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Wireless User Requirements for the Factory Workcell

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Abstract

Wireless communication is becoming crucial to advanced manufacturing. Industry 4.0 and Smart Manufacturing depend on networked industrial automation systems. The term Industrial Internet of Things (IIoT) has been used to describe the deployment of interconnected machines, sensors, and actuators within modernized factories. The adoption of wireless systems is essential to these IIoT deployments. Wireless automation significantly reduces capital investment costs including conduit, cables, networking equipment, and labor of installation. To enable the adoption of wireless systems at the factory-floor level, wireless requirements must be established to realize the benefits of wireless communication systems within those factories. One challenge is that existing wireless standards lack technical specifications that support low-latency and high-reliability communication for factory applications. Additionally, requirements for such capabilities are published or advertised without validation of said requirements. Often, requirements published by standards development organizations appear excessively strict and unvalidated by empirical study. Moreover, those requirements ignore the capabilities of the applications to use their own intelligence to compensate for lost reliability in the network. This report analyzes existing wireless user requirements stated by industry organizations and it produces a combined perspective on wireless user requirements for the factory workcell with supporting rationale.

Key words

Smart Manufacturing; Industry 4.0; Industrial Internet of Things (IIoT); Wireless communication; Wireless in Industry; Factory Communications

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1 Introduction

Industry 4.0 and Smart Manufacturing paradigms describe the vision of creating smarter factories that embody high adaptability and efficiency. The aim is to connect and computerize traditional industries, including manufacturing, to improve efficiency and adaptability [1].

The industrial internet of things (IIoT) represents the use of the internet of things (IoT) in manufacturing [2]. IIoT can be realized by the development of connected devices that utilize sensing and processing capability. Developing reliable ways to connect these sensing and processing devices will enable progress towards IIoT. On the factory floor, wired connections provide highly reliable, but costly and physically-restrictive connectivity. Wireless connectivity, however, offers many benefits over wired solutions. First, lower expenditures and decreased long-term maintenance costs can be achieved with wireless solutions by the elimination of conduit and cable. Second, wireless connections can be utilized in otherwise impractical locations, using low-power monitoring devices, thus eliminating the difficulties inherent in physically routing cables. Third, wireless communication allows mobility and reconfigurability; with wireless communication, it is possible to have easily relocatable and reconfigurable workcells [3].

Wireless communication solutions have certain known disadvantages when compared with wired solutions. These disadvantages may include reduced transmission reliability and increased end-to-end transmission latency due to the radio-harsh propagation environment of the factory [4]. In addition, the bandwidth of wireless networks may be lower than with wired solutions resulting in lower maximum data rates. The simple replacement of wired links, with currently available general-purpose wireless networks in industry, may not lead to desired performance, due to issues in meeting reliability and latency requirements of the factory application.

Typical industrial wireless applications require a deterministic and highly reliable communication network to achieve desired performance for mission-critical applications. Meeting industry's wireless communications requirements is not trivial and more research in the field is needed to design wireless solutions that meet these challenges. It is essential to begin the design process with realistic user requirements that have been validated and that exemplify current and future needs of the factory.

This report will discuss several wireless user requirements perspectives from industry. The report also provides a NIST perspective on wireless user requirements for the factory workcell. We center these requirements around the workcell because the size of factories varies considerably. We believe that by focusing on requirements for the workcell, rather than for the entire factory, will provide requirements with greater applicability [5].

The intended audience of this document includes network engineers, information technology experts, factory floor engineers, and system integrators, who are interested in deploying wireless systems in industrial environments. The requirements provided in this report are a work-in-progress that will evolve as we improve our understanding of the requirements needed for wireless communication in a factory workcell.

2 Requirements Considerations

Requirements considerations for designing or implementing a wireless communication system in a factory workcell include latency, reliability, scalability, range, payload size, update rate, operation and implementation cost, security, and system resiliency. These requirements are important aspects of a wireless network [6]. We believe that these requirements have particularly influential roles in implementing a wireless communications system in a factory environment. A one-size-fits-all approach is not possible; therefore, it is necessary to determine requirements that meet most demands for industry applications.

2.1 Latency

Most non-industrial wireless systems are designed for higher data rates without regard for latency. However, for industrial applications, low latency is an important factor in control-based tasks as transmissions that occur outside of the latency threshold are considered failed transmissions. Industrial applications use smaller packet sizes with precise timings, signifying the critically of latency.

2.2 Reliability

Industrial functions such as safety transmissions or critical control processes are examples of functions that require an extremely high degree of reliability because a "missing" transmission could have serious consequences to safety, production, and/or equipment integrity. High-reliability in industrial communication is crucial for numerous mission-critical applications.

2.3 Scalability

Scale, in an industrial wireless point-of-view, is the number of devices that can be deployed on the network while retaining reliability, speed, and data-rate at set requirements. Scalability is important for dynamic networks where devices come-in and go-out of use. One distinct advantage of wireless communications is the ease with which nodes can be added to the network without the need for laying wire or cable.

2.4 Range

Range is the maximum distance to which a wireless link can extend while maintaining all other requirements. In general, as the distance of the wireless link increases, the channel losses increase and the signal power between nodes decreases. Excess range affects the reliability and latency of transmission. Specifically, in an industrial environment, meeting a required range specification is more challenging than an outdoor scenario due to increased path loss.

2.5 Payload Size

Payload size is the size, in bytes, of the information portion of a transmission; however, the payload excludes header, framing, and error-correction information. Differentiating the payload size from the overall individual packet size allows the designer to ascertain the size of the information portion of the transmission. Many industrial applications, such as safety and control applications, the payload size is small.

2.6 Update Rate

Certain manufacturing applications require higher update rates to achieve desired workcell performance. A wireless network must be capable of supporting required update rates needed by all the applications on that wireless network. For example, a force feedback control application that utilizes a wireless force-torque sensor may require 125 Hz sample rate. An example of such an application may be found in reference [7]. Update rate is an important factor that impacts the deployment and configuration of wireless networks and it dictates the effectiveness of frequency planning [8].

2.7 Operation and Implementation Costs

A consideration for implementing industrial wireless communications is the cost savings. For a wireless communications system, there is no need to install and, later, replace cabling due to degradation and wear. In wireless communications, redundancy can be achieved without cables. Wireless communications require lower labor costs as remote monitoring and control extend the ability to monitor and manage remote sites; onsite personnel is unnecessary. Electricity cost is lower for wireless installations, due to the relatively low power draw of wireless communications.

2.8 Security

Security in wireless communications is not equivalent to security in wired communications in that wireless networks offer a different potential for exploitation; wireless uses air for communication which provides easier access to remote foreign actors. Along with the threat of remote jamming, there exists the possibility, absent adequate security protection, that wireless networks could be accessed if the keys to the public-key cryptography are discovered and encrypted transmissions are revealed. Wireless for industrial applications must be reliant to security related threats as the loss of communication can be costly and may damage equipment or personnel. Detailed requirements for wireless security are not discussed further in this report but more information can be found in [9].

2.9 System Resiliency

Overall system resiliency in a factory environment must be considered as issues with networking may lead to unnecessary inefficiency. For example, if power is disrupted a network must be able to reestablish connectivity within seconds. Intelligent applications may also be required to overcome network communication issues. Achieving a resilient network is not trivial as current wireless device may require long periods of time to reestablish connections within the network. For example, mesh networks based on low-data-rate protocols can often take minutes to reestablish an operational network after an intermittent loss of power. System resiliency is outside the scope of this report; however, system resiliency issues such as recovery time after power loss must be considered in the design of wireless technology for use in factory workcells.

3 External Wireless User Requirements

This section will cover the present-day wireless requirements by standards development organizations and industry, and, subsequently, will present a NIST-staff perspective on wireless user requirements for the factory workcell.

3.1 ISA's Perspective on Wireless User Requirements

The International Society of Automation (ISA) is a non-profit standardization body that produced *Wireless User Requirements for Factory Automation* [10]. ISA provided classes that categorized industrial applications and use cases, and assigned wireless user requirements for latency, jitter, and block error rate (BLER).

Table 1, adapted from [10], provides usage classes with their respective descriptions; these classes are grouped by domain, in factory automation use cases. In **Table 1**, it is important to note that the "Factory Automation Use Cases" column references "Clauses" which describe applications in the usage classes in detail and are not discussed in this report. The Clauses discuss various industrial applications and such applications apply to different classes. For example, robot end-effectors for Class 1, track-mounted equipment and rotary equipment for Class 2, track-mounted equipment and rotary equipment, but with a human in the loop for Class 3; torque and gauge tools, mobile material containers, mobile high value assets (molds, dies, etc.), and mobile test and calibration fixtures for Class 4. Note that the report references similar applications for Class 4 as for Class 5, except with the purpose of logging, downloading, and uploading; also note that Class 0, was not discussed [10]. In section 4.2, "NIST Perspective on Wireless User Requirements," detailed definitions are provided for the classes as we adopt the same class scheme that the ISA uses. The ISA requirements, adapted in **Table 2**, define BLER as the probability of an erroneous block received at the application layer. It should be noted that all usage classes have a requirement of 10^{-9} BLER, an assumed requirement, without justification, in the ISA's report.

Table 1. ISA Descriptions of Classes

Domain	Usage Class	Description	Factory Automation Use Cases
Safety	Class 0: Emergency action	Always critical	
Control	Class 1: Closed loop regulatory control	Often critical	Clause 5.3
	Class 2: Closed loop supervisory control	Usually non-critical	Clause 5.4 Clause 5.5
	Class 3: Open loop control	Human in the loop	Clause 5.4 Clause 5.5
Monitoring	Class 4: Alerting	Short-term operational consequence (e.g., event-based maintenance)	Clause 5.6 Clause 5.7 Clause 5.8 Clause 5.9
	Class 5: Logging, Downloading, and Uploading	No immediate operational consequence (e.g., history collection, sequence of events, preventive maintenance)	Clause 5.6 Clause 5.7 Clause 5.8 Clause 5.9

Table 2. ISA Wireless Requirements Perspective

Use Case Class	Latency (ms)	Jitter (%)	BLER
Class 0	Not defined	Not defined	Not defined
Class 1	10	+/- 10	10^{-9}
Class 2 and 3	10-100	<10	10^{-9}
Class 4 and 5	100 avg.	+/- 10	10^{-9}

3.2 ETSI's Perspective on Wireless User Requirements

The European Telecommunications Standards Institute (ETSI) produced a requirements report titled *Reconfigurable Radio Systems (RRS); Feasibility study on temporary spectrum access for local high-quality wireless networks* [11]. The ETSI report included a detailed table, reproduced here in **Table 3**, which categorized specific industrial scenarios and listed certain requirement metrics such as latency, reliability, data rate, packet size, communication range, device mobility, device density, and energy efficiency. We find the ETSI report to be very detailed; however, justification of specific values and their derivations are not disclosed.

ETSI's industrial wireless communications requirements are separated into different sections, depending on the application. Under "Monitoring and Diagnostics", the application is focused on remote sensors that do not have strict latency or reliability requirements, compared to other applications. The column, "Condition Monitoring", includes applications that report physical parameters, such as temperature, humidity, vibration, acceleration, etc., and the column has similar wireless network requirements to "Process Automation". In discrete manufacturing, a countable number of items are produced which may take many steps to complete. In discrete manufacturing, machine tools, robots, sensors, and programmable logic controllers (PLCs) exchange small packets with short intervals, which requires low-latency communications. "Motion Control" has more strict latency requirements than general discrete manufacturing. Examples for "Motion Control" include a controller for an electric motor in an assembly line or a hydraulic cylinder controller for a press [11].

The "Logistics and Warehouse" category is separated into mobile vehicles, automated guided vehicles (AGV) and static systems such as cranes. AGVs can be mobile robots, transport vehicles, and mobile working platforms. It is stated in [11] that a latency of 15 ms – 20 ms and a reliability requirement of 10^{-6} should be ensured. The "General" subcategory for "Logistics and Warehouse" is not discussed or justified within the ETSI report. Process Automation typically involves chemical processes engineering, for example, oil and gas production or the generation of electricity. In the "Process Automation" category, steps are sequential, continuous, and irreversible. "Process Automation" applications need deterministic delivery of transmissions, thus, the relaxed latency requirements and reliability of 10^{-5}. The "Augmented Reality" category includes computer-assisted extension of reality. The "Functional Safety" category requires high reliability (10^{-9}) and low latency of 10 ms. Safety is critical to protect people, machines, and production environments, hence the stricter requirements.

Table 3. ETSI Wireless Requirements Perspective

	Monitoring & Diagnostics		**Discrete Manufacturing**		**Logistics and Warehouse**			**Process Automation**	**Augmented Reality**	**Functional Safety**
Key Performance Indicator	**General**	**Condition Monitoring**	**General**	**Motion Control**	**General**	**AGV**	**Cranes**			
Latency/Cycle Time (ms)	> 20	100	1 – 12	250 µs – 1 ms	> 50	15 – 20	15 – 20	50 – X s	10	10
Reliability (PER)	10^{-4}	10^{-5}	10^{-9}	10^{-9}	$>10^{-2}$	$>10^{-6}$	$>10^{-6}$	10^{-5}	10^{-5}	10^{-9}
Data Rate (bits/sec, bps)	Kbps-Mbps	Kbps	Kbps-mbps	Kbps-Mbps	Kbps-Mbps	Kbps-Mbps	Kbps-Mbps	Kbps	Mbps-Gbps	Kbps
Packet Size (bytes, B)	> 200 B	1-50 B	20-50 B	20-50 B	< 300 B	< 300 B	< 300 B	< 80 B	> 200 B	< 8 B
Communication Range (m)	< 100	100 m – 1 km	< 100	< 50	< 200	~2	< 100	100 m -1 km	< 100	< 10
Device Mobility (m/s)	0	< 10	< 10	< 10	< 40	< 10	< 5	< 10	< 3	< 10
Device Density (m^-2)	0.33 – 3	10 – 20	0.33-3	< 5	~ 0.1	~ 0.1	~ 0.1	10000/ Factory	> 0.33 – 0.02	> 0.33 – 0.02
Energy Efficiency	n/a	10 years	n/a	n/a	n/a	< 8 hours	n/a	10 years	1 day	n/a

3.3 An Industry Perspective on Wireless User Requirements

Another industry perspective presented in [12], targeted ultra-high-performance wireless for various scenarios ranging from building automation to the switching of power electronics equipment. An example of system-level requirements for different industrial communication scenarios is captured in **Table 4**. The scenario "Building Automation" consists of all control operations performed within buildings, such as lighting, heating, surveillance, energy management, etc. "Process Automation" is involved in chemical, mining, oil, and metallurgic processes. "Factory Automation" is a general term referring to the factory production line, such as assembly and packaging. More demanding scenarios include "Power Systems Automation" in which control for power distribution is performed. "Power Electronics Control" focuses on the synchronized control of power electronic devices. All these scenarios have distinct requirements. Luvisotto states that for a wireless high-performance (HP) system, a packet error rate (PER) of 10^{-9} is perceived as tolerable [12]. It is important to clarify this PER is at the application layer and it is possible to have a PER of 10^{-1} at the physical layer and still achieve 10^{-8} at the application layer with transmission and information redundancy [12]. It was proposed in the paper that a latency requirement of 10 μs is targeted for Wireless-HP. It is stated that "Factory Automation", "Power Systems Automation", and "Power Electronics Control are the scenarios where Wireless-HP is applicable.

Table 4. System-Level Requirements for Different Industrial Communication Scenarios

Scenario	# of nodes	Update rate	Goodput	System range
Building Automation	10^2-10^3	10^{-1} Hz	10^3-10^4 bps	10^1-10^2 m
Process Automation	10^2-10^3	10^1 Hz	10^5-10^6 bps	10^1-10^2 m
Factory Automation	10^2-10^3	10^3 Hz	10^7-10^8 bps	10^1-10^2 m
Power Systems Automation	10^1-10^2	10^4 Hz	10^7-10^8 bps	10^2-10^3 m
Power Electronics Control	10^2-10^3	10^5 Hz	10^9-10^{10} bps	10^1-10^2 m

4 Wireless User Requirements with Justification

This section will discuss the terminology and specification of wireless user requirements. This section will also provide justification for the requirements we propose. It is important to delineate the requirements and to justify each value proposition. These requirements may be used to evaluate wireless technology and to gauge whether a certain wireless technology may apply to specific classes of applications. The requirements are directed towards workcells in factory environments.

4.1 Terminology

Terminology for the NIST perspective on wireless user requirements are listed in **Table 5**.

Table 5. Definition of User Requirements

User Requirement	Definition
Payload Size	The information component in a transmission between applications with the network considered as a black box. The information component does not include network headers, framing, or redundancy for error correction typically associated with the term "packet." The size of a transmission has units of bytes (B).
Latency	The total time in milliseconds (ms) it takes for (1) the transmitter to send a packet from the application layer, (2) for the packet to travel through space, and (3) the time for the packet to be received and understood by the receiver at the application layer.
Reliability	The probability of transmission failure, e.g., information is either lost, received outside the latency requirement, or received with an error. The loss is perceived at the application layer interface.
Scale	The number of wireless links in a workcell.
Range	The distance in meters (m) between the receiver and transmitter with the expectation of meeting all other requirements.
Update Rate	The update rate of devices in Hertz (Hz).

4.2 NIST Perspective on Wireless User Requirements

Using present-day requirements from standardization bodies such as ISA [10], ETSI [11], and industry [12], along with our own rationale, we produce **Table 6**. Note that these requirements are a work-in-progress and values are not definitive. Requirements have a component of subjectivity and assumptions must be made to derive specific requirement values. More research needs to be performed on specific metrics for different classes, such as reliability and latency requirements. In order to specify the scale and certain metrics for each class, we have labeled each class individually.

We adopt the same ISA class-labeling scheme from **Table 1** to categorize applications. The ISA classification scheme groups applications according to mission-criticality, e.g., the more critical "Class 0: Emergency," versus the less critical "Class 5: Logging, Downloading, and Uploading." We chose not to include Class 5 in **Table 6** because the requirements are not adequately supported by existing wireless standards. We believe that existing wireless standards do not jointly meet the requirements for all the industrial use case classes presented; however, we believe that the design of new wireless technology that applies to industry can be accomplished using the requirements in **Table 6**.

We base the user requirements, shown in **Table 6**, on what we believe to be necessary for effective and realizable communications within factory workcells. Latency and reliability are fundamental requirements for time-sensitive applications. Latency and reliability can often be considered jointly as information that is delayed beyond a time threshold may be considered as lost information. Scale is important to enable large enough capacity for a network, while maintaining latency and reliability targets. Range provides a minimum expected distance between linked nodes. We developed our perspective with the philosophy of avoiding unreasonable performance expectations on the wireless systems. For instance, requiring a range of 100 meters for a workcell device that only needs to operate within 10 meters would be unreasonably strict and would be considered "overkill" for many applications where shorter range would be sufficient and more practical.

Table 6. Wireless User Requirements for the Factory Workcell

User Requirement		**Class 0: Safety**	**Class 1: Closed Loop Regulatory Control**	**Class 2: Closed Loop Supervisory Control**	**Class 3: Open Loop Regulatory Control**	**Class 4: Alerting Monitoring**
Latency (ms)	Typical	4	4	20	4	50
	Minimum	0.5	0.25	4	0.5	4
Reliability (Pr. of Loss)	Typical	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}
	Minimum	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
Scale (# of links)	Typical	8	10	10	1	100
	Maximum	16	30	30	4	300
Range (m)	Typical	10	10	10	10	10
	Maximum	30	30	30	30	30
Payload (B)	Minimum	6	8	8	8	12
	Maximum	24	1024	1024	1024	33K
Update Rate (Hz)	Typical	125	125	25	125	10
	Maximum	1000	2000	125	1000	125

4.3 Justification

For each class in **Table 6**, justification is provided for the user requirement values. For each justification, the typical value of the requirement is reproduced for the convenience of the reader. To determine specific values, assumptions must be made.

We assume that the typical workcell size is 10 m x 10 m, no more than one system failure every 1000 years is tolerable, individual transmissions are independent, and that one wireless link would be used in some scenarios involving multiple sensors/regulators. Assumptions will be discussed in this report when applicable.

Note that the "typical" and "minimum" latency requirements for all classes are derived directly from the update rate and/or are corroborated with external sources. It is assumed that the maximum latency tolerable for a transmission is half the time of one cycle. This allows time for processing of the transmission or a single failed transmission without system failure. Below is Eq. (1).

$$Latency = 1/(2 * Update\ Rate) \tag{1}$$

The required probability of a single transmission failure, P_m, is calculated with T representing the seconds in 1000 years, U representing the update rate, and n representing the number of failed transmissions consecutively that lead to a system failure (we assume n is 2). For the purpose of this

report we assume independent transmissions to be transmitted; however, this assumption may be flawed in practice, since transmissions depend on the propagation channel that individual transmissions share. Accounting for the effects of different propagation models is outside the scope of this report.

To solve P_m, one system failure per number of transactions sent in 1000 years is used. Calculations of all the reliability requirements use Eq. (2). Note that reliability values are truncated to fit into the 10^{-x} form, thus, the exact values are not shown in **Table 6**.

$$P_m{}^n = 1/(T * U) \tag{2}$$

4.3.1 Class 0: Safety

Applications that fall under Class 0 are highly critical, for example, safety integrated systems. These systems require high reliability and low latency, typically with very small payload sizes. Applications in Class 0 are used to prevent damage to equipment or personnel.

Latency**:** 4 ms. This latency requirement has basis from time critical emergency applications in Class 0, in which, added delay can lead to injury or equipment damage. Specific latency requirements do vary depending on the application; some applications may require latency as low as 0.5 ms.

Reliability**:** 10^{-7}. Our expectation for overall system reliability is that one system failure per 1000 years is acceptable for industrial applications. System failure is vastly different from transmission failure, which is the basis of the reliability requirement. With the assumption that a system failure occurs when two or more transmissions fail consecutively, we have calculated the required transmission reliability of 10^{-7}, which corresponds to 1000+ years of continuous operation without system failure. A system failure occurring during a critical point in time, such as the activation of an E-stop, should be a an extremely rare occurrence.

Scale**:** 8 links. The typical value of eight links for an emergency stop (E-stop) application is derived from two devices per edge of a rectangular workcell. The number of these safety devices could increase to 16 in an application requiring more nodes. For a safety application, we assume that the typical case is that each device communicates wirelessly utilizing one link; however, it is possible that multiple safety devices could have outputs ganged together and would communicate wirelessly using a single link to a controller.

Range**:** 10 m. The ten-meter range is the expected working distance. This range is based on previous observations of workcell size from site visits to measure factory RF propagation environments [4]. It is possible to have larger workcells that require a 30-meter range or more; however, 30 meters of range should not be a requirement for all applications.

Payload Size**:** 6 B - 24 B. Emergency-related transmissions are usually very short due to the nature of the type of transmission. In many applications, a single bit suffices as the payload size, as emergency situations can be classified as a Boolean logic "pass or fail". We assume that 6 B suffices for most applications in Class 0 with 4 B consisting of a single variable value and the remaining 2 B being used for device identification (ID). We also assume that in Class 0, the transmission of 1 - 4 variables using a single wireless link can occur. Four variables sent in one wireless link can be achieved by ganging four safety devices together, e.g., at each edge of the workcell. Note that the minimum payload size is less than other classes because applications in Class 0 do not require transmission of variable type, unlike all other classes.

Update Rate**:** 125 Hz. We have observed that an update rate of 125 Hz is typical for ethernet based E-stops. We assume that this 125 Hz update rate can be directly applied to wireless safety systems. Note that update rate is highly application dependent, where some automated safety systems may run at 1000Hz.

4.3.2 Class 1: Closed Loop Regulatory Control

Regulatory control consists of multiple single-input single-output control loops, designed to regulate local variables such as flow, speed, etc. Applications for Class 1 include robot end-effectors, arc-welders, laser cutters, spindle position/velocity control, robot docking/interlocking control, and precise position-based arm control.

Latency**:** 4 ms. Due to the nature of closed loop regulatory control, strict requirements on latency are crucial for avoiding the introduction of delay, uncertainty, and loss in a feedback-based control system. A target of 4 ms for all applications might not be accurate, since different applications may require a stricter, 0.25 ms, or less strict, 12 ms, latency requirement. We obtained the minimum and maximum latency requirements for Class 1 using the "Discrete Manufacturing" columns from **Table 3** and the update rate from this current class; however, we derived the typical latency requirement of 4 ms using **Equation 1** and the same rationale as Class 0.

Reliability**:** 10^{-7}. The same rationale for system reliability, that one system failure per 1000 years is acceptable, is used to calculate required reliability. Note that the typical and minimum requirements are equivalent in the table, however the actual values are $5.0 * 10^{-7}$ for 125 Hz and $1.3 * 10^{-7}$ for 2000 Hz.

Scale**:** 10 links. This is typical for the assumed workcell size, in which there are many pieces of equipment that use closed-loop regulatory control to perform tasks. We assume that equipment, such as a robot arm with multiple sensors and regulators, will be served by a single wireless communications device. This assumption is based on our experience in wired robots that communicate to a robot controller, in which a robot arm will have one cable providing power and data. It is possible to have as many as of 30 links in a larger workcell.

Range**:** 10 meters. This range is obtained using the same justification for Class 0; the range is based on the average observed size of a workcell.

Payload Size**:** 8 B - 1024 B. A payload size of 8 bytes per variable was derived using the same size for the value, 4 B, and device ID, 2 B, as Class 0, with the addition of 2 B for the variable type. We have observed the opportunity for multiple variables to be ganged together and sent from one wireless device. We have observed systems that have the potential for 128 unique variables to be sent. For 128 variables, with the payload of 8 B per variable, the maximum payload would be 1024 B as a maximum payload size. Since the number of bytes is highly application dependent, we do not provide a specific typical information size; however, it is possible to determine the payload size, given the number or single variables.

Update Rate**:** 125 Hz. This update rate is a typical value in a common use case of the reporting of force-torque values from a robot end-effector. It is possible that an application, such as a computer numerical control (CNC) [13], requires a 2000 Hz update rate.

4.3.3 Class 2: Closed Loop Supervisory Control

A typical application of Class 2 is a PLC-based supervisor. PLCs send commands to actors to complete tasks. Specifically, in discrete manufacturing, tasks are completed sequentially; thus, the

effect of increased latency in the communications link between a supervisor and actor will mainly influence the speed of production.

***Latency*:** 20 ms. This typical latency requirement and the minimum latency requirement were calculated using **Equation 1**, given the update rate. Since a supervisor's role is to command actors into completing tasks, less strict latency requirements, compared to Class 1, are tolerable. A calculation to show additional time for tasks to complete is as follows: if 10,000 transmissions that correspond to events must be completed in one day with instruction from the supervisor, at a maximum latency at 20 ms, 190 additional seconds, per day, of production time would be introduced, compared to a 1 ms latency.

***Reliability*:** 10^{-7}. This reliability requirement was calculated using **Equation 2**.

***Scale*:** 10 links. The number of links for this class is based on the scale for Class 1. Our rationale is that the number of Class 1 links for should match the number of Class 2 links, as Class 1 applications would report to Class 2 applications, such as a supervisory PLC.

***Range*:** 10 m. This range is obtained using the same justification for Class 0, the range is based on the average observed size of a workcell.

***Payload Size*:** 8 B - 1024 B. This value is derived from 2 B for device ID, 4 B for variable value, and 2 B for variable type. Again, we assume that no more than 128 different variables will be sent in one transmission.

***Update Rate*:** 25 Hz. This update rate is from the supervisor in the collaborative workcell in [14], in which a supervisory PLC communicates to four other PLCs and two robot controllers. It is possible to run at a higher update rate, 125 Hz for instance.

4.3.4 Class 3: Open Loop Regulatory Control

In Class 3, control is performed manually (human in the loop) rather than through feedback. Typical applications in this class include heavy lifting using a remotely controlled gantry system, or manual operation of rotary equipment.

***Latency*:** 4 ms. The typical latency requirement and the minimum latency requirement of 0.5 ms were calculated using **Equation 1**.

***Reliability*:** 10^{-7}. This reliability requirement was calculated using **Equation 2**.

***Scale*:** 1 link. One device per workcell is typical as the operation of multiple human-controlled wireless control-based applications would be uncommon. For the maximum value, it could be possible to have up to 4 pieces of equipment in operation concurrently that require a single wireless link each.

***Range*:** 10 meters. This range is obtained using the same justification for Class 0; the range is based on the average observed size of a workcell.

***Payload Size*:** 8 B - 1024 B. These minimum and maximum values are obtained using the same rationale as Class 1 and Class 2.

***Update Rate*:** 125 Hz. The same update rate requirements apply to class 3, except for the maximum update rate. An update rate of 1000 Hz for Class 3 is used in rotary equipment.

4.3.5 Class 4: Alerting and Monitoring

Typical applications of Class 4 consist of sensing and monitoring devices. Many of these devices do not require low-latency and high-reliability for an individual transmission.

***Latency*:** 50 ms. This requirement is calculated from the typical update rate of 10 Hz for Class 4 applications. Since the typical application is not used for regulatory control, such as Class 1, this latency requirement is tolerable.

***Reliability*:** 10^{-6}. This requirement is less strict than other applications because the required update rate is considerably lower at 10 Hz. Since the update rate is low, fewer cycles occur per 1000 years, leading to the less strict reliability requirement, compared to other classes.

***Scale*:** 100 links. Assuming that each device has a single wireless link, 100 devices per workcell was calculated using the device density from the general case of condition monitoring in **Table 3**, and assumes 1 device per square meter in a 100 m^2 workcell. A maximum of 300 links is also possible for larger workcells.

***Range*:** 10 m. This range is obtained using the same justification for Class 0; the range is based on the average observed size of a workcell.

***Payload Size*:** 12 B - 33 kB. This is derived from 2 B for device ID, 2 B for variable type, 4 B for variable value, and 4 B for time. The maximum scenario is defined for a single 1080p video stream at 30 frames per second using the H.264 video encoder, a typical frame rate for moderate to high quality video streams, within the workcell. Video streams in a workcell could be used for product or product line inspection. Video bitrate will vary depending on the application and necessary video quality.

***Update Rate*:** 10 Hz. This is a typical update rate for Class 4 as some devices in this class may hibernate; however, when they activate, these devices may send transmissions at a specific “update rate” until the transmission is received by the access point and then understood by the monitoring or alerting device. Update rates as high as 125 Hz may be used for monitoring and alerting applications.

4.3.6 Class 5: Logging, Downloading and Uploading

Class 5 is not included in **Table 6** as these tasks are usually not mission-critical and supported by existing wireless technology. Class 5 usually requires the highest data rate of all classes, with potentially large payloads.

5 Conclusion

This report has discussed the qualitative and quantitative aspects of industrial wireless requirements and has reviewed existing requirements from standards development organizations as well as other perspectives. From these existing external requirements, along with our own rationale and experience, we have produced a NIST-staff perspective on wireless user requirements for the factory workcell. It should be emphasized that we have found latency, reliability, scale, minimum range, payload size, and update rate to be the most important requirements for applications in Classes 1 to 4. This report also discusses skepticism about existing requirements for BLER or PER, as values as low as 10^{-9} are difficult to justify and measure. The wireless user requirements in **Table 6** are a work-in-progress as new information will shape increasingly accurate requirements. We believe that wireless user requirements for industry must be broad, as each application will have its unique requirements. There exist many standards that can reasonably fit applications in Classes 2, 4, and 5, but as of now, Classes 0, 1, and 3 have yet to define a clear standard that fits the requirements stated. Interestingly, the scale for Classes 3 to 5 is quite massive and there is opportunity for wireless to replace wired networks with current or near-future wireless standards. More research must be conducted into the characterization of wireless technology under factory environments to reveal the reliability, latency, and minimum range of wireless technologies in a factory environment.

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