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Impact of Channel Prediction on the Performance of MIMO E-SDM Systems in Actual Dynamic Channels

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1. Introduction

By transmitting orthogonal eigenbeams and controlling transmit data resource allocation, the Multiple-Input Multiple-Output (MIMO) system using an Eigenbeam-Space Division Multiplexing (E-SDM) technique, namely MIMO E-SDM system, performs very well and is considered as one of the promising candidates for future high-rate wireless communications [1–3]. However, the system performance may be degraded due to the processing delay at both the transmitter (TX) and the receiver (RX) in dynamic channels. Considering the delay in the channels, an effective approach in adaptive systems is to predict the channel values at the future data transmission time. We have proposed some channel prediction methods [4,5], and simulation results based on Jakes channel model [6] showed that MIMO E-SDM systems using the methods outperformed the conventional unpredicted system in Rayleigh fading environments.

In actual communications, scatterers may not be uniformly distributed around the RX and/or the TX, and MIMO systems may be used in Rician fading environments. Also, mutual coupling between antenna elements, which affects the MIMO system performance, could not be ignored. Therefore, more investigations into the system performance using the proposed methods in realistic cases are necessary.

Most of the MIMO measurement campaigns have been conducted in time-invariant (i.e., Doppler frequency of 0 Hz) fading environments until now. However, due to mobile terminals' and/or scatterers' motion there will be time-varying fading in actual environments. So, measurement campaigns for such environments are very important. Unfortunately, to the best of our knowledge, just a few MIMO measurement campaigns assuming the environments have been conducted [7].

We conducted MIMO measurement campaigns in indoor time-varying fading environments. Based on the measured data, we evaluated the impact of the channel predictions on the performance of the 2×2 MIMO E-SDM system in actual dynamic channels.

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, $1,601\times500 = 800,500$ channel matrices were obtained for each 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.

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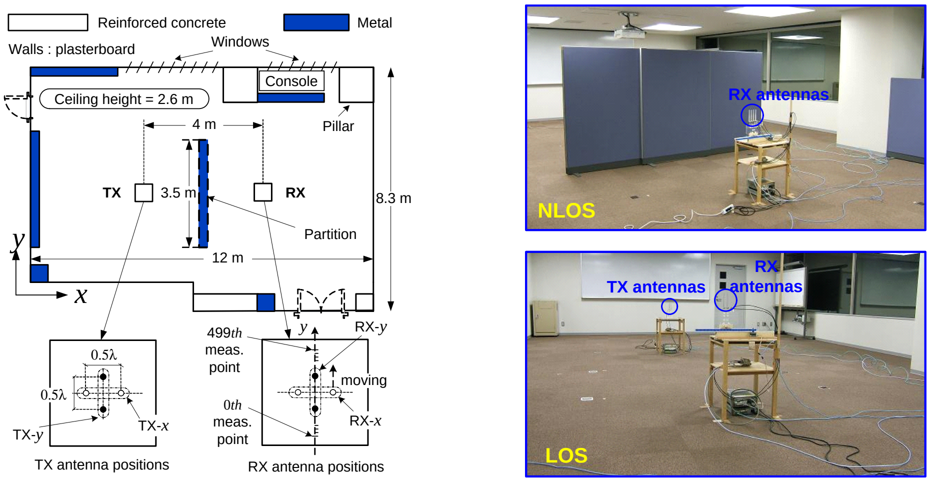
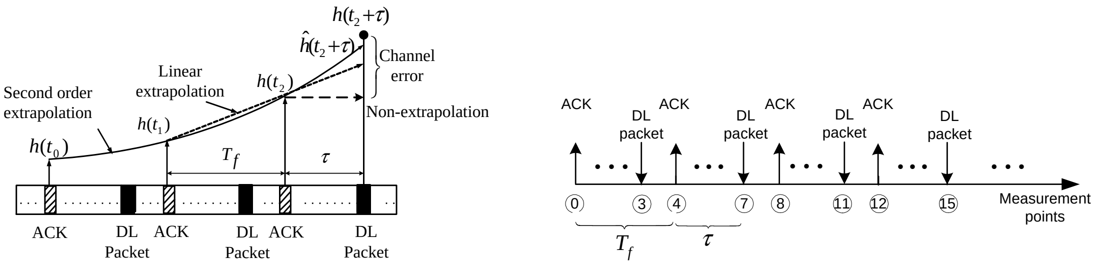


(a) Top view (b) NLOS and LOS environments

Figure 1: Measurement site.



(a) Extrapolation schemes (b) Uplink and downlink packets with $f_{\mathrm{dm}} = 30.9$ Hz

Figure 2: Channel predictions in a TDD system.

3. Channel Prediction Schemes

In dynamic channels, the time interval from the transmit weight matrix determination to the actual data transmission should be considered because a channel change during the interval may degrade the performance of MIMO E-SDM systems. Taking into account the problem, we have proposed some channel prediction methods [4, 5]. A brief description of two prediction methods is as follows. We assume that the E-SDM technique is used for the downlink (DL) transmission at time $t_2 + \tau$ in a time division duplexing (TDD) system as shown in Fig. 2(a). A transmit weight matrix is determined by channel responses estimated using uplink ACK packets. Unlike the conventional case in which the transmit weight is calculated at time t_2, in our methods channels are extrapolated to the actual DL data transmission time $t_2 + \tau$. Then, based on the predicted values the transmit weight is formed.

In the linear extrapolation method, channel responses are linearly extrapolated based on the last two successive sounding packets denoted by ACK as shown in Fig. 2(a), and the predicted CSI value is given by

$$\hat{h}_L(t_2+\tau) = h(t_2) + \tau\left(h(t_2)-h(t_1)\right)/T_f\ . \tag{1}$$

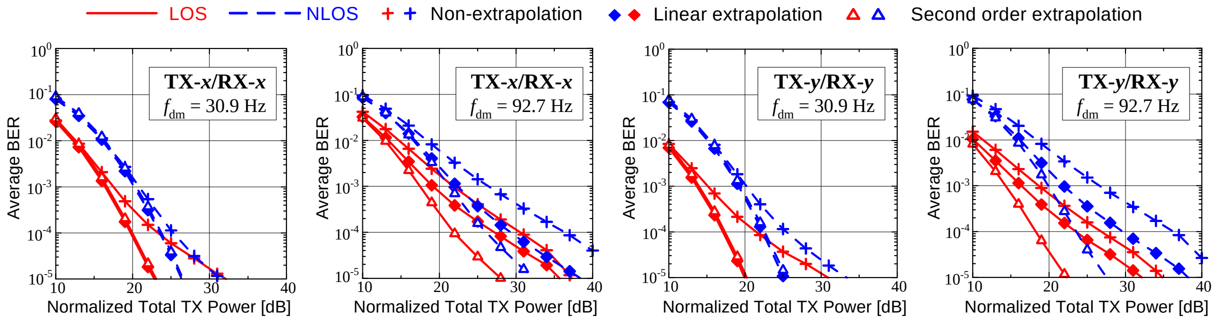
In the second order extrapolation method, the predicted channel value is calculated using the last three successive channel values as shown in Fig. 2(a):

$$\hat{h}_S(t_2+\tau) = h(t_0) + \frac{2T_f+\tau}{T_f}(h(t_1)-h(t_0)) + \frac{(2T_f+\tau)(T_f+\tau)}{2T_f^2}(h(t_2)-2h(t_1)+h(t_0))\ . \tag{2}$$

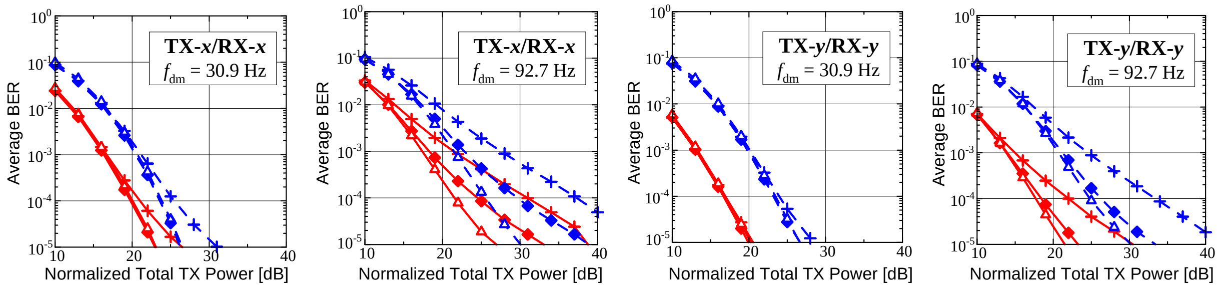
In (1) and (2), T_f is the frame duration of the TDD system, τ is the time interval between the weight determination and the actual data transmission for the DL packet, $h(t_0)$, $h(t_1)$ and $h(t_2)$ are the measured channel values at times t_0, t_1 and t_2, respectively. It should be noted that channel prediction is applied

Table 1: Measurement points used for different extrapolations.

f_{dm}(Hz)	Measurement points for uplink ACK packets			Measurement points for DL packets
	Second Order Extrapalation	Linear Extrapolation	Non-Extrapoaltion	
30.9	$4k, 4(k+1), 4(k+2)$	$4(k+1), 4(k+2)$	$4(k+2)$	$4(k+2)+3$
92.7	$12k, 12(k+1), 12(k+2)$	$12(k+1), 12(k+2)$	$12(k+2)$	$12(k+2)+9$



(a) RX array motion along the *x*-axis



(b) RX array motion along the *y*-axis

Figure 3: BER performance of 2×2 MIMO E-SDM system.

to all MIMO channel responses, thus indices $_{ij}$ of $h_{ij}(t)$ ($1 \leqq i \leqq N_R$, and $1 \leqq j \leqq N_T$) in (1) and (2) are omitted for simplicity, where N_R and N_T denote the number of the RX and TX antennas, respectively.

4. BER Performance in Actual Dynamic Channels

A mobile terminal is assumed to be moving at a constant velocity v. The relationship among the maximum Doppler frequency f_{dm}, wavelength λ, time interval Δt, and travel distance Δl is given by

$$f_{\mathrm{dm}} = \frac{\Delta l}{\lambda\,\Delta t}\,. \tag{3}$$

Here, we assumed that the frame duration T_f was 2 ms as the HIPERLAN/2 standard [8], and the time delay τ of the actual DL data transmission from ACK was 1.5 ms. If the MIMO channel responses at measurement points $4k$ ($k = 0, 1, \cdots$) were those for the uplink ACK packets, then the MIMO channel responses at the measurement points $4k + 3$ were those for DL packets as shown in Fig. 2(b). This is because the ratio τ/T_f was 3/4. With these assumptions, f_{dm} was calculated from (3) as $f_{\mathrm{dm}} = 4 \times 0.88$ mm / (5.7 cm $\times$ 2 ms) $=$ 30.9 Hz, where the carrier frequency was assumed to be the center of the measurement band (5.275 GHz), and it should be noted that the spacing between the adjacent measurement points was 0.88 mm as stated in Section 2 ($\Delta t = T_f = 2$ ms, $\Delta l = 4 \times 0.88$ mm). If the mobile's velocity increased up to $3v$, then f_{dm} also went up to 92.7 Hz. In this case, the MIMO channel responses at the uplink ACK and DL packet times were given by ones at the measurement points $12k$ and $12k + 9$, respectively. The MIMO channel measurement points used for the uplink ACK and DL packets corresponding to the f_{dm} values are summarized in Table 1.

The average BER performance of 2×2 MIMO E-SDM system versus normalized total TX power at $f_{\mathrm{dm}} = 30.9$ and 92.7 Hz is shown in Fig. 3. 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. The details on the other simulation parameters are described in [5].

BER performance in the LOS environment is better than that in the NLOS one due to higher received power. The BER performance is also dependent on the direction of RX motion and the array orientation. This is because of the effects of Doppler spectrum and mutual coupling between antenna elements.

The BER performance for the non-extrapolation case is seriously degraded not only at $f_{\mathrm{dm}} = 92.7$ Hz for two cases of the RX motion, but also at $f_{\mathrm{dm}} = 30.9$ Hz when RX array motion along the x-axis. This is because the channel transition during the time interval τ caused the large loss of subchannel orthogonality, which resulted in large inter-substream interference. Moreover, the channel transition did not lead the allocated resource to the optimal condition anymore.

On the other hand, the BER performance is much robust to the channel transition by using two channel prediction methods. The reason is that the extrapolation methods compensated for the channel change, then the resource allocation was still adequate, and inter-substream interference was much reduced. At $f_{\mathrm{dm}} = 30.9$ Hz, the BER performance for both of the extrapolation methods is almost the same. However, at $f_{\mathrm{dm}} = 92.7$ Hz the linear extrapolation is not good enough due to the prediction error. In such a case, the second order extrapolation is the better choice for robustness of the BER performance. As a result, we can say that the extrapolation techniques are effective also in the actual indoor environments.

5. Conclusions

Based on the indoor measurement campaigns, we have examined the BER performance of 2×2 MIMO E-SDM system in dynamic channels. The results showed that the BER performance can be seriously degraded due to the processing delay at the transmitter and the receiver in actual time-varying fading environments. It has been also shown that by using our proposed channel prediction methods, the BER performance of MIMO E-SDM systems can be significantly improved in the environments. In a low Doppler frequency region, it is better to use the linear extrapolation for simplicity. The second order extrapolation on the other hand needs to be used in a high Doppler frequency region.

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