Evaluating EtherNet/IP and CIP Safety Communication over 5G

Shinji Kobayashi, Hiroaki Yamada
Technology Development Division HQ.
Industrial Automation Company
OMRON Corporation

Presented at the ODVA
2023 Industry Conference & 22nd Annual Meeting
October 18, 2023
El Vendrell, Spain

Abstract

5G wirelessization is being considered for use in industrial networks in factories. While the communication performance requirements for various use cases in factories have been identified, there is limited information available regarding the specific evaluation of communication performance achieved through 5G wireless transmission in factory settings.

In this study, we evaluate the communication performance of EtherNet/IP controller-to-controller communication using Sub6 of 5G SA in the 4.8GHz band. We measure packet loss and latency during 5G transmission of EtherNet/IP communication. The communication evaluation is conducted using Implicit communication between Controller 1 node and N nodes (N: 1 to 7). Implicit communication employs both multicast and unicast communication methods, with RPI intervals ranging from 1 to 200 milliseconds.

Furthermore, we conduct measurements of safety reaction time and stability evaluation over a period of 24 hours by transmitting CIP-Safety over 5G for robot cells, serving as a specific use case.
Through these evaluations, we clarify the expected communication performance in 5G factory use cases.

Keywords

5G Sub6, EtherNet/IP, CIP Safety

Definition of terms

BBU:	Baseband Unit
BS:	Base station; a device that provides wireless communication services in Private 5G
DL:	Downlink; transmission of data from a the 5G base station to a user device
EPI:	Expected Packet Interval
iperf	Command-line tool used to measure network performance by establishing a client-server connection and testing throughput, latency, and packet loss.
NDAC:	NOKIA Digital Automation Cloud
RPI:	Requested Packet Interval
RRH:	Remote Radio Head
SA:	Stand-Alone; a network architecture in Private 5G
Safety Reaction Time:	The time required for the system to enter a safe state in a worst-case scenario after the occurrence of a safety-related input (press of an emergency stop pushbutton switch, interruption of a light curtain, opening of a safety door, etc.) or device failure.

Sub6: Sub-6 GHz; a frequency band
TDD: Time Division Duplex; a type of communication method used in wireless communication
UL: Uplink; transmission of data from a user device to the 5G base station
VPN: Virtual Private Network

Introduction

In factories, there is a shift from the previous dominant wireless technology, Wi-Fi, to Private 5G. Consequently, there is a consideration on the wirelessization of industrial networks that have traditionally relied on wired connections. 5G offers features such as high-speed and large capacity, low latency, and massive connectivity. However, these features are not all maximized at the same time. Depending on the actual operating environment and use case, some features may be prioritized over others. Additionally, it should be noted that not all wired networks in factories will be replaced by wireless networks through 5G adoption, as the feasibility depends on some specific applications.

The acceptable latency for communication required in various applications is illustrated by NICT (National Institute of Information and Communications Technology) in Figure 1.Except mission-critical applications for some control and safety use, many applications require an acceptable latency ranging from 10 milliseconds to 10 seconds.

At Omron, based on the communication capabilities of 5G Sub6, we have determined and set a target range of 10 milliseconds or more for the wirelessization of industrial networks, transitioning from wired cables to 5G.

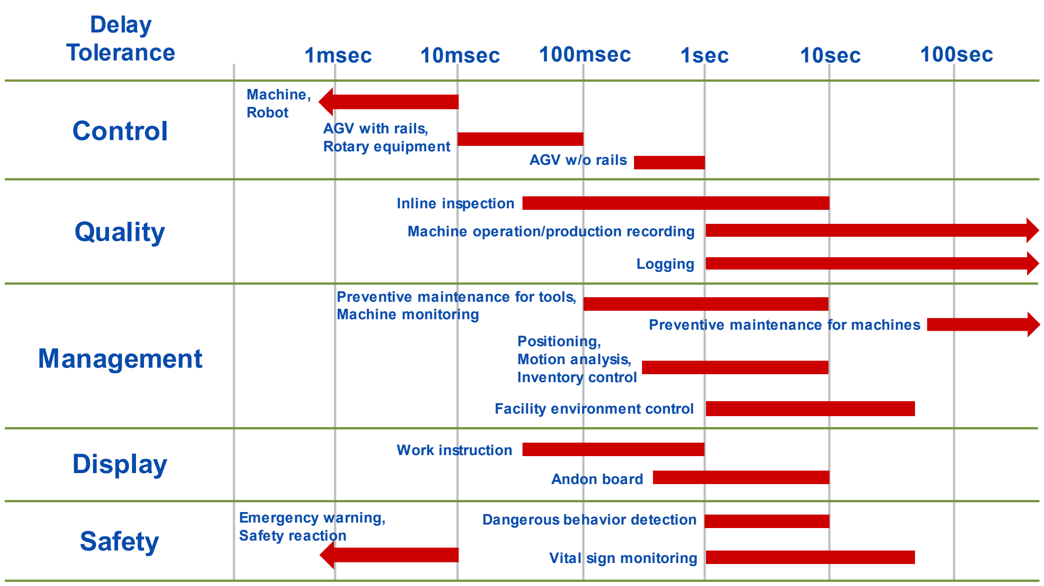

Figure 1: Permissible Latencies of Representative Wireless Use Cases [1]

Although the requirements for wirelessization in various use cases in factories have been identified, there is limited information available regarding the actual communication performance achieved when transmitting industrial networks over 5G.

Additionally, according to the Voice of the Customer (VOC), there is an issue where the wired network between production equipment hinders the flexible placement of production equipment during the configuration of production lines or layout changes.

Therefore, with the aim of validating the 5G wirelessization of Ethernet/IP for each controller that manages the production equipment, we conducted a performance evaluation of EtherNet/IP over 5G transmission as a use case for controller-to-controller communication.

In 5G, we utilized BS in the 4.8GHz band for SA mode. To evaluate communication performance for controller-to-controller communication, we used EtherNet/IP's Implicit communication, varied the RPI (cyclic period), and measured communication latency and packet loss of the communication packets. We evaluated both Multicast and Unicast communication methods, which are commonly used in EtherNet/IP communication. These evaluations have revealed the expected level of communication performance when transmitting EtherNet/IP over 5G in Factory Automation (FA) applications.

In addition, we performed a specific use case evaluation of CIP Safety over 5G transmission for FA applications. In this case, we assumed a robot cell line that integrates three robot cells with a single safety line controller. Firstly, we measured the basic characteristics of CIP Safety packet transmission over 5G, including its latency and packet loss.

Next, to verify whether the system's safety functions adequately perform their roles when transmitting CIP Safety over 5G, we measured the Safety Reaction Time. The Safety Reaction Time was measured by transmitting safety process communication of CIP Safety over 5G, pressing the emergency stop button in the robot cell, and measuring the time until the power was cut off.

The latency, the packet loss, and the Safety Reaction Time measurements were conducted for both 5G transmission and wired LAN, and the results were compared.

Finally, we kept the three robot cell safety controllers and the safety line controller powered on for 24 hours to verify the presence of safety communication errors caused by communication interruptions or communication delays. This allowed us to validate the stability of the line under CIP Safety 's 5G transmission.

Based on the above, the current performance of the FA application that transmits CIP Safety over 5G has been clarified.

System Configuration for Evaluation of EtherNet/IP over 5G Transmission

The system configuration which EtherNet/IP packets with Multicast are transmitted over 5G between controllers, and the packet loss and communication delay of the transmitted packets are measured is shown in Figure 2.

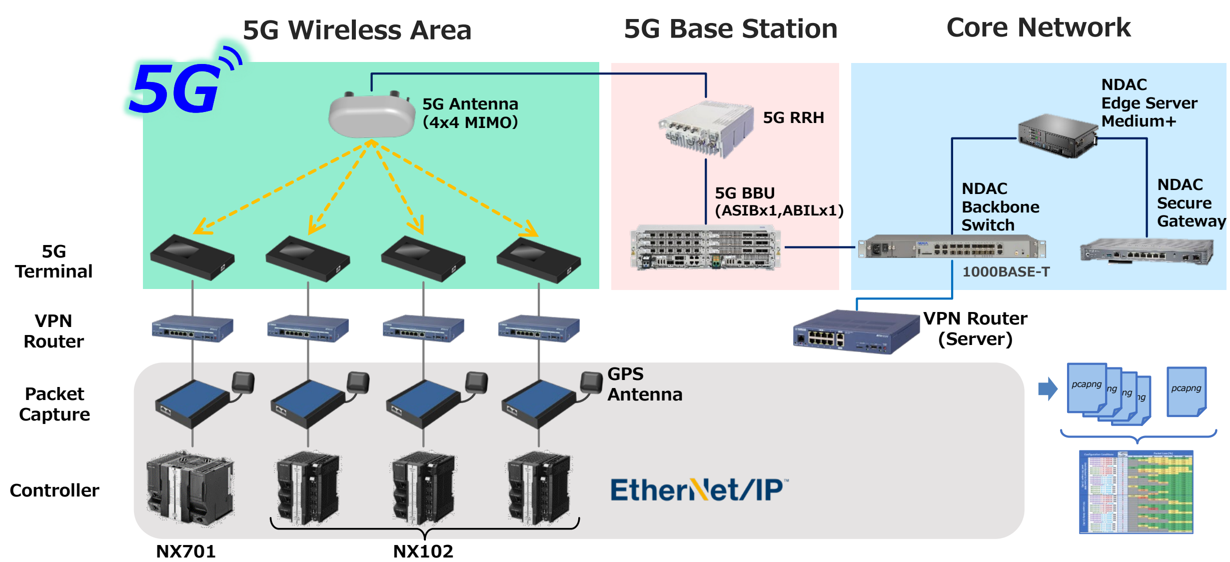

Figure 2: System Configuration for EtherNet/IP over 5G Transmission between Controllers

The system consists of the following components:

- **Core Network:** Consisting of the NDAC Edge server, NDAC Switch, and NDAC Secure Gateway (Nokia), to control the 5G system.
- **5G Base Station:** Comprising a BBU and RRH, the 5G Base Station connects to omnidirectional antennas (4x4 MIMO) in the 5G Wireless Area. It converts digital communication frames from the network system into 5G wireless signals. The 5G signal operates in the 4.8GHz band (n79) with a signal bandwidth of 100 MHz. The TDD frame structure follows the synchronization method of Japan's communication carrier band, with a transmission ratio of 3.25:1 for DL and UL.
- **5G Wireless Area:** This area is established by the arrangement of omnidirectional antennas (4x4 MIMO) and 5G devices, forming a wireless space. In the evaluation environment, SHARP's local 5G devices were used, which achieved a DL throughput of 784Mbps (4x4 MIMO) and an UL throughput of 51Mbps (SISO).
- **EtherNet/IP Network:** For the measurement purposes, we used one controller NX701 (Omron) and N (1 to 7) controllers NX102 (Omron). The controllers were connected to the 5G devices via Packet Capture (Profitap: Profishark1G+) and a VPN router (YAMAHA: RX830). The Packet Capture device is equipped with a GPS antenna, enabling time synchronization between packet captures using GPS clock synchronization. By comparing the timestamps of the captured packets from each capture device, it is possible to accurately measure the communication latency between the packet captures. The VPN tunneling communication is used to ensure that multicast communication frames reach all 5G devices by virtually constructing an L2 network. Since the network system, including the 5G base station, operates primarily on L3 communication, EtherNet/IP's multicast communication, which is L2 communication, cannot be directly transmitted to other layers. Therefore, we encapsulated EtherNet/IP packets using L2TPv3 tunneling with the VPN router, and performed tunneling communication between the VPN client and VPN server. The VPN server (YAMAHA: RX1220) was connected to the switch in the Core Network.

In this configuration, Multicast packets from the NX701 connected to the 5G devices are transmitted through the Edge Server in the Core Network to the VPN server. There, the packets are replicated and routed back through the Edge Server to the VPN clients under the N 5G devices in the 5G Wireless Area. Finally, the packets are forwarded to the NX102 controllers.

5G Wireless Configuration

The wireless configuration used for this evaluation utilizes the 4.8GHz band with a signal bandwidth of 100MHz and follows the carrier band synchronization method used in Japan, as shown in Figure 3(a). The DL to UL ratio is 3.25:1, indicating a configuration which DL has a higher priority than UL. At the time of conducting this evaluation, this synchronization method was the only one available in Japan, and therefore, it was adopted for the evaluation. The introduction of the semi-synchronous method, as depicted in Figure 3(b), which provides a DL to UL communication performance ratio of 1.25:1, began after December 2022 and has been spreading in Japan.

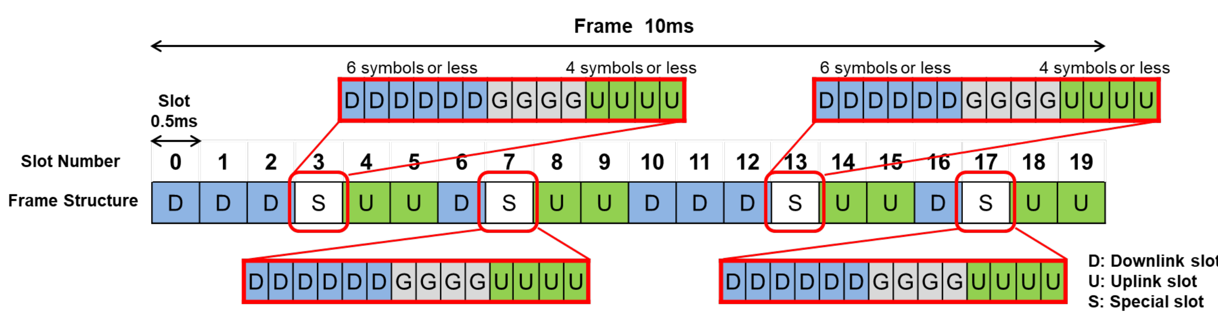

Figure 3(a): Synchronization pattern in Japan employed in the experiment

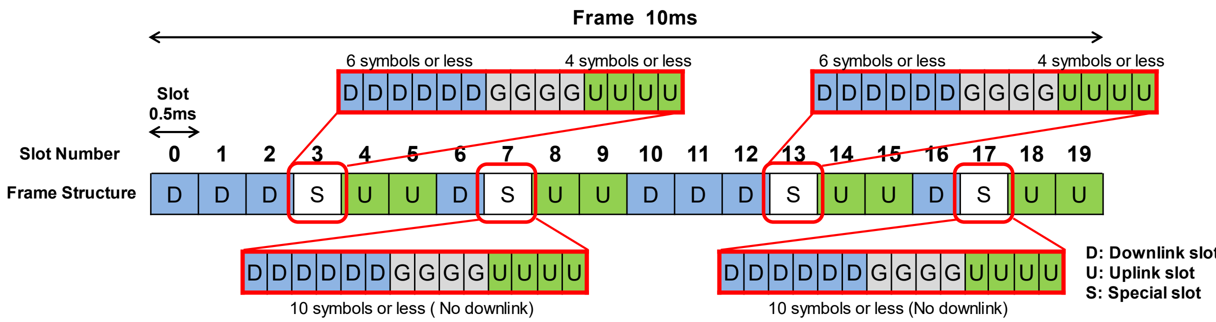

Figure 3(b): Semi-synchronization pattern in Japan

Figure 3: 5G NR TDD configuration [2]

The throughput evaluation results of the 5G device (SHARP: Local5G Router01) used in this evaluation, conducted through iperf in the 5G experimental environment, are shown in Figure 4. A DL throughput of 784Mbps (4x4 MIMO) and an UL throughput of 51Mbps (SISO) were achieved.

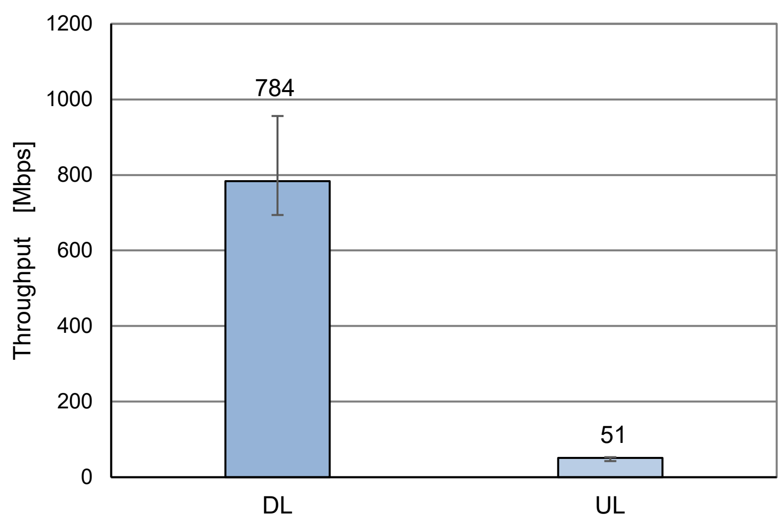

Figure 4: Results of throughput evaluation test using iperf on 5G terminal

Measurement Configurations and Conditions for EtherNet/IP over 5G Transmission

The variations in measurement configurations (Type I to VIII) are shown in Figure 5.

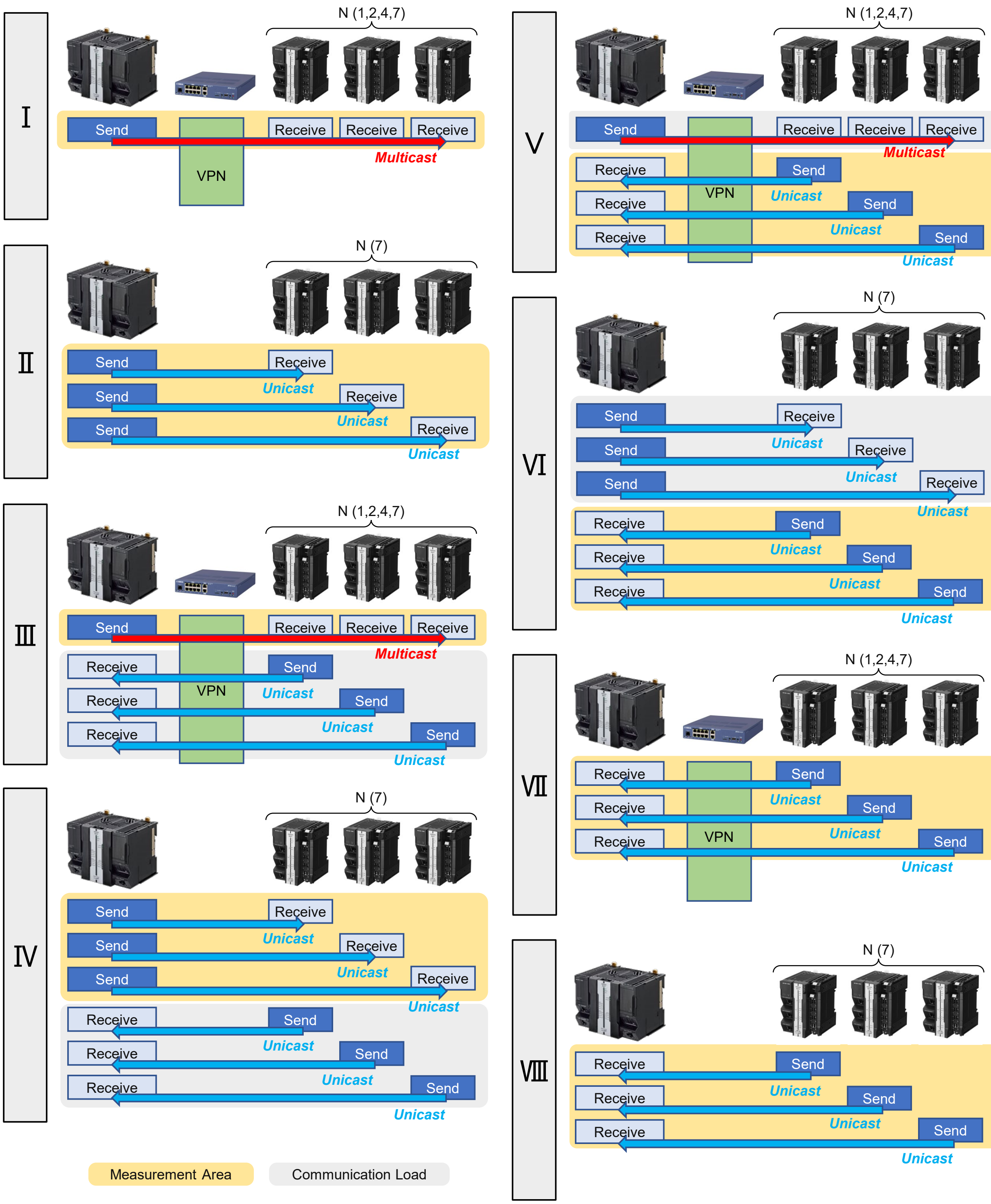

Figure 5: Variation of Measurement Configuration for EtherNet/IP over 5G Transmission Evaluation between Controllers

The performance measurement conditions are as follows:

- **Measurement Parameters:** Packet loss and latency were measured.
- **Communication Modes:** Measurements were conducted with "w/VPN" and "w/o VPN" configurations. In particular, "w/VPN" was mandatory for multicast while "w/VPN" and "w/o VPN" were set for unicast.
- **Number of NX102 Nodes (N):** Measurements were conducted with 1, 2, 4, and 7 NX102 nodes.
- **RPI (Controller-to-Controller Implicit Communication Period):** RPI values were set at 1, 5, 10, 20, 50, 100, and 200 ms.
- **Number of Connections:** Each NX102 node had 32 connections, with a maximum of 224 connections for NX701 (N nodes × 32). In conditions where the RPI period is short, the maximum achievable number of connections for each RPI condition was set. Based on the specification constraints of NX102, the maximum resource of 32 connections was varied across two test configurations. In Fig.5, when there is no communication load, all 32 connections were used for measuring the communication. When there is a communication load, 16 connections were used for measuring the communication, and the remaining 16 connections were used for the opposite direction communication load. The reason for using the maximum resources is to maximize the load.
- **Data Size:** The Implicit communication from the controller had a uniform data size of 600 bytes.
- **Number of Measurements:** Each condition combination was measured three times, with a duration of 3 minutes per measurement.

Table 1: Required Communication Bandwidth for Uplink (UL) under Packet Loss and Latency Measurement Conditions

Type	Measurement Conditions	Additional Load Conditions	# Nodes \ RPI [ms]	UL required communication bandwidth [Mbps] 1	5	10	20	50	100	200
I	1->N Multi.	-, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	57.7	37.8	19.2	10.1	4.6	2.7	1.4
			4	46.4	39.0	19.8	10.6	5.2	3.3	1.7
			7	23.4	28.1	20.7	11.5	6.0	4.2	2.1
II	1->N Uni.	-,-	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
III	1->N Multi.	N->1 Uni., VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	86.3	56.2	28.5	14.8	6.5	3.8	1.9
			4	115.2	94.0	47.8	24.8	11.1	6.5	3.3
			7	92.2	103.7	76.6	39.9	17.9	10.6	5.3
IV	1->N Uni.	N->1 Uni., -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
V	N->1 Uni.	1->N Multi, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	86.3	56.2	28.5	14.8	6.5	3.8	1.9
			4	115.2	94.0	47.8	24.8	11.1	6.5	3.3
			7	92.2	103.7	76.6	39.9	17.9	10.6	5.3
VI	N->1 Uni.	N->1 Uni., -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
VII	N->1 Uni.	-, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	114.9	74.5	37.8	19.5	8.5	4.9	2.4
			4	183.9	149.0	75.7	39.0	17.0	9.7	4.9
			7	160.9	179.3	132.5	68.3	29.8	17.0	8.5
VIII	N->1 Uni.	-, -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2

Table 2: Required Communication Bandwidth for Uplink (DL) under Packet Loss and Latency Measurement Conditions

Type	Measurement Conditions	Additional Load Conditions	# Nodes \ RPI [ms]	DL required communication bandwidth [Mbps] 1	5	10	20	50	100	200
I	1->N Multi.	-, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	114.7	73.9	37.3	18.9	7.9	4.3	2.1
			4	183.4	147.2	73.9	37.3	15.3	79	4.0
			7	160.5	176.8	128.9	64.7	26.3	13.4	6.7
II	1->N Uni.	-,-	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
III	1->N Multi.	N->1 Uni., VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	114.8	74.2	37.6	19.2	8.2	4.6	2.3
			4	183.7	148.1	74.8	38.1	16.1	8.8	4.4
			7	160.7	178.1	130.7	66.5	28.0	15.2	7.6
IV	1->N Uni.	N->1 Uni., -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
V	N->1 Uni.	1->N Multi, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	114.8	74.2	37.6	19.2	8.2	4.6	2.3
			4	183.7	148.1	74.8	38.1	16.1	8.8	4.4
			7	160.7	178.1	130.7	66.5	28.0	15.2	7.6
VI	N->1 Uni.	N->1 Uni., -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2
VII	N->1 Uni.	-, VPN	1	57.5	37.3	18.9	9.8	4.3	2.4	1.2
			2	114.9	74.5	37.8	19.5	8.5	4.9	2.4
			4	183.9	149.0	75.7	39.0	17.0	9.7	4.9
			7	160.9	179.3	132.5	68.3	29.8	17.0	8.5
VIII	N->1 Uni.	-, -	7	149.5	165.7	121.7	62.0	26.2	14.3	7.2

In Table 1, when comparing the required communication bandwidth for multicast communication in Type I and unicast communication in Type VII, it becomes apparent that the required communication bandwidth for multicast communication is reduced, indicating that multicast communication allows for communication traffic reduction.

This is because in multicast communication, after UL transmission, packets are replicated at the VPN server on the core network side, reducing the required bandwidth consumed by UL. Therefore, the utilization of multicast communication can be an effective means to reduce communication overhead in 5G networks with limited bandwidth.

Measurement Results for EtherNet/IP over 5G Transmission Evaluation between Controllers

Table 3 presents the packet loss results obtained from measurements under each condition.

Table 3: Measurement Results of Packet Loss over 5G for EtherNet/IP between Controllers

Type	Measurement Conditions	Additional Load Conditions	RPI [ms] / # Nodes	Packet Loss [%] 1	5	10	20	50	100	200
I	1->N Multi.	-, VPN	1	0.659	0.001	0.000	0.000	0.000	0.000	0.000
			2		10.714	0.000	0.000	0.000	0.000	0.000
			4			5.066	1.494	0.000	0.000	0.000
			7					1.595	0.000	0.000
II	1->N Uni.	-,-	7					0.004	0.004	0.004
III	1->N Multi.	N->1 Uni., VPN	1		0.000	0.000	0.000	0.000	0.000	0.000
			2		4.161	0.000	0.000	0.000	0.000	0.000
			4			13.551	0.000	0.000	0.000	0.000
			7					0.001	0.000	0.000
IV	1->N Uni.	N->1 Uni., -	7					0.005	0.005	0.003
V	N->1 Uni.	1->N Multi, VPN	1		0.000	0.000	0.000	0.000	0.000	0.000
			2		0.062	0.000	0.000	0.000	0.000	0.000
			4			0.109	0.000	0.000	0.000	0.000
			7					0.000	0.000	0.000
VI	N->1 Uni.	N->1 Uni., -	7					0.002	0.002	0.003
VII	N->1 Uni.	-, VPN	1		0.000	0.000	0.000	0.000	0.000	0.000
			2		2.865	0.000	0.000	0.000	0.000	0.000
			4			3.390	0.000	0.000	0.000	0.000
			7					0.000	0.000	0.000
VIII	N->1 Uni.	-, -	7					0.002	0.002	0.002

Table 3 presents the packet loss results obtained from measurements under each condition. The green cells indicate no occurrence of packet loss, while the color transitions to yellow and red as the packet loss increases. The gray cells represent conditions where the connection could not be established, resulting in the inability to conduct measurements.

In Table 3, the conditions that achieved successful communication without packet loss are highlighted within the blue border. Additionally, to examine the impact of packet loss on the UL communication performance limits, the purple borders from Table 1 are transcribed.

Here are the packet loss measurement results for each condition:

- **Type I [1->N Multicast, VPN]:** No packet loss was observed up to RPI 10ms for 1 and 2 nodes, RPI 50ms for 4 nodes, and RPI 100ms for 7 nodes. Communication was successful without any issues.
- **Type III [1->N Multicast & N->Unicast, VPN]:** No packet loss was observed up to RPI 5ms for 1 node, RPI 10ms for 2 nodes, RPI 20ms for 4 nodes, and RPI 100ms for 7 nodes. Comparing with Type I results, it was observed that at 4 nodes, communication was possible without packet loss even with a shorter RPI of 20ms.
- **Type V [N->1 Unicast & 1->Multicast, VPN]:** No packet loss was observed up to RPI 5ms for 1 node, RPI 10ms for 2 nodes, RPI 20ms for 4 nodes, and RPI 50ms for 7 nodes. Communication was successful without any issues.
- **Type VII [N->1 Unicast, VPN]:** Similar results were obtained as in Type V results. Comparing with Type I results, it was observed that at 7 nodes, communication was possible without packet loss even with a shorter RPI of 100ms.
- **Type II, IV, VI, and VIII:** Packet loss was observed in all conditions.

Comparing the results within the blue border and purple border, in Type I: 1->N Multicast VPN configuration, it was observed that under conditions with fewer connected nodes and longer RPI, there was no packet loss, and satisfactory communication was achieved as expected. However, under conditions with a larger number of connected nodes and shorter RPI, packet loss occurred and connections could not be established, resulting in the outcomes deviating from the predictions based on the throughput performance of 5G devices.

In Type V and Type VII: N->1 Unicast VPN configuration, there were several conditions where the blue border and purple border overlapped, indicating favorable communication outcomes. However, in cases like Type V, where there was multicast communication in the opposite direction as the communication load, packet loss occurred as a result of the influence of the multicast communication.

The measurement results for latency (average values) are shown in Table 4.

Table 4: Measurement Results of Latency over 5G for EtherNet/IP between Controllers

Type	Measurement Conditions	Additional Load Conditions	RPI [ms] / # Nodes	Latency [ms]						
				1	5	10	20	50	100	200
I	1->N Multi.	-, VPN	1	419.4	24.2	22.1	22.0	19.9	21.4	20.9
			2		344.2	25.1	22.9	20.9	21.4	20.9
			4			136.1	74.3	25.3	23.2	21.7
			7					86.3	27.5	24.6
II	1->N Uni.	-,-	7					25.4	20.6	18.7
III	1->N Multi.	N->1 Uni., VPN	1		22.2	20.2	19.8	19.6	21.2	20.4
			2		601.8	23.0	22.3	21.1	22.0	21.1
			4			751.5	31.2	25.1	25.2	22.0
			7					31.6	26.0	23.4
IV	1->N Uni.	N->1 Uni., -	7					26.9	22.5	18.4
V	N->1 Uni.	1->N Multi, VPN	1		19.1	18.0	18.8	16.8	19.4	17.9
			2		21.0	19.3	18.0	19.1	17.6	17.9
			4			20.4	20.5	20.0	19.6	18.3
			7					22.2	21.4	20.1
VI	N->1 Uni.	N->1 Uni., -	7					21.5	21.4	19.9
VII	N->1 Uni.	-, VPN	1		20.7	19.6	18.6	17.7	18.6	18.6
			2		731.9	18.9	17.6	18.3	18.5	16.9
			4			1474.5	20.0	19.1	19.6	18.6
			7					21.8	19.9	19.5
VIII	N->1 Uni.	-, -	7					21.9	21.2	19.2

The latency measurement results indicate the conditions where packet loss did not occur, representing successful communication in this experiment (transcribing the blue border from the Packet Loss in Table 4 and the purple border from the UL communication performance limit in Table 1). The latency measurement results show that the green cells have low latency, while the latency increases as the cells become yellow or red.

Here are the latency measurement results for each condition:

- **Type I, III [1->N, Multicast, VPN]:** In the range of successful communication indicated by the blue border, latency values between 19.6ms and 31.2ms were obtained. For example, with Type I at 10ms, while maintaining an RPI of 10ms, an additional latency of 22.1ms will be added before the data arrives. One condition (Type I: 1->N Multicast, VPN, 4 nodes, RPI 20ms) did not yield the expected results, and packet analysis was conducted. The analysis revealed that there were duplicate packets not being output from the VPN server for the input packets, indicating insufficient throughput performance of the VPN multicast. This indicates that even if the UL communication bandwidth is reduced through multicast communication, if the VPN multicast throughput performance is not sufficient, the VPN server becomes a bottleneck in communication.
- **Type IV, VI [N->1, Unicast, VPN]:** In the range of successful communication indicated by the blue border, latency values between 16.8ms and 22.2ms were obtained.

- **Type II, IV, VI, VIII [Unicast w/o VPN]:** Despite the communication volume being lower than the throughput limits of the 5G devices for both UL and DL required bandwidth, packet loss occurred and communication was not successful for any of the conditions. Unfortunately, the specific causes of packet loss could not be identified even after conducting the packet analysis. The system complexity and the time consumption to pinpoint the cause of the problem are some of the issues of 5G.

From the results above, multicast communication was achieved using L2TPv3 tunneling with a VPN router for EtherNet/IP, which is a Layer 2 communication protocol. In the 1->N multicast communication, latency ranging from 19.6ms to 31.2ms was observed. Additionally, in the N->1 unicast communication with VPN, latency ranged from 16.8ms to 22.2ms. Furthermore, whether the delay being longer than the RPI is a problem or not requires judgment based on the purpose of the application being used. It was not treated as a problem in this context.

In this evaluation, it is possible that achieving a small latency at the level of 10ms was difficult due to the use of synchronization with the communication carrier band in Japan. The TDD frame structure, which maintains a communication performance ratio of 3.25:1 between DL and UL, may have resulted in lower UL performance, making it challenging to achieve a latency of 10ms or lower.
Multicast communication can help reduce UL communication load, but the VPN multicast functionality of the VPN server became a bottleneck in this setup. Therefore, in the case of multicast communication between controllers using 5G transmission, the VPN server's VPN multicast performance becomes a critical factor in determining the system's performance.

System Configurations for Evaluation of CIP Safety over 5G Transmission

As a use case for an FA application utilizing 5G, we assumed a system that integrates three robot cells into a single safety line controller. Based on this use case, we transmit multicast CIP Safety packets over 5G between controllers and measure packet loss, communication delay, and the Safety Reaction time of CIP Safety packets. The system configuration for this measurement is shown in Figure 6.

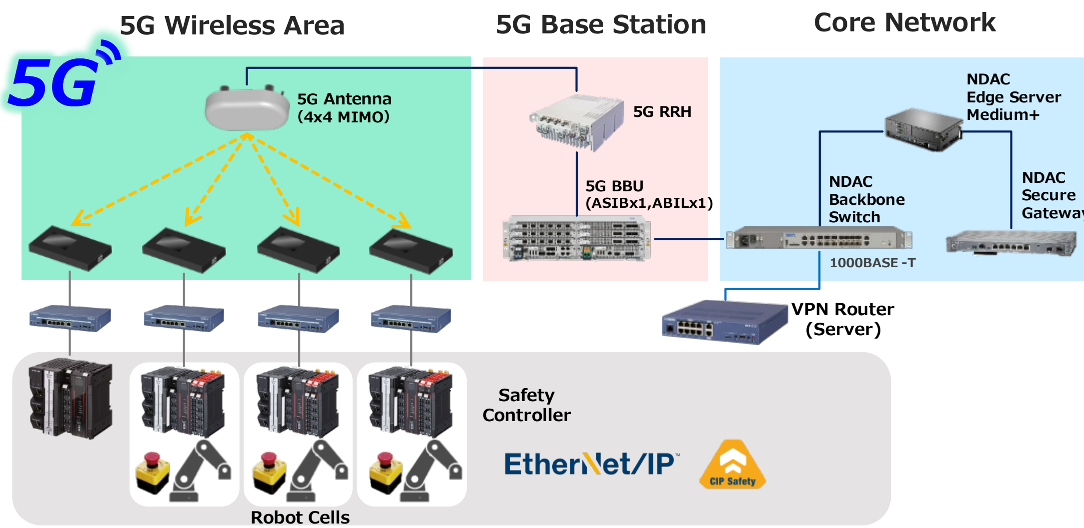

Figure 6: System Configuration for CIP Safety over 5G Transmission Evaluation between Manufacturing Equipment

The system components of this configuration are as follows:

- **Safety Controller:** One single safety line controller using NX102+SL5500 (Omron) oversees the safety within the control system and integrates the safety controllers of the three robot cells.
- **CIP Safety Network:** Similar to the configuration for measuring packet loss and latency in an EtherNet/IP network, each controller is connected to a 5G device via packet capture and a VPN router. Additionally, a VPN server is connected to the switch in the Core Network."

Measurement Configurations and Conditions for CIP Safety over 5G Transmission

The variations in the measurement configurations are shown in Figure 7 and Figure 8.

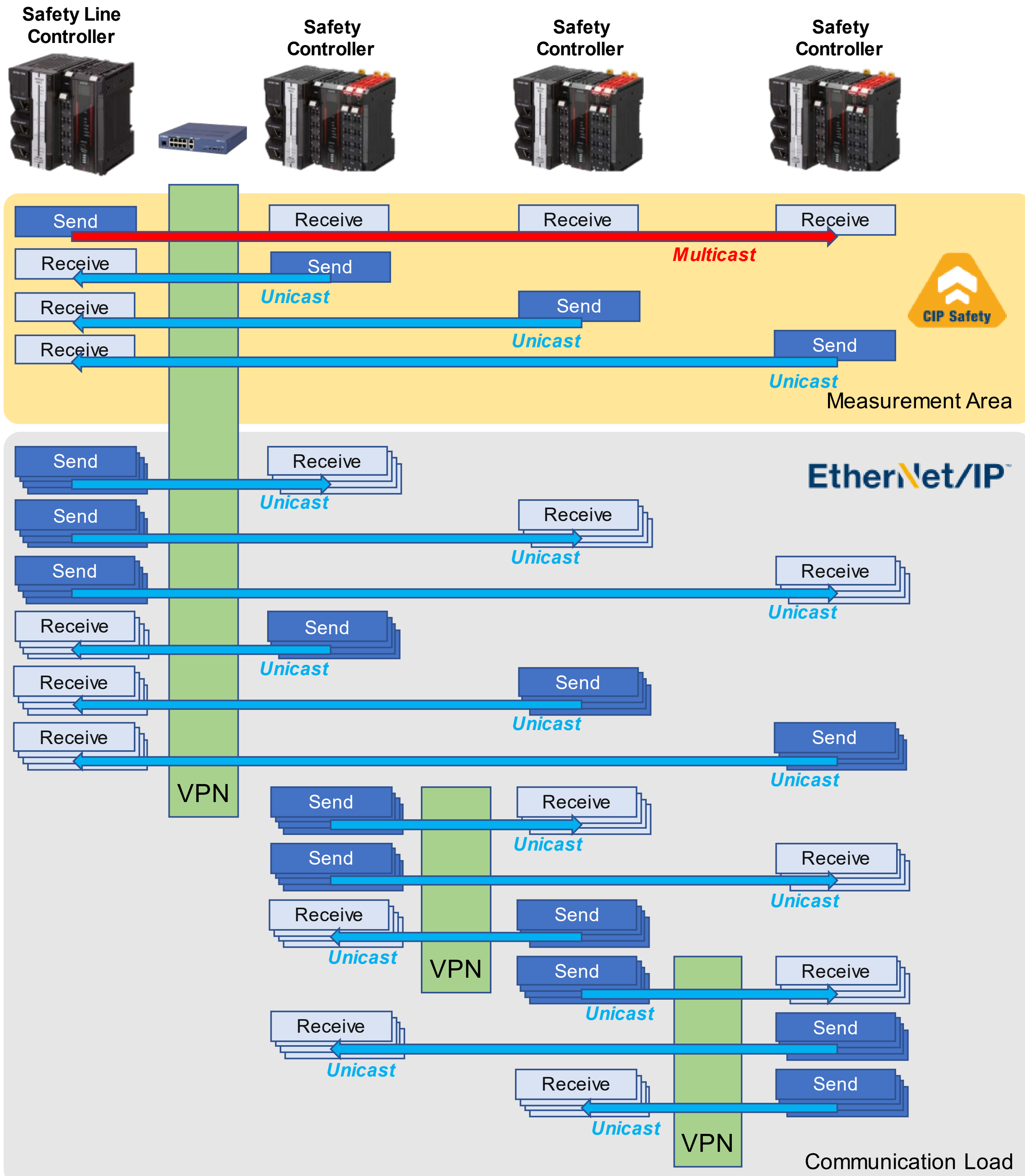

Figure 7: Measurement Configurations for CIP Safety over 5G Transmission between Safety Controllers with Multicast and VPN

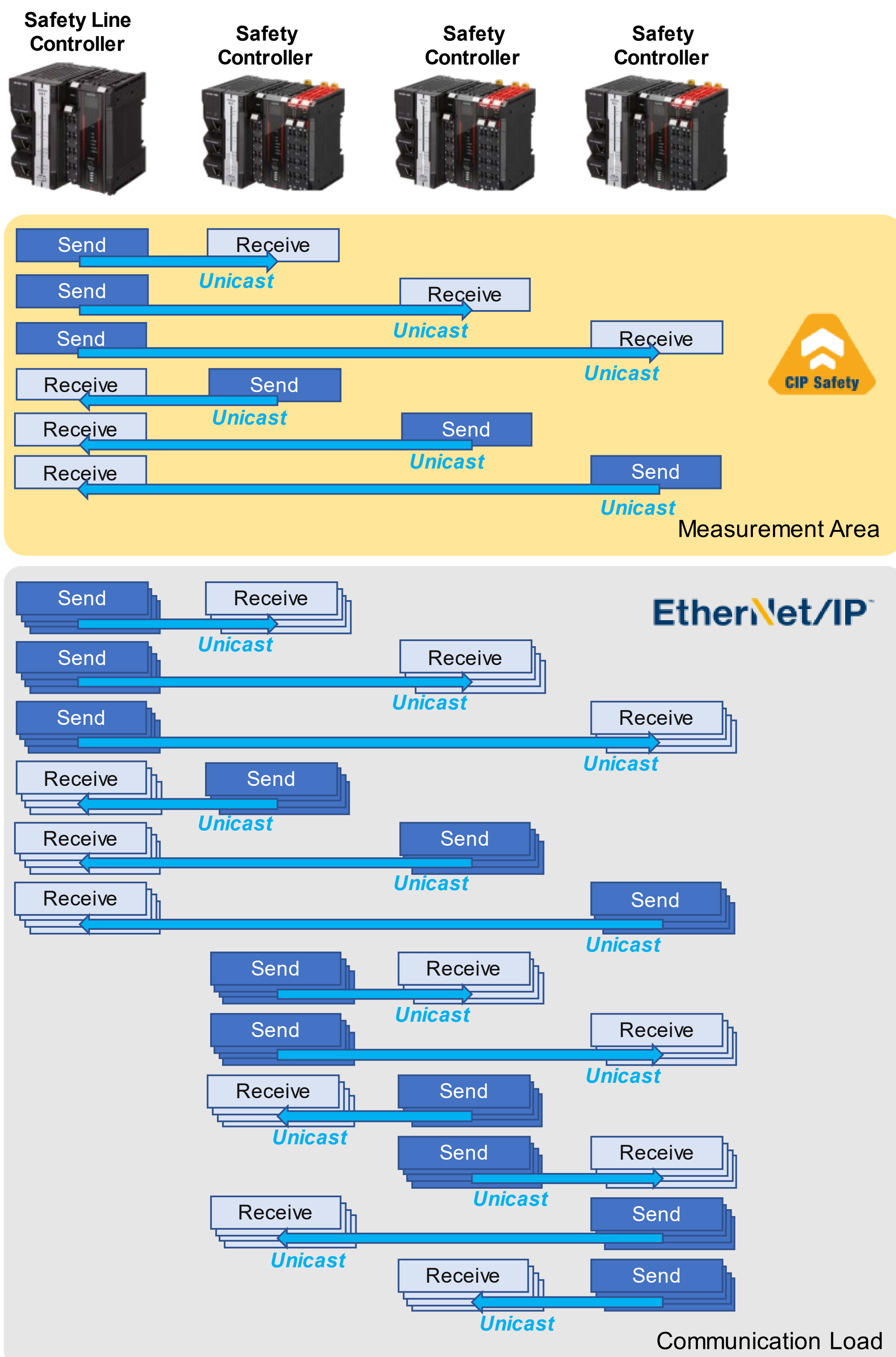

Figure 8: Measurement Configurations for CIP Safety over 5G Transmission between Safety Controllers with Unicast Only

The conditions for performance measurement are as follows:

- **Number of CIP Safety Connections:** CIP Safety connections were established between the safety line controller as the target and the three safety controllers as originators, as well as between each of the three safety controllers as targets and the safety line controller as the originator.
- **EPI (CIP Safety Communication Period):** The EPI for safety process communication was set to 60ms (fixed).
- **Data Size:** CIP Safety packets required for this use case were set to 46 bytes.
- **Communication Load:** To simulate real-world usage, standard process communication was used to add communication load to CIP Safety communication. A maximum of 24 standard process communication connections per safety controller (12 as originators and 12 as targets) were established between each safety controller, including the safety line controller. The RPI (Request Packet Interval) was varied at 1ms, 5ms, 20ms, 50ms, 100ms, and 200ms to introduce different communication loads, and CIP Safety packet loss and communication delay were measured.
- **Wired LAN Measurement:** The safety line controller and the three safety controllers were connected to an L2 switch (CISCO: CBS350-16T-E-2G-JP) via Ethernet cables for measurement using packet capture.
- **Safety Reaction Time:** Safety reaction time was measured between the emergency stop circuit connected to the safety controller and the safety relay circuit connected to another safety controller (★->★). An oscilloscope was used for measurement, and the time was measured from the voltage drop in the emergency stop circuit after pressing the emergency stop button until the safety relay opened and the voltage of the connected power supply dropped. The system configuration and communication flow for safety reaction time measurement are shown in Figure 9.
- **Number of Measurements:** Referring to ISO13855:2010 [3], 10 measurements were conducted without using standard deviation determination, considering the worst-case scenario.

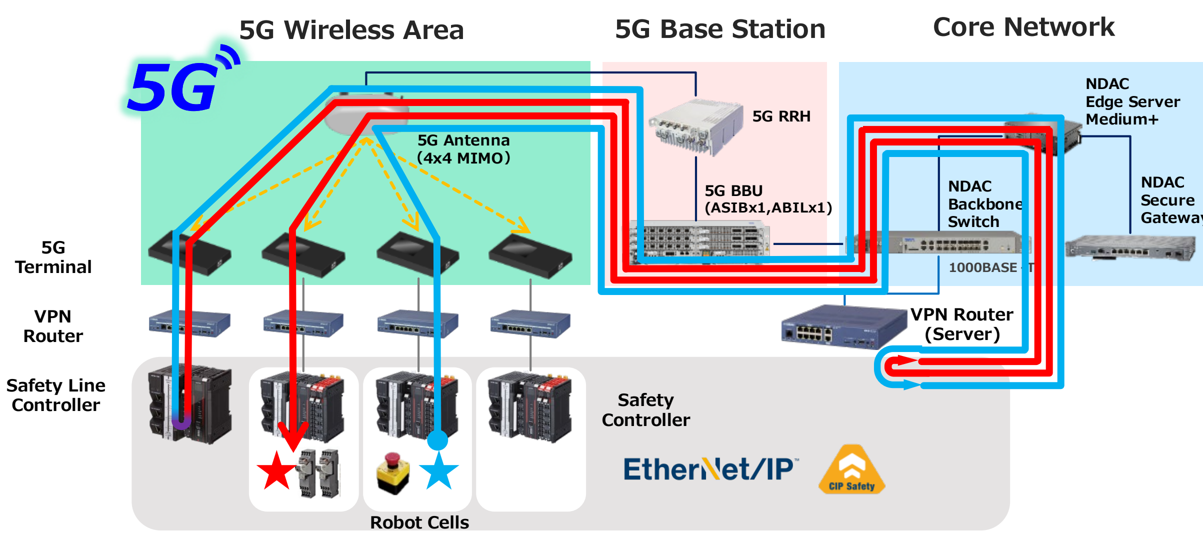

Figure 9: System Configurations and Communication Flow for Measurement of Safety Reaction Time

In addition to performance measurement, we conducted a 24-hour continuous communication test between the safety line controller and the safety controllers of the robot cells to verify the stability of the safety system with CIP Safety over 5G transmission and to check for any timeout errors. The operating conditions for the continuous communication are as follows

- **Timeout Error Trigger Condition:** The timeout error condition was set to 120ms, which is EPI (CIP Safety Communication Period) multiplied by 2, as the default setting for Omron safety controllers.
- **Number of CIP Safety Connections:** Same as the conditions for performance measurement.

- **EPI (CIP Safety Communication Period):** Same as the conditions for performance measurement.
- **Data Size:** Same as the conditions for performance measurement.
- **Communication Load:** Same as the conditions for performance measurement.

Measurement Result for Evaluation of CIP Safety over 5G between Manufacturing Equipment

Table 5 presents the measurement results of packet loss and latency (average measured value) for CIP Safety packets in both 5G and wired LAN environments. It shows the results for multicast and unicast communication of CIP Safety packets in 5G and wired LAN.

Table 5: Measurement Results of Packet Loss and Latency over 5G and Wired for CIP Safety between Manufacturing Equipment

Measurement Conditions	Packet Loss [%]							Latency [ms]						
RPI for Comm. Load [ms] (EPI: 60ms Fixed)	1	5	10	20	50	100	200	1	5	10	20	50	100	200
5G *Multicast* w/ VPN	0.000	0.000	0.000	0.000	0.000	0.000	0.001	20.7	20.0	17.0	16.3	13.3	12.2	11.6
5G *Unicast Only*		0.002	0.009	0.009	0.004	0.006	0.002		19.4	17.6	16.5	13.0	12.8	12.3
Wired *Multicast w/o VPN*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.02	0.02	0.02	0.01	0.01	0.01	0.01
Wired *Unicast Only*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.02	0.01	0.02	0.01	0.01	0.01	0.01

In 5G multicast, packet loss occurred only when the standard process communication load RPI was set to 200ms. In 5G unicast, packet loss occurred under all conditions. However, there were no observed packet losses in the wired LAN environment.

Focusing on the condition of the standard process communication load RPI of 20ms, Figure 10 presents a histogram of the latency distribution of CIP Safety packets.

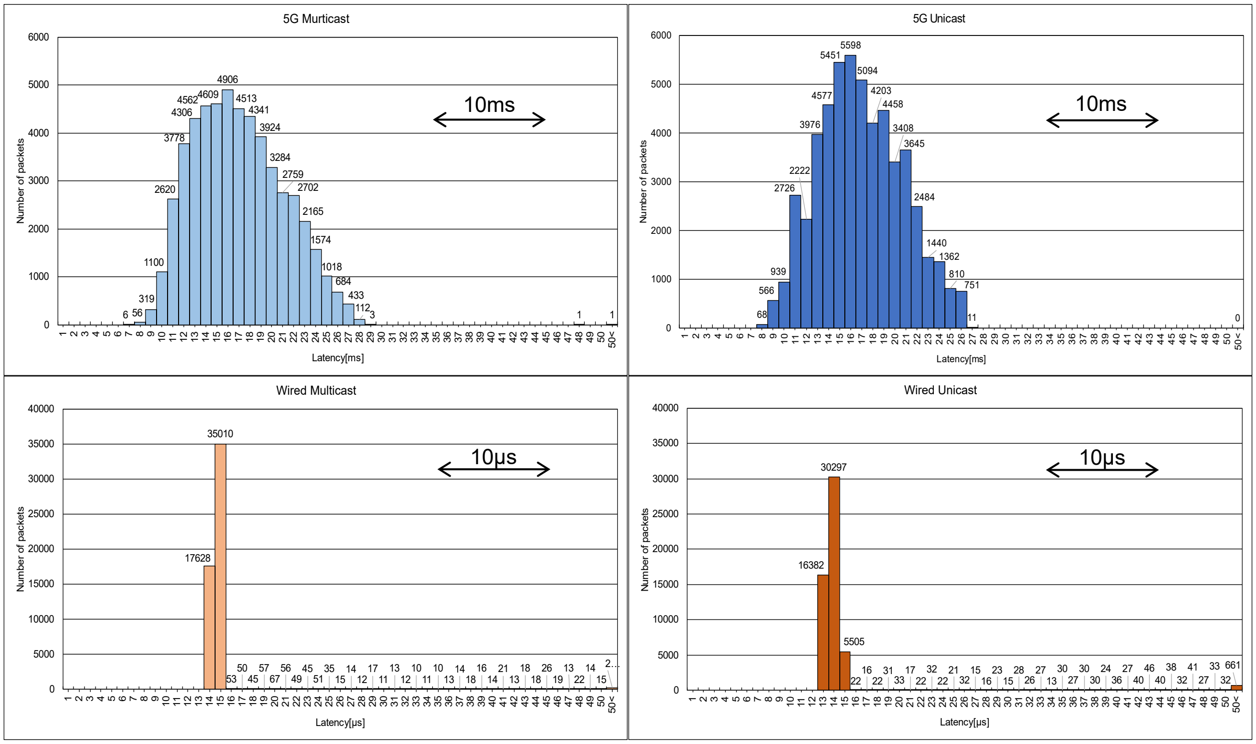

Figure 10: Histogram of Latency over 5G and Wired for CIP Safety between Manufacturing Equipment（20ms RPI for Communication Load）

Comparing 5G multicast and unicast, 5G multicast shows a slightly broader shape in terms of CIP Safety packet latency performance. However, there was no significant difference between multicast and unicast. Both 5G multicast and unicast achieved latency of 30ms or below for almost all CIP Safety packets. However, there were outliers with higher latency in the multicast case. Although the cause of it has not been analyzed, it is assumed to be due to the performance of the VPN multicast (packet retention within the VPN system) of the VPN server.

Furthermore, in the wired LAN environment, regardless of multicast or unicast, the latency performance of CIP Safety packets was consistently below 1ms.

Figure 11 shows the measurement results of safety reaction time. Safety reaction time was measured based on the worst-case scenario, without using standard deviation determination, and taking 10 measurements.

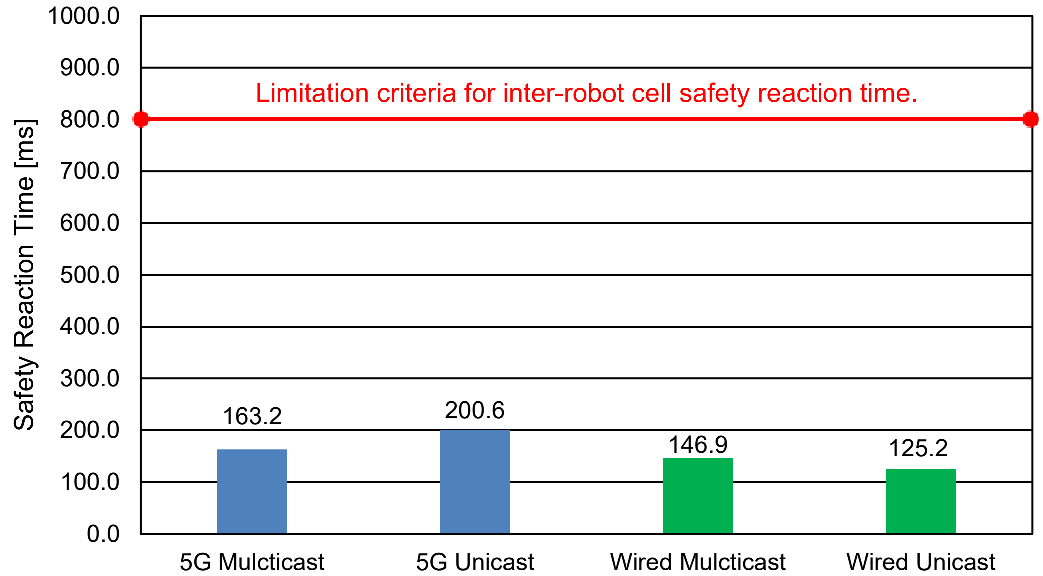

Figure 11: Measurement Results of Safety Reaction Time over 5G and Wired for CIP Safety between Manufacturing Equipment (EPI=60ms, Load RPI=20ms、n=10)

The results showed that in 5G, multicast had shorter safety reaction time, while in wired LAN, unicast had shorter safety reaction time. When comparing 5G to wired LAN, the higher latency in 5G resulted in larger safety reaction time.

Based on the system configuration depicted in Fig.9, the safety reaction time calculated from Fig.12 was 677ms. Considering those the acceptable limit requirement for this use case is 800ms, it was confirmed that 5G transmission is sufficiently usable.

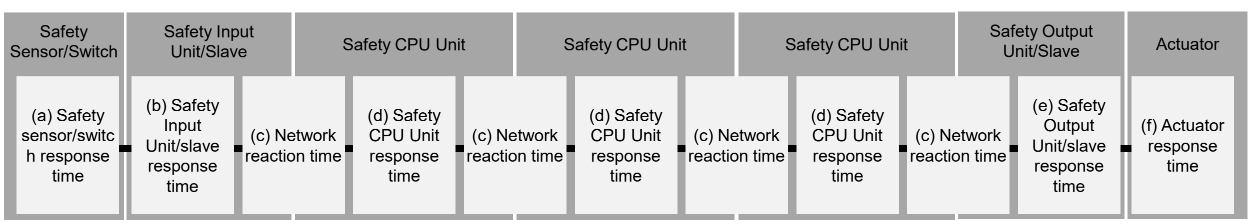

Figure 12: Safety Reaction Time in Network Configuration between Controllers [4]

Finally, in the evaluation of running the system continuously for 24 hours using the system configuration shown in Figure 6, no timeout errors occurred in either multicast or unicast communication, and the system operated stably for the entire 24 hours. This confirms that safe communication between the equipment can be achieved using CIP Safety over 5G transmission.

Based on these results, CIP Safety multicast communication demonstrated practicality in terms of communication stability, obtained safety reaction time, and the evaluation of 24-hour system operation using 5G transmission. However, in CIP Safety multicast communication, there were instances of packet loss and latency outliers. If the operation time is extended, timeout errors may occur, which may lead to a safety stop on the equipment line. To prevent safety stoppages on the line due to wireless communication issues, it is desirable to further reduce packet loss and latency outliers.

Conclusion

The conclusions obtained from applying 5G communication for controller-to-controller communication, evaluating EtherNet/IP performance, measuring safety reaction time of CIP Safety in the robot cell line use case, and conducting a 24-hour continuous power evaluation are presented below.

- When applying 5G communication for Implicit communication between controllers, multicast communication from Controller 1 to N nodes (N = 1, 2, 4, 7) achieved an average latency of 19.6-31.2ms, while unicast communication from N nodes to Controller 1 achieved an average latency of 16.9-22.2ms. This indicates that it can provide the expected performance for AGV control as defined by NICT in Figure 1. However, it was not possible to achieve the required latency of 10ms or below for "Machine, Robot control."
- The results presented in Table 4 indicate that the VPN multicast capability of the VPN server can potentially become a bottleneck in system performance for EtherNet/IP multicast communication over 5G transmission.
- When applying 5G communication to CIP Safety in the robot cell line use case (where the operator operates a safety button), it was confirmed that the achieved safety reaction time met the performance requirement of 800ms (163.2ms). However, it was not possible to achieve the required latency of 10ms or below for "Emergency warning" as defined by NICT, which requires high-speed reaction times where the operator does not make safety judgments (e.g., safety light curtains).
- In the system where CIP Safety was transmitted over 5G, it was confirmed that there were no timeout errors and that stable operation was possible for 24 hours.

Looking ahead, improvements are expected in the UL performance through changes in the performance ratio of DL and UL in TDD for 5G Sub6, the introduction of URLLC (Ultra-Reliable and Low Latency Communications) including 5G devices, advancements in private 5G using 5G millimeter-wave technology, and improvements in VPN multicast throughput of VPN servers. These advancements are anticipated to enable the realization of a latency of 10ms using 5G wireless technology. Furthermore, with improved operational reliability of private 5G, it is expected that stability of 5G communication applications, including CIP Safety, can be enhanced by reducing packet loss and latency within the system.

References

[1] "Wireless use cases and communication requirements in factories (abridged edition)",Version 1.0, February 2018, NICT. https://www2.nict.go.jp/wireless/en/ffpj-wp.html
[2] “Promotion of Local 5G and Other Initiatives by the Ministry of Internal Affairs and Communications (MIC)” https://www.soumu.go.jp/main_content/000739007.pdf
[3] ISO 13855:2010 “Safety of machinery - Positioning of safeguards with respect to the approach speeds of parts of the human body”
[4] “Safety Network Controller, NX-series, Safety Control Unit/ Communication Control Unit User's Manual” https://www.fa.omron.co.jp/data_pdf/mnu/z395-e1-14_nx-sl5_si_so_csg.pdf?id=3813