Technology Reports

4×4 MIMO | 256QAM | Advanced C-RAN

Base-station Equipment and Router-type Mobile Terminal Supporting 4×4 MIMO and 256QAM for 682 Mbps Maximum on Downlink

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NTT DOCOMO launched mobile communication services called PREMIUM 4G with a maximum data rate of 225 Mbps on the downlink in March 2015. It then began services with a maximum downlink data rate of 375 Mbps by enhanced CA technology in May 2016 and services with a maximum downlink data rate of 370 Mbps using TDD in the 3.5-GHz band in June 2016. Since then, we have developed base-station equipment and a router-type mobile terminal supporting 4×4 MIMO technology and 256QAM technology to increase downlink data rate even further, and by combining these technologies with deployed CA technology, we launched commercial services with a maximum downlink data rate of 682 Mbps in March 2017. In this article, we describe 4×4 MIMO and 256QAM technologies and present base-station equipment and a router-type mobile terminal for achieving a maximum downlink data rate of 682 Mbps.

1. Introduction

The demand for higher data rate in the mobile network has been growing as the use-case of applications for smartphones and high-volume content services oriented to smartphones expands.

In March 2015, NTT DOCOMO launched mobile communication services with a maximum data rate of 225 Mbps on the downlink as PREMIUM 4G. Then, in May 2016, it began services with a maximum downlink data rate of 375 Mbps by enhanced Carrier Aggregation (CA)*1 technology, and

*1 CA: A technology that achieves high data rate communications through bandwidth expansion while maintaining backward compatibility with existing LTE by performing simultaneous transmission and reception using multiple component carriers.

in June of 2016, it began services with a maximum downlink data rate of 370 Mbps using Time Division Duplex (TDD)*2 in the 3.5-GHz band [1]. We have since developed base-station equipment and a router-type mobile terminal supporting 4×4 Multiple Input Multiple Output (MIMO)*3 technology and 256 Quadrature Amplitude Modulation (QAM)*4 technology to achieve a dramatic increase in maximum data rate. Then, in March 2017, we combined these technologies with deployed CA technology to launch commercial services with a maximum downlink data rate of 682 Mbps, which represents a threefold increase compared with the maximum data rate at the time of the PREMIUM 4G launch.

NTT DOCOMO successfully deployed PREMIUM 4G and increased the data rate efficiently through the application of Advanced Centralized Radio Access Network (Advanced C-RAN)*5 architecture [2]. Furthermore, by designing the base-station equipment to configure this Advanced C-RAN architecture with enough future extensions, we were able to provide new mobile communication services supporting 4×4 MIMO and 256QAM by simply adding functions to the software of existing base-station equipment. This made it possible to provide coverage areas supporting a maximum downlink data rate of 682 Mbps in an economical and early manner.

In this article, we describe these 4×4 MIMO and 256QAM technologies and present base-station equipment and a router-type mobile terminal that can support a maximum downlink data rate of 682 Mbps.

2. Data Rate-enhancing Technologies

2.1 4×4 MIMO

Applying more advanced MIMO technology can improve the maximum downlink data rate. At NTT DOCOMO, we have developed 4×4 MIMO technology using four antennas as an advancement to 2×2 MIMO with two antennas, which we have been using up to now. The following describes this technology in detail.

1) Four-stream Transmission

(1) Overview

In MIMO transmission, the number of simultaneous transmission data sequences to be multiplexed is called the "number of streams." In 2×2 MIMO, a maximum of two streams can be transmitted, but in 4×4 MIMO, the ability to transmit a maximum of four streams at once enables approximately twice the amount of transmission data thereby increasing the maximum data rate. In LTE specifications, there are multiple Transmission Mode (TM) specifications for achieving 4×4 MIMO. For example, TM3 and TM4 specified in the LTE Release 8 specification (hereinafter referred to as "LTE Rel. 8") support the transmission by a maximum of four streams using four antennas worth of a Cell-specific Reference Signal (Cell-specific RS)*6. In addition, TM9 and TM10 specified in LTE Rel. 10 and LTE Rel. 11, respectively, support flexible precoding and Multi-User MIMO*7. In those TMs, Channel State Information-Reference Signal (CSI-RS)*8 and User Equipment-specific RS (UE-specific RS)*9 are specified

*2 TDD: A bidirectional transmit/receive system. It achieves bidirectional communication by allocating different time slots to uplink and downlink transmissions that use the same frequency band.

*3 MIMO: A technology for achieving high data rate transmission by simultaneously transmitting different signals from multiple antennas.

*4 QAM: A modulation method using both amplitude and phase.

*5 Advanced C-RAN: Network architecture promoted by NTT DOCOMO using CA technology to achieve inter-cell coordination between macro cells and small cells.

*6 Cell-specific RS: A reference signal specific to each cell for measuring received quality in the downlink.

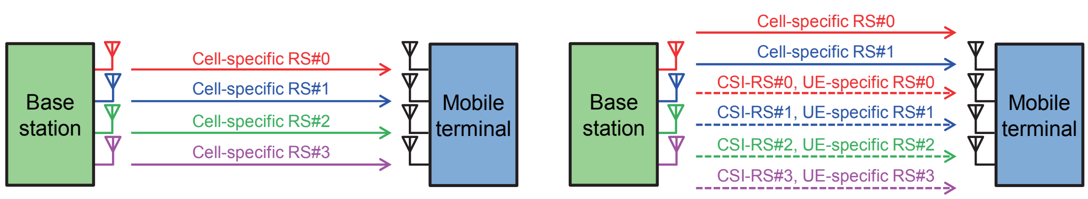
*7 Multi-User MIMO: Technology that uses MIMO transmission over the same time and frequency for multiple users.

in addition to Cell-specific RS to perform four-stream transmission [3]. That is, in TM3/4, only Cell-specific RS is used for measurement of the channel connectivity quality and channel state information for transmission data and for demodulation of transmission data on the downlink. In TM9/10, meanwhile, Cell-specific RS is used for measurement of the channel connectivity quality, CSI-RS for measurement of channel state information for transmission data, and UE-specific RS for demodulation of transmission data (**Figure 1**).

(2) 3GPP standardization approach

The original specifications had two key issues for TM9/10. NTT DOCOMO studied and proposed ways of improving these specifications thereby contributing to higher data rates.

- The first issue is a limitation on data transmission resources in the transmission timing of the synchronization signal. The frequency resource, the Resource Block (RB), allocated for transmission of the synchronization signal cannot be used for transmission of UE-specific RSs, so the TM9/10 transmission data cannot be allocated to those RBs. Moreover, a base station cannot allocate in units of RBs but in units of RB groups within some of the RBs for transmission to a mobile terminal. In the original specifications for TM9/10, transmission data could be allocated neither within the individual RBs used for transmitting the synchronization signal nor throughout the RB groups that include those RBs, which unnecessarily limited data transmission resources. In response to this issue, the specifications were revised to enable the RBs located within the RB groups containing the synchronization signal but not actually transmitting the synchronization signal to be used for data transmission (**Figure 2**).



Application	TM3/4	TM9/10
Measurement of channel connectivity quality	Cell-specific RS	Cell-specific RS
Measurement of channel state information for transmission data	Cell-specific RS	CSI-RS
Demodulation of transmission data	Cell-specific RS	UE-specific RS

Figure 1　RSs used for various TMs

*8　CSI-RS: A reference signal transmitted from each antenna to measure the state of the radio channel.

*9　UE-specific RS: A reference signal specifically for UE for demodulating the data signal in the downlink.

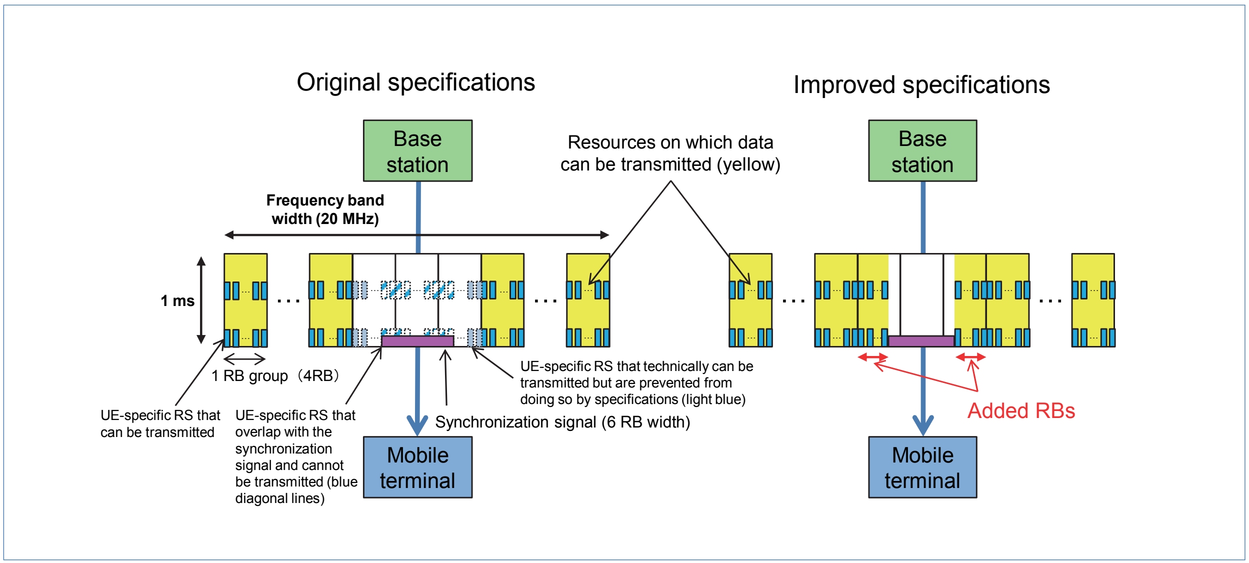


Figure 2　Easing of resource limit in transmission timing of synchronization signal

- The second issue is that the addition of RS overhead*10 in TM9/10 prevents the maximum amount of data in the original specifications from being transmitted. Several transmission bit patterns for the transmission time interval are established in the specifications. In the case of TM9/10, however, the amount of data achieving the maximum data rate cannot be allocated due to the RS overhead, so the maximum amount of transmission data is limited requiring the base station to allocate the data without the maximum data rate pattern. Consequently, as the amount of transmission data at one time was limited in this way, the maximum data rate in TM9/10 could not be achieved in base-station equipment and mobile terminals. For this issue, we defined a new data-usage pattern taking RS overhead into account for TM9/10 specifications. As a result, we achieved a higher maximum data rate in base-station equipment and mobile terminals performing communications by TM9/10 (**Figure 3**).

2) Beamforming Based on Feedback

Base-station equipment forms optimal beams by using feedback information from a mobile terminal. This beamforming process improves not only the maximum data rate but channel quality as well. On the transmission side, the base station controls the amplitudes and phases on multiple antennas to form a directional pattern to increase or decrease antenna gain in specific directions. A base station can form the beams more powerfully by using four transmission antennas on 4×4 MIMO compared with 2×2 MIMO transmission. The mobile terminal, meanwhile, estimates the propagation channel using received RSs and reports an appropriate optimal beam pattern to

*10 Overhead: Control information needed for transmitting/receiving user data, plus radio resources used for other than transmitting user data such as reference signals for measuring received quality.

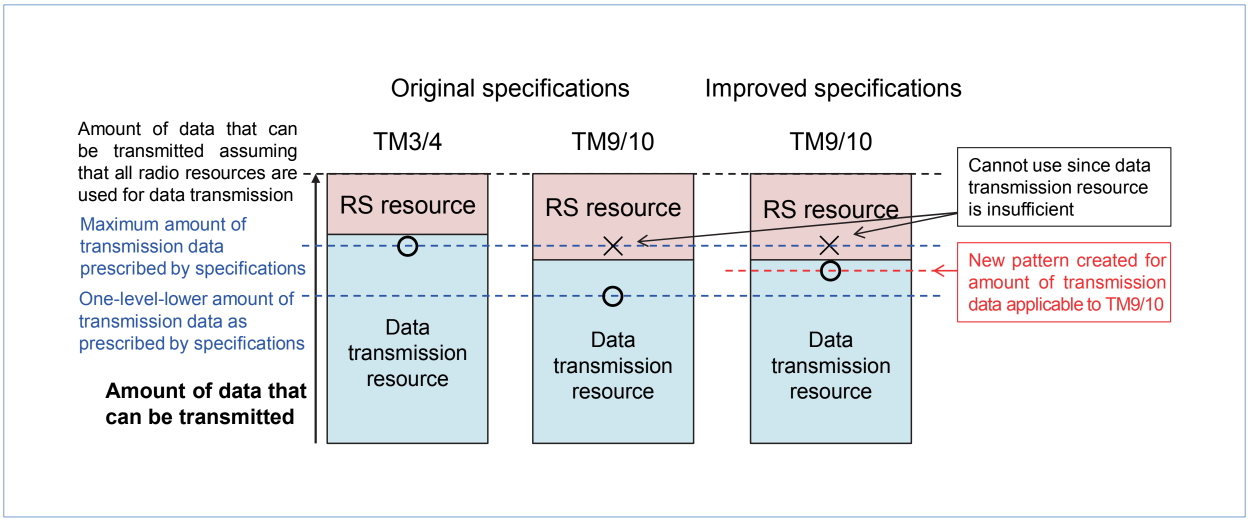


Figure 3　New pattern for amount of transmission data considering RS overhead

base-station equipment as a Precoding Matrix Indicator (PMI)*11. As feedback information, this PMI is returned together with the Channel Quality Indicator (CQI)*12 and Rank Indicator (RI)*13, the latter of which indicates the optimal number of streams. The base-station equipment now references the PMI and determines precoding weights*14 for the transmission signal sent to the mobile terminal. Finally, for TM3/4, the mobile terminal demodulates the data signal by referencing precoding information received from the base-station equipment, and for TM9/10, by referencing the UE-specific RS using the same precoding as transmission data.

3) Determining an Optimal Combination of Streams and Beamforming

There is a trade-off between number of streams and the beamforming effect: simply put, transmission with multiple streams reduces the beamforming effect. For this reason, the base-station equipment uses the feedback information reported by the mobile terminal, the amount of transmission data, etc. to decide on the optimal number of streams and the precoding to be used in beamforming. Finding an appropriate combination of number of streams and beamforming makes it possible to improve maximum data rate through multiple streams in areas with high quality near the base station and to improve received quality by beamforming in areas with low quality such as the cell edge (**Figure 4**).

2.2 256QAM

Higher data rates can be achieved by adopting a method that can transmit multiple bits per symbol*15 (multi-value modulation*16). NTT DOCOMO decided to support 256QAM for this reason. As a higher modulation scheme specified by LTE Rel. 12, 256QAM can transmit a maximum of 8 bits per symbol, which means that a downlink data rate approximately 1.3 times faster than that of 64QAM can be expected (**Figure 5**).

The use of a higher modulation scheme like

*11 PMI: Information fed back from the mobile terminal on precoding assumed to be optimal for the downlink.

*12 CQI: Information fed back from the mobile terminal on downlink quality.

*13 RI: Information fed back from the mobile terminal on the number of streams assumed to be optimal on the downlink.

*14 Precoding weights: Phase differences applied to each transmitting antenna during beamforming.

*15 Symbol: A unit of data for transmission. In Orthogonal Frequency Division Multiplexing (OFDM), it comprises multiple subcarriers. Multiple bits (2 bits in the case of Quadrature Phase Shift Keying (QPSK)) map to each subcarrier.

*16 Multi-value modulation: A modulation system that includes two or more bits of information in one signal.

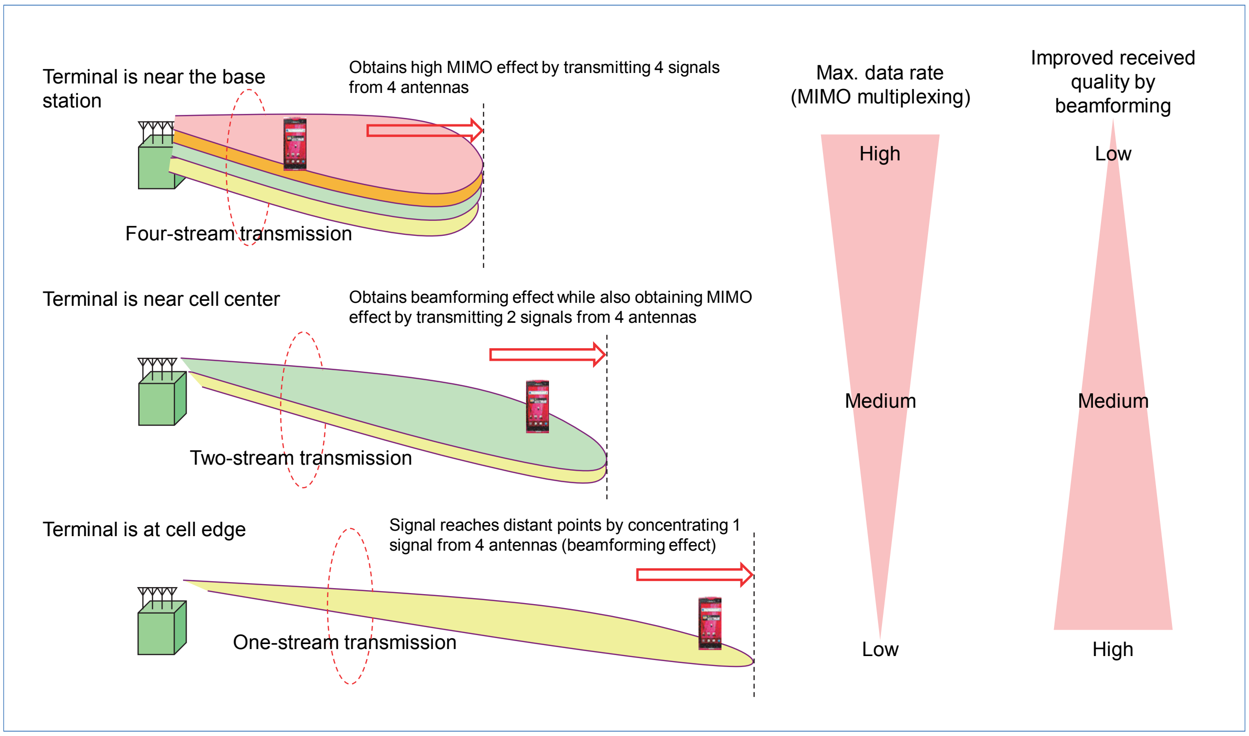


Figure 4　Number of streams and beamforming effect

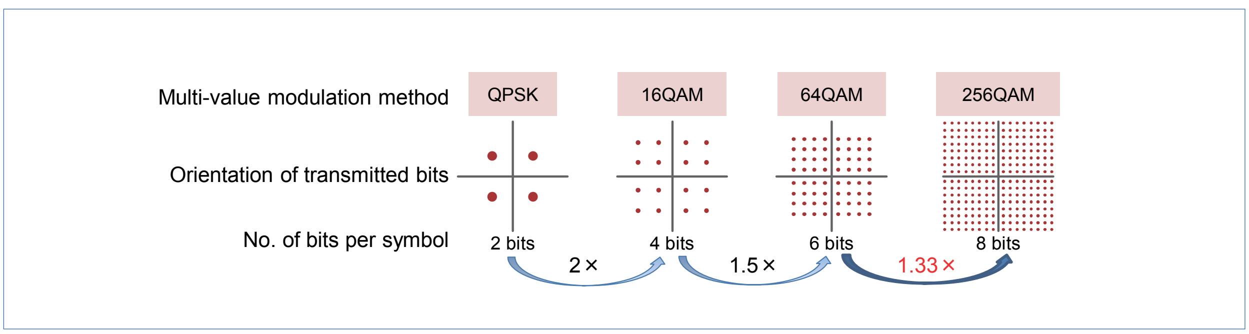


Figure 5　256QAM

256QAM requires a high-quality wireless environment, that is, an environment with a high Signal-to-Interference plus Noise power Ratio (SINR)*17. As a consequence, not all mobile terminals can necessarily use 256QAM all the time, and for this reason, the base-station equipment decides what modulation scheme a mobile terminal will use based on the CQI index reported by that terminal. The maximum data rate can be improved using 256QAM for a mobile terminal reporting a high CQI index.

To avoid having to increase the number of CQI indices on introducing 256QAM in LTE Rel. 12, the specification for the existing CQI table was modified so as to replace some of the indices with

*17 SINR: Ratio of desired received signal power to that of other received signals (interfering signals from other cells or sectors and thermal noise).

CQI indices corresponding to 256QAM [4] (**Figure 6**). Both the base-station equipment and mobile terminal store the existing 256QAM-non-supported CQI table and the 256QAM-supported CQI table, and the base-station equipment informs the mobile terminal which table to use taking into account its current capability.

3. Base-station Equipment Supporting 4×4 MIMO and 256QAM

As described in section 2.1, the number of antennas must be increased from two to four to support 4×4 MIMO. NTT DOCOMO decided to introduce 4×4 MIMO in the 3.5-GHz band for two main reasons: the high frequencies of this band enable antenna downsizing and the availability of a 40 MHz bandwidth in this band makes for a high data rate-enhancing effect.

The network architecture supporting 4×4 MIMO and 256QAM is shown in **Figure 7**. This architecture can achieve a maximum data rate of 682 Mbps on the downlink by applying both 4×4 MIMO and 256QAM to the 3.5 GHz band and only 256QAM to the other frequency bands. This is made possible by a CA configuration that combines the 3.5-GHz band having a 40 MHz bandwidth using TDD with the other frequency bands having a maximum 20 MHz bandwidth using Frequency Division Duplex (FDD)*18. The low power Small optical remote Radio Equipment (SRE)*19 that configures small cells in the 3.5-GHz band was originally developed as a unit consisting of four transceiver systems (branches) with consideration to supporting 4×4 MIMO, so SREs that had already been deployed could be immediately used as 4-branch

256QAM non-supported

CQI index	Modulation method	Code rate
0	out of range	
1	QPSK	0.076
2	QPSK	0.117
3	QPSK	0.188
4	QPSK	0.301
5	QPSK	0.438
6	QPSK	0.588
7	16QAM	0.369
8	16QAM	0.479
9	16QAM	0.602
10	64QAM	0.455
11	64QAM	0.554
12	64QAM	0.650
13	64QAM	0.754
14	64QAM	0.853
15	64QAM	0.926

QPSK area reduced

Shift upward by filling in the gap

256QAM supported

CQI index	Modulation method	Code rate
0	out of range	
1	QPSK	0.076
2	QPSK	0.188
3	QPSK	0.438
4	16QAM	0.369
5	16QAM	0.479
6	16QAM	0.602
7	64QAM	0.455
8	64QAM	0.554
9	64QAM	0.650
10	64QAM	0.754
11	64QAM	0.853
12	256QAM	0.694
13	256QAM	0.778
14	256QAM	0.864
15	256QAM	0.926

256QAM added by shifting existing CQI upward

Figure 6 256QAM non-supported/supported CQI tables

*18 FDD: A scheme for transmitting signals using different carrier frequencies and bands on the uplink and downlink.

*19 SRE: Radio equipment for small cells installed in places remotely located from BDE (see *21) using optical fiber, etc.

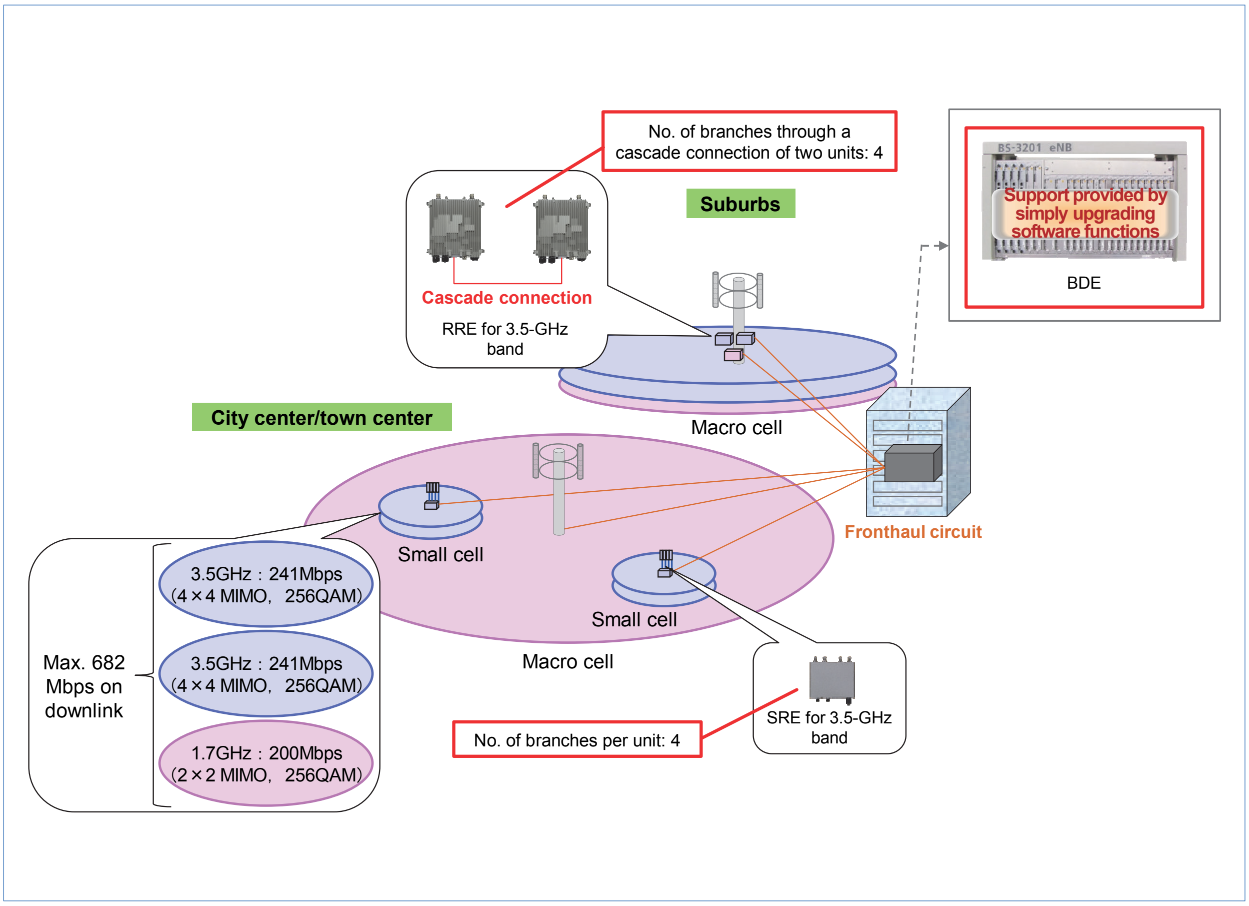


Figure 7 Network architecture supporting 4×4 MIMO and 256QAM

base-station equipment. In addition, the Remote Radio Equipment (RRE)*20 for macro cells in the 3.5-GHz band, while consisting of two branches per unit taking into account equipment size at the time of 2×2 MIMO deployment, have been designed to operate as 4-branch base-station equipment through a cascade connection of two units. As a result, 4×4 MIMO can be supported in a macro cell by adding and connecting in cascade one RRE unit to a previously deployed RRE unit. In both small cells and macro cells, 4×4 MIMO can be achieved by simply adding functions to the software of the Base station Digital processing Equipment (BDE)*21 and SRE/RRE units.

Furthermore, base-station equipment supporting 4×4 MIMO can transmit 2×2 MIMO signals with its four antennas to an existing UE supporting 2×2 MIMO thereby increasing total transmission power of the base station and raising the received level at the UE.

At the same time, adding 256QAM functions to BDE software makes it possible to support 256QAM in all areas of existing base-station equipment regardless of FDD or TDD use.

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*20 RRE: Radio equipment installed in places remotely located from BDE (see *21) using optical fiber, etc.

*21 BDE: Digital signal processing equipment for base stations in the LTE system, equipped with a baseband processing section and maintenance/monitoring functions.

4. Router-type Mobile Terminal Supporting 4×4 MIMO and 256QAM

4.1 Overview

The external appearance of a newly developed router-type mobile terminal is shown in **Photo 1**. This mobile terminal operates by 4×4 MIMO in the 3.5-GHz TDD band and supports 256QAM. As in the case of base-station equipment, it achieves a maximum data rate of 682 Mbps on the downlink by applying 4×4 MIMO and 256QAM simultaneously in a CA configuration that combines the 3.5-GHz band having a 40 MHz bandwidth with other frequency bands having a FDD 20 MHz bandwidth.

Photo 1 External appearance of router-type mobile terminal supporting 4×4 MIMO

4.2 Antenna Configuration

The antenna arrangement in this router-type mobile terminal supporting 4×4 MIMO is shown in **Figure 8**. Among these four antennas, one operates as a main antenna having both transmitting and receiving functions while the other three operate as sub-antennas having only a receiving function. In addition to the 3.5-GHz band, both the main antenna and sub-antennas support other cellular frequency bands (2 GHz, 1.7 GHz, etc.).

Metallic components such as Wi-Fi®*22 antennas, battery, display, and substrates mounting various

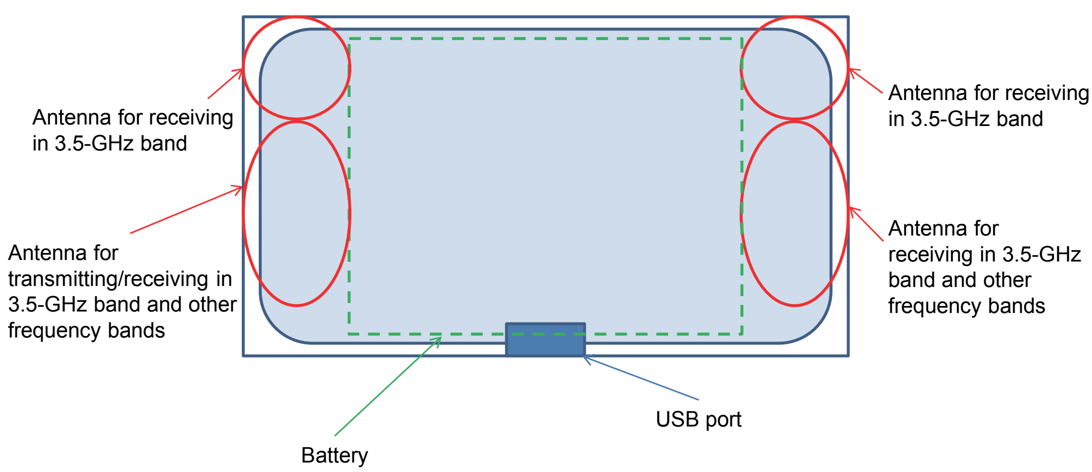

Figure 8 Antenna arrangement in router-type mobile terminal supporting 4×4 MIMO

*22 Wi-Fi®: A registered trademark of the Wi-Fi Alliance.

devices in the vicinity of a cellular antenna can affect antenna performance. Consequently, to maintain antenna performance while preserving the compact configuration (62×98×13.6 mm) of this mobile terminal, the antennas must be kept a certain distance from other metallic components.

On the other hand, there is concern that arranging two 3.5-GHz band antennas in close proximity to each other will result in high inter-antenna correlation*23, which can prevent MIMO performance from being sufficiently demonstrated and degrade the data rate. In response to this concern, we devised a measure for keeping antenna correlation low even for antennas in a close-proximity arrangement in combination with existing technology for downsizing antennas accommodating multiple frequencies.

In this mobile terminal, we also adopted the USB 3.0 standard to meet the need for increasing the data rate of the unit's external interface to keep up with increases in radio data rates. However, the use of such a USB interface with a high data rate can increase the amount of noise added to the cellular frequency bands and negatively affect downlink performance. We therefore incorporated several noise countermeasures to prevent this degradation in performance such as enhancing the metallic shield around the USB connector, adding a noise-removal filter, and optimizing the connector and antenna position. These measures help prevent a drop in data rate at the time of USB tethering*24.

4.3 Evaluation of Antenna Performance

The 4×4 MIMO antenna measurement system for the developed router-type mobile terminal is shown in **Figure 9**. The configuration shown here is for a 3 DownLink CA (3DL CA) consisting of a FDD frequency band + 3.5-GHz + 3.5-GHz (where the 3.5-GHz band is used for 4×4 MIMO). We used this measurement system to evaluate downlink data rate from base-station equipment to the mobile terminal. In the figure, a reverberation chamber is used to construct a fading*25 environment in which signals from the base-station equipment arrive at the Device Under Test (DUT) from various directions.

An LTE signal is generated for each Component Carrier (CC)*26, so in this measurement system, 4×4 MIMO signals consisting of signal 1 of Secondary CC (SCC)*27 1 (SCC1 p1) and signal 1 of SCC 2 (SCC2 p1) are combined by a combiner unit and transmitted from a single antenna. The same configuration holds for signals SCCp2 – p4, but Primary CC (PCC)*28 signals are transmitted from separate antennas. This system simulates CA on the downlink consisting of FDD 2×2 MIMO + 3.5-GHz 4×4 MIMO + 3.5-GHz 4×4 MIMO signals.

We evaluated the downlink data rate for the DUT using this measurement system and confirmed that a maximum performance of 682 Mbps could be guaranteed for a 4×4 MIMO, 256QAM, 3DL CA configuration.

5. Conclusion

In this article, we introduced 4×4 MIMO and 256QAM technologies to increase the maximum data rate in the downlink of NTT DOCOMO PREMIUM 4G. We also described base-station equipment and

*23 Correlation: An index expressing similarity between different signals. Expressed as a complex number, its absolute value ranges from 0 to 1. Similarity increases as the value approaches 1, in which case signal separation at the receiver is difficult resulting in degraded throughput in MIMO communications.

*24 Tethering: A function which enables a mobile terminal to be used as an external modem, so that Wi-Fi devices such as game machines or PCs can connect to the Internet through the mobile phone's connection.

*25 Fading: A phenomenon in mobile communications in which radio signals having different propagation paths due to reflection, etc. arrive at different times thereby affecting amplitude and phase.

*26 CC: In LTE, a carrier is treated as a single frequency block having a bandwidth of 20 MHz in both the uplink and downlink.

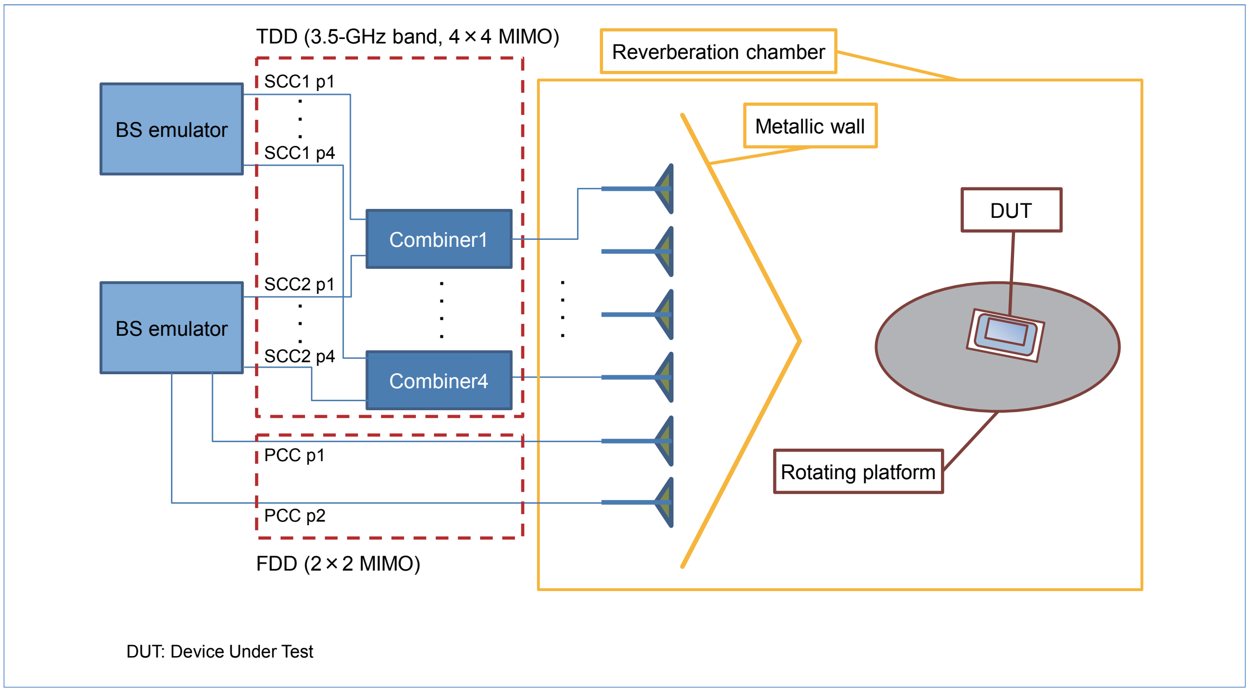

Figure 9 4×4 MIMO + 3DL CA throughput measurement system

a router-type mobile terminal for achieving a downlink data rate of 682 Mbps. Going forward, we plan to continue our development efforts toward even higher maximum data rates in PREMIUM 4G.

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*27 SCC: In CA, a carrier that provides radio resources in addition to PCC (see *28).

*28 PCC: In CA, a carrier that ensures connectivity between UE and the network.