Technology Reports Ultra-high-speed Data Communications High-speed Mobility Improved Spectral Efficiency

Latest Radio Access Technologies for 5G Systems and Field Testing Results —Technologies Realizing Ultra-high-speed Data Transport, High-speed Mobility, and Improved Spectral Efficiency—

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Various radio access technologies have been studied for 5G, to support wide frequency bands and a wide range of use cases. NTT DOCOMO has been collaborating with major global vendors to test these technologies. This article introduces some of the latest field testing results conducted with these vendors, including the first 20 Gbps high-speed data transmission tests done in collaboration with Ericsson, high-speed mobile data transmission tests done at 150 km/h on a racing circuit (the fastest in the world as of November 2016) done in collaboration with Samsung Electronics, and tests achieving very high spectral efficiency of up to 79.82 bps/Hz/cell done in collaboration with Huawei Technologies.

1. Introduction

Hopes are now raising around the world for the introduction of Fifth Generation mobile communications systems (5G) by the year 2020. Discussion at the 3GPP has begun on standards for a new 5G radio interface standard called New Radio (NR), and major organizations studying 5G in various countries are announcing plans for commercialization and testing of 5G [1]. NTT DOCOMO began studying 5G in 2010 and has promoted various activities such as proposing technology concepts, transmission testing, and leading discussion on standardization [2]. In particular, NTT DOCOMO has conducted testing of various 5G radio transmission technologies in collaboration with major global vendors, focused on high frequency-band, multi-antenna transmission technologies [3] that are being studied for 5G. Details of these were introduced in this journal [4]. This article describes highlights of the latest test results as of March 2017, from on-going 5G transmission testing being done in collaboration with major global vendors.

2. Testing Ultra-high-speed Communication

Use of high frequencies over 6 GHz for 5G, is being studied so that wide, continuous frequency bands of almost 1 GHz can be used. Massive Multiple Input Multiple Output (MIMO)*1 technology [3] with large numbers of antenna elements is used for such ultra-wideband transmission, applying techniques such as beam forming*2 and spatial multiplexing. This will enable mobile communication systems providing coverage with ultra-high-speed data communication of over 10 Gbps per user. NTT DOCOMO has been testing this sort of ultra-high-speed data communication using Massive MIMO in collaboration with Ericsson. Specifically, we have achieved communication speeds exceeding 10 Gbps with 800 MHz ultra-wideband transmission in the 15 GHz band, using MIMO transmission with up to four streams*3 per user and 256 Quadrature Amplitude Modulation (256QAM)*4. We have also achieved transmission exceeding 20 Gbps per base station [5] to multiple users simultaneously (total transmission speed to two users) with Multi-User MIMO (MU-MIMO)*5 and beam forming for the first time in an outdoor environment.

Results of joint ultra-high-speed data communication testing done with Ericsson are described below. These include an overview of the testing and results for ultra-high-speed MU-MIMO transmission achieving over 20 Gbps communication [6] as mentioned above, and for technical elements for Massive MIMO using multiple transmission points and reflections from buildings to increase communication speed [7] [8].

2.1 Testing Ultra-high-speed MU-MIMO Transmission

1) MU-MIMO Transmission Function and Equipment Overview

A schematic diagram of the MU-MIMO transmission function used in our tests is shown in **Figure 1**. The Base Station (BS) periodically sends a Mobility Reference Signal (MRS) (Fig. 1 (1)) for each candidate beam from the antenna units (called Radio Units (RU))*6, for use in beam selection. Mobile Stations (MS) use the MRS to calculate the MRS Received Power (MRSRP) for each beam. MSs compare the MRSRP of each beam and feedback the MRSRPs and beam ranking to the BS (Fig. 1 (2)). The BaseBand Unit (BBU)*7 in the BS selects the beam with the highest MRSRP for each MS (Fig. 1 (3)), transmitting beams from RU #1 and #2 to MS #1, and from RU #3 and #4 to MS #2 (Fig. 1 (4)).

External views of the RU are shown in **Figure 2**. Each RU consists of two antenna panels corresponding to horizontally and vertically polarized signals, enabling it to transmit two streams. Each antenna panel consists of a flat array antenna with 64 antenna elements at intervals of 0.7λ. The antenna gain*8 is 24 deciBel isotropic (dBi)*9, and the transmission power per panel is 14 deciBel milli (dBm)*10. In our experiments, we used four RUs, transmitting up to eight streams to two users (for a theoretical peak transmission capacity of 31.2 Gbps).

2) Test Environment and Measurement Results

The tests were conducted in a 100 × 100 m

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*1 **Massive MIMO:** Large-scale MIMO using a very large number of antenna elements. Since antenna elements can be miniaturized in the case of high frequency bands, Massive MIMO is expected to be useful in 5G.

*2 **Beam forming:** 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.

*3 **Stream:** A data sequence that is spatially-multiplexed when using multiple transceiver antennas with MIMO technology.

*4 **256QAM:** Quadrature Amplitude Modulation (QAM) is a modulation method using both amplitude and phase. In 256QAM, 256 (2^8) symbols exist, so this method allows for the transmission of 8 bits at one time.

*5 **MU-MIMO:** A technology that uses MIMO to transmit signals to multiple users at the same time using the same frequency.

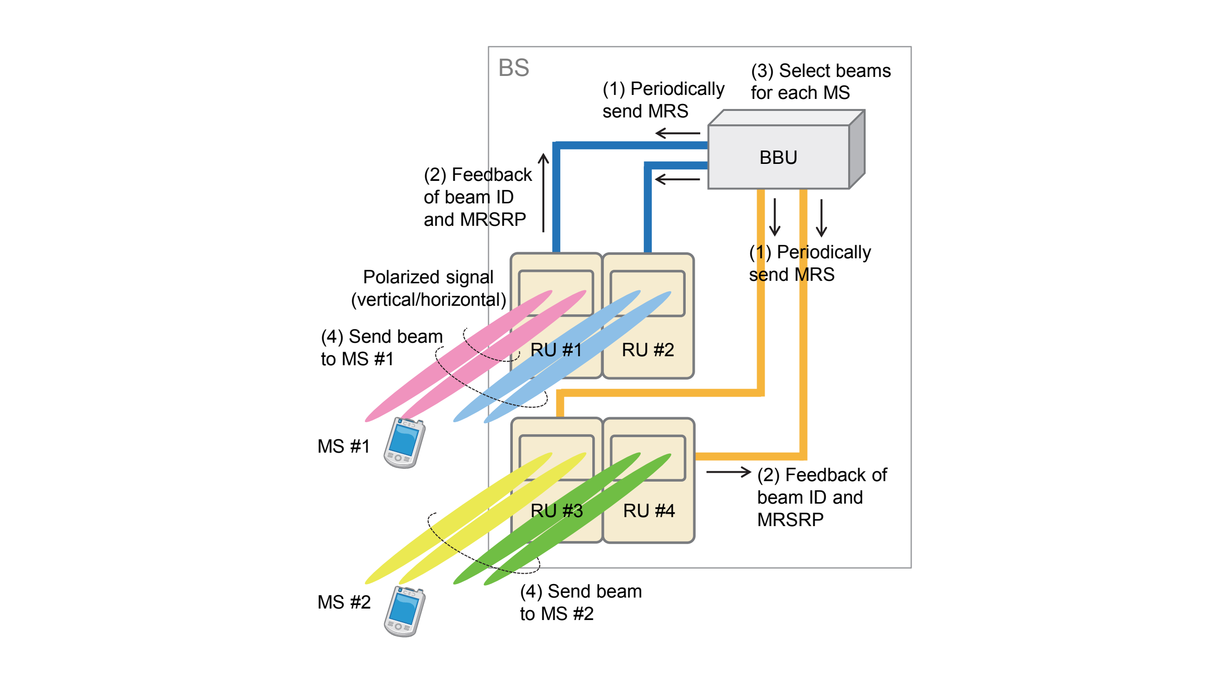

Figure 1　Test equipment MU-MIMO beam transmission function

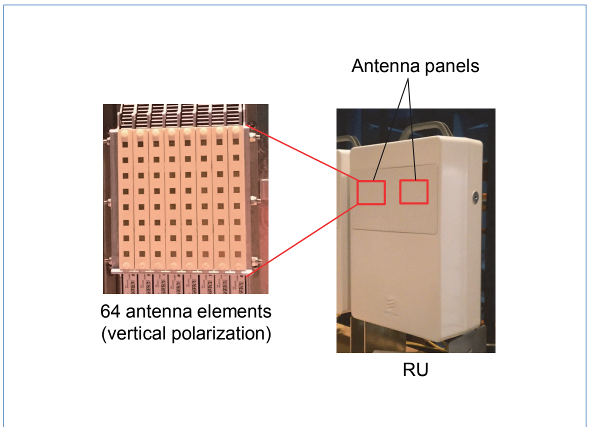

Figure 2　RU external views

area in the outdoor parking lot of the DOCOMO R&D Center in the YRP region of Yokosuka City, Kanagawa Prefecture. The measurement area was an open environment, providing Line-Of-Site (LOS)*11 conditions everywhere. MS #1 moved at walking speed (approx. 3 km/h) within the measurement area, while MS #2 was placed at fixed positions along the course.

The total transmission capacity (system throughput) characteristics for MU-MIMO transmission to two MSs, distributed according to MS #1 position and plotted in color on a map of the measurement area, is shown in **Figure 3**. In Fig. 3 (a), MS #2 is located near the edge of the measurement area, and in Fig. 3 (b) it is near the center.

The figures show that when the angular direction from the BS to MS #2 is different than the direction to MS #1, relatively higher system throughput is achieved. In particular, MS #2 is at the edge of the measurement area in Fig. 3 (a) (lower left), so when MS #1 is at the opposite side (upper right) of the measurement area, relatively high

*6 RU: Part of the equipment comprising a base station, which performs transmission and reception by converting digital signals to a radio signals, amplifying them and sending or receiving them from the antenna elements. It also performs processing necessary to generate beam forming for Massive MIMO.

*7 BBU: One component of base station equipment performing digital signal processing of transmit/receive information when communicating with a mobile terminal.

*8 Antenna gain: Radiated power in the direction of maximum radiation usually expressed as the ratio of radiated power to that of an isotropic antenna.

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

*10 dBm: Power value [mW] expressed as 10log (P). The value relative to a 1 mW standard (1 mW=0 dBm).

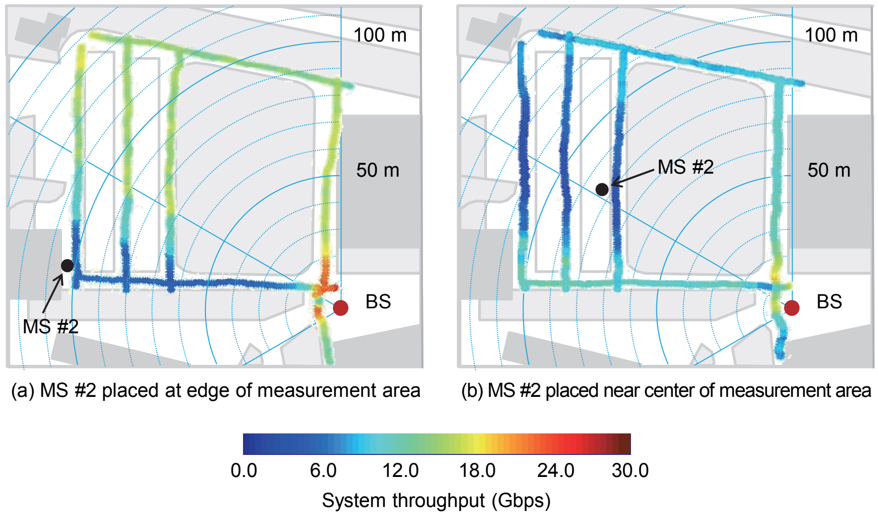

Figure 3 Ultra-high-speed MU-MIMO transmission test results

throughput between 15 and 20 Gbps is achieved. This is because when the angular directions to MS #1 and #2 are close, there is interference between the beams sent to each. High system throughput exceeding 20 Gbps is observed when the angular directions to each MS are farther apart and when MS #1 is relatively near to the BS. Specifically, system throughput of 25.9 Gbps was achieved when MS #1 was within 15 m of the BS in Fig. 3 (a), and 20.5 Gbps was achieved when MS #1 was within approximately 20 m of the BS in Fig. 3 (b).

2.2 Testing Elemental Technologies for Massive MIMO

Increasing propagation losses*12 and channel correlation*13 are two known issues due to the propagation characteristics of high frequency bands [4]. To resolve these issues, we have studied and tested technologies to improve communication speed, including beam forming with Massive MIMO to compensate for propagation losses as mentioned above, and use of multiple transmission points and reflections from buildings to reduce channel correlation.

1) Distributed MIMO Technology

Results from testing distributed MIMO*14 technology, which uses MIMO multiplexing to transmit separate streams from multiple transmission points, are shown in **Figure 4** [7]. Two RUs are used in these tests, transmitting the same beam for non-distributed MIMO, and different beams from RUs in different locations for distributed MIMO. The measurement course was the same as in Fig. 3, in the outdoor parking lot of the DOCOMO R&D Center. Throughput characteristics for non-distributed MIMO (two RUs at the same position) are shown in Fig. 4 (a), and for distributed MIMO (RUs placed 7 m apart) in Fig. 4 (b). Comparing these shows that applying distributed MIMO improved throughput characteristics greatly over the entire

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*11 LOS: Describes an environment where there are no obstacles between the transmitter and receiver, allowing them to communicate via direct waves.

*12 Propagation losses: The amount of attenuation in the power of the signal emitted from the transmitting station till it arrives at the reception point.

*13 Channel correlation: An index indicating the similarity among multiple signals, with values near 1 (one) indicating similarity (correlation) and values near 0 (zero) indicating dissimilarity.

*14 Distributed MIMO: A MIMO transmission technology that transmits different MIMO streams from multiple base stations to a single mobile station.

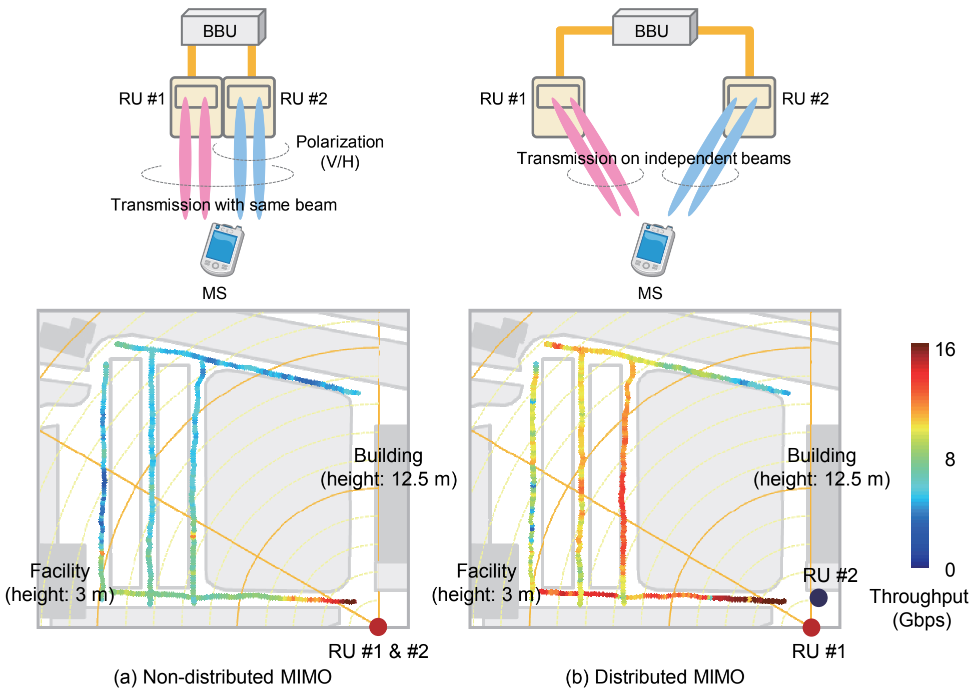

Figure 4 Test results of distributed MIMO technology

measurement area. This shows that transmitting different beams from different locations reduced channel correlation. When we checked the number of MIMO multiplexed streams (the rank), we found that the value for the cumulative distribution of 50% rose from 2.7 to 3.8, meaning that almost all of four streams (the maximum) were transmitted. As a result, we achieved throughput of over 10 Gbps in more than 40% of our measurement area by applying distributed MIMO.

2) Technology Using CSI Estimation to Transmit Independent Beams between RUs

Figure 5 shows results from testing a technology that transmits independent beams from different RUs by estimating Channel State Information (CSI)*15, which was developed to improve throughput using reflections from buildings. By selecting independent beams from each RU, for example one direct signal and one from a different direction reflected by a building, channel correlation can be reduced, making it possible to increase communication speed. In these experiments, the two beams expected to yield the highest throughput are selected from the four beams with the highest MRSRP by estimating the CSI [8]. The tests assume a street environment where reflections from buildings are common, and were conducted over a roadway between two buildings at the DOCOMO

*15 CSI: Information describing the state of the radio channel.

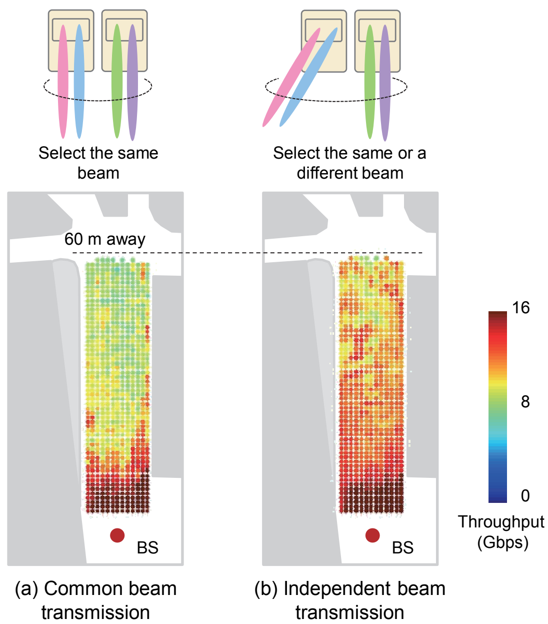

Figure 5 Test results of RU independent beam transmission using CSI estimation

R&D Center. The throughput characteristic when using the same beam for both RUs (i.e. the beam with the highest MRSRP) is shown in Fig. 5 (a), and that when selecting independent beams using CSI estimation is shown in Fig. 5 (b). Comparing the two shows significant improvement in the throughput characteristics for the measured area when selecting independent beams for each RU. Comparing areas in which throughput of 10 Gbps or more was achieved, only about 30% of the area was covered when transmitting the same beam, while over 85% of the area was covered when transmitting independent beams from the two RUs.

This shows that when applying Massive MIMO in high frequency bands, technologies that use multiple transmission points or reflections from buildings are effective in improving communication speeds.

3. Demonstration of 150 km/h High-speed Mobile Data Transmission

The 28 GHz band is promising as a candidate for 5G because ultra-widebands of several hundred MHz can be used, but these bands are difficult to apply to mobile communication because signals are highly directional and propagation losses are large. In the past, NTT DOCOMO collaborated with Samsung Electronics in Korea and successfully tested 28 GHz band MIMO transmission while travelling at 60 km/h [9]. This time, in Japan, to demonstrate the possibility of high-speed wireless data transmission with 5G systems in an even faster mobile environment, we conducted Massive MIMO transmission tests while travelling at 150 km/h, which was the fastest speed ever achieved as of November, 2016. An overview of these tests and the results are given below [10] [11].

3.1 Test Overview

External views of the test equipment are shown in **Figure 6** and the main specifications of the equipment are given in **Table 1**. Both BS and MS have a beam forming function through the use of two sub-arrays. Each sub-array in the BS has 48 antenna elements, implementing Massive MIMO with a total of 96 elements. For each sub-array, the beam with the highest reception power is selected every 10 ms from among the candidates shown in **Figure 7** (8 horizontally × 2 tilt*16 for the BS, 8 horizontally for the MS) to realize beam tracking in a mobile environment. For example, traveling at 150 km/h results in travelling approximately 0.42 m in 10 ms, so at 10 m from the BS, the angular range of motion would be approximately 2.4°. For the BS, which can form a narrower beam than the MS, the beam half-value angle*17 is 10°, so selecting a beam every 10 ms can be expected to track the motion adequately. This equipment supports two-stream MIMO transmission and achieved a maximum transmission rate of 3.77 Gbps using 64QAM*18 with a coding rate*19 of 3/4, and 2.59 Gbps using 64QAM and a coding rate of 1/2.

Transmission tests were conducted at the Fuji Speedway in the town of Oyama, Sunto District, Shizuoka Prefecture. Overhead and horizontal views

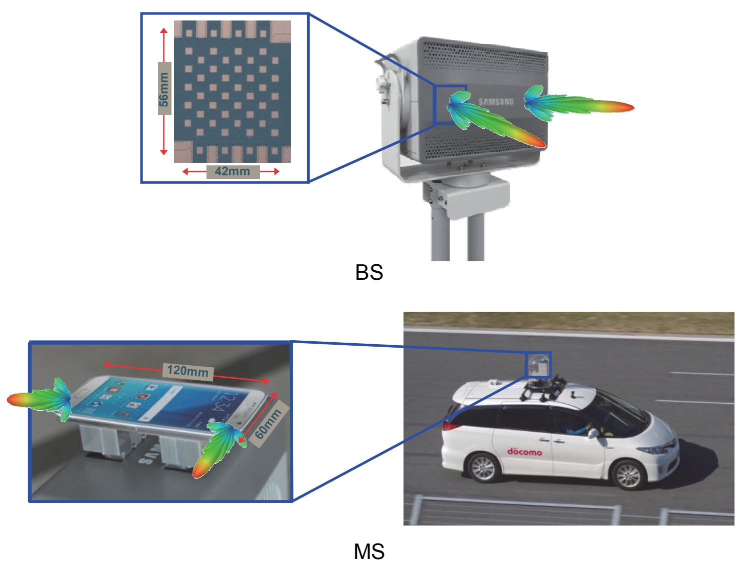

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Figure 6 Equipment external view

*16 Tilt: Inclination of an antenna's main beam direction in the vertical plane.

*17 Half-value angle: The angular range over which the power emitted from an antenna goes from its maximum value to half of that value. Expresses how sharpness of the directivity.

*18 64QAM: A digital modulation method that allows transmission of 6 bits of information simultaneously by assigning one value to each of 64 different combinations of amplitude and phase.

*19 Coding rate: The proportion of data bits to the number of coded bits after channel coding. For example, if the coding rate is 3/4, for every 3 data bits, 4 coded bits are generated by channel coding.

Table 1　Equipment specifications

Main specifications	BS	MS
Central frequency	27.925 GHz	
Bandwidth	800 MHz	
Duplexing	TDD	
Modulation	64QAM/OFDM	
Channel coding (coding rate)	LDPC coding (1/2, 3/4)	
Antenna elements per sub-array	8 × 6 (=48)	4
Number of sub-arrays	2	2
Spatial multiplicity	2	
Array gain	21 dBi	10 dBi
Transmit power per sub-array	37 dBm	26 dBm

Low-Density Parity Check (LDPC) coding: A type of error correction coding. Linear coding using a sparse parity check matrix with low density non-zero components.

OFDM: Orthogonal Frequency Division Multiplexing

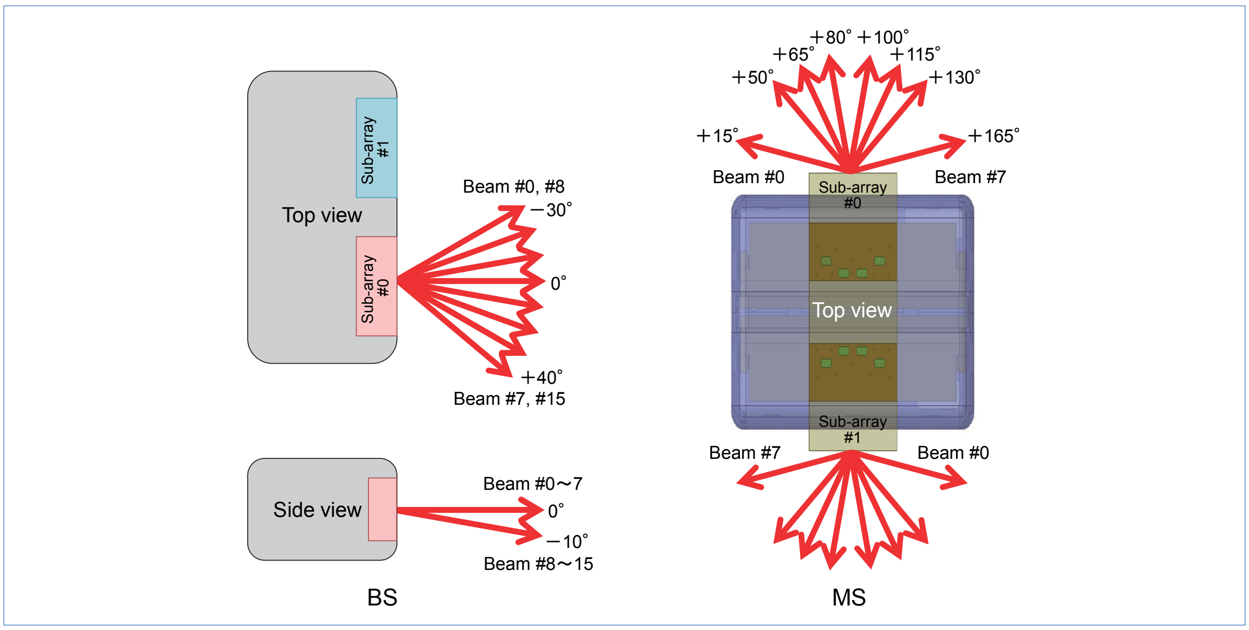

Figure 7　Device beam patterns

of the test environment are shown in **Figure 8**. The home stretch is located between the grand stand and the control center/paddock. The BS was installed in the grand stand, with the tilt angle, θ_{tilt},

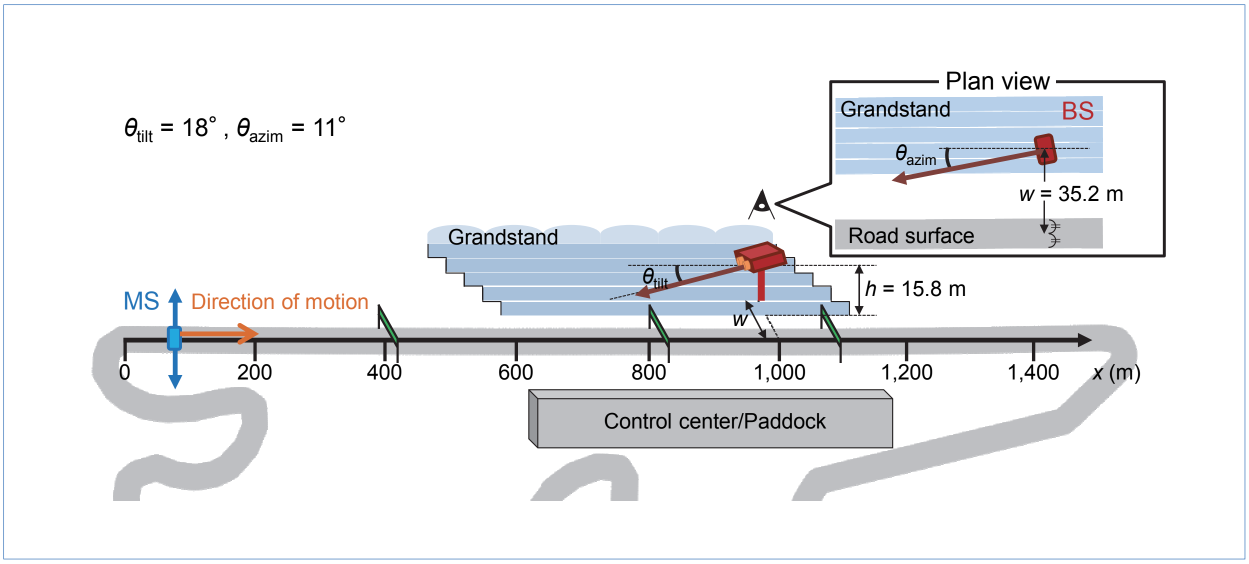

Figure 8 Test environment

of the antenna unit set to 18°, and the azimuth angle, θ_{azim}, set to 11° relative to the direction of the track. The height of the BS antenna was 15.8 m above the track surface. The MS was installed on the roof of the test car with the antennas facing 90° to the direction of movement. The height of the MS antenna was 2.4 m from the track surface. The test vehicle drove along the home stretch from a position approximately 1,000 m from the BS (position $x = 0$ m).

3.2 Test Results

Measured transmission characteristics are shown in **Figure 9** [10]. Fig. 9 (a) shows throughput when using 64QAM with coding rate fixed at 1/2, and Fig. 9 (b) shows the speed of the MS. The horizontal axis in both cases is the position of the MS along the home stretch. At a coding rate of 3/4, degradation of the transmission characteristic at high speeds was large, so a coding rate of 1/2 was used.

The figure shows that even in the range where speed exceeded 150 km/h, around $x = 820$ m, high transmission rates of 2.59 Gbps were achieved. On the other hand, in the range of $x < 500$ m, reception power was low due to attenuation with distance, so the maximum throughput was around 2 Gbps. In this area, there are no particular objects such as buildings to cause reflections, but there should be MIMO transmission, selecting both the direct signal path and the path reflecting from the roadway. In the region of $500 \text{ m} < x < 900$ m, reception power increases as the MS approaches the BS, so even in the range where the MS speed exceeded 150 km/h, the maximum throughput, according to specifications, of 2.59 Gbps was obtained. In this region, the direct path and a path reflecting from buildings (paddock, etc.) could be used effectively, so even with LOS, MIMO transmission was possible. Note that near $x = 700$ m,

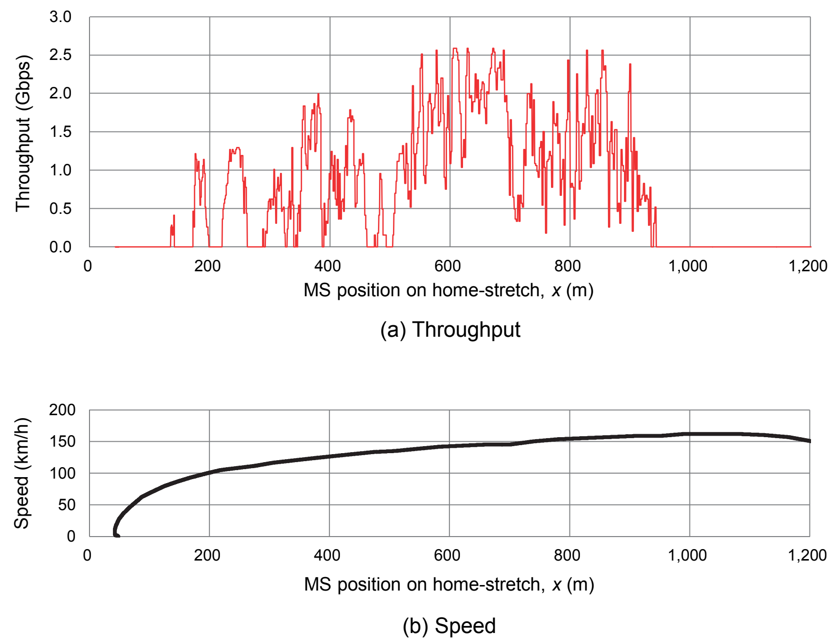

Figure 9　High-speed mobility test results

the effects of gates positioned on the home stretch blocked the direct signal path, causing sudden degradation of throughput. However, the adaptive modulation and coding[*20] and rank adaptive control[*21] functions were able to mitigate the sudden drop in throughput [11]. Also, for $x > 900$ m, the MS was outside of the range covered by the beam of the BS, located at $x = 1{,}000$ m, so the throughput dropped greatly.

4. Demonstration of Further Improvements in Spectral Efficiency

So far, we have introduced results of tests done in high frequency bands over 6 GHz, but there are also 5G candidate bands below 6 GHz, relatively close to bands currently in use. In these bands it is difficult to secure widebands approaching 1 GHz, so to realize the ultra-high-speed and high capacity communications required for 5G, spectral efficiency must be greatly increased. NTT DOCOMO has been testing Massive MIMO transmission technology to improve spectral efficiency using the 4.5 GHz band in the Minato Mirai 21 District of Yokohama City, in collaboration with Huawei Technologies [12] [13]. An overview of these tests and their results is given below.

4.1 Test Overview

The specifications of equipment used in this test are shown in **Table 2**. The 4.5 GHz band was used and system bandwidth was 200 MHz. External

*20 Adaptive modulation and coding: A method of modifying the modulation and coding schemes according to radio propagation path conditions. Modulation and coding schemes are modified to increase reliability when the propagation environment is poor, and to increase throughput when it is good.

*21 Rank adaptive control: A method that changes the number of spatially multiplexed streams adaptively according to the state of the radio propagation path. If the propagation environment has a large number of eigenspaces (rank), which are needed for spatial multiplexing, the number of spatially multiplexed streams is increased to obtain higher throughput.

Table 2 Equipment specifications

Item	Value
Frequency band	4.55 - 4.75 GHz
Subcarrier interval	15 kHz
TTI length (slot length)	0.5 ms
Number of OFDM symbols per TTI	7
CP length	Long CP: 5.2 μs (160 samples) Short CP: 4.17 μs (128 samples)
Modulation encoding format	LTE
System bandwidth	200 MHz
Bandwidth per CC	20 MHz
Number of subcarriers per CC	1,320 (110 RB)
Number of subcarriers in entire system	1,320 × 10
Slot structure ratio (Normal)	DL : S : UL = 5 : 1 : 1
Slot structure ratio (Special)	DL : S : UL = 4 : 2 : 1
Number of antenna elements	BS: 192, MS: 8
Antenna element intervals	BS: 3.72 cm × 5.21 cm, MS: 12.5 cm
Antenna tilt angle	16.4°
Antenna installation height	BS: 108 m, MS: 3.2 m
Maximum transmission power	BS: 46 dBm, MS: 23dBm
Maximum number of transmission streams	3 per MS, 24 per BS

CC: Component Carrier

CP: Cyclic Prefix

TTI: Transmission Time Interval

views of the BS and MS, and the location of BS installation in the test environment are shown in **Figure 10**. The BS antenna equipment used in these tests consisted of 64 antenna units (8 horizontally, 4 vertically, 2 polarizations) and each antenna unit consisted of three antenna elements. Thus, the BS had a Massive MIMO antenna structure with 192 antenna elements. Antenna height was approximately 108 m, and tilt was 16.4° (10.4° mechanical, 6° electrical tilt). The MS antenna structure was an eight-element linear array antenna*22, with antenna elements at approximately 12.5 cm intervals. BS and MS had maximum transmission power of 46 dBm and 23 dBm respectively. The maximum number of transmit streams per MS for downlink MIMO transmission was three, and the maximum number of

*22 Linear array antenna: An antenna with antenna elements arranged at fixed intervals in a straight line.

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Figure 10 External views of BS and MS

simultaneous transmit streams per BS to multiple MS using MU-MIMO was 24.

To generate orthogonal beams without interference between MU-MIMO streams or MSs, Eigen Zero Forcing (EZF)[*23] was used as a precoding[*24] method, which uses Singular Value Decomposition (SVD)[*25] of the propagation channels. Here, channel reciprocity[*26] between uplink and downlink with Time Division Duplex (TDD)[*27] can be used to estimate propagation channels, which is to say that the uplink signal can be used to estimate the downlink propagation channel. To maintain reciprocity between uplink and downlink channels, we introduced RF calibration[*28] of up and down links on the base station.

The test environment is shown in **Figure 11**. The maximum distance from BS to MS was 590 m, and the test area was approximately 100,000 m^2, the largest 5G transmission test environment in Japan. Within the test area, an MS simulating a high-end terminal, using the maximum bandwidth of 200 MHz, was placed at one location (MS11 in the figure), and pairs of MSs, using the upper and lower 100 MHz of the 200 MHz total bandwidth respectively, were placed at each of the other 11 locations. Thus, a total of 23 MS devices were placed in the test

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*23 EZF: A technique used with precoding and beam forming in the transmitter, in which the generalized inverse of the channel matrix is used to generate weighting coefficients such that interference between users goes to zero.

*24 Precoding: With MIMO, a process of multiplying the signal by weightings suited to the radio propagation path before it is transmitted in order to improve reception quality.

*25 SVD: In linear algebra, a matrix decomposition method for matrices with real or complex components.

*26 Reciprocity: The state in a bidirectional transceiver in which each received signal is affected in the same way. For example, using TDD and a carrier with the same Radio Frequency (RF) on both the uplink and a downlink, assuming there is no interference, channel fluctuation in the received signals of both the base station and the mobile station will be the same, resulting in transmission path reciprocity.

area. The test involved LOS measurements, and MS were arranged to ensure at least 50 m vertically and horizontally between MSs using the same frequency.

4.2 Test Results

These tests evaluated the MU-MIMO system throughput characteristics (total throughput for all MSs). The output screen showing the measured result from the test equipment is shown in **Figure 12**. The

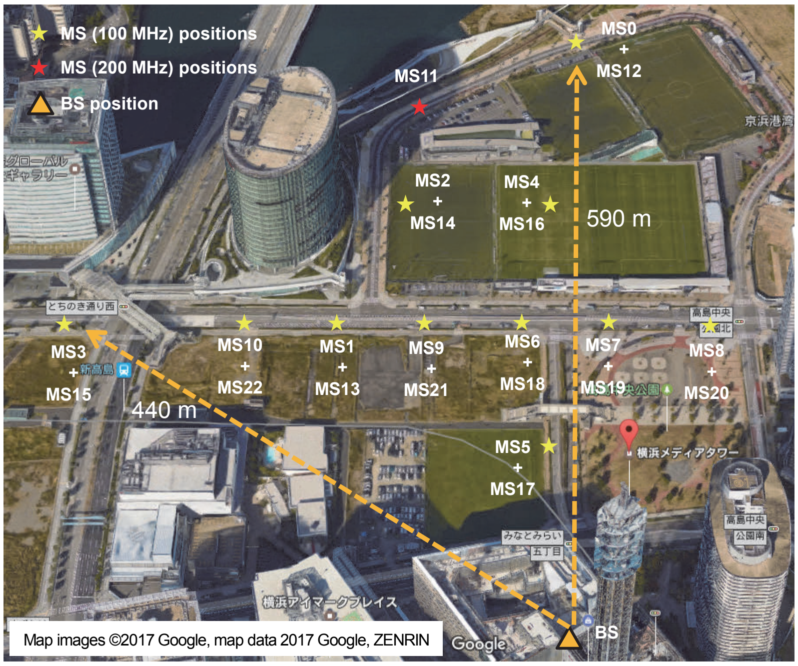

Figure 11　Test environment

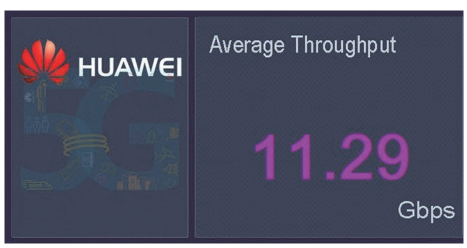

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Figure 12　Test equipment measurement results

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*27　**TDD**: A bidirectional transmit/receive mode, which achieves bidirectional communication by allocating different time slots to uplink and downlink transmissions that use the same frequency.

*28　**Calibration**: Pre-correction of imbalance in characteristics among antennas when arranging multiple antenna elements, etc. to emit signals in a suitable manner.

result shows that the average throughput per second peaked at 11.29 Gbps, verifying that in large-scale MU-MIMO transmission, TDD up/down link channel reciprocity can be used. This is equivalent to 79.82 bps/Hz/cell when converting to spectral efficiency, which is approximately five-times the theoretical spectral efficiency of LTE-Advanced 4 × 4 MIMO in frequency bands below 6 GHz (which is 15 bps/Hz/cell).

The throughput characteristics per MS are shown in **Figure 13**. They show that simultaneous communication with 23 MSs was supported, providing 500 Mbps-class throughput to all MSs without significant variation, and providing throughput of approximately 800 Mbps to the high-end MS (MS11) using 200 MHz bandwidth.

5. Conclusion

This article has introduced the most significant new test results on 5G transmission, which NTT DOCOMO has been conducting in collaboration with major global equipment vendors. We will continue to promote study and testing to establish radio technologies for 5G and its extension (5G+*29) in the future. Starting in May 2017, we plan to develop a new service and content utilizing 5G, called "5G Trial Site," in broad collaboration with industry partners, and to build an environment that will enable ordinary users to experience 5G [14] [15].

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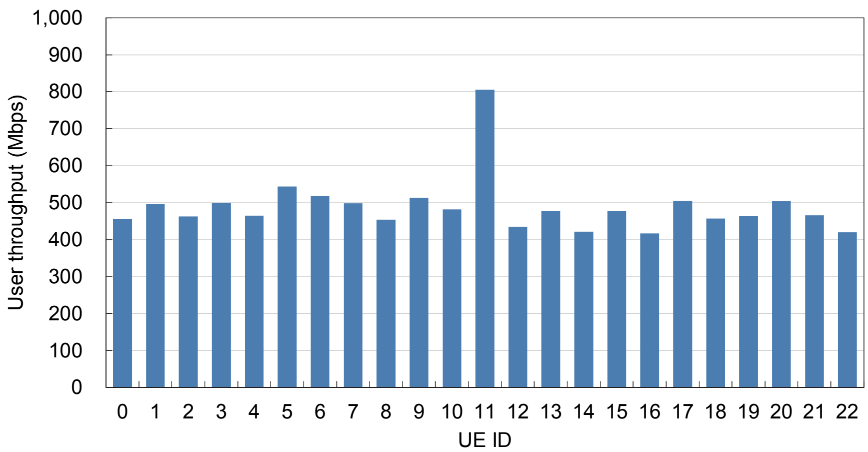

*Achieved a throughput of equal to or more than 400 Mbps per MS while simultaneously communicating with 23 users
=> Maximum throughput for 100 MHz MS is 543.8 Mbps, minimum is 416.3 Mbps.
=> Maximum throughput for 200 MHz MS (MS11) is 804.9 Mbps.

Figure 13 User throughput characteristics and testing results

*29 **5G+**: An abbreviation expressing development beyond 5G.

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