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



IEEE | 3 Park Avenue | New York, NY 10016-5997 | USA

DRAFT

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

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PDF: ISBN 978-0-7381-xxxx-x STDVxxxxx
Print: ISBN 978-0-7381-xxxx-x STDPDVxxxxx

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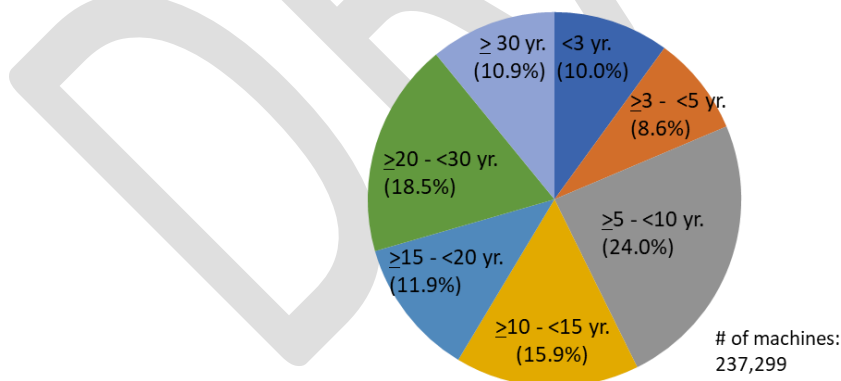
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1 Flexible Factory IoT: Use Cases and 2 Communication Requirements for 3 Wired and Wireless Bridged Networks

4 Introduction

5 Communication in factories has until now been mainly wired communication. A survey [1]
6 indicates that the market share of wired networks in factory automation is 94%. However, in
7 recent years shorter product development cycles have demanded greater flexibility in the layout
8 of 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]¹**
20

¹ Data were from a survey of 1033 Japanese factories administrated by Ministry of Economy, Trade and Industry of Japan in 2013. Total number of machines was 237,299, including 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.

1 This paper considers the need for network requirements in an evolving factory environment
2 referred to as “Flexible Factory”. The Flexible Factory represents an evolved site for flexible on-
3 demand manufacturing of variable product types with variable production volumes. Flexibility in
4 the factory environment emphasizes mobility and configurability of manufacturing facilities. In
5 support of the flexibility, human operators are engaged with the production process in order to
6 oversee the on-demand production. This new flexibility requires the factory network to evolve
7 to include wireless connectivity in support of increased mobility of humans and automated
8 vehicles and the reallocation of facilities.

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

16 The report presents an underlying end-to-end (E2E) network architecture that addresses the
17 operation and control of the various services in the factory network according to their dynamic
18 QoS requirements. It analyses the applicable standards and features in IEEE 802 technologies to
19 achieve the requirements in E2E network connectivity for integrated wired and wireless
20 connectivity in a factory environment.

21 **Scope**

22 The scope of this report includes use cases and communication requirements for wired and
23 wireless bridged networks. Dense use of wireless devices with differentiated QoS requirements
24 and operation in factory environment are taken into consideration. Gap analysis from existing
25 IEEE 802 standards and necessary technology enhancement are also covered in the context of
26 time-sensitive networks for the future.

27 **Purpose**

28 The purpose of this report is to document issues and challenges in managing reliable and time-
29 sensitive connectivity in the Flexible Factory, in which various equipment is attached to the wired
30 network via wireless connections. The report includes technical analyses of the identified features
31 and functions in wired and wireless IEEE 802 technologies for managing requirements in E2E
32 network connectivity. The results of the analysis lead to recommendations for enhancements of
33 IEEE 802 standards supporting the integration of wired and wireless factory networks.

34 **Factory Overview and Communication Network environment**

35 **Factory communication network environment**

36 Trends to connect devices such as sensors and cameras to factory networks are accelerated by a
37 strong demand for improving productivity under the constraints of pressure for cost reduction.
38 Connection of information on production processes and supply chain management within a
39 factory and across factories has become increasingly important. It is also important to consider

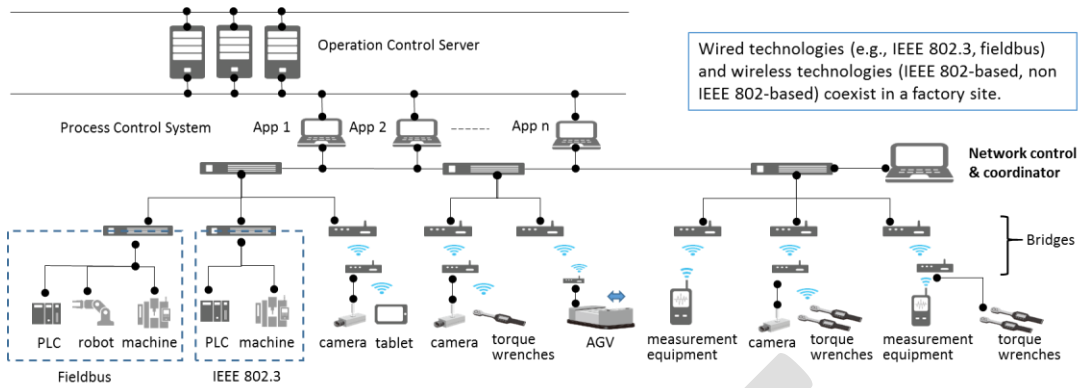
1 future needs of new technologies and networks deployments, in spite of the typical long lifetime
2 of any deployed technology in the factory floor. Communication networks in factories will
3 undoubtedly change in the next decade.

4 Figure 2 shows an example of a network for a vehicle assembly line in a factory today. Industrial
5 control systems, ranging in scale from a few modular panel-mounted controllers to thousands of
6 field connections, providing remote access to the data provided by, for example, sensors,
7 actuators and motors. The larger systems are usually implemented by Distributed Control Systems
8 (DCS) or Supervisory Control and Data Acquisition (SCADA) systems, which manage Programmable
9 Logic Controllers (PLC) in the field. The entities labelled in Figure 2 as 'App x' indicate system
10 applications, e.g., preventive maintenance, management of materials and products, and machine
11 movement monitoring.

12 The factory network infrastructure primarily provides the communication between and within
13 these components and systems. One of the distinctive features of factory networks is that the
14 physical devices connecting to the network are used to control and monitor real-world actions
15 and conditions. This results in a strong emphasis on differentiated Quality of Service (QoS).

16 Due to performance and market advantages, Ethernet has emerged as the dominant standard for
17 the physical and medium-access control layers of factory networks. Ethernet, unlike serial
18 protocols such as fieldbus [3], supports multiple higher layer protocols supporting the
19 interconnection of devices with various bandwidth requirements, including PLCs, HMI (Human
20 Machine Interface), and devices requiring high speed communications. In high-end industrial
21 communication markets, the use of Ethernet has become increasing favorable due to the
22 introduction of the determinism based on the IEEE 802 Time-Sensitive Networking (TSN)
23 standards. This set of standards for bridges and bridged networks, developed and supported by
24 the IEEE 802.1 TSN Task Group, supports deterministic services, such as guaranteed packet
25 transport with bounded latency, low packet delay variation, and low packet loss. For further
26 information about the TSN Task Group and list of approved standards and projects in
27 development, see the TSN Task Group webpage [4].

28 Installation of wires in a factory environment is costly. Future industrial factory networks are
29 expected to use more wireless to reduce the installation cost as well as to enhance flexibility. By
30 utilizing wireless communications, it is possible to collect useful information from IoT sensors, to
31 flexibly allocate equipment such as cameras, and to analyze the status of humans and machines.
32 Wireless is an essential element that enables flexible layout of machines and order of
33 manufacturing processes to adapt to variable-type, variable-volume production and mass
34 customization [5].



1

2

Figure 2 Example of network topology for a vehicle assembly line

3

Transmitting and receiving data over a wireless link is not as reliable as a wired link. More effort will be required for wireless communication because of its limited and shared radio resources and the sensitive nature of the environment in which it operates.

4

5

In order to configure, coordinate and maintain various QoS requirements end to end over the heterogeneous network integrating wired and wireless interfaces, as in Figure 2, some sort of network control and coordinator may be considered to aid the successful integration of wired and wireless systems.

6

7

Within the factory network, there is a variety of traffic types generated from different factory applications. Example of different traffic types in factory network are defined by [6]. These are characterised as either periodic with constant bit rate or sporadic with various packet sizes. There are a number of functions and mechanisms in the aforementioned IEEE 802 TSN standards that can be used for managing and prioritising traffic transmission across the factory network according to their QoS requirements. While these mechanisms work well for periodic traffic types with constant bit rate, their performance and efficiency would degrade significantly when processing multiple sporadic data streams. This is because the 802 TSN standards mechanism are designed for periodic traffic types with maximum bandwidth, such as video or audio data streams, for the transmission over a specified delivery time as indicated in Clause 34 in [7].

8

9

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

10

11

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

12

1 Successful factory automation with a high degree of flexibility, dynamic management and control
2 of end-to-end streams across mixed wired and wireless links may be facilitated by E2E
3 coordination as illustrated in Figure 2 above.

4 The impact of applying QoS control and time synchronization functions and protocols to
5 heterogeneous factory networks with mixed wired and wireless links is further analyzed below.
6 First, however details of the environment and causes of radio impairments to the factory
7 environment are presented.

8 **Coordination System for Factory Automation**

9 In current factories, various facilities and equipment with different standards, of different
10 generations, and by different vendors, coexist in the same site. This heterogeneous factory
11 environment is known as Brownfield [8]. Such networks must accommodate various wireless
12 interfaces. IEC has produced coexistence guidelines for manually configuring wireless systems
13 and networks for co-existence [9][10]. In order to overcome the variable environment for
14 wireless communications (see “Radio Environment within Factories” below), coordination may
15 prove superior to static configuration of network elements for co-existence. The same concept is
16 also discussed in [11].

17 **Radio Environment within Factories**

18 Some factory applications require reliable, low-latency, and low-jitter data transmission
19 compared with applications in other environments like offices and homes. Furthermore,
20 measurement results show that some factories are facing difficulties due to severe environment
21 for wireless communications and/or existence of uncoordinated and independent systems in the
22 same space.

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

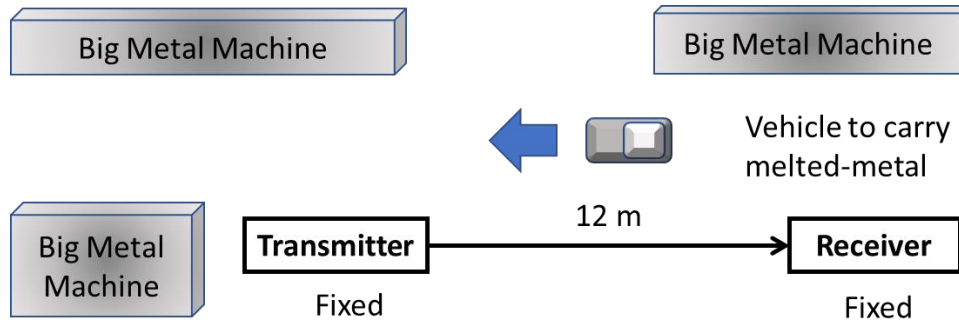
24 Two main sources of impairment to radio signals within the factory environment cause
25 unpredictable variations to channel capacity, namely:

- 26 1. Fluctuation of signal strength
- 27 2. Electromagnetic interference

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

29 **Example of Fluctuation of Signal Strength**

30 Figure 3 illustrates an environment in which the measurements of Figure 4 were collected. The
31 line of sight between the transmitter and the receiver was not blocked by any obstacle during
32 measurement.



1

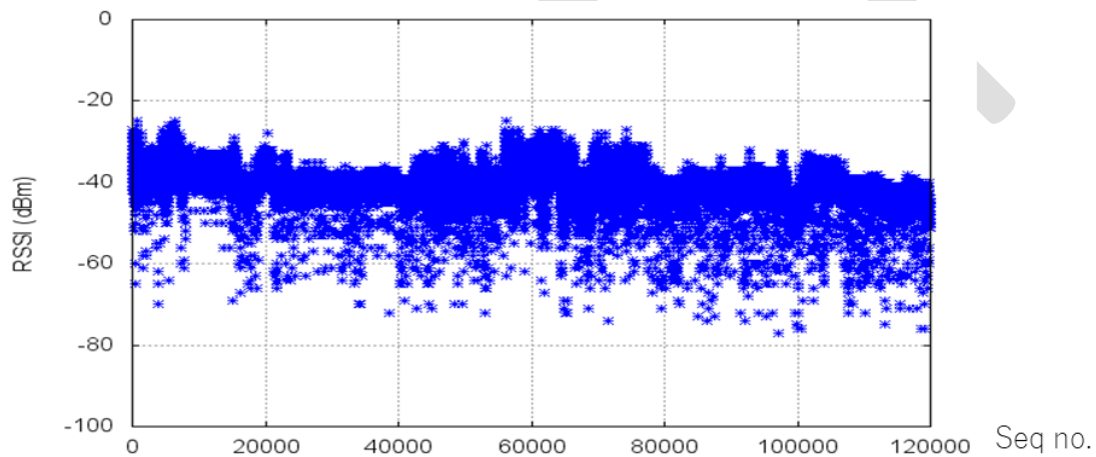
2

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

3

The observed Received Signal Strength Indicator (RSSI) measurement for this layout is shown in Figure 4 below. A packet with 54 bytes was sent at each sequential (Seq) number with 10 ms separation at a data rate of 6 Mbit/s.

5



6

7

Figure 4 RSSI Fluctuation in Factory

8

This fluctuation in RSSI show in Figure 4 may be due to motions of materials, parts, products and carriers in closed space, with multi-path reflections. Similar issues are reported in the NIST report on "Guide to Industrial Wireless Systems Deployments" [12].

10

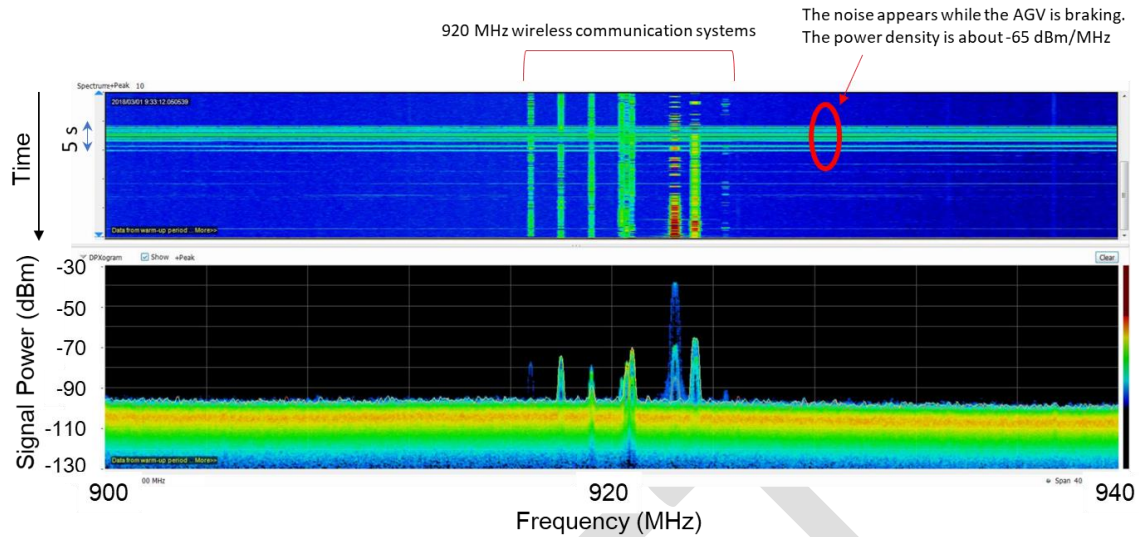
11 Example of Noises:

12

Measurements within one factory environment indicate considerable noise signal within the 920 MHz band. This is shown in Figure 5. The source of the noise signal has been confirmed as Automated Guided Vehicles (AGVs), as the noise appears while the AGV is breaking.

14

15



1
2

Figure 5 Measured noise spectral density

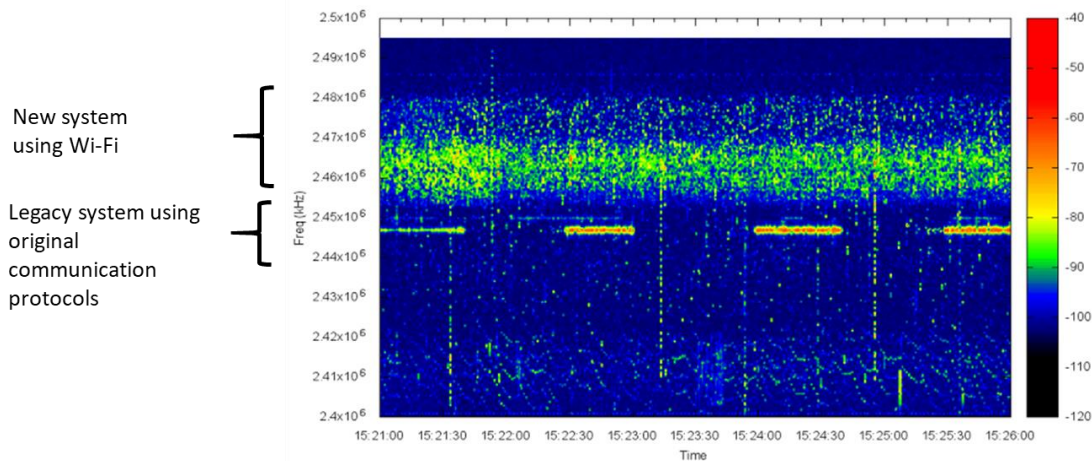
3 The observed noise power was -65 dBm/MHz, above the receiver sensitivity for the 920 MHz
4 wireless systems.

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

6 "The modernized factory environment leads to addition and reconfiguration of machines and
7 equipment, much of which is outfitted with wireless network interfaces. This new environment
8 brings about the requirement for coexistence of heterogeneous and legacy devices and systems.

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

16 Figure 6 shows wireless signals operating in the 2.4 GHz band in an existing factory site where two
17 systems coexist. The legacy system occupies one narrow channel, but only three Wi-Fi channels
18 are available. Because there is no common scheme for collision avoidance among different
19 communication protocols, an independent channel should be assigned for each system to ensure
20 stable factory operation. This limits the number of wireless systems, that different communication
21 protocols, which can operate in the same frequency band in a factory area.



1

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

5

6 **Wireless applications and communication requirements**

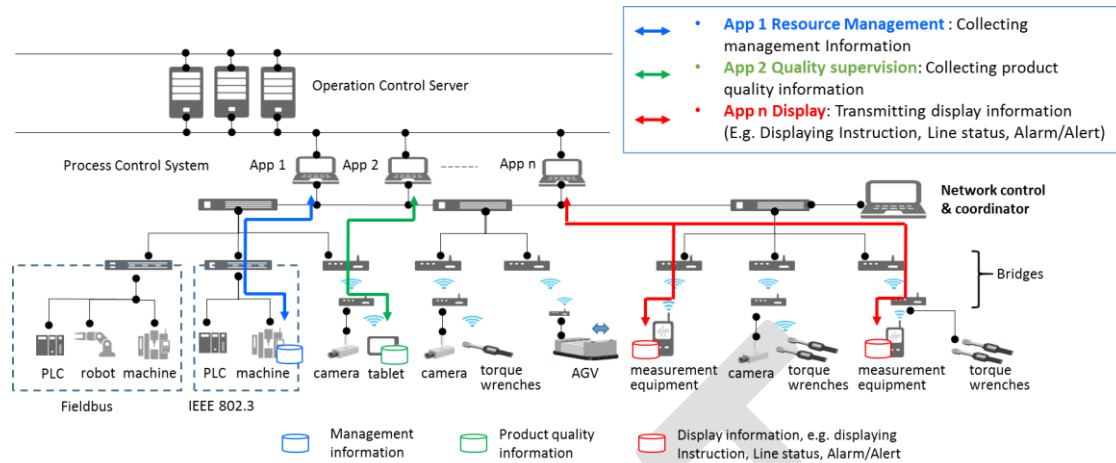
7 **Scope of wireless applications in factory**

8 The wireless applications considered in this clause illustrate wireless systems that are used
 9 currently or in the near future in factories and related facilities. The applications correspond to
 10 wireless systems that are installed for specific purpose.

11 For example, wireless applications are highlighted in the factory network as shown in Figure 7.
 12 The colored lines indicate the data streams planned for specific purposes such as “Collecting
 13 Management Information”. The wireless sub-networks consisting of multiple wireless
 14 connections are deployed to support the information transmission and aggregation for different
 15 applications.

16 The factory network must be built, configured and managed to support the successful operation
 17 with wireless links. In some cases, a critical application may demand a separate wireless segment
 18 setup due to special concerns.

19 The section entitled “Factory Usage Scenarios” below considers factory sites with large needs for
 20 wireless communication and describes usage scenarios in which multiple wireless applications
 21 coexist.



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Figure 7 Wireless applications in factory

Wireless applications

In a usage survey [13] of wireless communication in factories, characteristics of various applications were collected. These are classified according to their purposes, and organized by their communication requirements. Collected wireless applications are listed in Table 1. These were divided into six categories, (equipment control, quality supervision, factory resource management, display, human safety, and others), and then subdivided into thirteen classifications according to their corresponding purposes.

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 ² 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

² Physical objects such as materials and equipment related to production are called “things”

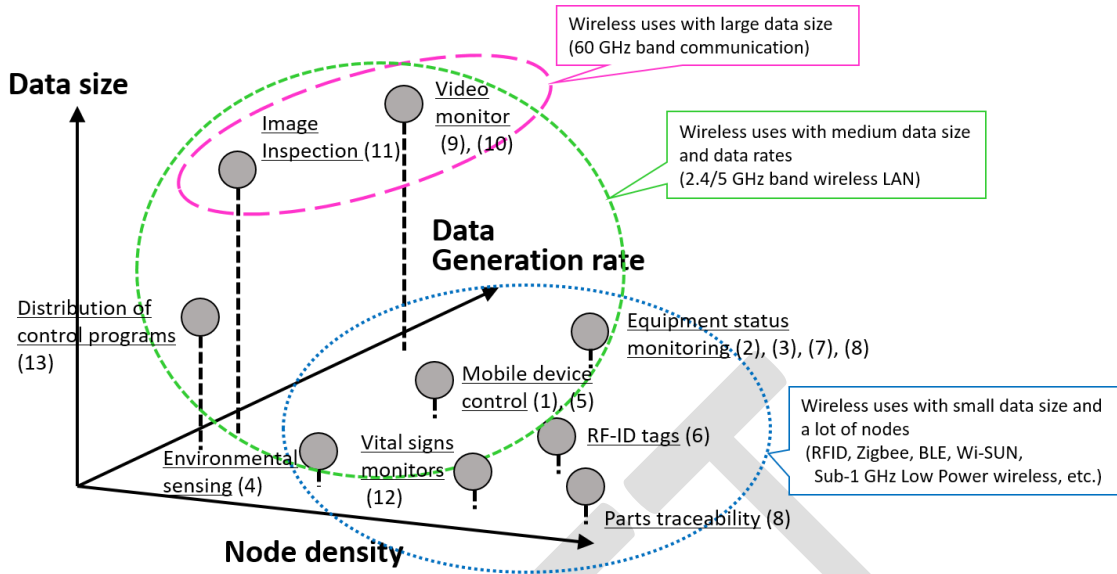
		(8) Appropriate recording of work and production status
Display	For workers, receiving necessary support information, for managers, monitoring the production process and production status	(9) Providing appropriate work support, such as instructions and tracking information (10) Visually display whether 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
Others	Communication infrastructure with non-specific purposes	(13) Cases other than the above

1

2 **Communication requirements**

3 Figure 8 shows representative wireless applications, with corresponding classifications (1)-(13)
4 from Table 1, and their wireless communication features. Values of data size, data generation
5 rate, number of wireless nodes, and so forth depend on the required functions of the systems.
6 Wireless networks use different wireless frequency bands and wireless standards. High frequency
7 bands such as 60 GHz band are expected to be effective for systems with relatively large data
8 volume requirements (image inspection equipment, etc.). 5 GHz band and 2.4 GHz band networks
9 are used for systems with medium requirements of data sizes and data generation rate, such as
10 distributing control programs and control of mobile equipment. Relatively low wireless frequency
11 bands such as below 1 GHz are being used for applications with low power requirements (such as
12 environmental sensing).³

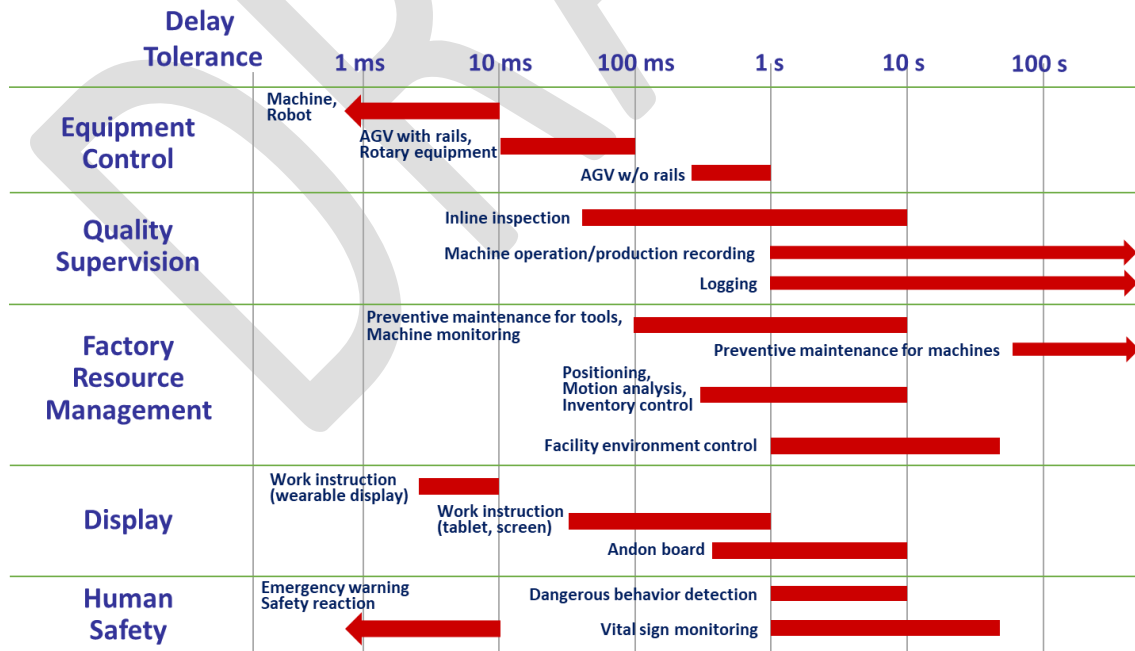
³ Lower-frequency radio waves propagate better than higher-frequency one. This allows a better range and lower transmitting power, resulting in low power consumption. Environmental sensing that requires long life battery operation is a good example of low power applications. Lower-frequency bands below 1 GHz have become typical for such applications [14] [15].



1

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

4 Figure 9 shows the permissible delay for representative wireless applications as in [13] and [16].
 5 For some wireless applications such as robot control and urgent announcement, the urgency and
 6 accuracy of information arrival timing requires less than one millisecond latency. On the other
 7 hand, particularly in the categories of quality (inline inspection, etc.) and management
 8 (preventive maintenance, etc.), there are many wireless applications that tolerate latencies larger
 9 than 100 ms.



10

11

Figure 9 Permissible delay of representative wireless applications

1 Details of wireless application and communication requirements

2 Communication requirements for the thirteen classifications of wireless applications are
 3 organized in Tables 2 to 14. Each table contains further detailed purpose of the wireless
 4 application, corresponding information, and the communication requirements of transmitted
 5 data size, communication rate, delivery time tolerance, and node density⁴. These attributes are
 6 based on a survey involving for a number of samples within many factories⁵.

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

9 (1) Controlling, operating and commanding of production equipment and auxiliary
 10 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 1 d	100 ms	5
3	AGV control	Go signal, positioning	100	Once per 1 min	100 ms	1 to 10
4	Bottle filling	Fill valves	400	Once per 1 ms	500 μ s	2
5	Warehouse	Stacker crane positioning	10	Once per 2 to 5 ms	1 ms	1 to 20

11
 12 **Table 3 List of wireless applications and communication requirements for Quality**
 13 **Supervision -1**

14 (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 1 s	5 s	1 to 5

⁴ Node density: number of terminals per 20 m x 20 m. This area dimension is based on the structure in a typical factory in which pillars are separated by 20 m.

⁵ The survey in [13] 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.

7	Detect defect state	Defect information (video)	500	Once per 100 ms	500 ms	1 to 5
8	Detect incorrect operation	Anomalous behavior due to adding impurities (e.g. Contamination)	1 M	Once per 1 s	10 s	1 to 5

1

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

4 (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 1 s	1 min	1
10	Monitoring of equipment	State of tools, disposables	A few hundreds	Once per 1 s	1 s	2
11	Counting number of wrench operations	Pulses	64	Once per 1 min	100 ms	10

5

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

8 (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 1 min	5 s	5
13	Managing carbon dioxide concentration	CO2 concentration	16	Once per 1 min	5 s	2
14	Preventive maintenance	Machine's temperature	A few tens	Once per event	1 s	2

9

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

12 (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 1 s	A few seconds	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 1 s	1 s	2
17	Measuring location of products	Location of products during manufacture	200	Once per 1 s	1 s	20

1

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

4 (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 1 s	1 s	20
19	Tracking parts, stock	RFID tag	1K	1~10 times per 30 min	100 ms	3 to 30

5

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

8 (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 1 s ~ once per 1 min	1 s ~ few tens of 1 s	1 to 10
21	Measuring energy	Energy, current fluctuation	64	Once per 1 min	1 min	1
22	Monitoring revolving warning light	Defect information	100	Few times per 1 h	1 s	25

9

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

12 (8) Appropriate recording of work and production status

Wireless application	Communication requirements

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

1

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

3

(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 s ~ 1 min	1~10 s	10 to 20
28	View work manual	Text data	100	Once per 1 h	10 s	9
29	display information (image display)	image (video/still image)	5M	once per 10 s ~ 1 min	few seconds	1 to 5

4

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

6

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

7

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)	A few bytes	Once per 10 s ~ 1 min	Few seconds	1 to 10
31	Managing operation activity	Activity of PLC	128	Once per 1 h	100 ms	2
32	Displaying revolving warning light	ON/OFF	A few bytes (a few contact points)	Once per 10 s ~ 1 min	0.5~2.5 s	30

8

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

2 (11) Visually display the production status, the production schedule, and any deviations or
 3 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 1 s (30fps)	500 ms	1
34	Supporting workers	PLC	200	Once per 10 s~1 min	500 ms	5
35	Supporting maintenance	Image, audio	200	Once per 100 ms	500 ms	1

4

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

6 (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 managing worker safety	Vitals information (wearable)	100	Once per 10 s	1 s	9
38		Vitals information (fixed, relay)	200	Once per 1 min	5 s	20
39		Gait	About 100K	~10 per 1 s (1 fps~10 fps)	1 min	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

7

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

9 (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 thousands bytes	Twice per year	Less than 500 ms (safety standard)	10
43	Relay of images moving	Video	20 K	30 per 1 s	20 ms	5
44	Techniques, knowhow from experts	Video, torque waveforms	24 K	60 per s (60 fps)	None	1

1

2 **Factory Usage scenarios**

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

- 5 - Metal processing site
- 6 - Mechanical assembly site
- 7 - Elevated and high temperature work site
- 8 - Logistics warehouse site

9 Below, we describe example factory usage scenarios and their collective applications used.

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

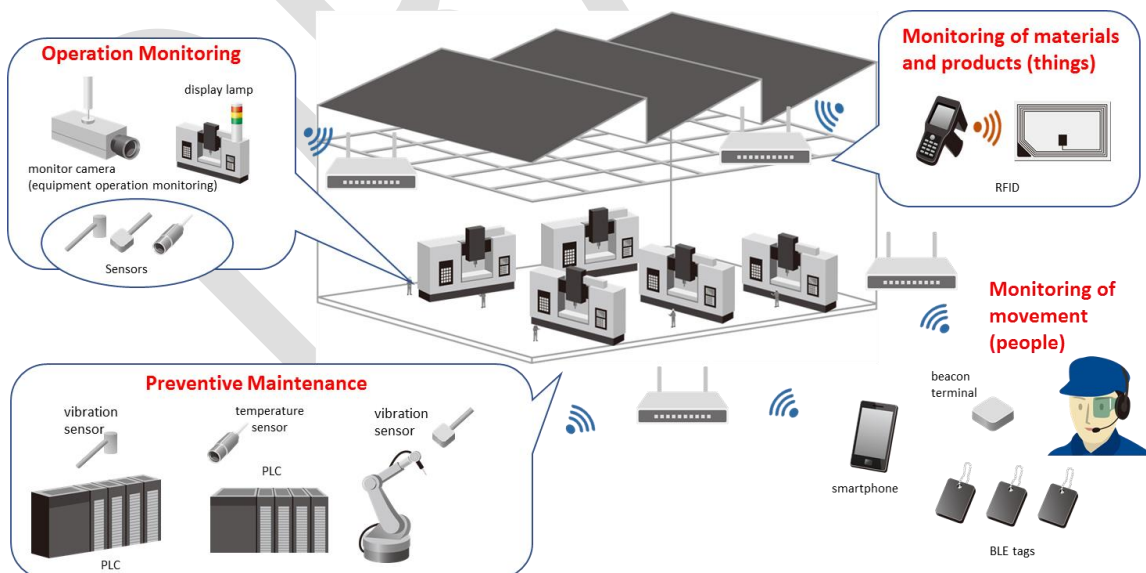
11 An illustration depicting a wireless usage scene at a metal working site is shown in Figure 10. A
12 building has a row of machine tools, and materials and products (things) are managed in a certain
13 area of the building. Workers are at locations within the building as needed to operate the
14 machines. In the case of operation monitoring and preventive maintenance, sensors may be
15 attached to machines. As machine tools may be used for twenty to thirty years, there may be
16 many old machines, with sensors attached after installation. Communication is necessary to
17 collect information from sensors, but if ceilings are high, installing wiring requires high site work,
18 making the cost of wiring expensive. The cost and long work times required by rewiring work
19 when machines are relocated make wireless communication desirable. In the case of
20 management of objects and analysis of worker movement, the subjects move, so the use of
21 wireless communication is a necessity.

22 In the case of operation monitoring, monitor cameras and sensors are installed on machines to
23 monitor the operation status of the machines. For wireless operation, wired LAN to wireless LAN
24 media converters are installed on wired LAN ports. On machines without wired LAN ports,
25 adaptors may be connected for wireless networking. A wireless network is formed between the
26 machines and a wireless access point, and when an intermittently operated machine is switched
27 on, a link with a wireless access point is established automatically without human intervention.
28 As the wireless interference conditions change with the ON/OFF of wireless devices operating in
29 coordination with the intermittent operation start and stop of nearby machines, it is necessary
30 for the wireless network to have flexibility, such as monitoring the radio environment and
31 switching the used frequency channel. Using this network, time series data such as vibration and
32 torque waveforms acquired by tools and sensors inside machines during operation are sent to a
33 server. Using the acquired data on the server, analysis software detects anomalies or anomaly

1 precursors, and informs a manager. According to requirements such as the number of devices,
2 transmitted data volume, and necessity of real time response, the data is transmitted by an
3 appropriate wireless network such as wireless LAN, Bluetooth, or Zigbee.

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

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



26
27 **Figure 10 Usage scene: Metal working site**
28

1 **Usage scenarios example: Mechanical assembly site**

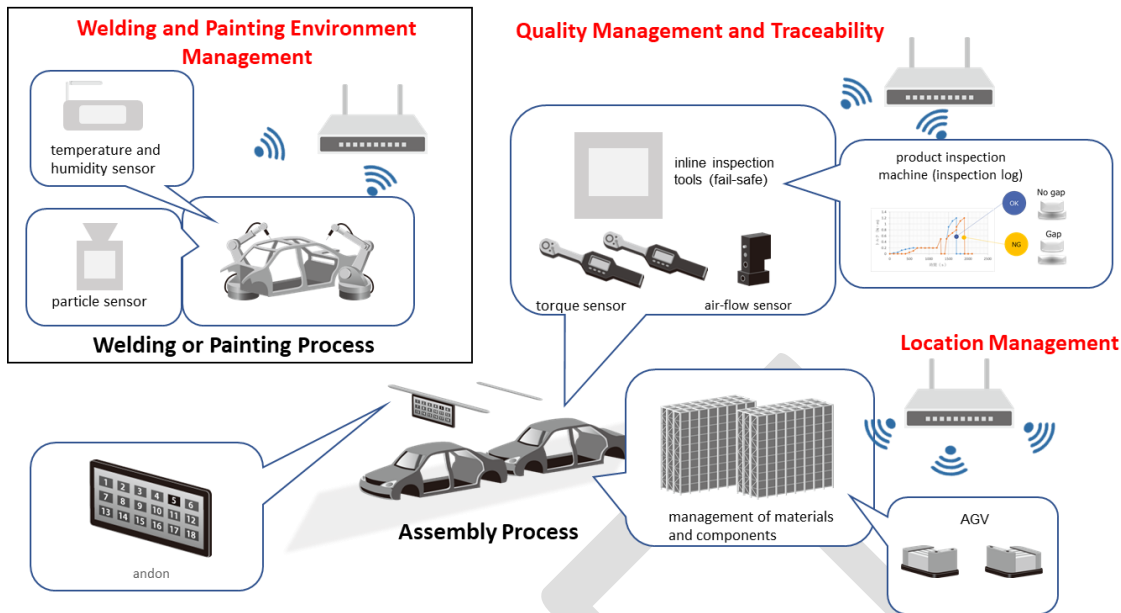
2 A wireless usage scene at a mechanical assembly site is shown in Figure 11 as an example in
3 automotive plant. In a mechanical assembly plant, the benefit of wireless communications is
4 expected where there is management of building systems for collection and analysis of data for
5 quality management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

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

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

21 In the case of AGV with autonomous driving ability, the AGV itself will be able to control its current
22 position and path. Each AGV will be sent a command “go from position A to position B” from a
23 parent device (fixed device) and the AGV will move accordingly. As an AGV may move over a wide
24 area in a factory, it is possible that in some locations the quality of wireless communication will
25 degrade due to physical obstruction by facilities and manufacturing machine tools. Hence, it is
26 necessary to consider the radio propagation environment when deciding where to place wireless
27 access points and to consider the use of multi-hop networks. The number of mobile vehicles used
28 in factories is continuing to increase, and the related issues of the radio environment will require
29 more consideration in the future.

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



1

2

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

3

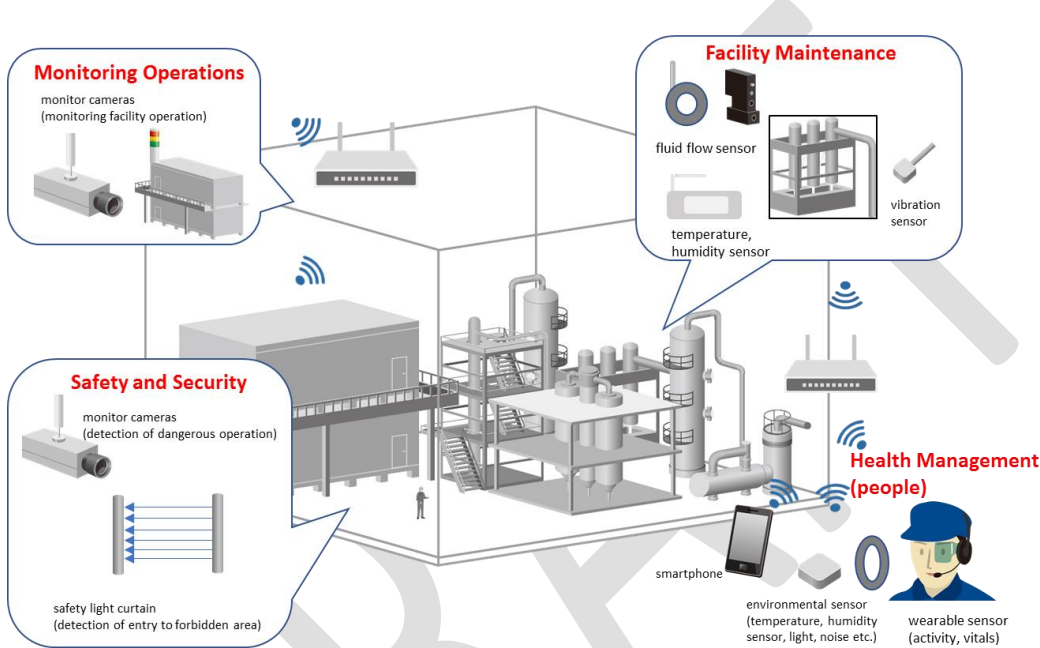
4 Usage scenarios example: Elevated and high temperature work site

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

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

27 The communication terminals in a production site may form a wireless multi-hop network, and
 28 upload sensor data to a cloud service or server (where the data is finally collected) via a gateway.

1 The uploaded data is used to monitor the worker's status. For example, in the case of a system
 2 with a path from a sensor attached to a worker via a gateway to a server, wireless communication
 3 from the sensor to the gateway might use 920 MHz band communication, wireless LAN, or
 4 Bluetooth. Communication from gateway to server will require connection via 3G/LTE or wired
 5 LAN. When the server is far from the gateway, and it is necessary to have a wireless connection
 6 (such as when wiring is not possible) a wireless mesh using wireless LAN, or a point-to-point 60
 7 GHz frequency band system may be used as a backbone. In this case, interference between the
 8 wireless backbone and the communication between sensors and gateway must be considered.



9
 10 **Figure 12 Usage scene example: Elevated and high temperature work site**
 11

12 **Usage scenarios example: Logistics warehouse site**

13 In a logistics warehouse⁶, as shown in Figure 13, three-dimensional automatic storage⁷ is used to
 14 increase spatial use efficiency. Operation of a three-dimensional automatic storage system
 15 requires monitoring of storage operation, preventive maintenance of the stacking system,
 16 management of automated guided vehicle (AGV) movement, and so on. A large scale warehouse
 17 has multiple storage racks placed in a rows, each of over 30 m height and 100 m length, and
 18 separated by a few meters or less.

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

⁶ A warehouse in which items are stored and managed in racks, and moved in and out automatically with computer control.

⁷ Equipment for transporting in and out of a three-dimensional automatic storage system.

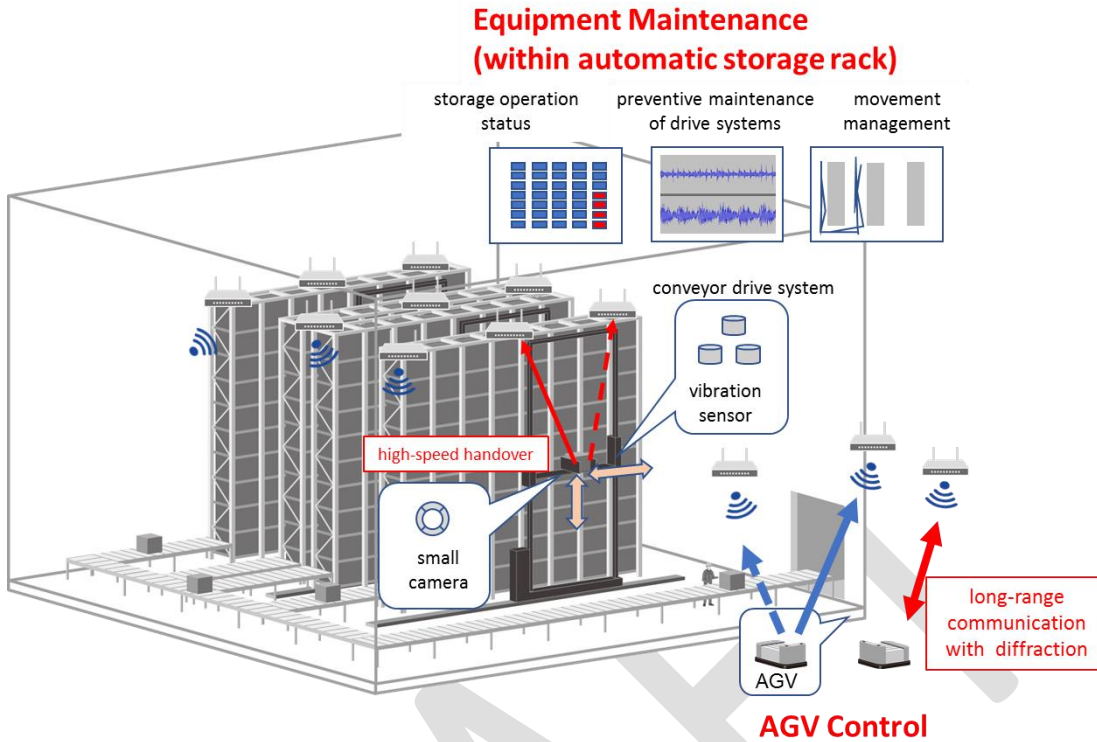
1 When the inspection and repair operation is in a high place, there is greater danger for the worker
2 and operation delay time increases. Previously, workers had to spend time checking the storage
3 even when there was actually no need to stop. Now cameras are used to remotely check the
4 situation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

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

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

24 In some cases, in order to increase the flexibility of the layout in the warehouse, the luggage
25 carried out by a stacker-crane is transported to another storage or work place by a forklift or AGV.
26 The magnetic tape that is used taped on the floor to guide the motion of a trackless AGV cannot
27 carry data, so control information such as destination is sent by wireless communication. Also,
28 forklifts and AGVs have devices for detecting their location, and location information is relayed
29 by wireless communication. Location information collected from forklifts and AGVs is used to
30 manage their operation, and methods are being developed to improve transport efficiency by
31 coordinating their motion with stacker-cranes, allowing the selection of the AGV with the shortest
32 travel distance, for example.

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



1

2

Figure 13 Usage scene example: Logistics warehouse site

3

Technological Enhancement of Networking for Flexible Factory IoT

4

Coexisting of wide variety of factory applications with different requirements

5

According to Figure 9 and Tables 2~14 in Section “Wireless Applications and Communication

6

Requirements”, examples of QoS tolerances in factory applications are summarized in Table 15.

7

Table 15 shows that tolerance of latency is classified into small, medium or large, tolerance of

8

bandwidth is classified into wide, medium or narrow, and tolerance of packet loss is classified into

9

loss intolerant or loss-tolerant. It means that factory applications may require a large number of

10

QoS classes more than the 8 classes specified in IEEE Std 802.1Q. To deal with a large number of

11

QoS class requirements, defining usage of tag fields may be needed for precise and fine QoS

12

control on L2.

13

In addition, there would be requirement to map priority from the 802.1 domain to the specific

14

media (e.g. wireless link) and achieve the required performance.

15

Table 15 Examples of QoS Tolerances in Factory Applications

Category of Wireless Applications	QoS Tolerances							
	Latency (ms)			Bandwidth (kbit/s)			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		✓	✓	✓			✓	✓

1

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

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

4

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

Working Group	Standard and Project	Title
802.1	IEEE Std 802.1Q-2018 Clause 35	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
	IEEE Std 802.1Q-2018 Clause 36	Priority-based Flow Control
	IEEE Std 802.1CF-2019	IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802(R) Access Network
	IEC/IEEE 60802	TSN Profile for Industrial Automation
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

6

7 TSN defines standard L2 technology to provide deterministic capability on 802.1Q bridged
8 networks. It guarantees end-to-end QoS for the real-time applications with bounded latency,
9 minimized jitter, and high reliability. Industries like automotive, industrial and professional audio
10 comprised by multiple network devices will benefit from deterministic connectivity and
11 optimization over Ethernet wires.

12 Future industrial wireless communications will take advantage of this infrastructure. The
13 wired/wireless integrated networks for future flexible factories IoT scenarios should be able to

1 accommodate various applications with different end-to-end QoS requirements. These
2 requirements can be guaranteed by closing the gaps within the following functions:

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

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

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

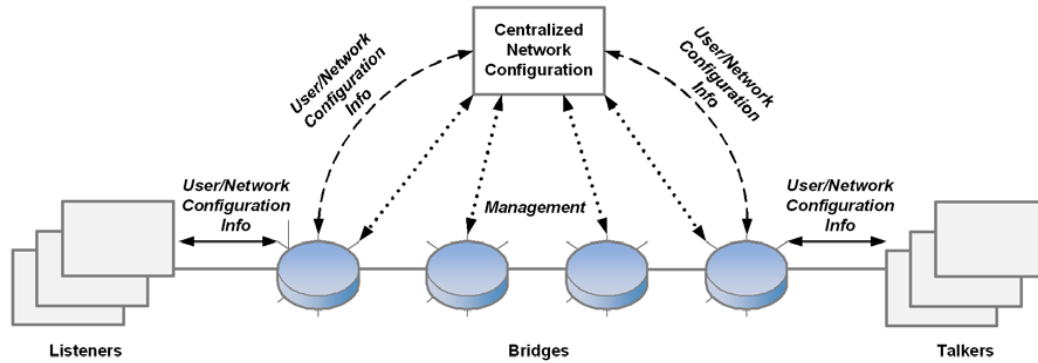
9 Streams are used to describe the data communication between end stations with strict time
10 requirements. In 2010, the 'Audio/Video Bridging (predecessor of TSN) Task Group' standardized
11 the Stream Reservation Protocol (SRP) as IEEE Std 802.1Q-2018 Clause 35, which was then
12 incorporated in the mainline 802.1Q standard.

13 The protocol allows end stations to register their willingness to "Talk" or "Listen" to specific
14 streams, and it propagates that information through the network to reserve resources for the
15 streams. Network bridges between the end stations maintain bandwidth reservation records
16 when a Talker and one or more Listeners register their intentions for the same stream over a
17 network path with sufficient bandwidth and other resources. SRP utilizes three signaling protocols
18 from IEEE Std 802.1Q-2018, MMRP (Clause 10.9), MVRP (Clause 11) and MSRP (Clause 35.1), to
19 establish stream reservations across a bridged network.

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

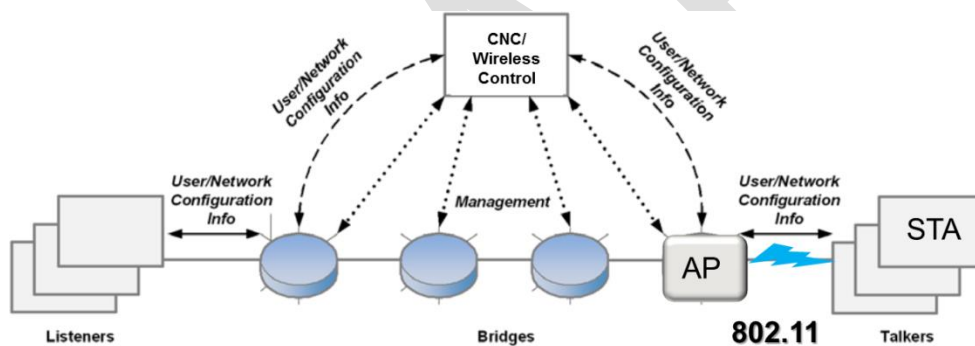
24 It is stated in Annex C.3 of 802.1Q that 'From the bandwidth reservation standpoint an IEEE 802.11
25 BSS network is modeled as a Bridge'. As one of the essential advantages of SRP, it provides a single
26 bandwidth reservation protocol across multiple media types of both wired and wireless.

27 The recent published standard IEEE 802.1Qcc specifies a set of large enhancements to SRP,
28 introducing the concept of centralized configuration model with a centralized network controller
29 (CNC). As shown in Figure 14, CNC is a new system level entity that may be capable of calculating
30 the best possible solution for a set of predefined configuration and configure the bridges to meet
31 those QoS demands conveyed through the User Network Interfaces (UNI). Within UNI, the
32 attributes about traffic specifics and maximum latency are shared with the CNC for proper stream
33 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.”⁸

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 ϵ , FRER would be expected to result in a frame loss rate of ϵ^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) [17]. 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

⁸ 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.

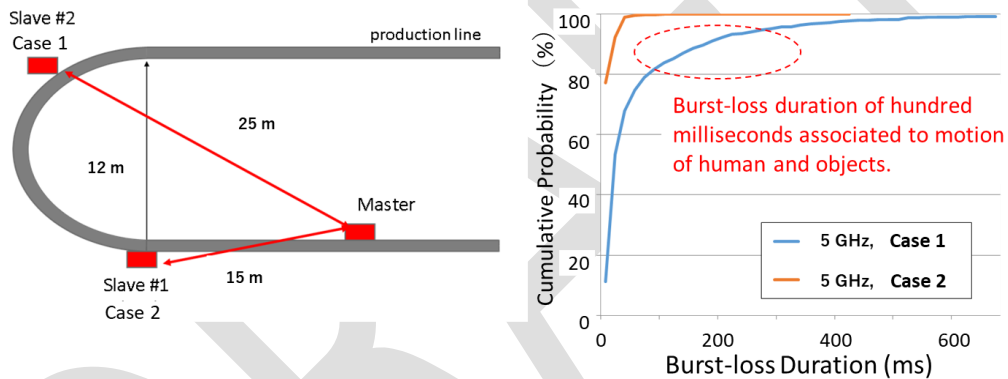
36 Concepts like FRER may find application in contributing to improved reliability and jitter in
37 wireless factory networks. However, some of the challenges discussed will first need to be
38 addressed and resolved.

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 ms to 10 s as shown in Figure 9. The lower boundary may be determined
2 by human reaction time [18]. For example, in an application in which an online inspection occurs,
3 an action by worker is checked by a system as to whether it is good or not. He/she shall receive
4 go/no-go signal from the system indicating to whether to proceed to the next action or not. In the
5 network accommodating factory, applications such as quality supervision, factory resource
6 management, display, and some of equipment control and safety, permissible latencies within
7 100 msec or less for communications between a terminal and a management system of the
8 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.

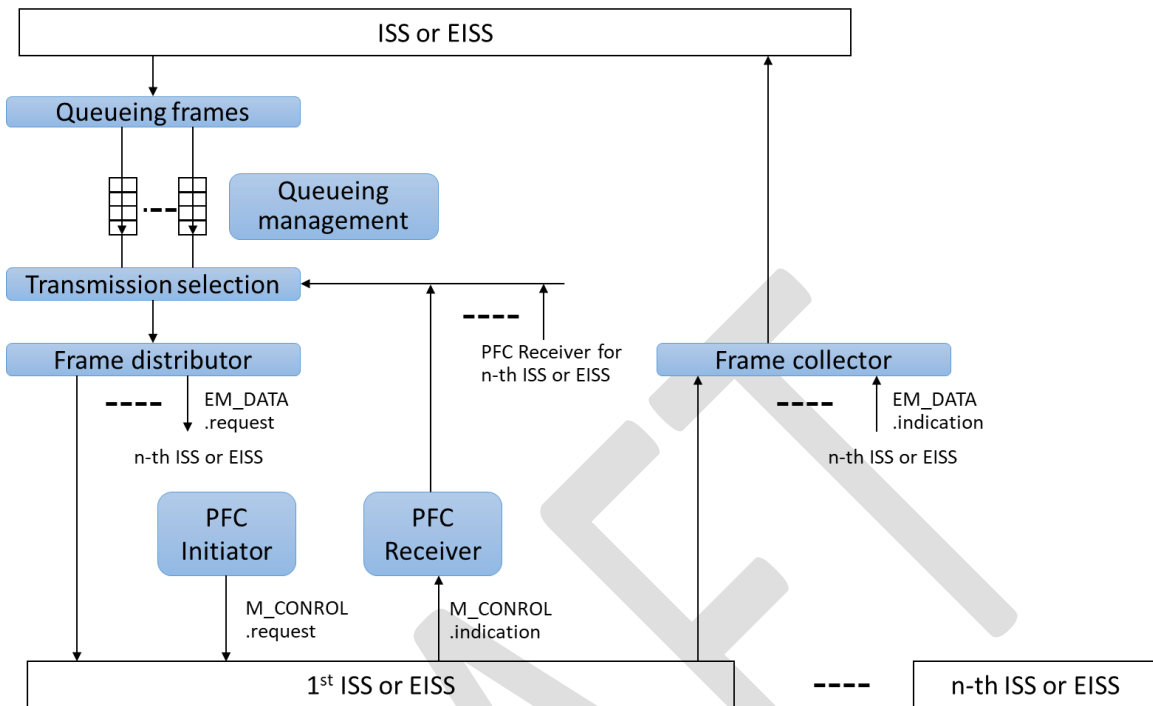


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Figure 16 Burst-loss measurement in a large machine assembly site [19]

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 IEEE Std. 802.1Q-2018, as shown in Figure
24 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 environment⁹. 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 [7]). 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.

⁹ Section 36.1.1 in IEEE 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 (IEEE Std.802.1Q-2018) and Functions to be enhanced**

Current PFC (IEEE Std.802.1Q-2018)	Functions to be enhanced
8(max) links can be independently paused and restarted by queue control. Only no loss is acceptable for data center environment.	Not only “pause” but also “discard” are acceptable if QoS requirements of factory applications permit it.
There is no specific description about “frame distributor”	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 a factory application for data rate reductions to determine if this reduction is acceptable to the application.

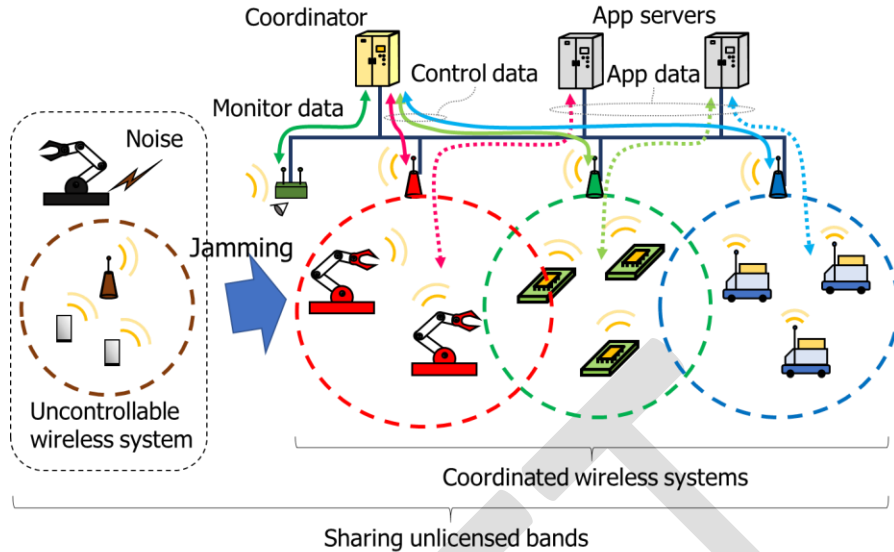
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5 The issue here is to adapt to rapid changes in wireless environments while ensuring a variety of
 6 QoS requirements across the end-to-end connection of the whole network. The rapid flow control
 7 at the bridge based on information of data attributes 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 that 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.



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Figure 18 Overview of coordinated wireless systems

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

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

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Future directions towards enhancements for Flexible Factory network

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End to end network control and coordination

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

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

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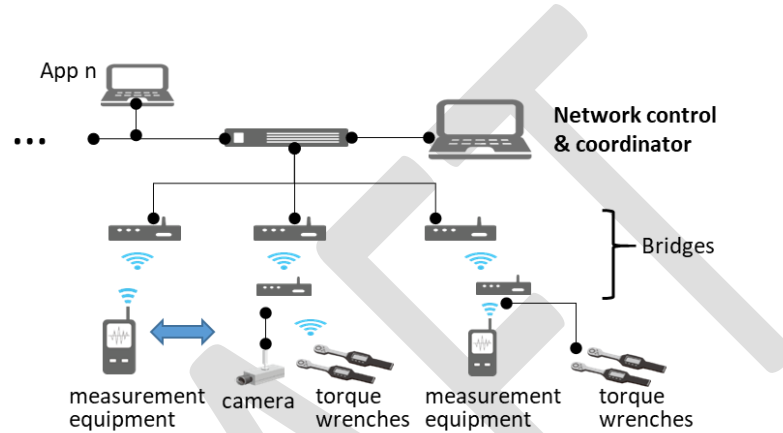
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- 1 1. Control of data flows across wireless links.
- 2 2. Joint coordination of frequency channel and forwarding paths.
- 3 3. Spatial control for wireless links, i.e. power and antenna directivity.

4

5 Coordination is achieved by a coordinator managing the factory network. As illustrated in Figure
 6 19, the Bridge/AP of each sub-network is deployed for various applications. L2 data frames need
 7 to communicate between individual devices or towards the application server. The control policy
 8 could be provided by the coordinator for each sub-network for the ease of implementation, in
 9 cases where they should be provided on individual device basis by an application specific policy
 10 template.



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Figure 19 typical network scenario for flexible factory IoT

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

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

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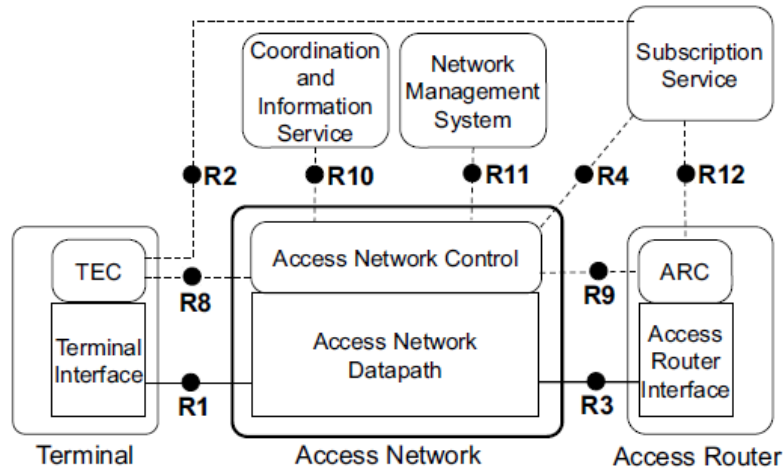
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To realize the hierarchical control, more information needs to be concentrated on the centralized controller enabling an autonomous operate in quick response. For this purpose, the following three items need to be considered for standardization.

- 1 A) Control policy: messages and interfaces between a coordinator and various systems.
- 2 B) Information on wireless environment: link/path quality.
- 3 C) Data attributes: common information including various requirements, e.g. data rates (or
- 4 data size at an application level and data frequency), latency, affordability of packet loss.
- 5 The information is helpful for transportation of various traffics by better control of flows
- 6 when mapping to traffic classes, scheduling and forwarding.

7 **An unified network reference model**

8 Network reference model (NRM) for flexible factory IoT network is a generic representation which
 9 includes multiple network interfaces, multiple network access technologies, and multiple
 10 applications. The NRM defined in IEEE P802.1CF [20] is appropriate for this purpose and can be
 11 used to generalize the concept of centralized configuration paradigm and to explain how data
 12 attributes are managed as informative description as well. The minimum enhancement could be
 13 achieved by creating a factory profile consisting of the reference model and data attributes. Detail
 14 investigation is required if any protocols shall be added.

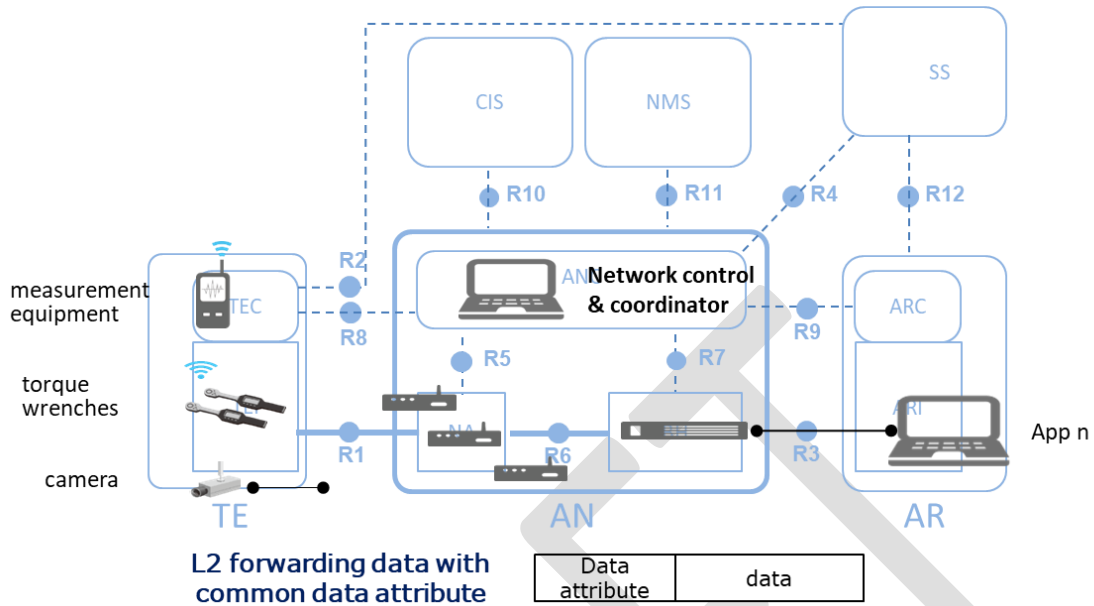


15 **Figure 20 network reference model defined in IEEE P802.1CF**

17 The aforementioned network scenarios shown in Figure 20 can be mapped to IEEE Std 802.1CF
 18 NRM as depicted in Figure 21. Bridge/AP represents the node of attachment (NA) providing
 19 wired/wireless access through R1 to the terminals (devices). L2 data frames with common data
 20 attributes are aggregated and forwarded to the second level bridges, represented as backhaul
 21 (BH) through R6 datapath interface. The coordinator is located in the access network control (ANC)
 22 providing control policy to the underlay bridges and APs through R5 and R6 control interfaces¹⁰.

¹⁰ Refer to Clause 5 of the IEEE Std 802.1CF [20] for detailed information of network reference model (NRM).

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Figure 21 mapping factory network to 802.1CF NRM

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The centralized coordinator fits well in the role of ANC provides enhancements to IEEE 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 seamlessly 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" [12] 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

1 Communication in factories has until now been mainly wired communication. There are increasing
2 expectations for the use of wireless connectivity amongst machines in the manufacturing and
3 factory processes. Future industrial factory networks are expected to use more wireless to reduce
4 the installation cost as well as to enhance flexibility. As such, the factory network needs to support
5 the successful operation of various wireless applications.

6 This report addresses integrated wired and wireless Internet of Things (IoT) communications in
7 the factory environment, and includes use cases and requirements with a focus on bridged Layer
8 2 networks. It presents problems and challenges observed within the factory and reports on
9 possible solutions for overcoming some of these issues in order to enable flexibility within
10 factories.

11 One distinct aspect of factory networks is that the physical devices connecting to the network are
12 used to control and monitor real-world actions and conditions. This requires the provisioning of
13 QoS for a variety of traffic types that may be characterised as either periodic or sporadic. In a
14 flexible factory, humans are engaged in the control and monitoring system and therefore need to
15 be interconnected with the network in order to interact with physical devices and machinery.

16 When the factory network is extended over radio, some incompatibility in QoS provisioning
17 between wired and wireless segments becomes apparent due to unpredictable variations in the
18 available bandwidth over the radio segment. In order to overcome the variable environment for
19 wireless communications, coordination amongst network elements is required.

20 The report considers communication requirements for six categories of wireless applications,
21 which are classified according to their purpose.

22 For factory applications, QoS latency tolerance is classified into small, medium or large. Bandwidth
23 tolerance is classified into wide, medium or narrow, and the tolerance for packet loss is classified
24 into loss intolerant or loss-tolerant. This implies that factory applications may require a large
25 number of QoS classes, more than the 8 classes specified in IEEE Std 802.1Q. To deal with a large
26 number of QoS class requirements, defining usage of tag fields may be needed for precise and
27 fine QoS control over L2. Any priority tag must be understood in both wired and wireless
28 networks, which may require tag translation amongst the two.

29 Future industrial wireless communications will take advantage of TSN functions and features
30 specified in IEEE 802.1. The wired/wireless integrated networks for future flexible factories IoT
31 scenarios should be able to accommodate various applications with different end-to-end QoS
32 requirements. These requirements can be met by closing the gaps within the following
33 functions:

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

38 Coordination mechanism is required in order to ensure end-to-end QoS provisioning over the
39 entire factory network. The following control functions over the wired/wireless network are
40 anticipated for coordination purpose.

- 1 4. Control of data flows across wireless links.
- 2 5. Joint coordination of frequency channel and forwarding paths.
- 3 6. Spatial control for wireless links, i.e. power and antenna directivity.

4

5 For the purpose of reliability, queueing and forwarding, mechanisms for redundancy need make
6 use of data attributes over the network. The coordinator can set policies for transmission of
7 application data in a way that tolerates the degradation in the network due to the bandwidth
8 changes that can occurs over the wireless links.

9 Hierarchical control system consists of centralized coordinator and distributed coordination agent
10 on each individual Bridge/AP. For the purpose of satisfying requirements of each factory
11 applications, the following considerations need to be standardized.

- 12 a) Control policy: messages and interfaces between a coordinator and various systems.
- 13 b) Information on wireless environment: link/path quality.
- 14 c) Data attributes: common information including various requirements, e.g. data rates
15 (or data size at an application level and data frequency), latency, affordability of
16 packet loss.

17 When wireless is used in factory networks and systems, some TSN features may be required to
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19 challenges that need further consideration, such as the impact on latency and reliability of the
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23 deployment.

24

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