On Mode Adaptation for MIMO-OFDM-BICM Based on Measured Indoor Channels

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***Abstract*— This paper examines mode adaptation for MIMO-OFDM-BICM systems. Our results are based on measured MIMO-OFDM channels in an indoor environment at 5 GHz. We demonstrate that a simple zero-forcing spatial multiplexing system using four transmitters and four receivers can achieve four times the SISO data rate over the real measured channels with less than 6 dB increase in SNR. We also observe that it in fact has less mode switching compared to SISO, which can have certain implementation advantages.**

I. Introduction

The use of multiple-input multiple-output orthogonal frequency division multiplexing bit interleaved coded modulation (MIMO-OFDM-BICM) has been considered for the physical layer transmission scheme of the next generation wireless communication systems [1]. This technology enables the frequency bandwidth efficiency of a wireless link in a multipath environment to be increased by a factor approaching the minimum of the number of transmitters and the number of receivers. A commercial product utilizing two transmitters and three receivers achieving 6 bps/Hz bandwidth efficiency for wireless local area networks (WLAN) is currently available, while the WLAN standardization group is aiming to achieve 15 bps/Hz bandwidth efficiency using four transmitters [2].

Adaptive bit-interleaved coded modulation is a method to increase the bandwidth efficiency and/or bit error performance of a wireless link by optimizing/sub-optimizing the transmission scheme depending on the particular channel [3]. Popular IEEE 802.11a based devices may use a simple adaptive scheme (also known as link adaptation), in which the signal constellation can be selected from BPSK, QPSK, 16QAM, and 64QAM, and the coding rate from $1/2$, $2/3$, and $3/4$ depending on the available signal to noise ratio (SNR) [4]. While the standard does not specify how the modulation and coding scheme (MCS) should be selected for a particular channel, it is typically implemented by the transmitter using knowledge of the packet error rate (PER) at the receiver [5]. If the packet error rate observed with a particular MCS exceeds a predetermined threshold, an MCS with a smaller constellation size and/or lower coding rate should be used in order to reduce the packet errors in the faded channel.

In this paper, the variation in optimum mode as a function of the location of the receiver in a local area when using a MIMO-OFDM-BICM system with mode adaptation is examined. We use MIMO-OFDM channels measured in an indoor environment at 5 GHz. In particular, the advantage of a MIMO system over a single-input single-output (SISO) system is highlighted by comparing the variability of the modes as a function of displacement of the receiver.

The paper is structured as follows. The procedure and the results of MIMO-OFDM channel measurements performed in an indoor environment are given in Section II. The MIMO-OFDM-BICM system under consideration is briefly described in Section III. The PER performance for various MCSs and the results of link adaptation simulation, both based on the measured MIMO-OFDM channels, are given in Section IV and Section V, respectively. Conclusions are given in Section VI.

II. MIMO-OFDM Channel Measurement

A. Measurement Procedure

The MIMO-OFDM channel measurement was performed by using a MIMO testbed developed by the CSIRO ICT Centre. Currently the testbed is equipped with four transmitters and four receivers and is expandable to eight transmitters and eight receivers. Commercially available omnidirectional antennas are used both for transmitter and receiver arrays. The antenna elements are placed in a square array fashion with a spacing of three wavelengths for the transmitter emulating an access point and two wavelengths for the receiver emulating a laptop PC client. The testbed operates at a carrier frequency of 5.25 GHz and supports an operational bandwidth of up to 40 MHz. Users can generate, via software, signals which are simultaneously sent from the transmitters, and captured as multiple signal streams at the receivers.

For the purpose of the channel estimation, the channel training sequence defined in [2] is utilized. The receiver antenna array is connected to an antenna array positioner which moves the receiver antenna array within an area of four wavelengths $\times$ four wavelengths with 0.05 wavelength increment, resulting in 6400 locations. The MIMO-OFDM channel which consists of 16 MIMO sub-channels each using 114 OFDM sub-carriers is characterized at each of 6400 receiver antenna array locations, resulting in approximately 12 million complex channel coefficients per a local area.

The measurement was performed in the CSIRO's Radio Physics Laboratory in Sydney, Australia. A non-line-of-sight path was established by placing the transmitter and the receiver in different rooms with a direct separation distance of approximately 8 m. The measurement was conducted during

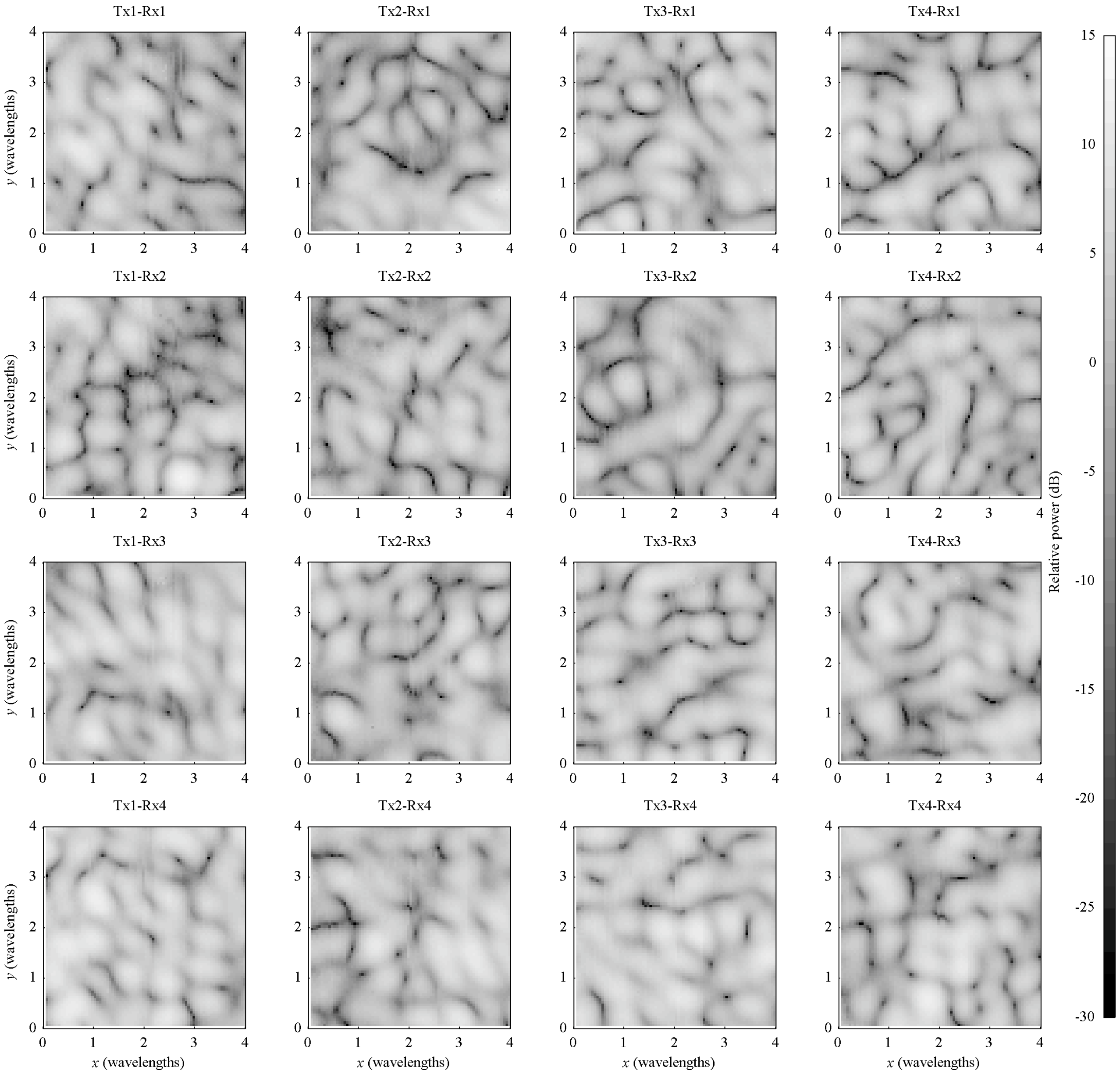


Fig. 1. Small-scale fading map for the 4×4 MIMO sub-channels at one of the OFDM sub-carriers.

night to avoid channel variation due to human activities. More details about the measurement are given in [6].

B. Measurement Results

Fig. 1 shows an example of the small-scale spatial fading pattern measured for one of the OFDM sub-carriers over each of the 16 MIMO sub-channels. Deep fading typical of a multipath environment can be seen with no apparent correlation between the MIMO sub-channels. The distribution of the channel gain was found to be Rayleigh [6] while the cross correlation magnitude of the MIMO sub-channels was observed to be 0.22 on average [9], indicating good uncorrelated Rayleigh MIMO channels. This set of measured MIMO-OFDM channels was used for the evaluation of selected modes in SISO and 4×4 MIMO-OFDM-BICM systems in the following sections.

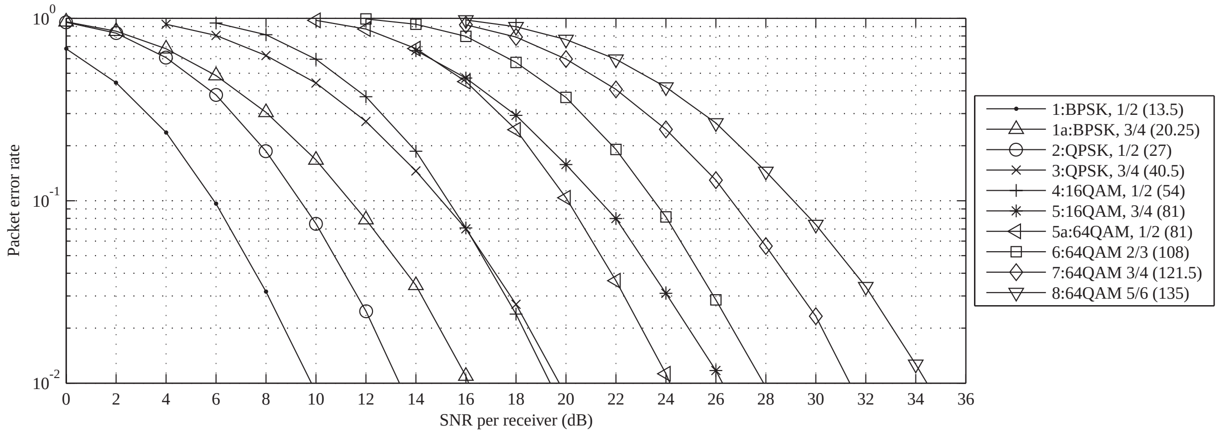
III. MIMO-OFDM-BICM SYSTEM

The draft proposal to the IEEE 802.11n Standard by the TGn Sync group [2] specifies the use of various modulation and coding combinations, a subset of which are given in Table I. In referring to the different combinations, the MCS Index is used in [2] while the Mode Index is used in this paper for simplicity. For MIMO signal detection, simple zero-forcing detection (ZFD) [7], [8] is used, which is believed to be a popular implementation for the initial deployment of the 4×4 MIMO-OFDM-BICM systems. The mandatory convolutional code rather than the optional low-density parity check code

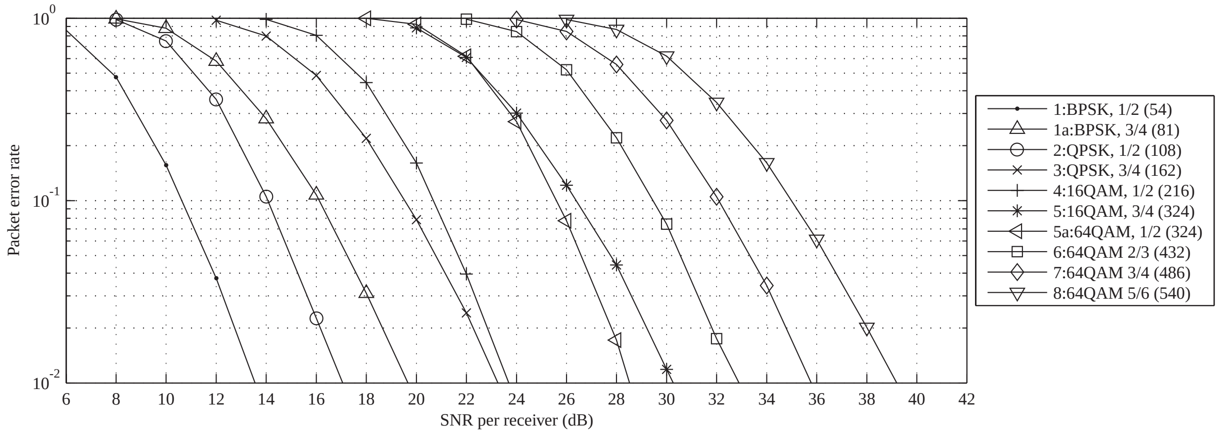
TABLE I

MCS SPECIFIED IN [2] FOR 4×4 MIMO.

MCS Index	24	25	26	27	28	29	30	31
Mode Index	1	2	3	4	5	6	7	8
Modulation	BPSK	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM	64QAM
Coding Rate	$1/2$	$1/2$	$3/4$	$1/2$	$3/4$	$2/3$	$3/4$	$5/6$
Data Rate (Mbps)	54	108	162	216	324	432	486	540
Bandwidth Efficiency (bps/Hz)	1.35	2.7	4.05	5.4	8.1	10.8	12.15	13.5



(a) 1×1 SISO-OFDM-BICM results.



(b) 4×4 MIMO-OFDM-BICM results.

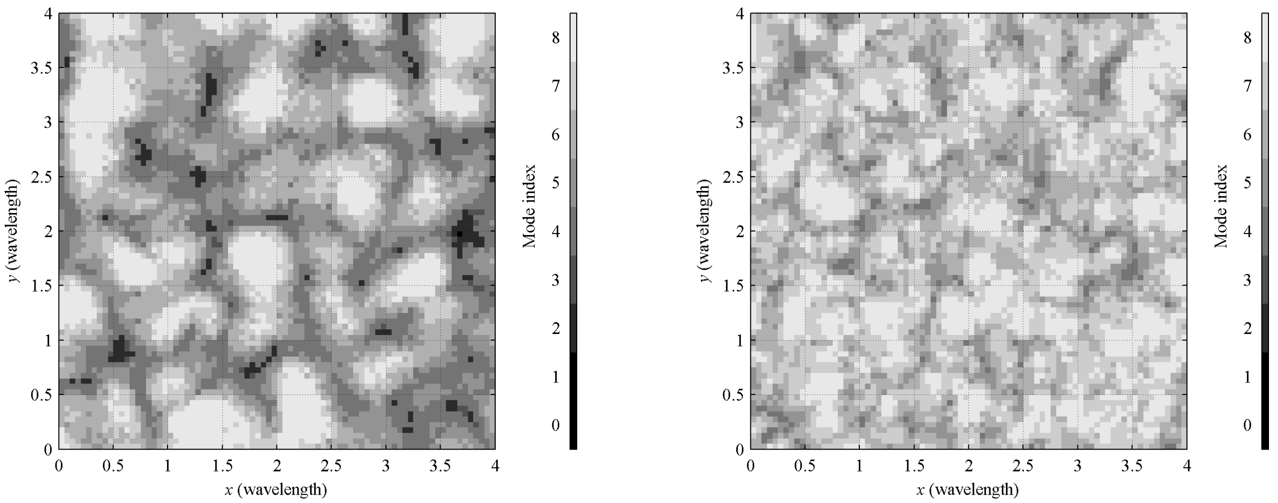
Fig. 2. Packet error rate as a function of SNR per receiver. The number in parenthesis indicates supported data rate in Mbps.

is used in the following analysis. The traceback length of the soft Viterbi decoder is set to 140 which has been found to provide enough convergence with the highest coding rate of $5/6$ used in the following simulation. The data part of a packet consists of 30 OFDM symbols which amounts to a number of information bits ranging from 12,960 bits to 64,800 bits depending on the Mode Index used.

IV. PER PERFORMANCE BASED ON MEASURED CHANNELS

The packet error performance of a SISO- and 4×4 MIMO-OFDM-BICM system is shown in Fig. 2 for different MCS as given in Table I. The cuvers were generated by using the measured channels and adding the additive white Gaussian noise (AWGN). The SNR is calculated by averaging over all MIMO sub-channels, all OFDM sub-carriers, and all antenna array locations. This method provides a performance indicator related to average SNR over a local area and corresponds to the situation of constrained transmit power. For SISO-OFDM-BICM simulation, the channel from the transmitter 1 (Tx1) to receiver 1 (Rx1) is used. The effects of inter-symbol-interference are neglected, assuming that the guard interval of 800 ns employed is enough to mitigate the problem.

In addition to the modes as defined in Table I, the results for two new MCSs are given in Fig. 2. The first employs BPSK modulation with the rate $3/4$ coding, indicated as Mode 1a, and the second employs 64QAM modulation with the rate $1/2$ coding, indicated as Mode 5a. Mode 1a has been



(a) SISO-OFDM-BICM simulation result (SNR=20 dB).

(b) 4×4 MIMO-OFDM-BICM simulation result (SNR=30 dB).

Fig. 3. Maps of supported mode and 1×1 SISO and 4×4 MIMO OFDM-BICM systems.

used in the IEEE 802.11a standard as one of the mandatory modes. It is interesting to note that this mode performs worse (requires more SNR to achieve the same PER) than the Mode 2, which provides the higher data rate. This is believed to be the effect of punctured $3/4$ coding used in the IEEE 802.11a not performing well in the Rayleigh channel. Similarly, 64QAM with rate $1/2$ coding, Mode 5a, is performing better than 16QAM with rate $3/4$ coding, Mode 5, achieving the same data rate. Similar results for the SISO case have been reported by several researchers (e.g. [10], [11]). The performance of Mode 3 and 4 are found to be very close with crossing locations depending on the PER, which has also been reported in [11]. Note that the simulation is based on perfect knowledge of the channel at the receiver and that no system imperfections such as quantization noise are incorporated. The lower order modulation may be less degraded by such system imperfections than higher order modulation, so in practice the Mode 1a may well be performing better than the Mode 2. Note that the TGn Sync specification has removed the use of Mode 1a.

For an uncoded system with N_t transmitters and N_r receivers, it has been observed that the diversity order of the MIMO system using ZFD is $N_r - N_t + 1$ [8] while that using the maximum likelihood detection approaches N_r for large N_r [12], assuming independent and identically distributed Rayleigh fading channels. Hence if $N_t = N_r = N$ antennas are employed in a MIMO-ZFD system, the diversity order is equal to one. In this case, the symbol error performance of a SISO system and an $N \times N$ MIMO-ZFD system differ only by the change in the SNR of $10 \log_{10} N$ dB [13]. In our case, this should result in the shift of PER curves by 6 dB. By comparing the plots in Fig. 2, it can be observed that the MIMO PER curves have significantly less than the 6 dB shift of the corresponding SISO PER curves as mentioned above, and a sharper roll-off indicative of diversity.

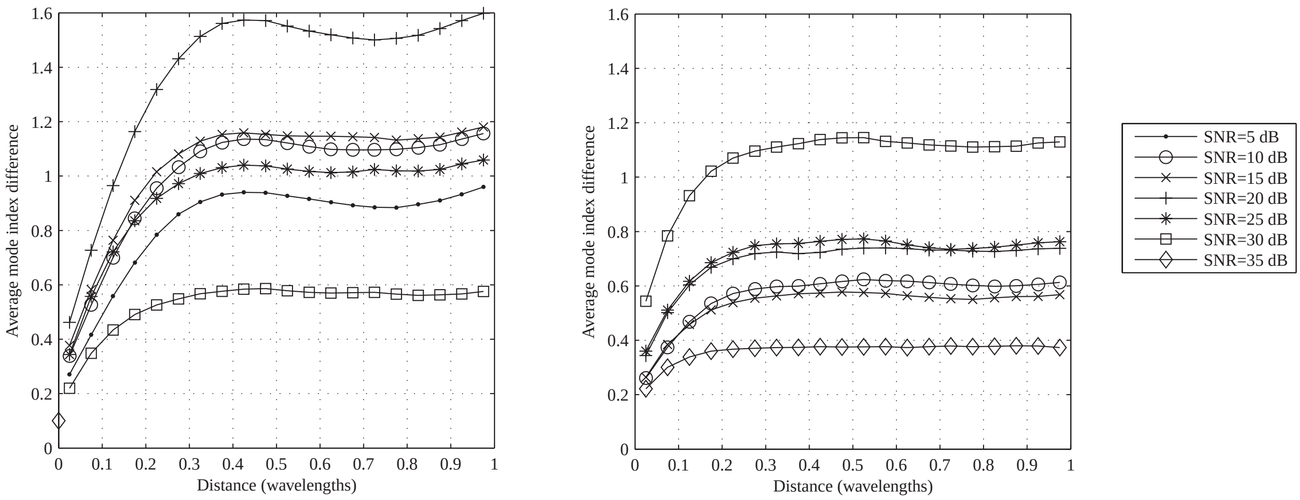
This effect is attributed to a spatial diversity component in the MIMO case, provided via the FEC decoder. Hence an extra space diversity gain can be obtained without sacrificing the spatial multiplexing gain by interleaving coded bits across different transmitters.

In summary, we have demonstrated that the simple MIMO-ZFD system employing four transmitters and four receivers can achieve four times the data rate of SISO system over the real measured channels with less than 6 dB increase in SNR requirement.

V. Link Adaptation Based on Measured Channels

We propose to investigate link adaptation in MIMO-OFDM-BICM systems by considering a basic mode switching strategy as follows: For each of the 6400 MIMO-OFDM channels, five packets are sent using the lowest mode (Mode 1) with random information bits and random noise with a specified average SNR per receiver. If the five packets were received without any errors, another five packets are sent using the next higher level mode. If any packet is received with an error, the simulator concludes that the highest mode selected for the particular MIMO-OFDM channel with the specified SNR is the one which allowed the transmission of five consecutive packets without any error. We have chosen this simple and practical strategy so that the effects of link adaptation can be seen clearly.

The link adaptation simulation was performed for various SNR values with 5 dB increament. It is noted that no mode switching would result if a very large or very small SNR value is specified. The largest mode variation was obsereved with the SNR value of 20 dB in the case of SISO system and with 30 dB in the case of MIMO system. Figures 3 shows examples of Mode Indices selected for the SISO- and 4×4 MIMO-OFDM-BICM systems with a specified average SNR per receiver of 20 dB and 30 dB, respectively. Substantial variation in selected mode, for example 2 to 3 differences in Mode Index within the distance of a wavelength, can be seen in the case of a SISO system. This indicates that, while the use of a wideband system



(a) SISO-OFDM-BICM

(b) 4×4 MIMO-OFDM-BICM

Fig. 4. Average mode index difference.

(40 MHz) mitigates the effect of narrowband fading, this is not enough to overcome the wideband fading experienced in this environment. The mode index variation in the case of a MIMO system exhibits relatively small variation with only a few occasions when the mode indices differ by 3 or more.

The maps of selected modes for different SNR values were then analysed in order to determine the average difference in mode indices as a function of receiver antenna array displacement. At each of 6400 receiver antenna array locations, the absolute difference between the selected mode indices at the original location and at the location d wavelength away in positive or negative x or y directions is determined. The values are averaged over all directions and for all receiver antenna array locations to give average absolute mode index difference, δ, at distance d. The results are given in Fig. 4.

As expected, δ increases as we move the receiver antenna array from the original location. However, δ does not continue to increase once the distance is more than 0.5 wavelengths. It can be seen that δ also depends on the specified average SNR per receiver. This can be explained by referring to Fig. 2 where if the SNR requirements of different modes are closely spaced, more variation in mode is expected within a small variation of the SNR.

However, in general, it can be seen from Fig. 4 that a 4×4 MIMO system shows smaller variation than that of a SISO system. This reveals that the MIMO system can sustain a more uniform link within a local area, even with a simple ZFD, due to added space diversity with a space-interleaved coding.

VI. Conclusions

In this paper, the performance of MIMO-OFDM-BICM system using four transmitters and four receivers was examined based on MIMO-OFDM channels measured in an indoor environment at 5 GHz. We showed that the 4×4 MIMO-OFDM-BICM system employing spatial multiplexing and simple zero-forcing MIMO detection could achieve four times the SISO data rate over practical channels with less than 6 dB increase in SNR requirement. We also showed that the MIMO system had less mode switching compared to SISO system. These results are useful in designing the next generation WLAN systems.

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