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Performance evaluation of MIMO broadcast systems for advanced digital terrestrial TV

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Abstract

The transmission performance of spatial multiplexing cross-polarized MIMO is studied to determine how to increase the capacity of digital terrestrial broadcasting and make it more robust. In this paper, the performance was evaluated in laboratory experiments and large-scale field experiments in central Tokyo under three deployment scenarios. The results showed that the required received power can be improved by 7.3 dB when MIMO is introduced to enhance transmission robustness, i.e., maintaining the same transmission capacity as SISO. Alternatively, the transmission capacity can be doubled by introducing MIMO for the same robustness as SISO, requiring a slight increase in received power of 0.9 dB compared with SISO. The field experiments were performed by using a prototype transmission system for advanced digital terrestrial TV broadcasting in Japan, but the results obtained are also valid for 5G broadcasting. Regarding the feasibility of the advanced terrestrial broadcasting system operating at a target bit rate of about 60 Mbps to distribute a VVC-based 8 K program within a 6-MHz channel bandwidth, an increased received power of 3.7 dB compared with SISO was required for MIMO to achieve a higher transmission capacity in the worst case for 28 reception points evaluated in urban areas.

Keywords: Digital terrestrial television broadcasting, Advanced ISDB-T, MIMO, FeMBMS, 5G broadcast, 8 K

1 Introduction

Digital terrestrial television broadcasting (DTTB) in Japan began in 2003 with Integrated Services Digital Broadcasting—Terrestrial (ISDB-T) [1]. Research on transmission methods for next-generation terrestrial broadcasting is currently underway. A national program called “Research and Development for Advanced Digital Terrestrial Television Broadcasting System” started in 2016 with the participation of broadcasters, manufacturers, and universities. The objective is to study technologies that will improve transmission efficiency while inheriting the features of the current DTTB and to establish a single frequency network (SFN) that promotes the effective use of the radio spectrum. The project has explored different ways of advancing the current terrestrial broadcasting transmission system, ISDB-T, to provide ultra-high-definition television (UHDTV)

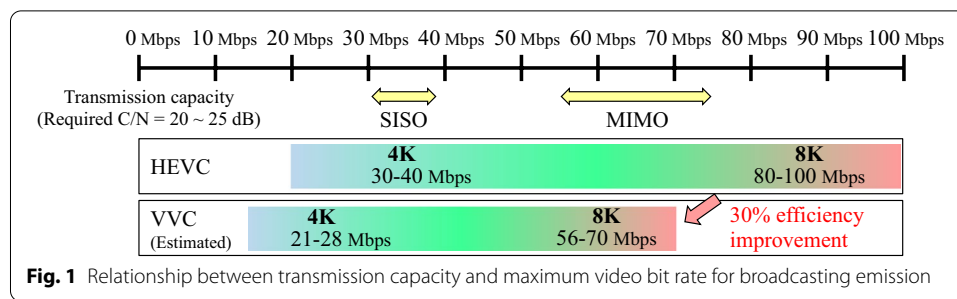
and high-definition television (HDTV) services within a single 6-MHz channel [2]. To provide 4 K/8 K UHD TV services through terrestrial broadcasting in a 6-MHz channel, the transmission capacity must be further increased. One option for increasing the capacity is to use multiple-input multiple-output (MIMO) antenna systems with spatial multiplexing [3].

Terrestrial MIMO TV broadcasting in the low ultra-high-frequency (UHF) band has been demonstrated in field trials by the public broadcasters BBC (U.K.) [4, 5] and NHK (Japan) [6, 7], in which a cross-polarized (horizontal and vertical) antenna was introduced to retain full spatial multiplexing capabilities in line-of-sight (LOS) conditions. MIMO technology was introduced for the first time in a DTTB specification with DVB-NGH [8], and it has been further developed and standardized in ATSC 3.0 [9]. MIMO technology provides a higher spectral efficiency via spatial multiplexing and/or higher transmission robustness via spatial diversity [10]. Although a MIMO TV broadcasting system requires updating both transmitting and receiving antennas, the enhancement of the transmission system allows broadcasters to select the configuration that better suits the capacity and coverage requirements per service.

Meanwhile, the Third-Generation Partnership Project (3GPP) completed, in LTE-Advanced Pro Release 14, the standardization of a DTTB-like mode (e.g., receive-only, broadcast and downlink only, free to air, support for high-power high-tower HPHT infrastructure, etc.) based on evolved multimedia broadcast multicast service (eMBMS) [11]. In Release 14, the eMBMS radio interface efficiency and flexibility are greatly enhanced [12], and thus, the name has been further evolved to multimedia broadcast multicast service (FeMBMS). However, MIMO technology was not introduced. Release 16 defined a so-called LTE-based 5G Terrestrial Broadcast solution based on the work in Release 14 [13, 14]. The target is to enable a Multimedia Broadcast multicast service Single Frequency Network (MBSFN) to support SFN with a cell coverage range of up to 100 km and mobile reception with speeds up to 250 km/h [15]. However, Release 16 do not support MIMO broadcasting either.

In an earlier study, we conducted preliminary field experiments to evaluate the transmission characteristics of MIMO by using small-scale experimental test stations built in a rural area and confirmed the feasibility of SFN in MIMO broadcasting [16]. On the other hand in this paper, we compare the characteristics of SISO and MIMO in a large-scale HPHT network in an urban area using the signal structure of the advanced ISDB-T system currently being studied in Japan [2]. The evaluation was conducted under three scenarios. The aim of the first scenario was to improve the transmission robustness by using a more robust modulation scheme and error correction code while maintaining the same transmission capacity as SISO. The second one aimed to increase the transmission capacity with MIMO, keeping the same signal robustness as SISO. The last scenario was to maximize the transmission capacity even at the expense of reducing the robustness compared with SISO with a carrier modulation scheme and error correction code having more capacity.

Figure 1 shows the relationship between the transmission capacity and the maximum video bit rate for broadcasting emission. The recommended video bit rates when using the high-efficiency video coding (HEVC/H.265) standard are 30–40 Mbps for 4 K and 80–100 Mbps for 8 K [17]. The next-generation video coding standard, versatile video coding



(VVC), has been developed [18]. The coding efficiency of VVC has been targeted to be 30 percent better than that of HEVC. The required video bit rates when using VVC can be estimated as 21–28 Mbps for 4 K and 56–70 Mbps for 8 K. The advanced ISDB-T proposal can transmit one UHDTV 4 K service by using HEVC in a single 6-MHz channel for fixed SISO reception. For VVC, it is expected that an UHDTV 8 K service can be transmitted by using the MIMO system. Methods for improving the coding efficiency for 8 K broadcasting should be further developed to transmit 8 K when using the SISO system [19].

This paper shows a novel perspective on the MIMO broadcast transmission performance. A performance comparison between SISO and MIMO under three scenarios was conducted in urban areas with an HPHT network configuration. In previous studies [4, 5], the characteristics of MIMO transmission were evaluated with a modulation scheme and code rate having the same robustness as the reference SISO configuration. In other studies, like [6, 16], the MIMO transmission performance was evaluated with several modulation schemes and code rates, but the performance was not compared with SISO. In this study, it was clarified that the amount of degradation in the required received power for MIMO was higher than that for SISO with several modulation schemes and code rates having different levels of robustness. As a follow-up verification to the earlier field experiments [20], this paper introduces a novelty in the system evaluation with channel snapshots captured in the field experiments, removing uncertainties such as a fluctuation in the electric field strength or the effect of man-made noise occurring at the time of measurement. The results of the field experiments and the follow-up laboratory experiments confirmed that the degradation in MIMO transmission performance was not negligible compared with SISO. In addition, this paper has the novelty of being a feasibility study on a next-generation terrestrial broadcasting system that operates at a target bit rate of about 60 Mbps so that a VVC-based 8 K program can be distributed within a single 6-MHz channel.

This paper is structured as follows. Section 2 reviews the transmission system used in this paper. The methodologies and the setup for the laboratory and field experiments are presented in Section 3. Section 4 presents the results and discussion on the experiments. The conclusions are summarized in Section 5.

2 Transmission system

This section presents an overview of the advanced ISDB-T system examined in the MIMO experiments. This system adopts frequency division multiplexing (FDM) based on a segment structure, which is a feature of the current terrestrial broadcasting transmission system, ISDB-T [21]. The segment structure is similar to the resource block

structure introduced in the downlink physical channel in LTE [22]. The transmission parameters of advanced ISDB-T are listed in Table 1. For comparison, the numerology of LTE-based 5G terrestrial broadcasting for HPHT networks specified in 3GPP Release 16 is shown in Table 1 [23]. Note that we focus on a broadcasting system for fixed reception with a 6-MHz bandwidth in this paper, and the numerology of LTE-based 5G terrestrial broadcasting for fixed reception in HPHT networks with a 5-MHz bandwidth is excerpted for comparison in the table. The carrier modulation of advanced ISDB-T ranges from QPSK to 4096 QAM with non-uniform constellations [24] to improve the robustness performance. The system also supports MIMO transmission in order to provide large capacity content. An open-loop plain spatial multiplexing with cross-polarized 2×2 MIMO can be configured.

Figure 2 shows a block diagram of the channel coding for the SISO/MIMO system used for the experiments. Input data is fed and divided into hierarchical levels, labeled layers A, B, and C. Transmission parameters, such as carrier modulation, code rate, and scattered pilot pattern, can be configured for each layer. The input data goes through BCH coding, low-density parity check (LDPC) coding, bit interleaving, and mapping. For MIMO transmission, data symbols are divided into two groups for transmitter (Tx) 1 and 2. After combining the data symbols from the three layers, time and frequency interleaving is conducted. Then, an OFDM frame is constructed by using data carrier symbols, pilot signals, and control signals. Finally, inverse fast Fourier transform (IFFT) processing is conducted, and a guard interval (GI), which is referred to as the cyclic prefix (CP) in the 3GPP specification, is added.

Table 1 Transmission parameters of LTE-based 5G terrestrial broadcast and advanced ISDB-T

	LTE-based 5G terrestrial broadcast	Advanced ISDB-T		
Modulation	Cyclic prefix-OFDM			
Channel bandwidth	5 MHz	6 MHz		
Occupied bandwidth	4.5 MHz	Normal mode: 5.83 MHz Compatible mode: 5.57 MHz		
Number of segments	25 resource blocks	Normal mode: 35 Compatible mode: 33 + adjusting bands		
Bandwidth of segments	180 kHz	167 kHz		
FFT size	41,472	8,192	16,384	32,768
Number of carriers	12,150	7,561	15,121	30,241
Carrier spacing	370.37 Hz	771.60 Hz	385.80 Hz	192.90 Hz
Scattered pilot ratio	1/6, 1/12	1/3, 1/6, 1/12, 1/24, 1/48		
Carrier modulation	QPSK, 16QAM, 64QAM, 256QAM (uniform)	QPSK, 16QAM, 64QAM, 256QAM, 1024QAM, 4096QAM (uniform, non-uniform)		
Number of OFDM symbols per frame	13	224	112	56
Effective OFDM symbol length	2700 μ s	1296 μ s	2592 μ s	5184 μ s
Guard interval ratio	1/9	1/4, 1/8, 800/8,192	1/4, 1/8, 1/16, 800/16,384	1/8, 1/16, 1/32, 800/32,768
Inner code	Turbo code	LDPC code		
Outer code	N/A	BCH code		
System	SISO	SISO, MIMO, MISO		

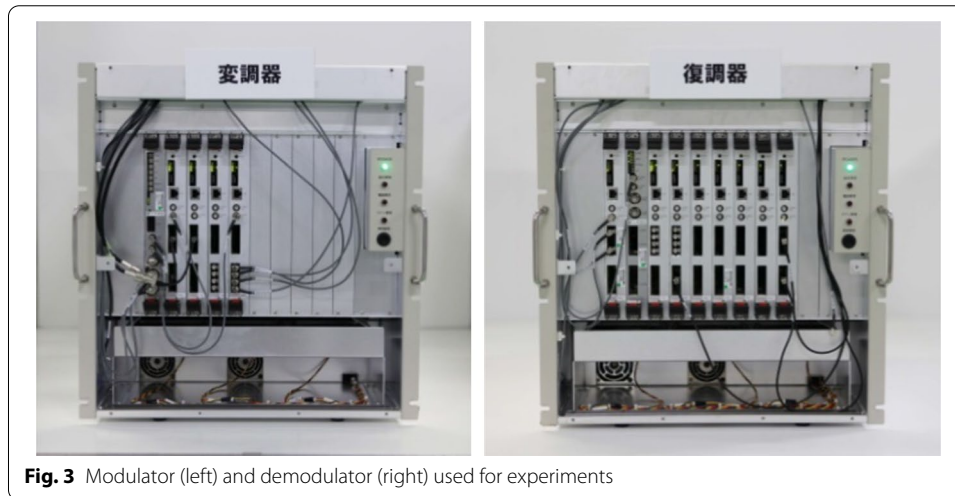
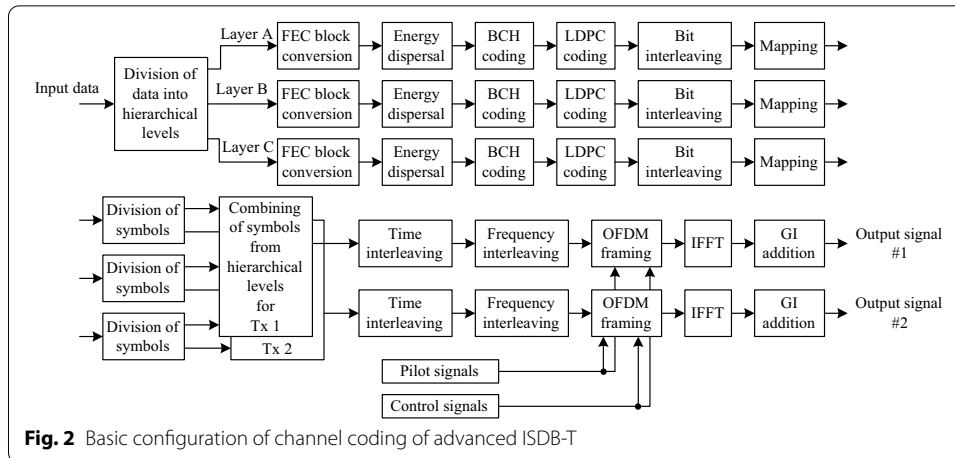


Figure 3 shows a prototype FPGA-based modulator and demodulator used for the experiments.

Figure 4 shows a transmitting antenna installed at the experimental test station and a receiving antenna that was equipped on a measurement vehicle.

Table 2 shows details on the station. We installed a cross-polarized (horizontal and vertical) transmitting antenna shared by SISO/MIMO at Tokyo Tower, located in Shiba, central Tokyo. Two transmitters were installed at the station to handle the MIMO transmission.

Table 3 shows details on the receiving antenna. A dual-polarized Yagi antenna was used to receive SISO/MIMO signals. The receiving antenna was mounted on a pole so that the orthogonal antenna elements were horizontal and vertical.

3 Methodologies and setup

This section describes the performance comparison methodologies and the experimental setup for SISO/MIMO. Measurements were carried out in three steps: laboratory experiments for advance verification, field experiments, and laboratory experiments for follow-up verification. The detailed methodologies are shown in the following sections.

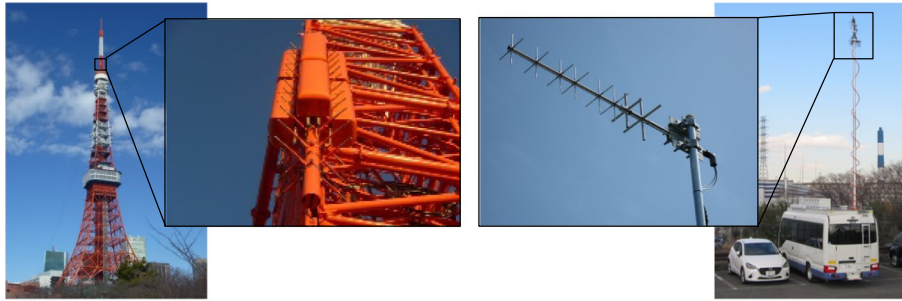


Fig. 4 Transmitting antenna (left) and receiving antenna (right) used for field experiments

Table 2 Specifications of experimental test station

Transmitter site	Tokyo Tower (Shiba Minato-ku, Tokyo)	
Transmission frequency	563.143 MHz (UHF Ch 28 in Japan)	
Polarization	Horizontal	Vertical
Transmission power	1 kW	1 kW
E.R.P	2.1 kW	2.1 kW
Transmitting antenna type and configuration	Dual-polarized multi-stage dipole antenna two-stage three-sided	
Transmitting antenna height	280 m above sea level	

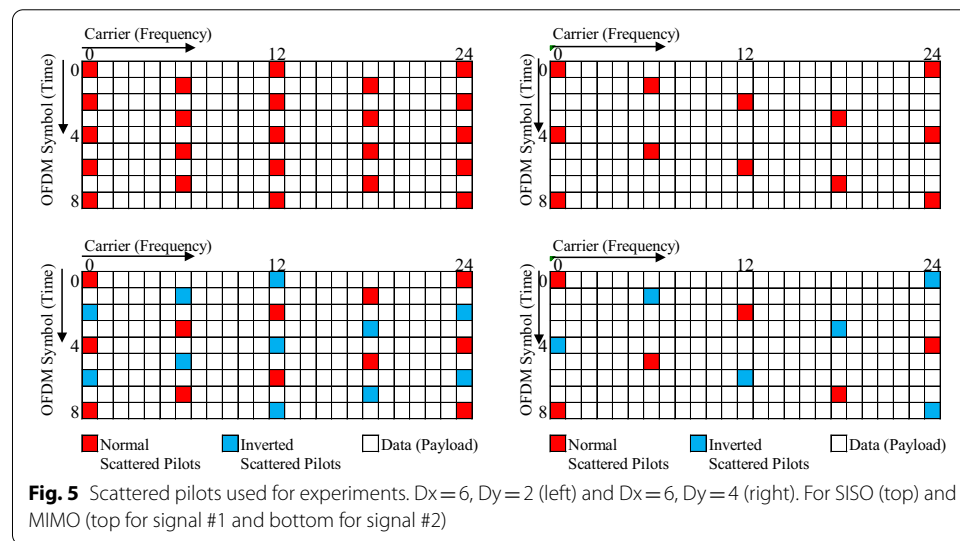
Table 3 Specifications of receiving antenna

Antenna type	8-element dual-polarized Yagi antenna
Gain	9.0 dBd
Front-to-back ratio	Over 13 dB
Cross-polarization discrimination	Over 25 dB (Boresight)

The experiments were conducted with a single SISO transmission configuration and three MIMO configuration sets for the advanced ISDB-T system, as summarized in Table 4. The SISO parameters were a reference and assumed to have the same robustness as the operational parameters of the current DTTB system, ISDB-T, for fixed reception in Japan (64 QAM, code rate = 3/4). The required carrier-to-noise ratio (C/N) of the operation parameters of ISDB-T is about 20 dB. In the advanced ISDB-T, when 31 out of all 35 segments are used for UHDTV transmission, the transmission capacity reaches 26.1 Mbps. MIMO parameter set No. 1 (scenario 1) introduces MIMO with the same transmission capacity as the reference SISO configuration. We evaluated how the required received power improves compared with SISO. MIMO parameter set No. 2 (scenario 2) introduces MIMO with the same robustness as the reference SISO configuration. We evaluated how the required received power varies when the transmission capacity is doubled compared with SISO. The last parameter set No. 3 (scenario 3) introduces MIMO to greatly increase the capacity to provide 8 K programming assuming a bit rate of around 60 Mbps with VVC. The required C/N or the required received power was defined as the minimum C/N or the minimum received power at which the

Table 4 Parameter sets for experiments

	Parameter set			
	SISO (reference)		MIMO	
			No. 1 (scenario 1)	No. 2 (scenario 2) No. 3 (scenario 3)
Occupied bandwidth	Normal mode: 5.83 MHz			
Number of segments	Normal mode: 35 (31 segments used for fixed reception evaluation)			
FFT size	16,384			
Scattered pilot ratio	1/12			
Carrier modulation	256QAM	16QAM	256QAM	1024QAM
	Non-uniform	Non-uniform	Non-uniform	Non-uniform
Guard interval ratio (duration)	800/16,384 (126 μ sec)			
Inner code rate	12/16			
System	SISO (horizontal)	MIMO (open-loop spatial multiplexing 2×2 cross-polarized)		
Transmission capacity (31 segments)	26.1 Mbps	26.1 Mbps	52.3 Mbps	62.8 Mbps



value of the bit error rate (BER) before error correction of the outer code (BCH code) is below $1\text{E-}7$ [25]. The number of observation bits was set to $1\text{E}+10$, which corresponds to about 6 min in SISO, although the quasi-error-free (QEF) condition of a digital television broadcasting signal means less than one uncorrected error event per hour [26].

Figure 5 illustrates the pilot signals used for the experiments. For SISO, the number of carriers between the scattered pilot bearing carriers (D_x) was set to 6, and the number of symbols between the scattered pilots in a single pilot bearing carrier (D_y) was set to 2, which is shown in Fig. 5 (top, left). MIMO parameter sets No. 1 and 2 were configured to have the same scattered pilots as SISO for output signal #1 and sign inverted scattered pilots for output signal #2, which are shown in Fig. 5 (top, left) and (bottom, left), respectively. For MIMO parameter set No. 3, $D_x=6$ and $D_y=4$, shown in Fig. 5 (right), were selected to increase the transmission capacity.

3.1 Laboratory experiments for advanced verification

We evaluated the required C/N of each parameter set in an ideal additive white Gaussian noise (AWGN) channel for the SISO/MIMO configuration in laboratory experiments. Figure 6 shows a block diagram of the experiments. The output signals of the modulator were input to a channel simulator, and two independent AWGNs were added to the signals.

The required C/N was defined as the average value of the required C/N s between input signals #1 and #2 to the demodulator. In preliminary MIMO field trials, a difference in electric field strength between the horizontally and vertically polarized waves was observed [27]. The required C/N with a specific difference between the C/N values for input signals #1 and #2 was also evaluated for the MIMO parameter sets.

3.2 Field experiments

Figure 7 shows a block diagram of the transmission and reception for the field experiments. A single pseudo-random bit sequence was generated, coded with BCH codes and LDPC codes, and then modulated in the prototype advanced ISDB-T modulator. The modulated SISO/MIMO signals were converted into RF signals at the same frequency and amplified to the desired power level. After that, the signals were transmitted from the dual-polarized antenna installed at the experimental test station. At the receiver site, the transmitted signals were received by the dual-polarized Yagi antenna. Each received signal was filtered by a band-pass filter and attenuated by a variable attenuator (ATT). The required received power was measured while setting the input point of a low-noise amplifier (LNA) as the specified point for the received power. In the prototype demodulator, the received signals were demodulated, and the BER was measured on a measurement vehicle.

In the field experiments, SISO performance was evaluated by transmitting a horizontally polarized radio wave with the experimental test station. The required received power was specified at the input point of the LNA for horizontal wave with the horizontal element of the receiving antenna. For MIMO parameter sets No. 1, 2, and 3, radio waves were transmitted with horizontal and vertical polarization, and the required received power was specified as the average received power of the horizontally and vertically polarized waves. The required received power was measured by inserting the same

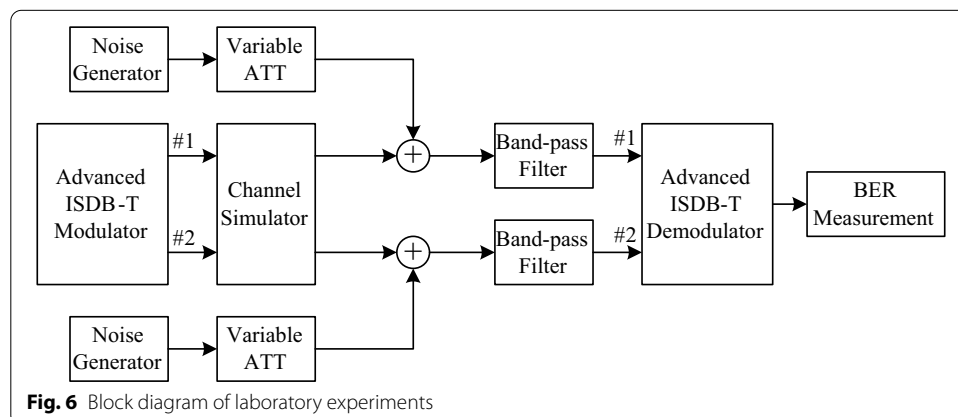
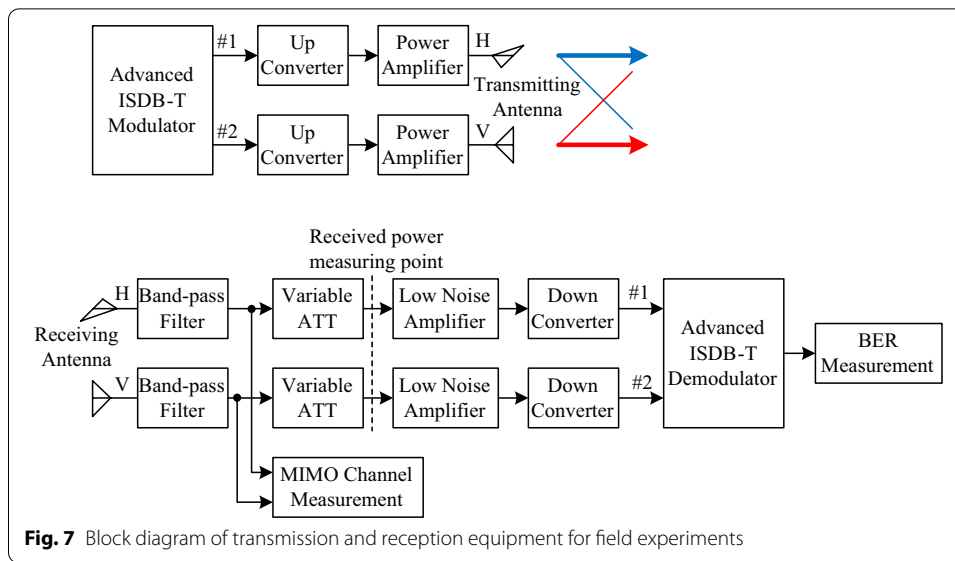


Fig. 6 Block diagram of laboratory experiments

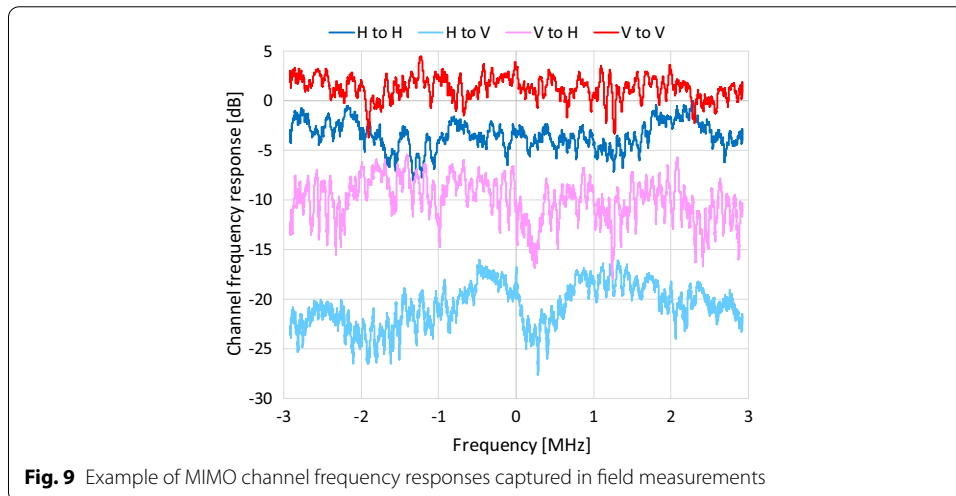
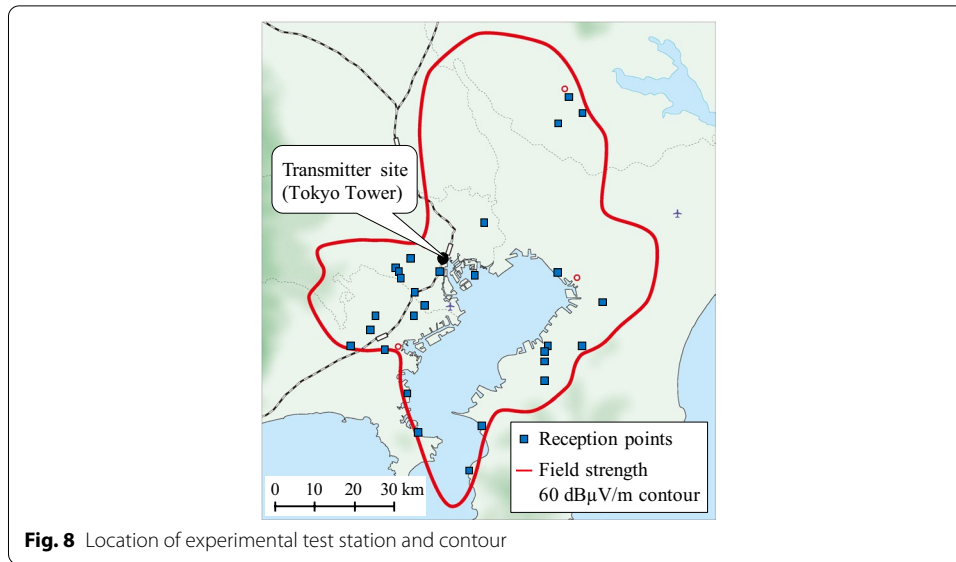


amounts of attenuations into both received signals of the horizontally and vertically polarized waves, decreasing the received power, and when a BER of $1\text{E-}7$ or less was achieved, the average value was calculated as the required received power. Assuming fixed rooftop reception in an HPHT network, the receiving antenna height was set 10 m above ground level. The required received power in an ideal AWGN channel with the experimental equipment was measured, and the degradation in the required received power from the ideal channel was evaluated in the field experiments.

The location of the station is shown in Fig. 8. The contour, indicated by a red line, corresponds to the service area for the current DTTB system, ISDB-T, with an electric field strength of $60\text{ dB}\mu\text{V/m}$. We selected 28 reception points within the contour, and the required received power was measured. For follow-up verification, a MIMO channel snapshot was captured at each point.

3.3 Laboratory experiments for follow-up verification

In field experiments, BER measurement results could be affected by several factors, such as fluctuation in the electric field strength, movement of the vehicles passing by the measurement vehicle, and man-made noise occurring at the time of each measurement. To remove those influences on the evaluation results, we evaluated the required C/N in the laboratory by using the MIMO channel snapshots captured in the field experiments. The snapshots were configured in the channel simulator shown in Fig. 6, and the actual reception environments were reproduced for follow-up verification. The SISO performance was evaluated with the channel frequency response (CFR) from the horizontal transmitting antenna to the horizontal receiving antenna. To evaluate the MIMO performance, four CFRs were used to reproduce the MIMO channel in the channel simulator. Figure 9 shows an example of the four CFRs of a snapshot in which we observed the highest difference in field strength between horizontally and vertically polarized waves in the field measurements. The reason for the difference, namely in the average value, was considered to be that the strength varied in the height direction due to the



difference in the reflection characteristics. In the experiments, the receiving antenna height was fixed to 10 m above ground level, but it was observed that the values of the vertical and horizontal electric field strengths varied independently depending on the reception height.

4 Results and discussion

4.1 Laboratory experiments for advanced verification

Figure 10 shows the BER characteristics for each parameter set in an ideal AWGN channel measured in the laboratory. The required C/N values are summarized in Table 5. It was confirmed that the difference in the required C/N compared with SISO was -9.6 dB, 0 dB, and $+2.6$ dB for MIMO parameter sets No. 1, 2, and 3, respectively.

Figure 11 shows the average value of the required C/N s between input signals #1 and #2 with a specific difference between the C/N values for signals #1 and #2 for all MIMO

parameter sets. The results showed that the required C/N s gradually degraded as the difference between each C/N increased. The degradation was below 1 dB compared with the ideal condition (0 dB difference in C/N) when the difference was less than 3 dB.

4.2 Field experiments

4.2.1 Field strength

Figure 12 shows the measurement results of the field strength of the horizontally and vertically polarized waves at 28 points. The values of the horizontal wave (solid blue circles in Fig. 12) were measured with the horizontal element of the receiving antenna while transmitting the radio wave from only Tx 1 (horizontally polarized antenna). Likewise, the values of the vertical wave (red circles in Fig. 12) were observed by emitting the signal from only Tx 2 (vertically polarized antenna). As shown in Fig. 12, the results of the field strength measured within 20 km of the transmission distance were lower

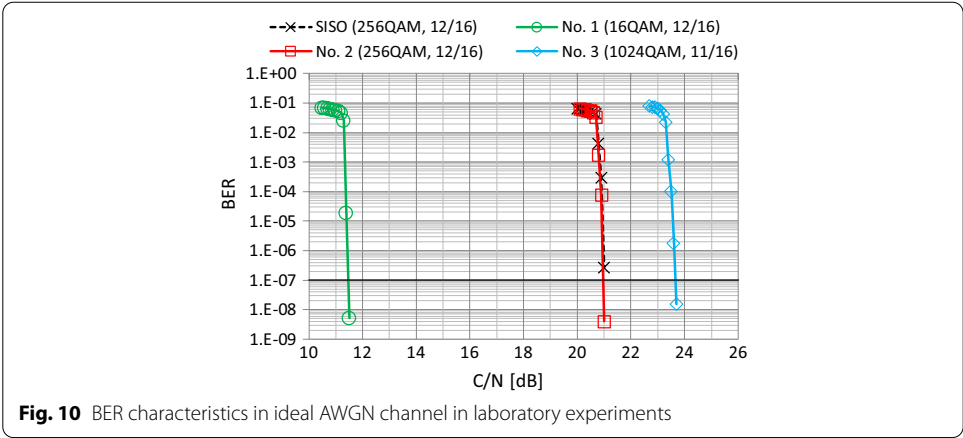


Fig. 10 BER characteristics in ideal AWGN channel in laboratory experiments

Table 5 Required C/N in laboratory experiments

	Parameter set			
	SISO (reference)	MIMO		
		No. 1 (scenario 1)	No. 2 (scenario 2)	No. 3 (scenario 3)
Required C/N in AWGN channel	21.1 dB	11.5 dB	21.1 dB	23.7 dB

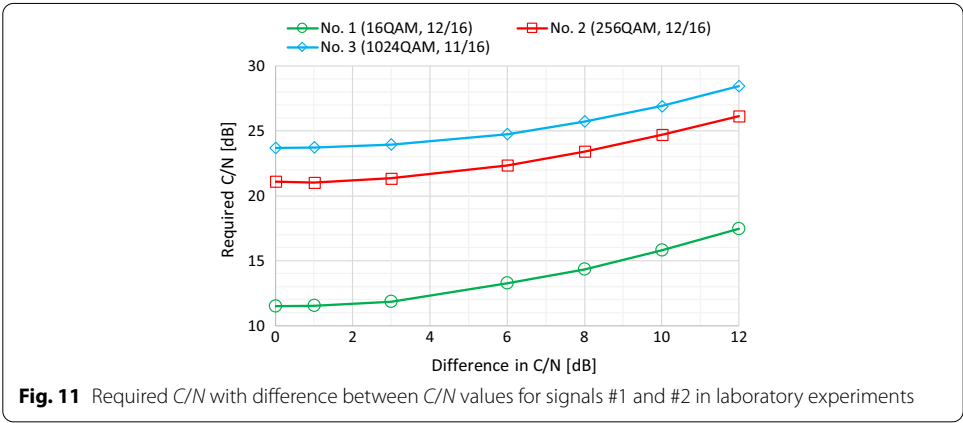


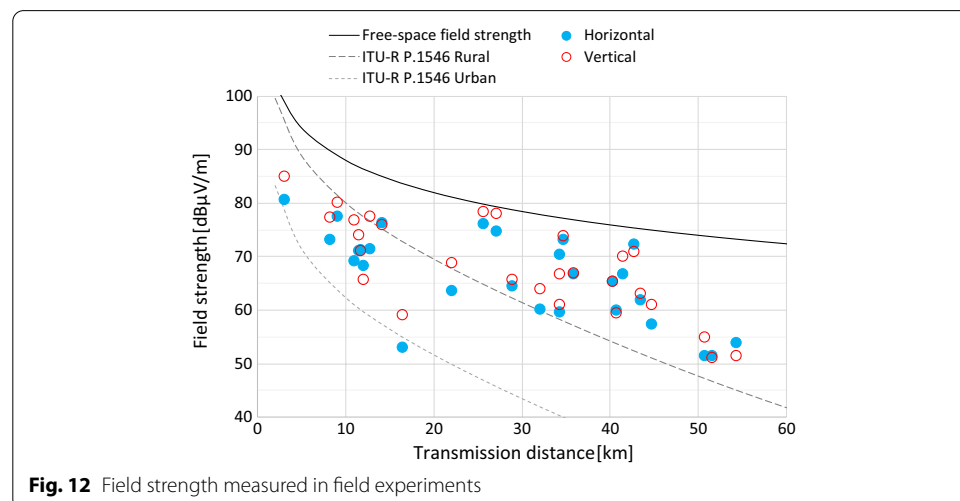
Fig. 11 Required C/N with difference between C/N values for signals #1 and #2 in laboratory experiments

than the calculated values with a prediction model for rural areas [28], and those closer points were objectively in urban areas. The field strength for the reception points located beyond a 20-km transmission distance was distributed along with or higher than the values predicted for rural areas, and those points were in rural areas.

Figure 13 shows the distribution of the field strengths of the horizontally and vertically polarized waves at the 28 points. As shown, the strengths of both waves were almost equally distributed. The transmission facility was designed so that the effective radiation power ($e \cdot r \cdot p$) of the experimental test station had the same value for both the horizontally and vertically polarized waves.

Figure 14 shows the distribution of the difference in field strength obtained by subtracting the field strength of the horizontally polarized wave from that of the vertically polarized wave. That is, when the difference in the field strength was a positive value, it meant that the vertical field strength was high. The maximum difference was 7.5 dB, at which the value of vertical polarization was higher than that of horizontal polarization. The results showed that the difference was independent of the transmission distance, and the field strength of vertical polarization tended to be higher than that of horizontal polarization. The reason the vertically polarized waves were high in the field experiments was the difference in the propagation path. It has been mentioned that one advantage of using horizontal polarization is that undesired polarization is not received because of the greater directivity obtainable at the receiving antenna at UHF [29], which reduces the effect of reflected waves, particularly in urban areas. The experimental results shown in this paper align with this description; however, the number of samples (reception points) was limited in this paper, so detailed analysis with a higher number of samples is needed to analyze the propagation for each polarization.

Figure 15 shows the cumulative probability of the absolute value of the difference in field strength between horizontal and vertical polarization. As shown, the 50-percentile absolute difference in the field strength observed was about 2.5 dB. It can be concluded that when introducing dual-polarized MIMO, a difference in received power is unavoidable. The transmitter power can be increased in one of the polarizations to compensate for this difference. However, it is impossible to compensate for the differences



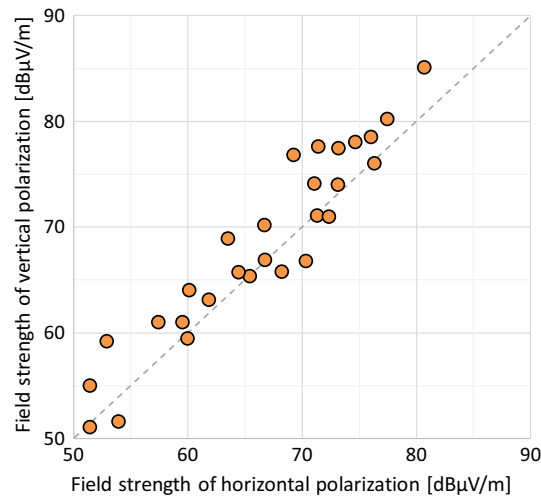


Fig. 13 Distribution of field strength of horizontal and vertical polarization in field experiments

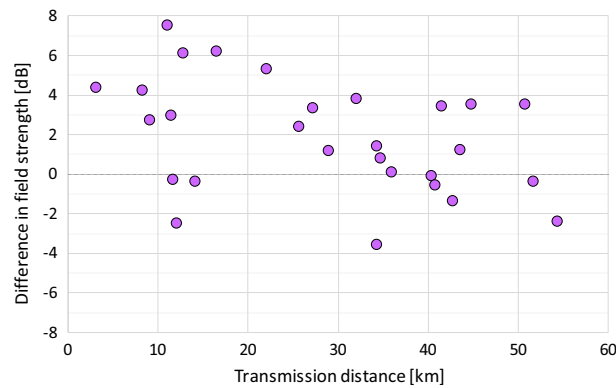


Fig. 14 Difference in field strength between horizontal and vertical polarization (vertical minus horizontal) in field experiments

for all receivers since the difference in the electric field strength differs depending on the reception environment.

4.2.2 Required received power

Next, we compared the required received power of the SISO and MIMO parameter sets. Figure 16 shows the results of plotting the required received power of SISO and MIMO against the transmission capacity. The results showed that the plots of MIMO were widely distributed compared with SISO.

Table 6 summarizes the values of the required received power obtained in the field experiments. Theoretical values were also calculated on the basis of the required C/N_s measured in the laboratory test results in Table 5 assuming a noise power of -104.5 dBm at the LNAs as based on the noise figure of 1.8 dB specified in the LNA product data sheet. The required received power in an ideal AWGN channel for the experimental equipment measured in the laboratory is shown as a reference. It was

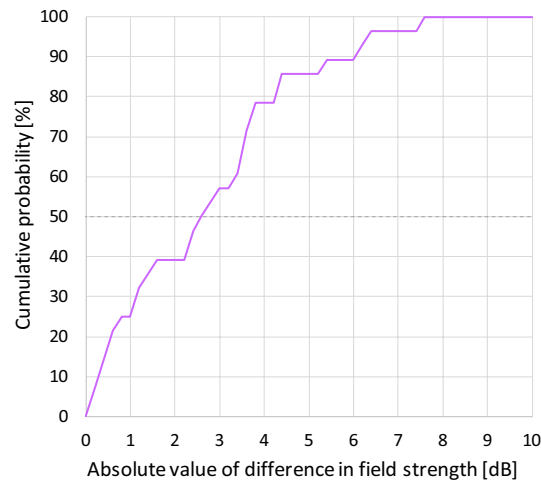


Fig. 15 Cumulative probability of absolute value of difference in field strength between horizontal and vertical in field experiments

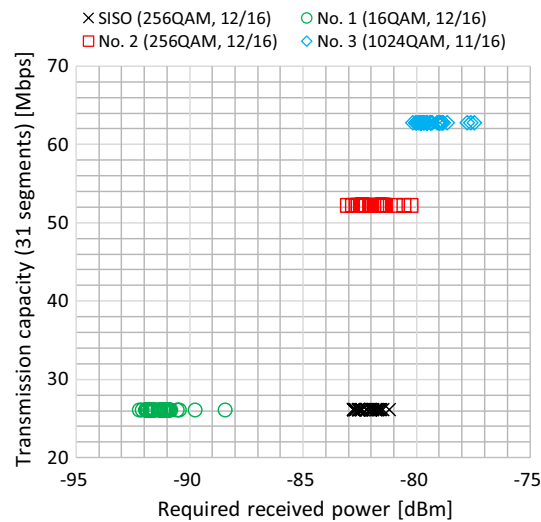


Fig. 16 Distribution of required received power for all parameter sets

considered that the difference of 0.2 dB observed in the laboratory tests between SISO and MIMO parameter set No. 2 was introduced due to an individual difference of the noise figure characteristics at the LNAs used. The minimum, median, and maximum values of the required received power in the field experiments are shown for comparison.

Table 7 shows the degradation in the required received power measured in the field experiments compared with the laboratory results. As shown, the median value of the deterioration in SISO was 0.8 dB. In MIMO parameter sets No. 1, 2, and 3, the median values were 1.0, 1.1, and 1.1 dB, confirming that MIMO did not experience a significant increase in required received power compared with SISO. It should be noted that the maximum degradation in SISO was 1.7 dB, while the maximum degradations

Table 6 Required received power in field experiments

	SISO (256QAM, 12/16)	MIMO		
		No. 1 (16QAM, 12/16)	No. 2 (256QAM, 12/16)	No. 3 (1024QAM, 11/16)
Theoretical (dBm)	− 83.4	− 93.0	− 83.4	− 80.8
Laboratory (dBm)	− 82.9	− 92.4	− 83.1	− 80.5
Field (dBm)				
Minimum	− 82.8	− 92.2	− 83.0	− 80.2
Median	− 82.1	− 91.4	− 82.0	− 79.4
Maximum	− 81.2	− 88.5	− 80.3	− 77.5

Table 7 Degradation in required received power measured in field experiments compared with laboratory results

	SISO (256QAM, 12/16)	MIMO		
		No. 1 (16QAM, 12/16)	No. 2 (256QAM, 12/16)	No. 3 (1024QAM, 11/16)
Field (dB)				
Minimum	0.1	0.2	0.1	0.3
Median	0.8	1.0	1.1	1.1
Maximum	1.7	3.9	2.8	3.0

were 3.9, 2.8, and 3.0 dB for MIMO parameters sets No. 1, 2, and 3. That is, the degradation can increase in MIMO transmission in the worst case. Since there is considered to be no difference in urban noise (man-made noise) regarding polarization, the degradation in the MIMO system performance could have been influenced by urban buildings or terrain that caused a difference in reflection characteristics related to polarization. To verify this, a field experiment in a rural area is required.

Figure 17 shows the comparison of the degradation in the required received power of SISO and MIMO in the field experiments. As we can see, the degradations in the required received power were almost the same and distributed on the dotted line, which indicates the same degradation for SISO and MIMOs except for a few reception points. Figure 18 shows the degradation in the required received power plotted against the transmission distance. The results showed that the degradation amount was independent of the transmission distance. Figure 19 shows the degradation in the required received power versus the absolute value of the difference in received power between horizontal and vertical polarization. The results showed that the degradation in the required received power increased as the difference in the received power increased. Note that the difference in the received power was calculated on the basis of the received power measured for each polarization while transmitting horizontally and vertically polarized waves with Tx 1 and 2 simultaneously in the field experiments.

Table 8 summarizes the differences in the required received power in the MIMO parameter sets compared with SISO, which were calculated by subtracting the required received power of SISO from the values of MIMO obtained in the field experiments as shown in Table 6. That is, when the difference in the required received

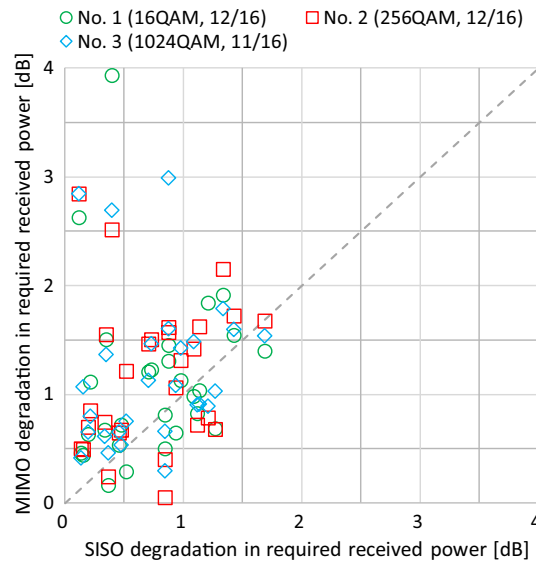


Fig. 17 Comparison of degradation in required received power between SISO and MIMO in field experiments

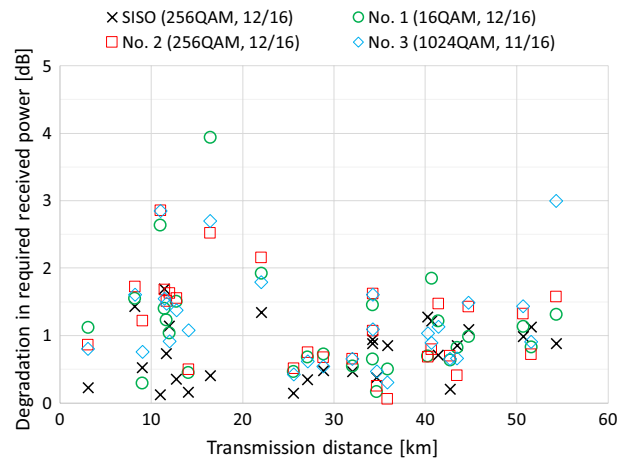


Fig. 18 Degradation in required received power from viewpoint of transmission distance in field experiments

power was a positive value, it meant that MIMO requires a higher received power compared with SISO. The required power can be improved by at least 7.3 dB with MIMO parameter set No. 1, in which MIMO is introduced with the same transmission capacity as the reference SISO configuration. This demonstrated that by introducing MIMO, we can expect transmission to be robust in a real environment. It was confirmed that the required power is degraded by at most 0.9 dB with MIMO parameter set No. 2, in which MIMO is introduced with the same carrier modulation and code rate as the reference SISO, doubling the transmission capacity. The required power is also deteriorated by at most 3.7 dB with MIMO parameter set No. 3, in which a transmission capacity of 62.8 Mbps is achieved for fixed reception assuming

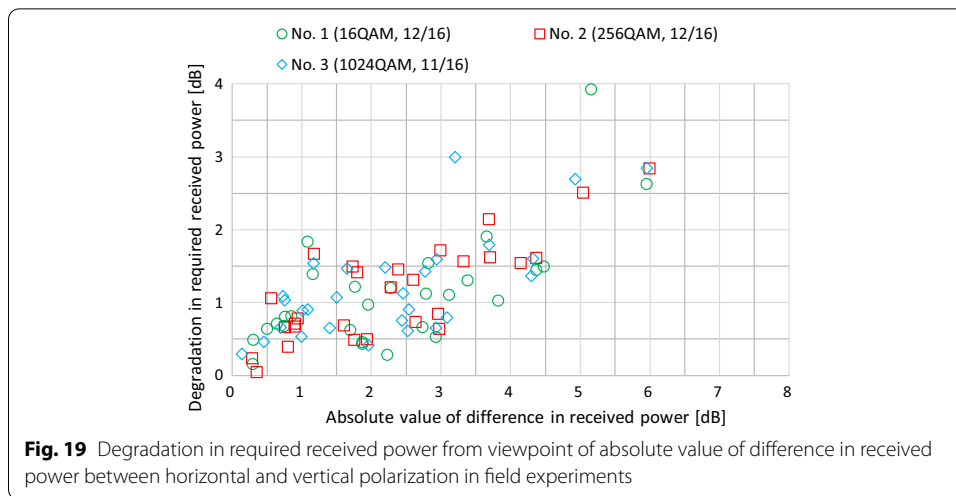


Table 8 Difference in required received power compared with SISO in field experiments (positive value means higher received power required)

	MIMO		
	No. 1 (64QAM, 12/16)	No. 2 (256QAM, 12/16)	No. 3 (1024QAM, 11/16)
Minimum	− 9.4	− 0.2	+ 2.6
Median	− 9.3	+ 0.1	+ 2.7
Maximum	− 7.3	+ 0.9	+ 3.7

the provision of a VVC-encoded 8 K program within a single 6-MHz channel. It is necessary to note that the MIMO gain (7.3 dB in robustness or greatly increased capacity) was obtained on the condition that the transmission power for MIMO is doubled compared with SISO.

4.3 Laboratory experiments for follow-up verification

As the main motivation to introduce MIMO in DTTB was improving the transmission capacity, parameter sets No. 2 and 3 were verified in the laboratory experiments. Figure 20 shows the results of plotting the degradation in the required C/N of SISO and MIMO by using the MIMO channel snapshots captured in the field experiments compared with the values measured in the AWGN channel shown in Table 5. The results showed that the degradation in the required C/N for SISO was smaller than that for MIMO at all 28 reception points when removing the uncertainties that affected the evaluation results in the field experiments. We observed in the experiments that the received power fluctuated. It was concluded that the fluctuation in the received power during the observation time slot for the $1\text{E} + 10$ bits would have affected the evaluation results in the experiments.

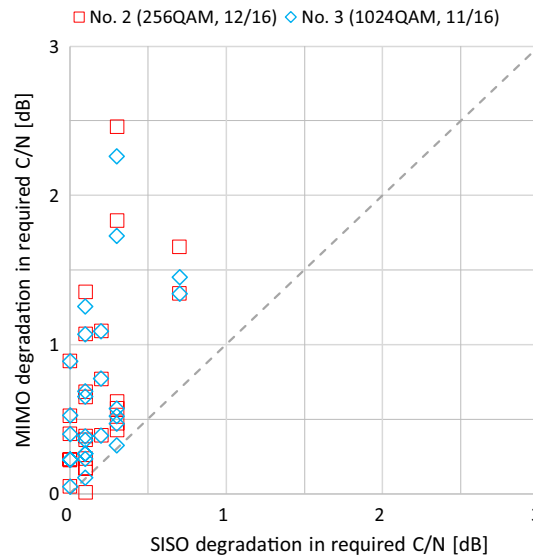


Fig. 20 Comparison of degradation in required C/N between SISO and MIMO for each MIMO channel snapshot compared with required C/N in AWGN channel in laboratory experiments

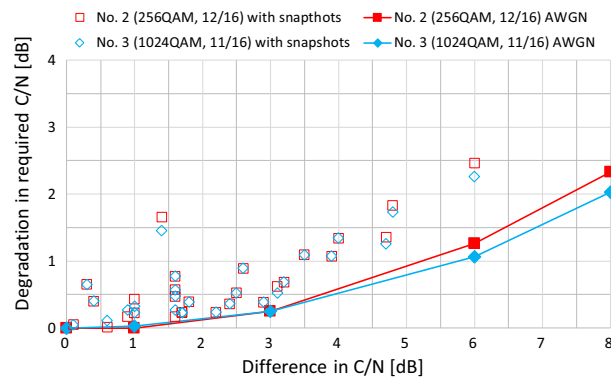


Fig. 21 Degradation in required C/N from viewpoint of difference in C/N between horizontal and vertical polarization for each MIMO channel snapshot compared with required C/N in AWGN channel in laboratory experiments

Figure 21 shows the degradation in the required C/N versus the difference in C/N between horizontal and vertical polarization with the MIMO channel snapshots compared with the values measured in the AWGN channel shown in Table 5. It was concluded that the degradation in the required C/N increased along with the increase in the difference in C/N between both polarizations. It was also confirmed that the degradation in required C/N for MIMO parameter sets No. 2 and 3 was almost the same at the 28 reception points.

Table 9 summarizes the degradation in required received C/N measured with the MIMO channel snapshots compared with that in the AWGN channel measured in the laboratory. As shown, the median value of the deterioration in SISO was 0.1 dB. For MIMO parameter sets No. 2 and 3, the median values were 0.5 dB, confirming that

MIMO did not experience a significant increase in required C/N compared with SISO when compared with the median values. The maximum degradation in SISO was 0.7 dB, while the maximum degradations were 2.5 and 2.3 dB for MIMO parameter sets No. 2 and 3. It was concluded that the degradation can increase in MIMO transmission in the worst case even in the reproduced static channel. It should be noted that the required C/N for MIMO was defined as the average value of horizontally and vertically polarized waves and that a difference in C/N can produce a certain level of degradation in MIMO transmission.

5 Conclusion

This paper presented the world's first MIMO terrestrial broadcast field measurements in an urban scenario with an HPHT network configuration. The field measurement results were validated with laboratory tests. The results showed that the required received power can be improved by at least 7.3 dB when improving transmission robustness while maintaining the same transmission capacity as SISO. Moreover, we confirmed that the transmission capacity can be doubled by introducing MIMO with the same modulation scheme and error correction code as SISO, although the required received power increased by 0.9 dB compared with SISO. Regarding the feasibility of the next-generation terrestrial broadcasting system operating at a target bit rate of about 60 Mbps to distribute a VVC-based 8 K program within the bandwidth of a single 6-MHz channel, received power increases of 3.7 dB and 2.7 dB were required compared with SISO at the maximum and median values for 28 reception points evaluated in urban areas, respectively.

The electric field strength for horizontal and vertical polarization was also evaluated. It was confirmed that the field strength differed up to 7.5 dB at the maximum and 2.5 dB at the median. The measurement results demonstrated that the field strength of vertical polarization tended to be higher than that of horizontal polarization at the reception points located in urban areas. The results showed no relationship between the transmission distance and the difference in field strength for horizontal and vertical polarization.

In terms of the median value of the degradation in required received power, the deterioration in MIMO was trivial compared with SISO for the three MIMO deployment scenarios. However, when we evaluated the maximum value of the degradation in received power at 28 locations, MIMO showed a significant deterioration in the worst case. The significant deterioration was confirmed at a few reception points at which the differences

Table 9 Degradation of required C/N measured with MIMO channel snapshots compared with AWGN channel in laboratory experiments

	SISO (256QAM, 12/16)	MIMO	
		No. 2 (256QAM, 12/16)	No. 3 (1024QAM, 11/16)
Minimum	0	0	0.1
Median	0.1	0.5	0.5
Maximum	0.7	2.5	2.3

in received power between the horizontal and vertical polarization were also significant. There was no relationship between the transmission distance and the amount of deterioration in the required received power.

Additionally, we compared the SISO and MIMO transmission performance by using MIMO channel snapshots excluding uncertainties occurring during field experiments, such as fluctuation in the field strength or the effect of a man-made noise occurring at the time of measurement. From the results of the laboratory experiments with the reproduced 28 channels, it was confirmed that the degradations in the required C/N of MIMO transmission were worse than those of SISO for all locations. The maximum amount of the degradation in the required C/N was 0.7 dB for SISO, while it was 2.5 dB for MIMO with the same modulation and code rate with the reproduced 28 channels. When introducing dual-polarized MIMO, a difference in the received power is unavoidable, and the required received power was considered to have deteriorated due to the difference in the received power.

These experiments were performed by using the signal format for advanced ISDB-T. These results should provide useful knowledge for introducing MIMO for terrestrial broadcasting over HPHT networks in the UHF band. For the next-generation FeMBMS system based on the state-of-the-art wireless communication system 5G [30], enhancements with MIMO that utilize multiple reception antennas equipped with receivers can be considered in future releases of 3GPP.

Abbreviations

ATT: attenuator; AWGN: additive white Gaussian noise; BER: bit error rate; CFR: channel frequency response; CP: cyclic prefix; C/N : carrier-to-noise ratio; DTTB: digital terrestrial television broadcasting; eMBMS: evolved multimedia broadcast multicast service; FDM: frequency division multiplexing; FeMBMS: further evolved multimedia broadcast multicast service; GI: guard interval; HDTV: high-definition television; HEVC: high-efficiency video coding; HPHT: high power high tower; IFFT: inverse fast Fourier transform; ISDB-T: integrated services digital broadcasting—terrestrial; LDPC: low-density parity check; LNA: low-noise amplifier; LOS: line-of-sight; MBSFN: multimedia broadcast multicast service single frequency network; MIMO: multiple-input multiple-output; QEF: quasi-error-free; Tx: transmitter; UHF: ultra-high frequency; UHDTV: ultra-high-definition television; VVC: versatile video coding; 3GPP: Third-Generation Partnership Project.

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Authors’ contributions

TS, NS, AS, and SK planned and conducted the laboratory/field experiments and analyzed the measurement results. TI, HM, SA, and TT took care of the implementation of the prototype modulator, demodulator, and MIMO channel analyzer. KK, MN, TN, and MO managed the experimental test station and funding. KT headed the program titled “Research and Development for Advanced Digital Terrestrial Television Broadcasting System.” All authors read and approved the final manuscript.

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