5G | Massive-element Antenna | Beamforming

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5G Multi-antenna Technology

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NTT DOCOMO is researching and developing the fifth-generation mobile communications system (5G) toward the provision of super-high-speed, super-high-capacity wireless communications services. In 5G, the aim is to widen the bandwidth of transmission signals by using frequency bands higher than those of existing frequency bands. However, as radio propagation loss increases in high frequency bands, this loss must be compensated for by adaptively controlling antenna directivity using massive-element antennas as 5G multi-antenna technology. This article describes 5G multi-antenna technology and discusses the feasibility of super high bit rates above 10 Gbps.

1. Introduction

NTT DOCOMO is researching and developing "5G" toward the provision of super-high-speed, super-high-capacity wireless communications services [1] [2]. The idea behind 5G is to increase transmission bit rates by using frequency bands higher than those of existing frequency bands and widening the signal bandwidth. However, as radio propagation loss increases in high frequency bands, the application of massive-element antennas each consisting of more than 100 antenna elements has been studied as 5G multi-antenna technology [1]–[5]. Application of a massive-element antenna makes it possible to compensate for the radio propagation loss by adaptively controlling antenna directivity*1 and increase bit rate by the spatial multiplexing of signals. In this article, we begin by describing the operation and effect of massive-element antennas as 5G multi-antenna technology, which NTT DOCOMO has been promoting worldwide through technical studies and transmission experiments [6]. We then describe technical issues in the application of massive-element antennas in high frequency bands and NTT DOCOMO's efforts in resolving those issues. Next, we present the results of computer simulations using massive-element antennas and discuss the feasibility of super-high-speed communications.

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*1 **Antenna directivity:** The directional characteristics of the radiated or received strength of the antenna.

2. Operation and Effect of Massive-element Antennas

2.1 Introduction of Massive-element Antennas through Phantom Cells

1) C/U Separation by Phantom Cells

The Phantom cell concept shown in **Figure 1** has been proposed as a basic 5G architecture [2]. Here, a conventional macro cell[*2] contains multiple instances of a small cell[*3] (or quasi-macro cell) in an overlay[*4] configuration. In this scheme, the macro cell uses the Ultra High Frequency (UHF) band (0.3–3 GHz) employed by the existing system while overlaid small cells use higher frequency bands, namely, the low Super High Frequency (SHF) band (3–6 GHz), high SHF band (6–30 GHz), and Extremely High Frequency (EHF) band (30–300 GHz). This scheme also establishes a connection link for the Control Plane (C-plane)[*5] that handles control signals via the macro cell and a connection link specifically for the User Plane (U-plane)[*6] that handles user data via overlaid cells, i.e., C/U split connections. While the macro cell maintains the service area using the UHF band, the overlaid cells widen signal bandwidth and achieve super high bit rates using high frequency bands.

2) Introduction of Massive-element Antennas in High frequency band Cells

Achieving super high bit rates greater than 10 Gbps requires bandwidths of several 100 MHz. To this end, we have been studying the use of high frequency bands, but it is known that radio propagation loss increases at higher frequencies. This issue can be resolved by introducing massive-element antennas in high frequency band cells. In such a configuration, high frequency bands become available for use by suppressing the radio propagation loss through the application of massive-element antennas. Macro-cell-assisted operation of massive-element antennas is also possible.

2.2 Beamforming Effect of Massive-element Antenna

1) Beamforming by Massive-element Antenna

When using a flat antenna array with a uniform antenna spacing as a massive-element antenna in the 20 GHz band (**Figure 2**), and when setting the element spacing to half the wavelength (7.5 mm), it becomes possible to mount 256 elements in an area approximately 12 cm square. Generally, for the same area, the number of elements that can be mounted can be significantly increased when using higher frequency bands (shorter wavelengths). A massive-element antenna can be used to generate sharp beams (antenna directivity) by controlling the amplitude and phase of signals transmitted (received) from each element. This process is called "beamforming," which has the effect of compensating for radio propagation loss.

2) Beamforming Effect

The beamforming effect in the 3.5, 10, and 20 GHz bands given a total transmission power of 33 dBm[*7] for all an-

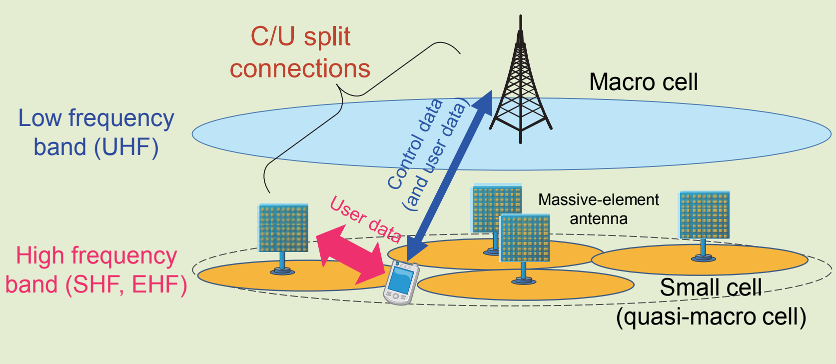

Figure 1 Combination of Phantom cell concept and Massive MIMO

*2 **Macro cell:** A cellular communication area in which one base station can cover a radius of from several hundred meters to several tens of kilometers.

*3 **Small cell:** General term for a cell covering a small area compared with a macro cell and having low transmission power.

*4 **Overlay:** The arranging of cells each covering a relatively small area within a macro cell area.

*5 **C-plane:** Plane that handles control signals. The process of exchanging control signals to establish communications, etc.

*6 **U-plane:** Plane that handles user data. The process of transmitting and receiving user data.

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

tenna elements is shown in **Figure 3**. Specifically, this figure shows beam-arrival distances for each of these frequency bands and for massive-element-antenna sizes of 20, 40, and 80 cm square. On comparing these results for the same number of elements, it can be seen that arrival distance becomes shorter as frequency becomes higher, but that it does not significantly decrease for the same antenna size even at 20 GHz. However, while the arrival distance jumps to 490 m for a 100 (10 × 10) element antenna in the 10 GHz band, more than 400 (20 × 20) elements would be needed to achieve about the same arrival distance for the same antenna size in the case of a 20 GHz antenna. In other words, the number of elements increases and costs rise as frequency increases. As a result, finding measures for reducing such costs in massive-element antennas has become an issue in 5G multi-antenna technology.

2.3 User Multiplexing and Spatial Multiplexing in Massive-element Antennas

1) Massive MIMO Effect by Massive-element Antenna

Multiple-Input Multiple-Output (MIMO)*8 transmission using a massive-element antenna is called "Massive MIMO" [7] [8]. As shown in **Figure 4**, appropriately controlling a massive-element antenna in Massive MIMO can expand the communication area through propagation loss compensation and can also increase the system capacity of the high frequency band cell through user multiplexing that simultaneously connects multiple users [9]. Massive MIMO can also increase the communication bit rate for an individual user through spatial multiplexing of more than one data stream*9.

However, to achieve these capabilities, a precoding*10 process is needed in the transmitter to prevent interference

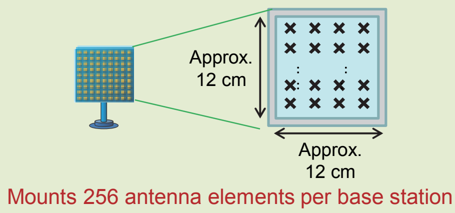

Figure 2 Effect of introducing Massive MIMO

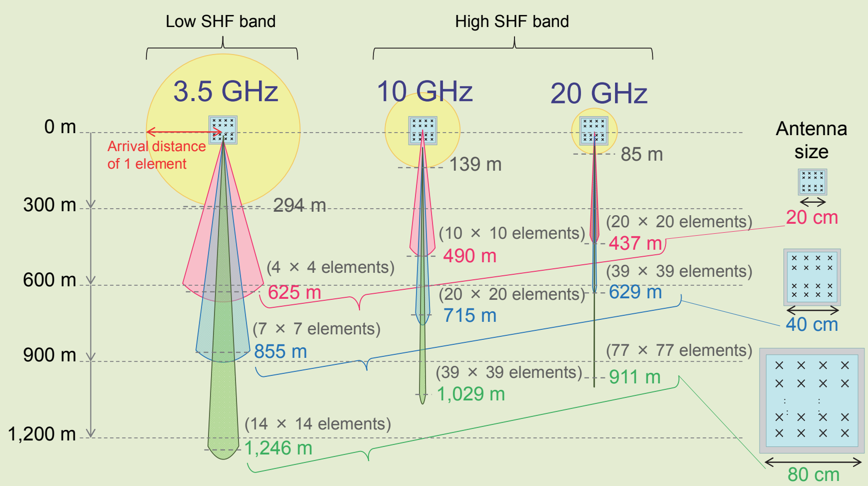

Figure 3 Beamforming effect

*8 **MIMO:** A signal transmission technology that improves communications quality and spectral efficiency by using multiple transmitter and receiver antennas to transmit signals at the same time and same frequency.

*9 **Stream:** A data sequence transmitted over a propagation channel using MIMO transmission.

*10 **Precoding:** A process for improving the quality of signal reception by multiplying signals before transmission with weights according to the current radio propagation channel.

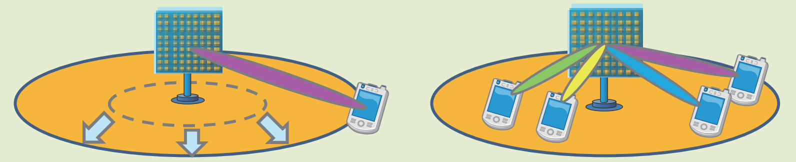

Figure 4 Effects of introducing Massive MIMO

between users and between streams. Furthermore, to achieve high-accuracy precoding, Channel State Information (CSI)*11 that conveys the state of the radio propagation channel is also needed in the transmitter, so CSI as estimated on the terminal side has to be fed back to the base station. A method that combines this CSI with CSI obtained by Time Division Duplex (TDD)*12-based channel reciprocity*13 can also be considered [7].

2) Optimal Operation of Massive MIMO

The antenna elements in Massive MIMO are used for both beamforming and user/spatial multiplexing and are therefore allocated as needed. However, for a fixed number of antenna elements, this means that the beamforming effect will suffer as the user/spatial multiplexing number increases. There is therefore a need to operate Massive MIMO in an appropriate manner in unison with CSI. Additionally, decreasing the user/spatial multiplexing number (increasing the number of antenna elements allocated to beamforming) can enhance the beamforming effect while also achieving a quasi-macro cell as shown in Fig. 1. Covering a wide area in this way can facilitate the construction of an efficient service area even in a suburban environment.

3. Technical Issues in High Frequency Band Massive MIMO and Efforts toward Deployment

3.1 Technical Issues in High-frequency-band Massive MIMO

As described above, the use of high frequency bands is essential to significantly improve system capacity and bit rate in 5G. However, there are not a few technical issues that need to be resolved to introduce Massive MIMO in high frequency bands, as described below.

- The spatial characteristics of the radio propagation path in high frequency bands assuming the use of a massive-element antenna have not yet been sufficiently explained [10]. Furthermore, in addition to propagation loss, shadowing loss due to structures and obstacles is large in high frequency bands compared with low frequency bands, so the shadowing effects caused by the body of a user holding a mobile phone must also be taken into account [10].
- To implement Massive MIMO in equipment at low cost, it will be necessary to achieve the high-frequency-band Radio Frequency (RF)*14 circuit and baseband*15 processing circuit on one chip to the extent possible using, for example, a silicon Complementary Metal Oxide Semiconductor (CMOS)*16 Integrated Circuit (IC). Recently, however, it has become possible to implement RF circuits for even the EHF band on silicon CMOS, so conditions for using high frequency bands in terms of implementing circuits are coming to be established.
- Although it is technically difficult to achieve high gain in a high frequency band power amplifier, Massive MIMO makes it possible to incorporate a power amplifier for each antenna and thereby greatly reduce the trans-

*11 **CSI:** Parameters indicating attenuation, phase rotation, and delay of a transmission signal after passing through a radio propagation channel between transmitter and receiver.

*12 **TDD:** A bidirectional transmission/reception method. It enables bidirectional communications by using the same frequency band in the uplink and downlink while allocating signals to different transmission times.

*13 **Channel reciprocity:** In bidirectional communications, the effects of same channel fluctuation on the receive signal in the uplink and downlink.

*14 **RF:** The carrier frequency of the radio signal.

*15 **Baseband:** Signal band before modulation or after demodulation.

*16 **CMOS:** A type of semiconductor circuit characterized by low power consumption that conducts very little current in a steady state.

mission power required per power amplifier. Achieving high gain here is consequently not a problem. On the other hand, the frequency synthesizer*17 exhibits a relatively high level of phase noise*18, so in 5G, that effect must be considered when setting radio parameters such as the subcarrier*19 spacing.

- Given the need to prepare many RF circuits in a number corresponding to the number of antenna elements, studies are also being performed on integrating filters and antennas [11]. Another problem here is that downsizing devices will require high-precision processing. Massive MIMO will require technology for fabricating and wiring circuits at super high densities, but the effects of mutual coupling between antennas and devices in such a super-high-density configuration can be large. To reduce such effects, there will be a need for calibration*20 so that the characteristics between antenna elements match.
- Although an array antenna*21 consisting of several tens of elements has already been achieved in the form of an adaptive array antenna*22 and Active Antenna System (AAS)*23, it will be necessary in 5G to greatly reduce costs compared with that of past systems in order to deploy many Massive MIMO base stations for use in high frequency bands.

3.2 Toward Massive MIMO in Low SHF Band

1) Distributed Massive MIMO

Massive MIMO presumes the use of massive-element antennas. In the low SHF band, concentrating more than 100 antenna elements at a single location results in a fairly large antenna as shown in Fig. 3. One method for avoiding such a large antenna is distributed Massive MIMO that arranges compact low-SHF-band many-element antennas at multiple locations so that antenna size becomes comparable to that of high-SHF-band massive-element antennas.

2) Combining Concentrated and Distributed Deployments According to Usage Environment

In the case of low-SHF-band Massive MIMO in a localized arrangement, a massive-element antenna will be installed on the roof of a building, for example, and sharp beams will be formed toward individual users from a relatively high location. In contrast, distributed Massive MIMO emits radio signals from multiple compact many-element antennas thereby mitigating the shadowing effects in an environment with many obstacles. Thus, in terms of usage environments, we can consider the use of localized Massive MIMO in the suburbs or comparatively large public squares or plazas and the use of distributed Massive MIMO in shopping malls or business districts. In actuality, however, a service area must be constructed with a flexible combination of concentrated and distributed deployments and a mechanism for doing so must be developed.

Fundamental transmission experiments have been held using a massive-element antenna consisting of 128 elements (**Figure 5**) as technical verification of concentrated Massive MIMO [12]. Furthermore, as technical verification of distributed Massive MIMO, fundamental transmission experiments have been held on installing compact many-element an-

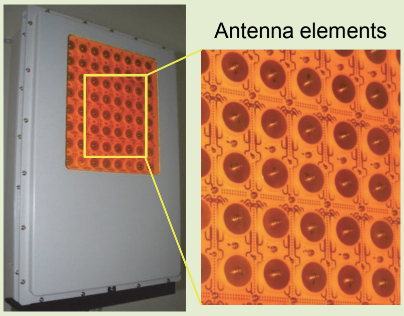

Figure 5　Example of a localized Massive MIMO antenna (128 elements)

*17 **Synthesizer:** Device for frequency and waveform modulation.

*18 **Phase noise:** Phase fluctuation that occurs due to frequency components other than those of the carrier frequency in a local oscillator signal.

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

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

*21 **Array antenna:** An antenna consisting of a matrix of multiple elements.

*22 **Adaptive array antenna:** An antenna array that can orient radio waves in the direction of their arrival at the receiver by controlling the phase of individual antenna elements.

tennas in high-density distributed deployments with coordinated multipoint transmission. These antennas are capable of flexible antenna configurations as shown in **Figure 6** [13].

3.3 Toward Massive MIMO in High SHF Band and EHF Band

Compared with the low SHF band, Massive MIMO in the high SHF band and EHF band features wideband signals and a greater number of antenna elements. There is therefore a need for cost-saving measures in the configuration of radio equipment that achieves Massive MIMO.

1) Full Digital Massive MIMO

The configuration of a typical Massive MIMO transmitter employing Orthogonal Frequency Division Multiplexing (OFDM)*24 is shown in **Figure 7**. This transmitter requires Digital to Analog Converters (DACs) and upconverters in the same number as transmitter antenna elements. Similarly, it also requires the baseband processing circuits that perform an Inverse Fast Fourier Transform (IFFT)*25 and attach a Cyclic Prefix (CP)*26 to signals as signal processing in exactly the same number as transmitter antenna elements. In this configuration, digital precoding using CSI becomes possible in the frequency domain*27 in a high-performance process called "full digital Massive MIMO." However, implementing full digital Massive MIMO in the high SHF band and EHF band is not without its problems. For example, it requires DACs and Analog to Digital Converters (ADCs) that are expensive and that consume relatively more power as a result of wider signal bandwidths, and it also requires massive-element RF circuits for which high-performance operation is difficult.

2) Hybrid Beamforming

Beamforming means orienting a beam

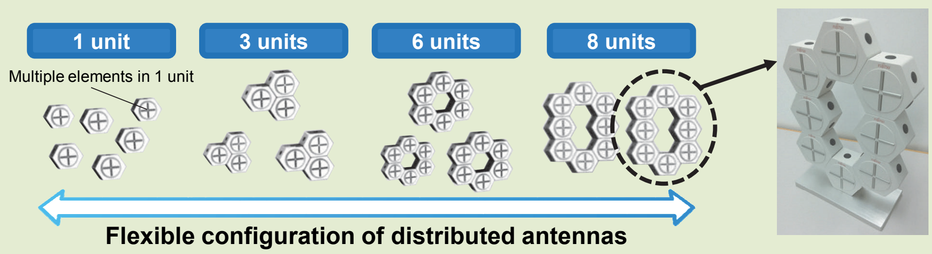

Figure 6 Distributed-type arrangements of compact many-element antennas

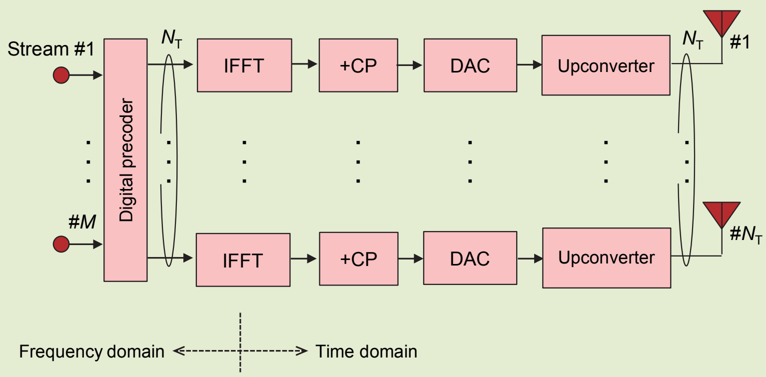

Figure 7 Typical Massive MIMO transmitter using OFDM (full digital Massive MIMO)

*23 **AAS:** A system that integrates antenna elements and RF circuits that have traditionally been separated thereby providing a more efficient system.

*24 **OFDM:** A parallel-transmission technique that divides data among multiple mutually orthogonal carriers.

*25 **IFFT:** A calculation technique for achieving high-speed processing of an inverse discrete Fourier transform that converts a sampled frequency domain (see *27) signal into a sampled time domain (see *28) signal. The inverse transform of a Fast Fourier transform (FFT) that corresponds to high-speed processing of a discrete Fourier transform.

*26 **CP:** A guard time inserted between symbols in OFDM signals, etc. to minimize interference between prior and subsequent symbols caused by multipath effects.

in the direction of radio-signal radiation (arrival), so common beamforming across the entire band can be considered after allowing for a certain amount of performance degradation. In this case, commonalizing the beamforming process across all subcarriers would enable beamforming to be moved to a position after IFFT processing and only beamforming in digital precoding to be moved to the time domain*28.

To achieve low-cost Massive MIMO transmitters, studies have been performed on a hybrid beamforming configuration that combines digital precoding and analog beamforming as shown in **Figures 8** and **9** [14] [15]. This configuration moves only the beamforming process in the full digital configuration to the time domain and replaces it with analog beamforming achieved by vari-

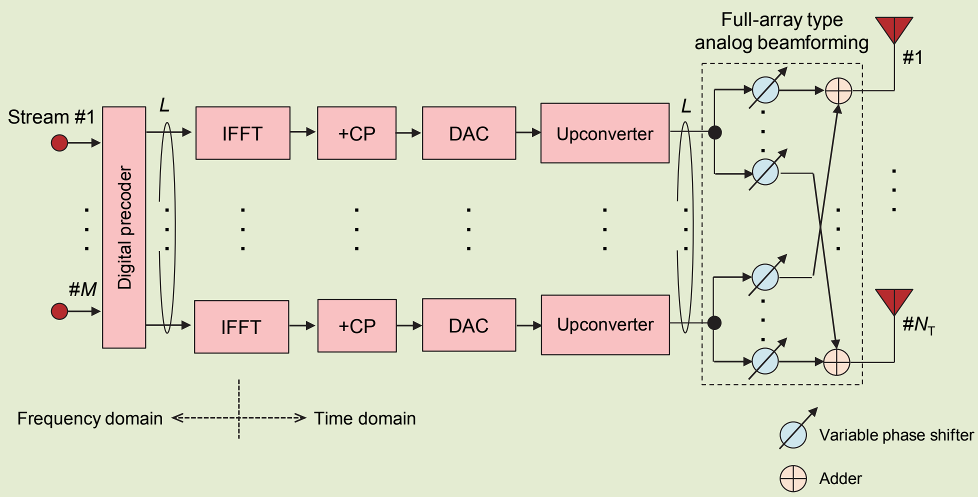

Figure 8　Full-array type hybrid beamforming

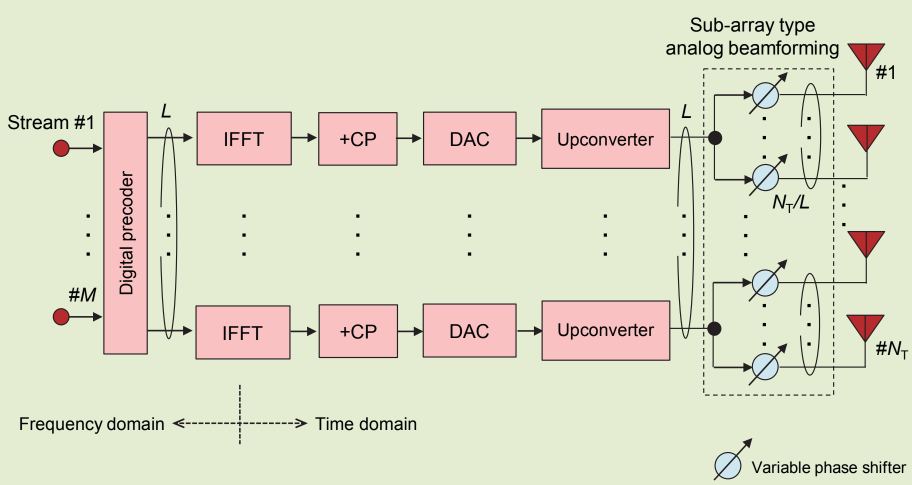

Figure 9　Sub-array type hybrid beamforming

*27 **Frequency domain:** In signal analysis, this domain is used to show the frequency makeup of a signal's components. A frequency-domain signal can be converted to a time-domain signal by an inverse Fourier transform.

*28 **Time domain:** In signal analysis, this domain is used to show the temporal makeup of a signal's components. A time-domain signal can be converted to a frequency-domain signal by a Fourier transform.

able phase shifters*29 in the RF circuits. In such a hybrid beamforming configuration, only beam-number L worth of DACs and upconverters need be prepared and the number of IFFT processes can be reduced.

Two types of hybrid beamforming can be considered here: a full-array type using all antenna elements as shown in Fig. 8 and a sub-array type using only some of the antenna elements as shown in Fig. 9. The full-array type requires adders*30 and many more variable phase shifters, but its performance is much higher.

3) Configuration with Analog Beamforming Only

As an even simpler configuration, there is also a method that uses only analog beamforming. In this case, there is no need for digital precoding, so the beamforming circuit can be simplified. Despite this advantage, if narrow beams generated by such analog beamforming cannot be made mutually orthogonal, inter-beam interference cannot be reduced. It would then be necessary to reduce the number of beams and increase the number of antenna elements for generating each beam. The potential of analog beamforming in the high SHF band and EHF band has been demonstrated by transmission experiments [16] [17].

4) FBCP Algorithm for Hybrid Beamforming

To achieve super high bit rates greater than 10 Gbps at bandwidths of several 100 MHz, the spatial multiplexing of streams using multiple beams will be required. Under this condition, a hybrid beamforming configuration can be considered from a cost-reduction perspective, and Fixed analog Beamforming and CSI-based Precoding (FBCP) as a specific algorithm for implementing such hybrid beamforming has been proposed [18]. This algorithm is summarized below.

(1) Spatially scan beams by angle-fixed analog beamforming and select L number of beam candidates in order of beams with highest received power at the terminal

(2) Transmit a reference signal using the selected beams generated by analog beamforming and estimate CSI at the terminal

(3) Feed back the estimated CSI to the base station, execute digital precoding using that CSI, and perform communications

As described above, reference-signal insertion loss can be minimized by transmitting a reference signal by the selected beams instead of transmitting it by all spatially scanned beam candidates.

4. Feasibility of Super High Bit Rates by Massive MIMO in High SHF Band

We set out to quantitatively clarify the feasibility of super high bit rates by Massive MIMO in the high SHF band through computer simulations. In these simulations, we compared the characteristics of full digital Massive MIMO with those of two types of hybrid beamforming using a 256-element antenna in the 20 GHz band. We applied the FBCP algorithm to hybrid beamforming.

Simulation conditions are listed in **Table 1**. Here, we made the number of receiver antenna elements the same for all users and fixed the total number of transmission streams to 16, which were divided up evenly among users in a Multi-User (MU) environment. As shown in **Figure 10**, we positioned the user in the Single User (SU) environment directly in front of the base station, and in the MU environment (no. of users N_U=4), we positioned the users in front of the base station at 20° intervals. Furthermore, for the modulation schemes and coding rates*31 shown in Table 1, we applied combinations of them using Adaptive Modulation and Coding (AMC)*32. In particular, the combination of 256 Quadrature Amplitude Modulation (256QAM)*33 and coding rate R=3/4 enabled a maximum transmission rate of 31.4 Gbps by 16-stream MIMO spatial multiplexing.

4.1 Comparison of Full Digital and Two Types of Hybrid Beamforming

The throughput characteristics of L=N_T=256 full digital Massive MIMO and hybrid beamforming using two types

*29 **Variable phase shifter:** A device for changing the phase of a radio signal to another phase.

*30 **Adder:** A device for adding multiple electrical signals and outputting the result.

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

*32 **AMC:** A method for making transmission more efficient by adaptively changing the combination of modulation scheme and coding rate according to the propagation environment.

*33 **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.

of analog beamforming configurations are shown in **Figure 11**. For hybrid beamforming, we set the number of selected beams to L=32 for both N_U=1 and N_U=4 number of users and presented total throughput for all users in the case of N_U=4.

These simulation results show that full digital Massive MIMO and the two types of hybrid beamforming can achieve a throughput greater than 20 Gbps for average Signal to Noise Ratio (SNR)*34 above 16 dB. In addition, total throughput for all users can reach 20 Gbps for an average SNR lower than that of N_U=1. The reason for this is that interference between users in a MU environment can be appropriately reduced so that high-intensity radio signals arriving at multiple users can be used. Furthermore, the full-array type of analog beamforming achieves characteristics superior to those of the sub-array type, which is particularly noticeable for N_U=4. The reason for this can be given as follows. The number of antenna elements used for forming one beam in the full-array type is more than that in the sub-array type resulting in a narrow beam. Thus, in a MU environment, the effects of inter-user interference are small and an inter-user interference reduction effect can be obtained even for a relatively small number of beams.

Moreover, for N_U=1, the characteristics of full digital and full-array type of hybrid beamforming are nearly equivalent, which means that hybrid beamforming can achieve throughput close to that of full digital while keeping transmitter cost down.

Table 1 Simulation conditions

Carrier frequency	20 GHz
Bandwidth	400 MHz
No. of active subcarriers	Pilot: 32; data: 2,000
No. of antenna elements	N_T = 256, N_R = 16
No. of users	N_U = 1, 4
Total no. of streams	M = 16
Total no. of beams	L = 16, 32, 64, 128
Modulation schemes	QPSK*1, 16QAM, 64QAM, 256QAM (w/AMC)
Channel coding	Turbo code*2 Coding rate R = 1/2, 2/3, 3/4 (w/AMC)
Fading*3	16 path Nakagami-Rice fading*4 (K = 10 dB)

*1 QPSK (Quadrature Phase Shift Keying): A digital modulation scheme that uses a combination of four signals with different phases to enable the simultaneous transmission of two bits of data.
*2 Turbo code: A type of error correction code that performs decoding repeatedly using reliability information of decoding results thereby achieving robust error correction.
*3 Fading: Fluctuation in the received level of a radio signal due to terminal movement or multipath effects.
*4 Nakagami-Rice fading: Model of a multipath environment that includes radio signals that arrive directly (with no reflection) from the base station (signal strength is high).

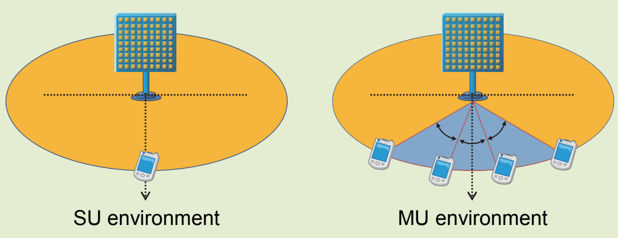

Figure 10 User arrangement

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

4.2 Effect of *L* Number of Beams in Hybrid Beamforming

As described above, throughput in the case of hybrid beamforming depends on number of beams *L*. Specifically, characteristics improve as *L* becomes larger, but on the other hand, making *L* smaller is advantageous for lowering costs, so there is a need here to optimize the number of beams used. Total throughput for all users versus number of beams *L* is shown in **Figure 12**. In this simulation, we set number of users to N_U=1 and 4 and average SNR to a constant value of 15 dB. We also set the characteristics of full digital to a fixed value irrespective of *L* since it performs no analog beamforming. Note that the value *L*=128 is not feasible in terms of cost reduction, but it is included in this evaluation to show how hybrid beamforming approaches the characteristics of full digital.

As shown by these results, hybrid-beamforming characteristics approach those of full digital as *L* increases. In particular, as *L* is divided up for beamforming and user multiplexing in a MU environment (N_U=4), characteristics improve dramatically at *L*=32 compared with *L*=16, which indicates that inter-user interference can be appropriately reduced at around *L*=32 in this environment. In addition, at *L*=128 for N_U=1, full-array type of hybrid beamforming actually exhibits characteristics higher than those of full digital. However, in this evaluation, no control of received quality according to the environment is performed; full digital can be expected to have higher throughput if such control were included.

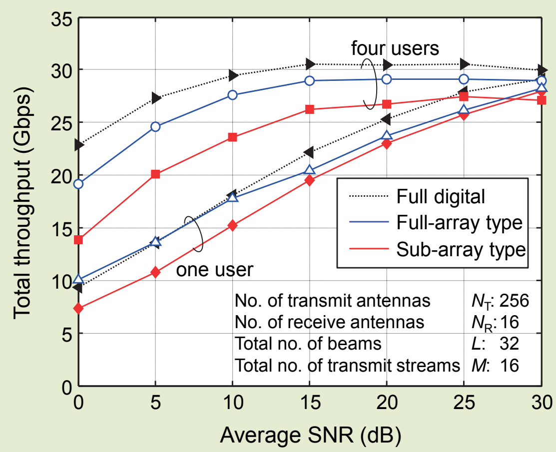

Figure 11 Total throughput versus average SNR

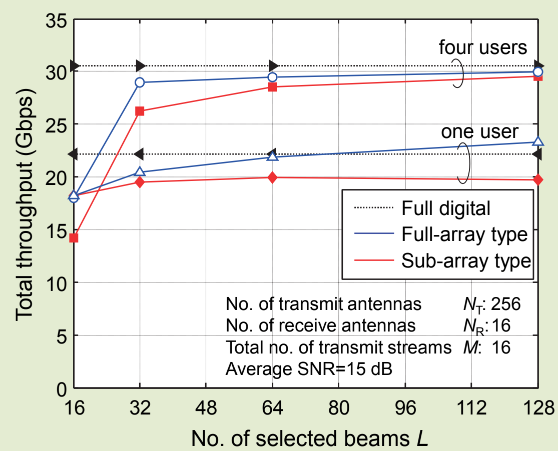

Figure 12 Total throughput versus no. of selected beams by analog beamforming

The simulation results presented above demonstrate that super high bit rates in the 20 GHz band are feasible when using a massive-element antenna and that hybrid beamforming with appropriately set parameters can achieve characteristics close to full digital.

5. Conclusion

In this article, we first described the operation and effect of massive-element antennas as 5G multi-antenna technology, a field in which NTT DOCOMO has taken a worldwide leading position. We then described technical issues surrounding massive-element antennas in high frequency bands and NTT DOCOMO's efforts in implementing practical antennas of this type. Finally, we presented the results of computer simulations in evaluating super high bit rates using a massive-element antenna in a high frequency band and discussed the feasibility of achieving super-high-speed communications in this way. Going forward, we plan to evaluate the possibility of super-high-speed communications by conducting outdoor transmission experiments using massive-element antennas.

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