NIST Advanced Manufacturing Series 300-8
Revision 1

Wireless User Requirements for the Factory Workcell

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https://doi.org/10.6028/NIST.AMS.300-8r1/upd

National Institute of
Standards and Technology
U.S. Department of Commerce

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October 2020
INCLUDES UPDATES AS OF 02-08-2021; SEE APPENDIX A

U.S. Department of Commerce
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National Institute of Standards and Technology Advanced Manufacturing Series 300-8 Revision 1
Natl. Inst. Stand. Technol. Adv. Man. Ser. 300-8 Rev. 1,
27 pages (October 2020) Includes updates as of 02-08-2021

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https://doi.org/10.6028/NIST.AMS.300-8r1/upd

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 installation labor. 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 invalidated 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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Acknowledgements

The authors would like to acknowledge the NIST industrial wireless technical working group (IWSTWG) members for their thoughtful and constructive comments that helped us to improve the overall clarity and accuracy of this report.

Hans-Peter Bernhard, Fjolla Ademaj, Muzaffar Raheeb, and Atiq Mahin, *Silicon-Austria Labs*

Iñaki Val, *IKERLAN*

Dave Cavalcanti, *Intel Labs*

Justin Shade, *Phoenix Contact*

Russ Gyurek, Tim Stammers, *Cisco Systems*

Zhibo Pang, *ABB Corporate Research*

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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. Currently, 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]. A factory environment is typically more populated with metallic and absorbing objects that respectively reflect and absorb electromagnetic waves at typical communication frequencies. Also, faster changes in the electromagnetic environment in factories may occur due to moving objects, such as robots and other machines, compared to a home or office environment. Undesirable effects such as shadowing, attenuation, multipath, and scattering may result in a weak wireless propagation channel. 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, may not lead to desired performance due to issues in meeting the reliability and latency requirements of industrial applications. Since wireless devices transmit using air as the transmission medium, they are prone to interference and contention from other devices in proximity. Interference can be avoided by proper frequency planning and time-sensitive networking. Guidance for deploying industrial wireless networks can be found in [5].

Typical industrial wireless applications require a deterministic and highly reliable communication network to achieve the desired performance for mission-critical applications. Meeting industry's wireless communications requirements is not a trivial task. More research in the field is needed to design wireless solutions that meet the demanding needs of the factory workcell. Beginning the design process with realistic user requirements that have been validated and exemplify the factory's current and future needs is a necessary first step in achieving the goals of Industry 4.0 and Smart Manufacturing.

This report will discuss requirement considerations, external wireless user requirements perspectives from standards development organizations and industry, and then provide a NIST perspective on wireless user requirements for the factory workcell. We center the wireless user requirements around the workcell because the size of factories varies considerably. Factories will often divide the factory floor into workcells, which can be reconfigured for a dynamic task schedule [6]. We believe that by focusing on requirements for the workcell, rather than for the entire factory, will provide requirements with greater applicability [7].

It is important to note that we consider the application layer, according to the Open Systems Interconnection (OSI) model [8], to be the most applicable layer to perceive loss and latency. Multiple retries due to packet loss at the lower layers, such as the link layer, may occur, but ultimately, the application only receives the message that is transmitted through the application layer interface. From the perspective of an automation or control application, the reliability of information between the application layer of the communicating nodes is most significant. To achieve higher reliability at the application layer, retries at the lower layers may occur, but they are not perceived by the application.

The qualitative requirement considerations provided in Section 2 are meant to preface the quantitative requirements, later presented in Section 4, to provide considerations that may influence the design or selection of wireless technology. The first six qualitative requirements are also the requirement metrics that are selected in Section 4. Note that the terminology in Section 4.1, **Table 5**, should be understood prior to the wireless user requirements in Section 4.2, **Table 6**, to avoid confusion.

This documents' intended audience includes network engineers, information technology experts, factory floor engineers, and system integrators interested in designing or deploying wireless technologies in industrial environments.

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2 Requirement Considerations

This section discusses the qualitative requirement considerations that may influence the selection or design of a potential wireless technology candidate for use in the factory workcell. Requirement 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 availability. Additional technical considerations and discussion of the problem space for industrial wireless are discussed in [9]. We believe that these requirement considerations have an influential role 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 End-to-End Latency

For this report's purpose, we discuss end-to-end latency as it refers to the endpoints of the application layer interfaces. End-to-end latency is comprised of the communication and application processing time. Existing industrial wireless systems are mainly designed to enable wireless coverage or provide necessary radio frequency (RF) bandwidth, of which, latency requirements have not been fully addressed. For the operation of demanding industrial applications, low end-to-end latency is an important factor in safety and control-based tasks as transmissions that occur outside of the latency threshold may be considered as failed transmissions. Industrial applications typically use smaller packet sizes with precise timings, signifying the importance 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 as 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. Sufficient reliability is needed in mission-critical applications to ensure that the replacement of wired communication systems with wireless solutions will not compromise performance. In the effort of increasing reliability, techniques exist that should be considered to improve reliability, such as frequency planning, redundancy in space, frequency, and time, and precision time-scheduling [10].

2.3 Scale

In an industrial wireless point-of-view, scale is the number of devices that can be deployed on the network while retaining other requirement metrics such as reliability, latency, and data-rate. Scalability is relevant to wireless communications as co-channel interference and contention from other wireless nodes in the network may cause a decrease in reliability and latency. The ability to support many wireless links may be desired as better knowledge and control of the workcell can be achieved through many sensors, actuators, and controllers. There are tradeoffs between many requirement metrics, as the wireless channel has a maximum capacity. A wireless technology candidate must support sufficient scale, which is a crucial aspect for industrial wireless adoption. A comprehensive survey regarding the effective capacity of wireless networks can be found in [11].

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, thus the signal power between nodes decreases. Excess range affects the reliability and latency of transmission as a low signal-to-interference ratio increases the probability of failed packets, leading to reduced reliability at the application layer interface, and increased latency due to retries. Specifically, in an industrial environment, meeting a required range specification is more challenging than in an outdoor scenario due to increased fading due to electromagnetic shadowing and multipath scenarios.

2.5 Payload Size

Payload size is the size, in bytes, of the information portion of a single 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. In 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. The update rate is related to the application's control cycle, and thus, dictates the end-to-end latency requirement at the application layer interface. A wireless network must be capable of supporting the required update rates needed by the applications on that wireless network. For example, a force feedback control application that utilizes a wireless force-torque sensor may require a 125 Hz sample rate. An example of such an application may be found in [12]. Update rate is an important factor that impacts the deployment and configuration of wireless networks, and it dictates the effectiveness of frequency planning [5].

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 are unnecessary. Electricity cost may be lower for wireless installations, due to the relatively low power draw of wireless communications, compared to wired networks. Note that some wireless technologies, which transmit high-power signals, may consume more power than wired solutions.

2.8 Security

Security in wireless communications is not equivalent to security in wired communications. Wireless networks offer a different potential for exploitation; wireless uses air as the medium of communication, which provides easier access to remote foreign actors than wired communications. 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 resilient to security-related threats, as the loss of communication can be costly, in terms of

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availability, and in the worst case, may damage equipment or personnel. Detailed requirements for wireless security are not discussed further in this report; however, more information regarding network security is discussed in the Guide to Industrial Control Systems (ICS) Security [13].

2.9 System Availability

Overall, system availability in a factory environment must be considered as any downtime from networking issues leads to economic losses due to industrial process unavailability. For example, if power or communication is disrupted, a network must be able to re-establish connectivity within seconds. If a safety system has a significant communication disruption, then operation should be stopped, leading to less availability. Intelligent applications may also be required to overcome network communication issues. Achieving a resilient and available network is not trivial as current wireless devices may require long periods of time to re-establish connections within the network. Wireless mesh networks that are based on low-data-rate protocols can often take minutes to hours to re-establish an operational network after an intermittent loss of power to critical routing components. System availability is not discussed in this report quantitatively; however, system availability issues, such as recovery time after power loss, must be considered in designing and implementing wireless technology for use in the factory.

3 External Wireless User Requirements

This section will cover the present-day wireless requirements by standards development organizations and industry. These external wireless user requirements are not centered around the workcell, but rather, the factory on a larger scale. Subsequently, in section 4, a NIST-staff perspective is presented on wireless user requirements for the factory workcell, which utilize, in part, the lessons learned from external wireless requirements.

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* [14]. ISA provided classes that categorized industrial applications and use cases. Wireless user requirements for latency, jitter, and block error rate (BLER) were assigned for each class.

Table 1, adapted from [14], 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, which apply to different classes. Examples include 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 for logging, downloading, and uploading; note that Class 0 was not discussed in [14]. 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

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noted that all usage classes have a requirement of 10^{-9} BLER, which appears to be an assumed requirement, without justification.

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[1]	Latency (ms)	Jitter (%)	BLER
Class 1	10	+/- 10	10^{-9}
Class 2 and 3	10-100	<10	10^{-9}
Class 4 and 5	100 avg.	+/- 10	10^{-9}

[1] Class 0 was not defined in the original table from the ISA report.

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* [15]. The ETSI report included a detailed table, reproduced 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 [15].

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 the report that a latency value of 15 ms – 20 ms and the 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 for this report 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 tend to be less time sensitive than factory automation applications; thus, the relaxed latency requirements and reliability of 10^{-5}. The "Augmented Reality" category includes a 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.

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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 ms – 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	1-50	20-50	20-50	< 300	< 300	< 300	< 80	> 200	< 8
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

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3.3 An Industry Perspective on Wireless User Requirements

Another industry perspective presented in [16], 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 of 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 [16]. It is important to clarify this PER is at the application layer. 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 [16]. 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

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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 be used in specific classes of applications in the factory workcell.

4.1 Terminology

Terminology for the NIST perspective on wireless user requirements is listed in **Table 5**. These definitions of user requirements are used for the user requirements in **Table 6**.

Table 5. User Requirement Definitions

User Requirement	Definition
End-to-end Latency	The maximum allowable time in milliseconds (ms) it takes for the transmitter to send a packet from the transmitter's application layer to the receiver's 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 total number of wireless links in a workcell supported, with the condition that all other requirement metrics are also met.
Range	The minimum required distance in meters (m) between two wireless nodes that form a single wireless link, with the condition that all other requirement metrics are also met.
Payload Size	The information component in the 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 payload size of a transmission has units of bytes (B).
Update Rate	The number of transmissions that occur in one second at the application layer of a device. The update rate has the units of hertz (Hz).

4.2 NIST Perspective on Wireless User Requirements

Using present-day requirements from standardization bodies such as ISA [14], ETSI [15], and industry [16], along with our own rationale and justifications, we produce **Table 6**. Note that these

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requirements have a component of subjectivity as assumptions must be made to derive specific requirement values.

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 we believe that existing wireless technology satisfies the demands of Class 5. In regards to Classes 0-4, we believe that existing wireless standards do not jointly meet the requirements for the typical industrial use cases applicable to each class; however, we believe that the design of new wireless technology, which would be low-latency, ultra-reliable, and aimed to transmit a small payload size, can be accomplished using the requirements in **Table 6**.

We base the selection of the user requirement metrics, shown in **Table 6**, on what we believe to be necessary for effective and realizable communications within factory workcells. We do not include device mobility or energy consumption in our requirement metrics, as observed in **Table 3**, due to the typical operation and dimensions of the workcell. If a workcell requires the use of mobile wireless devices, the mobility should not adversely affect other requirement metrics. A mobile device will experience a dynamically changing channel, with potential electromagnetic related issues such as shadowing, non-line-of-sight (NLOS), and deep fades. Further discussion regarding mobility and energy consumption requirements is not provided this report.

The user requirement metrics selected include end-to-end latency, reliability, scale, range, payload, and update rate. End-to-end latency and reliability are fundamental requirements for any time-sensitive and critical application. Latency and reliability can often be considered jointly as information that is delayed beyond a time threshold may be considered as lost information. Note that since the success of a transmission is measured at the application layer, as defined in **Table 5**, failures and retries are allowed at lower layers. Scale is also included in the requirements as it is well known that populating a wireless network with many devices negatively impacts latency and reliability due to interference, contention, and spectral resource limitations on the wireless network. 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. Payload size is also important to define as a user requirement since many industrial applications typically do not require larger payload sizes, which are common in video stream transmissions, as an example. Update rate, in the context of our perspective, is not a strict requirement, such as reliability and latency; however, the update rate is a property of the application and is used to determine the hard limits for the latency and reliability requirements. The justifications for typical and maximum update rate values in **Table 6** are discussed in Section 4.3.

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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: Condition Monitoring**
End-to-end[1] Latency (ms)	Typical	4	4	20	4	50
	Strict	0.5	0.25	4	0.5	4
Reliability[2] (Pr. of Loss)	Typical	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}
	Strict	10^{-8}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
Scale (# of links)	Typical	8	10	10	1	100
	Maximum	24	30	30	4	300
Range (m)	Typical	10	10	10	10	10
	Maximum	30	30	30	30	30
Payload Size (B)[3]	Minimum	6	8	8	8	12
	Maximum	24	64	64	64	33KB
Update Rate[4] (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. Assumptions must be made to determine specific values for the requirement metrics.

We assume that the typical workcell size is 10 m x 10 m, the communication system has an assumed mean time to failure (MTTF) of 1000 years for non-safety related factory automation applications, individual transmissions are independent, and one wireless link would be used in some scenarios involving multiple sensors/regulators. Other assumptions made will be discussed in this report when applicable. These assumptions allow for the calculation of the user requirement metrics and can be easily modified to align with specific user requirements. In Table 3 of [18], there are various factory

[1] End-to-End Latency is measured at the application layer and is calculated using Eq.1.

[2] Reliability is rounded down to the nearest 10th and is calculated using Eq.2.

[3] Payload Size has a minimum and maximum value, which are highly application dependent. Justifications for the minimum and maximum values are provided in 4.3.

[4] The values for the Update Rate are justified in 4.3

automation use cases which have a typical MTTF of 10-27 years. Using the recommendation from IEC 61784 [19], for which communication failure should compose at most 1% of the MTTF, the communication failure should be at a minimum of 1000 years MTTF. A MTTF of 1000 years may allow traditionally wired communications to be replaced with wireless; however, it is possible to accept a MTTF of a few years to less than 1 year in cases where small losses in communication is tolerable, as communication loss would not impact human life or health, but impact system availability. A cost assessment may be performed to assess what MTTF is tolerable for a specific use case, but for the purpose of this report, we assume 1000 years for all classes, except Class 0, which has its own justification.

Note that the "typical" and "minimum" end-to-end latency requirements for all classes are derived directly from the update rate and are corroborated with external sources. It is also assumed that the maximum end-to-end latency tolerable for a single transmission is half the time of one communication cycle. This assumption allows for enough time for a single failed transmission without communication system failure. For this report, we assume that two consecutive failed transmissions result in a communication system failure. For applications that require a downlink and uplink, the end-to-end latency requirement should be halved, to allow for uplink and downlink transmission within half of the control cycle time to allow a single failed transmission without communication system failure. This assumption may be modified, depending on the application, to allow for either zero failures or more than two transmission failures at the application layer.

End-to-end latency, L_{e2e}, is calculated below using Eq. (1), in which U is the update rate of the communication system at the application layer interface and n is the number of failed transmissions that result in a communication system failure. For this report, and in **Table 6**, n is 2. This value of n may be adjusted to fit a specific wireless technology; however, this change will affect the end-to-end latency and reliability requirements.

$$L_{e2e} = \frac{1}{n*U} \tag{1}$$

The required probability of a single transmission failure, P_m, is calculated with T representing the expected total number of seconds in which a communication system failure is to not occur, U representing the update rate of the application, and n representing the number of failed transmissions consecutively that result in a communication system failure. To provide more context to Eq. (2), the line before it shows that the right-hand side of the equation is the reciprocal of the number of transmissions sent, given T and U. Thus, P_m is calculated below using Eq. (2). We also assume that the total number of seconds in 1000 years to be T. This is a general assumption for Classes 0-4, shown in **Table 6**, but this requirement may decrease for non-mission-critical applications. We assume that each class has mission-critical applications; thus, the requirements should reflect that case. For the purpose of this report, we assume that transmissions are independent to allow for the calculation of P_m; however, this assumption may be flawed in practice since each wireless transmission depends on the propagation channel that individual transmissions share. Accounting for the effects of different propagation models is outside the scope of this report. The assumption of independent transmissions allows for a relatively simple equation for P_m.

$$P_m{}^n = \frac{1}{T*U}$$

$$P_m = \sqrt[n]{\frac{1}{T*U}} \tag{2}$$

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Calculations for all reliability requirements use Eq. (2). Note that reliability values, shown in **Table 6**, are truncated to fit into the 10^{-x} form; thus, the exact values of P_m are not shown in the table.

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. Typical applications in Class 0 are used to prevent damage to equipment or personnel.

***End-to-End Latency*:** 4 ms. This calculated latency requirement has a basis from time-critical emergency applications in Class 0, in which an added delay can lead to injury or equipment damage. Specific end-end latency requirements vary depending on the application; some demanding applications may require latency as low as 0.5 ms, which is the "strict" case.

***Reliability*:** 10^{-8}. Our expectation for overall system reliability is that one communication system failure per 11400 years is acceptable for Class 0. The specific MTTF of 11400 years comes from IEC 61508 [17], which describes that for use cases of high-demand or continuous mode, the probability of dangerous failure per hour is 10^{-9} to 10^{-8} for a Safety Integrity Level (SIL) of 4. These failure rates correspond to 114000 to 11400 years MTTF, respectively. We assume a SIL of 4 for Class 0 as we assume that loss of life is a possibility and the frequency of communication is high. Using Eq. 2 with n equal to 2, T equal to the seconds in 11400 years, and U equal to 125 Hz, the required probability, P_m is 1.5×10^{-7} for the typical case. For the strict case, U is 1000 Hz and P_m is 5.3×10^{-8}. These values of P_m are rounded down to fit the 10^{-x} form, shown in **Table 6**. Note that on demand applications, such as an Emergency Stop (E-Stop), do not require as strict reliability requirements as continuous safety applications, as the occurrence of an E-Stop being pushed is infrequent.

***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. 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 to communicate wirelessly using a single link. The number of these safety devices could increase to 24 in an application requiring more wireless nodes. We assume that for a 30 m x 30 m workcell, which has a nine times size increase, compared to a 10 m x 10m workcell, has decreased device density. We assume that a larger workcell will have approximately one third of the device density compared to a 10 m x 10 m workcell, leading to an effective three times increase in scale for the 30 m x 30 m workcell. This assumption applies to the maximum case of scale for all classes, except for Class 3.

***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

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minimum payload size is less than other classes as applications in Class 0 do not require the transmission of variable type, unlike the other classes of applications.

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 the update rate is highly application dependent as some automated safety systems may update 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.

End-to-End 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}. Our expectation for overall system reliability is that one communication system failure per 1000 years is acceptable for industrial applications. With the assumption that a communication system failure occurs when two or more transmissions fail consecutively, we have calculated the required transmission reliability of 10^{-7} for the typical and strict case. Note that the typical and minimum requirements are shown to be equivalent in the table; however, the approximate values are 5.0×10^{-7} for 125 Hz and 1.3×10^{-7} for 2000 Hz, which rounded down for **Table 6**.

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 - 64 B. A minimum 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. A maximum value of 64 bytes is possible for various factory automation applications, as described in [18]. Note that this range of payload sizes applies to Classes 1-3, with the caveat that it is possible to gang together multiple devices to use one wireless node. Depending on the deployment scenario, such as interconnected cabinets in which a high density of input/output (I/O) devices aggregate, it is possible to have very large payload sizes. The maximum shown here is the typical expected maximum for deployments in which I/O devices are not aggregated prior to transmission. Since the number of bytes is highly application dependent, we do not provide a typical payload size.

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***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) [20], 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. For this Class 2 application, PLCs send commands to actors to complete tasks. Specifically, in discrete manufacturing, tasks are completed sequentially; thus, the effect of increased end-to-end latency in the communications link between a supervisor and actor will influence the speed of production. A communication MTTF of 1000 years is assumed for this class; however, this value can be modified by the user to fit their requirements.

***End-to-End Latency*:** 20 ms. This typical end-to-end 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 as the update rates are typically lower than closed loop regulatory control.

***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 should match the number of Class 2 links, as Class 1 applications would report to Class 2 applications, such as a supervisory PLC. It is possible to have multiple Class 1 applications that communicate with a single supervisor; however, we assume a one-to-one pairing of Class 1 nodes to Class 2 nodes for this report.

***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 - 64 B. This range of payload size was determined using the same justification provided in Class 1.

***Update Rate*:** 25 Hz. This value of update rate is from the supervisor in the collaborative workcell in [21], in which a supervisory PLC communicates to four other PLCs and two robot controllers. It is possible to run at a higher update rate, such as 125 Hz for supervisory control.

4.3.4 Class 3: Open Loop Regulatory Control

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

***End-to-End Latency*:** 4 ms. The typical end-to-end latency requirement and the minimum end-to-end 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. Note that the scale for this Class is smaller than other classes. The assumption is that few humans will be performing Class 3 applications inside the workcell due to the nature of the applications in Class 3, and the typical role of the workcell. We assume a scale of 1 link to be the typical case, in which a single human would be performing a Class 3 application inside the workcell, such as a remote-controlled gantry or lifting machine. In a larger workcell, the scale may increase to 4, assuming that multiple humans may perform Class 3 applications in the 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 - 64 B. This range of payload size was determined using the same justification provided in Class 1.

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 seen in rotary equipment.

4.3.5 Class 4: Condition 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. Note that the 1000 MTTF rate is assumed for this class, despite the "less critical" nature of the applications typical of this class, compared to Classes 0-3. Adjustment to the assumption that one single communication system failure per 1000-years is tolerable may be made on an individual application basis, which will relax the reliability requirement. Relaxing the reliability requirement may allow for more wireless technologies to work in less demanding Class 4 applications.

End-to-End 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 in Class 1, this end-to-end 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 a 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 one 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 a typical size of 2 B for the 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, despite some devices in this class utilize hibernation to save power; however, when they activate, these devices may send transmissions at a specific "update rate" until access point receives the transmission and is understood by the monitoring device. Update rates as high as 125 Hz may be used for condition monitoring 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 typically requires the highest data rate of all classes, with potentially large payloads.

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5 Conclusion

This report has discussed the qualitative and quantitative aspects of industrial wireless requirements and has reviewed existing perspectives on wireless requirements from standards development organizations and industry. From these existing external requirements, input from the Industrial Wireless Systems Technical Working Group (IWSTWG) members, along with our own rationale and experience, we have produced wireless user requirements for the factory workcell. Justifications and assumptions for every requirement value produced are also provided. Justifications and assumptions are provided in this report as we have found that current external wireless requirements lack sufficient justification and transparent assumptions. It should be emphasized that we have found latency, reliability, scale, minimum range, payload size, and update rate to be the most important requirements to specify for applications in Classes 0 to 4. The wireless user requirements presented in **Table 6** use transparent assumptions to determine specific requirement values. It is essential to clarify that these assumptions are modifiable to fit a specific application. 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 4 and 5, with relaxed reliability requirements, but as of now, Classes 0-3 have yet to define a popular wireless standard that fits the requirements stated. Interestingly, the scale for Classes 4-5 is quite massive, and there is an 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, such that the replacement of traditionally wired communications with wireless communications may become a reality.

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Appendix A: Change Log

Corrections made in an errata update do not alter existing or introduce substantive technical information, but rather are intended to remove ambiguity and improve interpretation of the work.

- 02/08/2021: added Zhibo Pang, *ABB Corporate Research* to Acknowledgements on page ii