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Challenging for the 5G Era Devices

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NTT DOCOMO is developing a fifth-generation mobile communications system (5G) as a company-wide effort for launch in 2020. The Communication Device Development Department that I belong to is part of this effort, and in addition to the development of 5G mobile communications, we are conducting ongoing studies on devices and services for the 5G era.

I was first assigned to the Communication Device Development Department more than ten years ago, and since that time, I have been in charge of developing NTT DOCOMO's first terminal for each new generation of the mobile communications system. The first of these was a hard-key, flip-type feature phone for the W-CDMA HSDPA system. We then moved on to terminals for the LTE system such as USB-dongle-type, data-centric devices as well as mobile phones featuring a large-screen touch panel, that is, today's widely popular "smartphones." After this, we continued our development efforts toward the further evolution of the mobile communications system, but for the time being, device form stayed pretty much the same as that of the smartphone. What kind of form, then, will devices take on in the 5G era?

As is often said, 5G will feature many enhancements of currently commercialized technologies such as high-speed/large-capacity operation, low-latency transmission, and massive device connectivity. But no less important in my mind are higher speeds in the uplink, network evolution with connection to Internet of Things (IoT) devices, and power-saving technologies.

We can associate higher speeds in the uplink with the trend toward transmitting video and other types of data-intensive information from devices whose main role has traditionally been to receive information. This feature reflects the expectation that ways of communicating will be changing, which is strongly related to "Creating a new future through diverse means of connection" as declared by NTT DOCOMO R&D. However, achieving higher speeds in the uplink presents many problems on the device side. These include finding ways of dealing with higher power consumption, developing technologies for enhancing antenna performance, and creating ways of improving the User eXperience (UX). Being responsible for terminal development, we are focusing our efforts on solving these problems by leveraging the technologies, skills, and know-how that we have so far developed and accumulated.

Furthermore, while the coming of the "Internet of Things" has long been proclaimed, it is no exaggeration to say that 5G is exactly suited to IoT. Of course, many and varied things equipped with communication functions have already been deployed in the real world, but issues such as limited network capacity, battery life, and cost still remain. As a result, we have not yet reached a state in which any and all devices are possible. Fortunately, 5G can solve these problems so that IoT can be deployed in a full-scale manner. With this in mind, we are working to develop devices that match diverse usage scenarios and needs by combining new and rapidly advancing technologies with the technologies that we have nurtured in our development of feature phones and smartphones.

By the way, our approach to development has changed greatly over these past ten years that I have contributed to device development. In the beginning, NTT DOCOMO would formulate detailed common specifications up to packaging requirements and each vendor would then develop devices in line with those specifications. However, I think the launch of the LTE system in 2010 marked a turning point in that process. For example, communication modems shifted from vendor-specific to the use of overseas vendors, terminal form factor changed from feature phones to smartphones, and areas of differentiation shifted from hardware to software and upper-layer applications. In short, NTT DOCOMO's stipulations changed from packaging specifications to service descriptions and requirements. We think this trend toward service-oriented specifications is accelerating. In particular, devices in the 5G era will not continue on the same evolutionary path—they will not simply be an extension of today's smartphones and tablets. Instead, we can expect many new devices to appear, and we plan to play a role in creating these devices. As I mentioned, a shift occurred from an era of outsourcing manufacturing to domestic vendors to an era of using the terminal platforms of overseas vendors. However, I believe we are now entering an era of free and creative development of both devices and services without being captive to a domestic or overseas industry framework. In other words, I think the time has come for "value co-creation activities with borderless partners" as described in NTT DOCOMO's Medium-Term Strategy 2020 "Declaration beyond."

The period that we are now entering is sometimes called the Fourth Industrial Revolution. With this in mind, we will take up the challenge of creating new value for our customers by introducing 5G and developing compelling 5G devices in collaboration with a wide variety of domestic and overseas partners. In doing so, we hope to create a new and exciting chapter in our history marked by a high level of collaboration.

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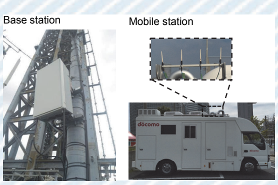

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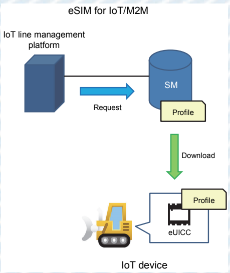

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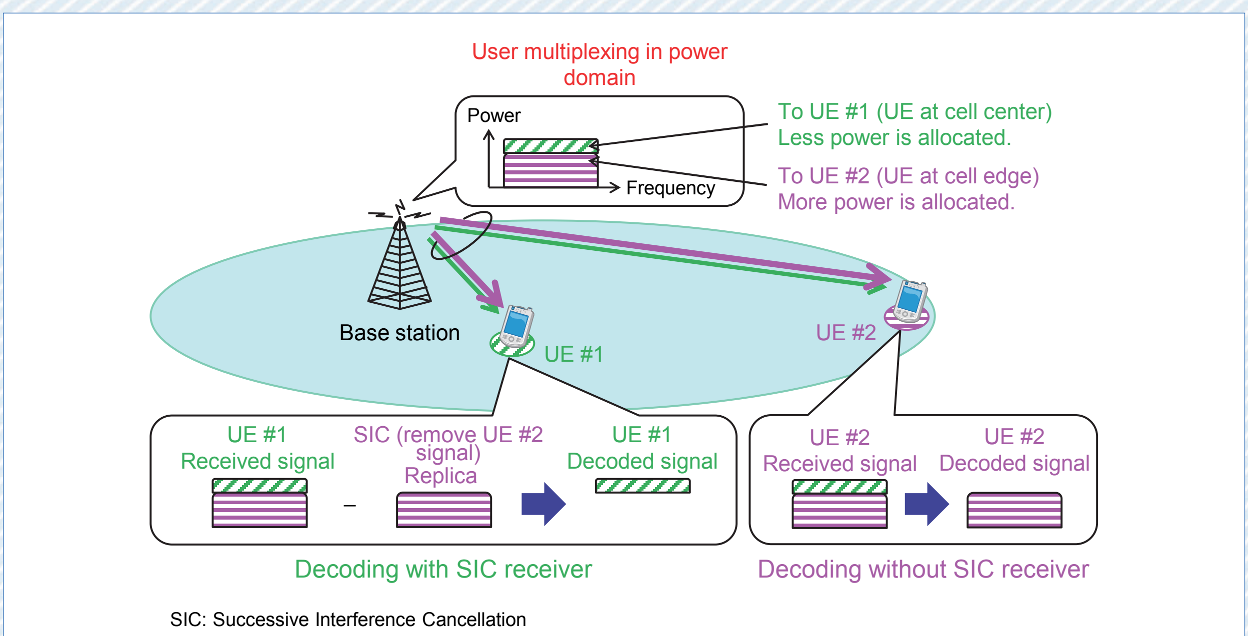

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Special Articles on Demonstration of New Technologies for 5G

Field Trials of Improving Spectral Efficiency by Using a Smartphone-sized NOMA Chipset

5G Laboratory, Research Laboratories Anass Benjebbour Yoshihisa Kishiyama Yukihiko Okumura

Standardization and field trials on the 5th Generation mobile communications systems (5G) are advancing with the goal to improve the quality of user experiences and system performance in the future. To realize the requirements of 5G, novel schemes for exploitation of new frequency bands are being developed and ways to improve spectral efficiency in existing bands are being studied. NTT DOCOMO has proposed a NOMA technology, able to transmit signals for multiple users simultaneously using the same radio resources, as a radio access technology that improves spectral efficiency. This article describes field trials done jointly between NTT DOCOMO and MediaTek to further advance NOMA technology.

1. Introduction

Since mobile communications systems became widespread in the 1980s, with the 1st Generation (1G) of analog voice services, each generation has been replaced roughly every ten years, and we advanced from LTE to LTE-Advanced, the current, 4th Generation (4G) system. For 5th Generation mobile communications systems (5G), there is a demand for various types of usage scenarios, including (1) enhanced Mobile BroadBand (eMBB), (2) massive Machine Type Communications (mMTC), and (3) Ultra-Reliable and Low-Latency Communications (URLLC) [1] [2].

At the 3GPP, an international standardization organization, began studies on 5G in March 2016 to realize these usage scenarios, by enhancing the radio communication systems of LTE-Advanced and by developing a New Radio (NR) that will not be backward compatible with LTE-Advanced. NR will support the frequencies used by current cellular systems as well as high frequency bands, including millimeter-wave*1 frequencies, and must realize a variety of service types, such as eMBB*2 and URLLC*3, within a single system. To further improve the quality of user experience and system performance, it will also be necessary to improve spectral efficiency*4 when using extended LTE-Advanced technologies and NR interfaces. Massive Multiple Input Multiple Output (Massive MIMO)*5 and Non-Orthogonal Multiple Access (NOMA) are key component technologies attracting attention for achieving higher spectrum efficiency in 5G [3] [4]. NOMA is a new multiple access method proposed by NTT DOCOMO which has attracted much attention recently and become a key topic in international projects and conferences [5]. Standard specifications related to NOMA were completed in 3GPP LTE Release 14 (LTE-Advanced Radio Interface), under the name "Multi-User Superposition Transmission" (MUST) [6]. There is much anticipation for the future extension and advancement of transceivers to incorporate NOMA on the NR interface.

In the past, NTT DOCOMO has conducted laboratory and field trials combining NOMA with open-loop*6 2×2 Single-User (SU) MIMO*7 to check NOMA performance in real propagation environments [7]. Then, in November 2015, we started planning for joint field trials with MediaTek Inc. [8]. The goals of these trials were to develop a chipset combining NOMA with closed-loop 4×2 SU-MIMO and to improve spectral efficiency relative to MUST by extending and advancing the radio interface (feedback information, signaling, etc.) and receivers. For these trials, a smartphone-sized terminal incorporating the NOMA chipset was developed, and the combination of NOMA with closed-loop 4×2 SU-MIMO in real transmission environments was established. This article describes the results of the field trials conducted from August to October 2017 by NTT DOCOMO and MediaTek, in Hsinchu City, Taiwan.

2. Downlink NOMA Technology

Multiple-access radio communications methods have evolved through Frequency Division Multiple Access (FDMA)*8 in 1G, Time Division Multiple Access (TDMA)*9 in 2G, and Code Division Multiple Access (CDMA)*10 in 3G. 4G used Orthogonal FDMA (OFDMA)*11, which uses orthogonality between subcarriers*12. In contrast to these, NOMA is a multiple-access method that multiplexes the downlink signals for multiple user terminals (User Equipment/UE) within a cell on the same radio resources at the base station and transmits them simultaneously. This can be expected to further increase spectral efficiency [9]. With NOMA, multiple user signals are intentionally multiplexed non-orthogonally in the power-domain. The basic principles of downlink NOMA are shown in **Figure 1**.

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*1 **Millimeter waves:** Radio frequency band with wavelengths in the range of 1 to 10 mm.

*2 **eMBB service:** A service requiring enhanced Mobile BroadBand (ultra-high speed, high capacity).

*3 **URLLC service:** A service requiring both high reliability and low latency simultaneously.

*4 **Spectrum efficiency:** Maximum amount of information that can be transmitted per unit frequency (bps/Hz).

*5 **Massive MIMO:** Large-scale MIMO using a very large number of antenna elements. Massive MIMO is promising for 5G implementations because antenna elements for high frequency bands can be made smaller. MIMO is a signal transmission technology able to improve communication quality and spectral efficiency by simultaneously transmitting signals of the same frequency on multiple transceiver antennas.

*6 **Open loop:** When the transmitter does not use information fed back from the receiver. Closed loop refers to when the transmitter uses information fed back from the receiver.

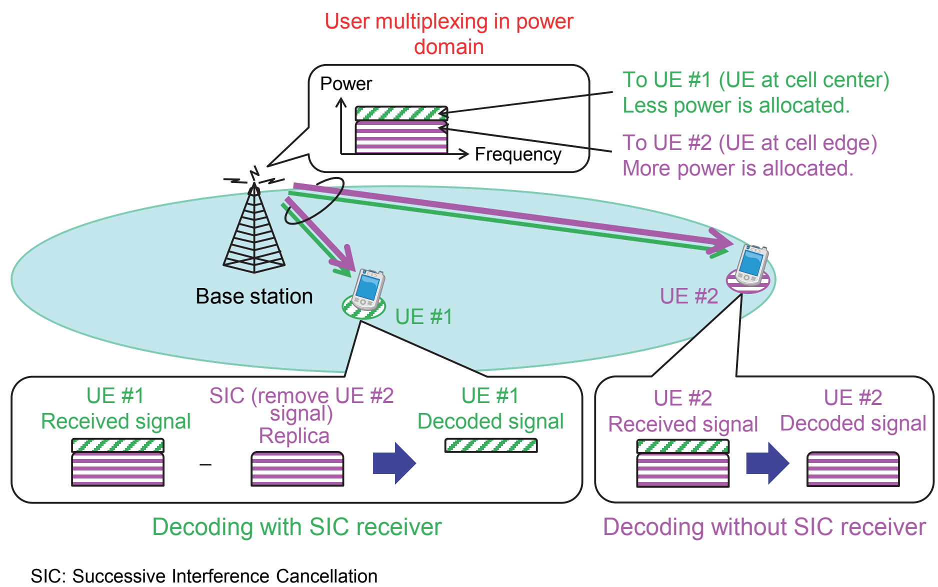

Figure 1　Downlink NOMA basic principles

In the downlink, a pair of UEs is selected among UEs within a cell, including a cell-center UE with good reception quality near the base station (UE #1 in Fig. 1), and a cell-edge UE (UE #2 in Fig. 1) with poor reception near the edge of the cell. The same frequency resource is used to transmit multiplexed data from the base station to both of them at the same time. Here, more power is allocated to the signal destined for UE #2, and less power to the signal destined for UE #1.

Upon reception, UE #1, which is closer to the base station, receives both the signal destined for UE #1 and for UE #2. As such, there is interference between the users, but the signals can be separated using a simple interference cancellation process when both signals differ in the power-domain by a certain amount.

The reception processes at UE #1 and UE #2 for this case are described below.

1) Reception at UE #1

The signal for UE #1, which is near the base station, can be separated and decoded by first decoding only the strong interfering signal destined for UE #2, using it to create a replica*13 of the UE #2 signal, and then subtracting it from the received signal. This type of signal separation process is called Successive Interference Cancellation (SIC)*14. There are two types of SIC, conducted at the symbol*15 level and the codeword*16 level (CodeWord level SIC (CWIC))*17, respectively. To cancel the interfering signal from UE #2 at the symbol level, symbols in the interfering UE #2

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*7　SU-MIMO: A technology for transmitting and multiplexing multiple signal streams by multiple antennas between a base station and terminal with one user as target.

*8　FDMA: Transmission of multiple user signals within the same radio-access-system band by using different frequencies.

*9　TDMA: Transmission of multiple user signals within the same radio-access-system band by using different time slices.

*10　CDMA: Transmission of multiple user signals within the same radio-access-system band using different diffusion codes.

*11　OFDMA: A radio access scheme that uses OFDM. OFDM transmits a high-data-rate, wideband data signal using multiple parallel low-data-rate subcarrier (see *12) signals, realizing high-quality transmission that is very tolerant of multipath interference.

*12　Subcarrier: An individual carrier for transmitting a signal in multi-carrier transmission schemes such as OFDM.

*13　Replica: A regeneration of the received signal using estimated values for the transmitted signal.

signal are demodulated and then re-modulated without decoding to generate a replica of the interfering UE #2 signal. This is then subtracted from the received signal. To cancel the interfering signal from UE #2 using CWIC, a replica of the interfering UE #2 signal is generated by taking the bit sequence[*18] obtained by demodulating and decoding the interfering UE #2 signal, turbo-coding[*19] and modulating it again, and subtracting it from the received signal.

This sort of SIC signal separation has been considered since 3G, but was difficult to implement due to the high computing capability it would require in UEs. With the recent, rapid increase in UE performance, practical implementations of this technology are becoming more promising.

2) Reception at UE #2

In contrast, lower power was allocated to the interfering UE #1 signal, so it is weak upon arriving at UE #2, and the UE #2 signal can be decoded directly, without applying SIC.

In the base station, the scheduler can dynamically select whether to apply NOMA at the level of a subframe[*20], so NOMA can be implemented on networks that support existing LTE/LTE-Advanced terminals. It can also be combined with technologies that have been applied to LTE/LTE-Advanced. For example, MIMO has been applied to LTE/LTE-Advanced, but by combining it with NOMA, more data streams[*21] than the number of transmit antennas can be multiplexed, further improving the system performance. NOMA can be positioned as a technology for enhancing LTE-Advanced, and could also be used with 5G NR.

3. Combining Downlink NOMA and SU-MIMO

The operating principles for combining downlink NOMA with SU-MIMO, when there is one base station and two multiplexed UEs, are shown in **Figure 2**. It shows the difference in transmit layer[*22] for each beam. We assume two UEs: UE #1 near the center of the cell, and UE #2 near the edge of the cell; with a large difference in path loss between them. A precoder is generated at the base station based on channel state information fed back from the UEs. After applying (multiplying) the precoder to the transmit signals for each UE, they are non-orthogonally multiplexed with differing transmit power levels and transmitted. It is assumed that multiple layers are transmitted to each UE, so in the case that the transmission rank[*23] is two for both UEs, the base station uses two transmit antennas, and a total of up to four streams are sent to the two UEs.

For LTE Transmission Mode 4 (TM4)[*24] closed-loop SU-MIMO using precoders, the precoders are decided based on channel state information fed back from the UEs. However, when combining NOMA with SU-MIMO using precoders, the amount of interference between users differs depending on the combination of precoders used. If the same precoder is used for both users, the amount of interference between users will be proportional to the multiplexing power ratio. In this case, since the precoders of both users are aligned, a different precoder than the one fed back from a particular user may be used, and thus the precoding[*25]

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*14 SIC: A signal separation method in which multiple signals making up a received signal are detected one by one and separated by a canceling process.

*15 Symbol: A unit of transmission data consisting of multiple subcarriers. A cyclic prefix is inserted at the front of each symbol.

*16 Codeword: A unit of error correction coding. One or more codewords are transmitted when using MIMO multiplexed transmission.

*17 CWIC: An SIC method that decodes the interfering-user signal, generates a replica of the interfering signal, and applies an interference cancellation process at the code word level.

*18 Bit sequence: A sequence of data bits called a word. A word groups together multiple bits, which are the smallest unit of information.

*19 Turbo coding: A type of error correction coding that achieves powerful error-correction performance through iterative decoding using reliability information in decoded results.

*20 Subframe: A unit of radio resources in the time domain consisting of multiple OFDM symbols (14 OFDM symbols in LTE).

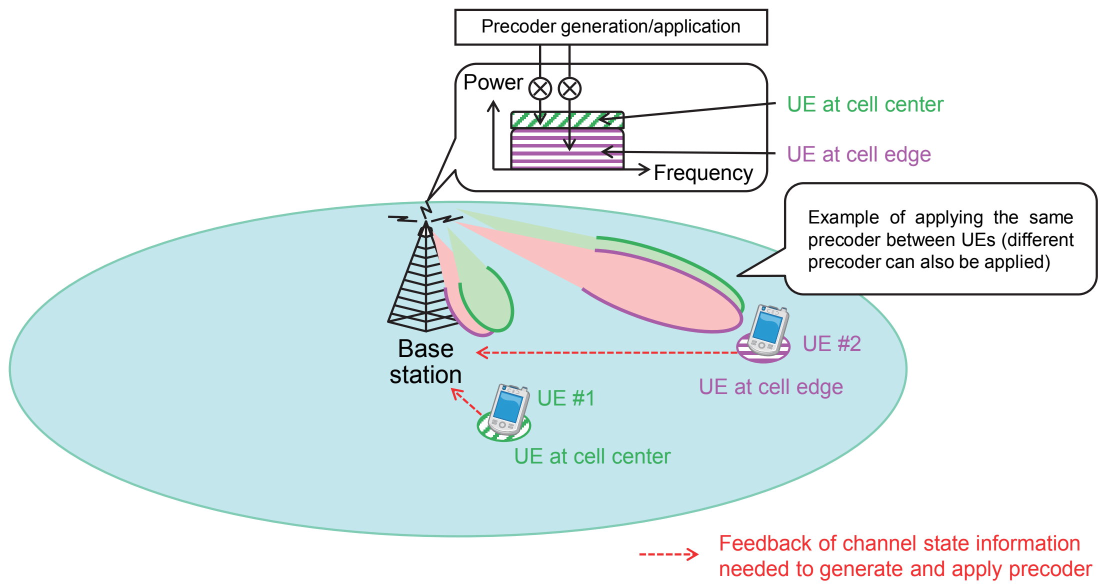

Figure 2 Principle of combining downlink NOMA with SU-MIMO

gain*26 of that particular user can be reduced. Conversely, if different precoders are applied to each user when combining NOMA with SU-MIMO, precoders based on feedback from the UEs can be applied, so the precoding gain for the desired signal can be maximized. However, focusing on UE #1, where SIC will be applied, the transmit precoder for UE #2 may not be optimal for the UE #1 channel. For this reason, the UE #2 precoding gain could be reduced at UE #1, which can reduce interference between users; however, the accuracy of the replicated UE #2 signal generated when applying SIC at UE #1 could be degraded.

4. NOMA Field Trials Overview

From April 2014 to July 2015, NTT DOCOMO conducted laboratory and field transmission tests. The throughput characteristics of two terminals that were non-orthogonally multiplexed using NOMA and that used downlink 2×2 open-loop SU-MIMO (TM3) were measured [7]. Then, starting in November 2015, NTT DOCOMO began a collaboration with MediaTek Inc. to advance NOMA even further [8]. From August to October 2017, the throughput characteristics of NOMA and SU-MIMO were measured in the field in experiments multiplexing signals of three smartphone-sized terminals equipped

*21 Data stream: The data sequence transmitted in MIMO transmission.
*22 Layer: A spatial stream in MIMO.
*23 Transmission rank: The number of layers (spatial streams) transmitted simultaneously in MIMO.
*24 LTE TM: The MIMO transmission mode specified for LTE.
*25 Precoding: In MIMO, a process of applying weightings to a signal before it is transmitted, based on the current propagation channel between transmitter and receiver, to improve the quality of signal reception.
*26 Gain: One of the radiation characteristics of an antenna. An indicator of how many times larger the radiation strength in the antenna's direction of peak radiation is relative to a standard omni directional antenna.

with a NOMA chipset and 4×2 closed-loop SU-MIMO (TM8). The equipment for these field trials is shown in **Photo 1**.

1) Trials Configuration

The frame structure was based on LTE Release 8 downlink [10], including a Cell-specific Reference Signal (CRS)[*27] used for channel estimation[*28], and data channel mapped into 1 ms subframes. Specifications for the base station and UEs are shown in **Table 1**. The base station maximum total transmit power was 500 mW, the antenna heights were approximately 10 m for the base station and 1.5 m for UEs, and the base station had four transmit antennas of the same polarization[*29], at intervals of 1.5 wavelengths. The UEs had two receive antennas. Transmit signals had a bandwidth of 10 MHz, with a center carrier frequency[*30] of 3.5 GHz. The total transmit power of each UE was 200 mW, and they were equipped with a MediaTek Helio®[*31] NOMA test chipset. Up to three UEs were multiplexed at the same time, data signals were independently turbo-coded for each UE, and data modulation and precoding were applied. Data for up to two users per beam (layer) was non-orthogonally multiplexed, and 4×2 closed-loop SU-MIMO based on LTE TM8 [3] was used for MIMO transmission. Up to two layers were used per user. The same precoder was used for users when applying non-orthogonal multiplexing. For precoder feedback information, a fixed transmission rank of two was assumed on the UE side, and 12 Precoding Matrix Indicators (PMI)[*32] designed for these trials were fed back using a modified version of TM8. The feedback interval was 10 ms.

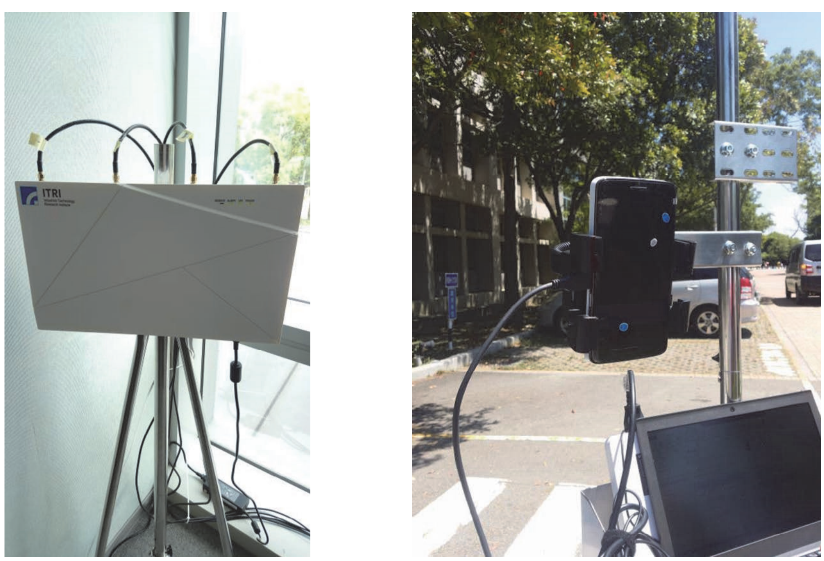

Photo 1　Base station (left) and mobile station (right) equipment

*27　CRS: A reference signal specific to each cell for measuring received quality in the downlink.

*28　Channel estimation: Estimation of the amount of attenuation and phase change in the received signal when a signal is transmitted over a radio channel. The estimated values obtained (the channel data) are used for separating MIMO signals and demodulation at the receiver, and to compute channel data which is fed back to the transmitter.

*29　Polarization: Direction of electric-field oscillation. Oscillation of the electric field in the vertical plane relative to the ground is called vertical polarization and that in the horizontal plane is called horizontal polarization.

*30　Carrier frequency: A carrier frequency is a radio wave that is modulated in order to transmit information.

*31　MediaTek Helio®: A registered trademark of Taiwan MediaTek Inc.

*32　PMI: Information fed back from the mobile terminal to specify a suitable downlink precoder. Notifies the index selected from the codebook.

Table 1 NOMA field trials equipment specifications

Item	Value
Carrier frequency	3.5 GHz
Bandwidth	10 MHz
Antenna height	Base station: 10 m, UE: 1.5 m
UE transmit power	Max. 200 mW
Base station transmit power	Max. 500 mW
Duplex	TDD
Subcarrier interval	15 kHz
Subframe length	1 ms
No. of UEs	Max. 3
No. of base station transceivers	4
No. of UE transceivers	2
MIMO mode	TM8 modified version (extended to 24 PMI feedback)
Feedback data period	10 ms
No. of layers	Max. 2 layers (per UE)
Receiver	CWIC, etc.

2) Trials Environment

The environment of field trials is shown in **Figure 3**. Tests were done at the Industrial Technology Research Institute (ITRI) campus in Hsinchu City, Taiwan. UE were placed at several measurement points along two roads, precoder and Modulation and Coding Schemes (MCS)*33 were selected adaptively to maximize user throughput, and user throughput was measured.

When combining NOMA with MIMO, we made it possible to handle reception quality at each user with flexibility by being able to set combinations of numbers of MIMO transmission layers (transmission ranks) arbitrarily (R_1:R_2:R_3). It was also possible to set the ratio of multiplexing power between non-orthogonally multiplexed users to be different for each layer.

3) Evaluation Scenarios

The main evaluation scenarios in these tests are shown in **Figure 4**. When NOMA is applied (Fig. 4, right), the three UEs are using the 10 MHz band at the same time. Here, the MCS and multiplexing power ratio combination to maximize total throughput to UE #3 are applied. The transmit rank of the closer UE (UE #1) is 2, while for the farther UEs (UE #2, UE #3) it is 1. When SU-MIMO is

*33 MCS: Combinations of modulation scheme and coding rate decided on beforehand when performing Adaptive Modulation and Coding.

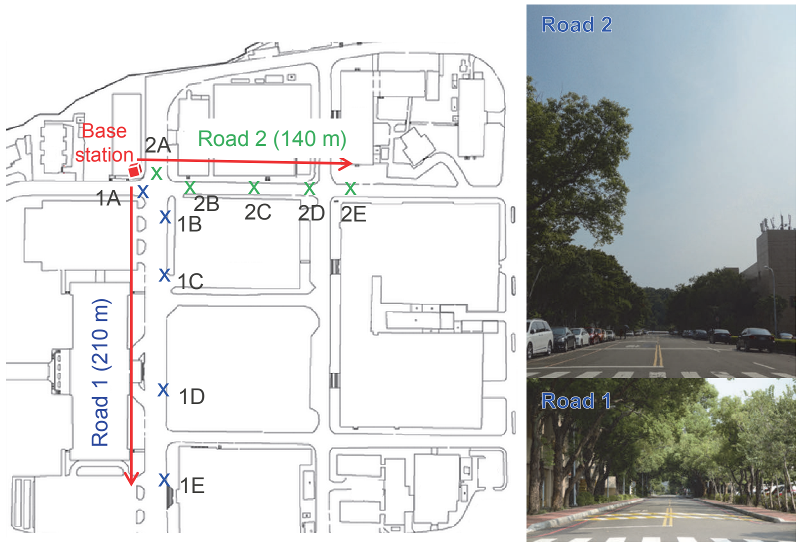

Figure 3　Environment of field trials (Hsinchu City, Taiwan, ITRI Campus)

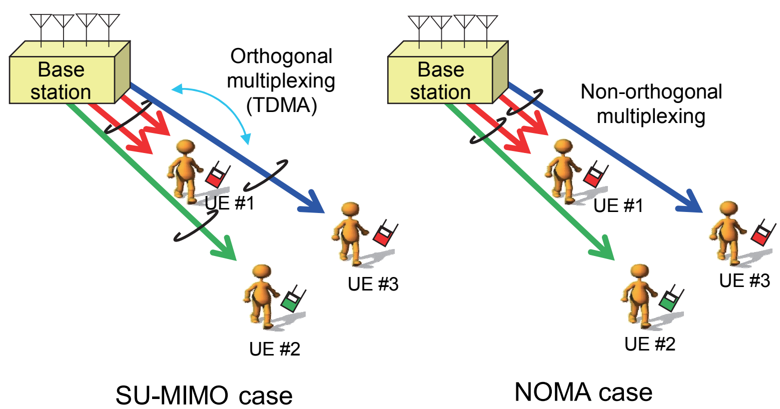

Figure 4　Evaluation scenarios

applied (left), the 10 MHz band is time-partitioned between the near and far UEs to distribute the resource.

For the receivers, the UE near the base station (UE #1) applies CWIC reception to the received signal, and the cell-edge UEs (UE #2, UE #3) detect the desired signals without applying SIC. A Reduced Maximum Likelihood (R-ML) detection criteria*34 MIMO signal detection [11] was used for MIMO stream separation at UE #1 and to cancel interference between users at UE #2 and UE #3.

5. NOMA Field Trials Results

The test results of the field trials using this prototype equipment in a real outdoor radio environment are shown in **Table 2**. The received Signal-to-Noise Ratios (SNR)*35 at UEs were computed using the CRS. The measured results were 30 dB for the near UE, at measurement point 2A, and 7 dB for the two far UEs at measurement point 2D. The transmission rank combination for the cell-center user (UE #1) and cell-edge users (UE #2, UE #3) (R_1:R_2:R_3) was 2:1:1, and the throughput when applying SU-MIMO and NOMA was measured. Table 2 shows the user throughput, the system throughput (total throughput for three users), and user throughput product together with the improvement gained by using NOMA. Note that the user throughput product is an indicator of fairness, and can be used as an index to measure proportional fairness*36.

The results in Table 2 show that NOMA increased the throughput for all UEs relative to SU-MIMO. System throughput when applying NOMA was also improved by 2.3 times compared to using SU-MIMO, and there was an 11-times gain in user throughput product.

6. NOMA Related Standardization

Study of MUST performance began at 3GPP in April 2015, as an LTE Release 13 Study Item (SI)*37, and was standardized in a LTE Release 14 Work Item (WI)*38 [6] [12]-[14].

3GPP is also examining application of NOMA to mMTC. An example of mMTC is having large numbers of sensors transmitting small packets simultaneously. For mMTC, a signal waveform design supporting wide coverage and asynchronous communication is important, but so are uplink NOMA [15] with the ability to increase the control channel capacity (so more users can be connected simultaneously), and a control channel design that does not require control data (e.g.: grant free access*39, which does not require permission before

Table 2 NOMA throughput improvement relative to SU-MIMO

UE location		UE #1 (2A)	UE #2 (2D)	UE #3 (2D)
	Received SNR (dB)	30	7	7
SU-MIMO	User throughput (Mbps)	16.3	2.63	1.53
NOMA	User throughput (Mbps)	39.9	5.1	3.6
NOMA vs. SU-MIMO	User throughput gain	+144.79%	+93.92%	+135.29%
	User throughput total gain	+137.54%		
	User throughput product gain	11.17 times		

*34 R-ML detection criteria: A Maximum Likelihood Detection (MLD) scheme that reduces the large amount of computation required for conventional MLD.

*35 Received SNR: Ratio of desired signal power to noise power in the received signal.

*36 Proportional fairness: An index for maximizing the balance between system capacity and fairness.

*37 SI: Work that involves investigating feasibility and roughly identifying all functions that should be specified.

*38 WI: Work that involves determining all functions needing specifying and formulating detailed specifications for those functions.

*39 Grant free access: A radio-channel access method that requires no pre-authorization from the base-station side prior to data transmission. This method enables a terminal to transmit data to the base station at any time.

transmitting data). At 3GPP, more than 16 uplink access methods, including uplink NOMA, have been proposed by major companies and are under consideration.

7. Conclusion

This article has described the results of field trials using terminals equipped with a NOMA chipset, and a combination of NOMA with 4×2 closed-loop SU-MIMO. The benefits of NOMA advancements in increasing spectral efficiency were confirmed. These trials have shown that with non-orthogonal multiplexing for three terminals using NOMA, it was possible to improve spectral efficiency in terms of system throughput by up to 2.3 times, compared to using SU-MIMO. By using smartphone-sized terminals equipped with the NOMA chipset, we have also shown that the interference cancellation technology needed for NOMA can be implemented. Our goal for the future is 3GPP standardization of this advanced NOMA, as a technology for developing 5G.

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Technology Reports

5G | URLLC | Demonstration

Special Articles on Demonstration of New Technologies for 5G

Field Experiments on 5G Ultra-Reliable Low-Latency Communication (URLLC)

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Standardization deliberation and technical demonstrations are progressing toward implementation of 5th Generation mobile communications systems (5G). One usage scenario that is anticipated for 5G is URLLC, which is needed for applications such as autonomous vehicles and remote controls. NTT DOCOMO has conducted field trials toward realization of URLLC. This article gives an overview of URLLC and discusses the field trials done jointly with Huawei Technologies, to demonstrate URLLC over distances up to 1 km, along with the latest test results.

1. Introduction

5th Generation mobile communications systems (5G) are highly anticipated for handling explosive increases in traffic and diversification of services. Organizations such as the 3GPP are deliberating on standards, and major organizations and enterprises throughout the world are conducting demonstrations toward introduction of 5G. NTT DOCOMO has also been actively working toward implementation of 5G since about 2010, proposing technology concepts, conducting experiments, and taking leadership in standardization deliberations.

Typical usage scenarios for 5G include (1) enhanced Mobile Broad Band (eMBB), (2) massive Machine Type Communications (mMTC), which realizes large numbers of simultaneous connections, and (3) Ultra-Reliable and Low-Latency Communications

(URLLC) [1]. URLLC has received particular attention for its potential in new use cases in the future, such as autonomous vehicles, tactile communications, and remote medicine. In collaboration with Huawei Technologies, NTT DOCOMO has conducted the first successful field trials simultaneously achieving both high reliability and low latency, as required for URLLC. This article gives an overview of URLLC and describes these field trials.

2. Overview of URLLC

5G use cases and technical requirements for realizing them have been discussed in industry organizations within and outside of Japan [1]-[3]. For eMBB, requirements have been set to extend speed and capacity, as they were with 4G and earlier.

On the other hand, expectations in industry are growing for the Internet of Things (IoT), so requirements for mMTC and URLLC have been set anticipating integration in industries other than mobile communications, such as automobiles, robots, and sensors.

2.1 URLLC Use Cases

URLLC is targeted mainly for services such as traffic control or remote control, which require both high reliability and low latency. The following use cases are typical examples [3].

1) Control of Autonomous Vehicles and Traffic Control

This use case involves sending warning signals between vehicles and other vehicles, roadways, and even pedestrians to reduce traffic accidents, improve traffic efficiency and support movement of emergency vehicles.

2) Robot Control and 3D Connection with Drones and Other Devices

Automation of manufacturing and logistics using robots at smart factories and other facilities is anticipated, and control of these is a use case for 5G. It is also expected to cover airborne as well as terrestrial applications, so ability to control drones and other devices in the air remotely is also specified.

3) Remote Surgery

Remote surgery can be implemented using optical communications or other fixed networks, but this is difficult to apply in disaster areas or other dangerous situations. Remote surgery in such locations is another use case for 5G.

All of the above use cases require high reliability and low latency, and in most cases, the wireless systems are to be used for sending the control signals. For these cases, there are strict requirements on 5G URLLC regarding reliability, low latency, and mobility rather than high transmission speed or large numbers of connected terminals.

2.2 URLLC Requirements and Issues

End-to-end target values for URLLC, including the core network, have been discussed, but this article describes only the URLLC requirements for the radio access network.

1) URLLC Requirements

There are various URLLC requirements that have been defined by industry organizations such as 3GPP, stating the certainty that an X-byte packet will be received successfully with latency under a set time [4]. Here, latency refers to the time from the start of processing of the service data unit*1 at wireless protocol layer*2 2 (or 3) in the transmitter, to when the packet has been received successfully. This is called the radio segment latency, or user plane*3 latency. The definition of user plane latency is shown in **Figure 1**. User plane latency is the one-way latency for successful reception of a packet, and includes the time for one or more retransmissions if packet reception fails. From the above, URLLC implementations must satisfy a probability that at least a set number of packets are received successfully (reliability), while also satisfying user plane latency below a set value (low latency). Concrete target values have also been proposed. 3GPP has set a target of "user plane latency of 1 ms or less for transmission of a 32-byte packet, with successful reception rates of 99.999% or better."

2) Issues in Meeting Requirements

To meet URLLC requirements for reducing latency requires (1) reducing radio signal transmission time, and (2) reducing time needed for retransmissions, and for increasing reliability, requires (3) improving successful packet reception rates. These requirements are described in detail below.

(1) Reducing radio signal transmission time

The longer the slot length, which is the unit of signal transmission, the longer the wireless signal transmission time will be. For example, with LTE-Advanced, which is a 4th generation mobile communications system (4G), the user plane latency to transmit just the wireless signal was over 1 ms. As described earlier, the user plane latency includes signal processing latency for both transmission and reception, so reducing the slot length is desirable.

(2) Reducing time needed for retransmissions

Successful packet reception rates can be increased through signal retransmission, but the retransmission procedure requires signaling on the uplink and downlink, which introduces delay. For example, if the mobile terminal does not receive a signal correctly on the downlink, or if the downlink signal is not received within a fixed time, a Negative ACKnowledgement (NACK)*4 signal is fed back on the uplink channel. When the base station receives the NACK signal, it sends a

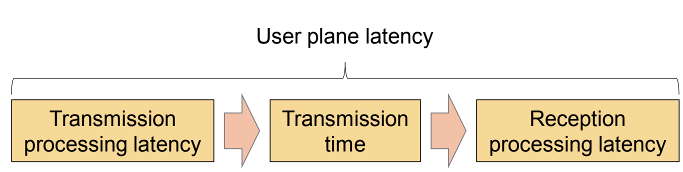

Figure 1　User plane latency definition

*1　**Service data unit:** The data without added headers, etc.

*2　**Protocol layer:** A communications protocol layer defined in the OSI reference model, which is a design guideline for network architectures. Protocol layer 2 refers to the data link layer, and protocol layer 3 refers to the network layer.

*3　**User plane:** The part of the signal sent and received in communication, which contains the data sent and received by the user.

*4　**NACK:** A signal sent to notify the sending party that the data was not received correctly. Note that a signal called an ACK is sent to indicate that the data was received correctly.

retransmission signal on the downlink channel. This improves the packet reception success rate, but the user plane latency increases due to the retransmission procedure. Thus, it is important to reduce the time required for retransmission in order to achieve both high reliability and low latency.

(3) Improving successful packet reception rates

To increase successful packet reception rates with low latency, it is desirable to receive packets successfully with one transmission, and avoid retransmissions to the extent possible. Packet reception success rates tend to drop particularly in multipath environments*5, where the radio channel tends to degrade due to fading*6. High successful packet reception rates must be maintained even in such environments.

3. Technologies for Realizing URLLC

New air interfaces have been discussed for high reliability and low latency, including new radio frame structures, retransmission schemes, and grant free access*7. Below, we describe technologies for realizing URLLC, focusing on the technologies used in our field trials. Note that the trials assumed a Time Division Duplex (TDD)*8 format.

3.1 Radio Frame Structure for Reducing Transmission Time

1) Radio Frame Structures Studied for NR

A New Radio (NR), which is not backward compatible with LTE-Advanced, is being studied in 5G deliberation at 3GPP. To meet various requirements such as supporting high-frequency bands, NR uses multiple different Orthogonal Frequency Division Multiplexing (OFDM)*9 subcarrier*10 intervals (15, 30, 60, and 120 kHz) [5]. Using wide OFDM subcarrier intervals like 120 kHz provides wider bandwidth per subcarrier, so that the same amount of information can be transmitted in a shorter time. This enables the transmission time for the radio signal to be shortened, reducing latency. However, it also reduces the number of subcarriers, so ignoring overhead, the amount of information that can be sent in a set period of time is the same.

An approach that introduces the mini-slot*11, with the conventional 15 kHz OFDM subcarrier interval, has also been proposed [6]. The time required for retransmissions can also be reduced by designing a radio frame that allows rapid switching of transmission between the uplink and the downlink. The trials described here use an approach with a wide OFDM subcarrier interval and a new radio frame design to reduce latency.

2) Radio Frame Structure Used in Trials

The radio frame structure used in testing is shown in **Figure 2**. This frame structure has a 60 kHz subcarrier interval, an OFDM symbol*12 length of 16.67 μs defined by the inverse of the subcarrier interval, and an added Cyclic Prefix (CP)*13 of length 1.56 μs. This frame structure is composed of special slots and normal slots. A normal slot has six-OFDM symbols for downlink or uplink data transmission and two-OFDM symbols for guard time*14. This results in 0.125 ms each on up and down links, for a total slot length of 0.25 ms. This enables the transmission time to be reduced. Note that a special slot requires more control signals and has twice the

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*5 Multipath environment: An environment in which the signal from the transmitter arrives directly, superimposed with signals reflected from buildings and other features in the environment.

*6 Fading: The phenomenon in which the level of the received signal fluctuates with movement of the mobile station and the passage of time.

*7 Grant free access: A format in which the mobile station can transmit without first receiving permission to transmit (grant) from the base station.

*8 TDD: A format in which downlink and uplink communication is segmented in time, with transmission and reception alternating.

*9 OFDM: A multi-carrier transmission scheme that uses orthogonal narrow-band carriers. Many wireless communication systems such as LTE-Advanced and Wi-Fi® use OFDM. Wi-Fi is a registered trademark of the Wi-Fi Alliance.

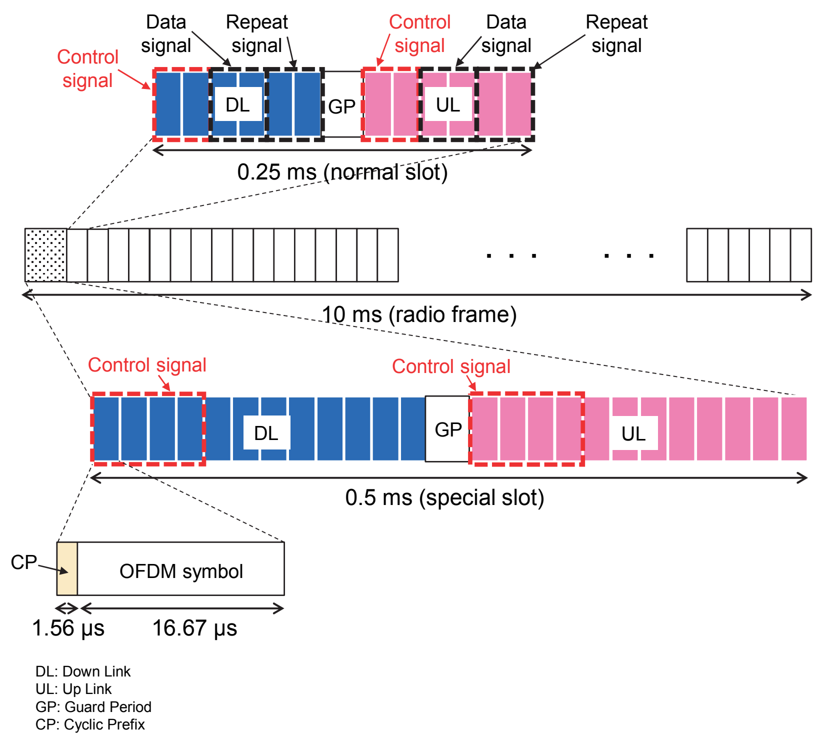

Figure 2 Radio frame structure used in trials

number of OFDM symbols for data and repeat signals of a normal slot, so the total slot length for up and down links is 0.5 ms. A radio frame contains one special slot.

This radio frame structure uses a TDD format. Since it switches between downlink and uplink every 0.125 ms, feedback signals such as ACK and NACK can be sent quickly, reducing the time required for retransmissions. With the LTE-Advanced TDD format, 10 to 11 ms was needed from signal transmission to retransmission, but this can be reduced to approximately 0.75 to 1 ms with this radio frame structure.

3.2 Transmission of Repeated Signals

As described earlier, packet success probability can be improved using retransmission, but it increases user plane latency. Packet success probability can also be improved by repeating transmission of signals even before feedback signals such as NACK are sent. Sending the same signal multiple times reduces transmission efficiency, but it is able

*10 Subcarrier: Individual carrier for transmitting signals with multi-carrier transmission such as OFDM.

*11 Mini-slot: A slot defined with a shorter than normal slot length.

*12 OFDM symbol: A unit of transmission data consisting of multiple subcarriers. A CP (see *13) is inserted at the front of each symbol.

*13 CP: The guard interval added to the beginning of an OFDM symbol. It reduces the effects of inter-symbol interference due to the previous OFDM symbol in delayed signals and loss of orthogonality among subcarriers.

*14 Guard time: An interval established when using a TDD format. Prevents collision of uplink and downlink signals due to transmission delay.

to improve packet success probability without increasing user plane latency. In the radio frame structure used in these trials, the first two OFDM symbols on the downlink or uplink are used as control signals, the next two OFDM symbols as data signals. Then, the two OFDM symbols after the data signal are used to send a repeat signal.

3.3 Multi-antenna Diversity Technology

Another approach of improving packet success probability is to use diversity technology*15 with multiple antennas. Diversity technology can be used to prevent a drop in packet success probability in multipath environments. Our trials adopted transmission antenna diversity technology with eight antennas on the base station and two antennas on the mobile terminal. The transmit antenna diversity technology used was a format called Space Frequency Block Coding (SFBC)*16, with two antennas [7]. Note that the two signals output with SFBC at the base station were each transmitted from four antennas, so a total of eight antennas were used.

4. URLLC Field Trials

URLLC field trials were conducted at NTT DOCOMO in collaboration with Huawei Technologies. An overview of the trials and results is given below.

4.1 Test Overview

The trials were conducted in the Yokohama Minato-Mirai 21 district.

Photographs of the test equipment are shown in **Figure 3**. The Radio Frequency (RF)*17 and Intermediate Frequency (IF)*18 units of the base station were located on the roof of the building, and the height of the antennas was approximately 108 m. The baseband*19 unit of the base station and other equipment were located inside the building and were connected to the IF unit by optical fiber. The mobile station antennas were mounted on top

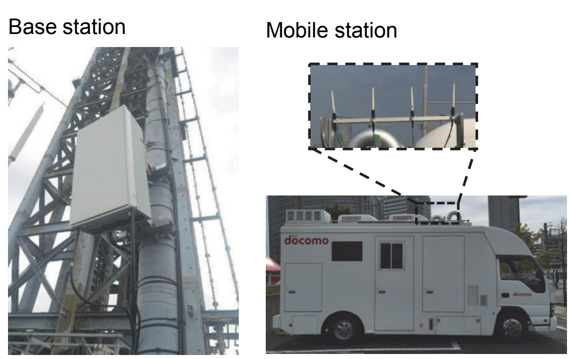

Figure 3 External view of test equipment

*15 Diversity technology: A technology that reduces drops in received-signal level due to fading by selecting among or synthesis from multiple received signals that have low correlation.

*16 SFBC: A type of transmit diversity technology in which Alamouti coding is used between adjacent subcarriers on two transmit antennas, and by coding between frequencies and antennas, diversity gain equivalent to maximal ratio combining can be obtained.

*17 RF: A signal or radio wave of frequency used as a carrier for radio communications.

*18 IF: An intermediate frequency used in transmitters and receivers when converting to the carrier signal frequency.

*19 Baseband: The signal band before modulation and after demodulation on the carrier wave of a radio signal.

of a test vehicle, at a height of 3.2 m. Other mobile station equipment was installed inside the vehicle.

Test equipment specifications are shown in **Table 1**. Tests were done using a 20 MHz bandwidth in the 4.5 GHz band, and measurements were taken using different Modulation and Coding Schemes (MCS)*20, depending on packet size. The packet sizes used in the trials were 32, 50, 100, and 200 bytes.

The test environment as seen from the base station is shown in **Figure 4**. Trials were done with the test vehicle both stationary and moving. Stationary tests were done at points A, B, and C with different transmission distances from the base station, as shown in Fig. 4, and at point D, which was not in the line-of-sight of the base station. The moving tests were done along the running course shown in Fig. 4. A driving speed was 25 km/h during the tests.

Table 1 Test equipment specifications

Main specifications	Base station	Mobile station
Central frequency	4.66 GHz	
System bandwidth	20 MHz	
Signal waveform	Filtered-OFDM	
OFDM subcarrier interval	60 kHz	
OFDM symbol length	16.67 μs	
Slot length	0.125 ms	
Guard time	31.25 μs	
CP length	1.56 μs	
Channel encoding	Polar coding	
MIMO mode	SFBC	
No. of MIMO streams	1	
No. of antenna elements	8	2
Antenna tilt angle	16.4°	0°
Antenna height	108 m	3.2 m
Max. transmission power	46 dBm	23 dBm
Traffic model	Transmitting packets of the same size at fixed intervals	
Packet size	32, 50, 100, or 200 bytes	

Polar coding: A communications coding method that uses polarization that occurs when repetitive operations are applied on the communication path.

*20 MCS: A combination of modulation scheme and coding rate determined beforehand when performing adaptive modulation.

Figure 4 Test environment

4.2 Test Results

In these trials, we evaluated the maximum packet size for which the 3GPP URLLC requirements could be achieved. The test results are summarized in **Table 2**.

1) Stationary Trials (within Line-of-sight)

In stationary testing, 200-byte packets were transmitted on both uplink and downlink over distances of approximately 0.33 km to point A and 0.8 km to point B, satisfying latency of 1 ms or less, and a packet success probability of 99.999% or better. The same URLLC conditions were also met over the distance of approximately 1.0 km to point C with 100-byte packets. This verifies that URLLC can be realized over this range of distances.

The conditions were not met for point C with 200-byte packets because adequate Signal-to-Noise Ratio (SNR)*21 could not be obtained. With the radio frame structure, user plane latency of 1 ms or less cannot be achieved unless one packet is transmitted per slot. However, the SNR was insufficient when using the MCS needed to transmit a 200-byte packet in one slot for point C, and the packet success probability dropped. Conversely, when using an MCS able to maintain the packet success probability, multiple slots were required to send a 200-byte packet, resulting in user plane latency over 1 ms. In this way, the MCS must be selected in

*21 SNR: The ratio of the desired signal power to the noise power.

Table 2 Test results

Terminal conditions	Distance from base station	Transmitted packet data (max)	Radio segment delay	Transmission success rates
Stationary (line-of-sight)	Approx. 0.33 km	200 bytes	0.5 to 0.7 ms	99.999 to 100%
	Approx. 0.8 km	200 bytes		
	Approx. 1.0 km	100 bytes		
Stationary (non-line-of-sight)	Approx. 0.35 km	Downlink: 200 bytes Uplink: 100 bytes		
Moving (speed: 25 km/h)	Approx. 0.3 to 0.6 km	100 bytes		

consideration of the packet size and SNR for URLLC. Link adaptation technology*22, which switches MCS adaptively according to SNR, is used in many wireless systems. However, to switch MCS adaptively for URLLC, it must be done with consideration for both packet size and SNR, instead of just SNR as in earlier systems. Thus, to improve the characteristics of URLLC, improvements must be made to the MCS selection algorithm and the radio frame structure.

2) Stationary Trials (Non-line-of-sight)

URLLC requirements were also achieved for point D, in a non-line-of-sight environment where multipath effects were observed, while transmitting 200-byte packets on the downlink and 100-byte packets on the uplink. Reasons that the URLLC requirements were not achieved for 200-byte packets on the uplink, could be that the transmission power is less than on the downlink, or fluctuations in SNR due to multipath effects. This shows that the amount of data that can be transmitted as URLLC is limited by the radio environment. Assuming that URLLC services will be expanded widely in the future, it will be important to clarify coverage and upper limits on the amount of information that can be transmitted when providing services.

3) Mobile Trials

In mobile trials, the URLLC requirements were met with 100-byte packets on both downlink and uplink, in spite of screening by trees and other objects, and changes in direction of movement. These trials demonstrate that URLLC can be realized even when moving by car or other vehicle in urban areas, and show the potential for applications such as autonomous cars.

5. Conclusion

This article has given an overview of URLLC as a 5G use case and described field trials conducted by NTT DOCOMO. The trials have demonstrated that the URLLC requirements of high reliability and low latency can be met at the same time. However, to provide stable URLLC, further improvements

*22 **Link adaptation technology:** The function that selects MCS according to the radio environment. An MCS with high transmission rate is selected when conditions are favorable with a low transmission rate when they are poor.

to the radio frame structure and control algorithms are needed.

To support future services with flexibility, it is also desirable to increase the volumes of data that can be transmitted while satisfying the requirements of URLLC. It will also be necessary to clarify the transmission coverage that is possible. We will continue work toward resolving the issues identified in the field trials and creating new services using URLLC.

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Technology Reports | 5G | Millimeter Wave | Long-distance Field Transmission Tests

Special Articles on Demonstration of New Technologies for 5G

5G Field Testing of Ultra-high-speed, Long-distance Transmission Using Millimeter-wave Signals

5G Laboratory, Research Laboratories Yoshihisa Kishiyama Atsushi Harada Bo Yu
Anass Benjebbour Yukihiko Okumura

NTT DOCOMO is conducting R&D on 5th Generation mobile communications systems (5G) with the goal of providing services by the year 2020. In addition to conventional frequency bands, 5G will use higher frequencies in the millimeter-wave band to achieve dramatic increases in communication speed and capacity. This article gives an overview of 5G field tests done in collaboration with Tobu Railway and Huawei Technologies. The tests used ultra-high-gain beam forming transmission technology to achieve high-speed communication over distances exceeding 1 km with millimeter waves, which are difficult to transmit over long distances due to rapid attenuation.

1. Introduction

Mobile communication traffic has increased by a factor of 1.6 each year since 2010 [1], and it is predicted to increase to more than 1000 times volumes when LTE was introduced in 2010, by the 2020s if this continues. 5G mobile communication systems will increase performance of networking systems in various ways. Capacity will increase to handle this rapid increase in traffic at the lowest cost and power consumption possible, but the system will also support ultra-high-speed communication over 10 Gbps, even lower latency, and connectivity for large numbers of terminals, as required due to the spread of the Internet of Things (IoT).

A major feature of 5G is that it will achieve dramatic increases in communication speed and capacity by using millimeter band frequencies (30 GHz and higher)* in addition to frequencies currently used for mobile communications (below 4 GHz). However,

* In the mobile communications industry, the 28 GHz band is in the range customarily called millimeter waves, so the term will be used in this article.

a characteristic of millimeter waves and other high-frequency bands is high attenuation with distance, so they are difficult to use over long distances. NTT DOCOMO has proposed a 5G technology concept called phantom cell*1/dual connectivity*2 [2], which combines these high-frequency bands with lower bands suitable for wide-area coverage to realize both stable communication and increased speed and capacity. On the other hand, it is important to provide as wide of coverage as possible, even with millimeter waves and other high-frequency bands, when providing ultra-high-speed communication in more diverse environments beyond urban areas, such as suburbs, the mountains, and other outlying areas.

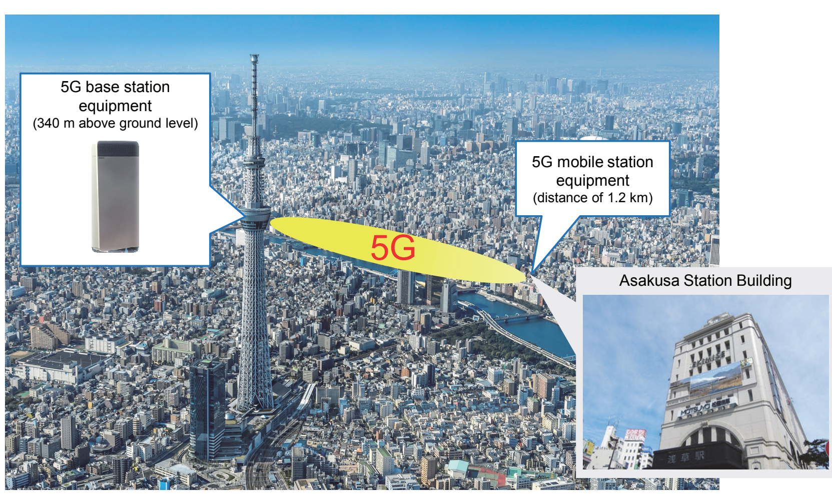
This article gives an overview of 5G radio access field tests done in collaboration with Tobu Railway and Huawei Technologies, implementing long-distance, high-speed transmission exceeding 1 km in a macrocell*3 environment with millimeter waves. This was achieved using an ultra-high-gain beamforming*4 transmission technology to resolve technical issues applying millimeter waves for mobile communications.

2. 5G Long-distance Transmission Tests between TOKYO SKYTREE and Asakusa Using the 28 GHz Band

In December 2017, we conducted long-distance transmission tests in collaboration with Tobu Railway and Huawei Technologies. Transmissions exceeding 1 km, between the TOKYO SKYTREE®*5 observation deck and Asakusa Ward, were done using the 28 GHz band, which is one of the frequency bands that is promising for use in 5G implementations [3].

2.1 Test Overview

The test environment is shown in **Figure 1**. These tests were done at a 5G Trial Site built by



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Test station representing base station: Oshiage, Sumida, Tokyo (TOKYO SKYTREE TEMBO DECK, Floor340)
Test station representing mobile terminal: Hanakawado, Taito, Tokyo ((Roof of Tobu Railway Asakusa Station Building), 28 GHz band (800 MHz))

Figure 1 Test environment (TOKYO SKYTREE area)

*1 **Phantom cell:** The advanced small-cell system being promoted by NTT DOCOMO.

*2 **Dual connectivity:** A technology that achieves wider bandwidths by connecting two base stations in a master/slave relationship and performing transmission and reception using multiple component carriers supported by those base stations.

*3 **Macrocell:** In mobile communications systems, a cell is the area covered by a single base station antenna. A macrocell covers a relatively large area with radius of 500 m or more.

*4 **Beamforming:** A technique for increasing or decreasing the gain of antennas in a specific direction by controlling the phase of multiple antennas to form a directional pattern of the antennas.

NTT DOCOMO in collaboration with Tobu Railway Uplink and downlink communication was between a test base station installed in the TOKYO SKYTREE TEMBO DECK®, Floor340 (Photo 1(a)), and a mobile phone approximately 1.2 km from the base station, represented by a mobile station installed on the roof of the Tobu Railway Asakusa Station building (Photo 1(b)).

The center frequency for the tests was 27.9 GHz. An Orthogonal Frequency Division Multiplexing (OFDM)*6 subcarrier*7 interval of 60 kHz and system bandwidth of 700 MHz (100 MHz per

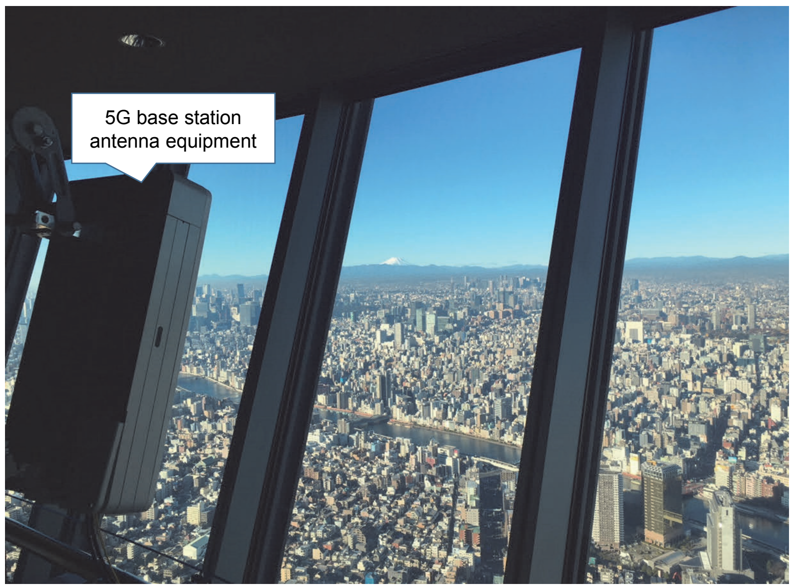

Photo 1(a) 5G base station installation (TOKYO SKYTREE TEMBO DECK)

Photo 1(b) 5G mobile station equipment (roof of Tobu Railway Asakusa Station Building)

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*5 TOKYO SKYTREE®: "TOKYO SKYTREE," "TOKYO SKYTREE TEMBO (Observation) DECK," "TOKYO SKYTREE TOWN" are registered trademarks of Tobu Railway Co., Ltd. and Tobu Tower Skytree Co., Ltd.

*6 OFDM: A digital modulation method where the information is divided into multiple orthogonal carrier waves and sent in parallel. It allows transmission at high frequency usage rates.

*7 Subcarrier: Each carrier in a multi-carrier modulation system that transmits bits of information in parallel over multiple carriers.

Component Carrier (CC)*8 × 7) was used.

In these tests, beam forming between TOKYO SKYTREE and Asakusa station was done using Massive Multiple-Input Multiple-Output (MIMO)*9, a key 5G technology that utilizes many antenna elements. Massive MIMO is able to form a tight beam at the 5G high frequencies by using 100 or more antenna elements to strengthen the signal in the direction of the mobile terminal.

2.2 Test Results and Demonstrations

In these tests, we applied the optimal Time Division Duplex (TDD)*10 slot ratios on both the downlink (from base station to mobile station) and the uplink (from mobile station to base station), and measured the throughput characteristics under conditions where the mobile station is stationary. The results in **Figure 2** show that communication speeds of up to 4.52 Gbps on the downlink and 1.55 Gbps on the uplink were achieved at a distance of approximately 1.2 km from the base station, despite using the high-frequency 28 GHz band. These tests were done together with two demonstrations using the large outdoor screen on the Asakusa Station Building (sponsored by Tobu Railway Co.). The first provided coverage of the "docomo 5G Trial Site" event held on December 8 to 10, 2017, in Space 634 on the 5th floor of TOKYO Solamachi®*11, and the second covered the "TOKYO SKYTREE Christmas Love Song Live" event held on December 8 on the TOKYO SKYTREE TEMBO DECK. The docomo 5G Trial Site event demonstrated a new concept of communication for the future as shown in **Photo 2**. Using a head-mounted display and Augmented Reality (AR)*12 technology, a person in the Asakusa Station Building, some distance from the TOKYO SKYTREE TOWN® event venue, was able to hold a conversation in real time and with low-latency, with a person who was not actually there but appeared to float above a chair. For the event on the evening of December 8, uninterrupted communication speeds over 3 Gbps were achieved even though the part of TOKYO SKYTREE above the observation deck was largely invisible due to rain, as shown in **Photo 3**. The demonstration successfully covered the event on the Asakusa Station Building outdoor screen.

Downlink　　Uplink

Figure 2　Communication speed achieved (downlink/uplink)

*8 CC: Term denoting each of the carriers used in Carrier Aggregation.

*9 MIMO: A radio communication format in which transmitted data is divided into multiple signals (streams) and then transmitted and received with the same frequency band using multiple antennas at both the transmitter and the receiver.

*10 TDD: A bidirectional transmit/receive system. This system achieves bidirectional communication by allocating different time slots to uplink and downlink transmissions on the same frequency.

*11 TOKYO Solamachi: A registered trademark of the Tobu Railway Co., Ltd.

Photo 2　Demonstration at 5G event

Photo 3　Test environment in rainy weather (roof of Asakusa Station Building)

3. 5G Long-distance Transmission Tests in the Yokohama Minato Mirai District Using the 39 GHz Band

In these tests done jointly with Huawei Technologies, long-distance 5G transmissions using the even higher-frequency 39 GHz band were attempted, anticipating ongoing development of 5G after 2020 [4].

3.1 Overview of Technology Used

The frequency band from 39.5 to 40.9 GHz was used in these tests. The OFDM signal subcarrier interval was 120 kHz, and the system bandwidth was 1,400 MHz (200 MHz/CC × 7).

To achieve long-distance transmission exceeding 1 km at high frequencies in the 39 GHz band, meta-materials*13 were used to create a lens antenna*14 able to achieve beamforming with ultra-high-gain (31 dBi (deciBel isotropic)*15), more than 1,000 times that of a non-directional antenna. Meta-materials are used in the lens antenna to form a specific distribution of dielectric constants, which focuses the signal emitted from the antenna in a particular direction similarly to beamforming using Massive MIMO, but with a smaller antenna. By having multiple emitters in the antenna, the direction of the transmitted beam can also be changed by switching among them. In the trials, the optimal beam for each polarization was selected from among 64 candidates, eight horizontally and eight vertically, as shown in **Figure 3**. The half-power beam width*16 of each candidate beam was approximately 3.5°. Signal reception quality can be improved by measuring reception quality for each combination of base station and mobile station beams and selecting the best one.

The radio frame*17 structure used in these tests is shown in **Figure 4**. The radio frame length was 10 ms, and the slot length was 0.125 ms, so each radio frame contained 80 slots. Using a radio frame structure with very short slot interval allowed the time needed to find the optimal beams on the base

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*12　**AR**: Technology for superposing digital information on real-world video in such a way that it appears to the user to be an actual part of that scene.

*13　**Meta-material**: An artificial material that behaves with respect to electromagnetic waves in ways not found in natural materials.

*14　**Lens antenna**: An antenna able to focus radio waves sharply in a particular direction, much like an optical lens. A lens antenna can be used to emit radio waves emitted broadly from the emitter, tightly in a particular direction, by refracting and aligning the phase of the radio waves.

*15　**deciBel isotropic**: A unit that describes antenna gain using a hypothetical isotropic antenna as the standard.

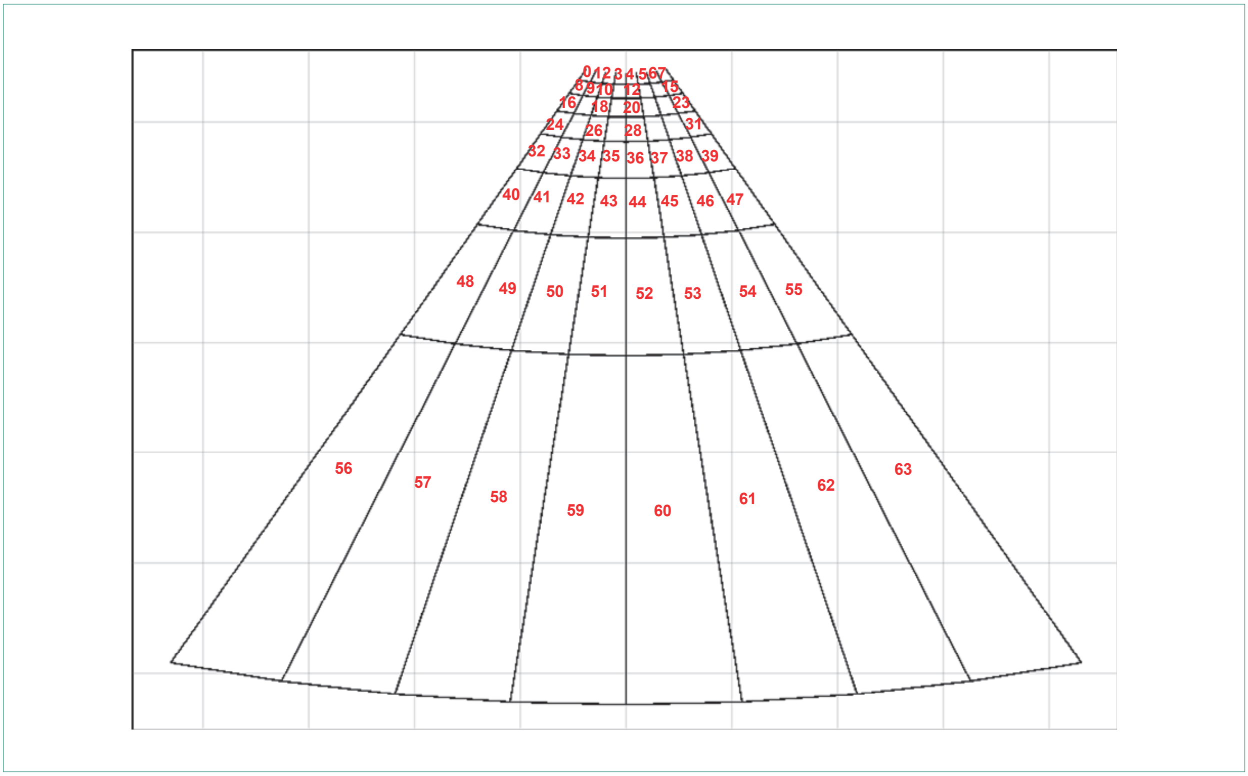

Figure 3 All 64 candidate beams

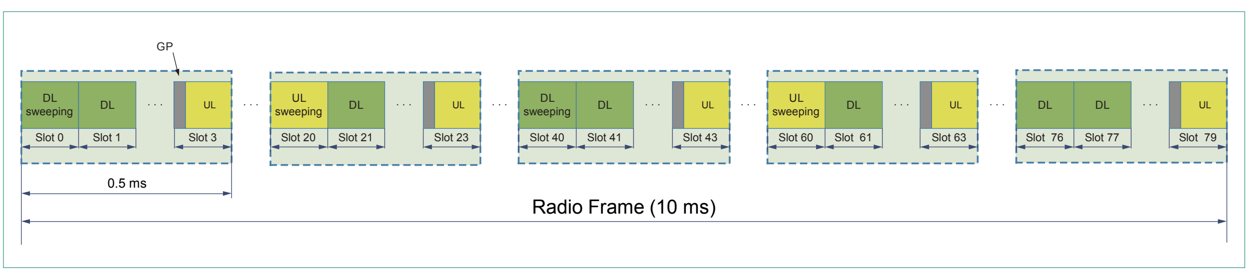

Figure 4 Radio frame structure

station and mobile station to be minimized. The following four types of slots are used in a single radio frame.

(1) DownLink (DL) beamsweeping slot: A slot for performing beam sweeps using a downlink reference signal (e.g.: Fig. 4 (Slot #0)).

(2) DL slot: A slot used to send data on the downlink, including data and control signals (e.g.: Fig. 4 (Slot #1)).

(3) UpLink (UL) slot: A slot used to send data on the uplink, including Guard Period (GP), data, and control signals (e.g.: Fig. 4 (Slot #3)).

(4) UL beam sweeping slot: A slot for performing beam sweeps using an uplink reference signal (e.g.: Fig. 4 (Slot #20)).

*16 Half-power beam width: The angular range from the maximum power emitted from an antenna to the half of that value. Indicates the sharpness of the antenna pattern.

*17 Radio frame: The smallest unit used for signal processing (encoding, decoding). A single radio frame is composed of multiple slots (or subframes) along the time axis, and each slot is composed of multiple symbols along the time axis.

To control beam sweeping and tracking, the reception quality was measured for each beam combination using reference signals in the DL and UL beam sweeping slots. Beam sweeping slots were sent every 2.5 ms, alternating on the up and downlinks, so that all beam combinations (64 (base station) × 64 (mobile station) = 4,096) were scanned in 160 ms. This enabled the optimal beams for transmission and reception at both base station and mobile station to be updated dynamically, according to motion of the mobile station and fluctuations in the radio channel.

The test equipment supported Quadrature Phase Shift Keying (QPSK)[*18], 16 Quadrature Amplitude Modulation (16QAM)[*19], and 64QAM[*20] with adaptive modulation. Large delay Cyclic Delay Diversity (CDD)[*21] and vertical/horizontal-polarization 2×2 MIMO transmission were also used.

3.2 Test Results

Testing was conducted in November 2017 in the Minato Mirai District of Yokohama City, in Kanagawa Prefecture. The transmission test equipment is shown in **Photo 4**, and the test environment is shown in **Figure 5**.

Table 1 shows the results of measuring throughput to the mobile terminal using the test equipment and in a real, outdoor radio environment under the various conditions shown in Fig. 5. The results show that ultra-high-speed communication was achieved between a Huawei 5G base station installed in the Yokohama Media Tower and mobile station approximately 1.5 km distant, receiving at up to 2.02 Gbps while moving at approximately 20 km/h, and up to 3.35 Gbps while stationary. Even at a distance of approximately 1.8 km from the 5G base station, reception rates up to 2.14 Gbps while stationary were achieved, and reception at rates up to 5.63 Gbps were achieved at a distance of approximately 0.3 km from the 5G base station. It is generally thought to be difficult to maintain coverage when using millimeter-band signals for mobile communication or long-distance transmission. In spite of this, we achieved throughput characteristics of 2 Gbps and greater over areas spanning 1 km or more with this transmission test equipment, which uses

5G base station equipment

5G mobile station equipment (in a monitoring vehicle)

Photo 4　Base station and mobile station equipment

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*18 QPSK: A digital modulation method that allows transmission of 2 bits of information at the same time by assigning one value to each of four phases.

*19 16QAM: A digital modulation method that enables the simultaneous transmission of 4 bits of information by assigning one value to each of 16 different combinations of phase and amplitude.

*20 64QAM: A digital modulation method that enables the simultaneous transmission of 6 bits of information by assigning one value to each of 64 different combinations of phase and amplitude.

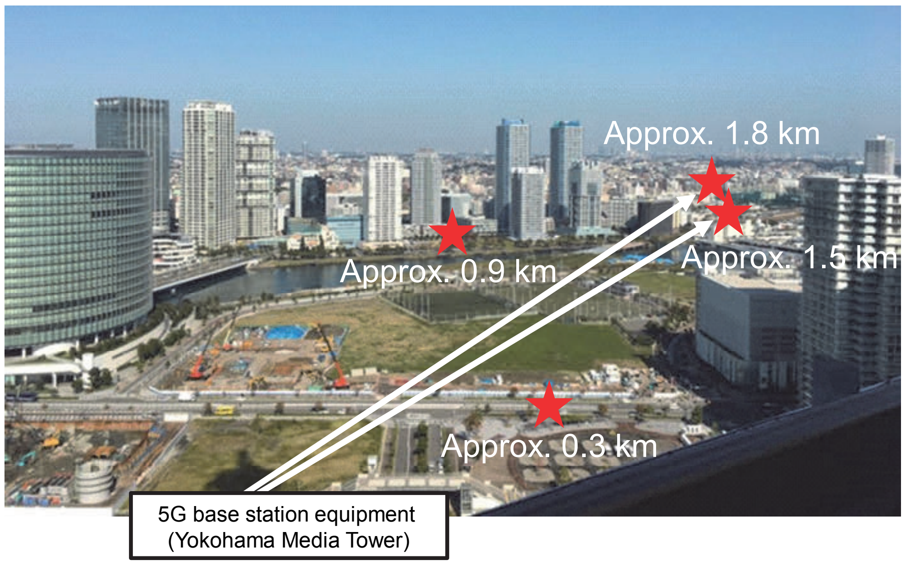

Figure 5 Test environment (Yokohama Media Tower area)

Table 1 Distance from base station vs. throughput characteristics

Mobile station conditions	Distance from base station (km)	Maximum Throughput (Gbps)
Speed (approx. 20 km/h)	1.5	2.02
When stationary		3.35
	1.8	2.14
	0.9	3.78
	0.3	5.63

high-speed beam switching and tracking technology and produces high beamforming gain. Although there was some deterioration in throughput characteristics while the UE was moving compared to when stationary, we were able to maintain throughput of 2 Gbps or greater.

4. Conclusion

This article has given an outline and results of long-distance field transmission tests done with 5G radio access transmission test equipment at millimeter-band frequencies (28 GHz and 39 GHz bands). As a result, high throughput of several Gbps was

*21 Large delay CDD: A type of transmit diversity technology, in which relatively large, differing amounts of cyclic delay are assigned to the same data signal between transmit antennas, producing frequency diversity while avoiding inter-symbol interference.

achieved transmitting over distances of 1 km and greater from the base station. These results demonstrate that technology using high-frequency-band radio signals, which attenuate quickly and have been considered difficult to use for propagation over long distances, can be used in more diverse environments that require transmission over distances relatively longer than in urban areas, such as suburbs, the countryside, and mountainous areas. In the future we plan to conduct further field testing to expand the coverage achievable using millimeter-band signals, in non-line-of-sight and other situations.

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Technology Reports

IoT/M2M eSIM SM

Building of GSMA3.1-compliant eSIM Commercial System for IoT/M2M through Partnership between Operators

Solution Service Department Koji Makino Daichi Kishi
IoT Business Department Jun Bian

In view of the global trend toward IoT/M2M products, NTT DOCOMO has created the world's first multivendor eSIM linkage system enabling flexible rewriting of SIM information through partnership with overseas operators.
This article describes the mechanism for achieving this eSIM for IoT/M2M.

1. Introduction

In June 2017, NTT DOCOMO and China Mobile Communications Corporation, a Chinese telecommunications carrier, completed development of an embedded Subscriber Identity Module (eSIM)*1 linkage system between different vendors. Based on the "Remote Provisioning Architecture for Embedded UICC Technical Specification Version 3.1" (hereinafter referred to as "GSMA3.1") specification formulated by the GSM Association (GSMA)*2, this is the world's first eSIM linkage system for multivendor Internet of Things (IoT)*3/Machine to Machine (M2M)*4 in commercial environments [1].

NTT DOCOMO is introducing this technology as a Business-to-Business (BtoB) solution for developing overseas businesses with automobiles, construction machinery and industrial devices etc.

This article describes a Remote Provisioning*5 system based on GSMA3.1 standard specifications.

2. eSIM for IoT/M2M

2.1 Differences with Conventional Technology

In the world of IoT/M2M, most designs have included an unremovable SIM directly embedded in the devices*6 mounted in IoT/M2M-enabled products

*1 eSIM: The generic name for SIMs in which the communications profile information of a telecommunications carrier can be remotely rewritten using Over-The-Air (OTA) radio communications, different from normal SIM cards.

*2 GSMA: The Global System for Mobile Communications. A global standardization organization in mobile communications businesses.

as requirements for achieving miniaturization and high reliability with fewer parts. Also, with the global trend toward these IoT/M2M businesses, the demand for products usable with the communication services of local telecommunications carriers in various countries is on the rise.

However, with conventional technology, the Mobile Network Operator (MNO) information written on to the SIM is fixed and cannot be rewritten, meaning that the only solutions for overseas use were to replace the SIM with one for the local telecommunications carrier or use roaming*7 etc.

Since there are increasing demands to use local telecommunications carrier communication services in various countries without changing the SIMs inserted in products, GSMA standardized technology to flexibly change the MNO information written to the SIM [2] [3]. NTT DOCOMO is one of the operators involved in the study of this architecture [4].

2.2 Differences with Consumer eSIM

In general, technologies used with eSIM services are divided into those for consumer uses, and those for IoT/M2M [5]. The applications and standard specifications for these are not the same. **Figure 1** provides a comparison of the technologies.

Consumer eSIM technology is used to enable the user to activate the line with simple operations using the initial settings of the terminal when it was first purchased. Consumer eSIM technology is also prescribed by GSMA [6] - [9].

eSIM for IoT/M2M technology is used by applications to switch telecommunications carriers from remote servers.

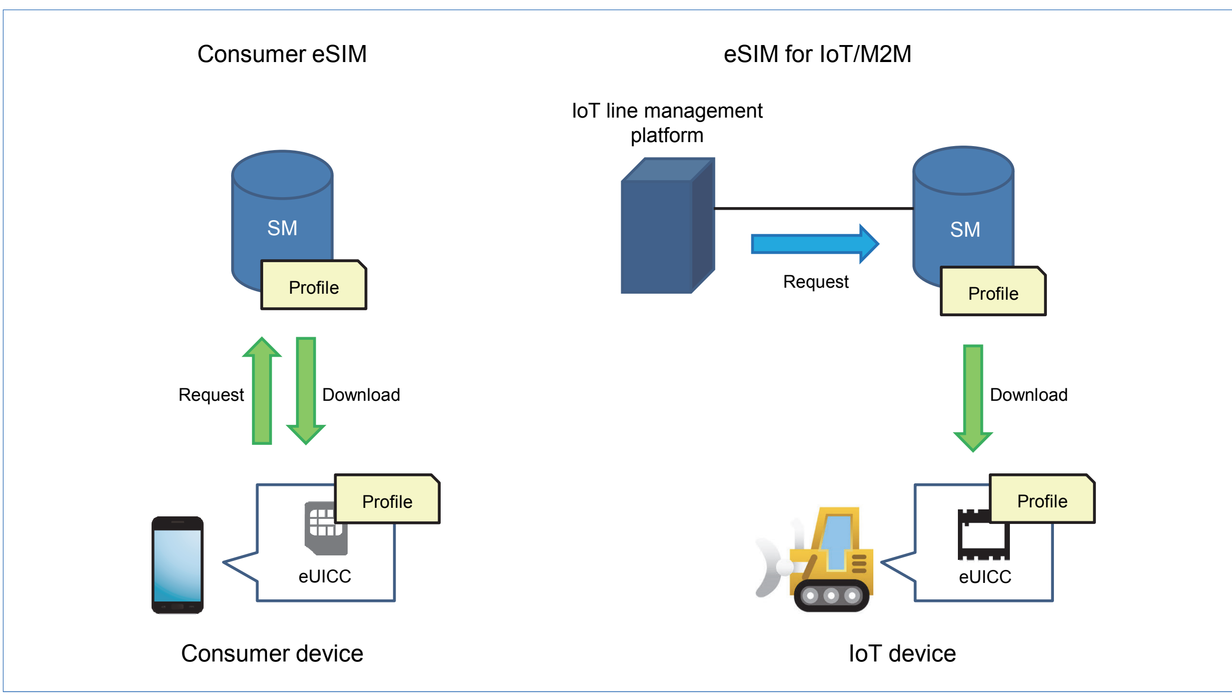

Figure 1 Differences between consumer eSIM and eSIM for IoT/M2M

*3 IoT: Mechanisms that entail various "things" connected to the Internet to enable a wide range of previously unachievable information sharing.

*4 M2M: Communications among machines.

*5 Remote Provisioning: Rewriting communications profiles remotely via OTA.

*6 Device: In this article, a "device" refers to a device such as an M2M module that has mobile communications functions.

*7 Roaming: A mechanism that enables users to use services similar to their subscribed carriers within the service areas of alliance partner carriers, but outside the service areas of their subscribed carriers.

As shown in Fig. 1, the profile*8 is downloaded via mobile terminal operations with a consumer eSIM, whereas with an eSIM for IoT/M2M, the profile is downloaded through a request from the IoT line management platform of the telecommunications carrier.

2.3 User Experience

This section describes the use case of remote provisioning using the example of exporting a Japanese-manufactured product from Japan that uses a DOCOMO line as its default setting. There are real demands for BtoB solutions as illustrated by this example.

First of all, the user applies to NTT DOCOMO for an eSIM, and receives the eSIM issued by NTT DOCOMO. Next, the user embeds the eSIM into their product, and after enabling communications through the activation of a DOCOMO line, the user performs shipping test etc. in Japan. After the product containing the eSIM is taken overseas, roaming is commenced for the DOCOMO line. After that, the user triggers switch over to the desired line by specifying the line and telecommunications carrier, and remote provisioning is done for the specified line via roaming. When this is complete, the product is enabled for communications using a local telecommunications carrier line, and those communications services become available.

2.4 Effects of GSMA3.1 Support

GSMA3.1 [3] prescribes the following standards, which logically enable multivendor connection between components in remote provisioning architecture.

- Embedded Universal Integrated Circuit Card (eUICC)*9 architecture
- Remote provisioning architecture interface
- Remote provisioning architecture security functions

The advantages of MNO through GSMA3.1 support include the ability to build multivendor systems for Subscription Manager (SM)*10 and eUICC. In addition, as an advantage to the user, requirements for devices embedded in equipment to achieve remote provisioning are becoming clarified, and future increases of supporting devices are expected.

Currently, the latest version for Remote Provisioning Architecture for Embedded UICC Technical Specification is 3.2 [10].

3. eSIM for IoT/M2M Mechanism

3.1 Overview of the Structure and Operations

The system that NTT DOCOMO has built with China Mobile adopts one of the structures prescribed by GSMA3.1. **Figure 2** describes an overview of the structure and its operations.

SM is divided into two functions - SM Data Preparation (SM-DP) and SM Secure Routing (SM-SR). The following describes an overview of these functions.

- SM-DP: Securely stores the MNO communications profile
- SM-SR: Retains the eUICC Information Set (EIS) and ensures secure communications with eUICC

*8 **Profile**: A collection of data including information such as a phone number, subscriber ID, and network information.

*9 **eUICC**: An embedded UICC or UICC that enables remote provisioning. In this article, eUICC is used to describe the remote provisioning mechanism. UICC is an IC card used to record a unique ID for specifying a subscriber. UICC and SIM card are used synonymously.

*10 **SM**: A server that rewrites an eUICC communications profile remotely.

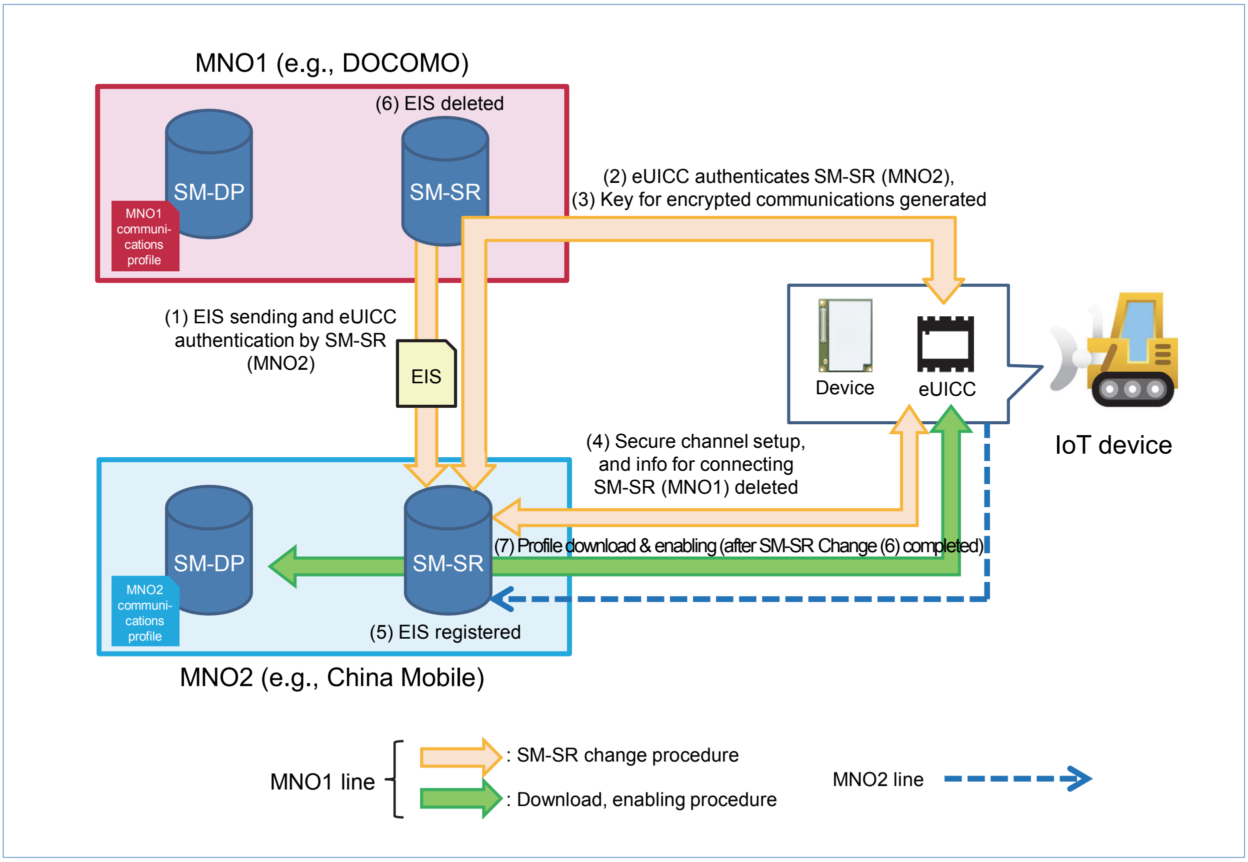

Figure 2 Overview of structure and operations

Fig. 2 describes switching communications profiles from the MNO to which the eUICC is first associated, called MNO1 (e.g., DOCOMO), to MNO2 (e.g., China Mobile).

In the figure, MNO1 and MNO2 communications profiles are stored in their respective SM-DPs.

With a structure like that in the example in the figure, remote provisioning is performed with the following procedure.

- SM-SR Change (Fig. 2 (1) to (6))
- Profile Download and Profile Enable (Fig. 2 (7))

If downloading the destination communications profile via the SM-SR associated with the destination MNO is required, SM-SR change procedures will be required in the remote provisioning procedure.

Note that in GSMA3.1 specifications, the configurations of SM-DP and SM-SR are not limited to the example in the figure.

3.2 Overview of SM-SR - eUICC Communications Routes

The following describes a general example configuration of a communications route between SM-SR and eUICC.

1) Types of Communications Routes

Figure 3 describes communications routes between SM-SR and eUICC.

GSMA3.1 prescribes communications methods with SMS and packets (HTTPS*11) between SM-SR and eUICC.

SMS is used for sending and receiving small-sized remote provisioning command, while packets (HTTPS) are used for sending and receiving large-sized remote provisioning command.

With packets (HTTPS), a Bearer Independent Protocol channel (BIP channel) is established between a device and an eUICC by sending a push-type SMS that instructs the establishment of BIP channel from the SM-SR to the eUICC before the communications route is established.

2) Configuration of the SM-SR - IoT Line Management Platform*12

Connections between SM-SR and the components of the IoT line management platform owned by the MNO are configured as follows.

- SM-SR and SMS Center (SMSC)*13 are connected using Short Message Peer to peer Protocol (SMPP)*14 to enable sending and receiving of commands via SMS between SM-SR and eUICC.
- SM-SR and the packet switch (Gateway GPRS Support Node (GGSN)*15 or Packet data network-Gateway (P-GW)*16) are connected using IP to enable sending and receiving of commands via packets between SM-SR and eUICC.

3) Structure between IoT Line Management Platform and Devices

This structure is configured with normal Global System for Mobile communications (GSM)*17/Universal Mobile Telecommunications System (UMTS)*18/LTE, so detailed descriptions are omitted.

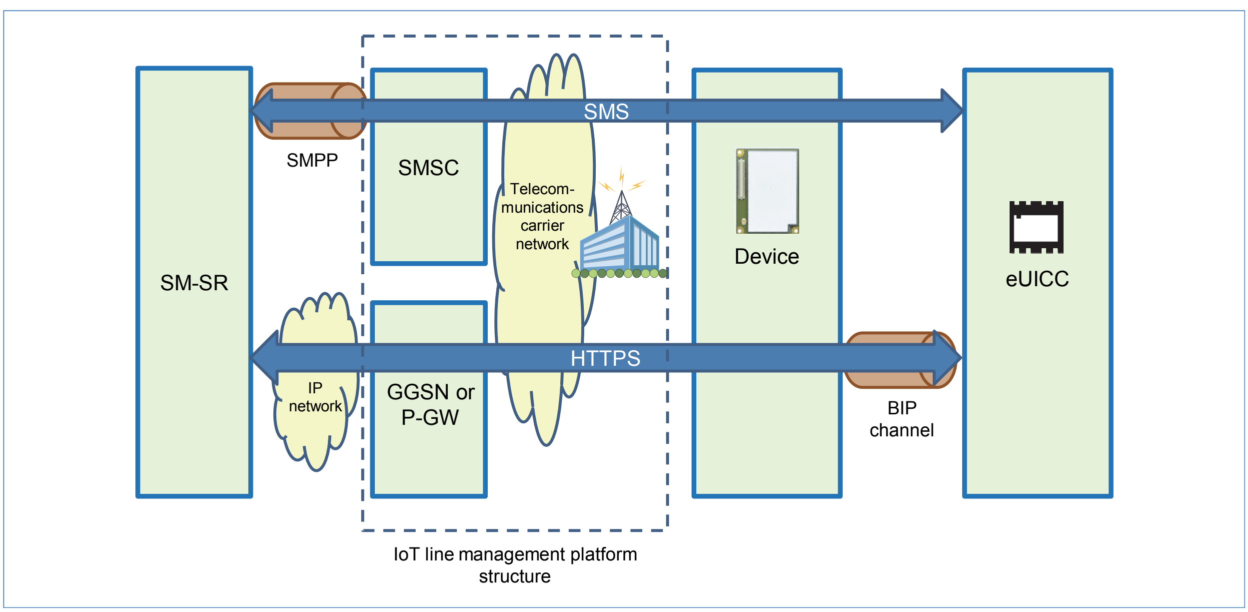

Figure 3 Overview of SM-SR - eUICC communications routes

*11 HTTPS: An HTTP communications method that uses TLS protocol to prevent attacks such as spoofing, intermediary attacks or eavesdropping. As well as HTTPS, Card Application Toolkit Transport Protocol (CAT-TP) is also prescribed in GSMA3.1 as a packet communications method.

*12 IoT line management platform: A platform that accommodates and manages IoT/M2M devices.

*13 SMSC: The SMS Center server. Stores and re-sends SMS data.

*14 SMPP: A communications protocol used between the SMSC server and applications for SMS sending and receiving.

*15 GGSN: A gateway connecting Packet Data Network (PDN) with functions for assigning IP addresses and forwarding packets to SGSN.

*16 P-GW: A gateway connecting PDN with functions for assigning IP addresses and forwarding packets to Serving Gatway (S-GW).

4) Structure between Devices and eUICC

Communications using BIP [11] [12] protocol are required between devices and eUICC to perform HTTPS communications between SM-SR and eUICC. GSMA3.1 Annex G Device Requirements including BIP support are necessary at the device side.

3.3 Remote Provisioning Sequence Overview

1) Information Elements Required for Remote Provisioning

The following describes the main information elements necessary for the remote provisioning mechanism.

- EID (eUICC ID): The eUICC serial number. The target eUICC is specified by the EID.
- EIS: A combination of eUICC authentication information and information for accessing eUICC, which is stored in SM-SR. Only the SM-SR with the corresponding EIS registered can issue commands to the target eUICC.

2) Remote Provisioning Sequence

Figures 4 and 5 describe the remote provisioning

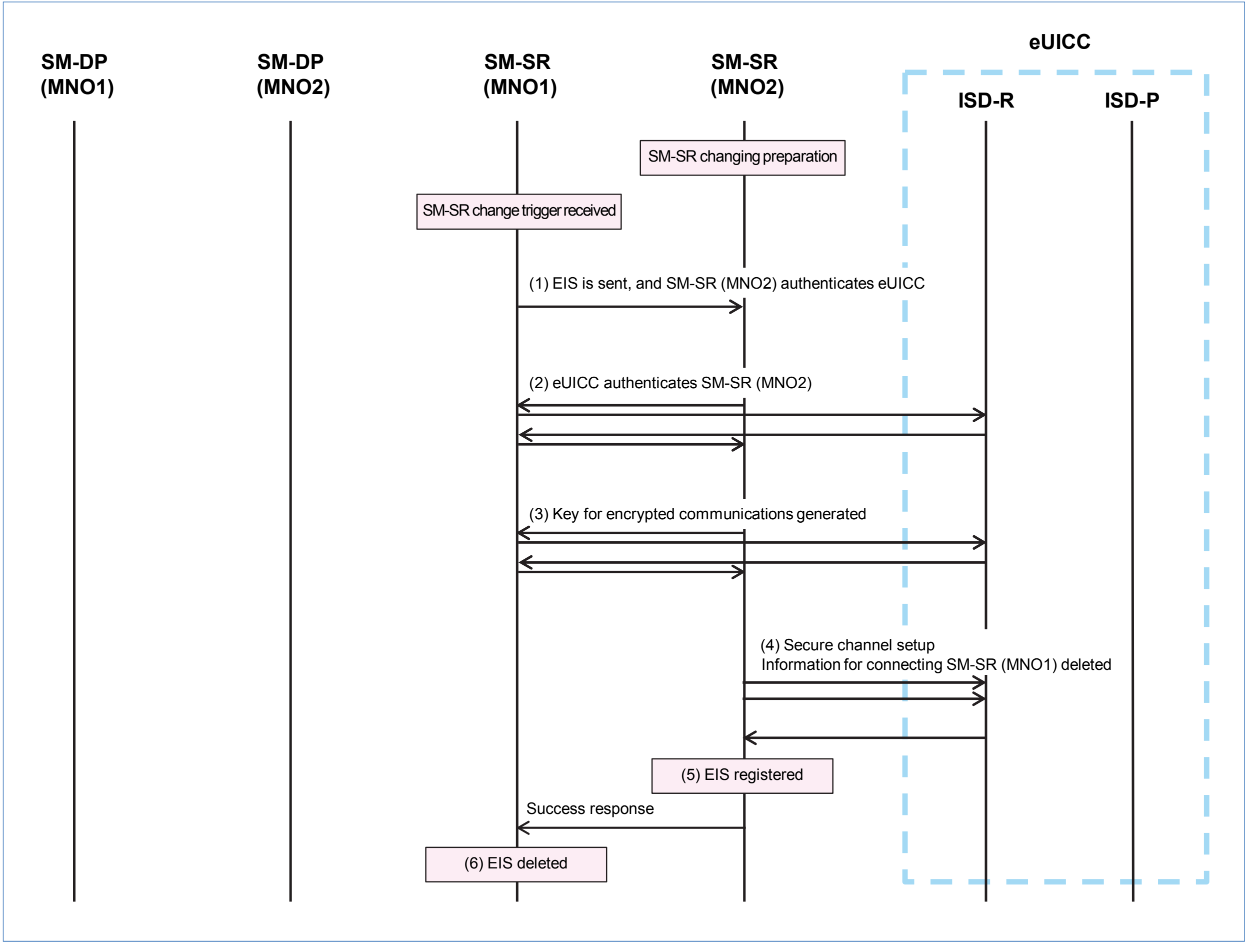

Figure 4 Overview of SM-SR change procedure

*17 GSM: A second-generation mobile communication system used widely around the world, especially in Europe and Asia.

*18 UMTS: A third-generation mobile communication system which includes W-CDMA (as used by NTT DOCOMO) and other access methods such as Time Division (TD)-CDMA.

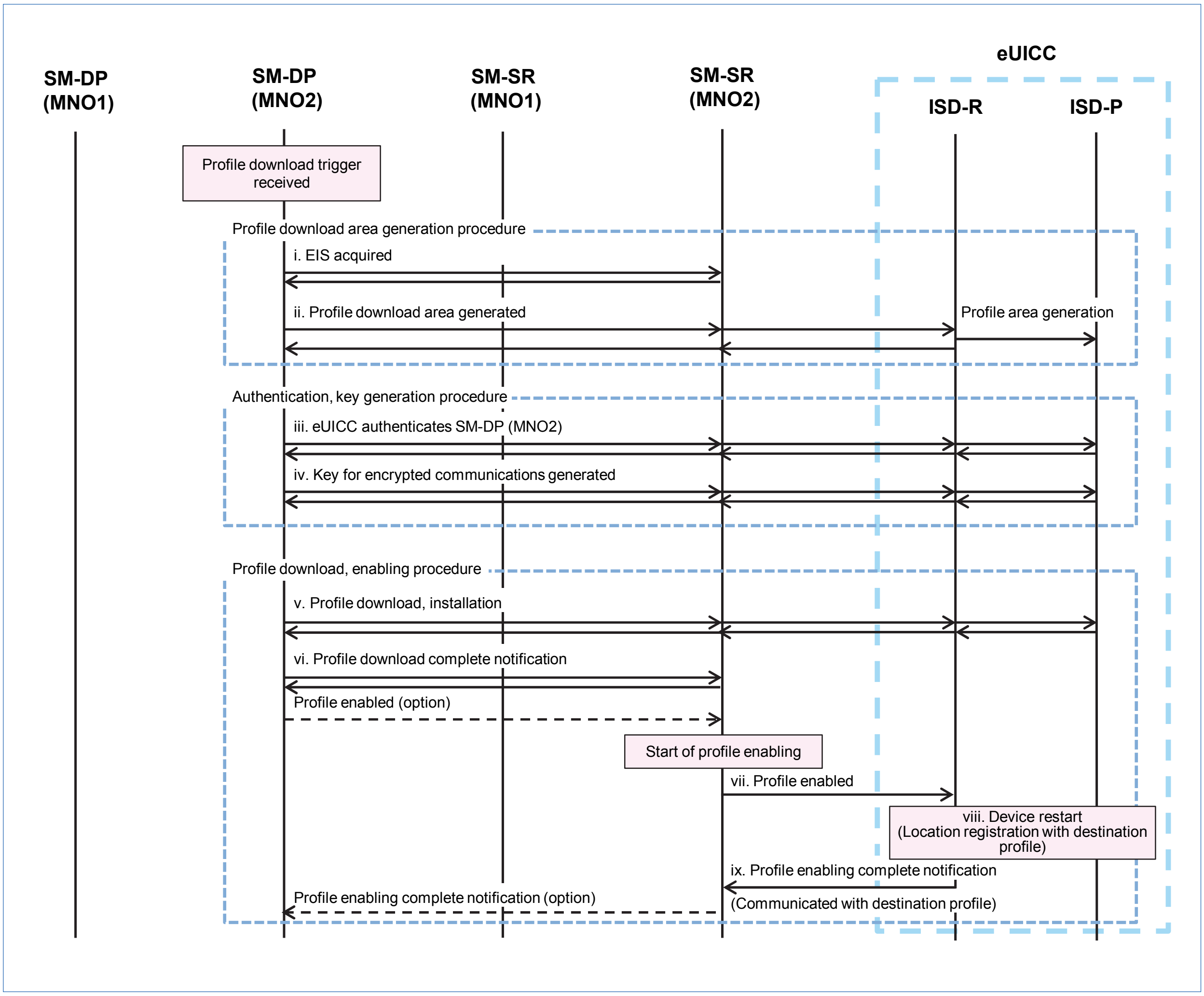

Figure 5 Overview of profile download & enabling procedures

sequence.

SM-DP/SM-SR and eUICC have preset internal authentication information verified by a common Certificate Issuer (CI)*19, and designed to enable secure mutual authentication in SM-SR change and profile download procedures.

Issuer Security Domain Root (ISD-R) and Issuer Security Domain Profile (ISD-P) areas are prescribed for eUICC.

- ISD-R: Only one exists in the eUICC for communicating commands with SM-SR.
- ISD-P: An area for storing profiles. Many exist in the eUICC for communicating commands with SM-DP.

Required authentication information is accessible by both ISD-R/ISD-P.

*19 CI: Issues electronic signatures required to achieve secure remote provisioning.

3) SM-SR Change Procedure (Fig. 4)

In the eUICC manufacturing stage, EIS is registered in the SM-SR which will be the first host, and has administrative rights to access the eUICC. The administrative rights are transferred when the EIS storage destination SM-SR is changed with the SM-SR change procedure.

As described in Fig. 4, the SM-SR change procedure entails transfer of rights to manage communications with eUICC from SM-SR (MNO1) to SM-SR (MNO2), and is executed in the sequence below.

(1) After SM-SR (MNO1) receives a trigger to change SM-SR, EIS is passed from SM-SR (MNO1) to SM-SR (MNO2). SM-SR (MNO2) authenticates eUICC based on EIS.
(2) Communications take place between SM-SR (MNO2) and eUICC ISD-R through SM-SR (MNO1), and eUICC authenticates SM-SR (MNO2).
(3) Communications take place between SM-SR (MNO2) and eUICC ISD-R through SM-SR (MNO1), and a key for encrypted communications between SM-SR (MNO2) and eUICC is generated.
(4) A secure channel is set up between SM-SR (MNO2) and eUICC ISD-R and key information for connecting SM-SR (MNO1) is deleted.
(5) EIS is registered in SM-SR (MNO2) (administrative rights are transferred to SM-SR (MNO2) at this time).
(6) EIS is deleted from SM-SR (MNO1) (eUICC can no longer be accessed from SM-SR (MNO1)).

4) Overview of Profile Download & Enabling Procedures (Fig. 5)

The destination MNO communications profile information is downloaded to the eUICC through the profile download procedure. After that, the eUICC is instructed to switch to the destination MNO communications profile through the profile enabling procedure.

As shown in Fig. 5, profile download & enabling is done in the following sequence to switch communications profiles.

i. SM-DP (MNO2) receives a profile download trigger, acquires EIS from SM-SR (MNO2), and performs necessary checks before the procedure starts.
ii. Communications are performed between SM-DP (MNO2) and eUICC, and a profile download area is generated as the eUICC ISD-P.
iii. Communications are performed between SM-DP (MNO2) and eUICC, and eUICC authenticates SM-DP (MNO2).
iv. Communications take place between SM-DP (MNO2) and eUICC, and a key for encrypted communications between SM-DP (MNO2) and eUICC is generated.
v. Communications are performed between SM-DP (MNO2) and eUICC, and the profile is downloaded and installed in ISD-P.
vi. A profile download complete notification is sent from SM-DP (MNO2) to SM-SR (MNO2).
vii. Communications are performed between SM-SR (MNO2) and ISD-R in eUICC, and a command to enable the downloaded profile is sent.
viii. Having received the commands to enable the

profile, ISD-R instructs the device to restart. Location registration with the newly downloaded communications profile is executed after the device restarts.

ix. After successfully registering location with the new communications profile, ISD-R sends a profile enabling complete notification to SM-SR (MNO2).

4. Conclusion

This article has described the mechanism of a Remote Provisioning system developed based on GSMA3.1 standards. We studied system integration by preparing environments to provide network services using SMs that support GSMA3.1 standards on commercial systems.

Multivendor connection is logically possible in GSMA3.1. In building the system, some issues with differences of interpretation of implementation occurred between various vendors, but efforts were made through NTT DOCOMO's partnership with China Mobile to quickly eliminate these issues and achieve the world's first GSMA3.1 standard specifications-compliant multivendor eSIM system.

Currently, various issues such as a lack of GSMA3.1-compliant devices required to use eSIM services are hindering full penetration of eSIM services. Also, system integration testing with devices embedded in products planned for commercial implementation will be required. Going forward, DOCOMO plans to continue working toward solving these issues.

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Best Paper Award at IEEE GLOBECOM 2017

Chenwei Wang of DOCOMO Innovations, Inc. and joint research partners, Messrs. A. Salman Avestimehr and Mehrdad Kiamari of the University of Southern California received the Best Paper Award at the Institute of Electrical and Electronics Engineers Global Communications Conference 2017 (IEEE GLOBECOM 2017) held in Singapore December 4-8, 2017.

IEEE GLOBECOM is one of the two flagship conferences (the other is the International Conference on Communications (ICC)) sponsored by the IEEE Communications Society, the major society of the IEEE, the World's largest technical engineering association. The first IEEE GLOBECOM meeting was held in 1957, and this meeting was its 60th anniversary. In recent years, in addition to technical sessions in which academic papers are announced, the conference now includes industry programs to promote exchange of opinions on the latest ideas, trends and product innovations in the industry.

At this conference, 2,630 papers were submitted, 1,026 papers (39%) were accepted, and 15 outstanding papers from each field received "Best Paper Award." The paper awarded this time was entitled "On Heterogeneous Coded Distributed Computing" and was announced in the Communications Theory field.

Mobile edge computing aims to achieve low latency and high throughput per unit area by deploying computing resources closer to users than the cloud. The winning paper provides an approach based on distributed encoding technologies to satisfy the low-latency, high-throughput conditions in 5G and beyond 5G. Particularly, the paper studies the fundamental limits of latency performance through the use of distributed encoding under the MapReduce framework widely used for big data processing.

Specifically, the paper proposes a new approach by designing data file splitting and assignment and leveraging redundant computation to design encoding/decoding mechanisms and algorithms to optimize communications latency of computing systems. This technology is applicable to a wide range of applications for both radio and wired networks. For example, Internet of Things (IoT) applications entail the use of multiple sensors to collect various desired information. Applying this new technology in this area will not only shorten communications latency with separated information processing of sensors, but also strengthen security of overall systems through distributed encoding. Also, using this technology in self-driving car scenarios to enable extremely quick exchange of vehicle sensor-acquired data between vehicles will raise the ability of vehicles to learn traffic information over a wider range to promptly respond to emergency vehicles and speed up emergency responses (e.g., the timing of slowing down) to accidents in the vicinity.

This paper received the award for its highly appraised proposal for a distributed processing algorithm and its distributed encoding theory. Although edge computing for mobile systems is still in the pre-commercialization stage, the theoretical knowledge gained from this research promises to contribute to the development and advancement of DOCOMO's 5G and beyond 5G.

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