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# Flexible Factory IoT: Use Cases and Communication Requirements for Wired and Wireless Bridged Networks



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# Flexible Factory IoT: Use Cases and Communication Requirements for Wired and Wireless Bridged Networks

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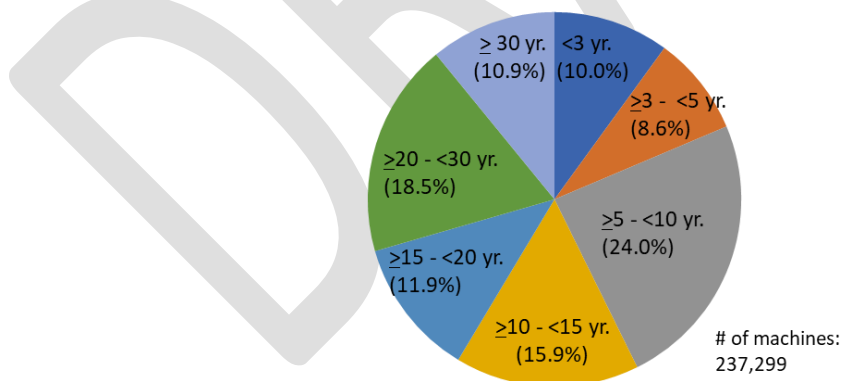
# 1 Flexible Factory IoT: Use Cases and 2 Communication Requirements for 3 Wired and Wireless Bridged Networks

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## 4 Introduction

5 Communication in factories has until now been mainly wired communication. A survey in [1]  
6 indicates that market share of wired networks in factory automation is 94%. However, in recent  
7 years shorter product development cycles have demanded greater flexibility in the layout of  
8 machines and sequence of processes. There are increasing expectations for the use of wireless  
9 connectivity amongst machines in the manufacturing and factory processes.

10 When considering the network evolution within factories, consideration should take into account  
11 legacy manufacturing machines that have been in service for many decades. Within factory  
12 installations, sensors are attached to machines for the purpose of monitoring operations and  
13 preventive maintenance. According to a survey by Japan's Ministry of Economy, Trade and  
14 Industry, the lifetime of production machines is long, and about 10.9% of them have been used  
15 for more than 30 years, as shown in Figure 1. In many cases, sensors continue to be used long  
16 after they have been introduced, resulting in the coexistence of sensors and their communication  
17 interfaces in different generations as well within machines.



18  
19 **Figure 1 Share of production machines by age [2]<sup>1</sup>**  
20

---

<sup>1</sup> Data were from a questionnaire survey for Japanese 1,033 factories by Ministry of Economy, Trade and Industry of Japan in 2013. Total number of machines was 237,299 in which grinders (12.5%), industrial robots (9.3%), automated assembly machines (8.8%), welding/fusing machines (8.7%), lathe machines (7.9%), press machines (6.7%), machining centers (5.5%), and others were investigated.

1 This report, developed under the IEEE 802 Network Enhancements for Next Decade Industry  
2 Connections Activity (NEND-ICA) addresses integrated wired and wireless Internet of Things (IoT)  
3 communications in the factory environment, considering its expected evolution to dense radio  
4 device utilization. The report includes use cases and requirements within the factory wireless  
5 environment, with a focus on bridged Layer 2 networks. It presents problems and challenges  
6 observed within the factory and reports on feasible solutions for overcoming these issues. Topics  
7 that may benefit from standardization are highlighted.

8 The report presents an underlying End-to-End (E2E) network architecture which addresses the  
9 operation and control of the various services in the factory network according to their dynamic  
10 QoS requirements. It analyses the applicable standards and features in IEEE 802 technologies to  
11 achieve the requirements in E2E network connectivity for integrated wired and wireless  
12 connectivity in a factory environment.

### 13 **Scope**

14 The scope of this report is capturing use cases and communication requirements for wired and  
15 wireless bridged networks. Dense use of wireless devices with differentiated QoS requirements  
16 and its operation in factory environment are taken into consideration. Gap analysis from existing  
17 IEEE 802 standards and necessary technology enhancement are also covered in the context of  
18 time-sensitive network for the future.

### 19 **Purpose**

20 The purpose of this report is to understand issues and challenges in managing a reliable and time-  
21 sensitive connectivity in “Flexible Factory” scenarios, where various equipment are attached to  
22 the wired network via wireless connections. The report includes technical analyses of the desired  
23 features and functions in wired and wireless IEEE 802 technologies for managing requirements in  
24 E2E network connectivity which can be used in an IEEE 802 standard solution based on time  
25 critical requirements for integrated wired and wireless connectivity within the factory  
26 environment.

## 27 **Factory Overview and Operation environment**

### 28 **Factory communication network environment**

29 Trends to connect devices such as sensors and cameras to factory networks are accelerated by a  
30 strong demand for improving productivity under the constraints of pressure for cost reduction.  
31 Connection of information on production process and supply chain management within a factory  
32 and across factories becomes important. It is also important to consider future needs of new  
33 technologies and networks deployments, given the typical long life time of any deployed  
34 technology in the factory floor. Commutation networks in factories will undoubtedly change in  
35 the next decade.

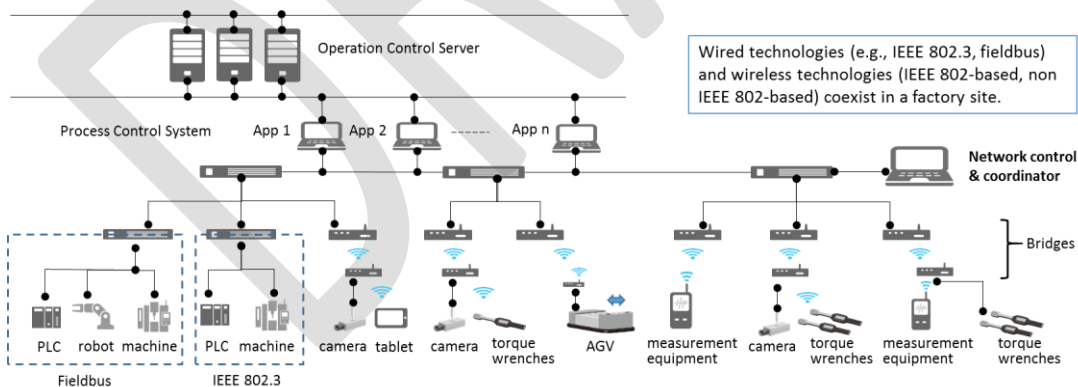
36 Figure 2 shows an example of a network for a vehicle assembly line in factory today. The industrial  
37 control systems are extensively applied for industrial process control and operation. Such systems  
38 can range from a few modular panel-mounted controllers to thousands of field connections, by  
39 being the universal means of remote access to the enormous data provided by e.g. sensors,

1 actuators and motors deployed in the field. The larger systems are usually implemented by  
 2 Distributed Control Systems (DCS) or Supervisory Control and Data Acquisition (SCADA) systems,  
 3 which manage Programmable Logic Controllers (PLC) in the field. The entities labelled as ‘App x’  
 4 illustrate several system applications, e.g., preventive maintenance, management of materials  
 5 and products, monitoring of movements and machine monitors, which are supported in the  
 6 factory network.

7 The factory network infrastructure primarily concerns the communication between and within  
 8 these components and systems. One of the essential differences between factory and commercial  
 9 networks is that the physical devices connecting to the network are used to control and monitor  
 10 real-world actions and conditions. This has resulted in an emphasis on a different set of Quality  
 11 of Service (QoS).

12 Because of performance and other advantages, Ethernet has emerged as the dominant standard  
 13 for the physical layer. Unlike serial protocols such as fieldbus [3], multiple higher layer protocols  
 14 can run on the same Ethernet physical layer. It is fairly easy to interconnect several devices such  
 15 as PLCs, HMI (Human Machine Interface), etc, remaining in high speed communication. Adding on  
 16 the deterministic features introduced by TSN, Ethernet are now taking over more shares at the  
 17 high-end industrial communication markets.

18 However, much of the cost of installation of wired networks is for the wire itself. Installation of  
 19 wires in a factory environment is costly. Future industrial factory networks are expecting to use  
 20 more wireless to eliminate the installation cost, as well as to enhance flexibility. By utilizing  
 21 wireless communications, it is possible to collect useful information from IoT sensors, to flexibly  
 22 allocate equipment such as cameras, and to analyze the status of humans and machines. It is an  
 23 essential element that enables flexible layout of machines and order of manufacturing processes  
 24 to adapt to variable-type, variable-volume production and mass customization.<sup>2</sup>



25

26 **Figure 2 Example of network topology for a vehicle assembly line**

27 The ability to transmit and receive data over a wireless link is not always going to work with the  
 28 same degree of certainty as a wired link. More effort will be required for wireless communication

<sup>2</sup> <https://www.ffp-a.org/news/index.html>

1 because of its limited and shared radio resources and the sensitive nature of the environment in  
2 which it will operate.

3 In order to configure, coordinate and maintain various QoS requirements E2E over the  
4 heterogeneous network integrating wired and wireless interfaces, as in Figure 2, the network  
5 control and coordinator is required. The successful integration of wired and wireless systems is  
6 indispensable.

7 One of the main considerations within the factory network is the need for the provisioning of QoS  
8 for a variety of machine-to-machine (M2M) data types generated from a variety of sensors,  
9 perhaps at the same time, with different priority-classes. These data types are periodic in nature  
10 and have relatively short packet size.

11 Advanced factories have typically employed wireline networks using the Fieldbus protocol.  
12 Wireless commutations have not been used extensively in factories, mainly because of concerns  
13 regarding their stability and reliability. Technology developments as well as standardization are  
14 keys to success for wireless utilization. If these efforts are proven successful, wireless use for IoT  
15 connectivity in factory can increase the connectivity of mobile or moving devices and units which  
16 cannot be connected to a wired network because of technology and topology constrains. Wireless  
17 communication helps to locate people and things moving around. It can also help to protect  
18 people in the factory floor and help them to identify critical situations more quickly while moving  
19 around.

20 When the factory network is extended over radio, some incompatibility in QoS provisioning  
21 between wired and wireless segments becomes apparent. One reason is dynamic variation in the  
22 available bandwidth over the radio segment due to wireless link quality variation resulting from  
23 non-deterministic noise/interference, distortion and fading.

24 Successful factory automation with a high degree of flexibility, dynamic management and control  
25 of end-to-end streams across mixed wired and wireless links requires E2E coordination as  
26 illustrated in Figure 2 above.

27 The impact of applying QoS and Time Synchronization functions and protocols to heterogeneous  
28 the factory network with mixed wired and wireless links is further analyzed in section "Gaps in  
29 existing IEEE 802 technologies" below. First, however details of the environment and causes of  
30 radio impairments to the factory environment are presented below.

### 31 **Coordination System for Factory Automation**

32 In current factories, various facilities and equipment with different standards of different  
33 generations, and by different vendors, coexist in the same site. This heterogeneous factory  
34 environment is known as Brownfield [4]. Such networks must accommodate various wireless  
35 interfaces. IEC has produced coexistence guidelines for manually configuring wireless systems  
36 and networks for co-existence [5][6]. In order to overcome the variable environment for  
37 wireless communications (see "Radio Environment within Factories" below), coordination may  
38 prove superior to static configuration of network elements for co-existence. The same concept is  
39 also discussed by IEC [7].

1 **Radio Environment within Factories**

2 Some factory applications require reliable, low-latency, and low-jitter data transmission  
 3 compared with application in other places like offices and homes. Furthermore, measurement  
 4 results show that some factories are facing difficulties due to (a) severe environment for wireless  
 5 communications, and/or (b) existence of uncoordinated and independent systems in the same  
 6 space.

7 **(a) The Severe Environment for Wireless Communications**

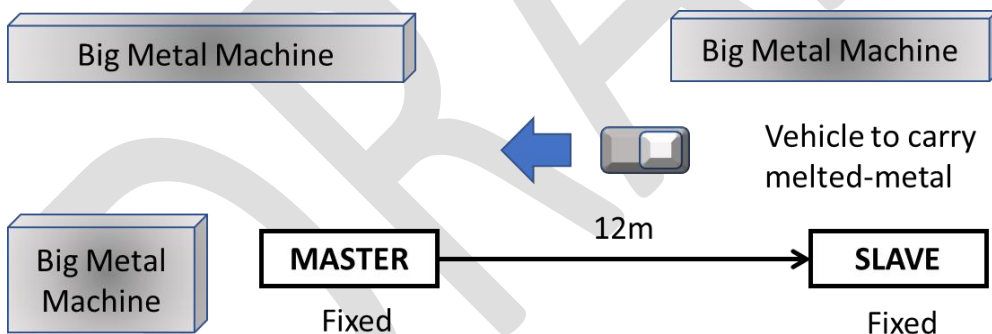
8 Two main sources of impairment to radio signal within the factory environment that cause  
 9 unpredictable variations to channel capacity, namely:

- 10 1. Fluctuation of signal strength
- 11 2. Electromagnetic interference

12 Following are examples of such impairments observed within the factory environment.

13 **Example of Fluctuation of Signal Strength**

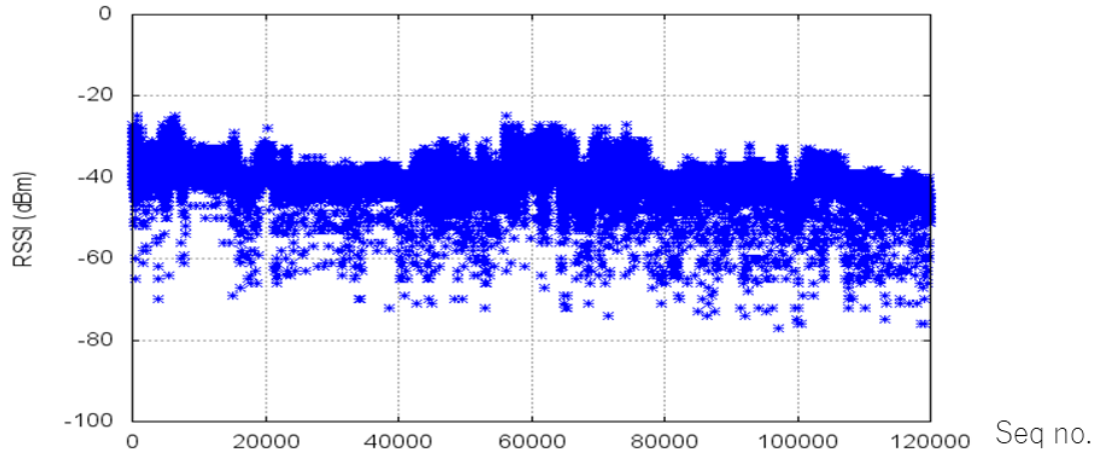
14 Figure 3 illustrates an environment in which the measurements of Figure 4 were collected. Master  
 15 and slave transceivers were located and there was no obstacle by a vehicle, human body and any  
 16 other objects in the line between the master and slave transceivers during measurement.



17

18 **Figure 3 Layout in factory for which measurement of RSSI is recorded**

19 The observed Received Signal Strength Indicator (RSSI) measurement for this layout is shown in  
 20 Figure 4 below. A packet with 54Bytes was sent at each sequential (Seq) number with 10-msec  
 21 separation at a data rate of 6Mbps.



1

2

**Figure 4 RSSI Fluctuation in Factory**

3

This fluctuation in RSSI may be due to motions of materials, parts, products and carriers in closed space, with multi-path reflections as indicated in the NIST report on "Guide to Industrial Wireless Systems Deployments." [8]

4

5

**Example of Noises:**

6

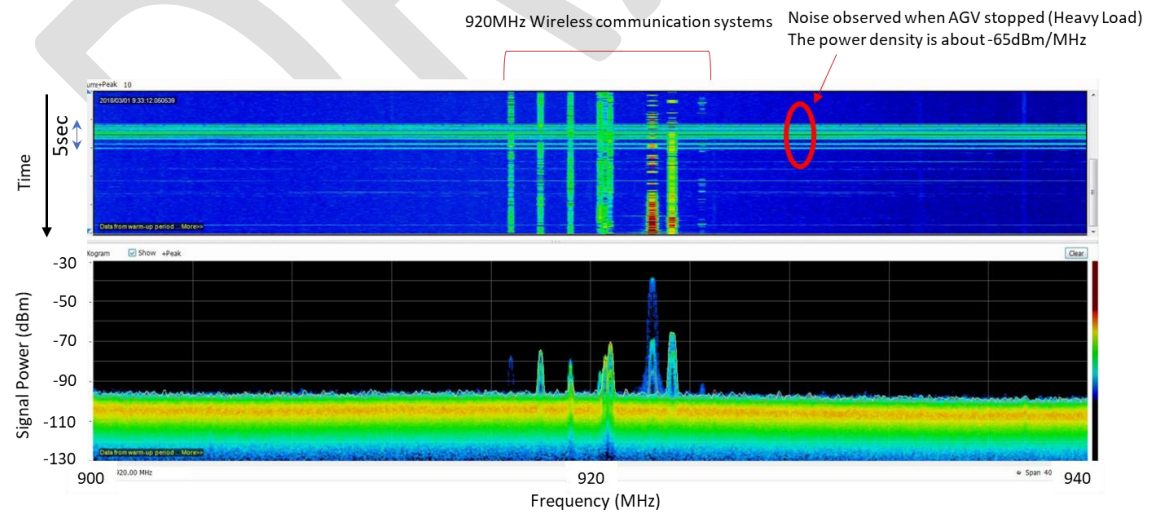
Measurement within the factory environment indicate considerable noise signal within the 920MHz band. This is shown in Figure 5. The source of the noise signal has been confirmed as Automated Guided Vehicles (AGVs) carrying heavy load, as the noise disappears when the AGV stops.

7

8

9

10



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12

13

**Figure 5 Measured noise spectral density within 920MHz band**

14

The observed noise power was -65dBm/MHz which were above the receiver sensitivity for the 920MHz wireless systems. Under 1 GHz band, noise appears to cause problems for the

15

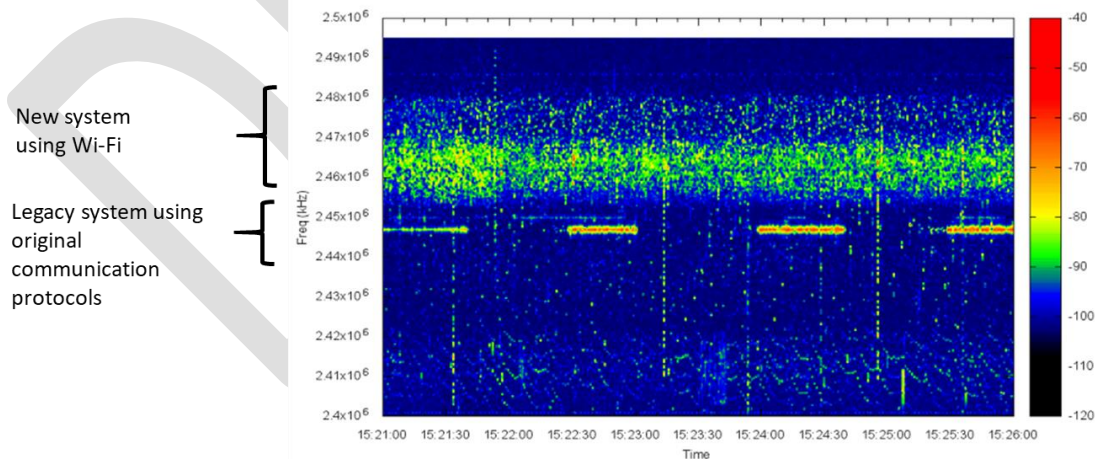
1 communication with sensing systems using 920MHz band wireless communications. The source  
 2 of the noise is attributed to manufacturing machines that are causing interference for the wireless  
 3 communication systems.

4 **(b) Uncoordinated and Independent Systems**

5 The progressive factory environment leads to addition and reconfiguration of machines and  
 6 equipment in the factory and therefore to the requirement for coexistence of heterogeneous and  
 7 legacy devices and systems.

8 When considering the coexistence of uncoordinated wireless systems, we observe the problem  
 9 of interference between the legacy wireless communications used by some machinery in the  
 10 factory with the new systems using Wi-Fi. In certain factories, many troubles of manufacturing  
 11 systems appear after introducing new systems using Wi-Fi. The cause of this trouble is due to  
 12 mutual interference between manufacturing systems using Wi-Fi, and legacy systems using  
 13 original communication protocols. Currently, the only way to avoid this problem is by assigning  
 14 two separate frequencies for the two systems.

15 Figure 6 shows wireless signals operating in the 2.4 GHz band in an existing factory site where two  
 16 systems coexist. Although the legacy system occupies one narrow Wi-Fi channel, nevertheless,  
 17 there are only three Wi-Fi channels that can be used without interference. Because there is no  
 18 common scheme for collision avoidance among different communication protocols, an  
 19 independent channel should be assigned for each system to ensure stable factory operation. This  
 20 limits the number of wireless systems, with different communication protocols, which can  
 21 operate in the same frequency band in a factory.



22

23 **Figure 6 Wireless signals with coexistence of different wireless technologies. The vertical**  
 24 **and horizontal-axes show frequency (Hz) and time, and color shows signal strength (dBm)**  
 25 **in a bar on the right hand side.**



1

## 2 Wireless applications and communication requirements

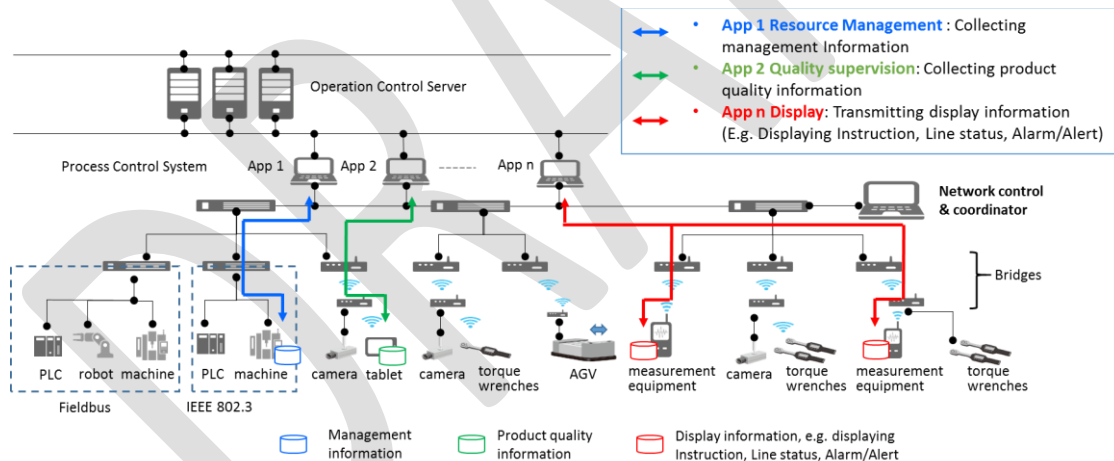
### 3 Scope of wireless applications in factory

4 The wireless applications considered in this clause illustrate the use of wireless systems that are  
 5 currently or soon-to-be used in factories and related facilities. The applications correspond to  
 6 wireless systems that are installed for specific purpose.

7 For example, wireless applications are highlighted on the factory network as shown in Figure 7.  
 8 The color coded lines indicate the data streams planned for specific purposes such as “Collecting  
 9 Management Information”. The wireless sub-networks consisting of multiple wireless  
 10 connections have to be deployed to support the information transmission and aggregation for  
 11 different applications.

12 The factory network has to be built, configured and managed in a way that is able to support the  
 13 successful operation in the wireless applications. In some cases, the critical application may  
 14 demand a separate wireless segment setup due to special concerns.

15 Section “Factory Usage Scenario” considers actual factory sites with large needs for wireless  
 16 communication and describes usage scenarios where multiple wireless applications coexist.



17

18

Figure 7 Scope of wireless applications in factory

19

### 20 Wireless applications

21 In a usage survey in [9] of wireless communication in factories, characteristics of various  
 22 applications were collected. These are classified according to their purposes, and organized their  
 23 communication requirements. Collected wireless applications are listed in Table 1. These were  
 24 divided into six categories, (equipment control, quality supervision, resource management,  
 25 display, human safety, and others), and then subdivided into thirteen classifications according to  
 26 their corresponding purposes.

1 **Table 1 Wireless applications**

Category	Description	Classification according to the purpose
Equipment Control	Sending commands to mobile vehicles, production equipment and receiving status information.	(1) Controlling, operating and commanding of production equipment, auxiliary equipment
Quality Supervision	Collecting information related to products and states of machines during production	(2) Checking that material is being produced with correct precision (3) Checking that production is proceeding with correct procedure and status
Factory Resource Management	Collecting information about whether production is proceeding under proper environmental conditions, and whether personnel and things <sup>3</sup> contributing to productivity enhancement are being managed appropriately	(4) Checking that the production environment (e.g. according to factors such as temperature, pressure, etc.) is being appropriately managed (5) Monitoring movement of people and things (6) Checking the status of equipment and checking the material, small equipment and tool stocks (7) Monitoring the maintenance status of equipment during operation (8) Appropriate recording of work and production status
Display	For workers, receiving necessary support information, for managers, monitoring the production process and production status	(9) Providing appropriate work support, such as instructions and tracking information (10) Visually display whether the process is proceeding without congestion or delay, production irregularities (11) Visually display the production status, the production schedule, and any deviations or operational abnormalities
Human Safety	Collecting information about dangers to workers	(12) Ensuring the safety of workers
Other	Communication infrastructure with non-specific purposes	(13) Cases other than the above

2

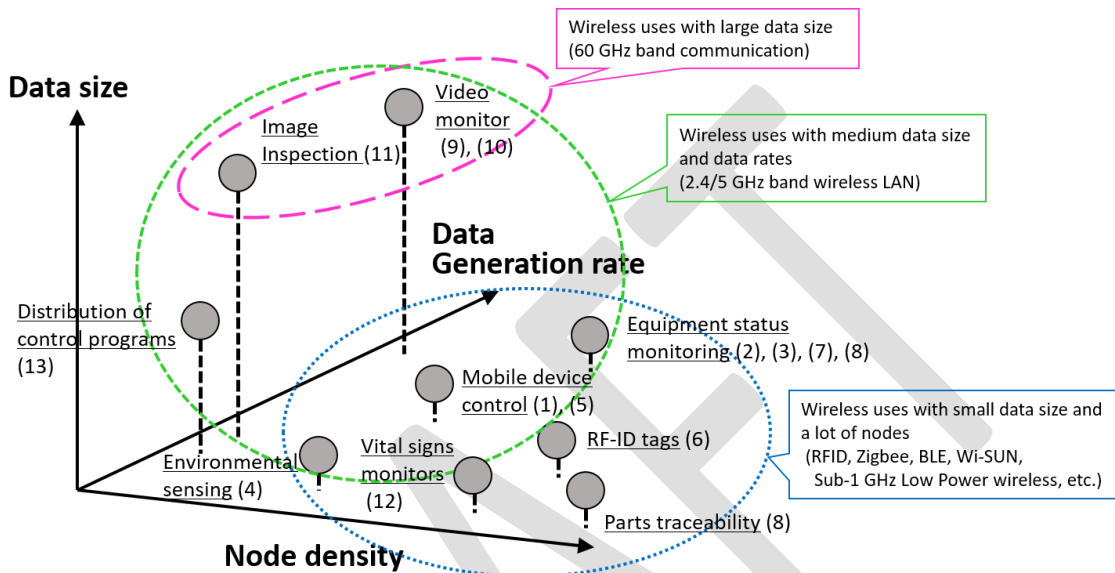
3 **Communication requirements**

4 Figure 8 shows representative wireless applications, with corresponding classifications (1)-(13)  
5 from Table 1, and their wireless communication features. Values of data size, data generation  
6 rate, number of wireless nodes, and so forth depend on the required functions of the systems.  
7 They use different wireless frequency bands and wireless standards. High frequency bands such  
8 as 60 GHz band are expected to be effective for systems with relatively large data volume  
9 requirements (image inspection equipment, etc.). 5 GHz band and 2.4 GHz band are being used

---

<sup>3</sup> Physical objects such as materials and equipment related to production are called “things”

1 for systems with medium requirements of data sizes and data generation rate, such as distributing  
 2 control programs and control of mobile equipment. Relatively low wireless frequency bands such  
 3 as Sub-1 GHz are being used for applications with low power requirements (such as environmental  
 4 sensing).<sup>4</sup>



5  
 6 **Figure 8 Representative wireless applications with corresponding classifications (1)-(13)**  
 7 **from Table 1 and their wireless communication features**

8 Figure 9 shows the permissible delay for representative wireless applications as in [9] and [11].  
 9 There are wireless applications, such as robot control and urgent announcements, for which the  
 10 urgency and accuracy of information arrival timing requires less than one millisecond latency. On  
 11 the other hand, particularly in the categories of quality (inline inspection, etc.) and management  
 12 (preventive maintenance, etc.), there are many wireless applications that tolerate latencies larger  
 13 than hundred milliseconds.

<sup>4</sup> Lower-frequency radio waves propagate better than higher-frequency. It achieves a better range and lower transmitting power, resulting in low power consumption. Environmental sensing which requires long life battery operation is a good example of low power applications. Lower-frequency band like Sub-1 GHz has become de facto standard for such applications [10].

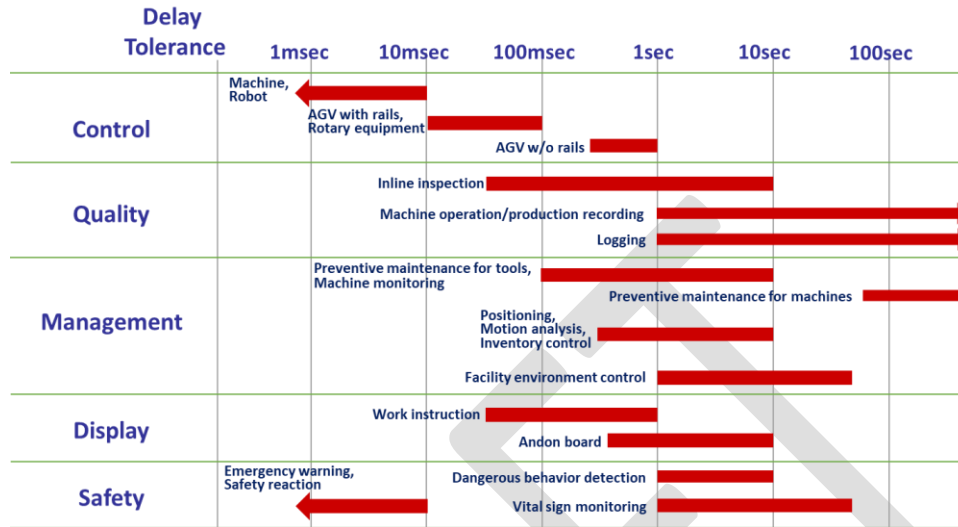


Figure 9 Permissible delay of representative wireless applications

### Details of wireless application and communication requirements

Communication requirements for the thirteen classifications of wireless applications are organized in Tables 2 to 14. Each table contains further detailed purpose of the wireless application, corresponding information, and the communication requirements of transmitted data size, communication rate, delivery time tolerance, and Node density<sup>5</sup>. These attributes are based on observation for a number of samples within the factories surveyed<sup>6</sup>.

Table 2 List of wireless applications and communication requirements for equipment control

(1) Controlling, operating and commanding of production equipment and auxiliary equipment

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
1	Control of liquid injection	Water volume	64	Once per 1 min.	100 ms.	1
2	Operation of conveyor control switch	PLC	16	5 per day	100 ms.	5

<sup>5</sup> Node density: number of terminals per 20m x 20m. This area dimension is based on the structure in a typical factory in which pillars are separated by 20m.

<sup>6</sup> The survey was conducted in 2016 by collecting information from factories of foods, beverages, steels, pulp and paper mill, semiconductors, electrical equipment, electronics devices, communication devices, automotive, chemical plant, precision instruments, and metal processing. The survey included information from companies that provide devices and equipment with communication functions to factories. Additional information available on the internet was also included in the survey results.

3	AGV control	Go signal, positioning	100	Once per 1 min.	100 ms.	1 to 10
4	Bottle filling	Fill valves	400	Once per ms	500 $\mu$ s	2
5	Warehouse	Stacker crane positioning	10	Once per 2 to 5 ms	1 ms	1 to 20

1

2 **Table 3 List of wireless applications and communication requirements for Quality**  
 3 **Supervision -1**

4 (2) Checking that products are being produced with correct precision

No	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
6	Size inspection by line camera (line sensor)	Size measurements	30K	Once per sec.	5 s.	1
7	Detect defect state	Defect information (video)	500	Once per 100 msec.	500 ms.	1
8	Detect incorrect operation	Anomalous behavior due to adding impurities (e.g. Contamination)	1M	Once per sec.	10 s	1

5

6 **Table 4 List of wireless applications and communication requirements for Quality**  
 7 **Supervision -2**

8 (3) Checking that manufacture is proceeding with correct procedure and status

No	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Data Size (bytes)	Communication Rate	Arrival Time Tolerance	Node density
9	Sensing for managing air conditioning	Air stream to control temperature in different zones	64	Once per sec.	1 min.	1
10	Monitoring of equipment	State of tools, disposables	A few hundreds	Once per sec.	1 s.	2
11	Counting number of wrench operations	Pulses	64	Once per 1 min.	100 ms.	10

9

10 **Table 5 List of wireless applications and communication requirements for Factory**  
 11 **Resource Management -1**

12 (4) Checking that the factory environment is being correctly managed

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
12	Managing clean room (booth)dust count	Dust count (particles)	32	Once per min.	5 s.	5
13	Managing carbon dioxide concentration	CO2 concentration	16	Once per min.	5 s	2
14	Preventive maintenance	Machine's temperature	A few tens	Once per event	1 s	2

1

2 **Table 6 List of wireless applications and communication requirements for Factory**  
3 **Resource Management -2**

4 (5) Monitoring movement of people and things

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
15	Movement analysis	Wireless beacon	A few tens	Twice per sec.	A few secs.	1 o 10
16	Measuring location of people and things, e.g. radio beacon	Transmission time (phase), radio signal strength, etc.	A few tens of thousands	Once per sec.	1 s.	2
17	Measuring location of products	Location of products during manufacture	200	Once per sec.	1 s	20

5

6 **Table 7 List of wireless applications and communication requirements for Factory**  
7 **Resource Management -3**

8 (6) Checking the status of equipment and checking the material, small equipment and tool stocks

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
18	Racking assets (beacon transmission)	Information of equipment and things	200	Once per sec.	1 s.	20
19	Tracking parts, stock	RFID tag	1K	1~10 times per 30 mins.	100 ms	3 to 30

9

1 **Table 8 List of wireless applications and communication requirements for Factory**  
 2 **Resource Management -4**

3 (7) Monitoring the maintenance status of equipment during operation

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
20	Managing facilities	Activity of PLC	4K	Once per sec. ~ once per min.	One ~ few tens of secs.	1 to 10
21	Measuring energy	Energy, current fluctuation	64	Once per min.	1 m	1
22	Monitoring revolving warning light	Defect information	100	Few times per hour	1 s	25

4

5 **Table 9 List of wireless applications and communication requirements for Factory**  
 6 **Resource Management -5**

7 (8) Appropriate recording of work and production status

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
23	Work record	Text data	100	Once per min.	1 s	9
24	Work proof	Certification data	1K	Once per 3 hours	10 s	9
25	Checking completion of process	Image, torque waveform	100K	Once per 1 sec ( up to 1 min.)	200 m	1 to 14
26		OK, NG	100	Once per 1 sec ( up to 1 min.)	200 ms	1 to 14

8

9 **Table 10 List of wireless applications and communication requirements for Display -1**

10 (9) Providing appropriate work support, such as instructions and tracking information

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
27	Work commands (wearable device)	Image	600	Once per 10 secs. ~ 1 min.	1~10 s	10 to 20
28	View work manual	Text data	100	Once per hour	10 s	9
29	display information	image (video/still image)	5M	once per 10 secs. ~ 1 min.	few s	1 to 5

	(image display)				
--	-----------------	--	--	--	--

1

2 **Table 11 List of wireless applications and communication requirements for Display -2**

3 (10) Visually display whether the process is proceeding without congestion or delay  
4 production irregularities

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
30	Managing congestion	Counter (number or remaining number)	Few bytes	Once per 10 secs. ~ 1 min.	Few s	1 to 10
31	Managing operation activity	Activity of PLC	128	Once per hour	100 ms	2
32	Displaying revolving warning light	ON/OFF	Few bytes (a few contact points)	Once per 10 secs. ~ 1 min.	0.5~2.5 s	30

5

6 **Table 12 List of wireless applications and communication requirements for Display -3**

7 (11) Visually display the production status, the production schedule, and any deviations or  
8 operational abnormalities

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
33	Managing operation activity	Image	6K	30 per sec (30fps)	500 ms	1
34	Supporting workers	PLC	200	Once per 10 secs. ~ 1 min.	500 ms	5
35	Supporting maintenance	Image, audio	200	Once per 100 msec.	500 ms	1

9

10 **Table 13 List of wireless applications and communication requirements for Human safety**

11 (12) Ensuring the safety of worker

No.	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
36	Detecting dangerous operation	Image	6K	10 per s (10fps)	1 s.	1
37	Collecting bio info for	Vitals information	100	Once per 10 s	1 s	9



	managing worker safety	(wearable)				
38		Vitals information (fixed, relay)	200	Once per 1 min	5 s	20
39		Gait	About 100K	~10 per s (1fps~10fps)	1 m	10 to 20
40	Detect entry to forbidden area	Body temperature, infrared	2	When event occurs	1 s	1
41	detect entry in the proximity of a machine	Position of human (via connected wireless unit)	10 - 30	100 to 1000 per s	2 to 20 ms	1 to 50

1

2

**Table 14 List of wireless applications and communication requirements for others**

3

(13)Cases other than above

No .	Wireless application		Communication requirements			
	Purpose	Corresponding Information	Transmit Data Size (bytes)	Communication Rate	Delivery Time Tolerance	Node density
42	Sending data to robot teaching box	Coordinates	Few hundred kilobytes	Twice per year	Less than 500 msec. (safety standard)	10
43	Relay of images moving	Video	20K	30 per s	20 ms	5
44	Techniques, knowhow from experts	Video, torque waveforms	24K	60 per s (60fps)	None	1

4

### 5 **Factory Usage scenarios**

6

The usage scenario represents a complete manufacturing process that utilize a number of factory applications to achieve a deliverable product. Examples of factor usage scenarios includes:

7

8

- Metal processing site

9

- Mechanical assembly site

10

- Elevated and high temperature work site

11

- Logistics warehouse site

12

As follows we give detail description of these example factory usage scenarios and their collective applications used, to within each of these manufacturing scenarios.

13

14

### **Usage scenarios example: Metal processing site**

15

An illustration depicting a wireless usage scene at a metal working site is shown in Figure 10. A building has a row of machine tools, and materials and products (things) are managed in a certain area of the building. Workers are at locations within the building as needed to operate the

16

17

1 machines. In the case of operation monitoring and preventive maintenance, sensors may be  
2 attached to machines. As machine tools may be used for twenty to thirty years, there may be  
3 many old machines, with sensors attached after installation. Communication is necessary to  
4 collect information from sensors, but if ceilings are high, installing wiring requires high site work,  
5 making the cost of wiring expensive. The cost and long work times required by rewiring work  
6 when machines are relocated make wireless communication desirable. In the case of  
7 management of objects and analysis of worker movement, the subjects move, so the use of  
8 wireless communication is a necessity.

9 In the case of operation monitoring, monitor cameras and sensors are installed on machines to  
10 monitor the operation status of the machines. For wireless operation, wired LAN to wireless LAN  
11 media converters are installed on wired LAN ports. On machines without wired LAN ports,  
12 adaptors may be connected for wireless networking. A wireless network is formed between the  
13 machines and a wireless access point, and when an intermittently operated machine is switched  
14 on, a link with a wireless access point is established automatically without human intervention.  
15 As the wireless interference conditions change with the ON/OFF of wireless devices operating in  
16 coordination with the intermittent operation start and stop of nearby machines, it is necessary  
17 for the wireless network to have flexibility, such as monitoring the radio environment and  
18 switching the used frequency channel. Using this network, time series data such as vibration and  
19 torque waveforms acquired by tools and sensors inside machines during operation are sent to a  
20 server. Using the acquired data on the server, analysis software detects anomalies or anomaly  
21 precursors, and informs a manager. According to requirements such as the number of devices,  
22 transmitted data volume, and necessity of real time response, the data is transmitted by an  
23 appropriate wireless network such as wireless LAN, Bluetooth, or Zigbee.

24 In the case of preventive maintenance, various sensors are installed on machine tools. The sensors  
25 and wireless communication device are implemented on a single terminal, and terminals may  
26 execute primary processing before sending, or the gateway may execute primary processing on  
27 data collected from sensors via a wireless network. When sensors and wireless device are  
28 implemented on a single terminal, the terminal may aggregate data received from other terminals  
29 within radio range and attach it to its own data when it transmits, to reduce the number of  
30 transmissions. It may be necessary to sample or compress the data to reduce the volume of data  
31 transmitted. Also, data may be normally recorded at the terminal, but limited under certain  
32 conditions in order to reduce the data volume.

33 In the case of management of objects and movement of workers, wireless communications such  
34 as Bluetooth Low Energy (BLE) are used to monitor the locations of people and things. A wireless  
35 location monitoring system uses tags which periodically transmit beacons, and gateways which  
36 receive the beacons. Multiple gateways are placed in the monitor area and tags are attached to  
37 each person or thing to be monitored. Beacons transmitted by a tag are received by multiple  
38 gateways and the received signal strengths are used determine the location of the tag. By  
39 obtaining acceleration information as well as tag ID, the accuracy of location information can be  
40 increased. Wireless communication is also used when an operator remotely operates a robot with  
41 a terminal called a teaching box. The operator moves around the robot to visually check the  
42 position of the robot and its relation with the object being processed. The movement of the  
43 operator is only around the robot and not over a wide area, but it is important that the response  
44 of the wireless communications is fast. In order to ensure safety, commands triggered by an  
45 emergency stop switch need to be transmitted immediately and reliably.

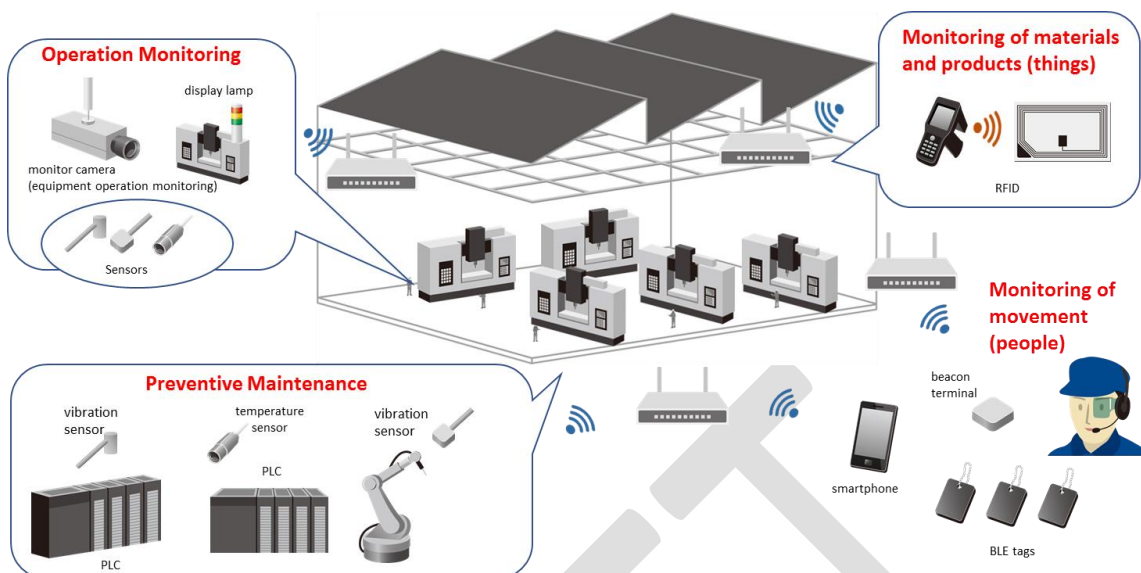


Figure 10 Usage scene: Metal working site

#### Usage scenarios example: Mechanical assembly site

A wireless usage scene at a mechanical assembly site is shown in Figure 11 as an example in automotive plant. In a mechanical assembly plant, the benefit of wireless communications is expected where there is management of building systems for collection and analysis of data for quality management and traceability, and management of operations, such as Automated Guided Vehicles (AGV) for transport of components.

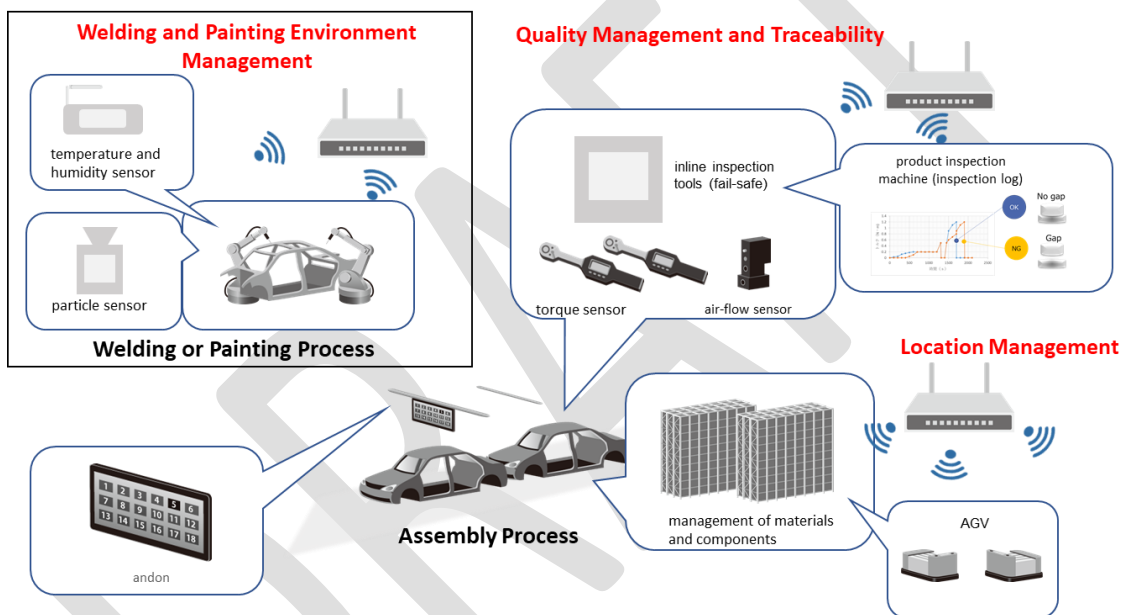
Wireless communication is used to send data to servers - inspection data from large numbers of workbenches, operation sequences in Programmable Logic Controllers (PLC) used for machine control, error information and environmental information. Also, work tools such as torque-wrenches, acquire and send data to servers such as the number of wrench operations and the success of the operations, and even time series data such as vibration and torque waveforms. As ISO 9001 specifies the mandatory recording of inspection data, it requires the reliable collection of data, although strict requirements are not imposed on communication latency. Hence when transmitting data, it is necessary to check radio usage in the neighborhood, and use available frequency bands and time slots (transmission times) according to the requirements such as number of machines, transmitted data volume and necessity of real-time response.

In the case of production management display (such as an “Andon” display board), in coordination with the above information, wireless communication is used to send data for real-time display of production status information, such as production schedule, production progress and production line operation status.

In the case of AGV with autonomous driving ability, the AGV itself will be able to control its current position and path. Each AGV will be sent a command “go from position A to position B” from a parent device (fixed device) and the AGV will move accordingly. As an AGV may move over a wide area in a factory, it is possible that in some locations the quality of wireless communication will degrade due to physical obstruction by facilities and manufacturing machine tools. Hence, it is

1 necessary to consider the radio propagation environment when deciding where to place wireless  
 2 access points and to consider the use of multi-hop networks. The number of mobile vehicles used  
 3 in factories is continuing to increase, and the related issues of the radio environment will require  
 4 more consideration in the future.

5 In a modern automotive plant, the welding or painting process is usually located adjacent to the  
 6 mechanical assembly. As such, IoT devices such as temperature, humidity and particle sensors are  
 7 used for environmental monitoring in places such as paint-shops or clean-booths as shown in  
 8 Figure 13. Wireless communication is used for collecting sensor information remotely at any time  
 9 from outside the rooms where the sensors are installed without requiring reconstruction work.  
 10 The sensors transmit collected environmental information to an upper layer server at periodic  
 11 time intervals. It is required that no data loss occurs. As such, communication routes can be  
 12 checked when necessary at times of trouble, and relay devices can be installed where radio signal  
 13 reception is weak without complex expert knowhow.



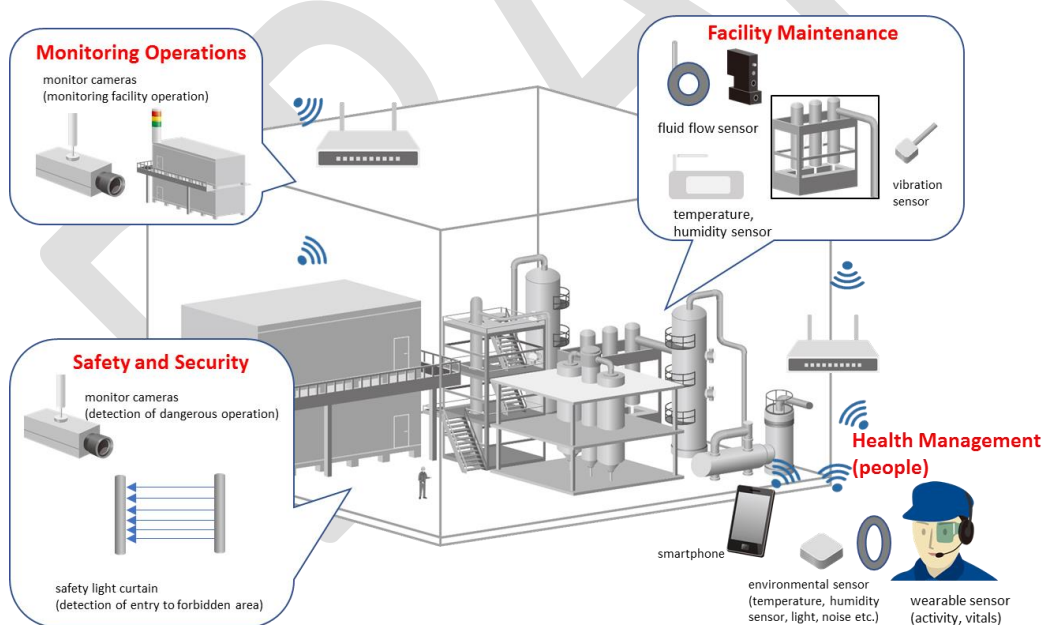
14 **Figure 11 Usage scene example: Mechanical assembly site (automotive plant)**

15  
 16  
 17 **Usage scenarios example: Elevated and high temperature work site**

18 Figure 12 shows an illustration of a wireless communication scene in an elevated and high  
 19 temperature work site. In production sites such as chemical plants and steel plants, there are  
 20 intrinsic dangers due to collisions and falls, and extreme environments with high temperatures  
 21 and high humidity. Monitoring each worker's location and situation from vitals sensors and visual  
 22 images will be an important application. Workers move about, so it is necessary to collect data  
 23 using wireless communication. It is assumed that production facilities will be used for many years,  
 24 so it is necessary to collect information about facility operation and monitor facility operation  
 25 from the point of view of preventive maintenance. In regard to collecting information from  
 26 existing facilities, the use of wireless systems that can be easily added are promising for  
 27 monitoring facility operation using cameras and indicator lights.

1 In a production site with elevated or high temperature work places, such as a drying furnace or a  
 2 blast furnace, wireless communication is used to manage the safety of workers, by collecting  
 3 workers' vitals sensor information (pulse, activity, body temperature, room temperature, posture  
 4 for fall detection, etc.) and environmental information (temperature and humidity, pressure, dew  
 5 point, etc.), and remotely monitoring the situation at the production site using cameras etc. In  
 6 such cases, wireless communications, such as multi-hop networks with wireless LAN / 920 MHz  
 7 communication, are used to collect data. Using sensors that detect entry into forbidden areas,  
 8 combined with BLE beacons, it is possible to monitor the location of workers and warn of entry  
 9 into dangerous areas. Wireless communications are basically used to transmit position  
 10 information and vital information of each worker, but it is also possible to send alerts to workers  
 11 and managers when an abnormal situation arises. Vitals sensors should be of types that do not  
 12 interfere with work, such as wristwatch type, pendant type, or breast-pocket type.

13 The communication terminals in a production site may form a wireless multi-hop network, and  
 14 upload sensor data to a cloud service or server (where the data is finally collected) via a gateway.  
 15 The uploaded data is used to monitor the worker's status. For example, in the case of a system  
 16 with a path from a sensor attached to a worker via a gateway to a server, wireless communication  
 17 from the sensor to the gateway might use 920MHz band communication, wireless LAN, or  
 18 Bluetooth. Communication from gateway to server will require connection via 3G/LTE or wired  
 19 LAN. When the server is far from the gateway, and it is necessary to have a wireless connection  
 20 (such as when wiring is not possible) a wireless mesh using wireless LAN, or a point-to-point 60  
 21 GHz frequency band system may be used as a backbone. In this case, interference between the  
 22 wireless backbone and the communication between sensors and gateway must be considered.



23 **Figure 12 Usage scene example: Elevated and high temperature work site**

24  
 25  
 26 **Usage scenarios example: Logistics warehouse site**

1 In a logistics warehouse<sup>7</sup>, as shown in Figure 13, three-dimensional automatic storage<sup>8</sup> is used to  
2 increase spatial use efficiency. Operation of a three-dimensional automatic storage system  
3 requires monitoring of storage operation, preventive maintenance of the stacking system,  
4 management of automated guided vehicle (AGV) movement, and so on. A large scale warehouse  
5 has multiple storage racks placed in a rows, each of over 30m height and 100m length, and  
6 separated by a few meters or less.

7 The operational status of the warehouse is monitored in conjunction with the transport of storage  
8 items in and out by a computer-controlled stacker-crane. When the stacker-crane makes an  
9 emergency stop due to detecting a stacking fault, workers might have to climb up a high ladder,  
10 tens of meters high, to manually check and repair the stack.

11 When the inspection and repair operation is in a high place, there is greater danger for the worker  
12 and operation delay time increases. Previously, workers had to spend time checking the storage  
13 even when there was actually no need to stop. Now cameras are used to remotely check the  
14 situation on the stacks and the stacker-crane to decide whether operation should be halted or  
15 continued, reducing the number of dangerous tasks of workers, and reducing the average time to  
16 recovering normal operation. However, in large-scale storage systems, the stacker-cranes move  
17 over large ranges, and wiring to cameras attached to stacker-cranes is difficult. Using wireless  
18 cameras eliminates the need for signal cables, and so the installation of wireless cameras in three-  
19 dimensional automatic storage systems is increasing. Information is sent from the wireless  
20 devices on the luggage platform of the stacker-crane to wireless access points (fixed stations)  
21 which are placed at one or both ends of the stacker-crane's floor rail.

22 The images sent from the camera could be video (for example, 30 frames-per-second VGA) or still  
23 images (for example, JPEG or PNG with VGA resolution). The speed of the luggage-platform could  
24 be as fast as 5 meters-per-second, and the wireless device should automatically select, connect  
25 to, and transmit data to the wireless access point with the best link quality. It should also avoid  
26 interference with wireless devices on other stacker-cranes which might be running on parallel  
27 racks separated by just a few meters.

28 In three-dimensional automated storage systems, higher speeds of stacker cranes and their  
29 continuous operation are required to increase the transport efficiency. Sensors are attached to  
30 the drive system that drives the vertical motion of the luggage-platform, and the drive system  
31 that drives horizontal motion of the crane along its rails. A wireless communication device relays  
32 the sensor data, and computer analysis and learning of the data is used for preventive  
33 maintenance of the drive systems.

34 In some cases, in order to increase the flexibility of the layout in the warehouse, the luggage  
35 carried out by a stacker-crane is transported to another storage or work place by a forklift or AGV.  
36 The magnetic tape that is used taped on the floor to guide the motion of a trackless AGV cannot  
37 carry data, so control information such as destination is sent by wireless communication. Also,  
38 forklifts and AGVs have devices for detecting their location, and location information is relayed  
39 by wireless communication. Location information collected from forklifts and AGVs is used to  
40 manage their operation, and methods are being developed to improve transport efficiency by

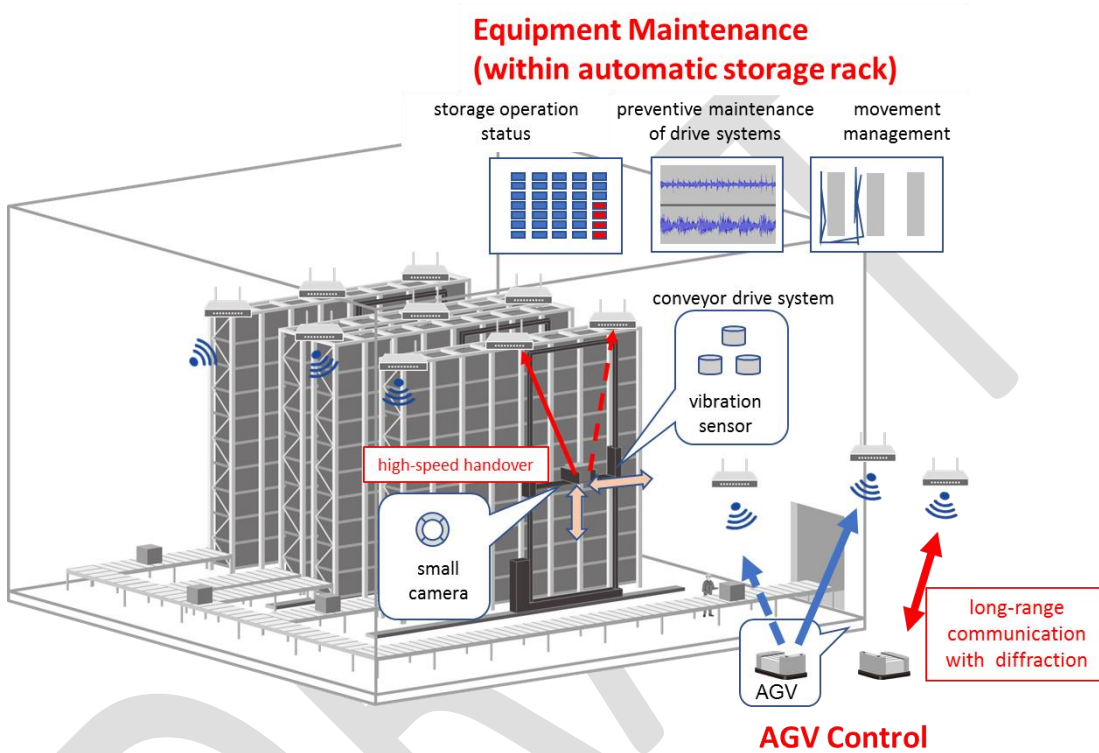
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<sup>7</sup> A warehouse in which items are stored and managed in racks, and moved in and out automatically with computer control.

<sup>8</sup> Equipment for transporting in and out of a three-dimensional automatic storage system.

1 coordinating their motion with stacker-cranes, allowing the selection of the AGV with the shortest  
 2 travel distance, for example.

3 In regard to use of sensors for preventive maintenance on drive systems of stacker-cranes, and  
 4 managing movement of forklifts and AGVs, in large scale factories, the range of motion may  
 5 extend over large areas with various large structures such as three-dimensional storage racks, so  
 6 the placement of wireless access points and the selection of wireless frequency band are  
 7 important issues.



8  
 9 **Figure 13 Usage scene example: Logistics warehouse site**

10 **Technological Enhancement of Networking**  
 11 **for Flexible Factory IoT**

12 **Coexisting of wide variety of factory applications with different requirements**

13 According to Figure 9 and Tables 2~14 in Section “Wireless Applications and Communication  
 14 Requirements”, examples of QoS tolerances in factory applications are summarized in Table 15.  
 15 Table 15 shows that tolerance of latency is classified into small, medium or large, tolerance of  
 16 bandwidth is classified into wide, medium or narrow, and tolerance of packet loss is classified into  
 17 loss intolerant or loss-tolerant. It means that factory applications may require a large number of  
 18 QoS classes more than the 8 classes specified in IEEE Std 802.1Q. To deal with a large number of  
 19 QoS class requirements, defining usage of tag fields may be needed for precise and fine QoS  
 20 control on L2.

1 In addition, there would be requirement to map priority from the 802.1 domain to the specific  
 2 media (e.g. wireless link) and achieve the required performance.

3 **Table 15 Examples of QoS Tolerances in Factory Applications**

Category of Wireless Applications	QoS Tolerances							
	Latency (msec)			Bandwidth (kbps)			Packet Loss	
	<100	100~1000	>1000	>1000	100~1000	<100	loss-intolerant	loss-tolerant
Equipment Control	✓	✓				✓	✓	
Quality Supervision	✓	✓	✓	✓	✓	✓	✓	
Factory Resource Management		✓	✓	✓	✓	✓	✓	✓
Display		✓	✓	✓	✓	✓	✓	✓
Human Safety	✓		✓	✓	✓	✓	✓	✓
Others		✓	✓	✓			✓	✓

4

5 **Overview of the standard landscape for Flexible Factory IoT**

6 A list of relevant existing standards and standard projects are provided in Table 16.

7

8 **Table 16 Standards and Projects relevant to Flexible Factory Network**

Working Group	Standard and Project	Title
802.1	802.1Qat	Stream Reservation Protocol (SRP)
	802.1AS-REV	Timing and Synchronization for Time-Sensitive Applications
	802.1BA	Audio Video Bridging (AVB) Systems
	802.1Qcc	Stream Reservation Protocol (SRP) Enhancements and Performance Improvements
	802.1CB	Frame Replication and Elimination for Reliability
	802.1Qbb	Priority-based Flow Control
	P802.1CF/D3.1	Recommended Practice for Network Reference Model and Functional Description of IEEE 802® Access Network
802.11	802.11aa	MAC Enhancements for Robust Audio Video Streaming
	802.11ak	Enhancements for Transit Links Within Bridged Networks
	802.11e	Medium Access Control (MAC) Quality of Service Enhancements
	802.11ae	Prioritization of Management Frames

9

10 TSN defined standard L2 technology to provide deterministic capability on 802.1Q bridged  
 11 networks. It guarantees end-to-end QoS for the real-time applications with bounded latency,



1 minimized jitter, and high reliability. Industries like automotive, industrial and professional audio  
2 comprised by multiple network devices will benefit from deterministic connectivity and  
3 optimization over Ethernet wires.

4 Future industrial wireless communications will take advantage of this infrastructure. The  
5 wired/wireless integrated networks for future flexible factories IoT scenarios should be able to  
6 accommodate various applications with different end-to-end QoS requirements. These  
7 requirements can be guaranteed by closing the gaps within the following functions:

- 8 • End to end stream reservation in a wired/wireless integrated network
- 9 • Wireless link redundancy for reliability and jitter improvement
- 10 • Adaptation to rapid changes in wireless environments
- 11 • Coordination among the wireless transmissions in the unlicensed bands

## 12 **Gaps analysis of existing standards and technologies for Flexible Factory network**

### 13 **End to end stream reservation in a wired/wireless integrated network**

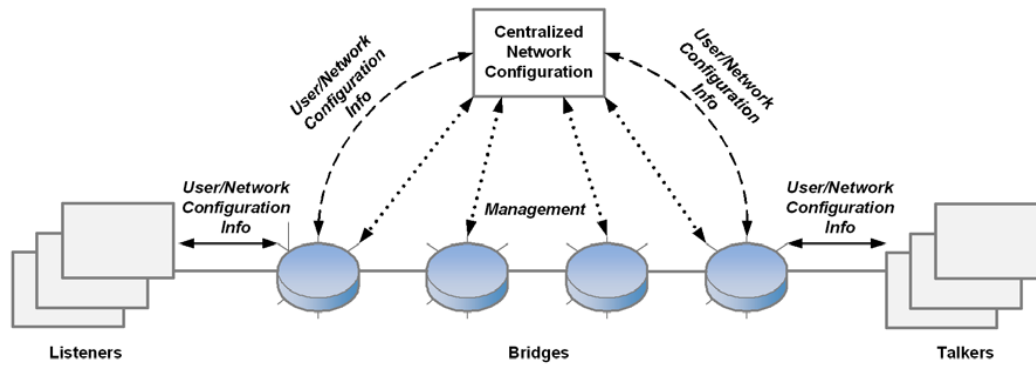
14 Streams are used to describe the data communication between end stations with strict time  
15 requirements. In 2010, the 'Audio/Video Bridging Task Group' (former TSN) standardized the  
16 Stream Reservation Protocol (SRP) as IEEE 802.1Qat, which was then incorporated in the mainline  
17 802.1Q standard.

18 The protocol allows end stations to register their willingness to "Talk" or "Listen" to specific  
19 streams, and it propagates that information through the network to reserve resources for the  
20 streams. Network bridges between the end stations maintain bandwidth reservation records  
21 when a Talker and one or more Listeners register their intentions for the same stream over a  
22 network path with sufficient bandwidth and other resources. The network signaling for SRP to  
23 establish stream reservation is defined as the Multiple Stream Registration Protocol (MSRP),  
24 which is also standardized in 802.1Qat.

25 IEEE 802.11aa specifies a set of enhancements to the original 802.11 MAC QoS functions which  
26 enables the transportation of AV streams with robustness and reliability over wireless shared  
27 medium. It defines the interworking with bridge networks to facilitate end-to-end stream  
28 reservations when one or more 802.11 wireless links are in between Talker and Listener.

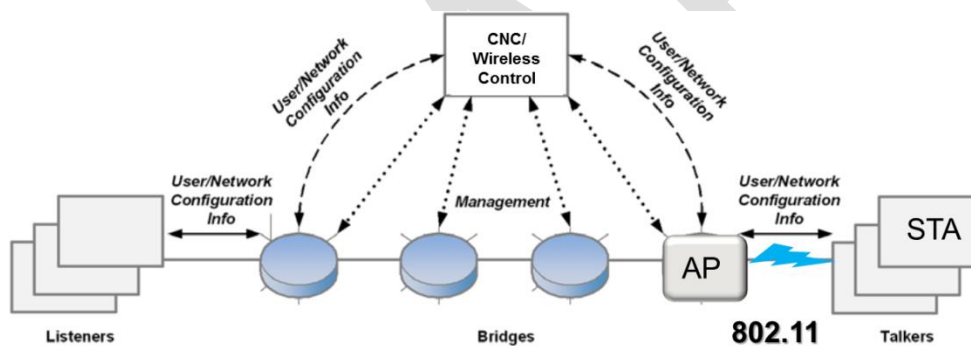
29 It is stated in Annex C.3 of 802.1Q that 'From the bandwidth reservation standpoint an IEEE 802.11  
30 BSS network is modeled as a Bridge.' As one of the essential advantages of SRP, it provides a single  
31 bandwidth reservation protocol across multiple media types of both wired and wireless.

32 The recent published standard IEEE 802.1Qcc specifies a set of large enhancements to SRP,  
33 introducing the concept of centralized configuration model with a centralized network controller  
34 (CNC). As shown in Figure 14, CNC is a new system level entity that will calculate the best possible  
35 solution and configure the bridges to meet those QoS demands conveyed through the User  
36 Network Interfaces (UNI). Within UNI, the attributes about traffic specifics and maximum latency  
37 are shared with the CNC for proper stream management in an end-to-end perspective.



1  
2 **Figure 14 Centralized configuration bridge network**

3 Such a new paradigm can be much appreciated in the wired/wireless integrated networks in  
4 flexible factories, as shown in Figure 15. If partial network resources like bandwidth can't  
5 temporarily meet the performance required by the traffic streams, the CNC will notify the user  
6 and work out a solution with modified configuration to accommodate the QoS requirements of  
7 the system. CNC kind of wireless controller for both bridges and 802.11 AP/STA will certainly be  
8 helpful in the scenario to address the unstable wireless bandwidth and latency issues. By  
9 managing all the traffic streams between all connections in the network, the robustness of the  
10 stream reservation and the network efficiency will be both improved.



11  
12 **Figure 15 Centralized configuration heterogeneous network**

13  
14 **Wireless link redundancy for reliability and jitter improvement**

15 Beginning in around 2012, efforts began in the IEEE 802 TSN Task Group to specify seamless  
16 redundancy in conjunction with TSN streams, particularly to address Layer 2 networks in industrial  
17 control and automotive markets. Eventually, this led to the completion and publication of IEEE  
18 Std 802.1CB-2017, specifying "Frame Replication and Elimination for Reliability" (FRER). IEEE  
19 802.1CB provides specifications "for bridges and end systems that provide identification and  
20 replication of packets for redundant transmission, identification of duplicate packets, and  
21 elimination of duplicate packets." Essentially, packets are duplicated and transmitted along  
22 differentiated paths; copies received at the destination, following the first, are discarded. The  
23 purpose is "to increase the probability that a given packet will be delivered," and to do so in a

1 timely manner. FRER “can substantially reduce the probability of packet loss due to equipment  
2 failures.”<sup>9</sup>

3 FRER emphasizes improvement in loss, rather than latency. FRER is built upon earlier TSN  
4 standards and groups and, accordingly, presumes that frames are parts of a stream carried along  
5 a provisioned reservation. Accordingly, the latency of the reservation may be determined and  
6 presumed bounded; the bounds, however, depend on the reliability of the network along the  
7 reserved path. For some applications, this reliability limitation is insufficient. FRER can, in effect,  
8 provide instantaneous backup of each frame. This dramatically reduces the likelihood frame loss  
9 rate due to independent failure of identical equipment, roughly squaring it. For example, if each  
10 link experiences a frame loss rate of  $\epsilon$ , FRER would be expected to have a frame loss rate of  $\epsilon^2$ .  
11 The difference may be highly significant in practice.

12 FRER is specified to apply only to frames carried in TSN streams. Not all streams in a network need  
13 to be subject to FRER; it can be limited to mission-critical streams only.

14 The concept of frame duplication and duplicate elimination preceded TSN discussions toward IEEE  
15 Std 802.1CB. In fact, the concept was standardized as early as 2010 in IEC 62439-3:2010, “Parallel  
16 Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR).” The standard  
17 supports the use of Ethernet in industrial applications. It is not based on TSN technologies and  
18 accordingly does not support the flexibility to sequence frames per stream. A number of industrial  
19 applications of PRP have followed.

20 The use of PRP wireless networks is not excluded and has been explicitly studied. This case is  
21 similar in principle but may be qualitatively different because the wireless link may be far more  
22 variable than the typical industrial wire link. As a result, a frame may be delayed significantly and  
23 unpredictably on a link without equipment failure. One implication is that, in the wireless  
24 environment, PRP may be more prominently used for jitter reduction rather than simply for frame  
25 loss.

26 Rentschler and Laukemann presented a study at the 2012 IEEE 17th International Conference on  
27 Emerging Technologies & Factory Automation (ETFA 2012) regarding PRP and wireless LAN  
28 (WLAN) [12]. Industrial applications were a key target. It noted that “wireless transmission is  
29 known to be error-prone and its error characteristics behave time-variable and non-deterministic.  
30 This labels wireless communication as not very well suited for industrial applications with tight  
31 reliability requirements, such as guaranteed maximum latency times for packet transmission.”  
32 The authors indicate that they consider “reliability, latency and jitter... as the most important  
33 criteria for industrial communication systems.”

34 Rentschler and Laukemann applied the standardized IEC PRP protocol to two parallel wireless  
35 LANs (WLANs) based on IEEE Std 802.11n; one of the two WLANs operated in the presence of  
36 interfering WLAN traffic. Regarding latency, the paper demonstrated that the minimum latency is  
37 attained without PRP, because the PRP processing adds delay. However, the maximum latency is  
38 attained with PRP, because PRP chooses the frame arriving first. PRP improved jitter (average

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<sup>9</sup> IEEE Std 802.1CB includes the following note: “The term packet is often used in this document in places where the reader of IEEE 802 standards would expect the term frame. Where the standard specifically refers to the use of IEEE 802 services, the term frame is used. Where the standard refers to more generalized instances of connectionless services, the term packet is used.”

1 deviation of the mean latency) by about 40% in an example. The paper reported examples in  
2 which frame loss was around 0.02% per individual WLAN but in which frame errors were not  
3 observed using PRP due to the unlikelihood of simultaneous loss of both packets.

4 Rentschler and Laukemann study do not address the resource requirements necessary to  
5 implement PRP. In the wired case, whether PRP or FRER, the additional bandwidth resources to  
6 support redundancy may be supported by a cable and some switch ports. However, in the wireless  
7 case, the primary resource is a radio channel. As noted, one of the two available wireless channels  
8 in the Rentschler and Laukemann experiment was dedicated solely to the link. However, as  
9 discussed throughout this report, spectrum resources are limited in the factory environment. Each  
10 duplicated frame consumes twice the spectral resource of a single frame. If interference and  
11 channel availability are limiting factors, transmitting each packet in duplicate seems likely to be  
12 counter-productive. However, in some circumstances, such as for low-bandwidth mission-critical  
13 control messaging, duplicate wireless transmission might prove effective.

14 Another issue that needs to be considered regarding the application of PRP or FRER duplication  
15 in the wireless setting is the degree to which the pair of wireless channels is independent. For  
16 many realistic scenarios, such independence is a reasonable assumption in many wired networks.  
17 In the wireless case, the LAN elements may be physically separate, but the wireless environments  
18 may nevertheless be correlated. Operating the two links in different radio channels, or better yet  
19 different radio bands, can help to separate the interference conditions. However, even then, it is  
20 easy to imagine scenarios that would result in simultaneous degeneration of both links. One  
21 example might be a broadband noise source that affects both channels. Another example is that  
22 of large moving machinery, such as a moving truck discussed earlier in this report, which blocks  
23 the direct line-of-sight of two antennas.

24 A number of WLAN applications of PRP have since been discussed in the literature, and wireless  
25 industrial applications of PRP have been introduced in the market, primarily regarding WLAN.  
26 However, no wireless applications of IEEE Std 802.1CB have been identified in the literature.  
27 Perhaps the best explanation is that 802.1 TSN is rarely implemented in wireless networks and  
28 wireless traffic is rarely carried in TSN stream reservations, and therefore 802.1CB FRER is  
29 inapplicable. Should 802.1 TSN functionality, including TSN streams, become introduced into  
30 wireless networks, techniques like FRER could be considered. However, it appears that some  
31 additional complications could arise. For example, FRER relies on sequence numbering in which  
32 the number of bits required depends on the maximum possible path latency difference that needs  
33 to be accommodated. In the wireless case, given the expected difficulty in ascertaining a tight  
34 latency bound, that number could be difficult to assign or could be impractically large without  
35 improvements in network control and management.

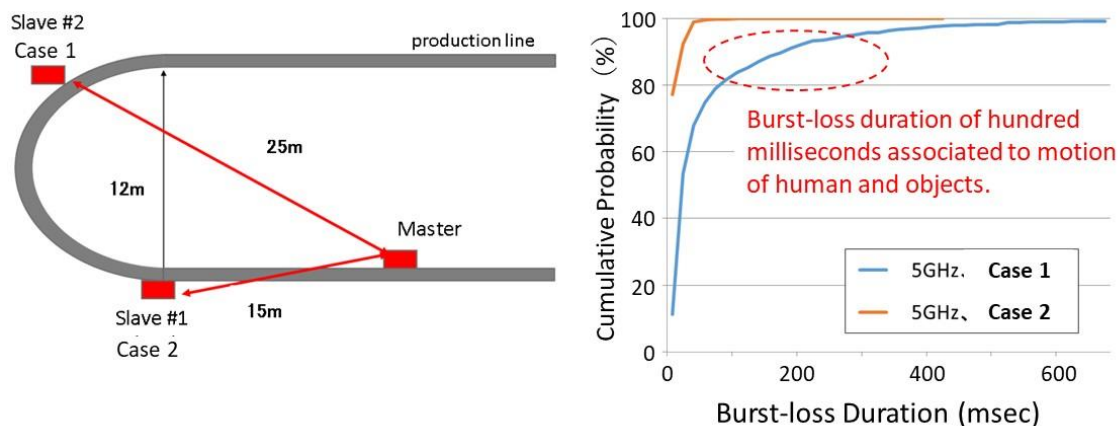
36 Concepts like FRER may find application in contributing to improved reliability and jitter in  
37 wireless factory networks. However, some of the challenges discussed will first need to be  
38 addressed and resolved.

### 39 **Adaptation to rapid changes in wireless environments**

40 Modern manufacturing process requires fast feedback to get immediate response after each  
41 action by worker in management and operation to increase high productivity and high quality of  
42 products, simultaneously, where human and machines tightly collaborate in high-mix and low-  
43 volume production. Permissible delay in feedback messages for most wireless applications in this

1 sense is ranging from 20 msec to 10 sec as shown in Figure 9. The lower boundary may be  
 2 determined by human reaction time [13]. For example, in an application in which an online  
 3 inspection occurs, an action by worker is checked by a system as to whether it is good or not.  
 4 He/she shall receive go/no-go signal from the system indicating to whether to proceed to the next  
 5 action or not. In the network accommodating factory, applications such as quality supervision,  
 6 factory resource management, display, and some of equipment control and safety, permissible  
 7 latencies within 100 msec or less for communications between a terminal and a management  
 8 system of the factory application are considered reasonable.

9 In a typical factory structure (or layout), there are many metallic objects that are moving in a  
 10 closed space, resulting in unforeseeable fluctuation in received radio signal indication (RSSI) due  
 11 to rapid change in propagation condition. An example of measurement in a metal casting site  
 12 showed RSSI changed by more than 20dB within a short time ranging from tens of milliseconds to  
 13 hundreds of milliseconds as discussed earlier in Figure 4. The bandwidth might decrease by one-  
 14 tenth in a case during RSSI dropped. Another example of measurement in a large machine  
 15 assembly site indicted burst-loss occurred for the duration of several hundred milliseconds as  
 16 shown in Figure 16.

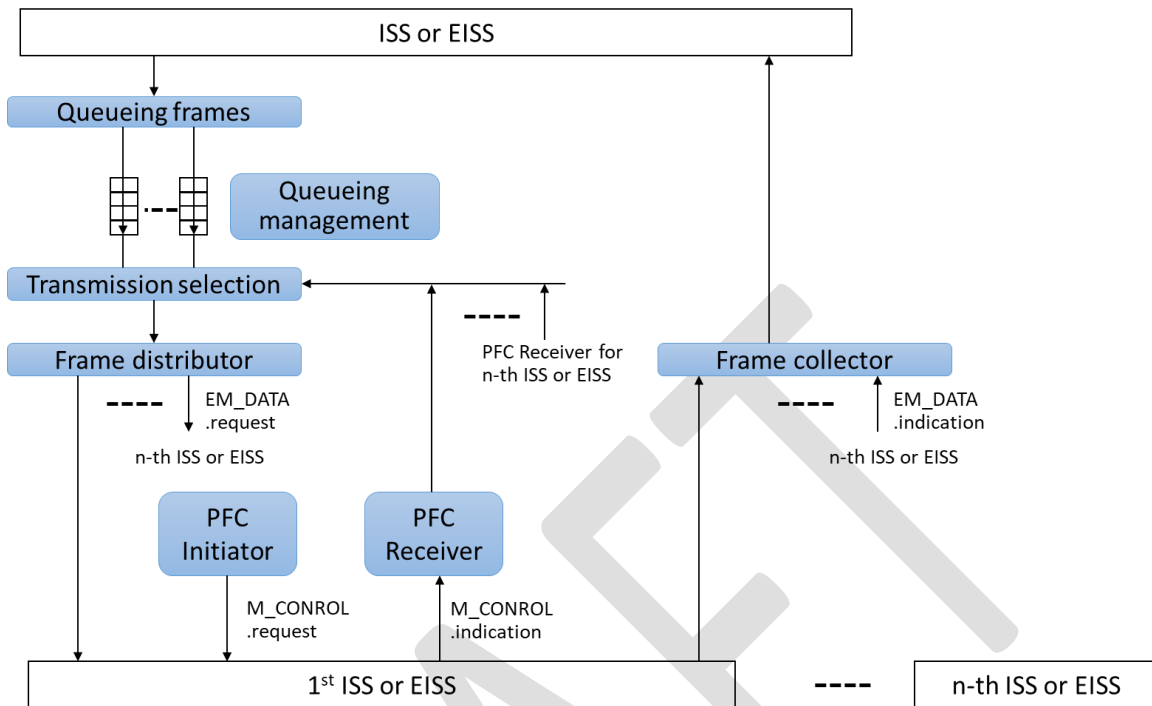


17  
 18

**Figure 16 Burst-loss measurement in a large machine assembly site [14]**

19 In order to ensure transfer of information between terminals in a dynamically changing wireless  
 20 environment within the allowed latency as required by factory applications, a fast and efficient  
 21 queueing control and forwarding mechanism to multiple links is needed while maintaining  
 22 required QoS for the application. For this purpose, we consider the applicability of the PFC  
 23 (Priority-base Flow Control) protocol specified in the Std. 802.1Q-2018, as shown in Figure 17.

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**Figure 17 PFC aware system queue functions with Link Aggregation  
(Rewritten Figure 36-4 in Std. 802.1Q-2018)**

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It should be noted that the application of PFC has been so far used in data center environment<sup>10</sup>. However, when used in a factory environment such as the one described above, the performance and efficiency of the PFC protocols can be degraded significantly due to reduced available bandwidth between terminals. A real time video streaming is a good example illustrating when the performance of the PFC function can be improved when operating in varying radio propagation conditions. Traffic for the video stream is allocated high priority in normal operation condition (i.e. traffic type for video has higher priority than traffic for critical applications according to Table I-2 in the Std.802.1Q-2018 [15]). With varying RSSI, the available bandwidth between terminals is reduced. In real time video streaming application, video quality can be adapted to available link bandwidth (along the end to end path) at the codec source. However, until this video adaptation is complete, while the bandwidth of the link is low and the video quality is degraded below its usable level, streaming is paused, although further packets are incoming to the queueing buffer which are not useable any more. This is the current operation of PFC because data loss is not allowed in a data center for which the PFC protocols was originally designed.

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Since the video packets are no longer usable, pause operation and preserving the video packets is no longer valid during this transition period. During this period, the packets for steaming shall be discarded and critical traffic shall continue to be sent. A more efficient operation method is to discard the unusable video packets until useful video packets are sent again. This occurs when video adaptation to a lower quality matching the available bandwidth, or the link bandwidth is recovered naturally or by switching to a new link with sufficient bandwidth.

<sup>10</sup> Section 36.1.1 in Std. 802.1Q-2018 says “Operation of PFC is limited to a data center environment.”

1 If another ISS (or EISS) connection becomes available for the video stream application, data frame  
2 can then be forwarded dynamically at the bridge. (Table 17)

3 **Table 17 Gaps between Current PFC (Std.802.1Q-2018) and Functions to be enhanced**

Current PFC (Std.802.1Q-2018)	Functions to be enhanced
<b>8(max) links can be independently paused and restarted by queue control. Only no loss is acceptable for data center environment.</b>	Not only “pause” but also “discard” are acceptable depending on data attributes to express a variety of QoS requirements in factory applications.
<b>There is no specific description about “frame distributor”</b>	Dynamic frame distributor mechanism is required to follow rapid changing bandwidth and to avoid burst losses for each ISS/EISS connected to a wireless media.
—	It is required to have negotiation function with factory applications based on data attributes. Data rate reductions is requested if the factory application indicates reduction is “acceptable” in the data attributes.

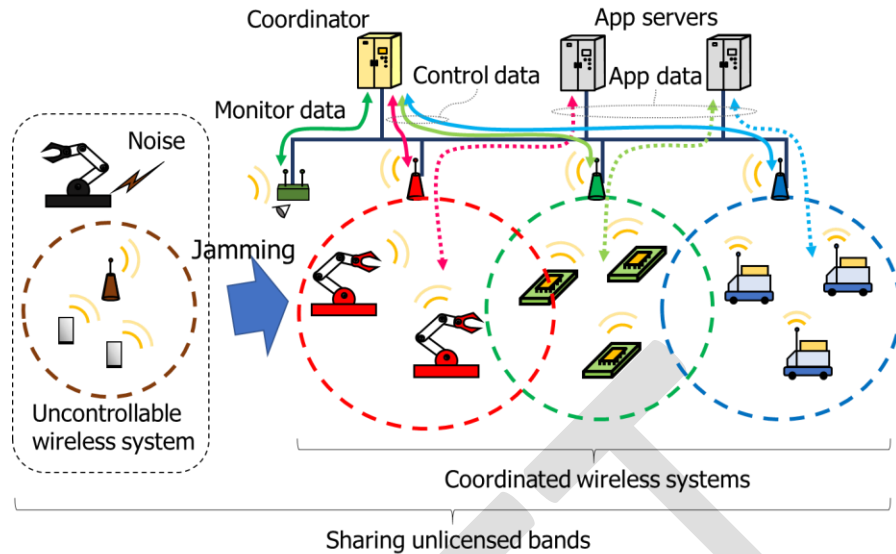
4

5 The issue here is to adapt to rapid changes in wireless environments while ensuring a variety of  
6 QoS requirements across the end-to-end connection of the whole network. The rapid flow control  
7 at the bridge based on information of data attributes and flow control over the entire network  
8 shall work together by a coordinator as shown in Figure 2.

### 9 **Coordination among wireless systems in unlicensed bands**

10 As for the factory IoT, wireless technologies which work in unlicensed bands are used in many  
11 cases because they have large cost advantage in network deployment. Normally, such unlicensed  
12 bands wireless technologies have MAC layer functionalities which enable coexistence with various  
13 wireless systems; CSMA/CA of Wi-Fi and frequency hopping of Bluetooth, for example. These  
14 functionalities make network deployment simple. However, stable quality of service is difficult to  
15 keep with such simple schemes especially when many wireless systems share the same wireless  
16 resources. It is because each wireless system, which consists of multiple wireless stations and is  
17 managed by a base station, works independently based on own probabilistic approach without  
18 any coordination with the other wireless systems. In the factory IoT usage scenarios, many  
19 wireless systems work in a broad area which is not separated completely in terms of wireless  
20 resource, and such competition of wireless systems in unlicensed bands are unavoidable.

21 To mitigate the impact of the competition in unlicensed bands, it is necessary to coordinate  
22 wireless systems in factory as much as possible. To assign channels of each wireless system  
23 according to required bandwidth of applications is a simple example of the coordination. Both  
24 distributed and centralized manner can be applied for the coordination. However, wireless  
25 systems need to be connected to the same wired network for exchanging control data. Wired  
26 network of the factory IoT needs to handle the control data for the wireless system coordination  
27 in addition to application data of each wireless systems. Figure 18 illustrates an overview of  
28 centralized type of coordinated wireless systems.



1

2

**Figure 18 Overview of coordinated wireless systems**

3 Ideally, all the wireless systems in an area should be connected to the same network and  
 4 coordinated together. However, it is difficult to root out uncontrollable wireless systems in all the  
 5 cases and noise from non-communication devices like machine tools also need to be taken into  
 6 consideration. It is necessary to monitor wireless channels, analyze behavior of such interferers  
 7 and estimate available wireless resources accurately for allocating wireless resources according  
 8 to demands of applications. Wired network of the factory IoT needs to handle the monitoring data  
 9 as well.

10 As latency of control data exchange and monitoring data exchange among wireless systems  
 11 becomes lower, more efficient wireless system coordination becomes available. Improvement of  
 12 latency of bridging is one of issues for the efficient coordination of the wireless systems.

### 13 **Future directions towards enhancements for Flexible Factory network**

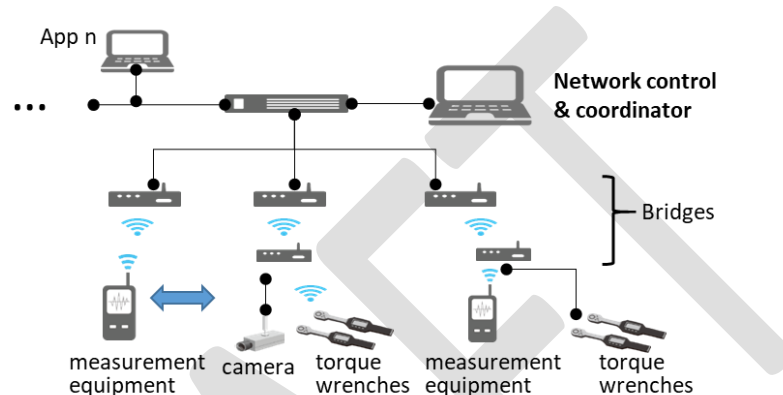
#### 14 **End to end network control and coordination**

15 Within flexible factory scenarios, networks need to meet various traffic requirements and provide  
 16 QoS at application level. There are different types of data flow between factory applications and  
 17 network nodes, such as devices, access points, gateways, switches, bridges, and routers. To keep  
 18 QoS across the factory network with prioritized control, data attributes are introduced at network  
 19 nodes. Data attributes are defined based on the type of application and its corresponding  
 20 requirements. These attributes are attached to the data field and mapped to appropriate traffic  
 21 types. Setting data attributes for factory applications rather than extending traffic types is  
 22 essential for backward compatibility to existing standards.

23 Centralized control and coordination mechanism is required in order to ensure end-to-end QoS  
 24 provisioning over the entire factory network, even in the brownfield where various facilities and  
 25 equipment with different standards, of different generations, and by different vendors coexist.  
 26 The following control functions over the wired/wireless network are anticipated for coordination  
 27 purpose.



- 1 1. Control of data flows across wireless links.
  - 2 2. Joint coordination of frequency channel and forwarding paths.
  - 3 3. Spatial control for wireless links, i.e. power and antenna directivity.
- 4 Coordination is achieved by a coordinator managing the factory network. As illustrated in Figure  
 5 19, the Bridge/AP of each sub-network is deployed for various applications. L2 data frames need  
 6 to communicate between individual devices or towards the application server. The control policy  
 7 could be provided by the coordinator for each sub-network for the ease of implementation, in  
 8 cases where they should be provided on individual device basis by an application specific policy  
 9 template.



10  
 11 **Figure 19 typical network scenario for flexible factory IoT**

12 Wireless link or path quality is changing rapidly (from milliseconds to seconds) due to multipath  
 13 fading and shadowing in the closed environment of factories where human, product and material  
 14 handling equipment e.g. forklift trucks and AGVs (automated guided vehicles) are moving. It is  
 15 required to reserve minimum bandwidth for priority application by enhancing bridge functions,  
 16 despite the degradation in the local link quality. For the purpose of reliability, queueing and  
 17 forwarding, mechanisms for redundancy need to be defined to use data attributes over the  
 18 network. The coordinator can set policies for transmission of application data in a way that  
 19 tolerates the degradation in the network due to the bandwidth changes. The control policies  
 20 should be established to ensure the low priority bulk data transfer does not impact the  
 21 transmission of the high priority critical messages and important data.

22 For coordination and control of a factory network made up of several tens of systems, a huge  
 23 tightly-controlled network and computing resources would be required. Tight control directly  
 24 conducted by the coordinator is impractical. This implies the necessity for hierarchical control  
 25 consisting of (1) centralized coordinator which implements the global control for coordination of  
 26 independent systems to satisfy requirements of each factory applications, and (2) the distributed  
 27 coordination agent on each individual Bridge/AP which serves as local control for each system  
 28 according to control policy. The control policy implies how radio resources of time, frequency,  
 29 and space are utilized to optimize operation of entire network in a factory.

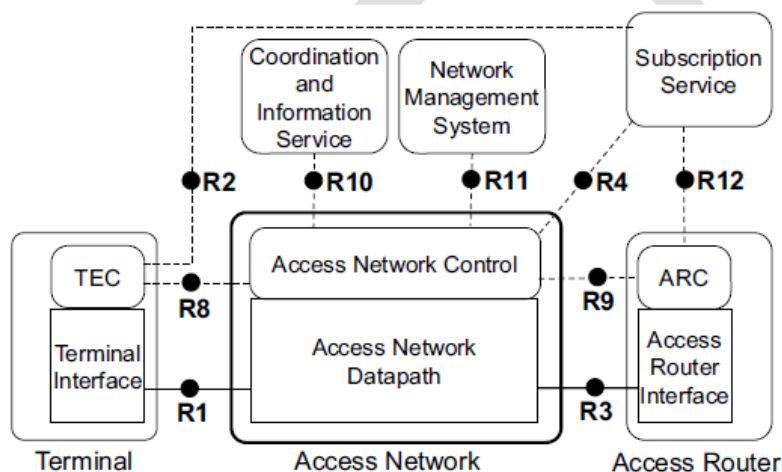
30 To realize the hierarchical control, more information needs to be concentrated on the centralized  
 31 controller enabling an autonomous operate in quick response. For this purpose, the following  
 32 three items need to be considered for standardization.

- 33 A) Control policy: messages and interfaces between a coordinator and various systems.

- 1 B) Information on wireless environment: link/path quality.
- 2 C) Data attributes: common information including various requirements, e.g. data rates (or
- 3 data size at an application level and data frequency), latency, affordability of packet loss.
- 4 Traffic types expressed by three bits may not be sufficient for factory applications.

5 **An unified network reference model**

6 Network reference model (NRM) for flexible factory IoT network is a generic representation which  
 7 includes multiple network interfaces, multiple network access technologies, and multiple  
 8 applications. The NRM defined in IEEE P802.1CF [16] is appropriate for this purpose and can be  
 9 used to generalize the concept of centralized configuration paradigm and to explain how data  
 10 attributes are managed as informative description as well. The minimum enhancement could be  
 11 achieved by creating a factory profile consisting of the reference model and data attributes. Detail  
 12 investigation is required if any protocols shall be added.

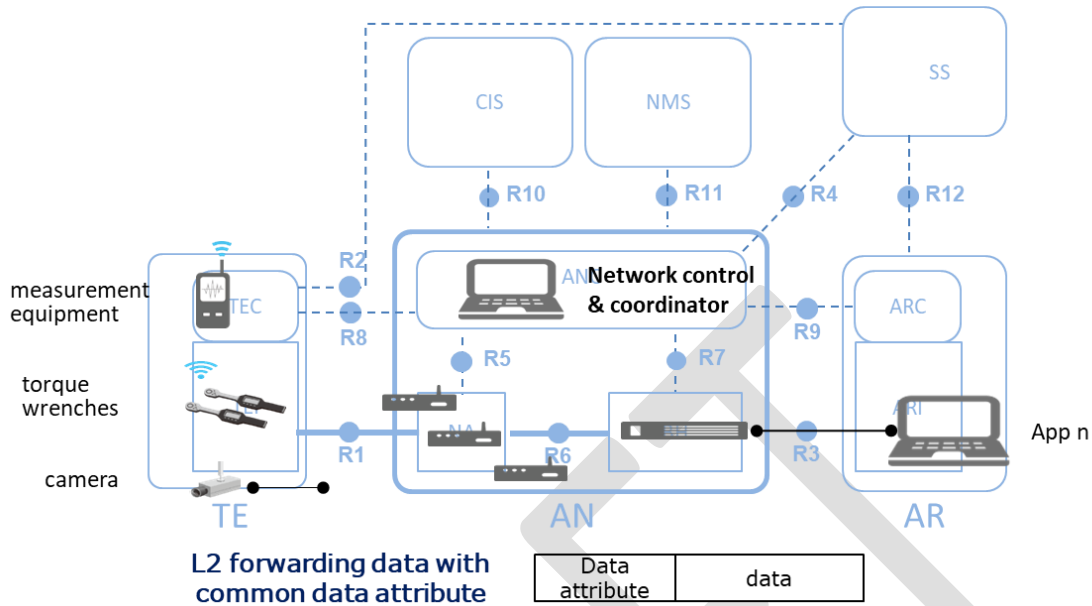


13 **Figure 20 network reference model defined in IEEE P802.1CF**

14 The aforementioned network scenarios shown in Figure 20 can be mapped to 802.1CF NRM as  
 15 depicted in Figure 21. Bridge/AP represents the node of attachment (NA) providing wired/wireless  
 16 access through R1 to the terminals (devices). L2 data frames with common data attributes are  
 17 aggregated and forwarded to the second level bridges, represented as backhaul (BH) through R6  
 18 datapath interface. The coordinator is located in the access network control (ANC) providing  
 19 control policy to the underlay bridges and APs through R5 and R6 control interfaces<sup>11</sup>.  
 20

<sup>11</sup> Refer to Clause 5 of Draft IEEE Standard P802.1CF/D2.1 [7] for detailed information of network reference model (NRM).

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**Figure 21 mapping factory network to 802.1CF NRM**

4

The centralized coordinator fits well in the role of ANC provides enhancements to 802.1 protocols and procedures, e.g. SRP, for time sensitive applications. More complex TSN use cases benefit from the complete knowledge of streams in the network, especially for the ones going through wireless mediums, which are stored and processed by the coordinator.

8

In the case that performance requirements cannot be guaranteed as promised due to e.g. bandwidth fluctuation, the coordinator may respond quickly based on its knowledge of the global network resources and adjust parameter settings amongst all bridges/APs. Control policy shall be provided to keep sufficient resources to accommodate short-term variance and to re-allocate network resources adaptively to establish stable streams even on wireless medium. It ensures that the end-to-end QoS provided by the factory network meet the different requirements from the wide variety of factory applications.

15

Further to the aforementioned considerations, when wireless is used in factory networks and systems, some TSN features may be required to perform at the same level as they would over the wired portion of the network. This implies additional challenges that need further consideration, such as the impact on latency and reliability of the wireless links at Layer 1/2.

19

The radio environment in the factory also poses additional challenges. The NIST report on "Guide to Industrial Wireless Systems Deployments" [8] gives good guidance on planning and deploying wireless systems within the factory environment. Characterization of radio channels in factory environments may additionally help, if available, with such planning and deployment.

## 23 Conclusions

24

{the conclusion section needs further review after the new draft.}

1 A factory is called a “brownfield” where various facilities and equipment with different standards,  
 2 of different generations, and by different vendors, coexist in the same sites. There is also a variety  
 3 of data from factory applications flowing into network nodes and data attributes attached to the  
 4 data field that need to be introduced for priority control at each node. The hierarchical control  
 5 consisting of global control for the coordination of independent systems and distributed and local  
 6 control for each system according to control policy is promising to adapt to short-term  
 7 fluctuations of wireless link and to optimize the wireless resources of an entire network in a  
 8 factory. Such operation is explained by network reference model to configure a flexible factory  
 9 profile.

10 Two approaches to realizing coordination have been described depending on situations where  
 11 single-standardized but decentralized and independent wireless systems coexist, and  
 12 heterogenous wireless and wired systems coexist in the same space. Each of them will be efficient  
 13 and both will be better to improve performance.

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