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Effects of Mutual Coupling and Doppler Spectrum on the Performance of 2 × 2 MIMO E-SDM Systems

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1. Intruduction

To satisfy the dramatically growing wireless mobile communication demands, using multiple antennas at both a base station and a mobile terminal, referred as a multiple-input multiple-output (MIMO) system, is a promising major breakthrough. Without additional power and spectrum compared with conventional single-input single-output (SISO) systems, channel capacity of MIMO systems can increase proportionally to the number of antennas in independent and identically distributed (*i.i.d.*) Rayleigh fading environments [1]. The performance of MIMO systems can be improved more by applying eigenbeam-space division multiplexing (E-SDM) technique when channel state information is available at a transmitter [2].

In actual communications, line-of-sight (LOS) waves may exist between the transmitter (TX) and the receiver (RX), and correlations between channels appear unlike *i.i.d.* fading environments. Also, mutual coupling between antenna elements, which affects the MIMO system performance, could not be ignored. In addition, due to the processing delay at the TX and the RX, a channel change during the delay may degrade the performance of MIMO E-SDM systems. Therefore, more investigations into the systems in realistic cases are necessary.

Doppler Spectrum is a useful measure to evaluate mobile communication applications [3]. There may be a relation between Doppler spectrum and the performance of MIMO E-SDM systems in time-varying fading environments. Besides, due to various scatterers' distribution, LOS wave existance, and multual coupling effect between antennas, Doppler spectrum of MIMO channels in actual environments may be different from the theoretical analyses. To the best of our knowledge, such work has rarely been considered. In addition, although measurement campaigns for time-varying fading environments are important, unfortunately, just a few MIMO measurement campaigns have been conducted in the environments until now [4].

We conducted MIMO measurement campaigns in indoor environments. Based on the measured channel data, in this paper we first examine average received power and Doppler spectrum in a case where the RX is moving while the TX and scatterers are fixed. Then, we evaluate the bit error rate (BER) performance of 2×2 MIMO E-SDM system in time-varying fading environments.

2. MIMO Channel Measurement Setup

The measurement campaigns were carried out in a metting room as shown in Fig. 1. In the room, 2 TX and 2 RX omnidirectional antennas were placed on two tables separated by 4 m. Channel responses were measured by a vector network analyzer and RF switches. The measurement band was from 5.15 GHz to 5.4 GHz, and we obtained 1,601 frequency-domain data with 156.25 kHz interval. The adjacent antenna spacing was 3 cm (half wavelength at 5 GHz), and two array orientations (TX-*x*/RX-*x*, TX-*y*/RX-*y*) along the *x*- and *y*-axes were considered. When there was a metal partition between the TX and RX antennas, we had a NLOS environment. In the absence of the partition, we had a LOS environment. At the RX side, a stepping motor was used to move the RX array along the *x*- or *y*-axis during the experiments. MIMO channels were measured at intervals of 0.88 mm, and we had in total 500 spatial measurement points. As a result, $1,601 \times 500 = 800,500$ channel matrices were obtained for each

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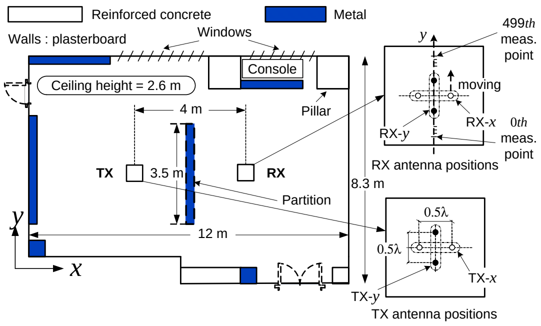
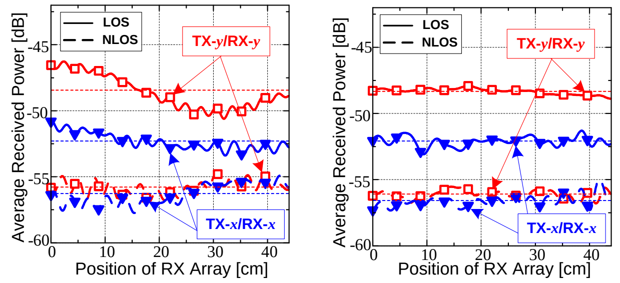
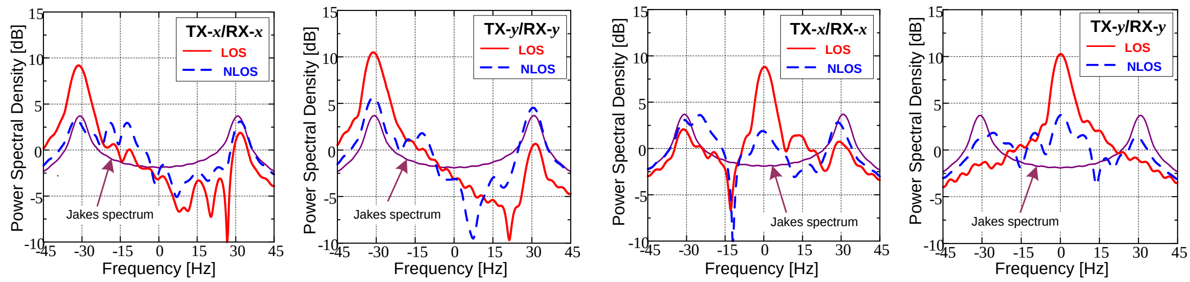


Figure 1: Measurement site (Top view).



(a) RX motion along the *x*-axis (b) RX motion along the *y*-axis

Figure 2: Average received power over antennas.



(a) RX array moves along the *x*-axis (b) RX array moves along the *y*-axis

Figure 3: Doppler spectrum.

case of the array orientation, LOS/NLOS condition, and direction of the receiver motion. It should be noted that the measurement campaigns were conducted while no one was in the room to ensure statistical stationarity of propagation.

3. Average Received Power

In this section, based on the measured channel data, we examine average received power of 2×2 MIMO channel with respect to the two cases of RX motion. The results are shown in Fig. 2. Higher received power is obtained for the TX-*y*/RX-*y* orientation than that for the TX-*x*/RX-*x* orientation, especially in the LOS case. This is because the antenna gain in a half-wavelength-spaced array for the opposite end in the MIMO system is higher for the TX-*y*/RX-*y* orientation than for the TX-*x*/RX-*x* orientation due to the effect of mutual coupling between antenna elements [5]. From the results, it is also seen that received power is more variable when RX array moves along the *x*-axis than when it moves along the *y*-axis. This is because of the effect of multipath signals in the fading environments.

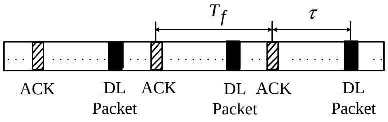
4. Doppler Spectrum of Actual MIMO Channels

We assume that a mobile terminal is moving at a constant velocity v. The relationship among the maximum Doppler frequency f_{dm}, wavelength λ, time interval Δt, and travel distance Δl for the terminal's motion is given by

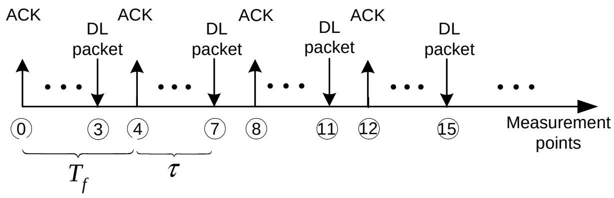
$$f_{\mathrm{dm}} = \frac{\Delta l}{\lambda\, \Delta t}\,. \tag{1}$$

Assuming that the time interval between the adjacent measurement points (Δl = 0.88 mm) is 0.5 ms (Δt = 0.5 ms), then f_{dm} is calculated from (1) as f_{dm} = 0.88(mm) / (5.7(cm) $\times$ 0.5(ms)) = 30.9 Hz, where the carrier frequency was assumed to be the center of the measurement band (5.275 GHz).

Based on the measured data, Doppler spectrum of 2×2 MIMO system when RX array moves along the *x*- and *y*-axes is estimated as shown in Fig. 3. The Doppler spectra of both the measured data and the Jakes model in Fig. 3 were calculated by applying the 450-point DFT process to the channel autocorrelation after multiplying it by the Hamming window.

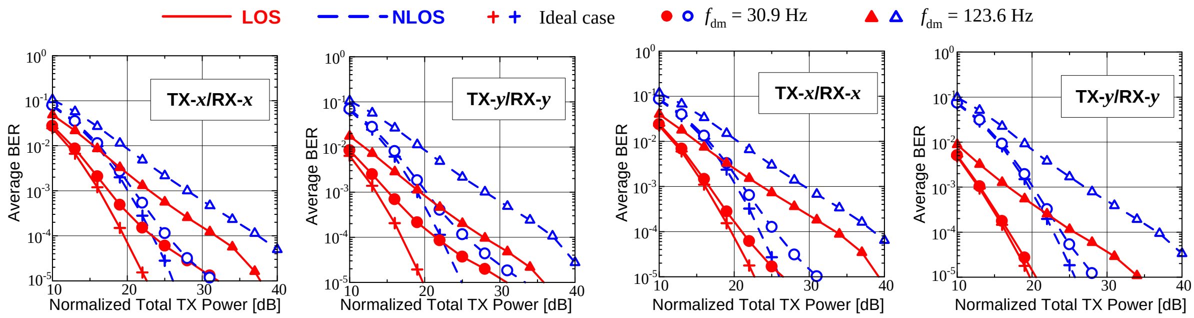


(a) TDD frame format



(b) Channels with f_{dm} = 30.9 Hz

Figure 4: Uplink and downlink MIMO channels in TDD transmission.



(a) RX array moves along the x-axis

(b) RX array moves along the y-axis

Figure 5: BER performance of 2×2 MIMO E-SDM system.

The results show that Doppler spectrum is much dependent on the direction of RX motion. In the LOS environment, when RX moves along the x-axis the Doppler spectrum is mainly concentrated at f_{dm} of ±30.9 Hz. On the other hand, when the array moves along the y-axis the Doppler spectrum is mostly distributed around 0 Hz. This is because most of dominant incoming waves were the direct wave (to $+x$ direction) from the transmitter to the receiver and the reflected wave (to $-x$ direction) from the wall. In the NLOS environment, the Doppler spectrum was expected to be the U-shaped Jakes' one. However, as shown in Fig. 3, the observed Doppler spectrum is quite different from one in the Jakes model. The reason for this is considered to be that scatterers in actual environments are not uniformly distributed around a receiver as those assumed in the Jakes model [6].

Doppler spectrum are also dependent on the antenna orientation. This is due to the effect of the mutual coupling between antennas at both TX and RX sides as described in the previous section.

5. Performance of MIMO E-SDM Systems In Time-Varying Channels

The terminal was assumed to be moving at a constant velocity v with $f_{\text{dm}} = 30.9$ Hz as stated in the previous section. The E-SDM technique was used for the downlink (DL) transmission in a time division duplex (TDD) system whose frame duration T_f was 2 ms as the HIPERLAN/2 standard [7]. Here, we also assumed that the time delay τ of the actual DL data transmission from ACK was 1.5 ms. The transmit weights were determined by the channel responses estimated by the uplink ACK packet periodically transmitted at times $i \times T_f$ $(i = 0, 1, \cdots)$, and DL packet transmission was done at times $i \times T_f + \tau$ as shown in Fig. 4(a). If the MIMO channels at the measurement points $4k$ $(k = 0, 1, \cdots)$ were those for the uplink ACK packets, then the MIMO channels at the measurement points $4k + 3$ were those for the DL packets as shown in Fig. 4(b). This is because the ratio τ/T_f was 3/4. If the terminal's velocity increased up to $4v$, then f_{dm} also went up to 123.6 Hz. In this case, the MIMO channel responses at the uplink ACK and DL packet times were given by ones at the measurement points $16k$ and $16k + 12$, respectively.

The average BER performance of 2×2 MIMO E-SDM system versus normalized total TX power with $f_{\text{dm}} = 30.9$ and 123.6 Hz is shown in Fig. 5. The normalized total TX power is the power that is normalized by the value yielding $E_s/N_0 = 0$ dB when a single antenna is used for transmission in an anechoic chamber with the same measurement setup as the LOS condition. In the ideal case in Fig. 5, the time delay from ACK to actual DL data transmission is equal to zero (i.e., $\tau = 0$). The details on the other simulation parameters are described in [8].

BER performance in the LOS environment is better than that in the NLOS one due to higher received power. BER performance is also dependent on the direction of RX motion and the antenna orientation. This is due to the effects of Dopper spectrum and mutual coupling between antenna elements. Considering with the Doppler spectrum shown in Fig. 3, we can see that the more concentrated to 0 Hz the Doppler spectrum is, the more robust to time-varying fading the BER performance is due to less channel transition. In addition, better BER performance can be obtained when both TX and RX arrays are oriented along the *y*-axis than that in the case where the arrays are aligned along the *x*-axis. From the results, it is also seen that the higher the f_{dm} is, the more the BER performance is degraded. This is because the more channel change in the time interval τ caused the larger inter-substream interference and did not lead the allocated bit and power adaptation to the optimal condition anymore. Therefore, a countermeasure such as a channel prediction scheme [8] is necessary for E-SDM transmission in time-varying fading environments.

6. Conclusions

In the paper, based on the MIMO measurement campaigns, we first examined the average received power and Doppler spectrum. The results showed that these fading properties are dependent not only on the direction of RX motion, but also on the array orientation. Simulation results based on the measured channel data also showed that the performance of MIMO E-SDM systems is affected by the mutual coupling between antennas and Doppler spectrum. It has been also shown that the channel changes during the interval between the transmit weight matrix determination and the actual data transmission can degrade the performance of MIMO E-SDM systems in actual communication environments.

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