Super High Bit Rate Mobile Communication | MIMO-OFDM | Outdoor Transmission Experiment

Collaboration Projects

10 Gbps Outdoor Transmission Experiment for Super High Bit Rate Mobile Communications

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To further increase transmission rate for mobile communications, we tested outdoor transmission using microwave 11 GHz band 8×16 MIMO-OFDM, and successfully achieved the world's first packet transmission over 10 Gbps in a mobile communication environment. This should enable super high bit rate mobile communications in mobile communication systems beyond IMT-Advanced. This research was conducted jointly with Suzuki & Fukawa Laboratory (Professor Hiroshi Suzuki, Associate Professor Kazuhiko Fukawa), Graduate School of Science and Engineering, Tokyo Institute of Technology as part of "The research and development project for expansion of radio spectrum resources" of The Ministry of Internal Affairs and Communications.

1. Introduction

The recent smartphone boom has caused a dramatic increase in mobile communication traffic. To process the enormous load, higher transmission bit rates will be required in future systems. While the 4th generation mobile communication system LTE-Advanced*1 aims for a maximum of 1Gbps, discussions have also been held on post LTE-Advanced at a workshop at the 3rd Generation Partnership Project (3GPP) in June 2012 to consider 10 Gbps transmission using higher frequency bands [1].

In December 2006, NTT DOCOMO successfully transmitted packets at 5 Gbps in the 4 GHz band, as part of a mobile transmission experiment [2]. This outdoor transmission experiment was performed using 11 GHz band 8×16 Multiple-Input Multiple-Output (MIMO)*2 - Orthogonal Frequency Division Multiplexing (OFDM)*3 experimental system developed by Tokyo Institute of Technology, and was the first time in the world that transmission bit rate greater than 10 Gbps was achieved in a mobile communications environment. This technology promises super high bit rate wireless transmission in future mo-

*1 **LTE-Advanced**: The enhanced LTE radio interface that has been standardized as 3GPP Release 10.

*2 **MIMO**: Technology to simultaneously transmit different signals on the same frequency from multiple antennas. It is possible to improve transmission rate by increasing the number of spatial multiplexed signals according to the number of transmitter antennas, although this requires high-performance signal detection in the receiver.

bile communication systems, and will enable low-cost services to provide users with large-volume content. This article describes the transmission system, details of the experiment, and results obtained.

2. 8 × 16 MIMO-OFDM Transmission System

2.1 System Specifications

Table 1 describes the specifications for the 8×16 MIMO-OFDM transmission system. This is an MIMO-OFDM transmission scheme with a maximum transmission power of 25 dBm per antenna. The carrier frequency was 11 GHz, with a 400 MHz occupied bandwidth. With a sampling frequency of 800 MHz, the system uses Fast Fourier Transform (FFT)*4 with 4,096 points, and subcarrier*5 spacing of 195 kHz. To support multipath delay*6 up to 1μs, we set the Guard Interval (GI)*7 to 1μs, which made the OFDM symbol*8 duration 6.1 μs. The number of OFDM symbols in a frame consisted of three symbols for the preamble*9 and nine symbols for data, which were tailored to the frame structure of the MIMO channel sounder*10 [5] sharing the experimental system. The number of pilot subcarriers*11 was 32, while the number of data subcarriers*12 was 2,000. We did not use the two subcarriers close to Direct Current (DC)*13 and the 14 subcarriers at the edges of the band. We used 64 Quadrature Amplitude Modulation (64QAM)*14 for the modulation scheme, and used turbo code*15 as the channel code. We set the code rate*16 R to 3/4 to give a maximum transmission rate of 11.8 Gbps. However, for the frame length, the number of symbols was limited due to system sharing with the MIMO channel sounder. Due to this limitation, we ignored preamble insertion loss to derive maximum transmission rate, because of a higher proportion of preamble for data in the initial frame design.

Table 1 Specifications of transmission system

Transmission scheme	MIMO-OFDM
Transmission power	25 dBm
Carrier frequency	11 GHz
Occupied bandwidth	400 MHz
Sampling frequency	800 MHz
No. of FFT points	4,096
Subcarrier spacing	195 kHz
OFDM symbol length	6.1 μs (GI: 1.0 μs)
No. of symbols in frame	Preamble: 3, data: 9
Effective no. of subcarriers	Pilot: 32, data: 2,000
Modulation scheme	64QAM
Channel code	Turbo code (code rate R = 3/4)
Maximum transmission rate	11.8 Gbps

2.2 System Configuration and Signal Processing

The 8×16 MIMO-OFDM transmission system consists of one transmitter and two receivers. The units are capable of modulation or demodulation processing with eight antennas.

1) Transmitter

The transmitter can be seen in **Photo 1**. It consists of BaseBand (BB)*17 circuit, Radio Frequency (RF)*18 circuit, 11 GHz band local oscillator*19, and a 10 MHz reference oscillator*20. The BB circuit consists of a CPU board for executing off-line transmission processing (post processing), Field Programmable Gate Array (FPGA)*21 board with memory, and an 800 MHz Digital-to-Analog Converter (DAC). The turbo coded MIMO-OFDM signals for each stream generated in the CPU board are written to memory in the FPGA board, and repeatedly output from the DAC as BB signals.

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*3 **OFDM**: A high-efficiency multi-carrier transmission method that uses orthogonal narrowband subcarriers. This method has been adopted for LTE because of its high tolerance with multipaths.

*4 **FFT**: A fast Fourier transform. A fast algorithm for converting discrete time-domain data into discrete frequency-domain data. The numbers of discrete data that can be processed in a batch are called points.

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

*6 **Multipath delay**: Reception of transmitted waves in the form of delay waves caused by the arrival of waves along different paths owing to reflection, scattering, or diffraction caused by buildings or topography.

*7 **GI**: A period of signaling that contains part of the last half of each OFDM symbol inserted at the beginning of symbols to control interference occurring between symbols due to multipath delay. This is called a Cyclic Prefix (CP).

*8 **OFDM symbol**: A unit of transmitted data, consisting of multiple subcarriers with OFDM. A GI is inserted at the beginning of each symbol.

*9 **Preamble**: A signal with a fixed pattern positioned at the beginning of packets. Receivers use these to detect packets, control gain, and synchronize frames and frequencies etc as preparation to receive the data portion.

*10 **MIMO channel sounder**: A system that measures radio propagation channels in MIMO.

*11 **Number of pilot subcarriers**: The number of subcarriers used to transmit pilot signals.

The RF circuit performs quadrature modulation*22 in the 11 GHz band on the BB signal output after it has passed through a Low-Pass Filter (LPF)*23 to limit the bandwidth. Because we used a high-precision 11 GHz band local oscillator in the transmitter, the effects of phase noise*24 could be ignored. We also used a cesium oscillator*25 as the 10 MHz reference oscillator.

2) Receiver

As seen in **Photo 2**, the receiver is similar to the transmitter, and consists of an 800 MHz Analog-to-Digital Converter (ADC) on the BB circuit. We achieved demodulation processing with 16 antennas by using two receiver units in the experiment. Identical local oscillator signals and reference oscillator signals were distributed to the two units. To synchronize timing, we connected the transmitter and receiver by coaxial cable and adjusted timing to be the same based on clock signals. We then disconnected the coaxial cable before performing the transmission experiment. Therefore, the accuracy of synchronization was dependent on the stability of the individual cesium oscillators. No adverse effects occurred.

RF signals input to the RF circuit from the receiver antennas are converted to BB signals, and after bandwidth is restricted by the LPF, the signals enter the ADC. The received signals are sampled at 800 MHz by ADC, and stored in memory on the FPGA board. When the process is complete, the CPU board obtains the received signals from the FPGA board and stores them on an external HDD.

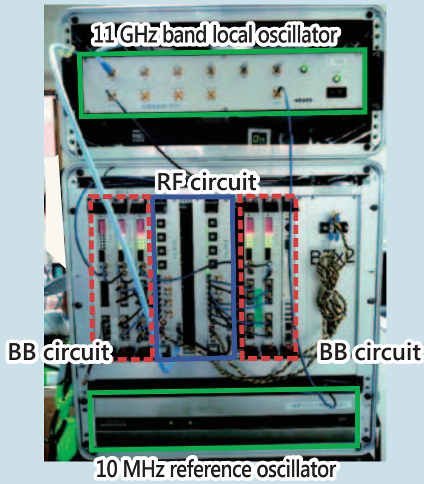

Photo 1 Transmitter

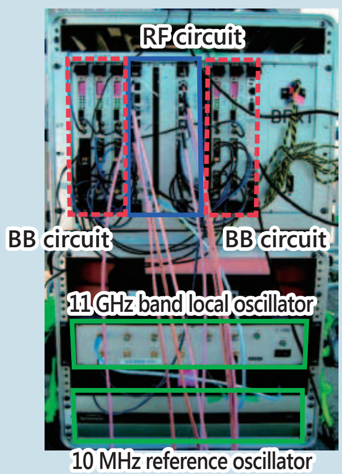

Photo 2 Part of the receiver

*12 **Number of data subcarriers**: The number of subcarriers used to transmit data signals.

*13 **DC**: The direct current component (frequency of 0 Hz).

*14 **64QAM**:A type of modulation scheme. 64QAM modulates 6 data bits through 64 different amplitude and phase signal points.

*15 **Turbo code**: Turbo code is a type of forward error correction code using 2 connected encoders for channel coding. For decoding, there are two decoders used for each encoder. Decoding is preformed repeatedly, and exchanges are made with coded bit reliability information obtained from the respective decoder - called Turbo decoding, this enables robust error correction capability.

*16 **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.

*17 **BB**: The signal band before modulation or after demodulation.

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

*19 **Local oscillator**: An oscillator that creates a carrier signal, for the purpose of modulating a BB signal to an RF signal, or to demodulate an RF signal to a BB signal.

*20 **Reference oscillator**: An oscillator that produces a high-precision standard frequency for generating sampling frequencies or carrier frequencies etc.

*21 **FPGA**: A large-scale integrated reconfigurable circuit array of hard-wired cells that can be logically and freely designed.

3) Turbo Detection

After the received signals are converted to the frequency-domain signals by FFT, the signals are detected by turbo detection. Turbo detection is one method of signal detection for coded MIMO transmission. We used turbo code as the channel code in this transmission system. Reception performance is improved by iterative processing using turbo decoding output for signal detection [6]. Initial processing of turbo detection operates as conventional linear detection*26. In contrast, in the iterative processing, received signal replicas*27 for all streams are generated from the coded bit reliability information obtained from turbo decoding. Next, received signal replicas of other streams that could cause interference in the desired stream are subtracted from the received signal. The outputs are then combined via a linear filter, and the coded bit reliability information is calculated. Finally, the coded bit reliability information is re-input into the turbo decoder. In this way, turbo detection enables improved reliability by eliminating the components of interference, and improves reception performance by iterating the series of processes.

4) High-Precision Calibration

To compensate for imperfections in the RF and BB circuits such as IQ imbalance*28, channel deviation*29, clock phase difference*30 in this transmission system, we performed RF and BB calibration in the transmission and reception processing to make the system more precise [3] [4]. By calibrating the RF circuits, we compensated IQ imbalance in the quadrature modulator and demodulator, by giving the inverse characteristics to the transmitted and received signals. Furthermore, with BB calibration, we adjusted ADC/DAC channel deviations and clock phase differences to achieve the desired signal quality.

3. 10 Gbps Outdoor Transmission Experiment

3.1 Experiment Specifications

To demonstrate super high bit rate mobile communications over 10 Gbps, we performed the outdoor transmission experiment in the Hamasaki-cho area, Ishigaki-shi, Okinawa Prefecture. In an uplink 10 Gbps transmission, **Photo 3** shows the Mobile Station (MS) with its transmitter. This setup was used to transmit 8 streams of MIMO-OFDM signals. Directivity*31 of MS antennas used were omnidirectional in the horizontal plane, antenna gain*32 was 4 dBi (deciBelisotropic)*33, and antenna installation height was 2.5 m. We also set up a base station (BS) on the 3rd floor of an apartment block, and set up a 16 element directional antenna on the balcony, as shown in **Photo 4**. In addition to the 12 elements, the radome*34 pictured contained 4 elements. We used a directional antenna with a half-value beam width*35 at 65° in the horizontal plane (8° in the vertical plane) for the BS antenna. The antenna gain was 15 dBi, and its height was 8 m. Both the MS and BS antenna elements were spaced approximately 3wavelengths apart, and vertical polarization was used.

As shown in **Figure 1**, the average

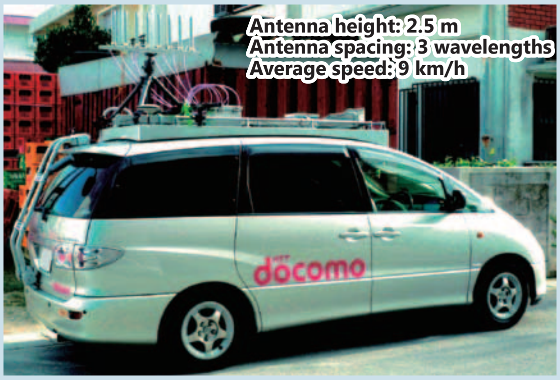

Photo 3 MS with 8-element omnidirectional antenna

*22 **Quadrature modulation**: A method of multiplying two sinusoidal signals with a 90° phase difference, which are then converted to RF signals by adding them to the in-phase and quadrature components of the BB signal.

*23 **LPF**: A filter that only passes low frequencies.

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

*25 **Cesium oscillator**: An atomic clock that produces an extremely accurate reference frequency using cesium to produce the reference signal.

*26 **Linear detection**: With MIMO transmission, a method of detecting signals by multiplying the weight coefficients for received signals at each antenna, and adding the multiplication results among all antennas. This is classified according to calculation method for the weight coefficients.

*27 **Received signal replica**: The estimated value of the received signal generated by the receiver.

*28 **IQ imbalance**: Amplitude deviation of the in-phase and quadrature components in the quadrature modulator and demodulator and phase error with the 90° phase shifter.

*29 **Channel deviation**: Amplitude and phase deviation between signals.

*30 **Clock phase difference**: Phase difference in clock signals that occurs due to jitter in oscillators etc.

*31 **Directivity**: A radiation characteristic of antennas - a pattern that describes the relationship between the antenna's electromagnetic radiation direction and the radiation intensity in that direction.

speed of the MS was 9 km/h around the measurement course. The length of the measurement course was 160 m. The BS antenna was pointed at that point A, 30 m from the start of the measurement course.

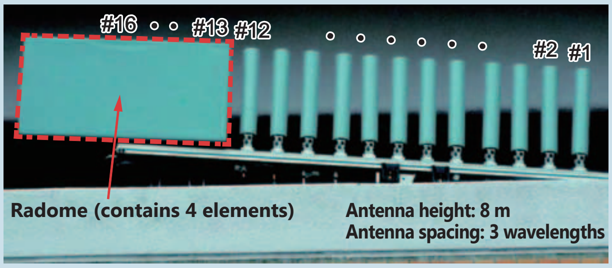

Photo 4 BS with 16-element directional antenna

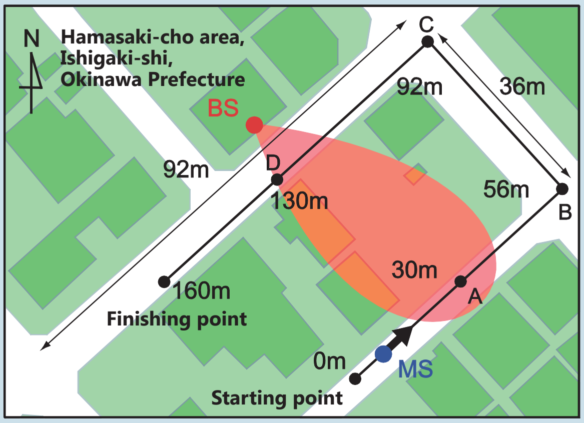

Figure 1 Measurement course for the outdoor transmission experiment

3.2 Experiment results

Figure 2 shows average Signal-to-Noise Ratio (SNR)[*36] measured at the BS when the MS traveled the measurement course. The average SNR for each receiver antenna was found by averaging the SNR measured at the 16 BS receiver antenna elements. The horizontal axis represents the distance traveled from the starting point of the measurement. The distance traveled was calculated from position data acquired from a GPS in the MS. As shown in Fig. 1, the distances at points A, B, C, D, are 30 m, 56 m, 92 m and 130 m respectively. Due to the effect of a building, line-of-sight was obscured up to 15 m from the starting point of the measurement course. However, the directivity effects of the antenna resulted in a high SNR observed around point A. The maximum SNR was 16.0 dB. The SNR deteriorated from point B to C due to the influence of buildings, however, a comparatively high SNR of 8 dB or higher was observed because line-of-sight was possible between points C and D. Although this area was not far away from the BS, the gain in the vertical plane of the directional antenna had deteriorated, so the SNR was not as high as around point A.

Figure 3 depicts the throughput[*37] performances with 64QAM, $R = 3/4$ which were calculated from the received signal measured in the outdoor transmission experiment in off-line processing. Throughput was calculated as (1 - block error rate) × 11.8 Gbps. A block consists of 1 OFDM symbol, encoded as those units. We set the maximum number of iterations in turbo detection to two. For each iterative processing, there were six iterations for turbo decoding. For comparison, Fig. 3 shows results for the initial turbo detection processing and the iterative turbo detection processing (two iterations). All segments in Fig. 3 show that throughput improved with the iterative processing. Notably, initial processing

*32 **Antenna gain**: A radiation characteristic of antennas – an index that describes the number of times greater the radiation intensity in the maximum radiation direction of an antenna, compared to a reference antenna.

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

*34 **Radome**: An enclosure to protect an antenna. These are made of materials that are transparent to radio waves.

*35 **Half-value beam width**: The radiating angle of an antenna in which the gain is within -3 dB of the maximum antenna gain. Also just simply called beam width.

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

*37 **Throughput**: Effective amount of data transmitted without error per unit time.

dropped below 10 Gbps between 100 m and 120 m, but throughput in excess of 10 Gbps with the iterative processing was always achieved.

Despite the high SNR for point A in Fig. 2, it was not possible to achieve 10

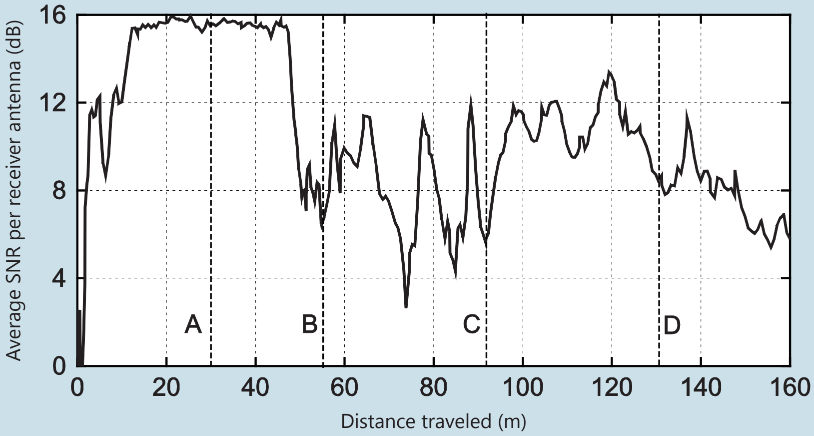

Figure 2 Observed SNR

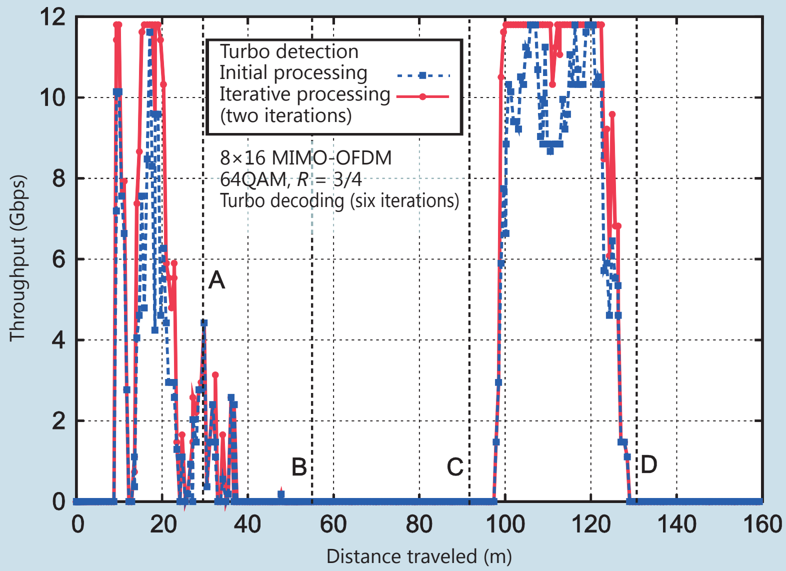

Figure 3 Throughput performance

Gbps for that point in Fig. 3, because direct waves dominant in the vicinity of point A caused high spatial correlation*38 which made MIMO signal detection difficult. Aiming to achieve throughput greater than 10 Gbps with this experiment, and only using 64QAM, R =3/4 for the modulation and coding scheme, transmission quality was unsatisfactory between points B and C, and after D, where throughput was 0 Gbps. In contrast, between 10 m and 20 m, and between points C and D, we achieved throughput greater than 10 Gbps, as signal detection was possible from increased multipath waves even though the SNR dropped because of lower effectiveness of line-of-sight waves.

4. Conclusion

This article has described a microwave 11 GHz band 8×16 MIMO-OFDM transmission system developed to demonstrate super high bit rate mobile communications. The article has also presented the details and results of a 10 Gbps outdoor transmission experiment, and has verified that this was the first time in the world that throughput greater than 10 Gbps has been achieved in a mobile communications environment. Thus, this work holds the promise of contributing to super high bit rate mobile communications in future mobile communication systems.

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*38 **Spatial correlation**: Fading correlation between two spatially separated channels, dependent on signal arrival conditions and the positional relationship between the two channels. A higher spatial correlation makes it more difficult to separate signals and reduces MIMO channel capacity.