at low smart meter loads.

Quantitative examples supporting these conclusions are provided in the ensuing sections. Implicit in their use is the fact that a network designer has to accurately measure the environment over a period of time to fully characterize the channel, and that only then can one make predictions about how the link will perform. For example, considering the interference and the wireless technology's ability to deal with it will be an important step in the design process. Determining the coverage area will also involve design tradeoffs that can be made only with an accurate picture of the environment in hand, and as projected to change over the life of the deployment. Finally, the network operator must make design decisions with future traffic growth in mind.

It is important to note that the quantitative data used in this section is for illustrative purposes only. While the degree to which the environment impacts a particular wireless technology depends on the technology itself and how it is implemented, the general implications of the environmental effects that will be discussed applies to any wireless link-layer technology that could be used to communicate over the link of interest.

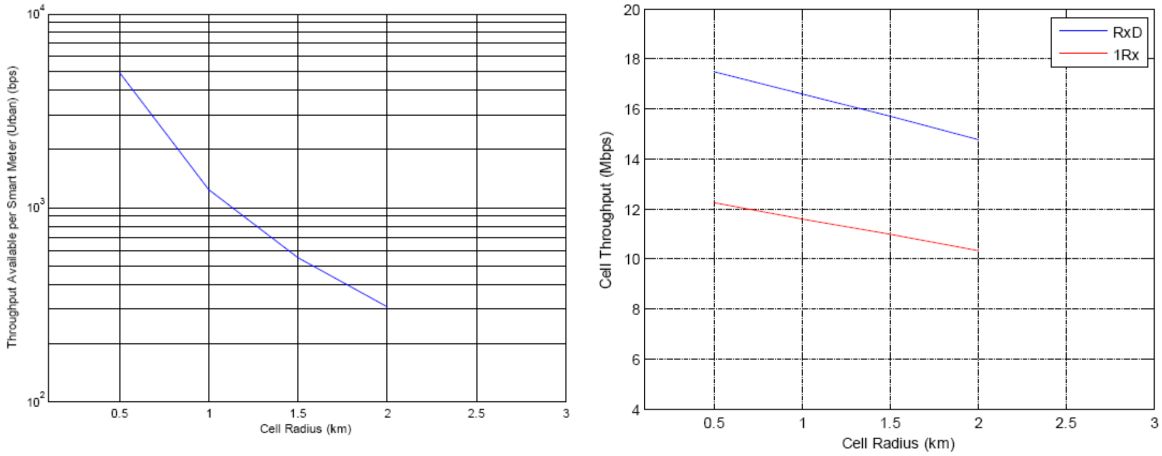
6.1 Performance Metrics and User Application Requirements

The performance metrics used below directly relate to the user requirements that have been compiled for this effort. They include the application throughput, the reliability (i.e. the probability that the frame can be successfully sent over the wireless link), and the average delay in sending a frame over the wireless link from one node to the next.

It is important to note that the user requirements are measured at the application layer, while the numerical data presented in this section is for the link performance and represents only a component of these requirements. Additional protocol and processing overheads may introduce additional components that need to be considered. For example, the link performance for latency is required to be less than the application latency requirement in order to account for the additional delay components and processing times introduced by higher layers.

6.2 The Coverage-Capacity Tradeoff

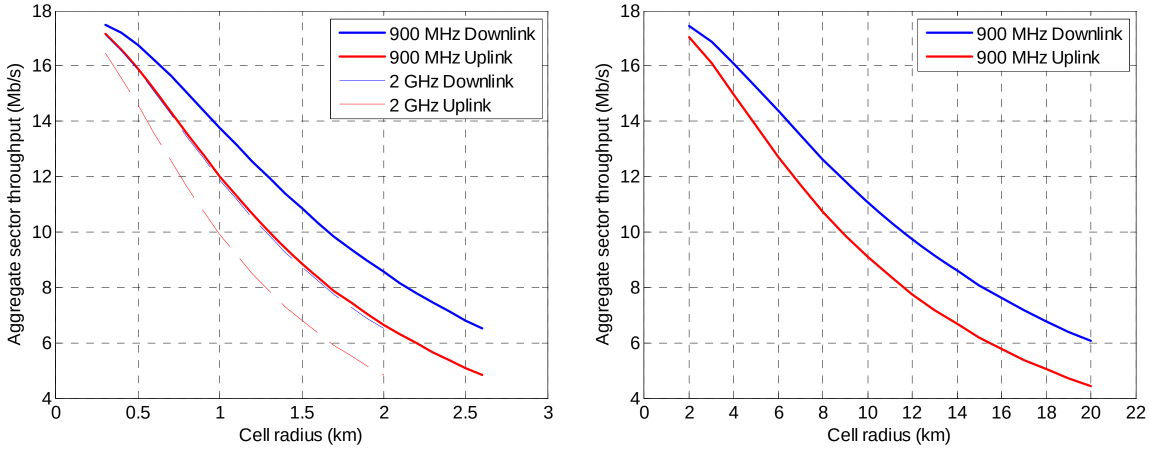
There are several factors which may influence the setting of the coverage range by a network designer. Typically, a designer wishes to extend the coverage range as much as possible, keeping in mind the changing capacity requirements over time. For example in the case of the link between a DAP and a smart meter, this enables the DAP to serve the greatest number of smart meters. In some other examples, the coverage range may be intentionally set lower in order to mitigate interference, conserve power, or increase the available capacity per device over time.



(a) Uplink throughput per smart meter

(b) Downlink throughput with 1 receiver (1Rx) and receiver diversity (RxD)

Figure 11 - Throughput vs. cell radius using model in Annex C



(a) Urban environment

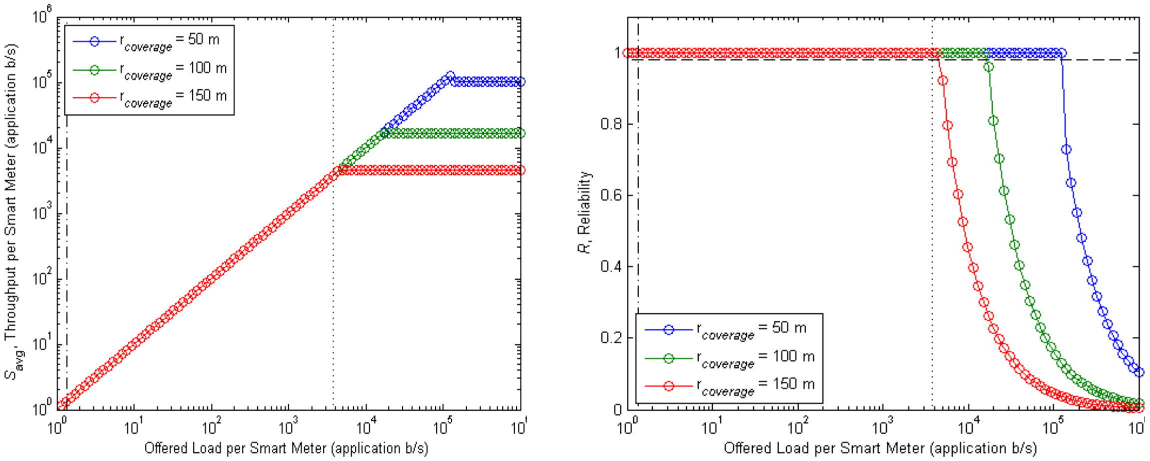
(b) Rural environment

Figure 12 - Average sector throughput vs. cell radius using model in Annex B

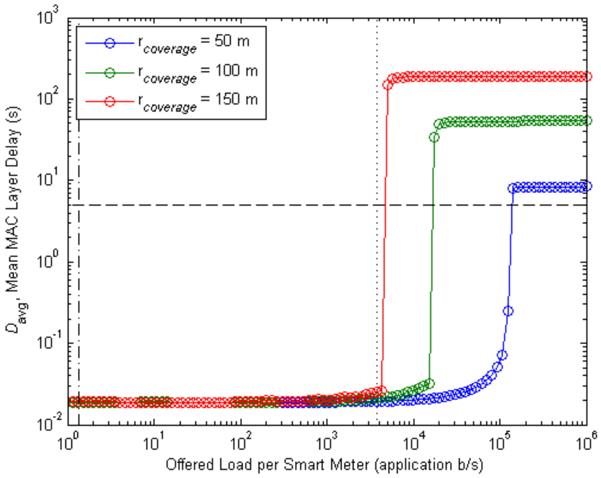
In general, as coverage increases, overall capacity in the coverage area decreases due to attenuation of the signal with distance. Furthermore, increasing the coverage area often means increasing the number of devices sharing the system capacity, further depressing per-device capacity. Numerical examples of this tradeoff in the context of wide area network cellular technologies are shown in Figure 11, reproduced here from Annex C, and in Figure 12, reproduced from Annex B. These graphs demonstrate the decrease in uplink and downlink throughput with increasing cell radius.

Similarly, in a local or neighborhood area network using carrier sense multiple access protocols, an increase in coverage area translates to more stations contending for access to the medium. Figure 13 shows results generated using the model in Annex A for the meter reading and service switch use cases (i.e., between DAP and smart meter) in a suburban environment. The graphs plot throughput per smart meter, reliability, and mean MAC sublayer delay versus the offered load per smart meter (measured in application bits per second) at three different coverage ranges of the DAP. In each graph, the peak and average offered loads per smart meter are indicated by dotted and dash-dotted vertical lines, respectively. In addition, dashed horizontal lines indicate a lower limit on the reliability (98%) and an upper limit on the delay (5 s). These offered load, reliability, and delay thresholds are derived from the use case requirements. In practice, these limits would be determined by the network designer based on the smart grid's operational requirements.

The critical values of the offered load, beyond which the system saturates and the performance becomes poor, are the values at which the throughput plot flattens, the reliability plot turns downward, and the delay plot jumps from a low unsaturated value to a higher saturated value. The results in Figure 13, which demonstrate acceptable performance for all three coverage ranges, even at peak offered load, also illustrate the coverage-capacity tradeoff. For example, Figure 13(a) shows lower saturation throughput levels for larger DAP coverage areas. In other words, as the coverage area increases, the sustainable load per smart meter decreases.



(a) Throughput (b) Reliability



(c) Mean MAC layer delay

Figure 13 - Performance vs. offered load for various coverage ranges using model in Annex A

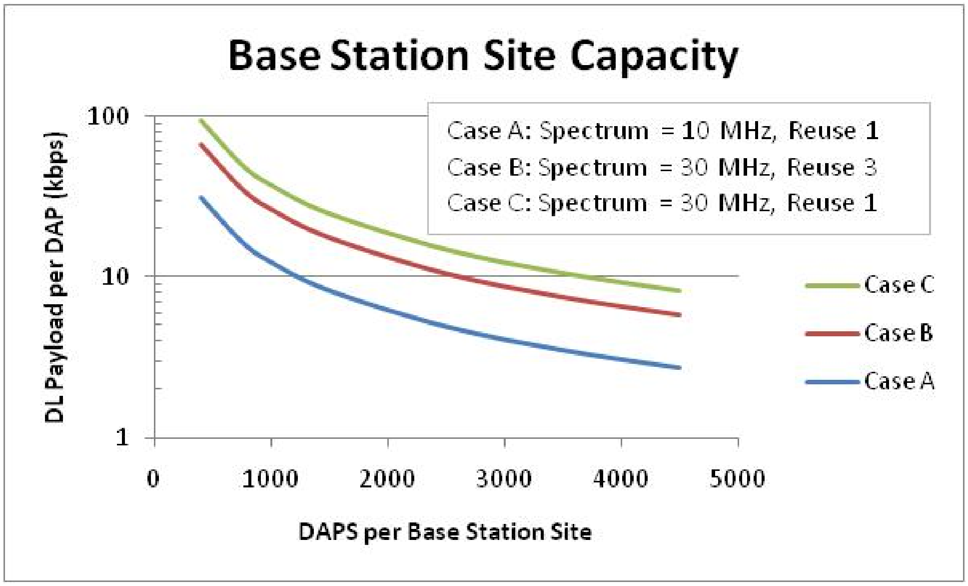


Figure 14 - Comparing base station site capacity by frequency reuse

Another factor that affects capacity in cellular deployments is frequency reuse. A three-sector base station with a reuse factor of 3 requires a unique channel to be assigned to each sector. This will result in a high channel or sector spectral efficiency since inter-sector interference is minimized, but this approach requires 3 times as much spectrum. With a reuse factor of 1, the same channel is reused in each of the three sectors. While inter-sector interference will result in a lower sector or channel spectral efficiency, the net site spectral efficiency can be higher in some cases.

A comparison of frequency reuse factors is made in Figure 14 in terms of downlink DAP capacity for an OFDMA-based metropolitan area network, reproduced here from Annex

E. Comparing reuse 3 with 30 MHz of spectrum to reuse 1 with 10 MHz of spectrum, the site capacity is approximately doubled, but at a cost of requiring three times as much spectrum. In this example, a frequency reuse factor of 1 provides a net 50% improvement in site spectral efficiency compared to reuse 3.

6.3 Extending Coverage with Multi-Hop Communications

Wireless deployments for the smart grid may be underutilized in some cases, leading to coverage-limited rather than capacity-limited scenarios.[16] In order to fully utilize the network resources in coverage-limited scenarios, multi-hop communications offers a means to extend coverage.

Multi-hop stations route through one or more relay stations in the network when there is no direct link to the base station or access point. However, a consequence of multi-hop communication is the buildup of traffic at the relay stations. Besides transmitting their own generated traffic, the relays are charged with forwarding traffic from stations routing through them. The stations with a direct link to the base station or access point are the most heavily taxed, since they must relay for all other stations. Their forwarded traffic can be orders of magnitude greater than their own generated traffic. As a result, they are the first to reach saturation. As the deployment range increases, so does the amount of forwarded traffic through them. At some deployment range, they reach full capacity at which point network resources are fully exploited.

Using the model described in Annex A.4, Figure 15 shows the effect of extending coverage with multi-hop communication on a network of smart meters connected to a DAP. The graph plots the throughput per smart meter versus the deployment range at peak offered load in three different environments: urban, suburban, and rural. At the nominal transmission power levels specified in section A.5, the single-hop coverage ranges are 113 m, 159 m, and 738 m in the urban, suburban, and rural environments, respectively, and are indicated on the plots by vertical dashed lines.

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[16] See, for example, the analysis in Annex D.

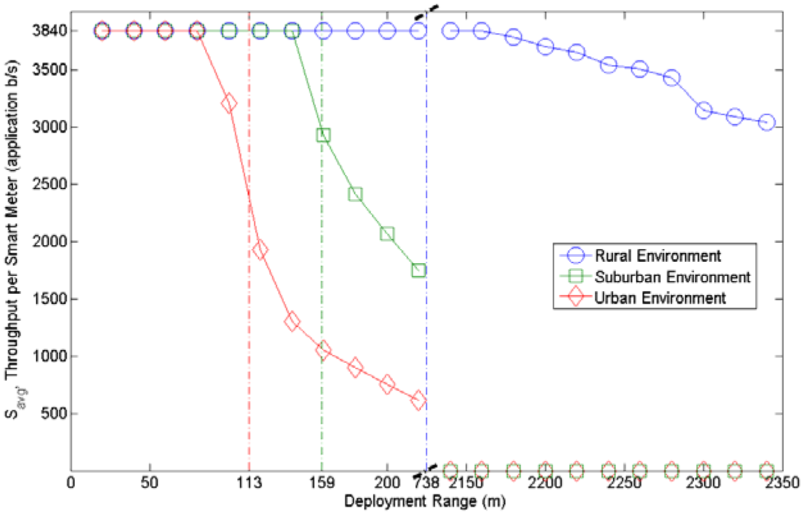


Figure 15 - Throughput vs. deployment range for various environments using model in Annex A.4

While saturation is reached prior to the single-hop coverage limits in the urban and suburban environments—implying a capacity-limited network in those environments—the rural environment is shown here to be a suitable candidate for multi-hop communication. Saturation in the rural environment is reached around 2150 m (note the discontinuity in the horizontal axis), which is nearly three times the single-hop range in that environment. While this example assumed peak offered load, coverage can be extended even further at more typical levels of offered load.

6.4 The Effect of the Wireless Link Environment

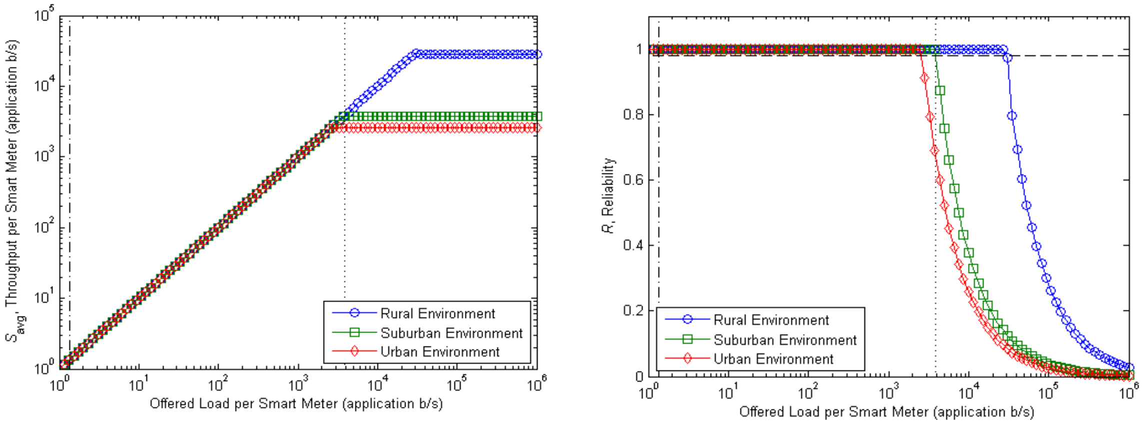
In the previous section, it was shown that a wireless deployment can be coverage-limited in some environments and capacity-limited in others. This section further investigates the impact of the RF environment.

As noted in section 5.2.1, the RF environment affects the degree to which a signal is attenuated with distance. In a flat, open area, for example, a signal will typically propagate longer distances than in an area with many buildings, mountains and foliage. Furthermore, the environment impacts how much the signal will vary from one location to another. The greater the variability, the more margin is needed in the link budget to maintain a certain reliability. Both attenuation and variability depend on the carrier frequency of the signal, as well as the transmitter and receiver antenna heights, and the models in section 5.2.1.2 attempt to model these dependencies.

In order to illustrate the impact on performance of a range of RF environments, three representative environments ranging from least challenging to most challenging in terms of signal reach and stability were selected. The “rural” environment is relatively benign, featuring shallow path loss and low-variance shadowing. The other environments, denoted as “suburban” and “urban,” feature steeper path loss and more severe shadowing, with the "urban" environment being the worst. The parameter values for these environments, corresponding to the channel model in section 5.2.1.1, are summarized in Table 8, reproduced here from section A.5. The last row of the table lists representative smart meter densities for these environments.

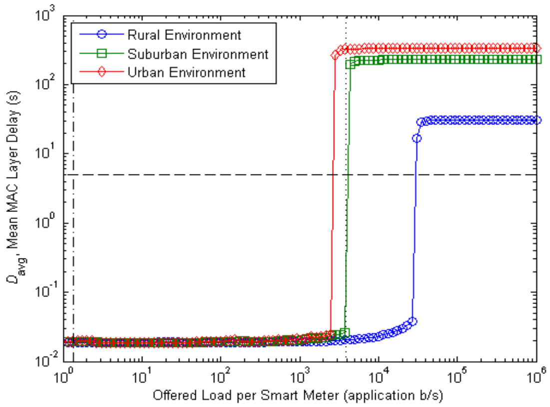
Table 8 : Channel parameters and smart meter density for rural, suburban, and urban environments

Environment	**Rural**	**Suburban**	**Urban**
n_0	2.1	2.7	3.6
n_1	7.5	N/A	N/A
d_1 (m)	650	N/A	N/A
L_0 (dB)	38.3	40	21.3
σ (dB)	2.2	7.4	7.4
m (Nakagami fading parameter)	1	1	1
ρ (smart meters per km^2)	10	800	2000



(a) Throughput

(b) Reliability



(c) Mean MAC layer delay

Figure 16 - Performance vs. offered load for various environments using model in Annex A

The performance of the link between smart meters and a DAP in each of these environments was then compared using the model in Annex A. The graphs in Figure 16 plot throughput, reliability, and delay versus the offered load. As the offered load increases, saturation is reached first in the urban environment, followed closely by the suburban environment, and finally the rural environment. At the average offered load of the meter reading and service switch use cases (denoted by the vertical dash-dotted line), the performance requirements (98% reliability and 5 s delay) can be met in all three environments in this example. However, under peak load conditions (vertical dotted line), these requirements can be met with certainty only in the more benign rural environment. In a suburban environment, the network is just barely able to meet the reliability and delay requirements. The difference in performance is due to better RF propagation characteristics and a lower density of smart meters in the rural environment.

The results suggest that, under average load conditions, the wireless link is coverage-limited in all three environments in this example. However, under peak load conditions, the link is capacity-limited in the urban and suburban environments but remains coverage-limited in the rural environment. The implication is that both traffic load and type of environment must be considered when assessing the coverage and capacity limits of a technology.

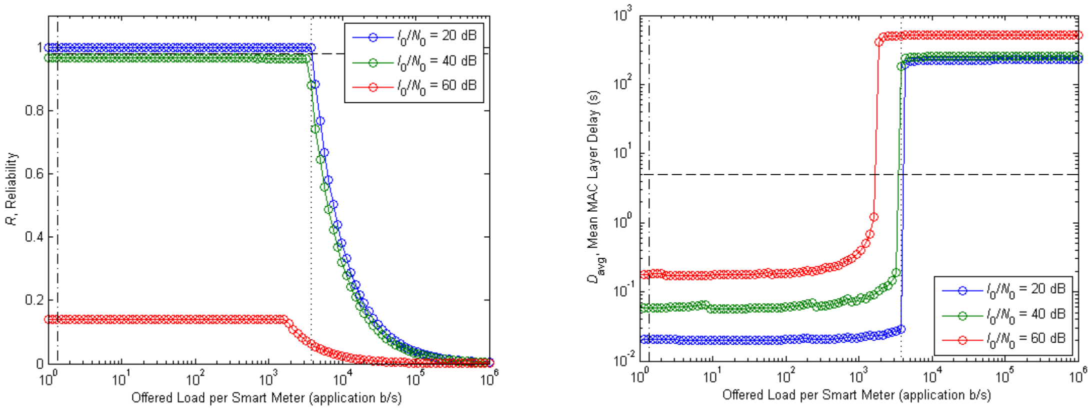
6.5 The Effect of Interference

An additional factor to consider in almost any wireless deployment is the potential for RF interference. The fact that spectrum is often a limited resource necessitates spectral reuse where appropriate to increase spectral efficiency. However, as spectral reuse increases, the potential for interference also increases. The source of interference can be other devices belonging to the same deployment or, in an unlicensed band, belonging to other operators.

In wide-area cellular deployments, carrier frequencies are reused from one cell to another. Depending on the level of reuse, inter-cell interference must be managed, especially at the cell edge. Another means to increase spectral efficiency is cell sectorization, whereby a cell is split into typically three or six sectors. As a result, inter-sector interference at the sector edges may also need to be managed.

In local or neighborhood area deployments, the technology may rely on random access to a shared channel. Here, the link experiences multiple access interference when two or more stations attempt to use the channel at the same time. Mitigation strategies include increasing the duration of the backoff window with the number of collisions.

In general, interference decreases the available link margin. If the margin is degraded enough, transmitted frames will be so severely corrupted that they will be unrecoverable and will have to be resent. This will in turn reduce throughput, decrease reliability, and increase the average frame delay. Whether the interference is inter-cell, multiple access, or the result of sharing an unlicensed band, it is important to assess its impact on the wireless deployment of interest and, if necessary, employ strategies to mitigate the impact.



(a) Reliability (b) Mean MAC layer delay

Figure 17 - Performance vs. offered load for various levels of interference using model in Annex A

To illustrate the impact of interference on performance, the following example considers the effect of a constant level of ambient interference on the link. The source of this interference might be other cells using the same channel or other wireless users in the case of an unlicensed band.

Using the model in Annex A, Figure 17 illustrates the impact of interference on a wireless network connecting smart meters to a DAP. The graphs plot reliability and mean delay versus offered load for three values of the ratio of the interference power spectral density to the noise power spectral density (I_0/N_0). Figure 17(a) shows that reliability is below the required 98% level even at very low loads under moderate and severe interference conditions. At peak load, the reliability is at around 100% when the interference is relatively small, but Figure 17 (a) shows that higher loads are unsupportable. Moreover, saturation occurs earlier under the highest interference conditions than it does when the interference is less severe.

Figure 17(b) shows the impact on delay. Here, the difference in performance between all three interference cases is apparent at low loads. Though the delays are within the limit at low loads, as shown in Figure 17(a) the reliability is unacceptably low in two of the cases. The moderate and high interference scenarios result in unacceptable delays at peak offered load and the low interference scenario results in acceptable performance, but the figure shows that the network is at its load limit.

While the numerical results presented here are specific to the model in Annex A, similar effects can be expected to be seen for other wireless technologies. The task for the network designer will be to identify the maximum tolerable interference strength for the technologies under consideration and determine, based on the ambient interference in the deployment environment, which subset of technologies is feasible. One must keep in mind that the exact value of the maximum tolerable interference will depend on the environment and the wireless technology that the network operator decides to use.

7 Conclusions

The goals of PAP 2 are to develop guidelines for the use 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 only 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 document 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 document and are available on the NIST PAP 2 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 document may be revised as needed in order to include additional material contributed by PAP 2 members. Additional material may include examples on how to combine security and communication requirements and their implications on performance, additional communication requirements and wireless technology evaluation examples and models.

8 References

ISO/IEC27001 - International Organization for Standardization/International Electrotechnical Commission Standard 27001 –Information technology -- Security techniques -- Information security management systems -- Requirements

NIST Special Publication 1108 - NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0, January 2010

NIST Internal Report 7628 - Guidelines for Smart Grid Cyber Security: Vol. 1, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements, August 2010

NIST Internal Report 7628 -Guidelines for Smart Grid Cyber Security: Vol. 2, Privacy and the Smart Grid, August 2010

NIST Internal Report 7628 -Guidelines for Smart Grid Cyber Security: Vol. 3, Supportive Analyses and References, August 2010

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Annex A IEEE 802.11

Based on the framework described in section 5, this annex presents a model that can be used to quantify the performance of an IEEE 802.11 system in a smart grid scenario. It is composed of a link traffic model, a physical (PHY) layer model, a medium access control (MAC) layer model, and a multilink model, each of which is described below.

A.1 Link Traffic Model

The numerical examples of this model used in section 6 are of a hypothetical link between a population of smart meters and a DAP. The link is loaded with traffic from applications associated with the following two use cases defined in [1]: Service switch (SS) and meter reading (MR). The example in section 3.6 translates the application requirements for these use cases into a form suitable for traffic modeling. It finds the aggregate message arrival rate to be 1.76×10^{-6} events per electric smart meter (emeter) per second on the downlink from the DAP to the smart meter, with an average application message size of 25 bytes. On the uplink from the smart meter to the DAP, it finds the aggregate arrival rate and average message size to be 9.12×10^{-5} events/emeter/s and 2133 bytes, respectively. These data points represent the average offered load in each direction of the two-way link. The model described below also permits varying the offered load across a continuum. For the purpose of analysis, it is assumed that the sources can be modeled as independent Poisson processes.

A.2 Physical Layer Model

The probability of failure of a transmission attempt is modeled as the probability that the received signal-to-interference and-noise ratio (SINR) is less than a threshold. The received SINR is modeled as random due to channel attenuation (fading, shadowing, path loss) and interference, both of which are treated as random processes. The SINR threshold model for transmission success/failure is based on the observation that for block transmissions the block error probability in the absence of fading and shadowing is a steep function of the SINR. The model approximates this function as a step function at a threshold value of SINR. According to this model, when the actual received SINR—after accounting for fading, shadowing, and the instantaneous interference power—is less than this threshold, the transmission is deemed a failure; otherwise, it is deemed successful. The probability of failure jointly accounts for loss due to a weak received signal, failure due to collision with other stations, and the possibility of capture in the presence of interfering transmissions. Mathematical expressions for the probability of transmission failure are detailed in [A2].

A.3 MAC Layer Model

The MAC layer model combines elements of the Bianchi and Zhai models of the IEEE 802.11 MAC[A3], [A4] to produce an extended MAC layer model for the half-duplex channel. This model contains novel elements that allow us to more accurately predict the performance of lightly loaded wireless networks that feature bidirectional traffic patterns on their links. The principal features of this model are described in detail in [A2].

A.4 Multilink Model

Given a maximum coverage range (described in 5.2.2) and a pair wise link metric between nodes, the multilink model described in [A5] generates multilinks between all pairs of source and destination nodes. The multilinks are defined through a routing topology, i.e. sequences of links between source, intermediate, and destination nodes. The routing topology is used to determine the offered loads at all links. The offered loads are not only a function of the routing topology, but also a function of the reliabilities of the intermediate links. The analysis uses the fact that less-than-perfect reliability results in the attrition of the loads over the multilink, so that the total load of the multilink is not merely a sum of the contributions of each.

A.5 Parameters and Assumptions Used in the Numerical Examples

For the numerical results in section 6, the modeling components described above are used to compare the performance of three environments: a rural environment, a suburban environment, and an urban environment. The channel parameters and the smart meter density associated with the three environments are shown in Table 9. The channel parameters based on ground-to-ground links were taken from [A6], [A7], and [A8].

Table 9 : Channel parameters and smart meter density for three environments at 2.4 GHz

Environment	**Rural**	**Suburban**	**Urban**
n_0	2.1	2.7	3.6
n_1	7.5	N/A	N/A
d_1 (m)	650	N/A	N/A
L_0 (dB)	38.3	40	21.3
σ (dB)	2.2	7.4	7.4
n (Nakagami fading)	1	1	1
ρ (smart meters per km^2)	10	800	2000

In Figure 18 outage curves for the three environments are shown. Each curve was generated by computing the outage probability for a given coverage range, assuming a station Effective Isotropic Radiated Power (EIRP) of 25 dBm. The graph shows that, for this range of outage probabilities, the coverage range in the rural environment far exceeds that of either the urban or suburban environments. Furthermore, the coverage areas that can be achieved in the urban and suburban environments are very close in size, especially as the value of the average outage probability decreases. Also shown is that the maximum coverage range of the rural environment approaches that of the urban and suburban environments as the average outage probability becomes large. However, the outage values at which this occurs are large enough to preclude effective communication.

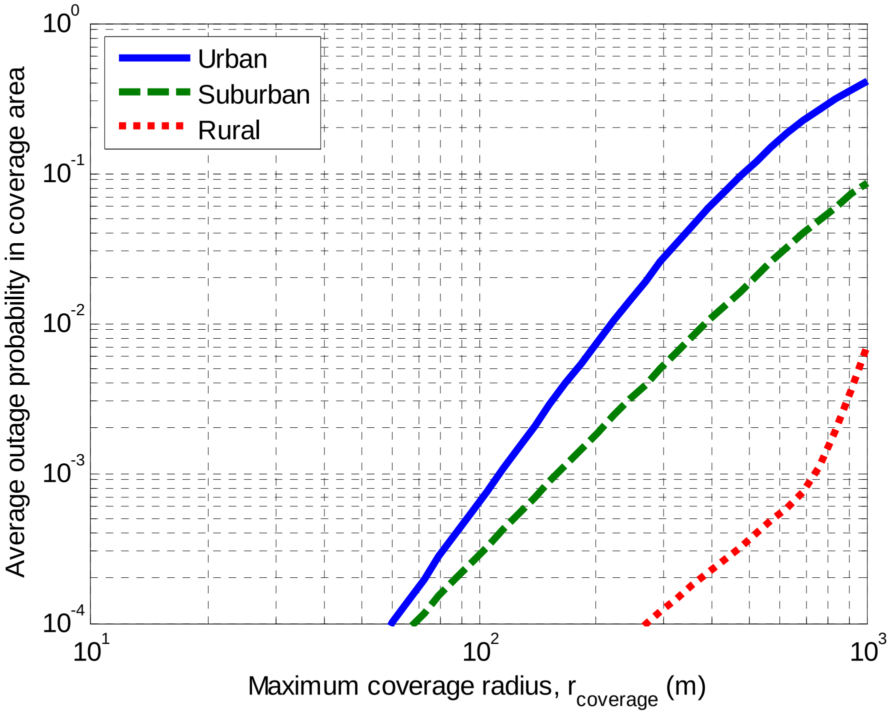

Figure 18 - Outage curves for three environments at 2.4 GHz (0.1 % outage ranges: 113 m, 159 m, and 738 m)

For each environment, the effect of interference and smart meter densities for various amounts of offered load per smart meter is examined. For the case where the interference to noise ratio was varied, the EIRP was set to 25 dBm. Using this value, the maximum coverage range of the DAP for each of the three environments was computed, given an outage probability of 0.001. The coverage ranges of 738 m, 159 m, and 113 m for the rural, suburban, and urban channels were obtained, respectively. For the smart meter densities shown in Table 9, the number of meters that can communicate with a DAP was obtained as follows:

$$N = \pi \left(\frac{r_{\text{coverage}}}{1000} \right)^2 \rho \qquad \text{(A-1)}$$

resulting in $N = 17$, 64, and 80 for the rural, suburban, and urban environments, respectively.

The values of EIRP = 25 dBm, $P_{\text{out}} = 0.001$, and their resultant values for r_{coverage} and N in each environment, together with an interference ratio of $I_0/N_0 = 10$ dB, provide a set of nominal PHY parameter values given in Table 10. This nominal set was used to generate the numerical results in section 6. Table 11 lists the parameters that are varied from this nominal set according to the figure number.

Table 10 : Nominal PHY parameter values used for the results in section 6.

Environment	Rural	Suburban	Urban
EIRP	25 dBm	25 dBm	25 dBm

Environment	Rural	Suburban	Urban
P_{out}	0.001	0.001	0.001
r_{coverage}	738 m	159 m	113 m
N	17	64	80
I_0/N_0	10 dB	10 dB	10 dB

Table 11 : Varied PHY parameters from their nominal values used to generate the indexed figures in section 6.

	Parameter varied from its nominal value
Figure 13	$r_{\text{coverage}} = \{50, 100, 150\}$ m
Figure 15	N varies according to Equation (10-1), however by replacing r_{coverage} with $r_{\text{deployment}}$; Offered load per Smart Meter = 3.84 kb/s from the application.
Figure 16	N/A
Figure 17	$I_0/N_0 = \{20, 40, 60\}$ dB

In Table 12 lists the input parameters that were used to implement the PAP2 model of the IEEE 802.11 wireless protocol. The MAC layer model was designed to capture some of the main features of the IEEE 802.11 half-duplex channel, and allows the user to characterize the remote stations (whose role is taken by the smart meters in this study) separately from the central access point (whose role is taken by the DAP). In the calculations for section 6, the frame arrival rate was varied for the smart meters and the DAP, so the arrival rate is not given in this table.

Table 12 : Input parameters for IEEE 802.11 model (2.4 GHz)

Parameter	Smart Meters	DAP
α (maximum number of retries)	7	7
K (buffer size in frames)	50	100
L (application data, bytes)	2133	25
C (channel data rate, Mb/s)	1.0	1.0

A.6 References

[A1] SG Network Systems Requirements Specification, v4.0, July 21, 2010. Available online at: http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/

[A2] Griffith, D., Souryal, M., Gentile, C., and Golmie, N., "An integrated PHY and MAC layer model for half-duplex IEEE 802.11 networks," in Proc. IEEE Military Communications Conference (MILCOM), Nov. 2010.

[A3] Bianchi, G., "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE J. Selected Areas Communications, vol. 18, no. 3, pp. 535–547, 2000.

[A4] Zhai, H.Q., Kwon, Y.G., and Fang, Y.G., “Performance analysis of IEEE 802.11 MAC protocols in wireless LANs,” Wireless Communications and Mobile Computing, vol. 4, no. 8, pp. 917–931, 2004.

[A5] Gentile, C., Griffith, D., Souryal, M., and Golmie, N., “Throughput and Delay Analysis in Half-Duplex IEEE 802.11 Mesh Networks,” submitted to IEEE Intl. Conf. on Communications (ICC), Sept. 2010.

[A6] Laselva, D., Zhao, X., Meinila, J., Jamsa, T., Nuutinen, J.-P., Kyosti, P., and Hentila, L., “Empirical Models and Parameters for Rural and Indoor Wideband Radio Channels at 2.45 and 5.25 GHz,” IEEE Intl. Symposium on Personal, Indoor, and Mobile Radio Communications, pp. 654-658, Sept. 2010.

[A7] Xia, H.H., Bertoni, H.L., Maciel, L.R., Lindsay-Stewart, A., and Rowe, R., “Microcellular Propagation Characteristics for Personal Communications in Urban and Suburban Environments,” IEEE Trans. on Vehicular Technology, vol. 43, no. 3, Aug. 1994.

[A8] Matolak, D.W., Remley, K.A., Gentile, C., Holloway, C.L., Wu, Q., and Zhang, Q. “Ground-Based Urban Channel Characteristics for Two Public Safety Frequency Bands,” Submitted to IEEE Trans. on Antennas and Propagation, Aug. 2010.

Annex B 3GPP Long Term Evolution (LTE)

This annex presents an analysis of the 3rd Generation Partnership Project (3GPP) long term evolution (LTE) technology for advanced metering applications.

The analysis below is representative of analyses that can be performed of cellular network technologies with scheduled traffic. It is more limited in scope than the model of Annex A, focusing on coverage and capacity rather than delay and reliability.

B.1 Modeling Approach and Assumptions

The approach to modeling LTE for advanced metering applications, illustrated in Figure 19, utilizes an analogous, but scaled-down version of the framework of section 5.2. The two core components are the coverage analysis and capacity analysis. The coverage analysis predicts the maximum coverage radius of a cell, based on a channel propagation model and parameters of the LTE deployment. The capacity analysis predicts the overall capacity of a sector (in bits per second) and, based on the geographic density of smart meters, estimates the average capacity per smart meter. The channel propagation model is driven by the deployment environment (e.g., urban, suburban, rural) and is used by both the coverage analysis and capacity analysis.

The analysis assumes that smart meters are randomly and uniformly distributed in the cell. A cell is sectorized into three 120° sectors. Inter-sector interference is neglected for now, but future work may revisit this point.[17]

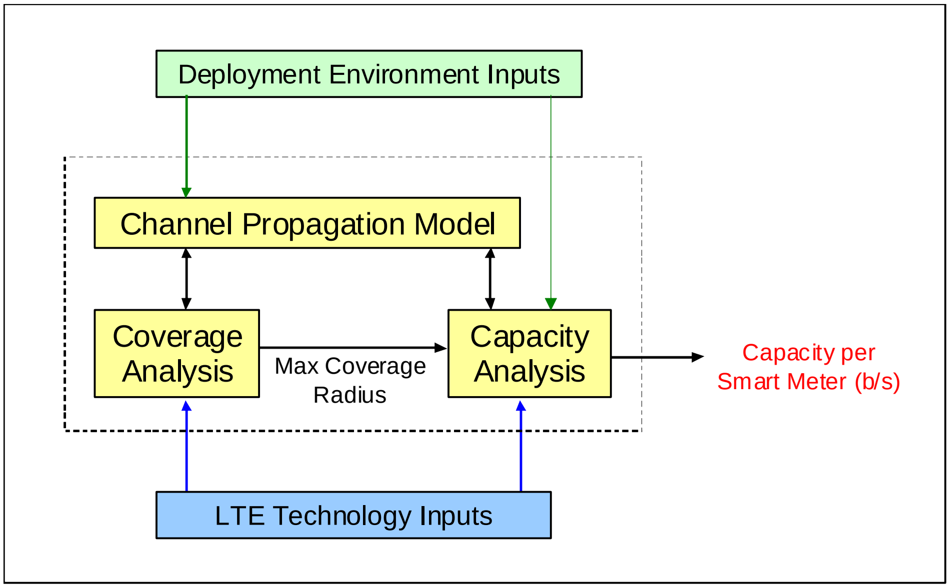

Figure 19 - Building blocks of modeling approach

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[17] With expected traffic load and smart meter deployment densities, channel utilization is anticipated to be very low. Low utilization permits fractional reuse of the spectrum whereby traffic in adjacent sectors is allocated to non-overlapping time/frequency resources, thereby reducing inter-sector interference.

The interface to the LTE network may reside directly in the smart meter, in which case the smart meter would send data to and receive data from the head end system directly. On the other hand, the interface to the LTE network may reside in a Data Aggregation Point (DAP) that aggregates traffic from smart meters, likely using a different technology, before relaying it to the head end. In the latter case, no aggregation efficiencies are assumed in this analysis.

For the purpose of providing example numerical results, specific values are chosen for certain LTE device parameters. These values are summarized in Table 13 and are taken from [B1]. In addition, the analysis assumes channel-dependent adaptation of the modulation and coding scheme (MCS) and the use of single-input / single-output (SISO) antennas. The radiation pattern of the base station (eNodeB) antenna is also taken from [B1] and is illustrated in Figure 20.

Table 13: LTE device parameters

Base Station (eNodeB)	Power per Downlink Traffic Channel	32 dBm
	Peak Antenna Gain	15 dBi @ 2 GHz 12 dBi @ 900 MHz
	Noise Figure	5 dB
Terminal (UE)	Transmission Power	24 dBm
	Antenna Gain (omnidirectional)	0 dBi
	Noise Figure	9 dBm
Bandwidth	Downlink	5 MHz
	Uplink	5 MHz

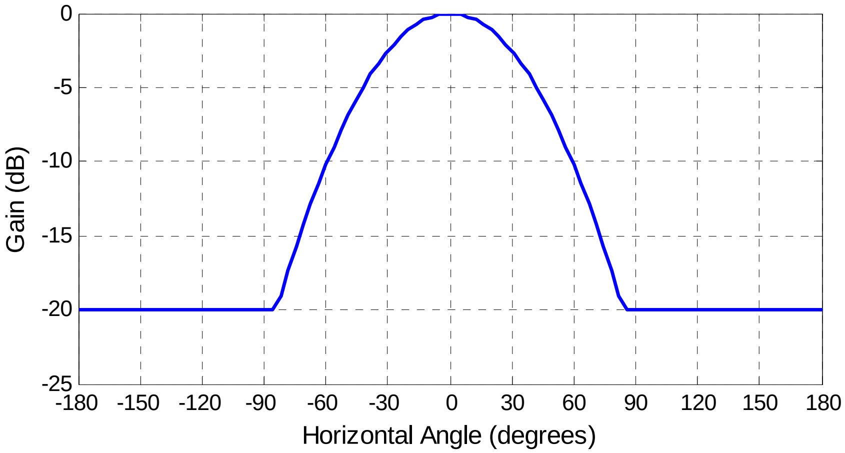

Figure 20 - Radiation pattern of base station (eNodeB) antenna

B.2 Channel Propagation Model

Using the recommended channel propagation model in [B1], the path loss (in dB) with distance *R* (km) is modeled by the following equation:

$$L = L_0 + 10n\log_{10}(R) + X$$

The values for the reference path loss (L_0) and the path loss exponent (n) are given in Table 14 for urban and rural environments. The last term, *X*, is a random component representing lognormal shadowing with a standard deviation of 10 dB.

Table 14 Path loss parameters[B1]

Environment	Carrier frequency	L_0	*n*
Urban Area	900 MHz	120.9 dB	3.76
	2 GHz	128.1 dB	3.76
Rural Area	900 MHz	95.5 dB	3.41

With the path loss and device parameters, one can calculate the received power and signal-to-noise ratio. The received power P_{rx} (dBm) is obtained as

$$P_{rx} = P_{tx} + G_{tx} + A_{rad} - L + G_{rx}$$

where P_{tx} is the transmission power (dBm), G_{tx} and G_{rx} are the transmit and receive antenna gains (dBi), respectively, and A_{rad} is the base station antenna radiation pattern (dB) shown in Figure 20.

The received signal-to-noise ratio (SNR) per subcarrier symbol (dB) is then given by

$$SNR = E_S / N_0 = P_{rx} - N_0 - 10\log_{10} R_S$$

where R_S is the symbol rate (sym/s) and N_0 is the power spectral density (p.s.d.) of the noise (dBm/Hz). The noise p.s.d. can be calculated from the temperature, *T* (°K), and the receiver's noise figure, *F* (dB), as

$$N_0 = -198.6 + 10\log_{10} T + F$$

The received SNR is used in both the coverage and capacity analyses.

B.3 Coverage Analysis

The purpose of the coverage analysis is to find the maximum cell radius that satisfies a performance criterion. That criterion could be a maximum outage probability, as stated in section 5. In this example analysis, the coverage criterion used is that the median *uplink* SNR is at least as high as that required by the lowest, most robust MCS. In general, the uplink is more limiting than the downlink because of the uplink's lower transmission power.

Expressed mathematically, the maximum cell radius is

$$R_{\max} = \max\left\{R : \overline{SNR_{UL}(R)} \geq \gamma_0\right\}$$

where γ_0 is the minimum SNR required to achieve a block error rate of 10^{-3} when using MCS 0.

Using the channel propagation model described in section B.2 and a value of 2.41 dB for γ_0, Table 15 lists the resulting maximum cell radii. With all other factors remaining equal, the rural cell coverage is larger than the urban cell coverage, and coverage with a 900 MHz carrier is larger than that with a 2 GHz carrier.

Table 15: Maximum cell radii

Environment	Carrier frequency	Maximum cell radius
Urban Area	900 MHz	2.7 km
	2 GHz	2.1 km
Rural Area	900 MHz	20 km

B.4 Capacity Analysis

The capacity analysis aims to estimate the total available throughput in a sector, as well as the available throughput per smart meter.

B.4.1 Sector Capacity

The approach is to evaluate the probability that each MCS is in use and, knowing the data rate achievable with each MCS, to use these probabilities to compute the average data rate.

The probability that an MCS is in use can be obtained from the statistics of the received SNR. According to the channel model used in this analysis (section B.2), the SNR varies with the distance from the base station and with the shadowing on the link. Based on the assumptions for these variables, the probability that the SNR lies between the minimum SNR value required by a given MCS and the SNR value required by the next higher MCS is evaluated. Denoting this probability as $P_{MCS,i}$, then

$$P_{MCS,i} = \Pr\left[\gamma_i \leq SNR < \gamma_{i+1}\right] .$$

The average data rate per resource block achievable in the sector is then computed through the following summation over all i:

$$C_{avg} = \sum_{i} C_{MSC,i} P_{MCS,i} .$$

Here, $C_{MCS,i}$ is the data rate obtained when using MCS i in a resource block. The total data rate is C_{avg} multiplied by the total number of resource blocks. This result assumes round-robin scheduling and saturated transmission (data is always available to send) and should be viewed as an upper bound on the actual achievable throughput. Actual throughput may be lower due to retransmissions and under-utilization of resource blocks.[18]

Example results using the assumptions stated in section B.1 and the sample SNR threshold values listed in Table 16 are illustrated in Figure 21 for the urban and rural environments. Each graph plots the sector capacity as a function of the cell radius for the uplink and downlink. The graph for the urban environment also compares capacity with 900 MHz and 2 GHz carriers. In all cases, as cell radius increases, capacity decreases because a larger fraction of the area experiences lower SNR, necessitating the use of lower data rates.

Table 16: Sample SNR thresholds for each MCS

MCS index	**SNR threshold (dB)**			**MCS index**	**SNR threshold (dB)**	
	Uplink	**Downlink**			**Uplink**	**Downlink**
0	2.41	2.41		15	12.90	12.90
1	2.97	2.97		16	13.50	13.50
2	3.63	3.63		17	15.00	14.45
3	3.86	3.86		18	15.25	15.70
4	4.47	4.47		19	16.50	15.82
5	5.31	5.31		20	18.06	16.89
7	6.81	6.81		21	17.76	17.76
8	7.65	7.65		22	18.66	18.66
9	8.45	8.45		23	19.77	19.77
10	9.07	8.80		24	20.55	20.55
11	9.27	9.27		25	21.35	21.35
12	10.25	10.25		26	22.20	22.20
13	11.23	11.23		27	23.67	23.67
14	11.79	11.79		28	23.74	23.74

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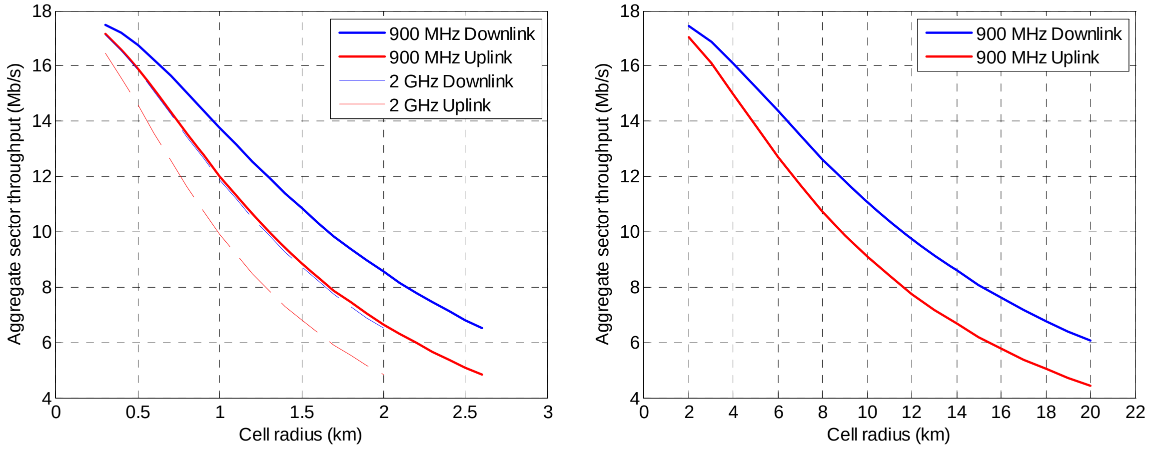
[18] For example, resource block efficiency may be reduced to satisfy a delay constraint.



(a) Urban environment (b) Rural environment

Figure 21 - Aggregate sector throughput vs. cell radius

B.4.2 Available Throughput per Smart Meter

An estimate of the available throughput per smart meter is obtained by first determining the minimum time interval needed between consecutive messages. Then, knowing the average message size, the maximum supportable throughput is calculated by taking the ratio of the two.

To determine the minimum time interval needed between consecutive messages, the number of transport blocks required to send a message needs to be calculated. Letting B_i represent the transport block size of MCS i, then the number of transport blocks required to send a message of length L bits is

$$N_i = \left\lceil \frac{L}{B_i} \right\rceil .$$

For the numerical results below, the average message sizes used are those computed in the example in section 3.6 for the meter reading (MR) and service switch (SS) use cases: 25 bytes on the downlink and 2133 bytes on the uplink. The number of overhead bytes per message is assumed to be 42.

Next, the average number of smart meters in the sector is calculated by:

$$K = \rho \pi R_c^2 / 3$$

where R_c is the cell radius (km) and ρ is the smart meter density (number of meters per square kilometer). The factor 1/3 in the denominator is due to sectorization. Table 17 lists example meter densities for three different deployment environments.

Table 17: Example meter densities

Environment	Meter density, ρ
Urban area	2000 / km^2
Suburban area	800 / km^2
Rural area	10 / km^2

The average number of transport blocks needed by all K smart meters in the sector to send or receive a message is given by

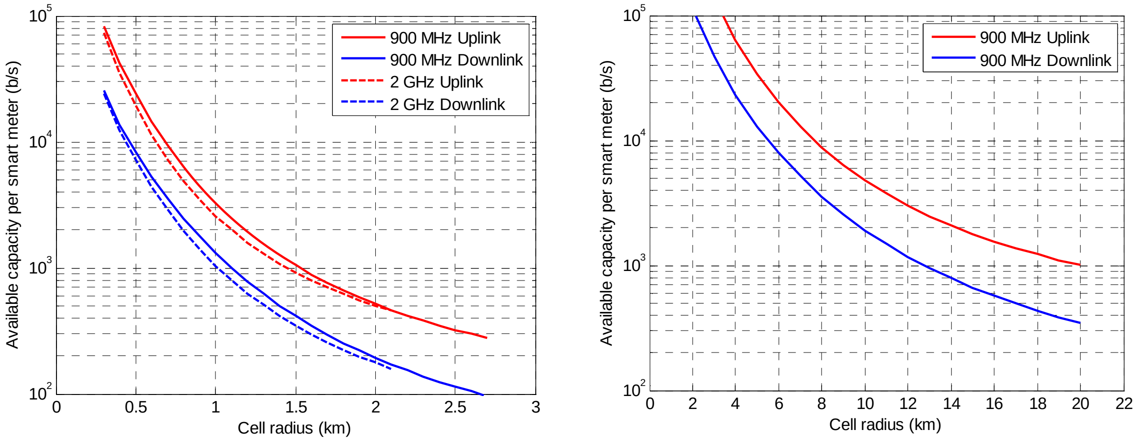
$$N = K \sum_i P_{\mathrm{MCS},i} N_i \ .$$

Then, the minimum time interval needed between successive messages, $\tau_{\min}$, is obtained by taking the ratio of the needed number of transport blocks to the transport block rate of the LTE system (i.e., the number of available transport blocks per second):

$$\tau_{\min} = \frac{K \sum_i P_{\mathrm{MCS},i} N_i}{R_{\mathrm{TB}}} \ .$$

For example, in a 5 MHz LTE system, the transport block rate, R_{TB}, is 25,000 blocks per second.

Finally, taking the ratio of the application message size to $\tau_{\min}$ gives an upper bound on the application throughput per smart meter. Figure 22 plots the resulting capacity per smart meter (maximum application throughput per smart meter) as a function of the cell radius for the urban 900 MHz, urban 2 GHz, and rural 900 MHz cases. Interestingly, though the aggregate sector capacity is higher in the downlink than the uplink (Figure 21), the reverse is true for the available capacity per smart meter. The reason is that the 42-byte overhead represents a much larger percentage of the downlink message size (25+42 bytes) than the uplink message size (2133+42 bytes).



(a) Urban environment

(b) Rural environment

Figure 22 - Capacity per smart meter vs. cell radius

B.5 References

[B1] Radio Frequency (RF) system scenarios, 3rd Generation Partnership Project, Technical Report 36.942, V8.2.0, June 2009.

Disclaimer: The information provided in this annex was submitted "as is", with little or no review of its contents. Some minor editing (e.g., spelling and formatting) may have occurred.

Annex C 3GPP High Speed Packet Access (HSPA)

This annex presents an analysis of the 3rd Generation Partnership Project (3GPP) High Speed Packet Access (HSPA) technology. The approach to modeling HSPA for advanced metering applications is done very much the same as what is described for long term evolution (LTE) in Annex B. As such, the primary concentration is on items that are specific to HSPA.

Also, the HSPA analysis is based only on a carrier frequency of 2 GHz as the performance at 900 MHz will be better.

C.1 Modeling Approach and Assumptions

The analysis assumes that smart meters are randomly and uniformly distributed in the cell. A cell is sectorized into three 120° sectors. Inter-sector interference is neglected for now, but future work should revisit this point.[19]

The interface to the HSPA network may reside directly in the smart meter, in which case the smart meter would send data to and receive data from the head end system directly. On the other hand, the interface to the HSPA network may reside in a Data Aggregation Point (DAP) that aggregates traffic from smart meters, likely using a different technology, before relaying it to the head end. In the latter case, no aggregation efficiencies are assumed in this analysis.

For the purpose of providing example numerical results, specific values are chosen for certain HSPA device parameters. These values are summarized below:

- Cell radius: Varied from 500 m to 2000 m
- Carrier frequency: 2 GHz
  - This is the worst case. Performance at 900 MHz will be better.
  - Path loss (dB) = $128.1 + 37.6 \cdot \text{Log}_{10} d_{km}$.
- Scenario: Urban
  - Again, this is the worst case in terms of UE density.
- Other cell interference is ignored
- PA3 channel (per 3GPP TR 25.896)
- Linear minimum mean squared error (LMMSE) Receiver w/RxD
  - With 1 Rx antenna, throughput falls by 30%.
- Lognormal shadowing: Standard deviation = 10 dB

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[19] With expected traffic load and smart meter deployment densities, channel utilization is anticipated to be very low. Low utilization permits fractional reuse of the spectrum whereby traffic in adjacent sectors is allocated to non-overlapping time/frequency resources, thereby reducing inter-sector interference.

- Two dimension (2D) antenna pattern with a 70 degree 3 dB beamwidth (per 3GPP TR 25.996)
  - DL antenna gain = 14 dBi
  - Penetration loss = 10 dB
- Noise figures:
  - UE: 9 dB
  - NodeB: 5 dB
- Downlink (DL) Single-input / multiple-output (SIMO) simulations (64-QAM allowed)
  - Cell throughputs averaged over several drops with fixed user density per km^2
- Uplink (UL) SIMO simulations (QPSK)
  - The expectation is that UEs to be ON only for a small amount of time. Effectively, this will be a Time Division Multiplex (TDM) system.
  - Fixed user density per km^2 assumed.

C.2 Analysis

An estimate of the average capacity per smart meter is obtained by dividing the total sector capacity, C_{total}, by the number of smart meters in the sector. Please note that in UL, the C_{total} is constant at 2.5923 Mb/s since a TDM system is assumed. Given the number of electric meters per square kilometer (ρ) in a deployment environment, the average capacity per smart meter can be calculated as

$$C_{meter} = \frac{C_{total}}{\rho \pi R_{\max}^2 / 3}.$$

The factor 1/3 in the denominator is due to sectorization. Table 18 lists example meter densities for three different deployment environments, and Figure 23 shows the cell throughput as a function of the cell radius for DL.

Table 18: Example meter densities

Environment	**Meter density, ρ**
Urban area	2000 / km^2
Suburban area	800 / km^2
Rural area	10 / km^2

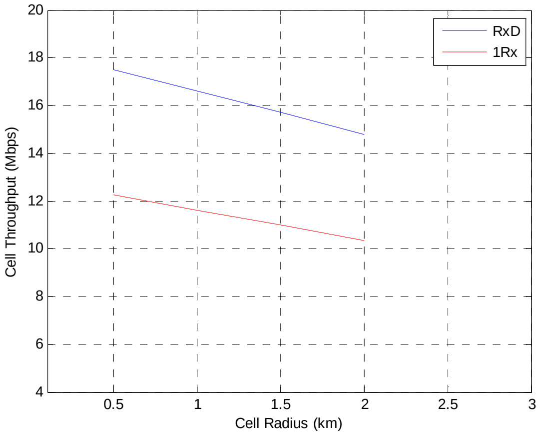

Figure 23 - Cell Throughput as a function of the cell radius for DL

Figure 24 shows the throughput available per Smart Meter.

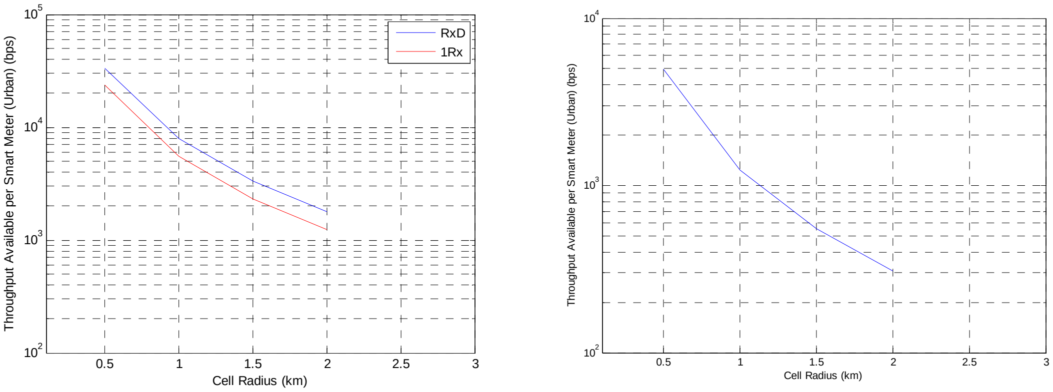

Figure 24 - Throughput available per smart meter vs. cell radius for DL (left) and UL (right)

C.3 Capacity-limited and coverage-limited scenarios

Depending on a given deployment environment, a smart grid system may be capacity-limited or coverage-limited. For example, in a dense urban area where there are many high-rise buildings, the system may be capacity-limited. However, in a rural area, a coverage limitation may prevail. As such, one must analyze the system based on both scenarios.

C.3.1 Scenario 1: Capacity-limited system

For this scenario, the maximum number of deployable smart meters is determined given the technology's channel capacity and assuming no limitation on the coverage. The maximum number of deployable smart meters per sector is given by

$$N_{cap} = C_{total} / \lambda_{meter} \ .$$

For example, considering a total uplink capacity of C_{total} = 2.5 Mb/s and a smart meter throughput of λ_{meter} = 2.5 b/s, one million meters would be required to fully utilize the sector's capacity.

To assist with this analysis, a spreadsheet (Analysis_Tool.xls) is available at:

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

C.3.2 Scenario 2: Coverage-limited system

For this scenario, the number of deployable smart meters that lie within the geographic coverage area of a single sector is the starting point. Then the percentage of radio channel utilization needed to support the traffic load generated by the meters is calculated. Given the geographic density of smart meters, ρ, the number of smart meters in a coverage-limited sector is

$$N_{\text{cov}} = \rho\left(\pi R_{\max}^2 / 3\right).$$

To assist with this analysis, a spreadsheet (Analysis_Tool.xls) is available at:

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

Then, the aggregate load and utilization are given, respectively, by

$$\lambda_{total} = N_{\text{cov}} / \lambda_{meter}$$

$$U = \lambda_{total} / C_{total} \ .$$

To assist with this analysis, a spreadsheet (Analysis_Tool.xls) is available at:

- http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/PAP02Wireless

Disclaimer: The information provided in this annex was submitted "as is", with little or no review of its contents. Some minor editing (e.g., spelling and formatting) may have occurred.

Annex D CDMA2000 1x and High Rate Packet Data (HRPD)

D.1 Introduction

This annex presents an analysis of the wireless wide area network (WWAN) related Smart Grid Interoperability Panel Priority Action Plan 2's requirements spreadsheet [D1] developed by the Open SG User Group. This sheet contains frequency, size, delay constraints, and other details about the various messages for some of the use cases in smart grid. The analysis looks at all messages from the listed use cases over the WWAN segment (between the Data Aggregation Point (DAP) and the advanced metering infrastructure (AMI) head end). These cases include meter reading (MR), plug-in hybrid electric vehicle (PHEV), service switching (SS), pre-pay metering (PP), and outage manage and recovery (ORM). The total amount of forward link (AMI head end to DAP) and reverse link (DAP to AMI head end) traffic is computed and compared with the system throughput of the cdma2000 1x and HRPD systems.

D.2 System Model

This analysis is based on the system model in Figures 1 and 2 of [D2]. In that model, there can be multiple (N) customers connected to a DAP which can be connected wirelessly to the fixed network containing the AMI head end. Further, one can imagine each customer has one electric meter and one gas meter. In this analysis, the actual value of N does not affect the end result in general, but one can assume the value of N ranges from 1 to 1,000 or even more. It is further assumed that of the N customers, there is a certain percentage of commercial/industrial customers. Figure 25 shows the DAP / AMI head end segment that is of interest to this analysis.

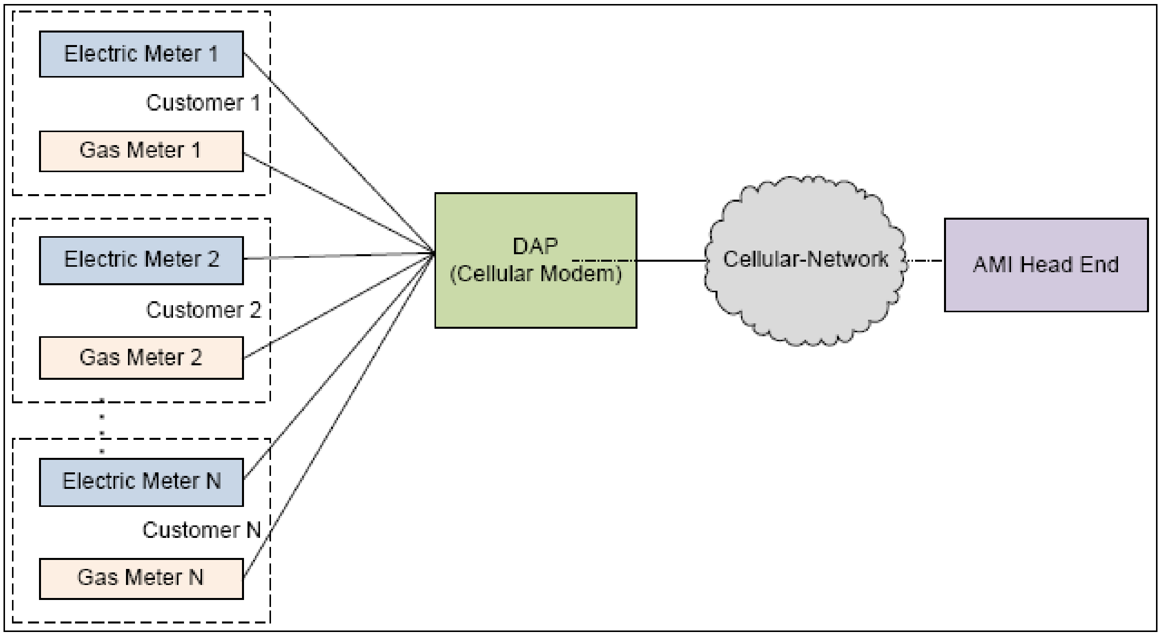

Figure 25 - Simplified model of smart grid supported by a cellular network

Note that the following assumptions were made to make sure the analysis has the largest possible load on the WWAN:

1. There is one electric meter and one gas meter for every customer. However, all smart meter messages listed in the spreadsheet are assumed to be to for the electric meter unless otherwise specified.
2. There is one PHEV for every customer.
3. Fifty percent of the customers are assumed to be commercial or industrial ones, and the rest are residential ones.
4. For use cases where the number of transactions is listed as a range of possible value, the largest value is used in the analysis.
5. Ten percent of all the customers also support additional pre-pay users on their meters in addition to the messages sent and received from the other use cases.
6. To compute the error event reporting message load, the communication error rate is assumed to be at 20% and application error 10%.
7. There is an overhead of 42 bytes in each message as discussed in the next section.

Figure 26 shows the assumptions made about this model, which includes overhead in each transaction (42 bytes). Note that the two bytes per transport layer header is somewhat arbitrary, but this should not materially affect the final conclusion.

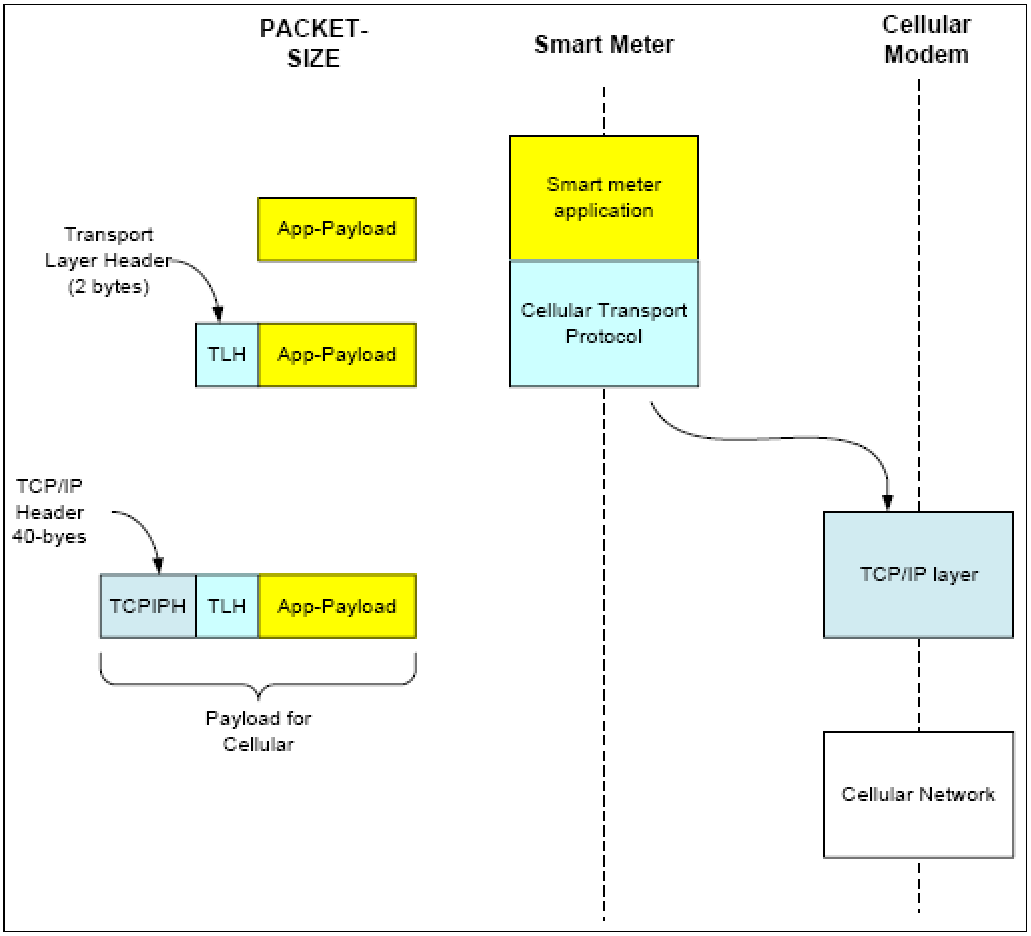

Figure 26 - Per transaction overhead of smart grid supported by a cellular network

Note also that the analysis assumes no bundling of messages at the DAP (for messages originating from different meters connected to the same DAP) or the AMI head end (for messages intended for meters attached to the same DAP), meaning that each message is sent over the cellular network individually, incurring the maximum amount of overhead possible.

D.3 Traffic between DAP and AMI head end

Table 19 lists the forward link (AMI head end to DAP) messages from the requirement [D1] and their total daily load of 1,714,657 bytes (including overhead) for 1,000 customers (1,000 electric meters, 1,000 gas meters, and 1,000 PHEVs) on the WWAN.

Table 19: Forward link (AMI head end to DAP) traffic per 1000 customers, worst case summary

Requirement Reference	**Requirements (assumed electric unless noted otherwise)**	**How Often**	**App Payload Size - bytes**	**Transactions per 1,000 customer per day**	**Traffic (including overhead) per 1,000 customer per day**
PP-082	AMI Head end shall be able to process & forward any of the Pre-pay messages (~10 different types) to DAP	25 trans per Pre-pay mtr with Cust. EMS per month	50 - 150	83.3	7,667
PP-096	AMI Head end shall be able to process & forward any of the Pre-pay messages (~10 different types) to DAP	25 trans per Pre-pay mtr with IHD per month	50 - 150	83.3	16,000
PP-110	AMI Head end shall be able to process & forward any of the Pre-pay messages (~10 different types) to DAP	25 trans per Pre-pay mtr with Cust. EMS per month	50 - 150	83.3	16,000
PP-122	AMI Head end shall be able to process & forward a cancel service switch operate request to DAP	1-2 trans per 1000 Pre-pay mtrs per day	25	0.2	13
PP-132	AMI Head end shall be able to process & forward a service switch operate request to DAP	1-50 trans per 1000 Pre-pay mtrs per day	25	5	335

Requirement Reference	**Requirements (assumed electric unless noted otherwise)**	**How Often**	**App Payload Size - bytes**	**Transactions per 1,000 customer per day**	**Traffic (including overhead) per 1,000 customer per day**
PP-141	AMI Head end shall be able to process & forward a service switch state request to DAP	1-50 trans per 1000 Pre-pay mtrs per day	25	5	335
PP-202	Head end shall be able to process & forward on-demand meter read requests to DAP	25 trans per 1000 Pre-pay mtrs per day	25	2.5	168
Total Load (Bytes per day per 1,000 customers)					1,714,657

Table 20 shows the reverse link (DAP to AMI head end) messages and their total load of 27,454,142 bytes per day for 1,000 customers (1,000 electric meters, 1,000 gas meters, and 1,000 PHEVs).[20]

Table 20: Reverse link (DAP to AMI head end) traffic per 1000 meters, worst case summary

Requirement Reference	**Requirements (assumed electric unless noted otherwise)**	**How Often**	**App Payload Size (bytes)**	**Transactions per 1,000 customer per day**	**Traffic (including overhead) per 1,000 customer per day**
MR- 58	Meter reading	DAP shall be able to forward Smart Meter (Gas Commercial) multiple-interval-data to AMI Head end	1-6 trans per DAPjm-gas-C/I-meter per day	1600 - 2400	3000

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[20] MR-58 is about DAP relaying messages from smart meters to the AMI head end. These relate to MR-32, 33, 34, and 35, which are labeled as for commercial gas meters, residential gas meters, commercial/industrial electric meters, and residential electric meters, respectively. It is assumed that MR-32, even though it is labeled as commercial gas meter to DAP, it also represents industrial meter to DAP statistics.

Requirement Reference	**Requirements (assumed electric unless noted otherwise)**	**How Often**	**App Payload Size (bytes)**	**Transactions per 1,000 customer per day**	**Traffic (including overhead) per 1,000 customer per day**
MR-62	Meter reading	DAP shall be able to forward Smart Meter (Gas Residential) multiple-interval-data to AMI Head end	1-6 trans per DAPjm-gas-resdnt-meter per day	1600 - 2400	3000
MR- 66	Meter reading	DAP shall be able to forward Smart Meter (Electric Commercial/Industrial) multiple-interval-data to AMI Head end	4-6 trans per DAPjm-elect-C/I-meter per day	200 - 1600	3000
MR- 26	Meter reading	DAP shall be able to forward Smart Meter (Electric Residential) multiple-interval-data to AMI Head end	4-6 trans per DAPjm-elect-resdnt-meter per day	1600 - 2400	3000
	Meter reading	DAP shall be able to process & forward multiple interval meter reading data (per specific meter request from MDMS) to AMI Head end	25 trans per 1000 DAPjm-mtrs per day	200 - 2400	25
MR- 28	Meter reading	DAP shall be able to report & send "DAP to Smart Meter on-demand meter read request communications errors", to AMI Head end	1 trans per meter per x on-demand cmds per time period	50	5

Requirement Reference	Requirements (assumed electric unless noted otherwise)	How Often	App Payload Size (bytes)	Transactions per 1,000 customer per day	Traffic (including overhead) per 1,000 customer per day
MR- 30	Meter reading	DAP shall be able to process & forward Meter on-demand read request app errors to AMI Head end	1 trans per each DAPjm-meters' app error event	50	2.5
MR- 31	Meter reading	DAP shall be able to process & forward on-demand meter read data from Smart Meter to AMI Head end	25 trans per 1000 DAPjm-mtrs per day	100	25
PHEV- 22	PHEV	DAP shall be able to forward "Send of Price Rate (from LM) to PHEV" communication failure to AMI Head end	1 trans per 1000 DAPjm-PHEV-mtrs-ESI-non-SMtr per day	50	0.8
PHEV- 72	PHEV	DAP shall be able to forward "Send of Price Rate (from LM) to PHEV" communication failure to AMI Head end	1 trans per 1000 DAPjm-PHEV-mtrs-ESI-SMtr per day	50	3.2
PHEV- 25	PHEV	DAP shall be able to forward "negotiate Power Charging Rate messages (from LMS) to PHEV" communication failure to AMI Head end	1 trans per 1000 DAPjm-PHEV-mtrs per day	50	4
PHEV- 26	PHEV	DAP shall be able to	150	100	150

Requirement Reference	Requirements (assumed electric unless noted otherwise)	How Often	App Payload Size (bytes)	Transactions per 1,000 customer per day	Traffic (including overhead) per 1,000 customer per day
		forward negotiate Power Charging Rate messages (from PHEV) to AMI Head end	trans per 1000 DAPjm-mtrs 2-4 times per day		
PHEV- 29	PHEV	DAP shall be able to forward charging status of the PHEV to AMI Head end	150 trans per 1000 DAPlm-PHEV-mtrs 2-4 times per day	100	600
PHEV- 30	PHEV	DAP shall be able to forward PHEV VIN information request to AMI Head end	1 trans per PHEV-mtrs connect per day	50	4000
SS- 29	Service Switch	DAP shall be able to process & send "service switch operate request (from CIS, or MDMS) communications failure" with Smart Meter, to AMI Head end	1-4 trans per 1000 mtrs-SW-oper per day	50	0.016
SS- 34	Service Switch	DAP shall be able to process & forward service switch state data to AMI Head end	1-50 trans per 1000 mtrs per day	100	50
SS- 28	Service Switch	DAP shall be able to process & forward service switch operate	1-2 trans per	25	2

Requirement Reference	Requirements (assumed electric unless noted otherwise)	How Often	App Payload Size (bytes)	Transactions per 1,000 customer per day	Traffic (including overhead) per 1,000 customer per day
		acknowledgment to AMI Head end	1000 mtrs per day		
SS- 31	Service Switch	DAP shall be able to process & forward service switch operate operate failure to AMI Head end	1 trans per 1000 SW-oper per mtr per day	50	0.016
SS- 32	Service Switch	DAP shall be able to process & forward metrology information after a successful service switch operate to AMI Head end	1-2 trans per 1000 mtrs per day	100	2
PP-152	Pre-pay	DAP shall be able to process & send "service switch operate request (from CIS - Utility, or MDMS) communications failure" with Smart Meter, to AMI Head end	1-4 trans per 1000 Pre-pay mtrs-SW-oper per day	50	0.0008
PP-162	Pre-pay	DAP shall be able to process & forward service switch state data to AMI Head end	1-50 trans per 1000 Pre-pay mtrs per day	100	5
PP-176	Pre-pay	DAP shall be able to process & forward service switch operate acknowledgment to AMI Head end	1-2 trans per 1000 Pre-pay mtrs per day	25	0.2
PP-185	Pre-pay	DAP shall be able to	1 trans	50	0.0002

Requirement Reference	Requirements (assumed electric unless noted otherwise)	How Often	App Payload Size (bytes)	Transactions per 1,000 customer per day	Traffic (including overhead) per 1,000 customer per day
		process & forward service switch operate operate failure to AMI Head end	per 1000 SW-oper per Pre-pay mtr per day		
PP-191	Pre-pay	DAP shall be able to process & forward metrology information after a successful service switch operate to AMI Head end	1-2 trans per 1000 Pre-pay mtrs per day	100	0.2
PP-213	Pre-pay	DAP shall be able to report & send "DAP to Smart Meter on-demand meter read request communications errors", to AMI Head end	1 trans per Pre-pay meter per x on-demand cmds per time period	50	20
PP-225	Pre-pay	DAP shall be able to process & forward on-demand meter read data from Smart Meter to AMI Head end	25 trans per 1000 DAPjm-Pre-pay mtrs per day	100	2.5
PP-244	Pre-pay	DAP shall be able to process & forward Meter on-demand read request app errors to AMI Head end	1 trans per each DAPjm-Pre-pay meters' app error event	50	0.25
ORM-03	ORM	DAP shall be able to	100	25	1

Requirement Reference	**Requirements (assumed electric unless noted otherwise)**	**How Often**	**App Payload Size (bytes)**	**Transactions per 1,000 customer per day**	**Traffic (including overhead) per 1,000 customer per day**
		send outage notifications to AMI Head end from Smart Meters	percent of meters that lose power per day		
ORM-14	ORM	DAP shall be able to send power restoration notifications to the AMI Head end from Smart Meters	100 percent of meters that returned to power per day	25	1
ORM-24	ORM	DAP shall be able to send a notification when DAP running on battery power AMI Head end	20 per 1000 DAP per system power outage event per day	25	0.02
Total Load: bytes per day per 1,000 customers					27,454,152

D.4 Number of Meters in a CDMA2000 1x or HRPD Sector

Using a site-to-site (base station to base station in a regularly spaced deployment) distance in [D4] of 2 km, one can compute the area of a given sector of a base station as approximately 1,154,701 m^2. If there are one thousand customers in this sector, one can arrive at a 1154.7 m^2 average area per customer. If there are M thousand customers, then the per-customer area is 1,155/M m^2.

D.5 CDMA2000 1x and HRPD System Throughput

The actual throughput of the cdma2000 system in a sector over a 1.25 MHz bandwidth RF carrier depends on many factors. Using the relatively large cell sizes in [D4] together with a mix of Rayleigh and Rician fading assumption for each of the terminals, [D5] has a set of HRPD throughput results without using multiple-input / multiple-output (MIMO):

- Forward link: 1.733 Mb/s to 2.08 Mb/s
- Reverse link: 1.26 Mb/s to 2.35 Mb/s.

Under a similar setting, [D6] and [D7] list the forward link throughput of cdma2000 1x in for 3 km/hr fading, which is expected to be less than the additive white Gaussian noise (AWGN) throughput which is more typical of the smart grid DAPs' environments:

- Forward link: 1.763 Mb/s to 1.845 Mb/s

Separately, [D8] lists the reverse link throughput simulated by Ericsson, LG Electronics, Nokia, Nortel, Samsung, and Qualcomm under a relatively lightly loaded condition of less than 5 dB of total reverse link received power above no-load level ("rise-over-thermal").

- Reverse link: 530 kb/s to 647 kb/s

Table 21 compares the demand from the smart grid use cases from 1,000 customers to the system throughput in 1.25 MHz carrier. One can easily see that these load levels are such a small percentage of the possible capacity of the cdma2000 1x and downlink only (DO) systems, that these two systems can support many thousands of customers per sector without problems.

Table 21: Smart grid use case demand versus CDMA2000 system throughput

	Smart Grid Demand per 1,000 Customers (b/s)	CDMA2000 1x System Throughput (b/s)	CDMA2000 HRPD System Throughput (b/s)
Forward Link	159	1,763,000-1,845,000	1,733,000 - 2,080,000
Reverse Link	2,542	530,000-647,000	1,260,000 - 2,350,000

D.6 Conclusion

The analysis shows that the total amount of forward link and reverse link traffic generated by these three use cases is very small compared with the system throughput of either the cdma2000 1x or HRPD system.

D.7 References

[D1] "SG-Network functional requirements spreadsheet, Version 3.0," http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Interium_Release_3/

[D2] "SG Network System Requirements Specification Interim Release 3," May 17, 2010, http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Interium_Release_3/

[D3] "Working draft of Guidelines for using wireless communications," http://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PAP02Wireless/NIST_Priotity_Action_Plan_2_r04.pdf

[D4] "cdma2000 Evaluation Methodology," 3rd Generation Partnership Project 2, 3GPP2 C.R1002-B, http://www.3gpp2.org/Public_html/specs/C.R1002-B%20v1.0_Evaluation_Methodology.pdf

[D5] "UHDR-DO Overview," Qualcomm Incorporated contribution to 3GPP2 TSG-C Working Group 3, C30-20060626-031R1, ftp://ftp.3gpp2.org/TSGC/Working/2006/2006-06-MiyazakiJapan/TSG-C-2006-06-Miyazaki%20-%20Japan/WG3/C30-20060626-031R1_QCOM_UHDR-DO_update.pdf

[D6] "Results of L3NQS Simulation Study," joint contribution from LG Electronics, Lucent Technologies, LSI Logic, Nortel Networks, Qualcomm Incorporated, and Samsung Electronics to 3GPP2 TSG-C Working Group 5, C50-20010820-011, August 20, 2001, ftp://ftp.3gpp2.org/TSGC/Working/2001/TSG-C_0108/TSG-C-0801-Portland/WG5/C50-20010820-011-Results%20of%20L3NQS%20Simulation%20Study.pdf

[D7] "System Simulation Results for the L3NQS Framework Proposal for cdma2000 1x-EVDV," joint contribution from LG Electronics, Lucent Technologies, LSI Logic, Nortel Networks, Qualcomm Incorporated, and Samsung Electronics to 3GPP2 TSG-C Working Group 5, C50-20010820-012, August 20, 2001, ftp://ftp.3gpp2.org/TSGC/Working/2001/TSG-C_0108/TSG-C-0801-Portland/WG5/C50-20010820-012%20L3NQS%20System%20Simulation%20Results.pdf

[D8] "Summary of system-level simulation results presented by various companies for Rev-D development," Qualcomm Incorporated contribution to 3GPP2 TSG-C Working Group 3, C30-20030812-062, August 12, 2003, ftp://ftp.3gpp2.org/TSGC/Working/2003/2003-08-Seoul/TSG-C-2003-08-Seoul/WG3/WG3%20Call,%202003.08.12/C30-20030812-062-Summary_system_simulation_results.doc

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Annex E IEEE 802.16/WiMAX Network

In this annex it is shown how some of the models and deployment considerations described in sections 5 and 6 apply to smart grid solutions based on the IEEE 802.16/WiMAX technology. In the analysis that follows, it is important to recognize that some of the parameters that comprise the system gain, a key component of the link budget, are vendor or equipment-specific. The values used for the analysis that are representative.

Figure 27, shows the range projections in the 1800 MHz band based on the modified Hata path loss model considering the different usage models described in section 5.2.2. A 10 dB fade margin is assumed for each of the usage models and the assumed receiver sensitivity is consistent with a cell-edge downlink (DL) channel data rate of approximately 3 Mb/s. Assumptions for other key device parameters for each of the usage models are as follows:

- Fixed Outdoor Subscriber Station (Fxd OD SS):
    - SS Antenna Gain = 14 dBi
    - SS Antenna Height = 10 m

- Vehicular-Installed Mobile Station (Veh-Ins MS):
    - MS Antenna Gain = 8 dBi
    - MS Antenna Height = 2 m

- Fixed Indoor Subscriber Station (Fxd ID SS):
    - SS Antenna Gain = 6 dBi
    - SS Antenna Height = 2.5 m
    - Building Penetration Loss = 10 dB

- Mobile Hand-Held Subscriber Station (Mob HH SS):
    - SS Antenna Gain = -1 dBi
    - SS Antenna Height = 1.5 m
    - SS Transmit Power = 200 mW
    - Building Penetration Loss = 10 dB

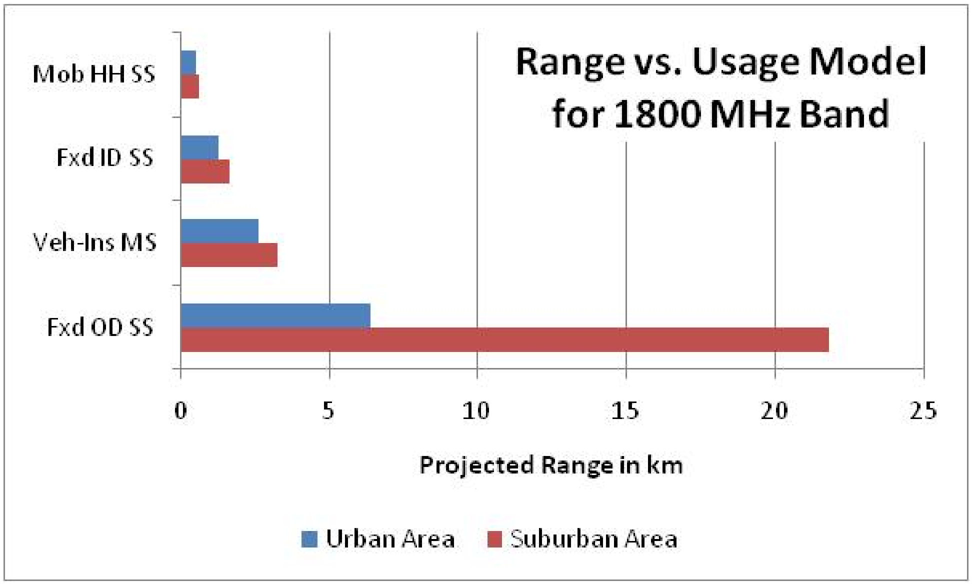

Figure 27 - Range and usage models

The range projections in Figure 27 can be used to provide some insights as to how the IEEE 802.16/WiMAX technology can apply to the backhauling of Data Aggegation Points (DAPs), a key requirement for a smart grid wide area network (WAN). It is anticipated that DAPs can be strategically deployed to take advantage of a reasonably high antenna height. This can be achieved by mounting the DAP antennas on existing utility poles, substation structures, etc. As seen from the previous analysis and the applicable channel models, the elevated antenna height can dramatically enhance the base station range and coverage. The following charts show the number of DAPs that fall within the projected base station coverage area for different DAP densities that might be encountered in urban or suburban environments. If a typical DAP were to support 500 to 1000 Smart Meters (SMs), 20 DAPs per km^2 would represent 10,000 to 20,000 SMs per km^2, an SM density consistent with many high population urban centers.

Although DAPs may represent the majority of actors to be covered with a smart grid WAN, there will, in most cases, be other actors as well. Video surveillance sites, for example, may be deployed throughout the same coverage area along with connections to emergency vehicles, remote offices, etc.

With the anticipated DAP densities and other smart grid actor sites, urban area deployments, especially in the lower frequency bands with limited spectrum, are likely to be capacity-constrained vs. range-constrained.

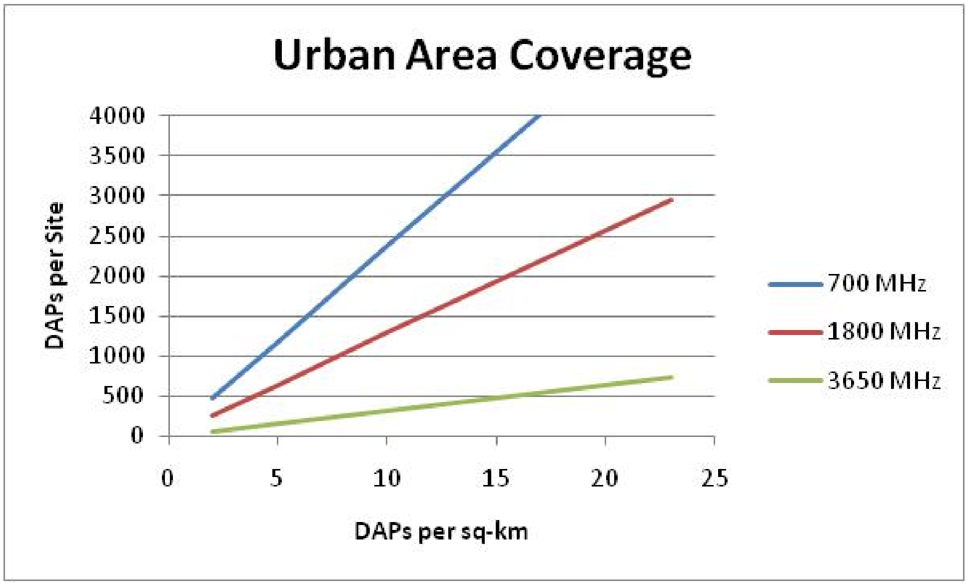

Figure 28 - Urban area DAP coverage

SM and DAP densities in suburban areas will be considerably less but with the increased range capability and the inclusion of other smart grid actors, deployments in frequency bands below 1000 MHz may still be capacity-constrained.

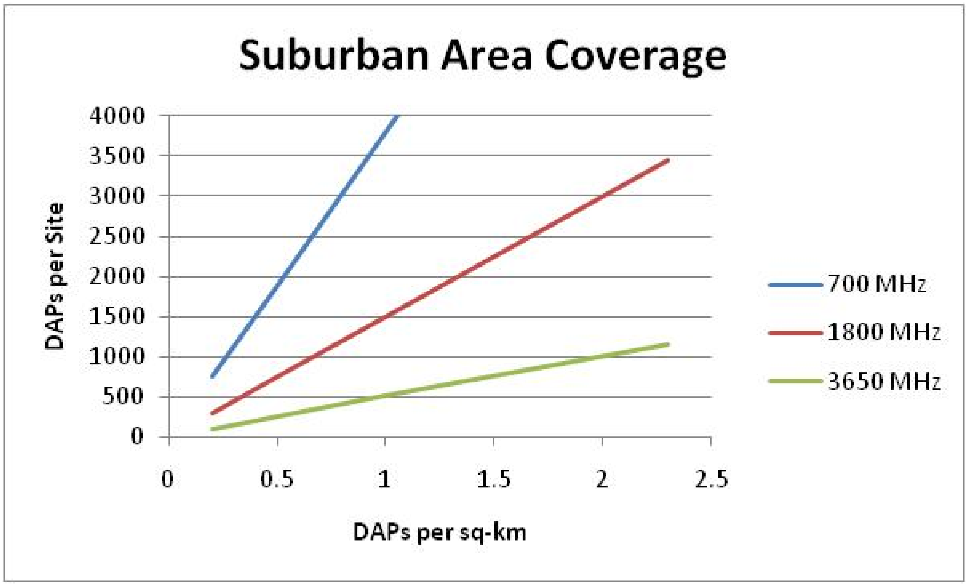

Figure 29 - Suburban area DAP coverage

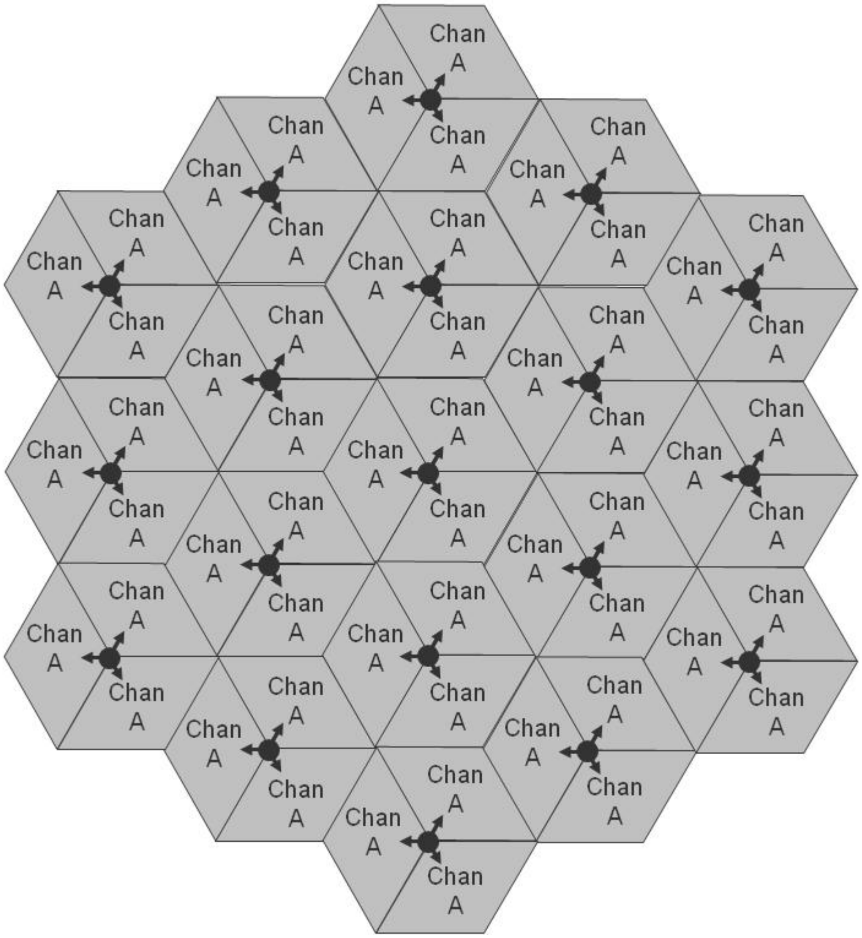

Figure 30 - Cluster of 19 three-sector base stations used for evaluation

Another important step in the technology assessment process is an analysis of channel, sector, and site capacity to ensure that the deployment meets requirements for the applications envisioned for the smart grid. The amount of available spectrum and whether it is shared with other applications, as would be the case in the license-exempt bands, or is uniquely allocated for smart grid is a key consideration. Whether licensed or un-licensed it is safe to assume that spectrum will always be at a premium making it important to consider spectral efficiency in the assessment of the alternative technologies for a WAN. Channel, sector and site capacity, and spectral efficiency for IEEE 802.16/WiMAX and other wireless technologies can be evaluated using an approach accepted by the IEEE 802.16 Working Group [E1] and ITU-R. This methodology, widely used to evaluate WiMAX/802.16 and long term evolution (LTE) solutions, assumes a cluster of 19 three-sector base stations (see Figure 30) in a range of deployment scenarios assuming 10 active users per sector. The methodology takes into account mobility (pedestrian and/or vehicular), multipath, inter-base station handoff, reuse factor, etc. Base station spacing is either 0.5 km or 1.732 km to reflect a micro or macro-cellular deployment.

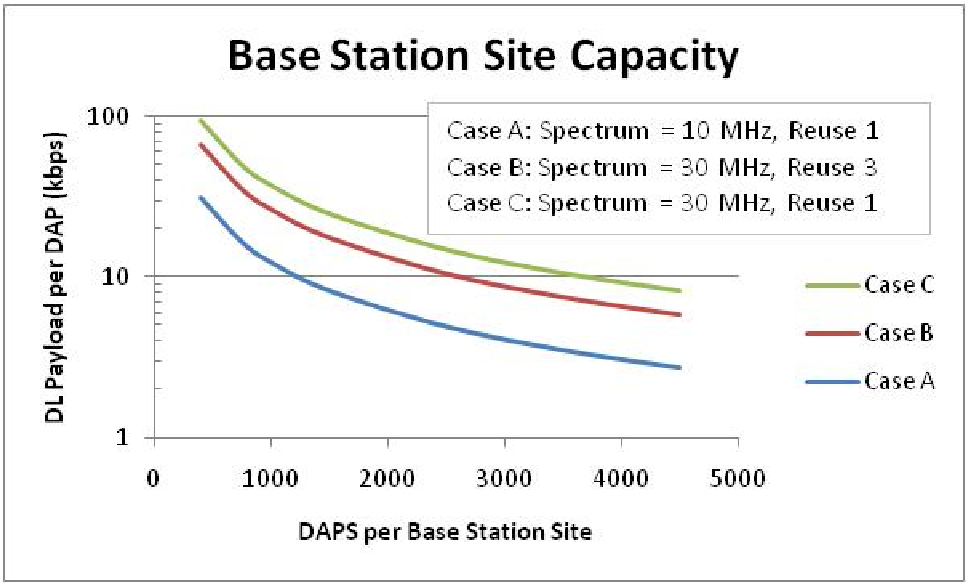

Figure 31 - Comparing base station site capacity and reuse

The frequency reuse factor plays a key role in determining net site spectral efficiency. A three-sector base station with a reuse of three requires a unique channel to be assigned to each sector. This will result in a high channel or sector spectral efficiency since inter-sector interference is minimized, but this approach requires three times as much spectrum. With reuse factor of one, the same channel is reused in each of the three sectors as shown in Figure 30. While inter-sector interference will result in a lower sector or channel spectral efficiency the net site spectral efficiency will be higher.

Orthogonal Frequency Division Multiple Access (OFDMA) based IEEE 802.16/WiMAX solutions can support a reuse of one. With OFDMA inter-sector and inter-cell co-channel interference is managed through the use of different subcarrier permutation zones [E2]. This is typically referred to as fractional frequency reuse.

Figure 31 shows the available payload per DAP for a typical IEEE 802.16/WiMAX deployment assuming a three-sector base station, 10 MHz Time Division Duplex (TDD) channels with a DL to uplink (UL) ratio of one with either 10 MHz or 30 MHz of available spectrum[21]. Comparing reuse three with 30 MHz of spectrum to reuse one with 10 MHz of spectrum the site capacity is approximately doubled, but at a cost of requiring three times as much spectrum. A frequency reuse factor of one provides a net 50% improvement in site spectral efficiency compared to reuse of three.

The above analysis is highly simplified in that it only looks at one aspect of a smart grid deployment, namely that of backhauling DAPs. Obviously a more detailed analysis would be necessary for a complete technology assessment with respect to capacity and coverage. The inclusion of additional actors and usage models, especially those with high capacity requirements such as video surveillance, would be required for a more complete study. There may also be a need to assess performance in other frequency

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[21] Results would be similar for FDD with a 5 MHz DL channel and a 5 MHz UL channel

bands, other channel bandwidths, etc. Other technology attributes must also be taken into account for a full smart grid suitability assessment. Latency, security, cell edge performance, quality of service (QoS), support for multi-casting, and location-based-services (LBS), etc. are all important to varying degrees when considering all the applications planned or envisioned for the smart grid network.

Nevertheless, the above examples based on the IEEE 802.16/WiMAX Network technology provide insights as to how the models described in section 5 can be utilized in assessing the suitability of the technology for a smart grid wide area network.

E.1 References

[E1] IEEE 802.16m Evaluation Methodology Document, IEEE 802.16m-08/004r5 <http://ieee802.org/16/tgm/core.html#08_004> http://ieee802.org/16/tgm/docs/80216m-08_004r5.zip.

[E2] Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation, August 2006