Technology Reports

5G | NOMA | Field Trial

Special Articles on Demonstration of New Technologies for 5G

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

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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**.

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

*2 eMBB service: A service requiring enhanced Mobile Broad-Band (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.

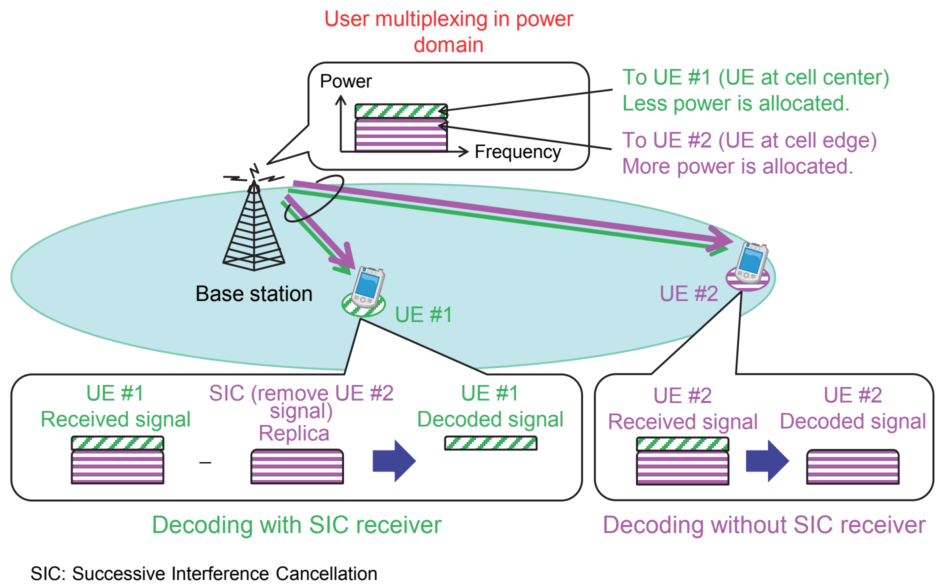

Figure 1　Downlink NOMA basic principles

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).

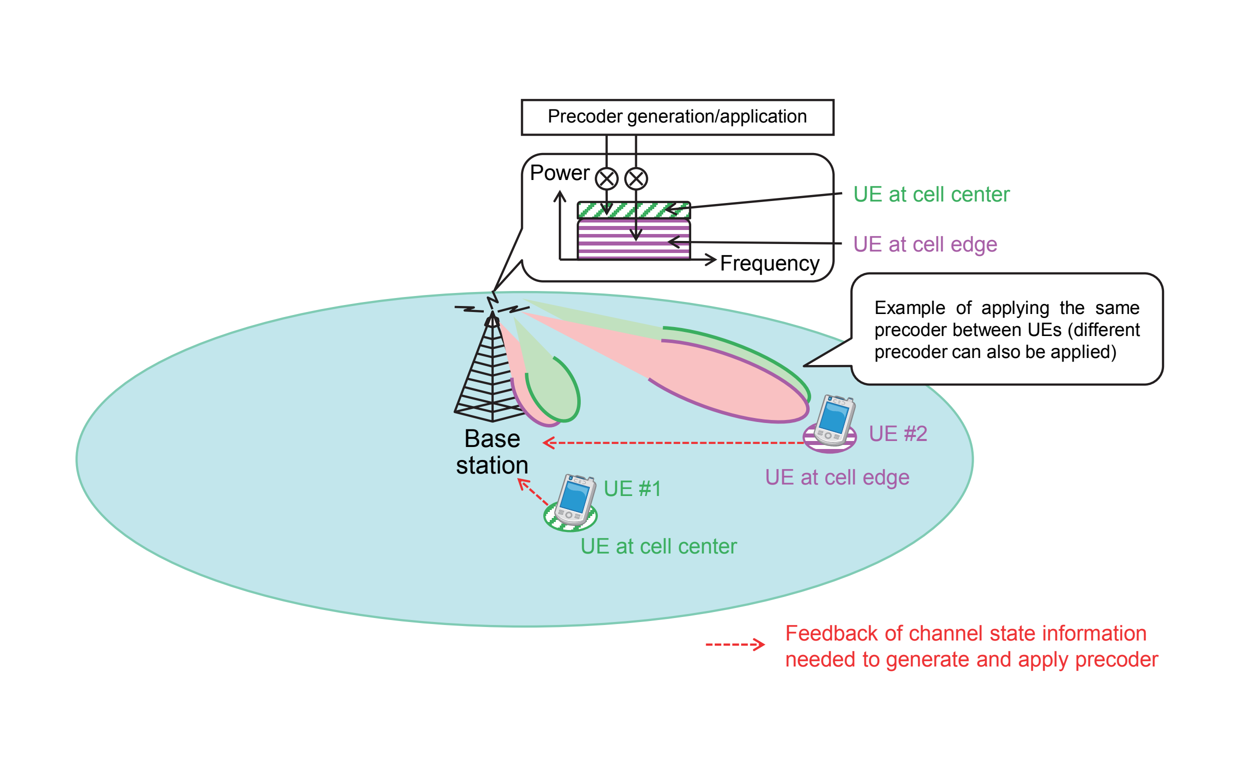

Figure 2 Principle of combining downlink NOMA with SU-MIMO

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.

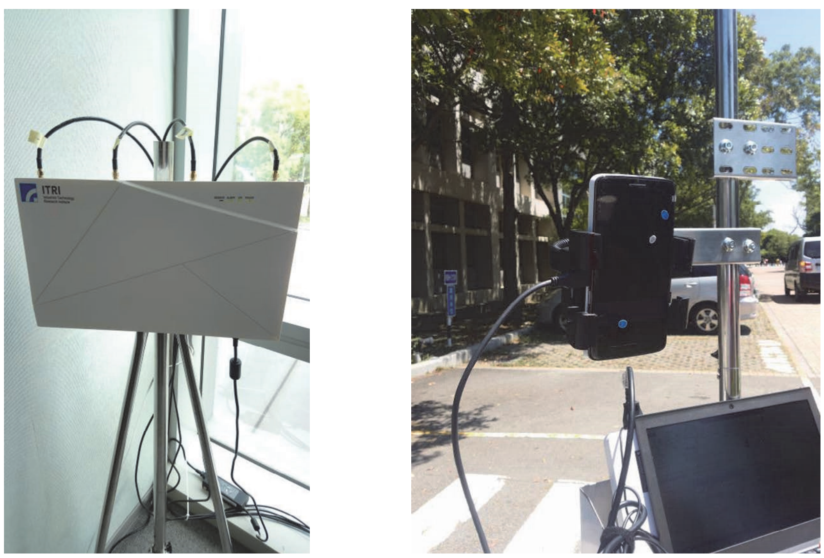

Photo 1 Base station (left) and mobile station (right) equipment

*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.

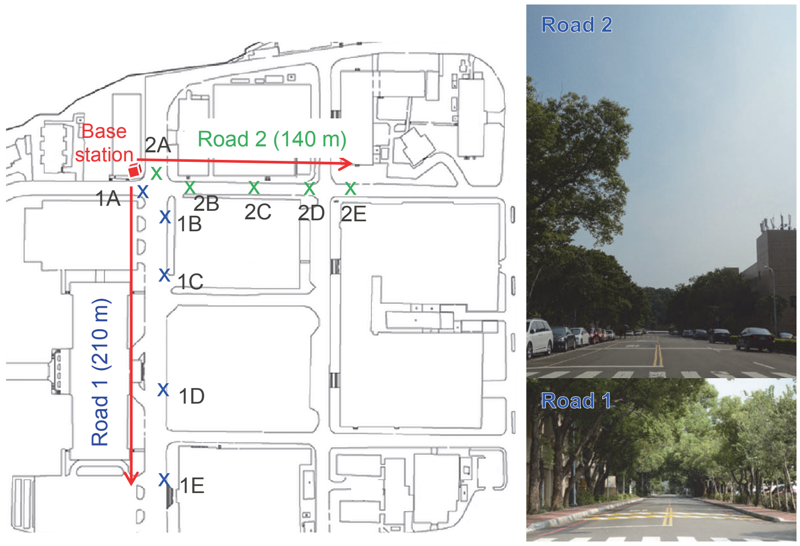

Figure 3　Environment of field trials (Hsinchu City, Taiwan, ITRI Campus)

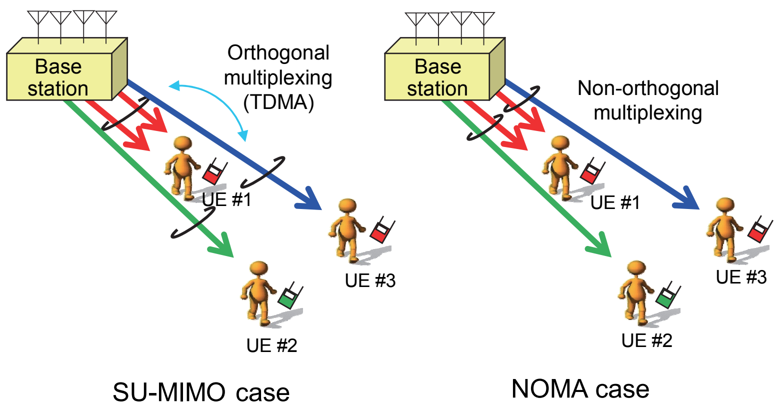

Figure 4　Evaluation scenarios

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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