Joint Demonstration Report

of the Private 5G Optimization Project

Ver 2.0

2026.3.27

All Participating Companies of the Private 5G Optimization Project

Revision History

Revision	Date	Update content
1.0	2025/2/25	First Edition
2.0	2026/3/27	■Updated the following contents to reflect the results upon completion of all tests for the P5G Optimization Project. 2.2 Main text 3.1.2 Table 3-3, Table 3-4 3.1.6 Main text, Table 3-7, Figure 3-3 3.1.7 Main text 3.2.5.1 Main text, Figure 3-12 3.2.5.2 Figures 3-13 to 3-32, Table 3-12, Table 3-13 3.3.5 Figure 3-35 ■Add new 3.1.6 Table 3-8 Added 3.2.6 Added Chapter 4 Added Chapter 6 Chapter 7 Main text

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1. Introduction

In November 2023, the "Private 5G Optimization Project" (hereinafter referred to as the P5G Optimization Project) was launched, initiated by NTT EAST, Inc. and involving 18 companies, including domestic and international telecommunications equipment vendors. With the objective of promoting the widespread adoption and expansion of Private 5G by further reducing costs and improving convenience, this project has been conducting interoperability tests and security enhancement tests on Private 5G equipment. As of February 2025, joint tests on over 300 combinations have been completed.

There is a wide variety of vendor equipment in the market that constitutes Private 5G systems, each differing in function, performance, and price. When providing Private 5G systems to users, combining Private 5G equipment from different vendors according to user requirements can potentially lead to the optimal proposal. On the other hand, when configuring a Private 5G system using equipment from different vendors, integration costs associated with system construction—such as the tuning of configuration parameters between devices and operation verification tests—often increase compared to single-vendor configurations. Consequently, it has become common to configure systems using equipment from a single vendor. However, in the case of single-vendor Private 5G configurations, depending on the use case, the functions or performance may be excessive. To further reduce the cost of Private 5G systems, we believe it is an effective approach to suppress integration costs during multi-vendor interoperability and to expand the range of equipment choices according to the use case.

This report outlines the vendor combinations where interoperability was successfully established and points to note during interconnection. It also publishes performance data, such as throughput and latency for these combinations, as well as the operation results of commercial security solutions. We believe this data will assist integration during system construction, and by utilizing this report, we expect it will lead to a reduction in system integration costs for vendor equipment configurations.

We hope that this report contributes to accelerating the societal implementation of Private 5G, promoting industrial digital transformation (DX), and solving regional issues.

2. Regarding the Private 5G Optimization Project

This project is being conducted in collaboration with various companies that brought their test equipment to the NTTe-City Labo of NTT EAST, Inc., under three themes. This chapter provides an overview of each theme.

The participating companies consist of 26 firms, as shown in Table 2-1. The Private 5G equipment brought in by each company is illustrated in Figure 2-1.

Table 2-1 List of Participating Companies in the Project

No.	Company Name
1	Airspan Japan
2	ANRITSU Corporation
3	Askey Computer Corporation
4	Compal Electronics
5	CTOne Inc.
6	D-Link Japan K.K.
7	FLARE SYSTEMS Co., Ltd.
8	Hewlett Packard Japan, G.K.
9	HTC Corporation
10	HYTEC INTER Co., Ltd.
11	Industrial Technology Research Institute （ITRI）
12	KYOCERA Corporation
13	LITE-ON Japan ltd.
14	LITE-ON Technology Corporation
15	NEC Corporation
16	NEC Magnus Communications, Ltd.
17	NTT EAST, Inc.
18	Nokia Solutions and Networks Japan G.K.
19	NTT TechnoCross Corporation
20	Panasonic Connect Co., Ltd.
21	Pegatron Japan Inc.
22	Quanta Cloud Technology Incorporated
23	REIGN Technology Corporation
24	Saviah Technologies
25	Sumitomo Electric Industries, Ltd.
26	Trend Micro Inc.

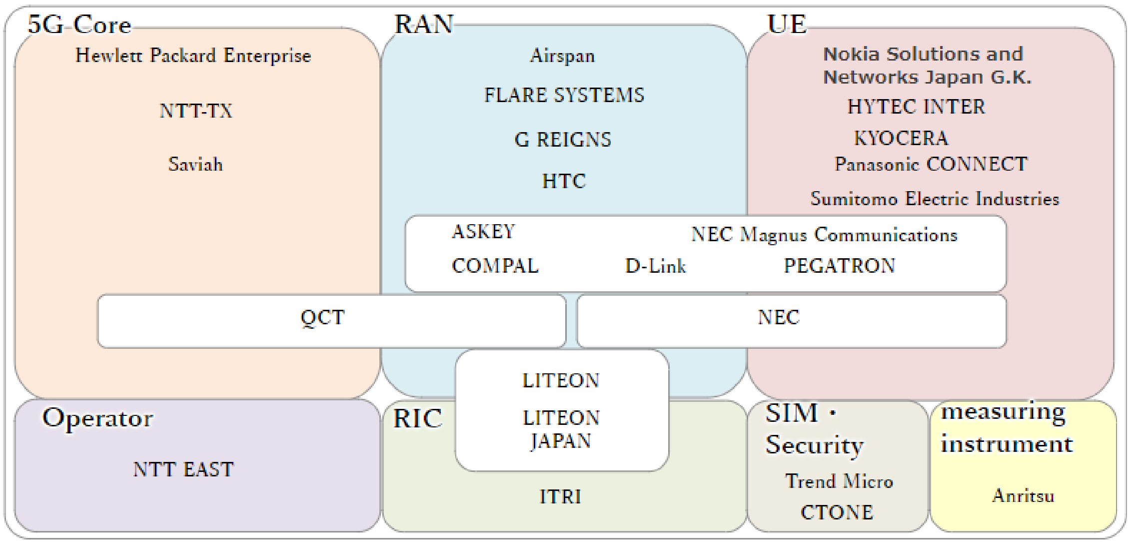


Figure 2-1 Private 5G Equipment Provided by Participating Companies

2.1. Theme 1 Overview (Private 5G Equipment Interoperability Test)

Theme 1 addresses interoperability tests between Private 5G equipment from different vendors.

When building a Private 5G system—comprising the 5G Core (5GC), which handles terminal authentication and network control; the Base Station (RAN), which performs radio control; and the User Equipment (UE), which connects to the Private 5G network and serves as the endpoint in communication—using equipment from different vendors, integration costs associated with system construction often exceed those of single-vendor configurations. These costs arise from tasks such as tuning configuration parameters between Private 5G devices and conducting operation verification tests. Consequently, it has become common practice to configure systems using Private 5G equipment from a single vendor.

However, single-vendor configurations may result in excessive functions or performance (over-spec) depending on the use case. To further reduce the cost of Private 5G systems, we believe it is effective to adopt an approach that curbs integration costs during multi-vendor interconnection, thereby expanding the range of Private 5G equipment choices tailored to specific use cases.

Therefore, in Theme 1, we will evaluate communication performance in successful connection patterns and assess communication quality in use cases such as high-definition video transmission. Additionally, we will compile instances where connections failed to clarify key considerations for interoperability.

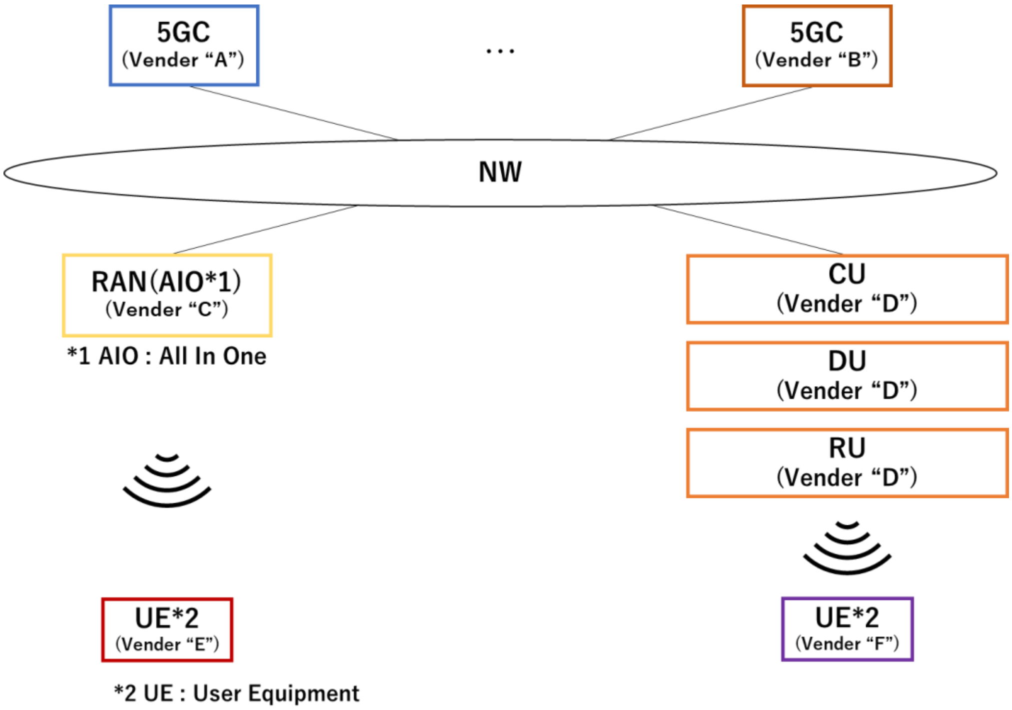


Figure 2-2 Overview of Theme 1

2.2. Theme 2 Overview (RIC Test in Private 5G Multi-vendor Configuration)

In Theme 2, we will conduct RIC tests in a multi-vendor Private 5G configuration tailored to specific use cases.

Private 5G is widely deployed in industrial applications and must accommodate diverse use cases. For instance, in environments such as factories, logistics warehouses, and wide-area outdoor inspections, parameters must be evaluated and manually adjusted whenever equipment is relocated or when a terminal changes its connecting base station (handover) to maintain and provide high-quality service. Consequently, there is a demand for a mechanism that controls parameters autonomously and automatically.

Addressing these issues, Theme 2 utilizes the RAN Intelligent Controller (hereinafter referred to as RIC) defined by the O-RAN ALLIANCE. The objective is to provide a high-quality Private 5G environment that supports diverse use cases, including energy efficiency and performance improvement under frequency interference. We aim to realize a mechanism that continuously provides high-quality Private 5G communications by testing the effectiveness of dynamic parameter optimization via the RIC and verifying interoperability between equipment from different vendors.

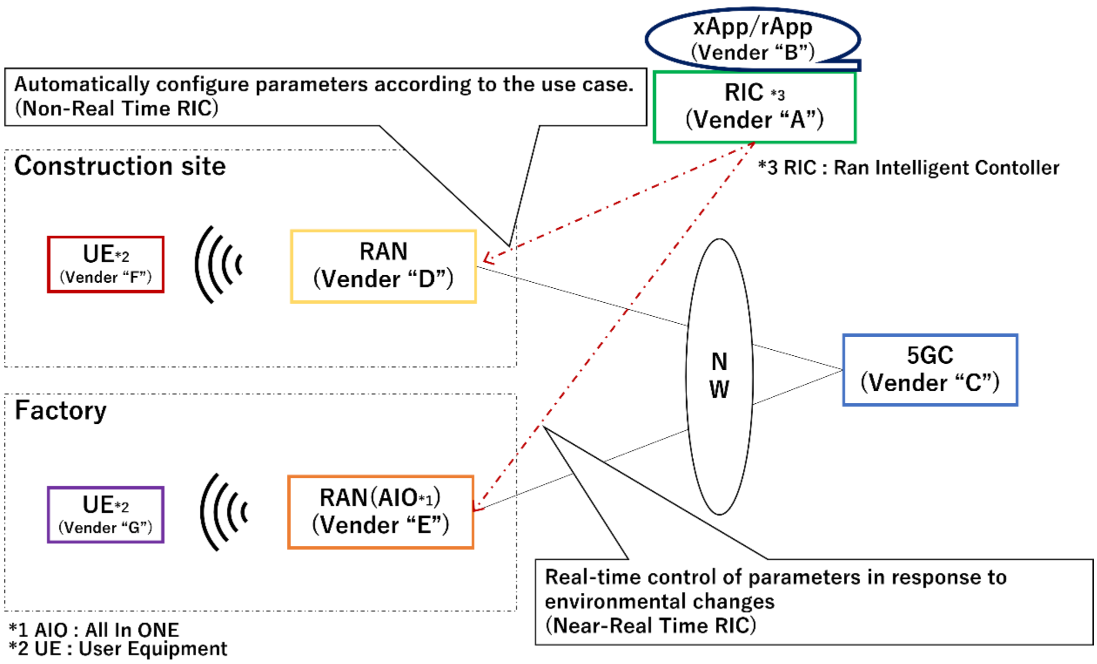


Figure 2-3 Overview of Theme 2

2.3. Overview of Theme 3 (Enhancement of Security Measures for Private 5G Utilization Environment)

In Theme 3, we will focus on enhancement of security measures for the Private 5G utilization environment. Furthermore, this theme was established as a new initiative based on discussions among project members since the project's inception.

While Private 5G is expected to enhance security through strict subscriber management and robust key management via SIM cards, there are many devices, such as IoT devices, that cannot implement traditional agent-based endpoint security measures.

Additionally, in environments such as factories and medical settings, there is a need to continue using older devices, making it difficult to upgrade the operating systems or related software. As a result, there are cases where devices must be operated with known vulnerabilities.

In a completely closed network where the introduction or removal of devices is not permitted, the use of such terminals and devices would not pose any issues. However, with the increasing opportunities for connection to external networks due to IoT and smart technology, there is growing concern that terminals and devices lacking adequate security measures may be exposed to threats.

Therefore, in Theme 3, we aim to enhance security measures in various Private 5G device utilization environments by leveraging the TMMNS solution provided by Trend Micro and CTOne. This will involve the integration of security SIM cards with network security features to create a more robust security framework.

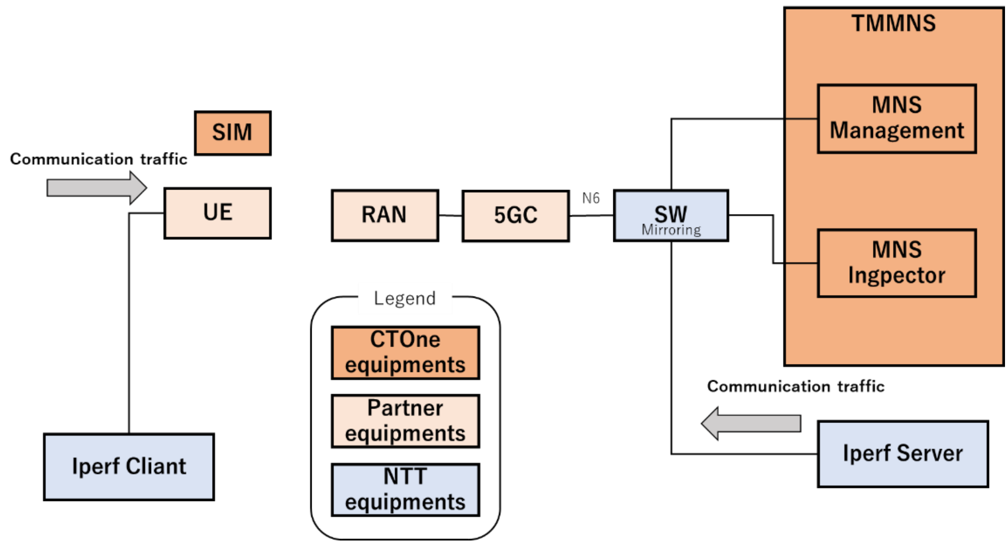


Figure 2-4 Overview of Theme 3

3. Theme 1 Test (Interconnection between Private 5G Devices)

Theme 1 will conduct interconnection tests between Private 5G equipment from different vendors. The specific details of the tests are shown in Table 3-1.

Table 3-1 Theme 1 Test Content

No.	Test Content
3.1 Interconnection Testing	・ Evaluate the feasibility of interconnection. ・ Summarize insights on interconnection through examples of failed interconnections.
3.2 Throughput Testing	・ Evaluation of communication quality in combinations that allow interconnection.
3.3 4K Video Transmission Delay Testing	・ Evaluation of delay characteristics during 4K video transmission as a specific use case for communication quality.

3.1. Interconnection Testing

3.1.1. Test Configuration

The test configuration is illustrated in Figure 3-1 and Figure 3-2. The RAN and UE will be deployed within a shielded box or a shielded tent.

Data communication after the UE connection is established will occur between the UE itself or a Client PC connected to the UE, and the N6 Server located at the N6 interface.

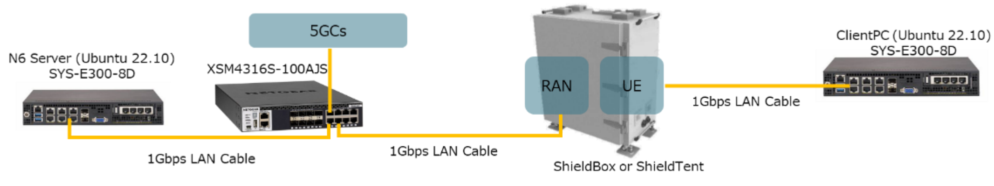


Figure 3-1 Interconnection Testing Configuration

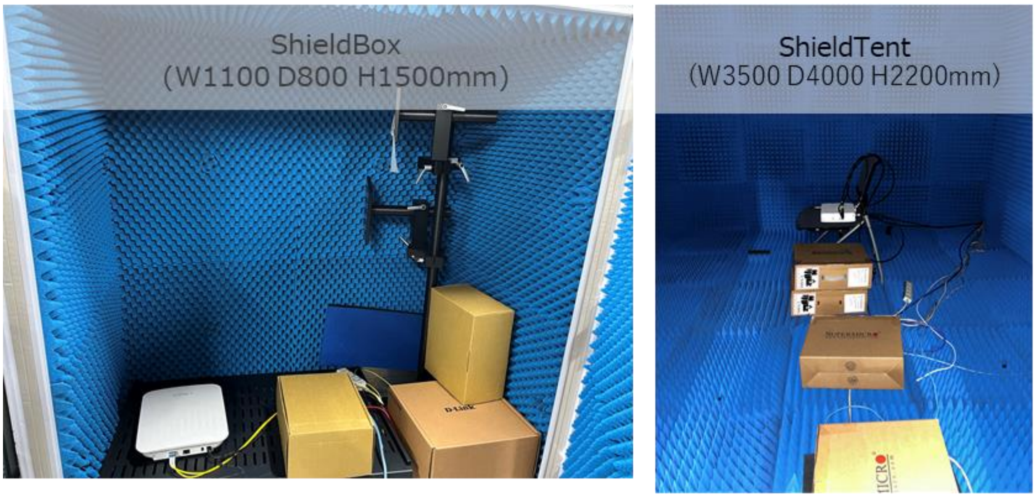


Figure 3-2 Shielded Box and Shielded Tent

To minimize the impact of environmental differences on the test results, the output power of the RAN and the placement of the UE were adjusted to achieve an RSRP value of approximately -70 dBm for the UE. The sizes of the shielded box and shielded tent, along with their effective field strengths, are shown in Table 3-2.

Table 3-2 Specifications of the Shielded Box and Shielded Tent

Product Name	Size(W×D×H)【mm】
Shielded Box	1,100×800×1,500
Shielded Tent	3,500×4,000×2,200

3.1.2. List of Test Equipment

The names and model numbers of the Private 5G equipment used in this test are shown in Table 3-3, and the specifications of the Private 5G equipment are presented in Table 3-4.

Table 3-3 Private 5G Devices Used in Interconnection Testing: Product Names and Model Numbers

Company Name	Abbreviation	Classification	Product Name/Model Number
Hewlett Packard Japan, G.K.	HPE	5GC	HPE Aruba Networking Private 5G Core
NTT TechnoCross Corporation	NTT-TX	5GC	-
Quanta Cloud Technology Incorporated	QCT	5GC	OmniCore
Saviah Technologies	Saviah	5GC	-
Airspan Japan KK	Airspan	RAN	Airspeed 1900
Askey Computer Corporation	Askey	RAN	NR xCell 80156C
Compal Electronics	Compal	RAN	Integrated Small Cell "Cedar"
FLARE SYSTEMS Co., Ltd.	FLARE SYSTEMS	RAN	-
HTC Corporation REIGN Technology Corporation	HTC G REIGNS	RAN	HPFG-0-0101
LITE-ON Technology Corporation	LITE-ON	RAN	FlexFi 5G Small cell ORAN-RU/FF-RFI079I04
NEC Corporation	NEC	RAN	RV1200
NEC Magnus Communications, Ltd.	NEC Magnus	RAN	FB2000SS
Pegatron Japan Inc.	Pegatron	RAN	5G ORAN Station/PG5200, Indoor RU 4T4R
Quanta Cloud Technology Incorporated	QCT	RAN	OmniRAN
Askey Computer Corporation	Askey	UE	NUQ3000M
Compal Electronics	Compal	UE	RAKU/91ZX533007A
D-Link Japan K.K.	D-Link	UE	DWP-1010W
HYTEC INTER Co., Ltd.	HYTECINTER	UE	HW5G-3100-SSD
NEC Corporation	NEC	UE	VersaPro/VJV50G-B
NEC Magnus Communications, Ltd.	NEC Magnus	UE	FG900CS
Nokia Solutions and Networks Japan G.K.	Nokia	UE	Industrial 5G Fieldrouter FRRO501c
Panasonic Connect Co., Ltd.	PCO	UE	XC-WN930J-01
Pegatron Japan Inc.	Pegatron	UE	Raptor V2/MG54AX
KYOCERA Corporation	KYOCERA(A)	UE	K5G-C-100A
KYOCERA Corporation	KYOCERA(B)	UE	DIGNO® SX4
KYOCERA Corporation	KYOCERA(C)	UE	DuraForce EX

KYOCERA Corporation	KYOCERA(D)	UE	DIGNO® Tab2 5G
Sumitomo Electric Industries, Ltd.	SEI	UE	industrial 5G terminals/IGW5111

Table 3-4 Specifications of Private 5G Devices Used in Interconnection Testing

Abbreviation	Classification	3GPP Rel Ver	Embedded CPU/SoC,modem	Layer (UL×DL)	Max QAM UL	Max QAM DL
HPE	5GC	Release16	Confidential	-	-	-
NTT-TX	5GC	Release16	Intel based CPU	-	-	-
QCT	5GC	Release15	Intel based CPU	-	-	-
Saviah	5GC	Release16	Confidential	-	-	-
Airspan	RAN	Release15	Confidential	Confidential	Confidential	Confidential
Askey	RAN	Release15	FSM10056	2×2	256	256
Compal	RAN	Release16	NXP LX2160A NXP LA1238	2×4	256	256
FLARE SYSTEMS	RAN	Release17	Confidential	2×4	256	256
HTC G REIGNS	RAN	Release15	Intel based CPU	2×4	64	64

LITE-ON	RAN	Release15	NXP LX2160	2×4	64	256
NEC	RAN	Release15	Confidential	Confidential	Confidential	Confidential
NEC Magnus	RAN	Confidential	Intel Icelake＋FPGA	2×4	256	256
Pegatron	RAN	Release15	Intel Icelake＋FPGA(BBU) Intel Arria 10 FPGA(RU)	2×4	Confidential	Confidential
QCT	RAN	Release15	Intel based CPU	2×4	64	256
Askey	UE	Release16	Snapdragon X65 5G Modem-RF System	2×4	256	256
Compal	UE	Release15	Snapdragon X55 5G Modem-RF System	2×4	256	256
D-Link	UE	Confidential	Confidential	Confidential	Confidential	Confidential
HYTECINTER	UE	Release16	Snapdragon X55 5G Modem-RF System	2×4	256	256
NEC	UE	Confidential	Confidential	Confident	Confident	Confident

				ial	ial	ial
NEC Magnus	UE	Confidential	Snapdragon X55 5G Modem-RF System	2×4	256	256
Nokia	UE	Release15	Qualcomm IPQ6010 Quectel RM505Q-AE with SDX55	Confidential	Confidential	Confidential
PCO	UE	Release15	Confidential	1×4	64	256
Pegatron	UE	Release16	Snapdragon X62 RM520N-GL	Confidential	Confidential	Confidential
KYOCERA(A)	UE	Release15	Snapdragon X55 5G Modem-RF System	2×4	256	256
KYOCERA(B)	UE	Release 16	MediaTek Dimensity®6100+	1×4	256	256
KYOCERA(C)	UE	Release 15	MediaTek Dimensity® 700	1×4	256	256
KYOCERA(D)	UE	Release 16	MediaTek Dimensity®6100+	1×4	256	256
SEI	UE	Release16	Snapdragon X65 5G Modem-RF System	2×4	256	256

3.1.3. Configuration Items

The configuration items required for each Private 5G device (node) in the interconnection testing are presented in Table 3-5. In this project, uniform configuration values were set for each Private 5G device, and tests were conducted under consistent conditions.

Table 3-5 List of Configuration Items

Configuration Item	Per-Node Configuration Item	Configuration Format	5GC	RAN (AIO)	RAN (CU)	RAN (DU)	RAN (RU)	UE
IP Address	5GC N2 IP address	-	○	-	-	-	-	-
	5GC N3 IP address	-	○	-	-	-	-	-
	5GC N4 IP address	-	○	-	-	-	-	-
	5GC N6 IP address	-	○	-	-	-	-	-
	RAN CU IP address	-	-	○	○	-	-	-
	RAN DU IP address	-	-	○	-	○	-	-
	RAN RU IP address	-	-	○	-	-	○	-
	5GC Management IP address	-	○	-	-	-	-	-
	RAN Management IP address		-	○	○	○	○	-
	UE Management IP address		-	-	-	-	-	○
VLAN	N2 VLAN	-	○	○	○	-	-	-
	N3 VLAN	-	○	○	-	○	-	-
RAN SW Mode	-	-	-	○	-	-	-	-
UE Pool IP Address	-	-	○	-	-	-	-	-
PLMN	-	6-digits	○	○	○	-	-	-
TAC/TAI	-	6-digits	○	○	-	○	-	-
SST	-	2-digits	○	○	-	○	-	--
SD	-	1to4-digits	○	○	-	○	-	-
DNN	-	Arbitrary string	○	○	○	-	-	○
5QI	-	1to3-digits	○	○	○	-	-	-
gNB-ID-Length	-	Any number	○	○	○	-	-	-
gNB-ID	-	Hexadecimal 6 digits	○	○	-	○	-	-

3.1.4. Test Items

The test items for this examination are presented in Table 3-6.

Table 3-6 Test Items in Interconnection Testing

No.	Test Item	Test Objective	Test Pass Criteria
1	Registration・PDU Procedure	Verify the connection operation of the UE under normal conditions.	Power on the UE after the 5GC and RAN have been initiated. Confirm that the registration is completed and that a PDU session can be established.
2	1Call test	Confirm data communication of the UE under normal conditions.	After the PDU session is established, confirm that it is possible to ping the server located at the N6 interface.
3	RF Power OFF/ON	Assuming a RAN shutdown and verify that the UE can successfully connect and enable data communication after the RAN is restarted.	After the PDU session is established, disable the RAN. When the RAN is re-enabled, confirm that the UE can successfully establish the PDU session again.
4	UE Power OFF/ON	Assuming user-initiated power OFF/ON operations for the UE and confirm that the UE can successfully connect and enable data communication after it is powered on.	After the PDU session is established, turn off the power of the UE. When the power is turned back on, confirm that the UE can successfully establish the PDU session again.
5	Airplane mode OFF/ON	Assuming user-initiated airplane mode ON/OFF operations and verify that the UE can successfully connect and enable data communication after airplane mode is disabled.	After the PDU session is established, enable the airplane mode on the UE. When airplane mode is disabled, confirm that the UE can successfully establish the PDU session again.

3.1.5. Test Procedures

In this test, we will verify the interconnection and data communication based on the signals specified in items 1 to 5 of the 3GPP specifications [1][2]. Each signal will be confirmed using packet capture.

1. Registration and PDU Procedure Verification
2. Verification of Data Communication Availability After UE Connection
3. Verification of Connection Availability and Procedures Between 5GC and UE After RAN Shutdown and Restart
4. Verification of Connection Availability and Procedures After UE Shutdown and Restart
5. Verification of Connection Availability and Procedures After Disabling Airplane Mode on UE

In the event that a connection failure occurs or signals outside of the 3GPP specifications are detected during testing, all parties will collaborate to analyze the root cause and work on improvements. If the cause is not identified within the testing period, a retest will be scheduled for the future.

3.1.6. Test Results and Discussion

The combinations that were confirmed to be interconnectable in this test are shown in Table 3-7. UEs labeled with 'OK' are those that have passed all test items. Regarding the UEs manufactured by Sumitomo Electric Industries (SEI), some combinations have not been tested due to their late participation in this project.

Since the NEC-manufactured UE reached End of Life and its product support ended in January 2025, this UE was excluded from the Tests conducted thereafter.

From October 2025, three additional KYOCERA-manufactured UE models were added, and interconnection Tests were carried out. As the total number of KYOCERA UE models became four, this document refers to the UEs by the abbreviations KYOCERA (A), (B), (C), and (D). Please refer to Table 3-3 for the official product names.

In the Tests using KYOCERA UE (B), (C), and (D), coordination of machine usage among the 5GC and RAN vendors became difficult, and therefore connection Tests for all combinations could not be completed. The results of the combinations for which the Tests were completed are shown in Table 3-8.

Table 3-7 Interconnection Test Results

5GC	RAN	UE										
		Askey	Compal	D-Link	HYTECINTER	NEC	NEC Magnus	Nokia	PCO	Pegatron	KYOCER A(A)	SEI
HPE	Askey	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
HPE	LITE-ON	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
NTT-TX	Askey	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
NTT-TX	LITE-ON	OK	OK	OK *2	OK	OK	OK	OK	OK	OK	OK	-
HPE	NEC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
NTT-TX	NEC Magnus	OK *2	OK	OK	OK *2	OK	OK	OK	OK	OK *2	OK	-
NTT-TX	Airspan	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
Saviah	Pegatron	OK *2	OK	OK *2	OK	OK	OK	OK	OK	OK	OK	-

HPE	Compal	*1	OK	OK	OK	OK	OK	*1	OK	OK	OK	-
Saviah	Airspan	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	-
Saviah	HTC G REIGNS	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
HPE	NEC Magnus	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	FLARESYST EMS	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
HPE	HTC G REIGNS	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
NTT-TX	FLARESYST EMS	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
HPE	Pegatron	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
QCT	FLARESYST EMS	OK	OK	*1	OK	*1	OK	*1	OK	OK	OK	OK
QCT	Airspan	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	NEC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
QCT	Askey	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
NTT-TX	HTC G REIGNS	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
QCT	NEC Magnus	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
NTT-TX	Pegatron	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
QCT	NEC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	QCT	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	LITE-ON	OK	*3	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	Compal	OK	*3	OK	OK	OK	OK	OK	OK	OK	OK	OK
NTT-TX	Compal	OK	*3	OK	OK	OK	OK	OK	OK	OK	OK	OK
Saviah	NEC Magnus	OK	*3	OK	OK	OK	OK	OK	OK	OK	OK	OK

*1: The combinations that are either not connectable or scheduled for retesting due to one of the connection failure events shown in Table 3-9. The cause analysis information for each combination will not be disclosed in this report.

*2: At the time of the first version of the report, the combination was not connectable, but it became connectable after subsequent retesting.

*3 Due to the End of Life of the product, it was excluded from the Test scope.

Table 3-8 Interconnection Test Results of Additional UEs (KYOCERA UE)

5GC	RAN	UE		
		KYOCERA (B)	KYOCERA (C)	KYOCERA (D)

NTT-TX	Askey	OK	OK	OK
NTT-TX	Compal	OK	OK	OK
NTT-TX	HTC	OK	OK	OK
NTT-TX	LITE-ON	OK	OK	OK
NTT-TX	NEC Magnus	OK	OK	OK
Saviah	Askey	OK	OK	OK
Saviah	Compal	OK	OK	OK
Saviah	HTC	OK	OK	OK
Saviah	LITE-ON	OK	OK	OK
Saviah	NEC Magnus	OK	OK	OK

The results of all 335 combinations that have been processed by October 2025 are shown in Figure 3-3. There are 330 connectable combinations, with a pass rate of 98.5% for the mutual connection tests.

The breakdown of the 11 combinations that were not connectable is shown in Table 3-9. Out of the 11 combinations that were not connectable, 6 have had their causes identified and the issues resolved, while the causes of the remaining 5 are still under investigation.

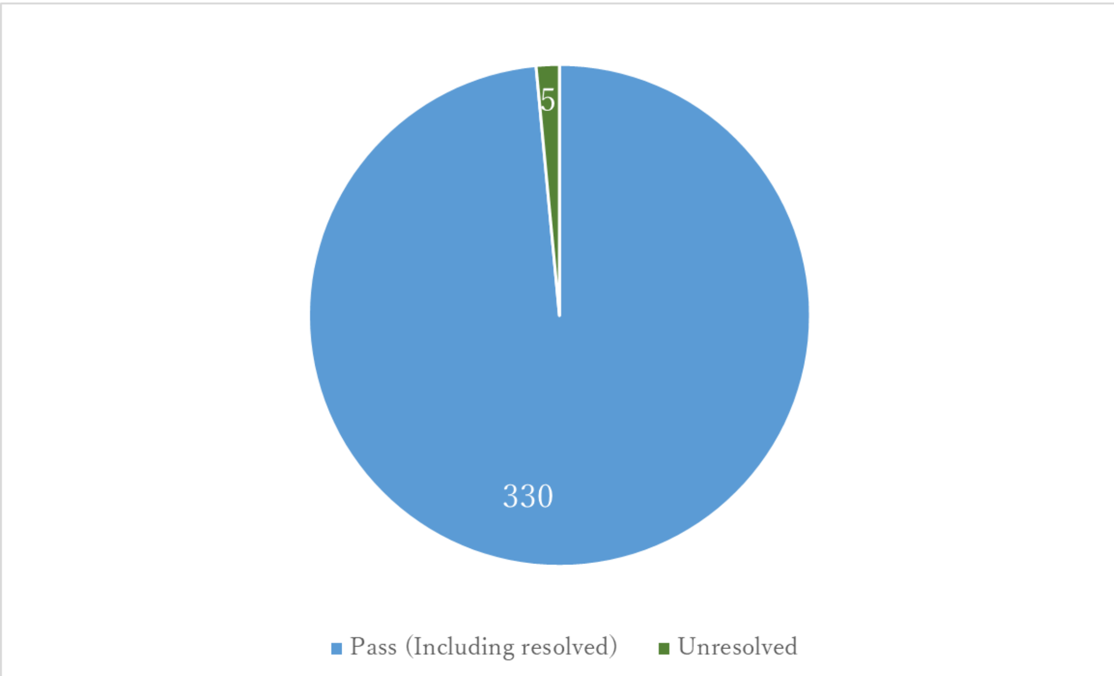


Figure 3-3 Interconnection Test Results

Table 3-9 Interconnection Test Issues

Status	Number of Issues (11)	Issue
Resolved	5	Behavior where the UE fails the Registration procedure and does not complete it.
	1	Behavior where the UE repeatedly releases and establishes PDU sessions after reconnecting.
Unresolved	1	An issue has occurred where the PDU session establishment has failed.
	2	An issue has occurred where data communication fails after the PDU session is established.
	1	An issue has occurred where the PDU session cannot be established after the RAN is powered off and then back on; however, reconnection is possible after restarting the UE.
	1	An issue has occurred where registration fails after the UE is restarted.

3.1.7. Considerations for Compliance in Interconnection and Specific Examples of Connection Failures

The Private 5G equipment used in this test has been developed in accordance with 3GPP specifications, and no exchanges of non-standard signals have been observed. On the other hand, while a connection success rate of 98.5% was achieved, there were instances where certain combinations initially failed to connect. However, through troubleshooting, it became possible to establish a connection in those cases. Through this troubleshooting process, the considerations for compliance in interconnection have been summarized as shown in Table 3-10. In addition, this section will introduce specific examples of connection failures.

Table 3-10 Points to Consider for Compliance in Interconnection

Target			Points to Consider
5GC	RAN	UE	
-	✓	✓	Confirm that the RAN can process the packet size sent by the UE, as the acceptable size of the UE Capability Information packet transmitted by the UE may vary in the RAN.
✓	✓	✓	Be aware of the versions of the 3GPP releases supported by the 5GC, RAN, and UE to avoid inconsistencies caused by unsupported signaling messages exchanged by the Private 5G equipment.
✓	✓	-	Some UEs may retain VoIP APN information, so ensure that the 5GC is configured to accept the APN.
✓	-	✓	During setup, verify the necessity of VLAN configuration and implement the appropriate VLAN settings (for N2 and N3 segment configurations).
✓	✓	-	Ensure that the 5QI values for the DNN are mutually supported by both the 5GC and RAN.

・Case Study 1: Connection failure due to the RAN node discarding the UE Capability Information signal.

There were UE devices that could not remain in the coverage area with a specific combination of 5GC and RAN. However, by analyzing the N2 packet capture and RAN logs obtained during the test, the cause was identified, and the issue was resolved through a software modification of the RAN.

An excerpt of the packet capture obtained during the occurrence of the issue is shown in Figure 3-4.

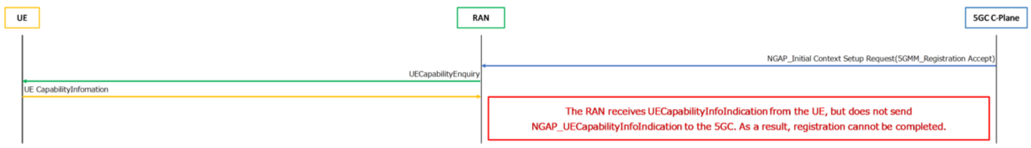


Figure 3-4 Case Study 1 Overview

According to the 3GPP specifications, when the RAN receives the 5GMM_Registration Accept from the 5GC, it is supposed to return the NGAP_UECapabilityInfoIndication to the 5GC. However, the RAN did not return this signal.

Analysis of the RAN system logs during the occurrence of the issue revealed that there was a failure in processing the UE Capability Information received from the UE, which led to its discard.

The UE Capability Information contains technical information, protocol information, security details, and other network function information supported by the UE. It was found that the UE experiencing the issue had a large amount of this information, resulting in an oversized packet that the RAN could not process.

Therefore, in this project, it was determined that the issue was due to a malfunction in the internal processing of the RAN, and not a problem arising from the combination of Private 5G equipment. The RAN vendor implemented a software modification, and the resolution of the issue was confirmed. Since then, no occurrences of the same or similar issues have been observed.

・Case Study 2：Connection Failures Due to Differences in Supported 3GPP Release Versions

There were User Equipments (UEs) that could not remain in coverage with a specific combination of 5G Core(5GC) and Radio Access Network(RAN). The signaling exchanges between Private 5G devices captured during the occurrence of the issue are illustrated in Figure 3-5.

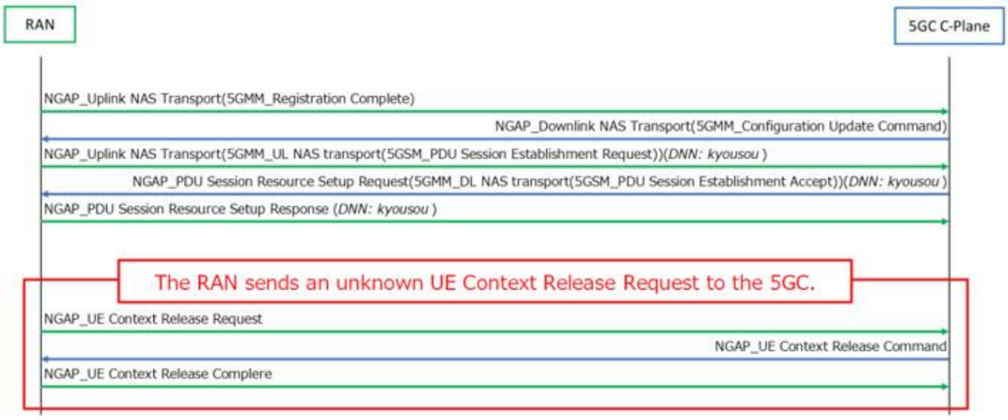


Figure 3-5 Case Study 2 Overview

Immediately after the PDU session was established, an unknown NGAP_UE Context Release Request was sent from the RAN to the 5GC. Analysis of the NGAP_PDU Session Establishment Request signal from the UE, along with the examination of the RAN system logs, revealed that the signals from the UE experiencing the issue contained messages from 3GPP Release 16 [3]. Additionally, it was determined that the RAN in use was not compliant with 3GPP Release 16.

After the RAN vendor implemented a software modification to skip the processing of Release 16 messages within the signaling, the issue was resolved. Since then, no similar issues have been observed.

・Case Study 3：Connection Failure Due to Rejection of Voice APN

There were UEs that could not remain in coverage with a specific combination of 5GC and RAN. Through packet analysis during the occurrence of the issue, we were able to identify the root cause and resolve the problem. An excerpt of the packets during the occurrence of the issue is shown in Figure 3-6.

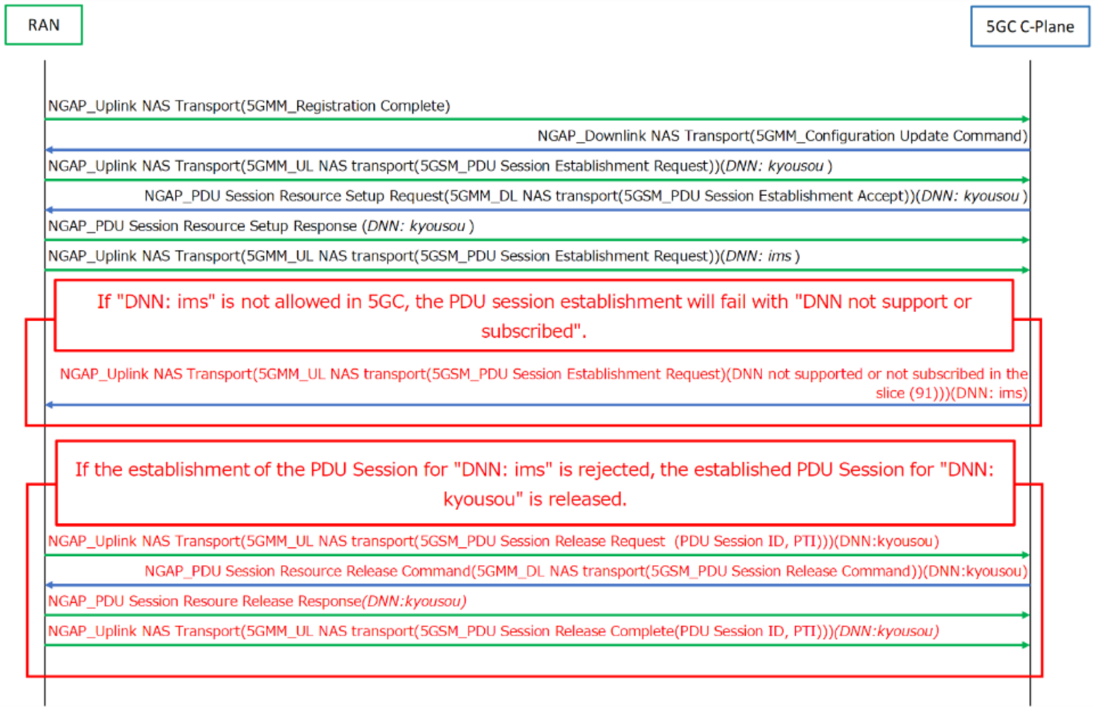


Figure 3-6 Case Study 3 Overview

In this project, we are conducting connection tests using the DNN “kyousou”. Additionally, there were UEs attempting to establish a PDU session using the DNN “ims”.

Since the 5GC did not have the DNN “ims” configured, it sent a PDU Session Release Command in response to the PDU session establishment request for “ims”, thereby rejecting the connection establishment. Subsequently, there were UEs that, after the failure of the PDU session establishment for “ims”, also disconnected the established PDU session for data.

According to the 3GPP specifications, the issue arises when UEs with an internal DNN of "ims" establishes a PDU session while the 5GC supports IMS_VoPS.

An example of the 5GMM_Registration_Accept signal[4] is shown in Figure 3-7.

```
v 5GS network feature support
    Element ID: 0x21
    Length: 1
    0... .... = MPS indicator (MPSI): Access identity 1 not valid in RPLMN or equivalent PLMN
    .0.. .... = Interworking without N26 (IWK N26): Not supported
    ..00 .... = Emergency service fallback indicator (EMF): Emergency services fallback not supported (0)
    .... 00.. = Emergency service support indicator (EMC): Emergency services not supported (0)
    .... ..0. = IMS voice over PS session over non-3GPP access indicator (IMS-VoPS-N3GPP): Not supported
    .... ...1 = IMS voice over PS session indicator (IMS VoPS): Supported
```

Figure 3-7 Example of NGAP Registration Accept Signal for 5GC Supporting IMS_VoPS

When the IMS VoPS bit is set, the UEs with an internal DNN of "ims" requests the establishment of PDU sessions using both the "kyousou" and "ims" DNNs.

The failure of connection establishment using the "ims" DNN can be avoided by either configuring the 5GC to allow the "ims" DNN or by ensuring that the 5GC does not support IMS_VoPS.

・Case Study 4：Connection failures due to misconfigurations in the Private 5G network settings.

A problem occurred where all UEs were unable to remain in coverage with a specific combination of 5GC and RAN, or if they were able to connect, they would be immediately disconnected. However, by analyzing the N2 and N3 packet captures obtained during the verification tests, along with network monitoring from the RAN, we were able to identify the root cause. The issue was resolved by modifying the configuration of the network switch.

The excerpt of the packet capture obtained during the issue is shown in Figure 3-8.

It was confirmed that a PDU Session Establishment Reject was returned from the 5GC immediately after the registration was completed.

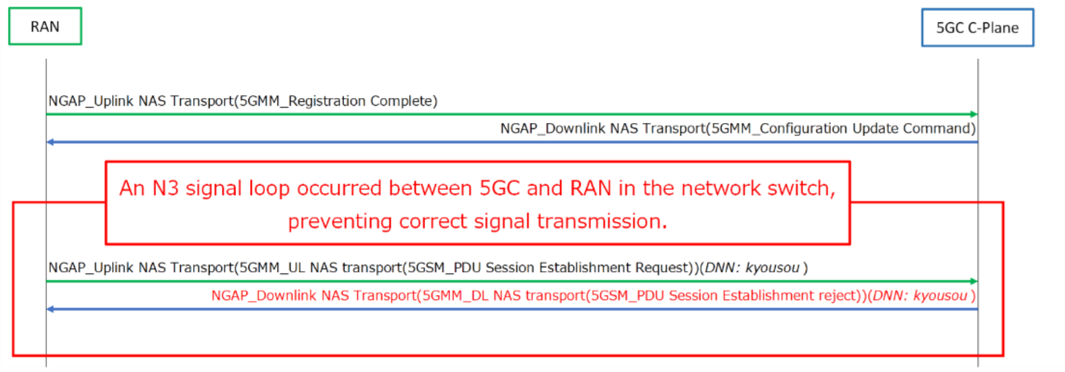


Figure 3-8 Case Study 4 Overview

Based on the information from the packet capture, we checked the system logs of the 5GC and RAN, as well as packet monitoring, and found that packets sent from the N3 port of the 5GC were reaching the N2 port of the RAN. This indicated that the packets were not arriving at the correct port.

The 5GC and RAN that experienced the issue required VLAN configuration on the network switch in the operating environment. Although the VLAN settings had been implemented, a configuration error led to packet mixing.

In the introduction of Private 5G equipment that includes VLAN in the operational requirements, it is essential to create a network diagram in alignment with all parties involved and to carefully consider and construct the test environment to prevent configuration errors.

・Case Study 5：Connection failure due to differences in the 5QI supported by the 5GC and RAN

There was a UE that could not remain in the coverage area with a specific combination of 5GC and RAN. However, by correlating the N2 packet capture obtained during testing with the RAN specifications, we identified and resolved the root cause of the issue. An excerpt of the packet capture obtained during the occurrence of the issue is shown in Figure 3-9.

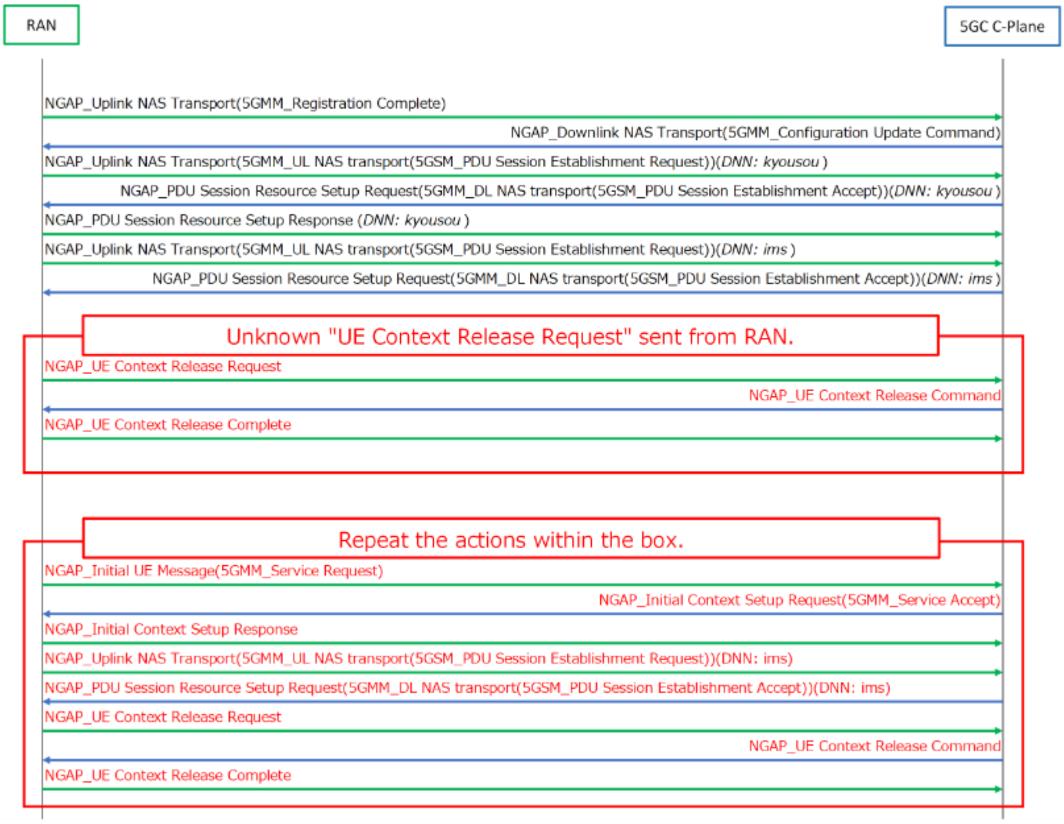


Figure 3-9 Case Study 5 Overview

When establishing a PDU session for the IMS DNN, the RAN was sending an unknown UE Context Release Command to the 5GC. Upon analysis, it was found that the 5QI parameter within the NGAP_PDU Session Establishment Accept signal from the 5GC for the IMS DNN was set to '4', which is a parameter not supported by the RAN.

The 5QI parameter within the PDU Session Establishment Accept signal [4], which was the cause of the issue, is illustrated in Figure 3-10. Please note that while the problematic behavior occurred during the PDU session establishment for the IMS DNN in this project, it is not limited to this specific DNN.

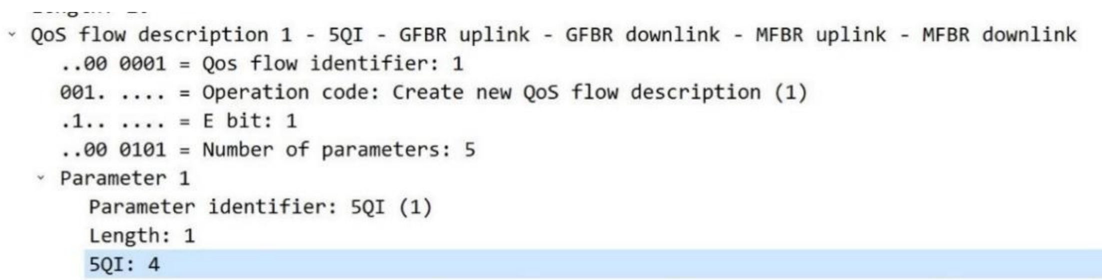


Figure 3-10 Example of PDU Session Establishment Accept Signal for 5QI=4

When the 5GC adjusted the 5QI parameter for the IMS DNN to a value acceptable by the RAN, the problematic behavior was resolved, and no further occurrences have been observed since. In interconnection testing and during commercial deployment, it is essential to verify the support information for 5QI and ensure appropriate configurations for the combination of 5GC and RAN.

3.2. Throughput Testing

3.2.1. Test Configuration

The configuration of this test is illustrated in Figure 3-11. The RAN and UE will be deployed within a shielded box or a shielded tent.

Similar to the interconnection testing, to minimize the impact of environmental differences on the test results, the output power of the RAN and the placement of the UE were adjusted to achieve an RSRP value of approximately -70 dBm for the UE.

Since the information regarding the shielded box and shielded tent is similar to that presented in Table 3-2, this section will be omitted.

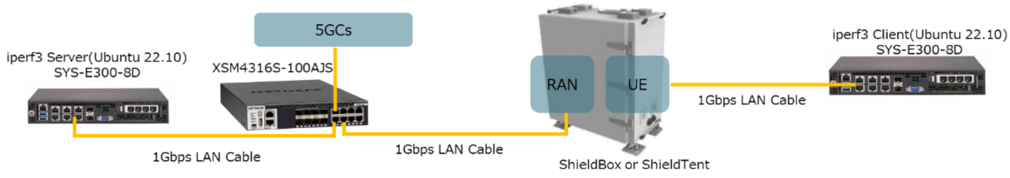


Figure 3-11 Throughput Test Configuration

3.2.2. List of Test Equipment

The names and specifications of the test equipment used in this trial are similar to the information presented in Table 3-3; therefore, this section will be omitted.

3.2.3. Test Items

The items for throughput measurement are shown in Table 3-11.

The transmission throughput for interconnectable combinations will be measured for both synchronous (TDD) and semi-synchronous (TDD1) modes, specifically for UDP and TCP in both uplink (UL) and downlink (DL) scenarios.

Additionally, we will verify that the throughput when the RAN is configured to semi-synchronous (TDD1) mode is consistent with the expected rates based on the configuration.

The tool used for the tests was iperf3.

Table 3-11 Throughput Test Items

No.	Sync (TDD)/Semi-sync(TDD1)	Protocol	Direction
1	Synchronous(TDD)	UDP	UL
2			DL
3		TCP	UL
4			DL
5	Semi-Synchronous(TDD1)	UDP	UL
6			DL
7		TCP	UL
8			DL

3.2.4. Test Procedures

The options and parameters for the iperf3 command to be executed were determined in agreement with all participating companies in the project, ensuring that no advantages or disadvantages arise for any Private 5G devices.

The execution command and option parameters are detailed below. The downlink throughput test will be conducted using iperf3 in Reverse Mode, without implementing any routing configurations on the Private 5G devices.

Furthermore, if sufficient performance is not confirmed, a re-test will be conducted within the testing period after analyzing the causes, using 70% of the nominal throughput values provided by each company as a guideline. Cases where the root cause cannot be identified will not be included in the discussion of this report.

・Synchronous(TDD) UDP

UP Link: iperf3 -u -c ***iperf3Server Addr*** -l 1300 -b 75M -P 10 -O 10 -t 60

Down Link: iperf3 -u -c ***iperf3Server Addr*** -l 1300 -b 75M -P 10 -O 10 -t 60 -R

・Semi-Synchronous(TDD1) UDP

UP Link: iperf3 -u -c ***iperf3Server Addr*** -l 1300 -b 49M -P 10 -O 10 -t 60

Down Link: iperf3 -u -c ***iperf3Server Addr*** -l 1300 -b 49M -P 10 -O 10 -t 60 -R

・Synchronous(TDD) / Semi-Synchronous (TDD1) TCP

UP Link: iperf3 -c ***iperf3Server Addr*** -l 1300 -P 10 -O 10 -t 60

Down Link: iperf3 -c ***iperf3Server Addr*** -l 1300 -P 10 -O 10 -t 60 -R

3.2.5. Test Results and Discussion

3.2.5.1. Test Results Compared to Target Values

The distribution chart shown in Figure 3-12 illustrates the percentage of throughput obtained from the test results compared to the nominal throughput values of each RAN device.

Since the test environments for each RAN device vary by vendor, it is expected that the results may not align perfectly with the nominal values. However, the fact that 80% of the results fell within the range of 100% ± 30% of the published values indicates that the test environment is considered appropriate for evaluating the performance of Private 5G devices from different vendors.

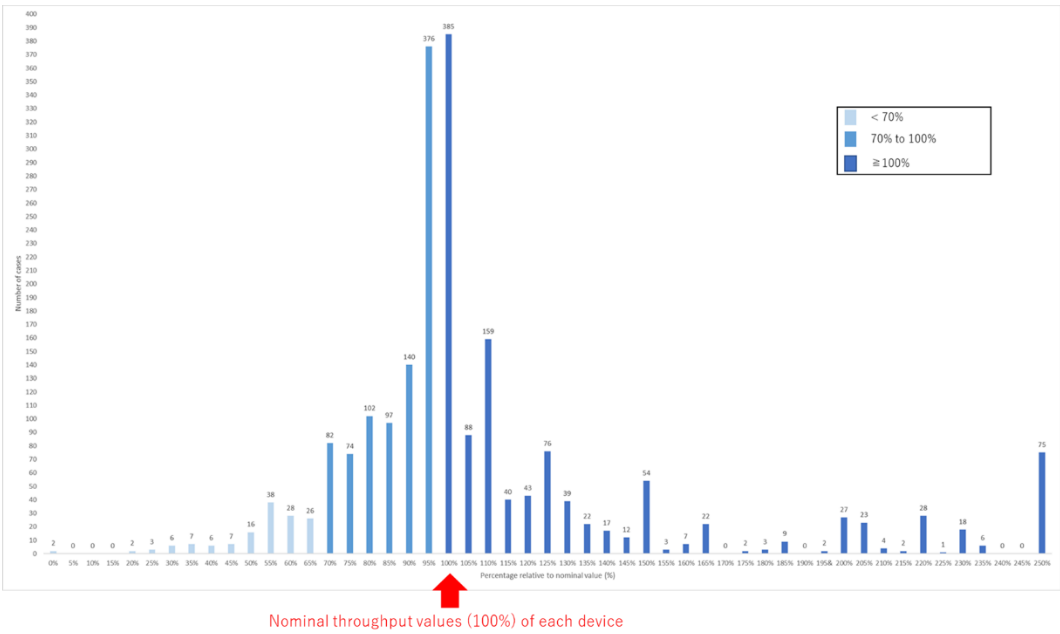


Figure 3-12 Nominal Value Achievement Rate and Pattern Count

3.2.5.2. Test Results from the Perspective of RAN and UE Performance

The throughput test results are presented in Figure 3-13 to Figure 3-32.

Differences in the test results were observed due to the supported QAM (Quadrature Amplitude Modulation) levels by the RAN and the number of antennas equipped on the RAN.

Based on Table 3-4, a grouping table categorizing the RAN used for measurements according to the QAM levels and the number of antennas equipped has been presented in Table 3-12.

The aggregation and analysis of the throughput test results will be conducted for each group.

Table 3-12 Groups divided by the number of UL antennas (QAM) x DL antennas (QAM) in the RAN

Group Number	RAN Specification
1	1(64)×2(256)
2	2(256)×2(256)
3	2(64)×4(64)
4	2(64)×4(256)
5	2(256)×4(256)

・Group 1: UL Antenna Count 1 (64QAM) x DL Antenna Count 2 (256QAM)

UL： The throughput speed remained almost the same regardless of the number of UL antennas in the UE(1 to 2). This is likely because the number of UL antennas in the RAN is 1, which means that variations in the number of UL antennas in the UE do not affect the throughput values.

In addition, in the semi-synchronous mode (TDD1), the proportion of UL communication is higher than in the synchronous mode (TDD). As a result, differences in throughput characteristics between the two modes were observed for both TCP and UDP.

DL：The throughput speeds yielded almost identical results, clustering within approximately 70% of the optimal throughput value.

Furthermore, in the semi-synchronous mode (TDD1), the proportion of DL communication is lower than in the synchronous mode (TDD). Consequently, differences in throughput characteristics between the two modes were observed for both TCP and UDP.

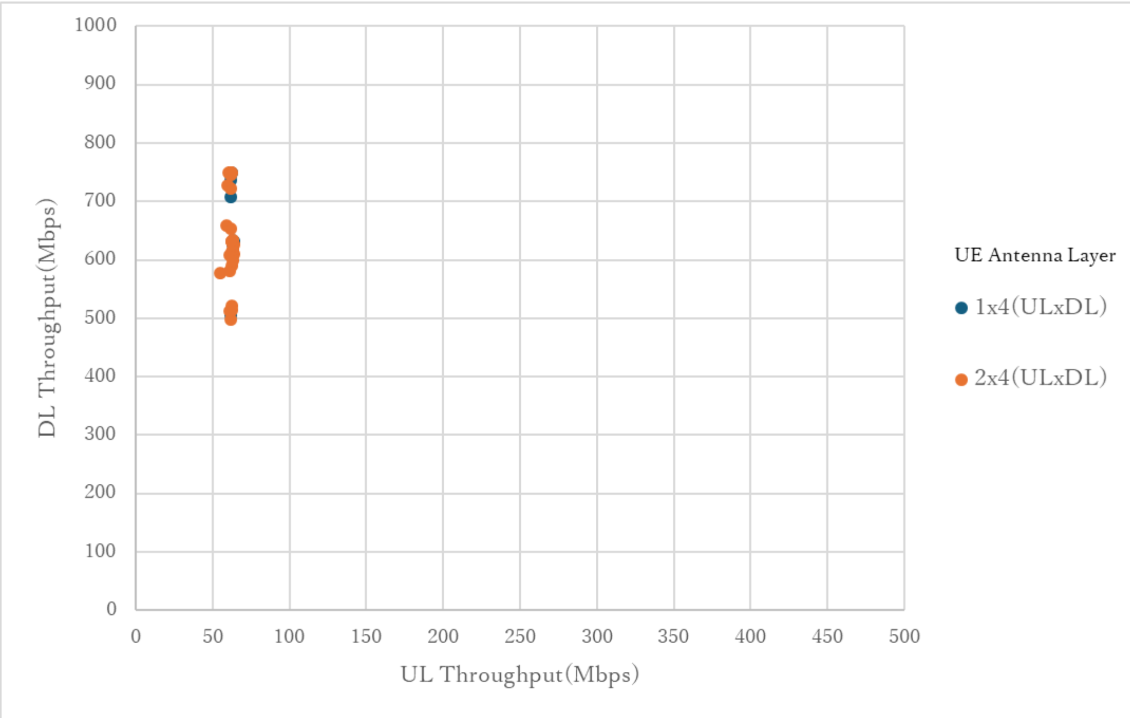


Figure 3-13 Synchronous UDP Throughput Test Results (Group 1)

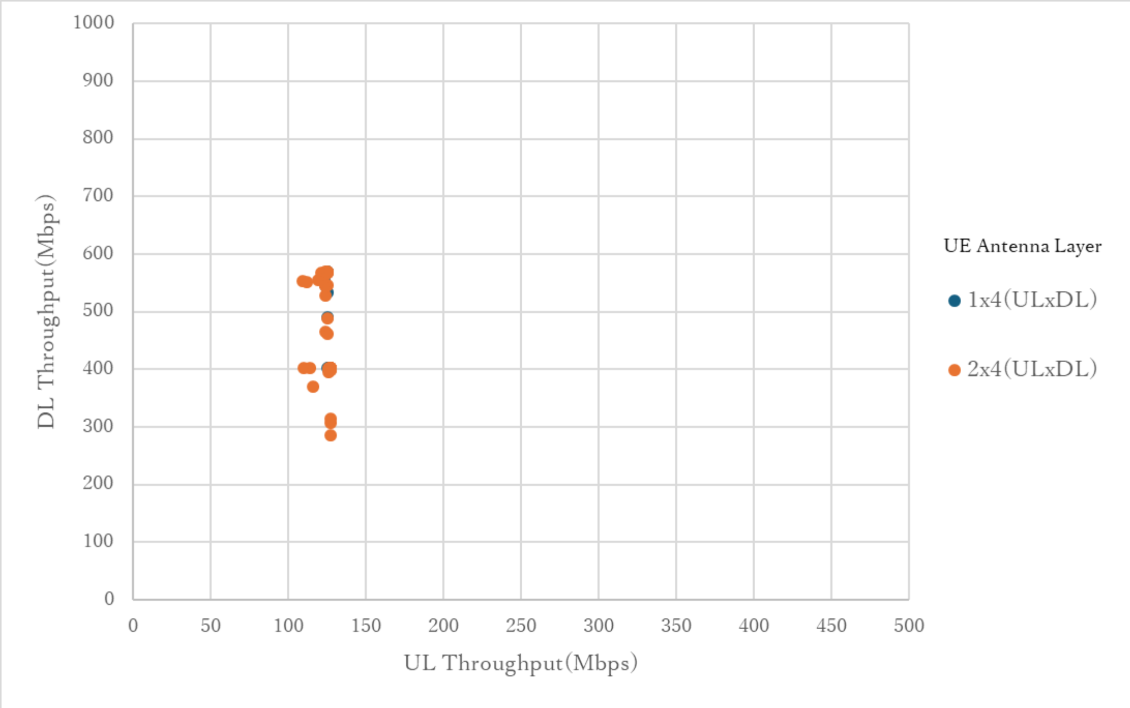


Figure 3-14 Semi-Synchronous UDP Throughput Test Results (Group 1)

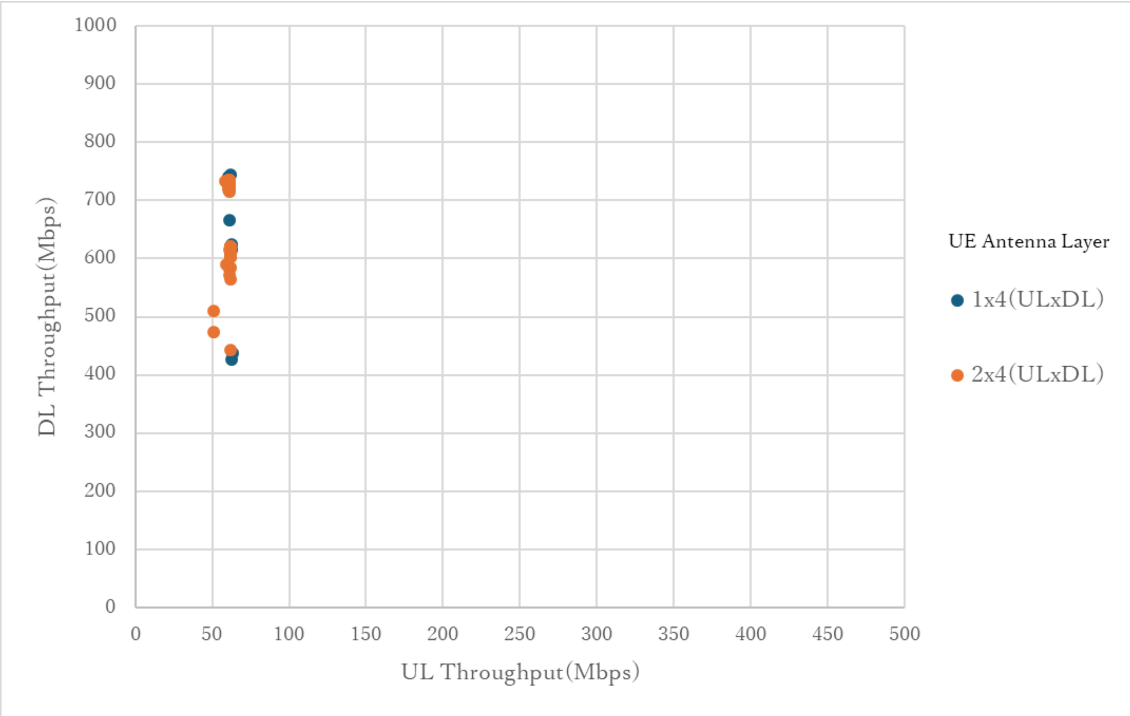


Figure 3-15 Synchronous TCP Throughput Test Results (Group 1)

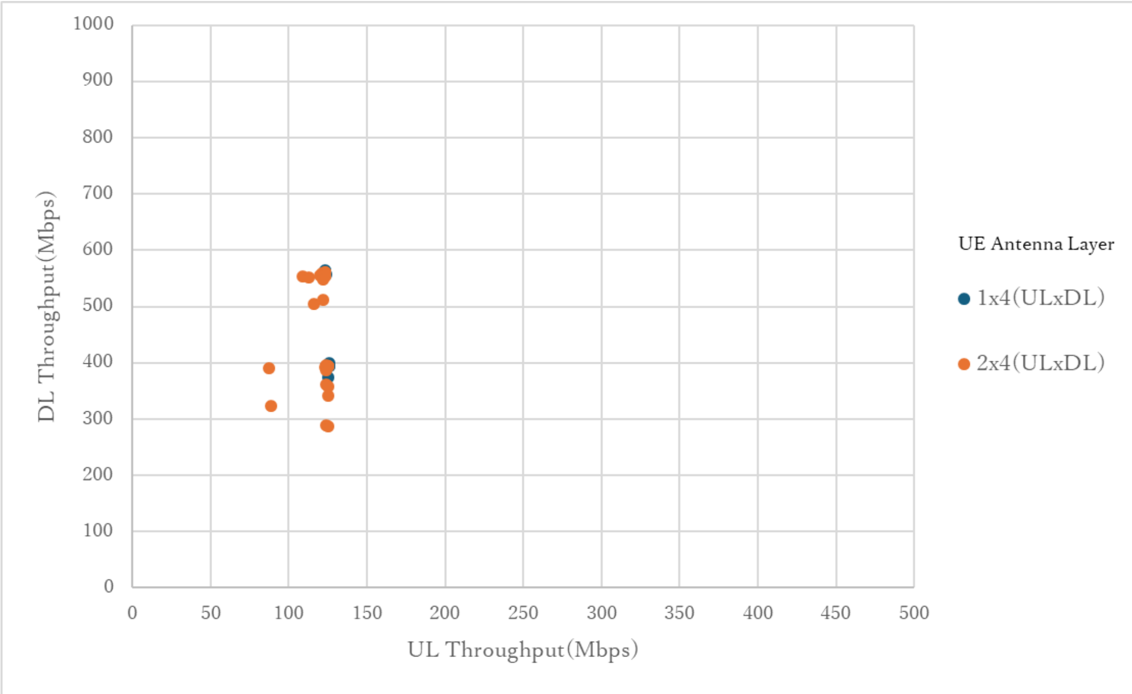


Figure 3-16 Semi-Synchronous TCP Throughput Test Results (Group 1)

・**Group 2: UL Antenna Count 2 (256 QAM) x DL Antenna Count 2 (256 QAM)**

UL：When comparing the optimal throughput values of UE with 1 UL antenna and 2 UL antennas, it is observed that the throughput speed with 2 UL antennas is approximately twice that of the configuration with 1 UL antenna.

This difference is likely attributed to the fact that the RAN has 2 UL antennas, which affects the number of antennas used by the UE for UL communication.

Additionally, in the semi-synchronous mode (TDD1), the proportion of UL communication is higher than in the synchronous mode (TDD). This resulted in observable differences in throughput characteristics between the two modes for both TCP and UDP.

DL：Throughput speeds were nearly identical, clustering within approximately 70% of the optimal throughput value. Additionally, in the semi-synchronous mode (TDD1), the proportion of DL communication is lower than in the synchronous mode (TDD), leading to observable differences in throughput characteristics between the two modes for both TCP and UDP. It was measured that both TCP and UDP exhibited better throughput in the synchronous mode compared to the semi-synchronous mode (TDD1).

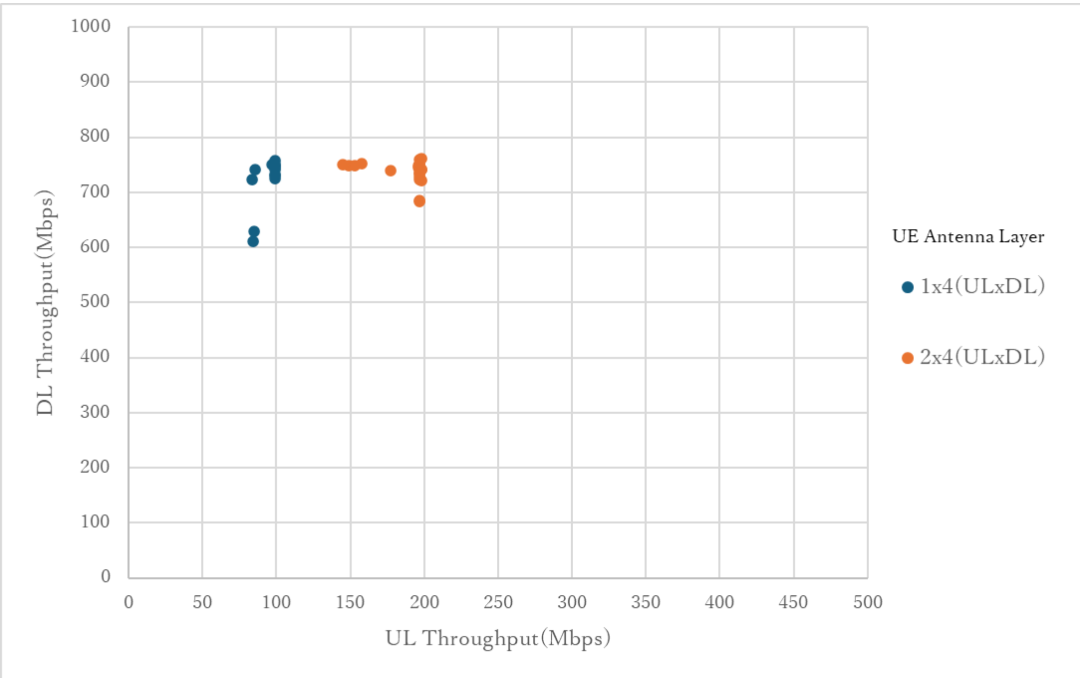


Figure 3-17 Synchronous UDP Throughput Test Results (Group 2)

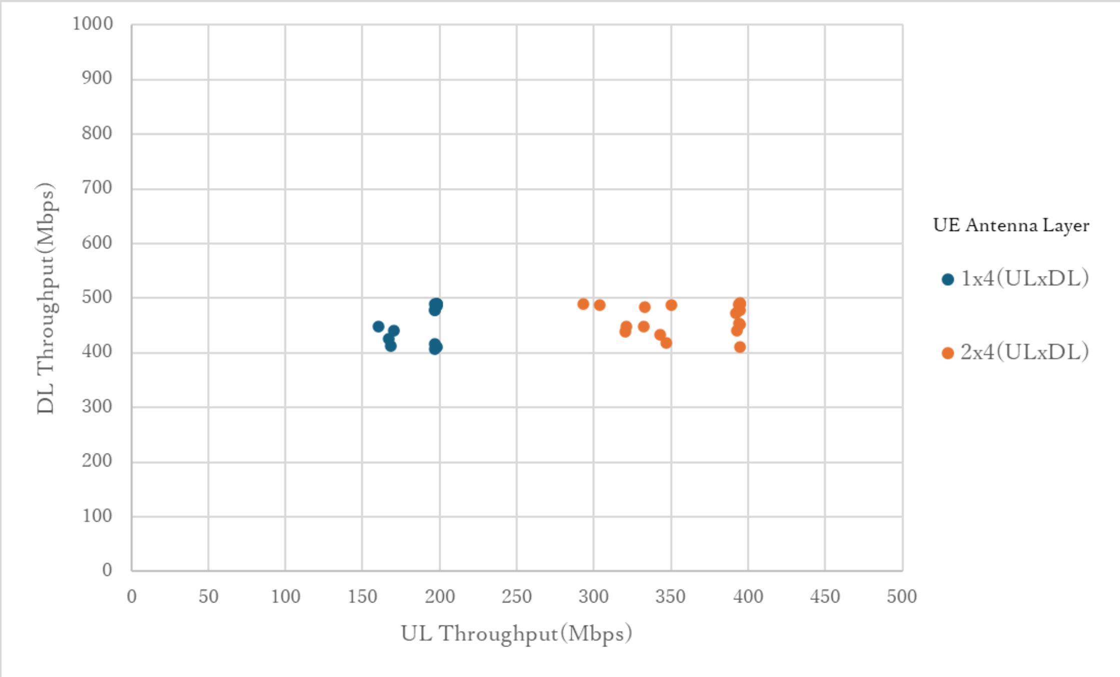


Figure 3-18 Semi-Synchronous UDP Throughput Test Results (Group 2)

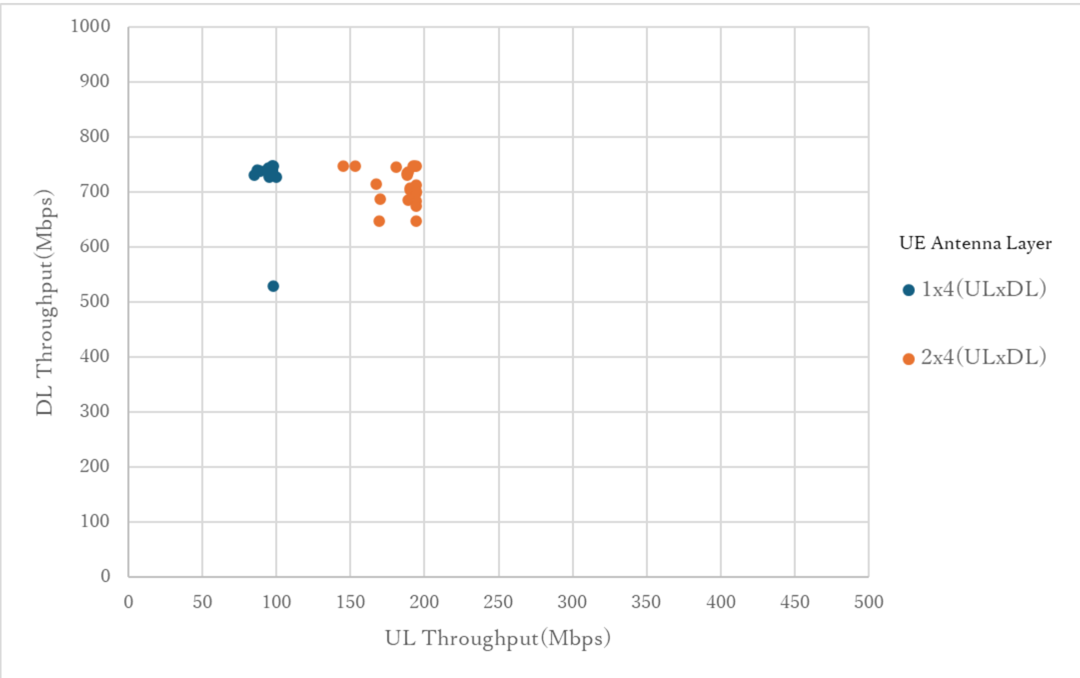


Figure 3-19 Synchronous TCP Throughput Test Results (Group 2)

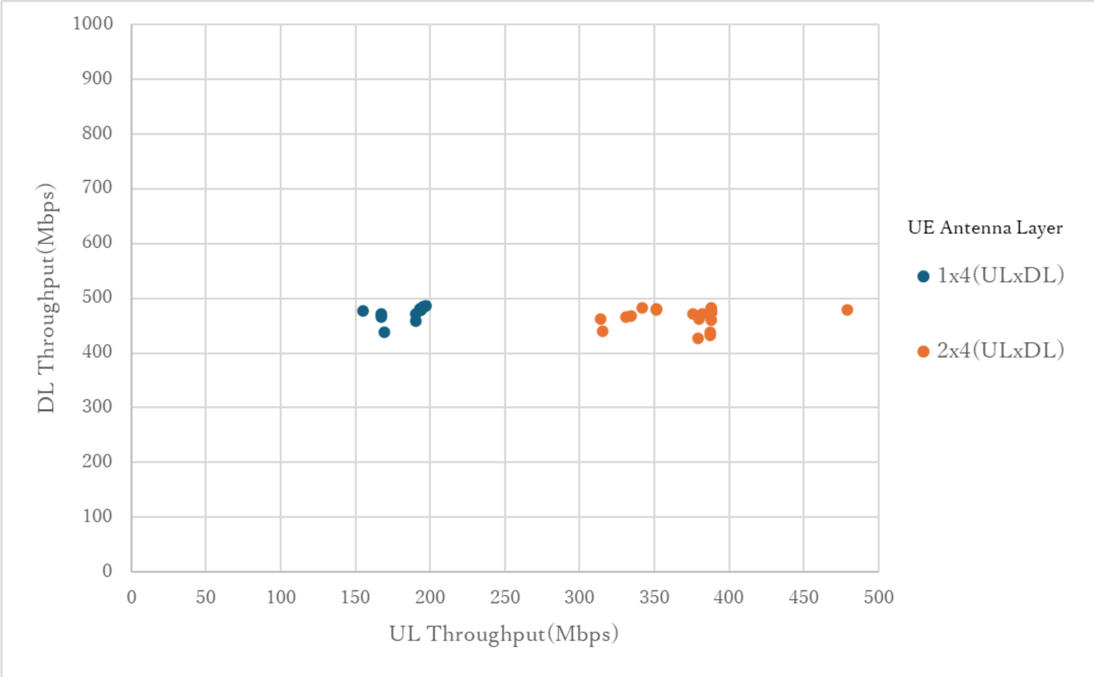


Figure 3-20 Semi-Synchronous TCP Throughput Test Results (Group 2)

・Group 3: UL Antenna Count 2 (64 QAM) x DL Antenna Count 4 (64 QAM)

UL： When comparing the best throughput values for UE with 1 UL antenna versus 2 UL antennas, it is observed that the throughput for 2 UL antennas is approximately twice that of the configuration with 1 UL antenna.

Additionally, in the semi-synchronous mode (TDD1), the proportion of UL communication is higher than in the synchronous mode (TDD), which allowed for the observation of differences in throughput characteristics between TCP and UDP.

DL：The throughput speeds are nearly identical, with the values clustering within approximately 70% of the best throughput value.

Furthermore, in the semi-synchronous mode (TDD1), the proportion of DL communication is lower than in the synchronous mode (TDD), which allowed for the identification of differences in throughput characteristics between TCP and UDP.

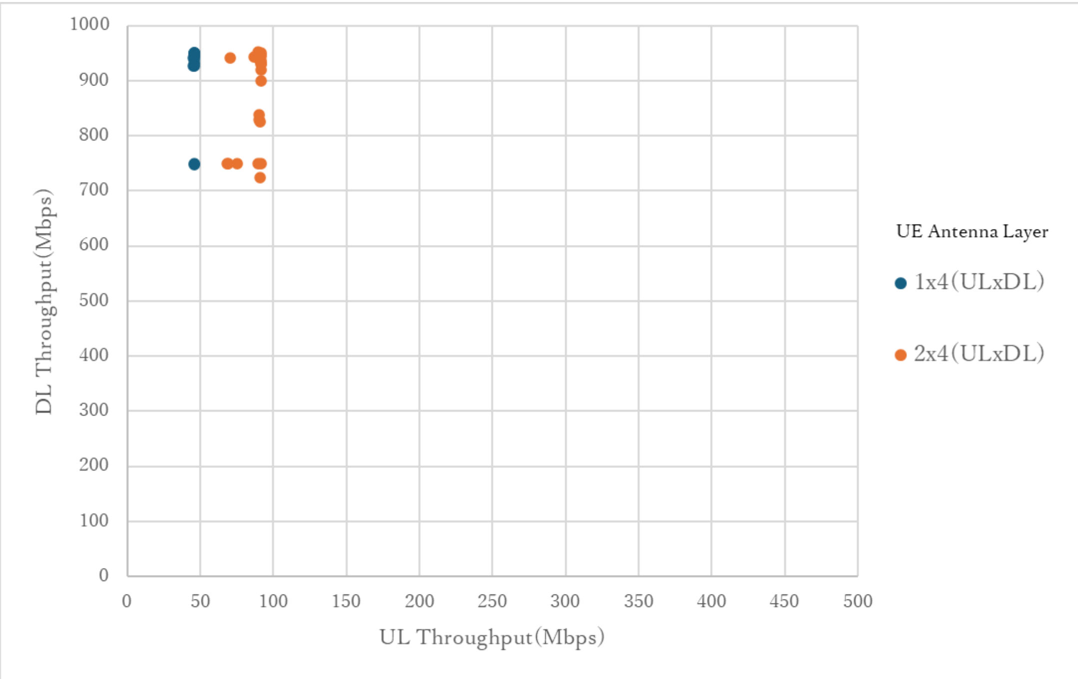


Figure 3-21 Synchronous UDP Throughput Test Results (Group 3)

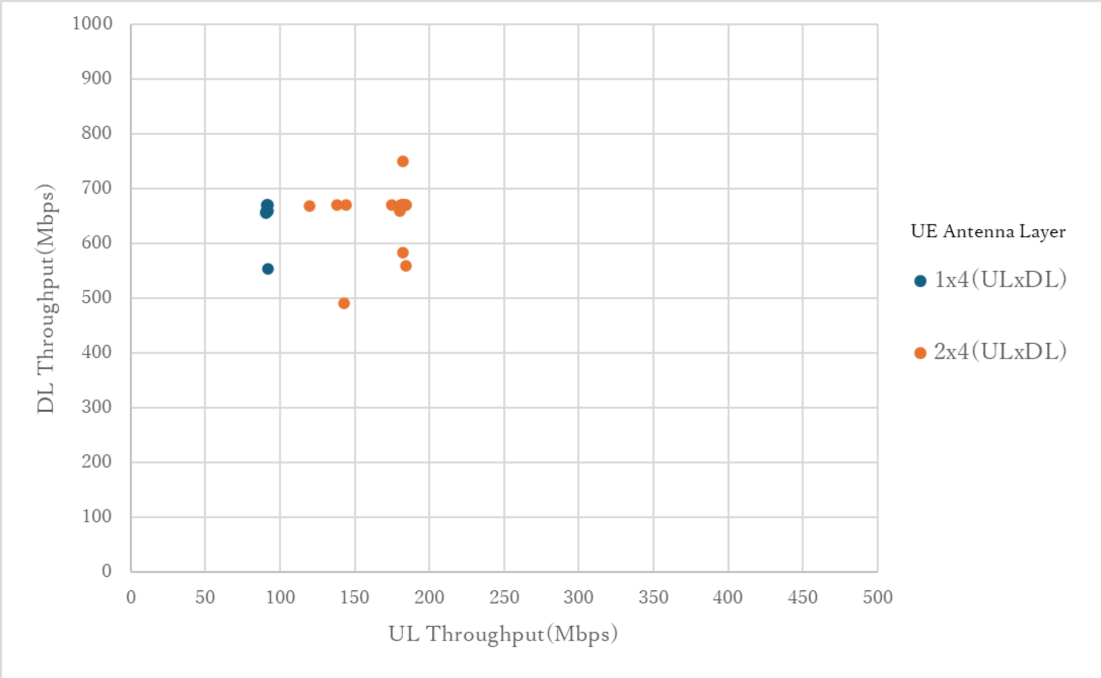


Figure 3-22 Semi-Synchronous UDP Throughput Test Results (Group 3)

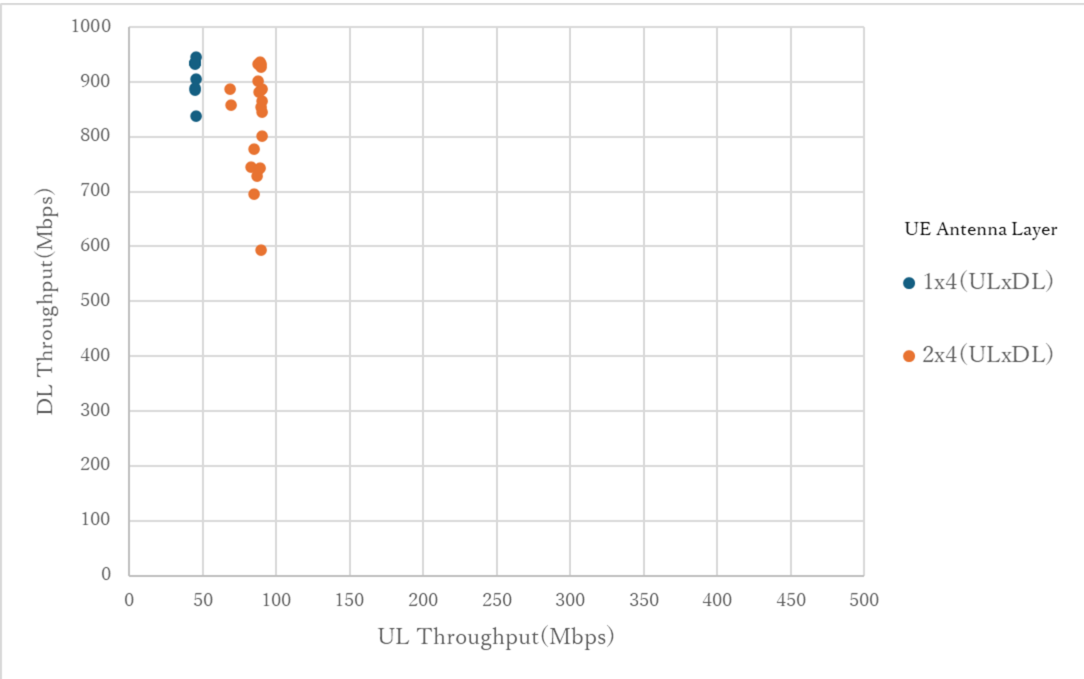


Figure 3-23 Synchronous TCP Throughput Test Results (Group 3)

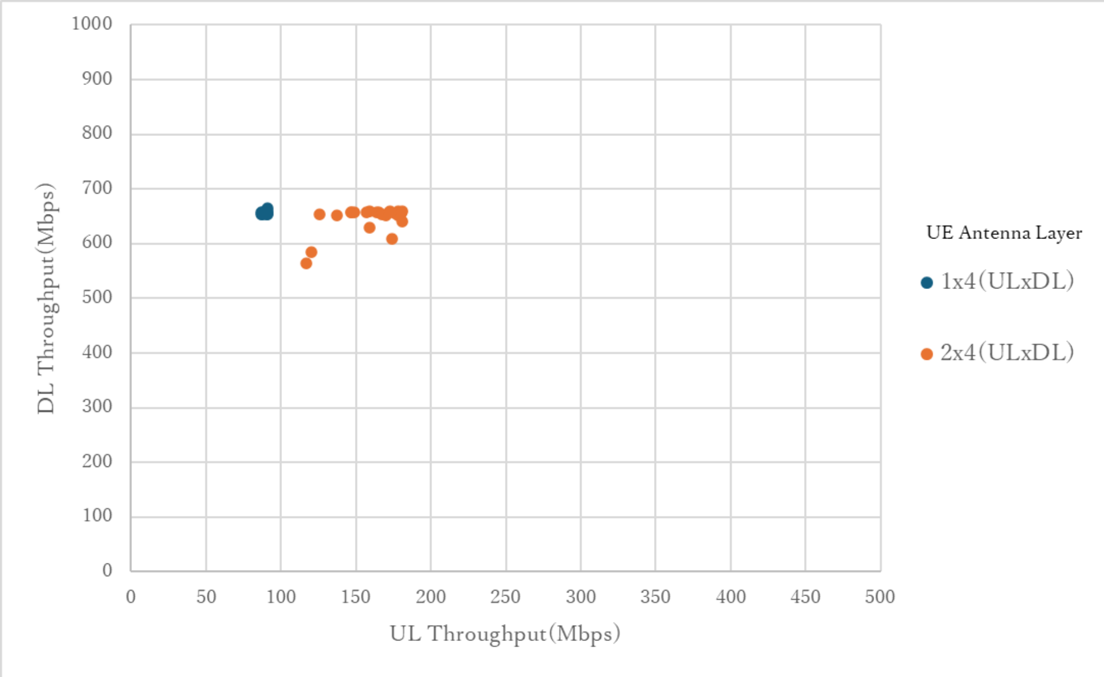


Figure 3-24 Semi-Synchronous TCP Throughput Test Results (Group 3)

・Group 4: UL Antenna Count 2 (64 QAM) x DL Antenna Count 4 (256 QAM)

UL：Due to the large number of RAN/UEs being measured, the results show some variability. When comparing the optimal throughput values for UE with 1 UL antenna and those with 2 UL antennas, it is observed that the throughput speeds for UE with 2 UL antennas are approximately twice that of the UE with 1 UL antenna.

Additionally, in the semi-synchronous mode (TDD1), the proportion of UL communication is higher than in the synchronous mode (TD), which allowed for the observation of differences in throughput characteristics between the two modes for both TCP and UDP.

DL：Due to the large number of RAN/UEs being measured, the results show variability. The DL throughput exceeded 350 Mbps, regardless of the differences between synchronous (TDD) and semi-synchronous (TDD1) modes, as well as between UDP and TCP.

Additionally, in the semi-synchronous mode (TDD1), the proportion of DL communication is lower than in the synchronous mode (TDD), which allowed for the observation of differences in throughput characteristics between the two modes for both TCP and UDP.

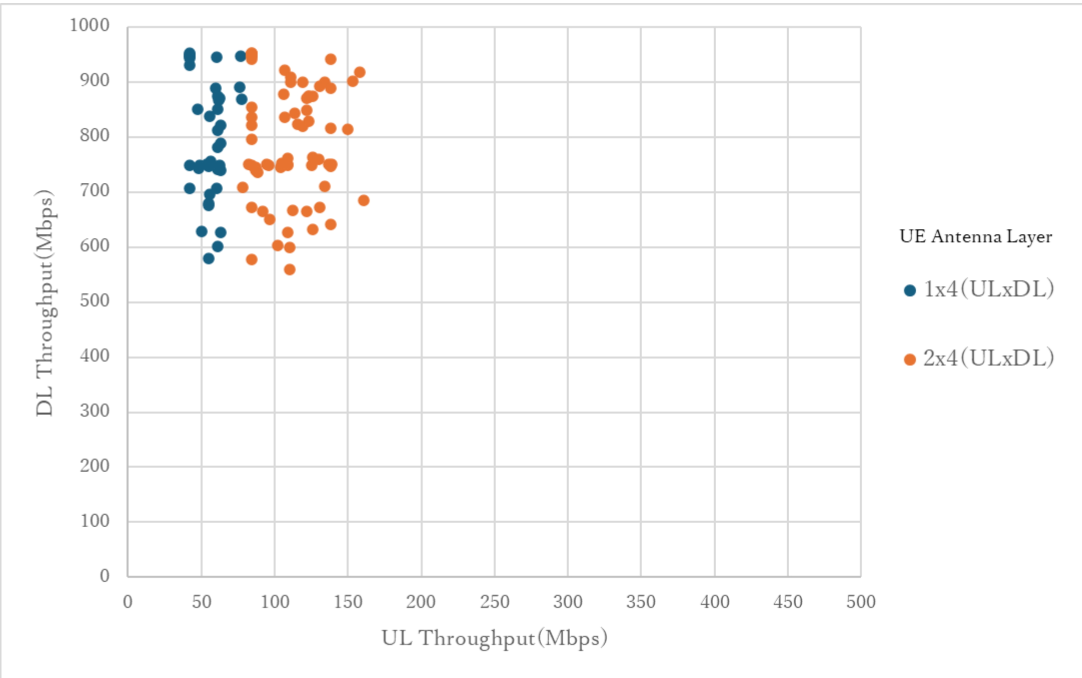


Figure 3-25 Synchronous UDP Throughput Test Results (Group 4)

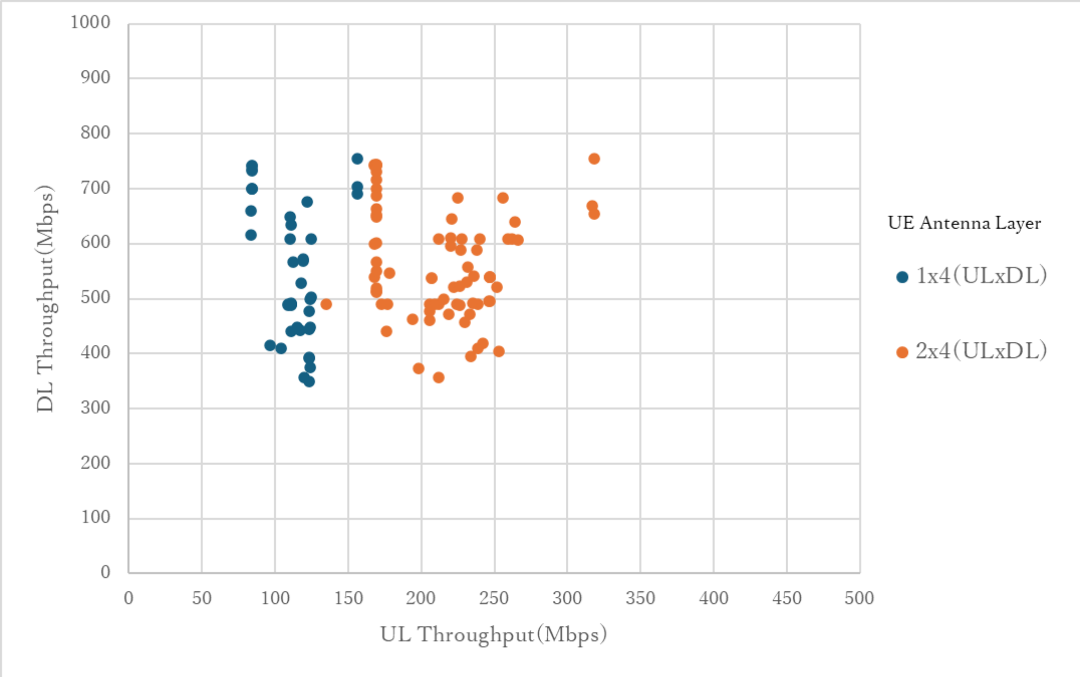


Figure 3-26 Semi-Synchronous UDP Throughput Test Results (Group 4)

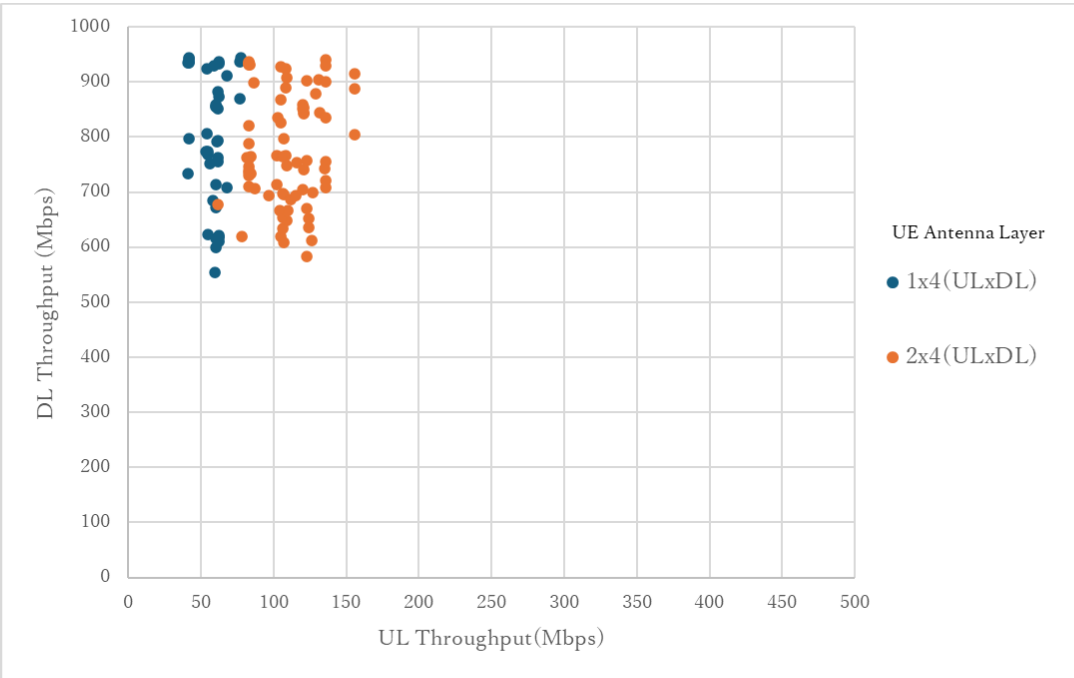


Figure 3-27 Synchronous TCP Throughput Test Results (Group 4)

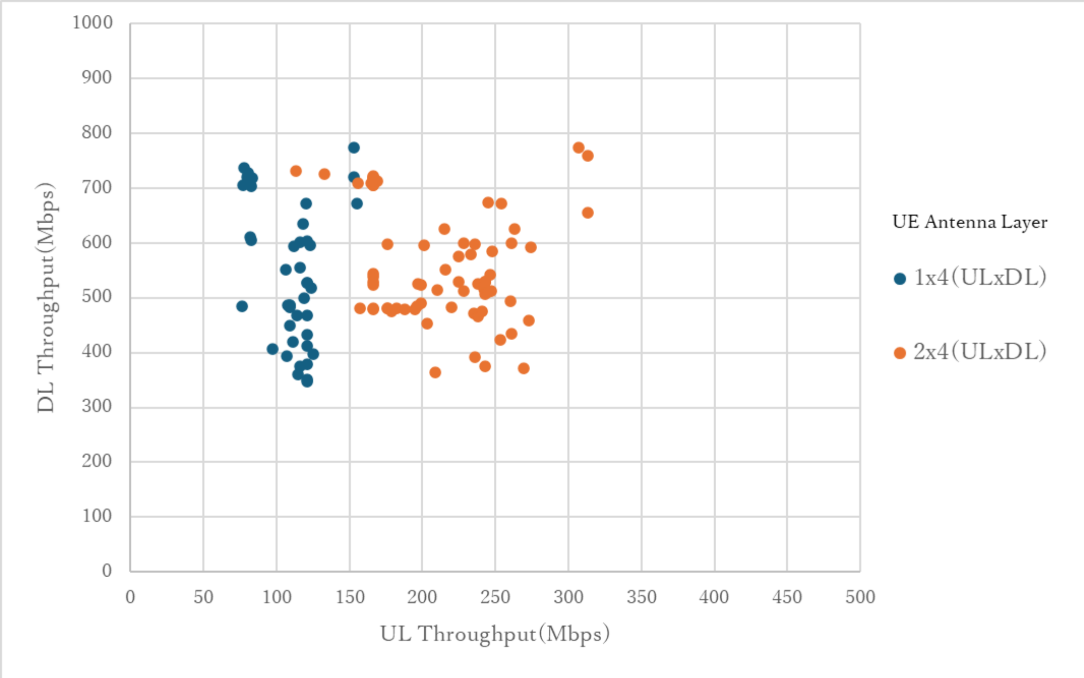


Figure 3-28 Semi-Synchronous TCP Throughput Test Results (Group 4)

・Group 5: UL Antenna Count 2 (256 QAM) x DL Antenna Count 4 (256 QAM)

UL：Due to the large number of RAN/UEs being measured, the measurement results exhibit variability.

When comparing the best throughput values for UE with 1 UL antenna versus those with 2 UL antennas, it is observed that the throughput for 2 UL antennas is approximately twice that of the configuration with 1 UL antenna.

Additionally, in the semi-synchronous mode (TDD1), the proportion of UL communication is higher than in the synchronous mode (TDD), which allowed for the observation of differences in throughput characteristics between the two modes for both TCP and UDP.

DL：Due to the large number of RAN/UEs being measured, the measurement results exhibit variability.

The DL throughput exceeded 500 Mbps, regardless of the differences between synchronous (TDD) and semi-synchronous (TDD1) modes, as well as between UDP and TCP.

Furthermore, in the semi-synchronous mode (TDD1), the proportion of DL communication is lower than in the synchronous mode (TDD), which allowed for the identification of differences in throughput characteristics between the two modes for both TCP and UDP.

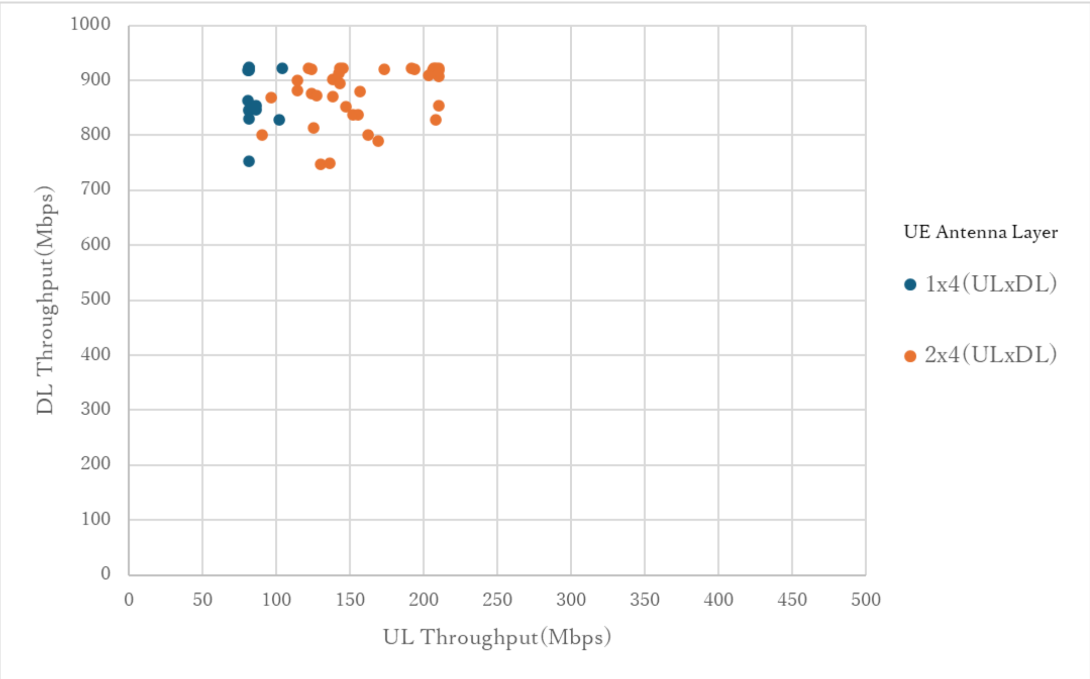


Figure 3-29 Synchronous UDP Throughput Test Results (Group 5)

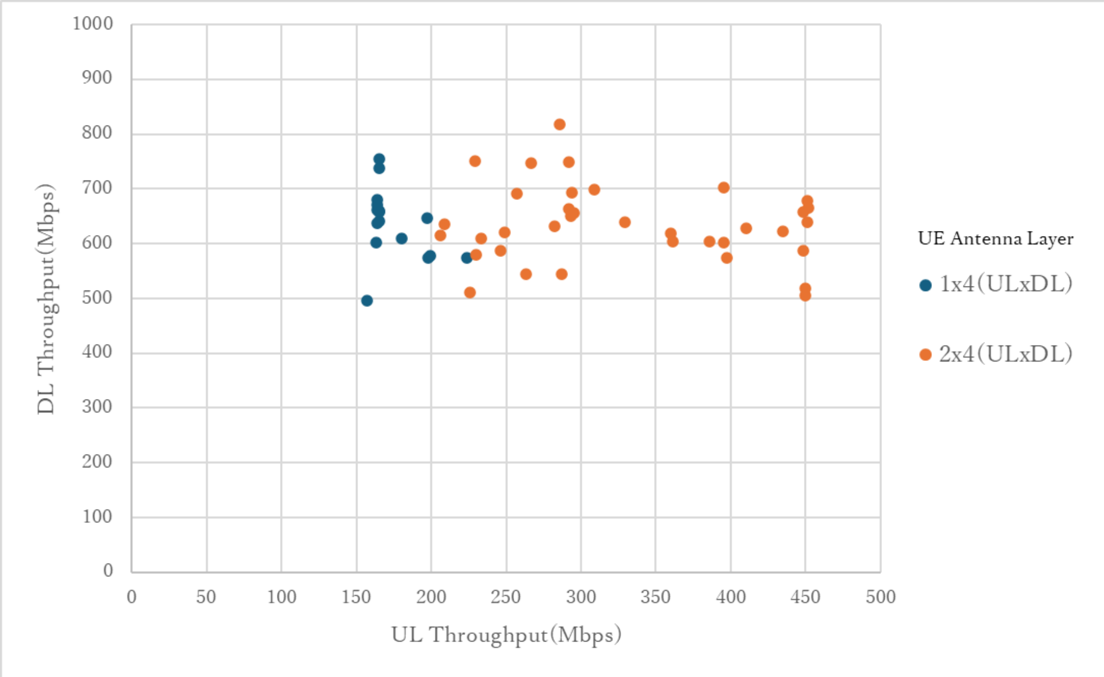


Figure 3-30 Semi-Synchronous UDP Throughput Test Results (Group 5)

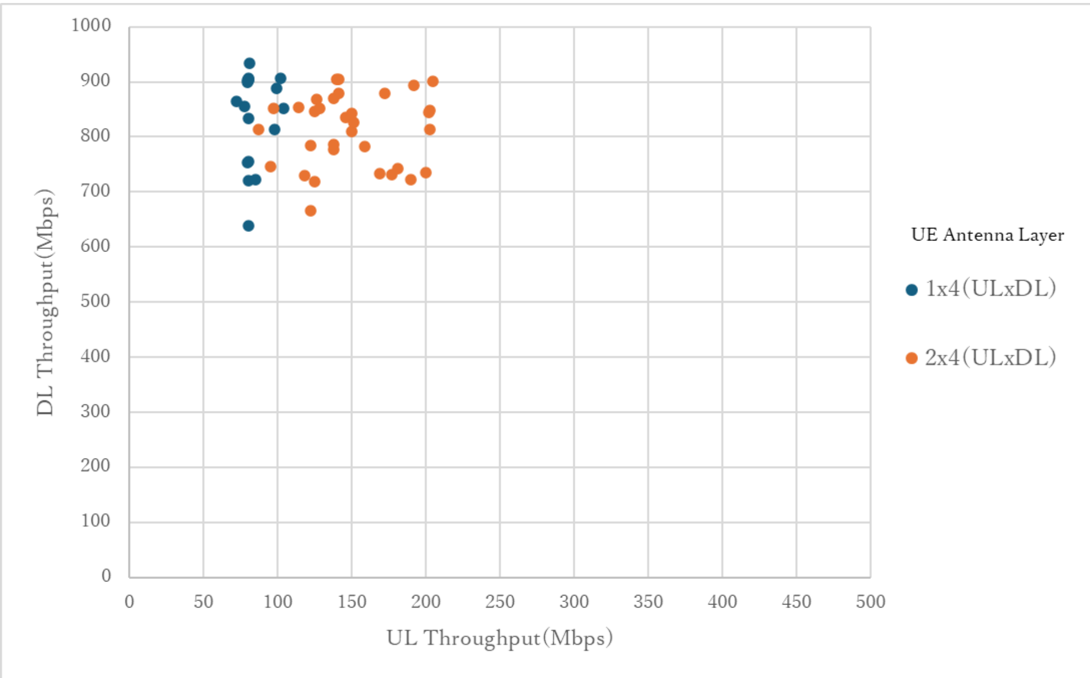


Figure 3-31 Synchronous TCP Throughput Test Results (Group 5)

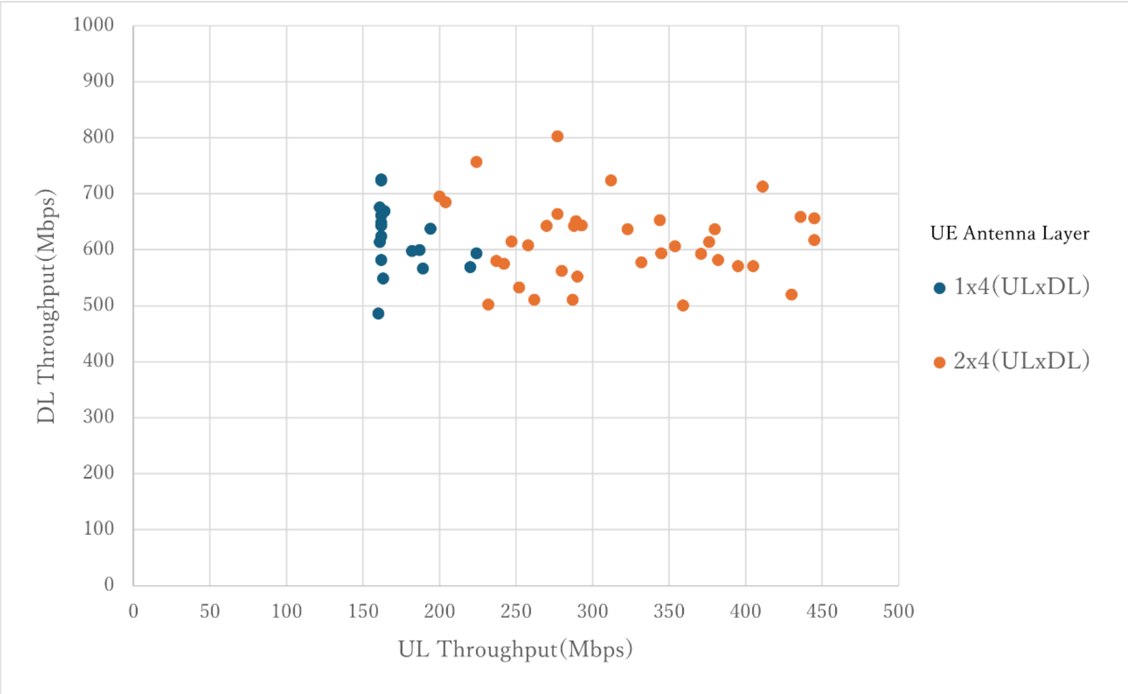


Figure 3-32 Semi-Synchronous TCP Throughput Test Results (Group 5)

The best throughput test results for each combination of the number of antennas equipped on the RAN and UE, along with the supported QAM(Table 3-12), are presented in Table 3-13 and Table 3-14.

Table 3-13 Group(UL 64QAM RAN) Test Results Best Values Summary

Group number	Number of UE Antenna Layers	Sync				Semi-Sync (TDD1)			
		UDP		TCP		UDP		TCP	
		UL	DL	UL	DL	UL	DL	UL	DL
Group1	1×4	63.7	749	63.1	744	127	569	126	565
	2×4	63.7	749	62	736	127	569	125	560
Group3	1×4	46	950	45.5	945	92.1	670	91.3	665
	2×4	91.7	952	90.2	937	184	750	181	660
Group4	1×4	77.2	952	77.3	945	156	755	155	774
	2×4	161	952	156	940	318	755	313	774

Note:

・Unit: Mbps

・n×m：**n** represents the number of uplink antenna layers, and **m** represents the number of downlink antenna layers

Table 3-14 Group(UL 256QAM RAN) Test Results Best Values Summary

Group Number	Number of UE Antenna Layers	Sync				Semi-Sync (TDD1)			
		UDP		TCP		UDP		TCP	
		UL	DL	UL	DL	UL	DL	UL	DL
Group2	1×4	98.8	757	99.8	747	198	490	197	486
	2×4	198	762	194	748	395	491	479	482
Group5	1×4	104	924	104	933	224	755	224	726
	2×4	210	922	205	904	452	818	445	803

Note:

・Unit: Mbps

・n×m：**n** represents the number of uplink antenna layers, and **m** represents the number of downlink antenna layers

3.2.6. Knowledge to improve communication quality.

In throughput tests, it is often the case that the results do not match the specified values, which made it challenging to conduct the tests. With the cooperation of the participating companies in the project, actions were taken to improve communication quality, and we were able to measure the throughput speed as specified. Knowledge will be shared based on Figure 3-33.

The information provided is knowledge obtained from the test results in a shielded tent; however, considering the effects of the direction of radio wave transmission, interference and reflection, external noise, and the optimal RAN Tx-Power according to the coverage area is also important in actual Private 5G usage scenarios. We hope this will serve as a reference when considering the optimal installation locations and Tx-Power for the RAN for Private 5G users.

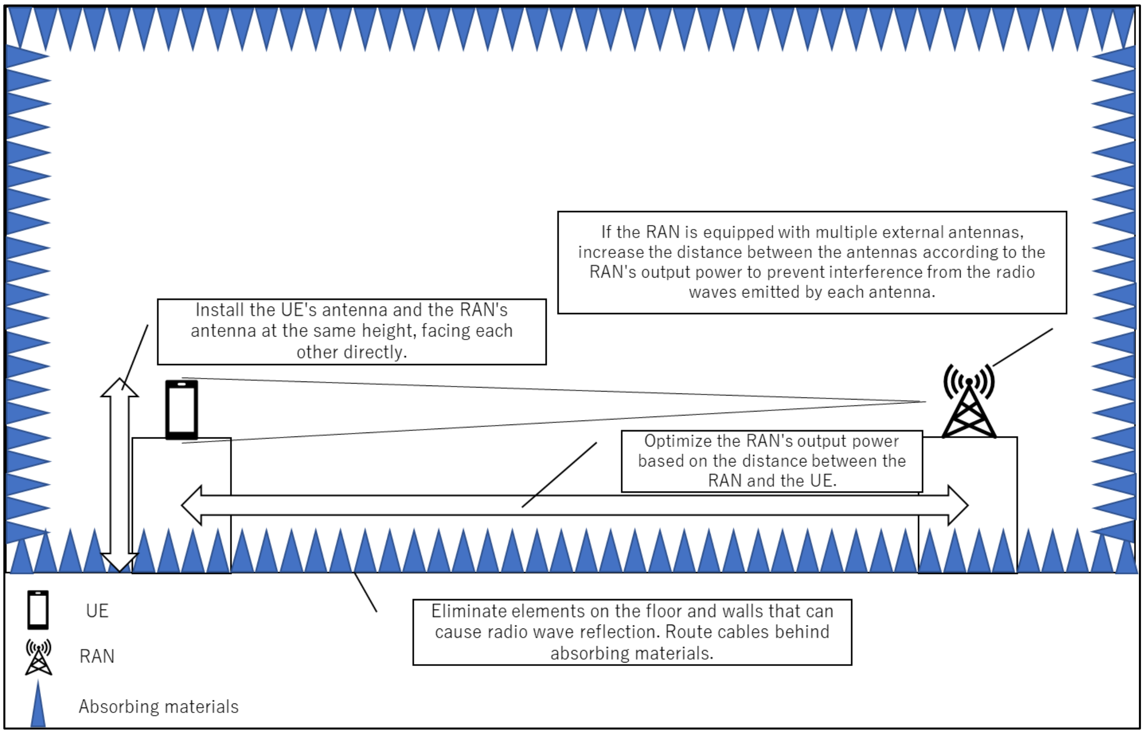


Figure 3-33 Actions taken to improve communication quality.

- **Optimization of installation position and antenna orientation.**

  In MIMO technology, the base station and the UE use multiple antennas to separate signals, enabling multi-stream communication.

  The lower the correlation between each antenna, the better the signal separation.

However, in environments where the installation location is restricted, such as in a shielded tent, the proximity of the antennas increases their correlation, which prevents the full benefits of MIMO from being realized. The analysis revealed that this was the cause of the decrease in throughput speed.
By implementing the following items summarized below, we were able to achieve throughput speeds as specified.

- The heights of the RAN and UE antennas were aligned, and the UE was installed in a position that allows it to receive the radio waves transmitted by the RAN.
- When using a RAN equipped with external antennas, the distances between the antennas were appropriately spaced to prevent interference between them.
- To prevent reflection and refraction of radio waves within the shielded tent, care was taken not to place any items that could obstruct the radio waves or cause reflections in the test environment. Additionally, cables were routed as much as possible under absorbent materials.

- **Optimization of the RAN's Tx-Power.**

In the connection between the RAN and UE, the UE sends the quality information of the radio signal (CQI report) to the RAN, and the RAN adopts the optimal modulation scheme based on the UE's conditions.
When the radio signal quality is high, higher-order modulation is employed, resulting in improved communication speeds. However, if the quality is poor, lower-order modulation is used, leading to a decrease in communication speed. This is a necessary operation to enhance the error correction capability (BLER) in 5G communication.
To improve radio quality and utilize higher-order modulation, it is necessary to optimize the distance and orientation of the antennas between the RAN and UE, as mentioned earlier, as well as to set the optimal Tx-Power for the RAN based on the operating environment.
The optimal Tx-Power for the RAN varies for each Private 5G operating environment, so it is necessary for Private 5G users to investigate and configure the settings accordingly.
Typical methods for Private 5G users to check radio quality information include observing the number of antenna bars displayed on the connected UE, as well as verifying the values of RSRP, RSRQ, and SINR. While it is desirable for the RAN side to also be able to check radio quality information, sufficient and necessary information can be obtained solely from the data received from the UE.

Table 3-15, Table 3-16, and Table 3-17 provide reference values for the metrics that represent the strength and quality of the radio signal. The strength and quality of the radio signal should be assessed not by evaluating each metric individually, but by considering them comprehensively. If one metric deteriorates, there is a possibility that the overall communication performance will decline. Additionally, excessive signal strength can also lead to a decline in quality, so caution is necessary. Specifically, when the RSRP value exceeds -50 dBm, the circuit reaches a saturation state, making accurate demodulation difficult. This condition can adversely affect MIMO technology, resulting in a decrease in communication speed. Furthermore, there is a risk of problems arising, such as the difficulty of wireless communication itself. In this project, the RAN's Tx-Power is appropriately set to maintain the RSRP value of connected UEs at -70 dBm and the SINR at 20 dB or higher.

Table 3-15 RSRP quality guideline

Value	Quality
> -50dBm	Poor (Excessive power)
-50dBm to -80dBm	Very good
-80dBm to -90dBm	Good
-90dBm to -100dBm	Poor
< -100dBm	Very poor

Table 3-16 RSRQ quality guideline

Value	Quality
> -10dB	Very good
-10d to -15dB	Good
-15dB to -19.5dB	Poor
< -19.5dB	Very poor

Table 3-17 SINR quality guideline

Value	Quality
> 20dB	Very good
13dB to 20dB	Good
0dB to 13dB	Poor
< 0dB	Very poor

3.3. Results of 4K Video Transmission Delay Tests

3.3.1. Test Configuration

The environment used for the tests is shown in Figure 3-34.

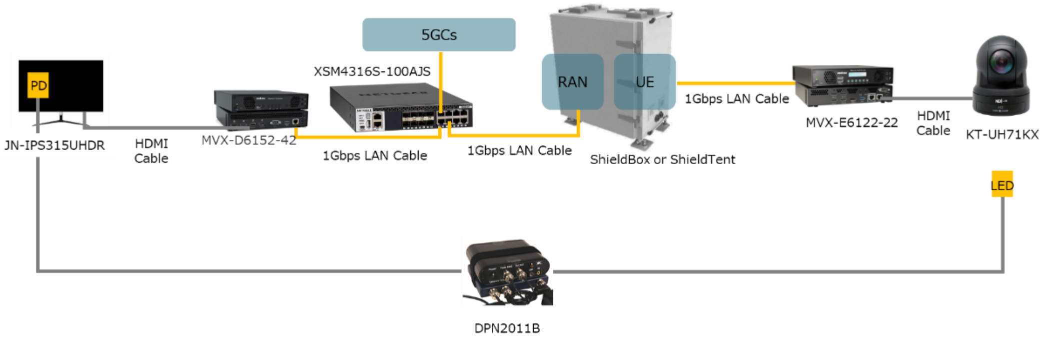


Figure 3-34 4K Video Transmission Delay Test Configuration

The RAN and UE are deployed within a shielded box or shielded tent. A video encoder and a 4K camera are connected under the UE, while a decoder and a 4K monitor are connected to N6.

The optical path delay measurement device (LED section) is placed in front of the 4K camera, while the optical path delay measurement device (PD section) is attached to the 4K monitor. The time difference between the video captured by the 4K camera and the video displayed on the monitor is measured as the delay.

To minimize the impact of environmental differences on the test results, similar to the interconnection tests and throughput tests, the output values of the RAN and the placement of the UE were adjusted to ensure that the RSRP value of the UE was approximately -70 dBm.

The information regarding the shielded box and shielded tent is similar to that presented in Table 3-2; therefore, it will be omitted in this section.

3.3.2. List of Test Equipment

The names and specifications of the test equipment used in this trial are similar to the information presented in Table 3-3; therefore, this section will be omitted.

A list of the test equipment used in the trial is presented in Table 3-18.

Table 3-18 List of Testing and Verification Equipment Used in the Test

Product name	Model number
4K camera	KT-UH71KTN
Encoder	MVX-E6122-22
Decoder	MVX-D6152-4
Optical path delay measurement device	PicoScope 2205AMSO

3.3.3. Test Items

The test items for this trial are presented in Table 3-19.

Table 3-19 Test Items for 4K Video Transmission Delay Testing

No	Test Item	Test Pass Criteria
1	Delay time	Confirm that the network latency in the Private 5G network segment is below 50 msec.
2	Block noise	Confirm that there is no block noise being output.

3.3.4. Test Procedures

A web camera, video encoder, and decoder are connected to the Private 5G test environment to transmit 4K video at 60 frames per second (fps) at a rate of 15 Mbits/sec. The transmission of the captured video is confirmed to be free of noise on the monitor screen through visual inspection. Additionally, a light path delay measurement device is used to measure the network delay time within the Private 5G network.

The network delay time is calculated by subtracting the delay time measured when the video encoder and decoder are directly connected from the delay time measured with the light path measurement device.

In cases where the network delay time is significantly greater than 50 ms or where screen noise persists, a root cause analysis is conducted during the testing period, followed by a retest.

3.3.5. Test Results and Discussion

Out of the 255 combinations tested, 90% were able to transmit 4K video with network delay times of 200 ms or less, demonstrating that 4K video transmission via interconnection is feasible without issues.

Furthermore, 80% of those combinations recorded network delay times of 50 ms or less, with a distribution observed in the range of 10 ms to 40 ms.

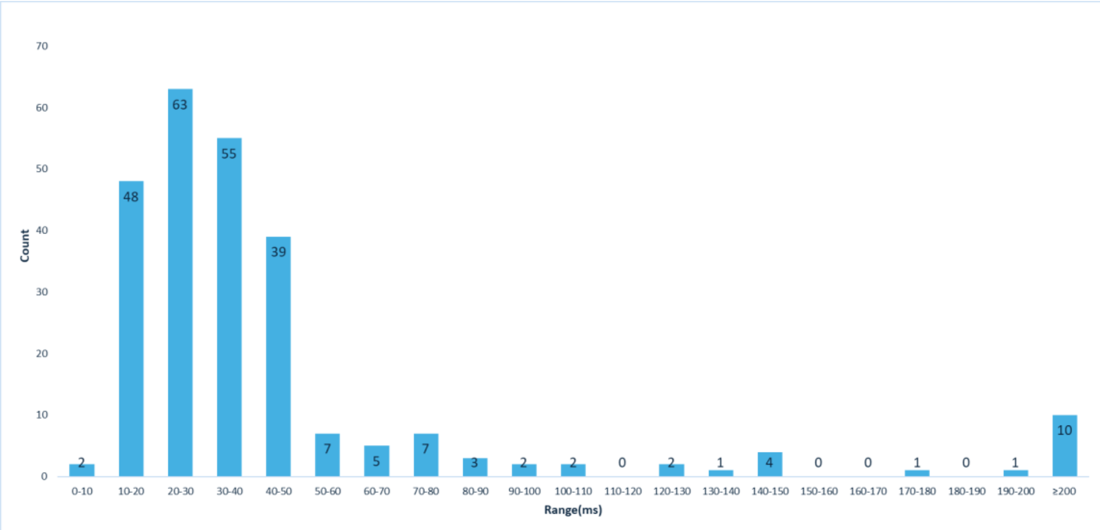


Figure 3-35 Delay Time and Number of Instances

The following insights were gained from this test.

1. The impact of the supported 3GPP Release versions of each Private 5G device on the test results was not observed.
2. Due to the network conditions during the testing, packet fragmentation of the transmitted video was observed. The issue was resolved by adjusting the MTU size that the 5GC notifies to the UE to match the network conditions of the testing environment.

4. Theme 2 Test (RIC Test in Private 5G Multi-vendor Configuration)

In the Theme 2 test, Tests based on various scenarios will be conducted with the aim of enhancing Private 5G functionality utilizing the RIC. The O-RAN Alliance defines two types of RICs: the Non-RealTime RIC (hereinafter referred to as the Non-RT RIC), which enables operation through non-real-time processing, and the Near-RT RIC, which enables operation through real-time processing. Additionally, applications called rApps are used in the Non-RT RIC , and xApps are used in the Near-RealTime RIC (hereinafter referred to as the Near-RT RIC), enabling processing based on specific use cases. In this Test, in addition to integration Tests to verify interoperability among O-RAN compliant equipment, performance evaluation Tests will be conducted to confirm performance differences with and without RIC implementation.

Table 4-1 Theme 2 Test Details

Item number	Test item
4.1 rApp (Power optimization)	・Integration Test ・Performance Evaluation
4.2. xApp (Private 5G Interference Mitigation Test utilizing RB Optimization)	・Integration Test ・Performance Evaluation

4.1. Test of RAN Transmission Power Optimization using rApp

This Test aims to optimize RAN transmission power based on surrounding communication conditions to achieve sustainable operation through the reduction of network power consumption.

In offices and schools, which are primary use cases for Private 5G, communication conditions are expected to change significantly depending on the time of day; for instance, a large number of devices connect during the day, while the number of connections decreases drastically at night and on holidays. Therefore, during periods when communication demand is low, the impact of reducing RAN transmission power is minimal. Furthermore, in deployments consisting of multiple RANs, significant power savings can be expected by powering off RANs in areas or during time periods with few devices.

However, it is anticipated that shutting down specific RANs could have a significant impact on some communications. Therefore, it is necessary to maintain communication quality by adjusting the transmission power of surrounding RANs to cover areas where devices are scattered.

In this Test, an rApp running on the Non-RT RIC will be used to dynamically optimize RAN transmission power for each area. By utilizing the rApp, the aim is to reduce operational costs by realizing dynamic power savings while maintaining communication quality.

4.1.1. Test Configuration

The configuration for conducting this Test is shown in Figure 4-1. It consists of a Private 5G system composed of O-RAN compliant CU/DU, RU, and 5GC; an SMO Framework possessing RAN monitoring and orchestrator functions; a Non-RT RIC; an rApp; and a single UE.

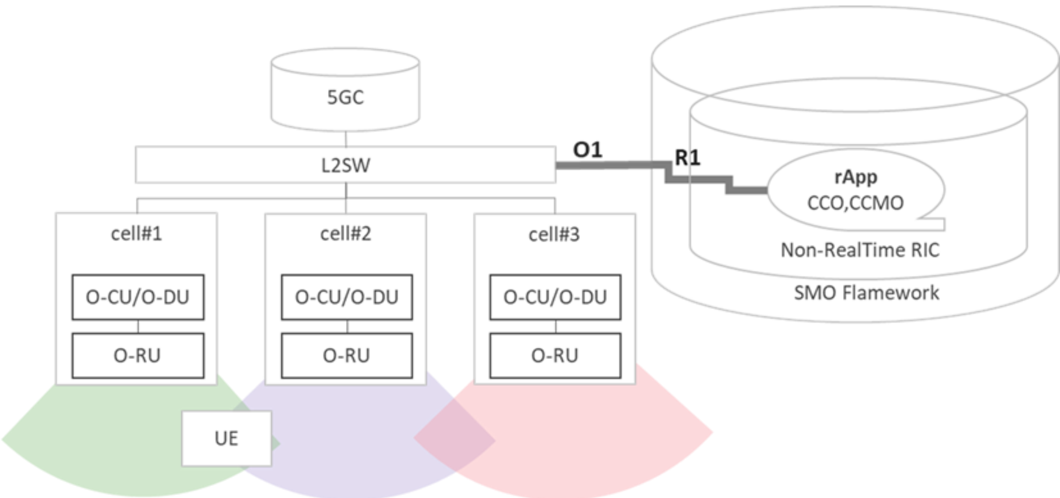


Figure 4-1 rApp Test Configuration

Table 4-2 Component Descriptions

Comport name	Connection destination	Roles	Usage
SMO Framework	Non-RT RIC, O-CU/O-DU, O-RU	Performs service management and orchestration for the entire network.	Performs lifecycle management, resource management, policy management, and monitoring of network functions.
Non-RT RIC	SMO Framework, rApp	Performs non-real-time RAN control and optimization.	Performs network configuration management and performance analysis using rApps.

rApp (CCO, CCMO)	Non-RT RIC	Applications running on the Non-RT RIC.	Performs network configuration changes, data collection, and analysis.
O1 Interface	SMO Framework, Management System	Performs management and monitoring of network equipment (Cells).	Performs retrieval and modification of network configurations, and data collection.
R1 Interface	SMO Framework (Non-RT RIC), rApp	Exchanges information between rApps and the RIC.	Retrieves performance data and transmits control instructions.

4.1.2. List of test Equipment

The equipment used in this Test is shown in Table 4-3.

Table 4-3 Product Names of Equipment Used in rApp Test

Maker	Nodes
LITEON	O-RU
G REIGNS(HTC)	O-CU/O-DU
LITEON	SMO framework
LITEON	Non-RT RIC
LITEON	rApp
Open5GS	5GC

4.1.3. Test Items

The Test items for this Test are shown in Table 4-4.

Table 4-4 rApp Test Items

No	Test Items		Confirmation point
1	Integration Test	O1 Interface	NETCONF Session establishment/termination
2			NETCONF Create MOI
3			NETCONF Read MOI
4			NETCONF Modify MOI Attributes
5			NETCONF Delete MOI
6		R1 Interface	SME-query services
7			SME-query single service
8			SME-update single service
9			SME-delete single service
10			DME-query infojob

11			DME-query single infojob
12			DME-update single infojob
13			DME-delete single infojob
14			DME-query single infojob status
15			DME-query infotypes
16			DME-query single infotype
17			DME-query infotypes
18			DME-query single infotype
19			DME-update single infotype
20			DME-delete single infotype
21			DME-query single infoproducer
22			DME-update single infoproducer
23			DME-delete single infoproducer
24			DME-query single infoproducer status
25			DME-query single infoproducer infojobs
26	Performance Evaluation	Performance Evaluation	Multiple scenario patterns are created, and performance evaluations of the rApp are conducted.

4.1.4. Test Scenario

The performance evaluation Test scenario is presented below. In the performance evaluation Test, it is verified that the rApp can execute the scenario architecture shown in Figure 4-2 and Table 4-5 within the test scenario shown in Figure 4-3. CCO (Coverage and Capacity Optimization) and CCMO (Cell Coverage Monitoring and Optimization) are implemented as the rApp. CCO optimizes communication area coverage and transmission power, while CCMO monitors and optimizes Cell coverage.

Cell transmission power and communication area coverage ratios are determined based on SINR values. To calculate SINR values within the target area for the Test, the rApp uses the Indoor Hotspot (InH) Non-Line-of-Sight (NLoS) model from ITU-R M.2135-1 "Guidelines for Evaluation of Radio Interface Technologies for IMT-Advanced." [5]

According to the standard specifications of the application, the Cell information acquisition interval can be applied at intervals of 5, 15, or 60 minutes based on user selection. For this verification, the shortest interval of 5 minutes is used to conduct a performance evaluation with higher real-time responsiveness.

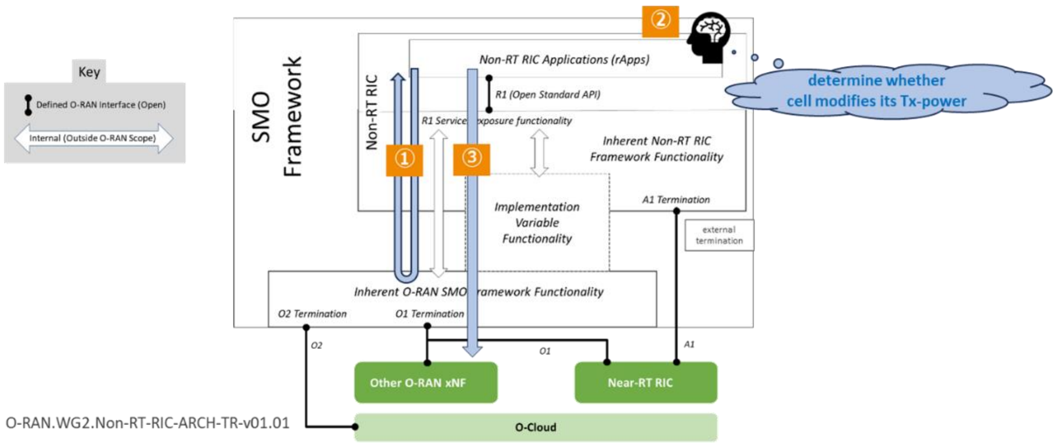


Figure 4-2 rApp Architecture

Table 4-5 Architecture Verification Points

#	Confirmation point
1	The rApp shall be able to retrieve cell information from the SMO via the R1 Interface every 5 minutes.
2	The rApp shall be able to calculate cell transmission power for coverage optimization and determine the optimal transmission power.
3	The rApp shall be able to execute commands to change transmission power via the O1 interface.

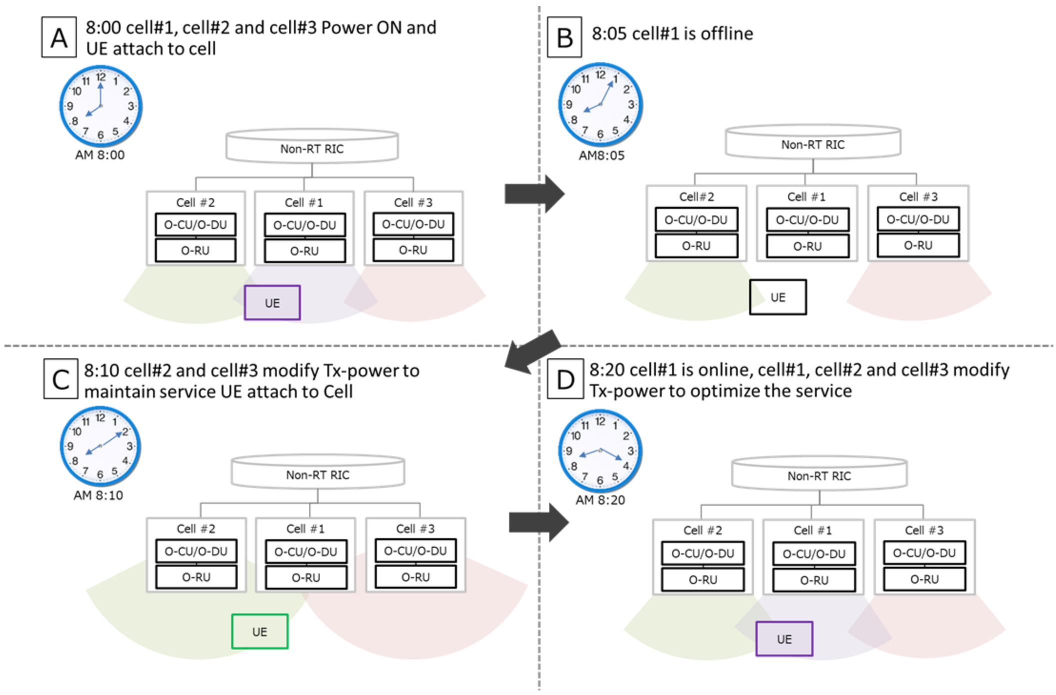


Figure 4-3 rApp Test Scenarios

4.1.5. Test Results and Discussion

4.1.5.1. Integration Test Results

The Integration Test results are shown in Table 4-6. These Test results demonstrated the following:

- The interface between the SMO and O-RAN (O-RU, O-CU/O-DU integrated node) is compliant with the O1 Interface specified in O-RAN.WG10.O1-Interface.0-R003-v13.00. [6]
- The interface between the rApp and the SMO is compliant with the R1 Interface specified in O-RAN.WG2.R1AP-R003-v04.00. [7]
- Interconnection is possible if O-RAN compliant interfaces are implemented in each functional group.

Table 4-6 rApp Integration Test Results

No	Test		Confirmation point	Pass / Fail	O-RAN Specification
1	O1 Interface	NETCONF Session establishment/ termination	Can generate NETCONF Session Termination	Pass	6.1.8 6.1.9
2		NETCONF Create MOI	Create Managed Object Instance successfully	Pass	6.1.2
3		NETCONF Read MOI	Read Managed Object Instance successfully	Pass	6.1.5
4		NETCONF Modify MOI Attributes	Modify Managed Object Instance successfully	Pass	6.1.3
5		NETCONF Delete MOI	Delete Managed Object Instance successfully	Pass	6.1.4
6	R1 Interface	SME-query services	Acquire service data	Pass	6.1.4.5
7		SME-query single service	Acquire service data	Pass	6.1.4.5
8		SME-update single service	Update service data	Pass	6.1.4.2
9		SME-delete single service	Delete service data	Pass	6.1.4.3
10		DME-query infojob	Acquire infojob data	Pass	7.3.5.2
11		DME-query	Acquire infojob data	Pass	7.3.5.3

		single infojob			
12		DME-update single infojob	Update infojob data	Pass	7.3.4.1
13		DME-delete single infojob	Delete infojob data	Pass	7.3.4.2
14		DME-query single infojob status	Acquire infojob data status	Pass	7.3.4.2
15		DME-query infotypes	Acquire infotype data	Pass	7.2.5.2
16		DME-query single infotype	Acquire infotype data	Pass	7.2.5.3
17		DME-query infotypes	Acquire infotype data	Pass	7.2.4.1
18		DME-query single infotype	Acquire infotype data	Pass	7.2.4.2
19		DME-update single infotype	Update infotype data	Pass	7.2.4.1
20		DME-delete single infotype	Delete infotype data	Pass	7.2.4.2
21		DME-query single infoproducer	Acquire infoproducer data	Pass	7.1.5.3
22		DME-update single infoproducer	Update infoproducer data	Pass	7.1.5.2
23		DME-delete single infoproducer	Delete infoproducer data	Pass	7.2.5.2
24		DME-query single infoproducer status	Acquire infoproducer data status	Pass	7.1.5.3
25		DME-query single infoproducer infojobs	Acquire infoproducer infojob data	Pass	7.1.5.3

4.1.5.2. Performance Evaluation Results and Discussion

The performance evaluation results are presented in Table 4-7.

At 08:00, the initial transmission power of Cell #1, Cell #2, and Cell #3 was 10 dBm; however, by connecting the rApp, the CCMO adjusted the transmission power to 18 dBm, achieving 100% coverage of the communication area.

At 08:05, Cell #1 was shut down, and the transmission power of Cell #2 and Cell #3 remained at 18 dBm, resulting in approximately 70% coverage.

At 08:10, with the activation of the CCMO, the transmission power was increased to 24 dBm, and the communication area coverage was restored to 100% within five minutes.

Since all evaluation criteria were passed, the rApps for CCO and CCMO successfully demonstrated the ability to dynamically adjust RAN parameters to maintain UE connectivity and optimize coverage.

Looking ahead, to support Private 5G deployment in more complex environments, we will continue to enhance the practical applicability of the O-RAN architecture. Additionally, by further developing the rApp to include automated RAN power control based on time-of-day conditions, we aim to achieve energy savings through intelligent power management.

Table 4-7 rApp Performance Evaluation Results

Test scenarios			Test items	Confirmation point	Pass/Fail
A	1	08:00 AM	cell#1 is online before rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	2		cell#2 is online before rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	3		cell#3 is online before rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	4		UE is attached to Cell	The UE attached status can be viewed by cell and UE	Pass
B	1	08:05 AM	cell#1 is offline before rApp optimization	The cell should be offline in both the command line and on LiteNetics, with no transmission power serving	Pass
	2		cell#2 is online before rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	3		cell#3 is online before rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	4		UE is not attached to Cell	The UE attached status can be viewed by cell and UE	Pass
C	1	08:10 AM	CCO calculate with output	The rApp should be able to calculate a certain output from the field optimization	Pass
	2		CCO apply with output	The calculation result should be able	Pass

				to apply to the managed cell	
	3		CCMO auto calculate with output	The rApp should be able to calculate a certain output from the field optimization or generate a log recording of such calculation	Pass
	4		CCMO auto apply with output	The calculation result should be able to apply to the managed cell	Pass
	5		UE is attached to Cell	The UE attached status can be viewed by cell and UE	Pass
D	1	08:20 AM	cell#1 is online after rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	2		cell#2 is online after rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	3		cell#3 is online after rApp optimization	The cell should be online in both the command line and on LiteNetics, with a certain transmission power serving	Pass
	4		UE is attached to Cell	The UE attached status can be viewed by cell and UE	Pass

4.2. Private 5G Interference Mitigation Test utilizing RB Optimization by xApp

This Test assumes the deployment of Private 5G in wide-area environments such as factories, logistics warehouses, and outdoor facilities, with the objective of maintaining communication quality even in environments subject to frequency interference.

In Japan, regulations regarding Private 5G sharing conditions in the Sub-6 GHz band mandate the use of a single channel within the 4.8–4.9 GHz range for outdoor environments. A challenge associated with single-channel operation is that frequency interference occurs in areas where radio waves of the same frequency coexist due to the presence of adjacent base stations. This leads to signal degradation, potentially causing a decline in communication quality, such as reduced throughput.

The following are examples of methods to mitigate frequency interference:

1. Operation via Frequency Division
2. Operation via Spatial Division
3. Operation via Time Division

1. Operation via Frequency Division:
   involves splitting the regulated 100 MHz bandwidth into multiple frequency bands. A specific example is dividing the band into two segments: the lower half (4.80–4.85 GHz) and the upper half (4.85–4.90 GHz). This avoids frequency overlap and mitigates interference. However, implementing this method requires both the RAN and UEs to support frequency division capabilities, and there are very few commercial off-the-shelf products that currently support this.
2. Operation via Spatial Division:
   involves designing the coverage area to ensure that the radio propagation ranges of Private 5G networks do not overlap. While it is common to conduct area simulations in advance for coverage planning, the complexity of the design increases proportionally with the number of base stations, requiring specialized skills and expertise.
3. Operation via Time Division:
   involves adjusting scheduling within the framework of the specified Downlink (DL) and Uplink (UL) TDD frame configurations. This scheduling adjustment can be achieved by controlling Resource Block (RB) allocation.

Widely adopted methods for existing interference mitigation include Fractional Frequency Reuse (FFR) and Enhanced Inter-Cell Interference Coordination (eICIC). FFR is an approach that suppresses interference by partitioning the available frequency band in advance and classifying areas into those without frequency interference (Cell-Center) and those with frequency interference (Cell-Edge), thereby differentiating frequency usage. On the other hand, eICIC is a method that reduces interference by adjusting base station transmission in the time domain using predefined patterns such as Almost Blank Subframes (ABS). However, these conventional methods are based on semi-static control and rely on pre-configured resource allocation policies. Consequently, they face challenges in adequately adapting to environments where surrounding interference conditions fluctuate significantly over short periods.

In contrast, this Test adopts a resource allocation mechanism capable of dynamically adjusting both time and frequency domains based on the relative location information of the UE. Furthermore, by leveraging the Near-RT RIC, we have realized a mechanism that continuously optimizes RB allocation in a closed loop while monitoring frequency interference conditions in real-time. Through this approach, we aim to mitigate interference more effectively while maintaining key communication performance metrics, such as throughput, even in environments characterized by severe and unstable interference.

4.2.1. Test Configuration

Figure 4-4 illustrates the configuration for conducting this Test. The setup consists of a Private 5G system, a Near-RT RIC, and 20 UEs. These 20 UEs are distributed across the Cell #1 area, the Cell #2 area, and the frequency interference area. UEs located in the area subject to frequency interference are referred to as "Edge UEs," while UEs located in areas free from interference are referred to as "Center UEs."

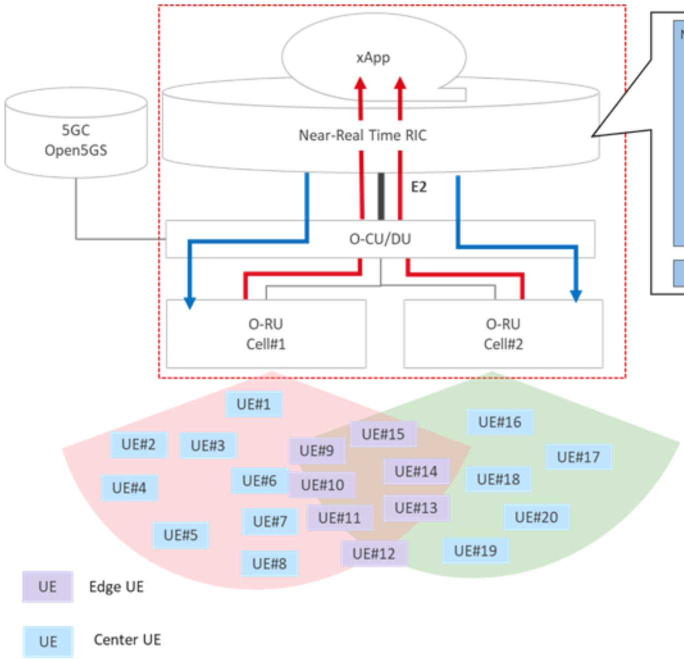


Figure 4-4 xApp Test Configuration

Table 4-8 Component Descriptions

Comport name	Connection destination	Roles	Usage
Near-RT RIC	RAN（O-CU/O-DU）	Performs near-real-time control and optimization.	Performs Radio Resource Management (RRM) and interference control.
xApp	Near-RT RIC	Applications running on the RIC.	Performs Radio Resource Management (RRM), interference control, handover support, etc.
E2 Interface	Near-RT RIC, RAN（O-CU/O-DU）	Performs real-time information collection and transmits/receives control instructions.	Performs Radio Resource Management (RRM), interference control, handover support, etc.

4.2.2. List of Test Equipment

Table 4-9 lists the equipment used in this Test.

Table 4-9 Product Names of Equipment Used in xApp Test

Maker	Nodes
Pegatron	RAN
Open5GS	5GC
ITRI	Near-RT RIC

Pegatron、Others	UE
NTT　EAST	xApp

4.2.3. Test Items

Integration tests and performance evaluations of the RIC were conducted. Table 4-10 lists the test items. The integration test conforms to O-RAN.WG3.E2TS-R003-v02.00. [8]

Table 4-10 xApp Test Items

No	Test Items		Confirmation point
1	Integration Test	E2 Setup Procedure	Complete the connection setting up.
2		RIC Subscription	Complete the subscribe procedure.
3		RIC Indication	Acquire the indication message.
4		RIC Control	Sent control message to E2 Node.
5	Performance Evaluation	Throughput Measurement	Throughput measurements are performed under multiple test scenarios.

4.2.4. Test Scenario

Figure 4-5 illustrates the xApp test concept. The Test is conducted using three scenarios: A, B, and C.

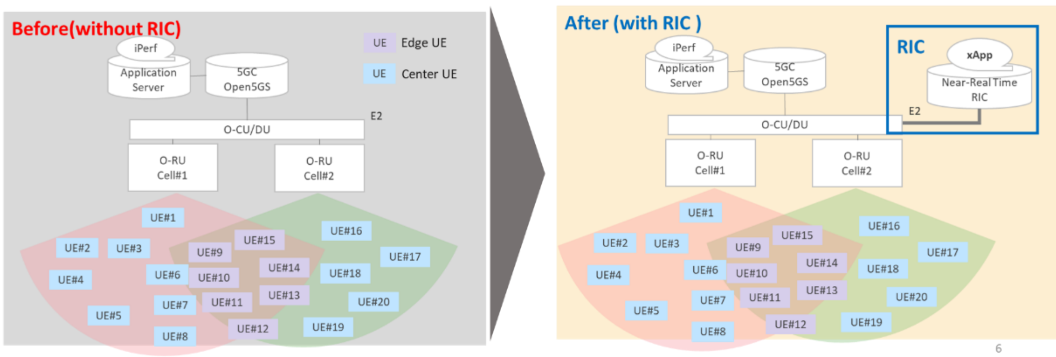


Figure 4-5 xApp Test Diagram

- Scenario A (Edge UE<Center UE)
  Using a combination of 7 Edge UEs and 13 Center UEs, throughput is measured both with and without the RIC enabled, and the results are compared.

- Scenario B (Edge UE=Center UE)
  Using a combination of 10 Edge UEs and 10 Center UEs, throughput is measured both with and without the RIC enabled, and the results are compared.

- Scenario C (Edge UE>Center UE)
  Using a combination of 13 Edge UEs and 7 Center UEs, throughput is measured both with and without the RIC enabled, and the results are compared.

In each scenario, when the RIC is enabled, the xApp executes the following steps:

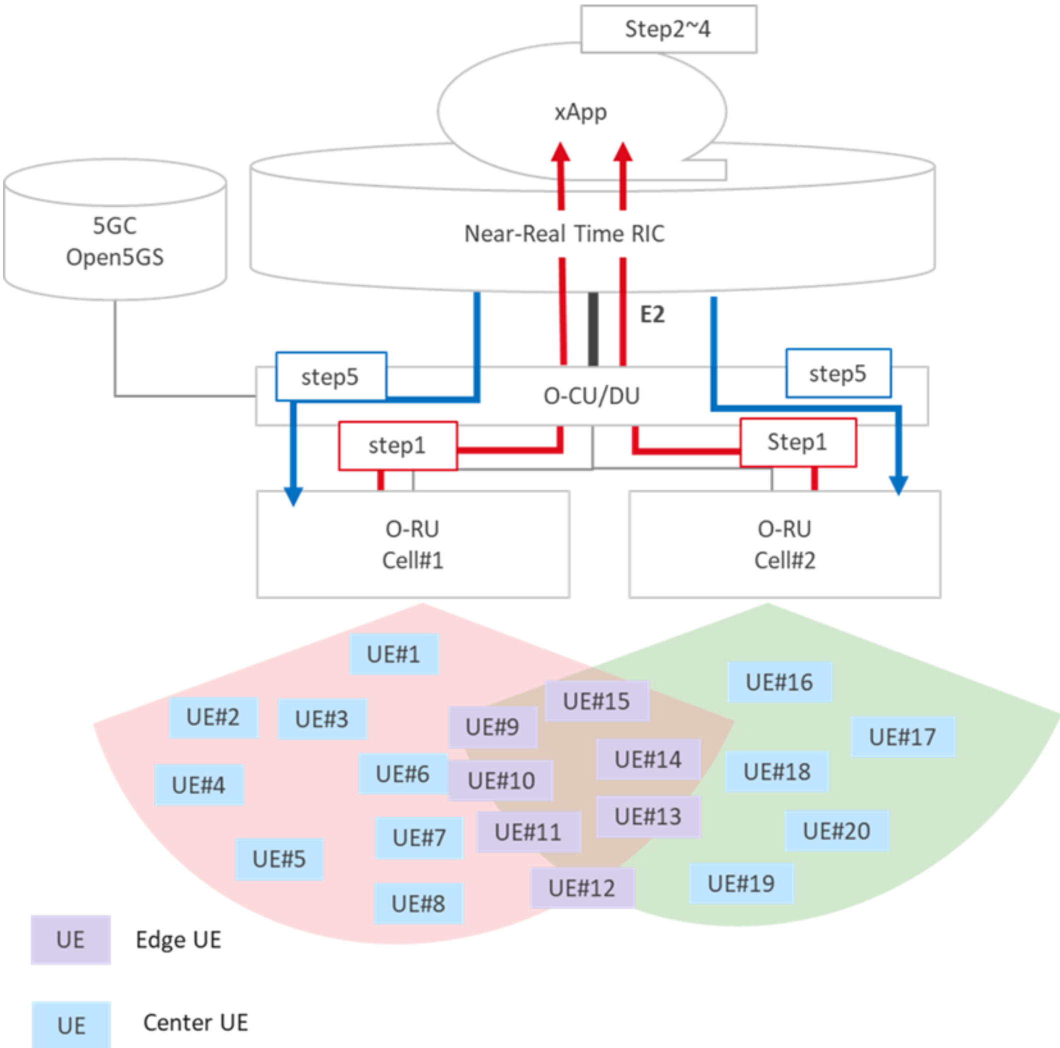


Figure 4-6 xApp Architecture

- Step 1
  Acquire all UE information via the E2 Interface with per-second granularity.
- Step 2
  Determine whether each UE is located in the Cell-Edge or within the Cell-Center.
- Step 3
  Monitor the current RB usage status.
- Step 4
  Evaluate the SINR and throughput of all UEs prior to RB allocation.
- Step 5
  Based on the evaluation results, send control messages to the RAN (O-CU/DU/RU) to reallocate RBs to UEs for performance optimization.

4.2.5. Test Results and Discussion

4.2.5.1. Integration Test Results

Table 4-11 presents the results of the integration tests. The integration testing is compliant to O-RAN.WG3.E2TS-R003-v02.00.

The Test results confirmed that the interface between the Near-RT RIC and the O-RAN nodes conforms to the E2 Interface defined in O-RAN.WG3.E2AP-02.00 [9] and O-RAN.WG3.E2SM-KPM v01.00. [10]

Table 4-11 xApp Integration Test Results

No	Test		Confirmation point	Pass / Fail	O-RAN.WG3.E2TS-R003-v02.00
1	Integration Test	E2 Setup Procedure	Complete the connection setting up.	Pass	5.2.1.1.1
2		RIC Subscription	Complete the subscribe procedure.	Pass	5.2.2.1.1
3		RIC Indication	Acquire the indication message.	Pass	5.2.2.4.1
4		RIC Control	Sent control message to E2 Node.	Pass	5.2.2.5.1

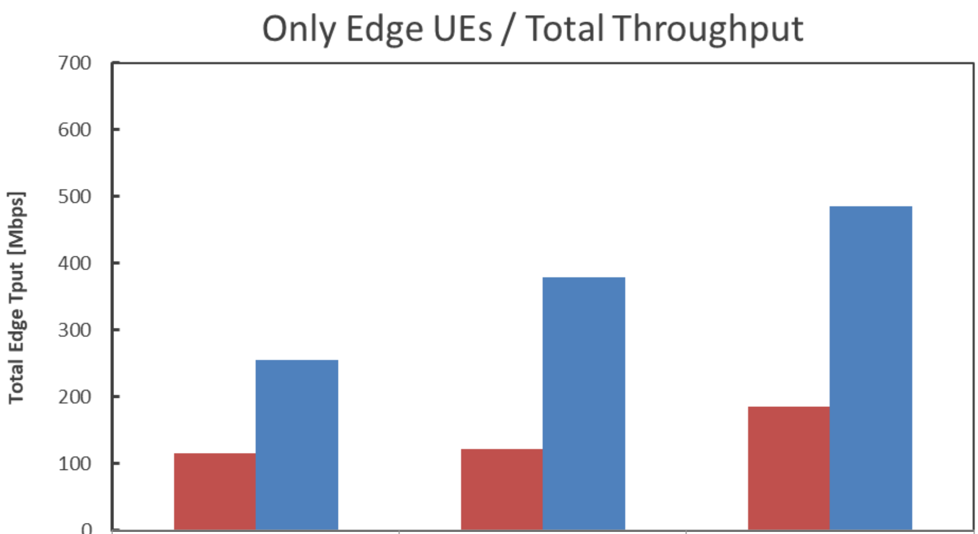
4.2.5.2. Performance Evaluation Results and Discussion

The performance Test results are presented in Figure 4-7 and Figure 4-8. Figure 4-7 shows the throughput measurement results for Edge UEs only, while Figure 4-8 shows the total throughput measurement results for both Edge and Center UEs.

As shown in Figure 4-7, after connecting the RIC, throughput improvements of 121.74% in Scenario A (Edge UE < Center UE), 210.16% in Scenario B (Edge UE = Center UE), and 162% in Scenario C (Edge UE > Center UE) were observed.

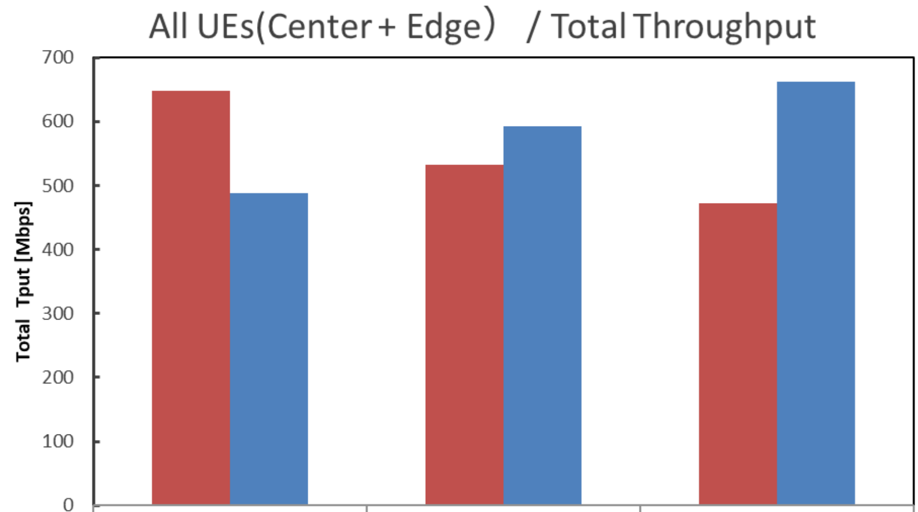
Figure 4-8 indicates that the total throughput in Scenarios B and C improved after connecting the RIC compared to the pre-connection state. Conversely, in Scenario A, the total throughput decreased after connecting the RIC. This is attributed to the sub-optimal reallocation of RBs from Center UEs to Edge UEs, which likely became more pronounced in Scenario A due to the higher number of Center UEs.

Future prospects include analyzing the determination logic for Edge and Center UEs and aiming to improve control accuracy in complex interference environments, such as by adding automatic control for toggling the RIC connection ON/OFF. We also plan to conduct tests experiments focused on adapting the system for mobile terminals, in addition to stationary ones.



	A: Edge UE< Center UE	B: Edge UE = Center UE	C: Edge UE > Center UE
without RIC	115	122	185
with RIC	255	379	485

Figure 4-7 xApp Performance Evaluation Results (Edge UE Only)



	A: Edge UE< Center UE	B: Edge UE = Center UE	C: Edge UE > Center UE
without RIC	648	532	472
with RIC	488	593	662

Figure 4-8 xApp Performance Evaluation Results (All UEs)

5. Theme 3 Test (Enhancement of Security Measures in Private 5G Utilization Environments)

5.1. Security Test

5.1.1. Test Configuration

The test configuration for this examination is illustrated in Figure 5-1. In this test, Trend Micro Mobile Network Security (hereinafter referred to as TMMNS), provided by Trend Micro and CTOne, will be used as the security solution in the urban environment.

Based on the specifications of TMMNS, it is assumed that there will be no operational differences due to variations in RAN equipment. Therefore, connection tests will be conducted based on the combinations of the 5GC and User Equipment UE. The UE will be equipped with a dedicated SIM card that includes security features specifically designed for integration with TMMNS.

The RAN and UE will be deployed within a shielded box or a shielded tent. Similar to the connection tests in Theme 1, adjustments were made to the RAN output power and the placement of the UE to ensure that the RSRP value of the UE is approximately -70 dBm, thereby minimizing the impact of environmental differences on the test results.

The details regarding the shielded box and shielded tent are similar to the information presented in Table 3-2, and therefore, will be omitted in this section.

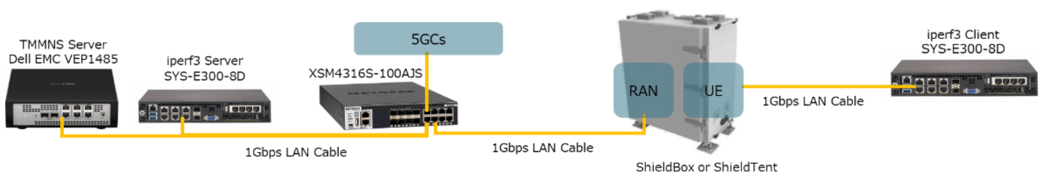


Figure 5-1 Security Test Configuration

5.1.2. List of Test Equipment

The names and specifications of the test equipment for this trial are similar to the information presented in Table 3-3, and therefore, will be omitted in this section.

5.1.3. Test Items

The test items for this trial are shown in Table 5-1. Basic operation tests of TMMNS and security threat scenario tests will be conducted. Assuming security threats such as device virus infection and SIM swapping, check the operation of functions to detect and quarantine them.

Table 5-1 Security Test Items

No	Test Item		Test Pass Criteria
1	Basic operation confirmation	Confirmation of UE display availability	Confirm that the IMEI of the UE and the IMSI of the SIM card are displayed in the TMMNS after the UE is in coverage.
2		Confirmation of UE control availability	Manually send a disconnect signal from the TMMNS server to the UE and confirm that the UE is forcibly disconnected.
3		Confirmation of UE information update interval	Verify that the information update signal is being sent from the UE to the TMMNS server, and check the sending interval.
4		Confirmation of traffic volume display	Confirm that the communication traffic volume of the test UE is displayed on the management screen of the TMMNS server.
5	Security threat scenario testing	Unauthorized access prevention	Execute the test scenario to detect unauthorized access and confirm that the test UE is forcibly disconnected by the TMMNS.
6		SIM swap prevention	Execute the test scenario to detect SIM swap and confirm that the test UE is forcibly disconnected by the TMMNS.

5.1.4. Security Threat Scenarios

5.1.4.1. Unauthorized Access Prevention Test Scenarios

Among the security threat scenario tests, the unauthorized access defense test scenario is illustrated in Figure 5-2. This test scenario aims to verify the defensive actions taken during unauthorized access incidents within the Private 5G network. The specific scenario is as follows:

① Using nmap (a port scanning tool), simulate unauthorized access by sending pseudo-communication from the UE to the PC located at N6.

② The TMMNS server detects the unauthorized access and sends a disconnection signal to the UE.

③ The UE is forcibly disconnected, and subsequent data communication becomes impossible.

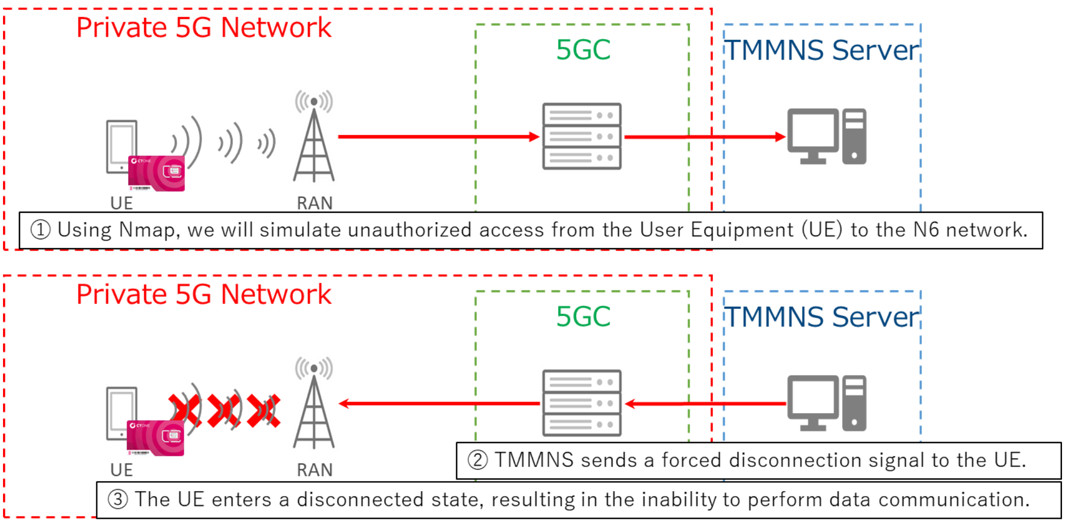


Figure 5-2 Unauthorized Access Prevention Test Scenarios

5.1.4.2. SIM Swap Defense Test Scenario

Among the security threat scenario tests, the SIM swap defense test scenario is illustrated in Figure 5-3. This test scenario aims to verify the defensive actions taken during SIM swap incidents within the Private 5G network. The specific scenario is as follows:

① Insert the SIM card currently in UE(A) into UE(B).

② The TMMNS server detects the SIM swap and sends a disconnection signal to UE(B).

③ UE(B) is forcibly disconnected, and subsequent data communication becomes impossible.

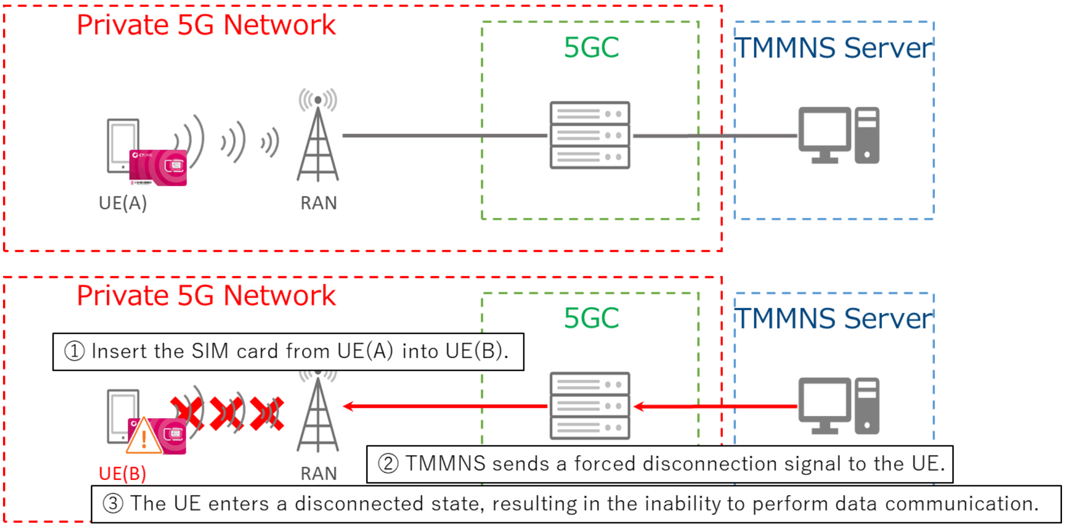


Figure 5-3 SIM Swap Prevention Test Scenarios

5.1.5. Test Results and Discussion

As of February 2025, the results of all 44 combinations that have been processed are shown in Table 5-2. Approximately 90% of the combinations resulted in normal operation of the TMMNS; however, for a specific model of UE, the UE information did not appear on the TMMNS management screen, resulting in a test failure (NG). The analysis revealed that the reason for the issue was that the necessary functions for integration with the TMMNS were disabled at the software level on the UE side. Currently, improvements to the operation of the affected UE are under consideration.

Table 5-2 Security Test Results

5 GC	Basic operation confirmation	Security threat scenario testing
HPE	pass(10) Retest Required(1)	pass(10) Retest Required(1)
NTT-TX	pass(10) Retest Required(1)	pass(10) Retest Required(1)
Saviah	pass(10) Retest Required(1)	pass(10) Retest Required(1)
QCT	pass(10)	pass(10)

	Retest Required(1)	Retest Required(1)

In the security testing, as shown in Figure 5-4, out of all 44 combinations processed as of February 2025, 40 combinations were found to be connectable, resulting in a pass rate of 90.9%.

The breakdown of the combinations that could not be connected is shown in Table 5-3.

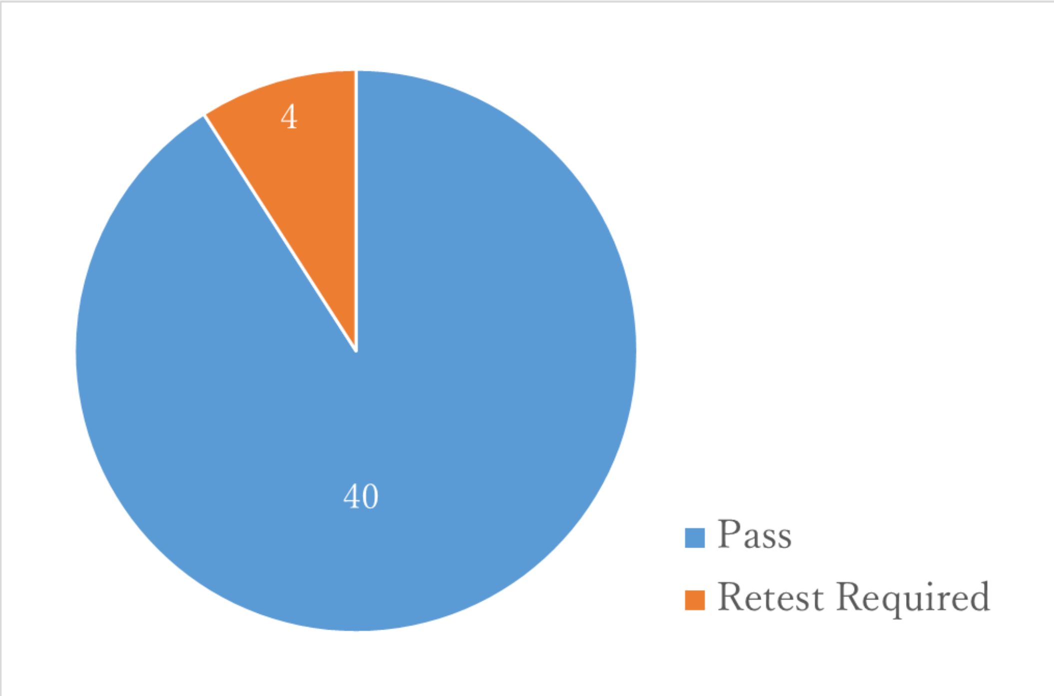


Figure 5-4 Security Test Results

Table 5-3 Security Threat Scenario Test Execution Failures

Status	Number of Issues(4)	Issue
Unresolved	4	An issue has occurred where a specific UE cannot be displayed on the TMMNS management screen.

5.1.6. Considerations to be Observed in TMMNS Connections

The considerations that must be adhered to for TMMNS connectivity, as identified through troubleshooting and confirmation with the UE vendor, are presented in Table 5-4.

Table 5-4 TMMNS Connection Compliance Considerations

Target			Points to Consider
TMMNS	5GC	UE	
✓	-	✓	To ensure integration with the TMMNS, it is necessary to equip the UE with a SIM card that has a dedicated security feature (applet). When connecting to the TMMNS, use a UE that is compatible with the applet on the SIM card.

6. Feedback from Participating Companies

This chapter presents the feedback received from the companies participating in the project.

6.1. Feedback on Theme 1

Figure 6-1 presents the feedback from each company regarding the Theme 1 Interoperability Test. The majority of companies participating in the Theme 1 test of this project responded that it "had a positive impact on their Private 5G business."

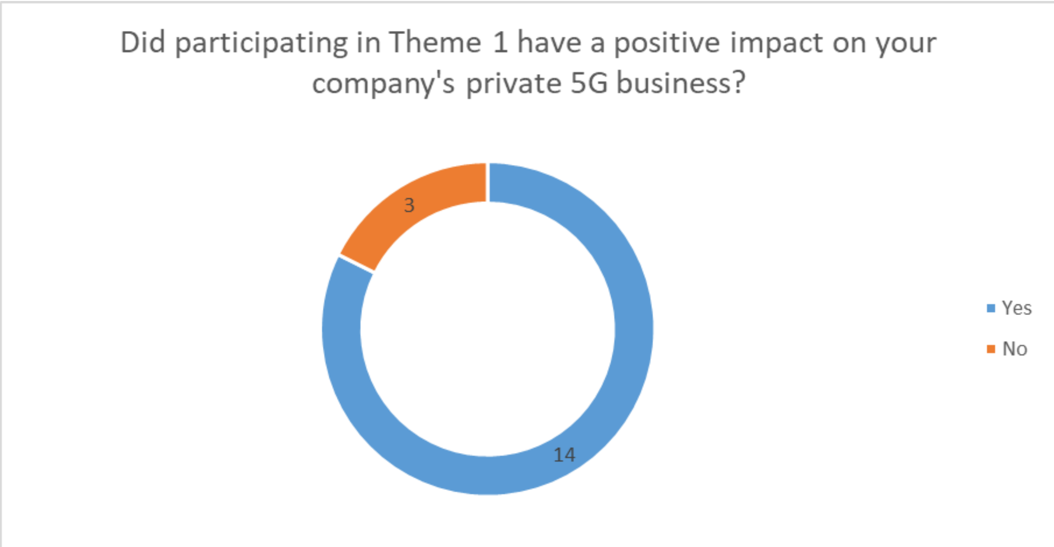


Figure 6-1 Company Responses Regarding Positive Impact on Private 5G Business (Theme 1)

Figure 6-2 illustrates the specific aspects of the positive impact. Among the companies that answered "Yes," "Collaboration and networking with other companies" was the most frequent response, followed by "Acquisition of connectivity track records," "Internal utilization," "Acquisition of new insights and use cases," and "Application to new products and services."

On the other hand, companies that answered "No" provided comments such as, "Unfortunately, it did not lead to the acquisition of new customers," and "Since the P5G Optimization Project is the first step toward promoting multi-vendor Private 5G environments, we look forward to future market developments."

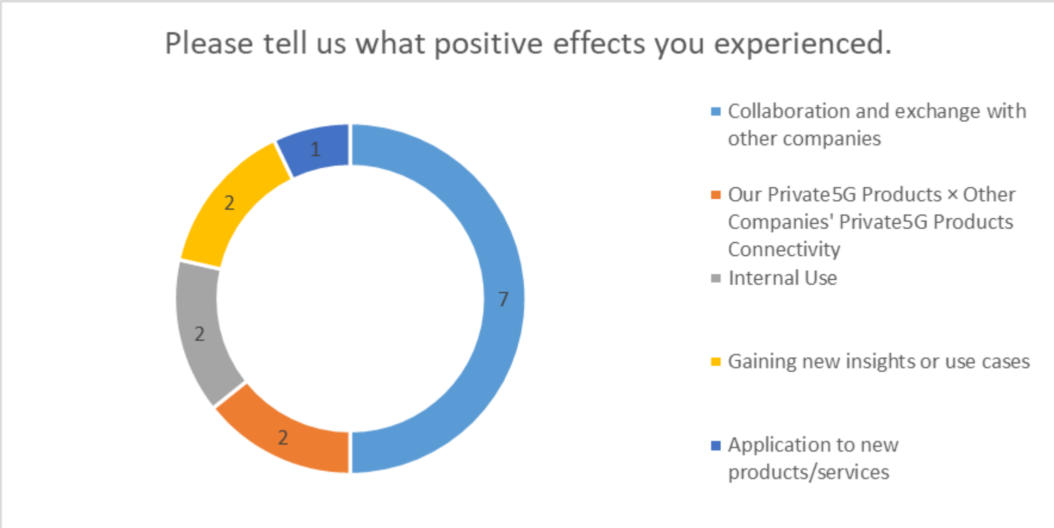


Figure 6-2 Breakdown of Positive Impacts (Theme 1)

6.2. Feedback on Theme 2

Figure 6-3 presents the feedback from companies participating in Theme 2 regarding the parameter optimization of Private 5G equipment. The results showed that the responses from companies participating in the Theme 2 test of this project were evenly split between "Yes" and "No."

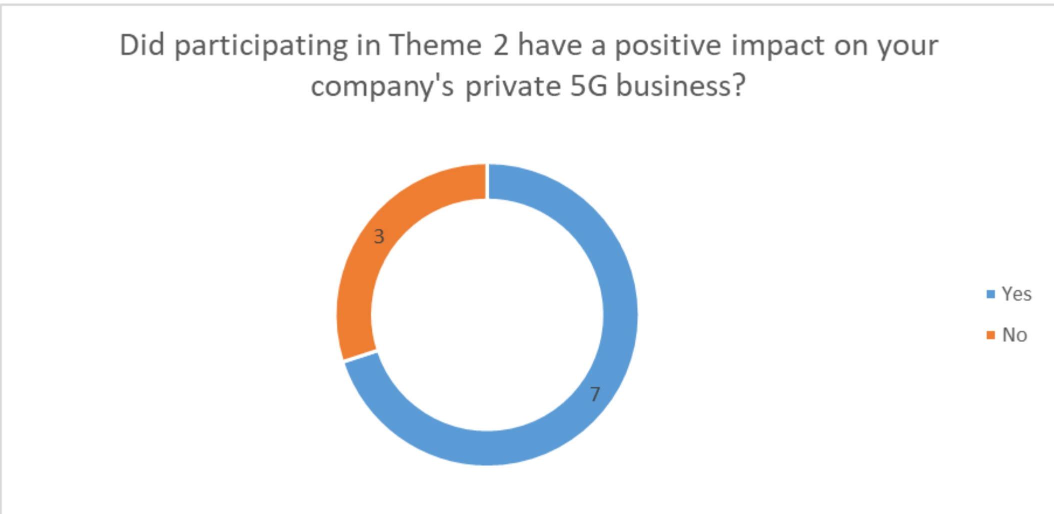


Figure 6-3 Company Responses Regarding Positive Impact on Private 5G Business (Theme 2)

Figure 6-4 illustrates the specific aspects of the positive impact. Among the companies that answered "Yes," many cited "Collaboration and networking with other companies," followed by "Application to new products and services," "Acquisition of new insights and use cases," and "Improvement of product and company visibility."

Additionally, a response was received stating, "We were able to objectively demonstrate the effectiveness of the RIC and applications through the verification test and participation in the O-RAN PlugFest."

From the companies that answered "No," comments included, "It is difficult to link this to commercialization at this stage," and "Since the commercialization of RIC technology is in its nascent stage, it is necessary to advance market formation by having more companies take an interest in RIC technology, engage in activities, and produce results."

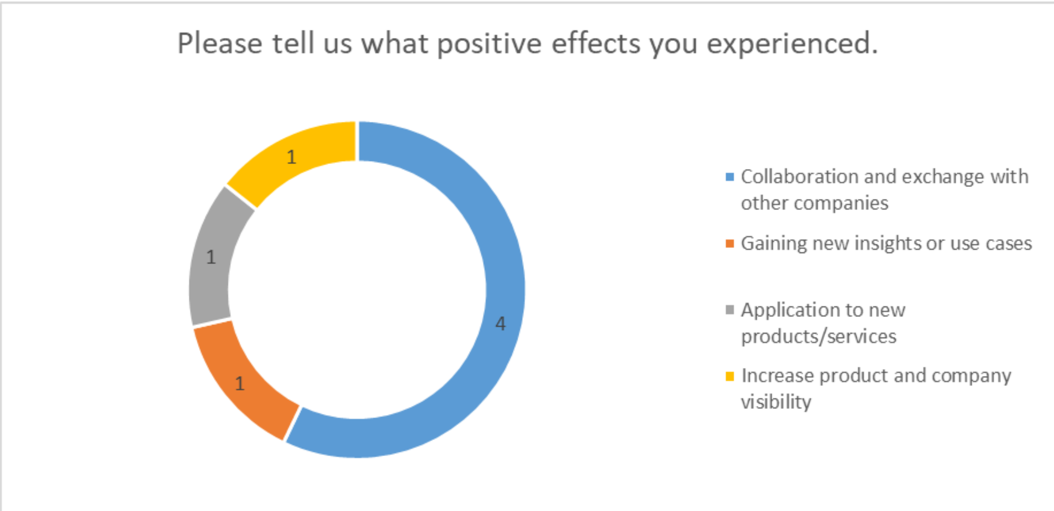


Figure 6-4 Breakdown of Positive Impacts (Theme 2)

Figure 6-5 shows the results of a survey regarding interest in RIC, conducted among companies not participating in Theme 2 of the P5G Optimization Project.

Although few companies currently plan for concrete commercialization, the results indicated that a significant number of companies hold an interest in RIC. The following comments were received:

- We intend to consider utilizing RIC by integrating it with our own products in the future.
- We anticipate rising demand for network operations automation.
- We find the RIC technology appealing for its ability to enable advanced RAN optimization and automation. However, we believe that further maturity of RIC technology within the market is required.
- We would like to engage more deeply with companies researching RIC technology.

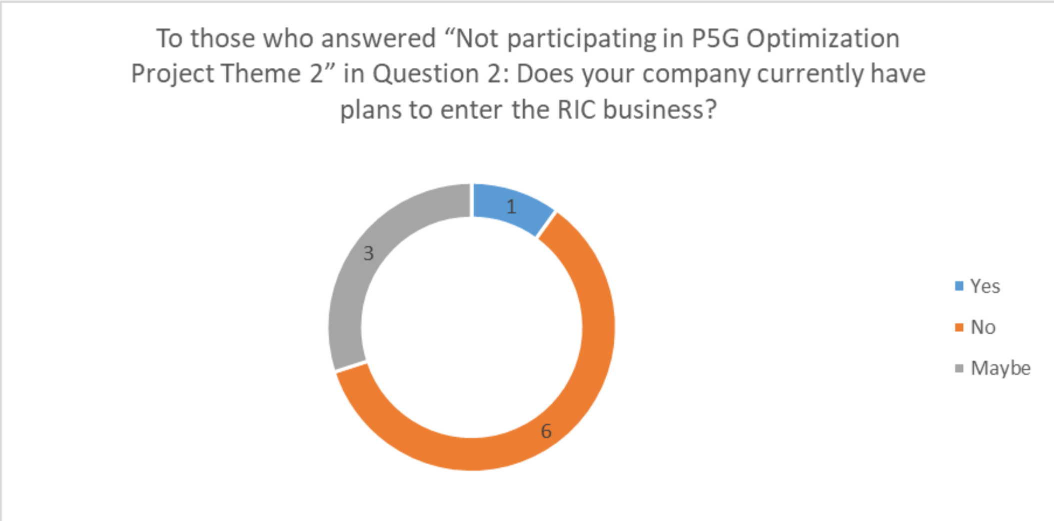


Figure 6-5 Willingness to Enter the RIC Market Among Companies Not Participating in Theme 2

6.3. Feedback on Theme 3

Figure 6-6 presents the feedback from each company regarding security measures for Private 5G environments in Theme 3. Regarding the test scenarios in the test, the "Unauthorized Access Prevention Test Scenario" attracted the most interest, followed by the "SIM Swap Prevention Scenario."

The participating companies demonstrated a high level of awareness regarding security measures. Below are the comments provided as reasons for their selections. Please note that similar responses have been consolidated.

- Reasons for selecting the SIM Swap Prevention Test Scenario
  - We anticipate demand to rise with the future proliferation of eSIMs.
  - It is crucial to prevent unauthorized usage resulting from the theft or loss of SIM cards.
  - In Private 5G environments, network connectivity for specific devices is strictly managed via SIMs; therefore, countermeasures against SIM swap attacks are directly linked to ensuring the security of the entire network.
  - Given the products we handle, we identified this scenario as critical.
- Reasons for selecting the Unauthorized Access Prevention Test Scenario
  - It enables us to promote higher security standards.
  - We consider unauthorized access a significant threat, making countermeasures essential.

- Network security is a global challenge, not limited to Private 5G.
- Since unauthorized access is prone to occur in actual operational environments and directly impacts the safety and reliability of the entire service, we were particularly interested in verifying this defense scenario.

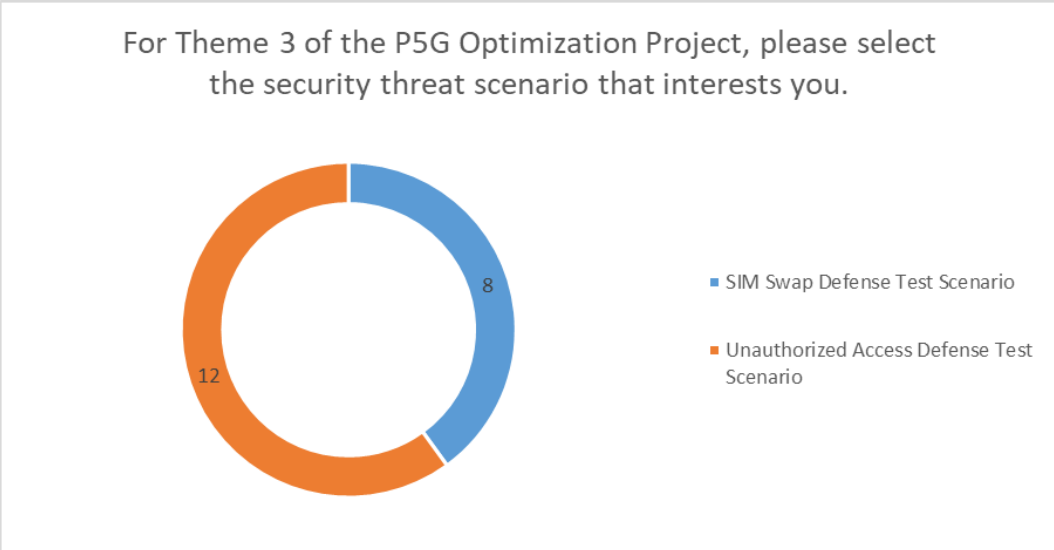


Figure 6-6 Security Defense Scenarios of Interest to Participating Companies

Furthermore, Figure 6-7 presents the results of the survey regarding independent security improvement initiatives by the participating companies.

Companies that responded "Yes" provided comments citing activities such as conducting independent security tests, performing joint tests with security vendors, and implementing encryption to strengthen authentication and communication protection within the 5GC.

Even among companies that responded "No," there were comments indicating that they gained new insights through the Theme 3 test. Therefore, we believe that this test was highly valuable.

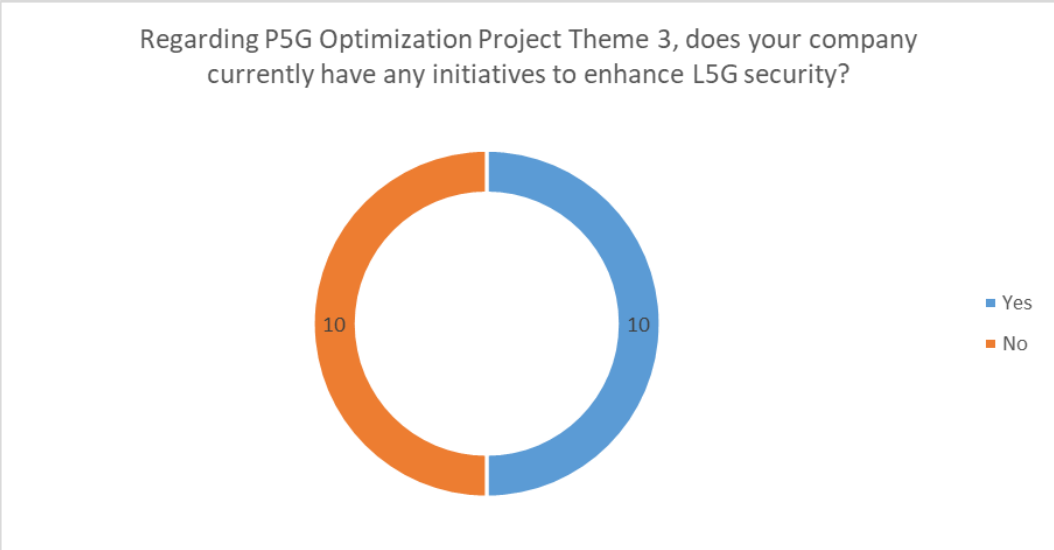


Figure 6-7 Unique Security Enhancement Initiatives by Participating Companies

6.4. Overall Project Feedback

Figure 6-8 presents the overall feedback for this project. The majority of participating companies responded that "participation in this project was beneficial."

Consistent with the responses in Theme 1 and Theme 2 citing the positive business impact of "collaboration and interaction with other companies," many companies commented that the project "contributed to the acquisition of new collaboration partners."

- We rarely have the opportunity to conduct interoperability tests with so many vendors. It was an excellent activity that allowed us to establish verification track records with various companies and engage in networking.
- In addition to technical evaluations, we gained significant insights through interaction and information sharing with other companies. This led to expanded business opportunities and increased visibility in the Japanese market. Therefore, we feel this was a highly beneficial project.
- We also consider the opportunity to build new cooperative relationships through interaction with other companies to be a major achievement.
- We obtained valuable information for understanding the needs of Private 5G users and market trends within Japan, which served as a reference for considering our future business strategy. The insights gained from this project have also been instrumental in our internal accumulation of technical expertise.
- Confirming connectivity with other companies' equipment using P5G frequency bands

was beneficial.

- We were able to secure a platform to showcase our products.
- We successfully completed the test and believe we were able to convey a certain level of understanding regarding the effectiveness of the RIC to everyone.
- Through this project, our engineering team gained insights and experience regarding PlugFest in Japan. Beyond dispatching engineers to the site for verification, we were also able to provide remote support for the test through rapid response and analysis.
- It was beneficial to access information and engage in activities related to Private 5G and O-RAN through the project, which would have been impossible to undertake independently.
- We gained a valuable opportunity to collaborate with multiple partners across various scenarios.
- Participating in a high-profile environment involving multiple vendors allowed us to widely showcase the stability and performance of our technology to the entire industry.
- By successfully conducting E2E interoperability tests with diverse UE and 5GC configurations, we demonstrated that we possess high compatibility with various industry players.

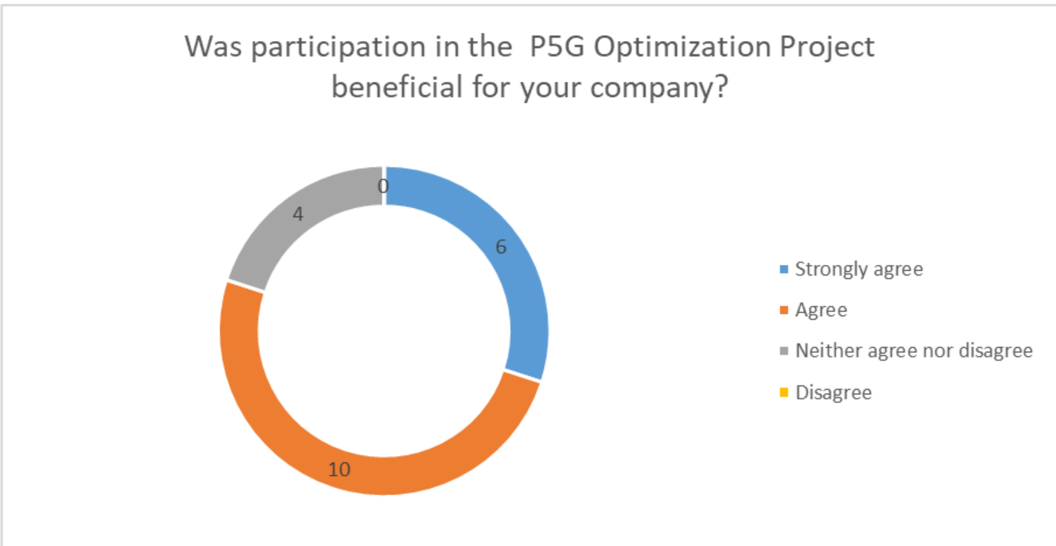


Figure 6-8 Overall Impressions of the P5G Optimization Project

7. Conclusion

In this project, participating companies have jointly conducted tests across three themes. In this report, we publish the results for each: Theme 1 covers interoperability tests between Private 5G devices; Theme 2 covers RIC tests in Private 5G multi-vendor configurations; and Theme 3 covers security enhancement tests for Private 5G usage environments.

In Theme 1, we disclosed combinations of commercial products that successfully achieved interoperability across vendor boundaries, points to note during connection, and performance results such as throughput and latency during 4K video transmission. Through this, we expect to dispel negative market perceptions such as "interoperability is impossible" or "performance is lacking."

In Theme 2, in addition to multi-vendor connections between Private 5G devices, we published test results demonstrating that applying xApps and rApps running on the RIC enables automatic parameter control and communication performance improvement. We hope this demonstrates the effectiveness of the RIC for Private 5G devices to the market and leads to further expansion of RIC-compliant products.

In Theme 3, utilizing commercial security solutions, we published test results showing that security measures can be strengthened through the coordination of security SIM cards and network security functions, even in diverse Private 5G environments. We expect this to realize safe and secure operations in Private 5G environments and promote the further spread of security solutions.

We believe that utilizing this report can curb integration costs in different vendor equipment configurations and widen the range of equipment choices according to use cases. With this report, this project concludes. Building on the connections with participating companies and the knowledge gained, we intend to accelerate the societal implementation of Private 5G. Furthermore, we will continue to promote co-creation in new technical domains, such as the realization of 6G -the next generation of communications- and network construction combining multiple wireless protocols, continuing our efforts toward promoting industrial DX and solving social issues.

We would like to express our deepest gratitude to everyone who participated in this project, and we would appreciate any feedback or comments from those who read this report.

8. References

[1] 3GPP TS23.501："System architecture for the 5G System (5GS)"

[2] 3GPP TS23.502："Procedures for the 5G System (5GS)"

[3] 3GPP TS38.331："NR;Radio Resource Control(RRC) Protocol specification"

[4] 3GPP TS24.501："Non-Access-Stratum (NAS) protocol for 5G System (5GS)"

[5] ITU-R M.2135-1："Guidelines for evaluation of radio interface technologies for IMT-Advanced"

[6] O-RAN O1 Interface Specification 13.0："O-RAN.WG10.O1-Interface.0-R003-v13.00"

[7] O-RAN R1 Interface: Application Protocols for R1 Services 4.0："O-RAN.WG2.R1AP-v04.00"

[8] O-RAN E2 Interface Test Specification 2.0："O-RAN.WG3.E2TS-R003-v02.00"

[9] O-RAN Near-Real-time RAN Intelligent Controller, E2 Application Protocol (E2AP) 2.0："O-RAN.WG3.E2AP-v02.00"

[10] O-RAN Near-Real-time RAN Intelligent Controller E2 Service Model (E2SM) KPM 1.0：ORAN-WG3.E2SM-KPM-v01.00