

Performance of Antenna Selection for MIMO-OFDM Systems Based on Measured Indoor Correlated Frequency Selective Channels

Zhongwei Tang, Hajime Suzuki and Iain B. Collings

CSIRO ICT Centre

Sydney, Australia

zhongwei.tang@csiro.au, hajime.suzuki@csiro.au, iain.collings@csiro.au

Abstract— This paper presents and compares antenna selection strategies for frequency selective MIMO-OFDM channels. Real channels are measured, and used to evaluate performance. Results for simulated TGn channel models are also presented. We show that the capacity gain predicted from the simulated channels, is significantly lower than can be achieved over real channels. This supports the use of antenna selection in practical MIMO-OFDM systems.

Keywords— antenna selection; channel capacity; frequency selective; MIMO measurement; MIMO-OFDM;

I. INTRODUCTION

Multi-antenna transmission (multiple-input multiple-output, MIMO) allows for high data rates and improved quality of wireless transmission. This is especially the case for orthogonal frequency division multiplexing (OFDM) systems [1]. Recently, MIMO has been adopted by the IEEE 802.11n Wireless LAN and IEEE 802.16e WiMAX standards. The performance gains can be significant, but the trade-off is that hardware requirements increase since full MIMO systems require multiple antenna elements and multiple RF chains to be deployed. This can be costly and power consuming. Antenna selection techniques present a compromise. They allow for the deployment of a small number of RF chains, each of which serves multiple antenna elements in a switched manner; thus capturing many of the advantages of MIMO systems.

Most antenna selection techniques have been developed for conventional flat fading narrowband channels [2-4]. These techniques need to be extended if they are to be applied to wideband OFDM WLAN systems. For example the proposed channel bonding technique in IEEE 802.11n occupies a bandwidth of 40 MHz. Such wideband channels have significant frequency selectivity. It is not clear that antenna selection transmission/reception techniques will work for such channels. To date, studies on antenna selection in MIMO-OFDM systems have been limited to simulation studies which neglect antenna effects [5, 6].

This paper presents a more complete and accurate performance evaluation using real measured MIMO-OFDM wideband channel data. Results for simulated TGn channel models are also presented for comparison. We show that the

capacity gain predicted from the simulated channels, is significantly lower than can be achieved over real channels. This supports the use of antenna selection in practical MIMO-OFDM systems.

Our results also point out that the achievable capacity gain of MIMO-OFDM antenna selection decreases with increasing frequency selectivity and bandwidth.

This paper is organized as follows. In Section II, we briefly discuss MIMO antenna selection for flat fading channels. In Section III, antenna selection for MIMO-OFDM system is introduced, including four selection methods. Sections IV and V present IEEE 802.11n channel models and our indoor MIMO-OFDM channel measurements. Section VI presents performance results of MIMO-OFDM antenna selection. Finally, we conclude and summarize the paper in Section VII.

II. MIMO ANTENNA SELECTION

MIMO antenna diversity methods such as beamforming improve the robustness of the communication systems in terms of bit error rate (BER), while MIMO spatial multiplexing transmits parallel independent data streams and thus achieves higher data rates. In this paper, we consider multiplexing schemes, but limit the data streams to a smaller number than the number of available antennas (to save on RF hardware). The multiple data streams are switched between selected antennas according to certain criteria, as discussed below.

For a flat fading MIMO system with N_T Tx and N_R Rx antennas, the MIMO signal is modeled as:

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad (1)$$

where \mathbf{s} is transmit vector symbol, \mathbf{r} is receive vector symbol, \mathbf{n} is the additive white Gaussian random vector, and \mathbf{H} is the flat-fading channel matrix. The channel capacity using all antenna elements, under uniform transmitting power allocation scheme, is given by

$$C_{full} = \log_2 \left\{ \det(\mathbf{I}_{N_R} + (\bar{\Gamma} / N_T) \mathbf{H}\mathbf{H}^H) \right\} \quad (2)$$

where $\bar{\Gamma}$ is the mean signal-to-noise ratio (SNR) per Rx branch.

By employing only a subset of selected antennas, the channel capacity becomes

$$C_{select} = \log_2 \left\{ \det(\mathbf{I}_{L_R} + (\bar{\Gamma}/L_T) \tilde{\mathbf{H}} \tilde{\mathbf{H}}^H) \right\} \quad (3)$$

where $\tilde{\mathbf{H}}$ is the channel matrix for the selected antennas, and L_R , L_T are the numbers of selected receive and transmit antennas, respectively.

Based on this capacity criterion, many research efforts have focused on finding the optimal $\tilde{\mathbf{H}}$ which maximizes C_{select} and various algorithms have been proposed [2-4, 6] for flat-fading channels and the value of antenna selection has been confirmed. However, very little work has been done for wideband frequency-selective channels.

For a MIMO-OFDM system, with N frequency subcarriers, the dimensions of the channel matrix before selection are $N \times N_R \times N_T$. After antenna selection at either one end or both sides, the dimensions reduce to $N \times L_R \times L_T$. It should note that the selected antenna sets are used for all OFDM subcarriers. With antenna selection, the channel capacity is given by

$$C_{select} = \frac{1}{N} \sum_{k=0}^{N-1} \log_2 \left\{ \det(\mathbf{I}_{L_R} + (\bar{\Gamma}/L_T) \tilde{\mathbf{H}}_k \tilde{\mathbf{H}}_k^H) \right\} \quad (4)$$

III. MIMO-OFDM ANTENNA SELECTION ALGORITHMS

In this paper, we present four MIMO-OFDM antenna selection methods (SM) and study them in a range of indoor propagation conditions.

SM 1: Capacity optimum search: This criterion was proposed for flat fading in [2, 3, 6]. In this paper, we extend the approach to MIMO-OFDM systems. It consists of selecting the subset of transmit/receive antennas that has maximum MIMO-OFDM capacity. It involves exhaustive searching over all possible antennas sets for all OFDM subcarriers and its complexity scales exponentially with L_T , N_T , L_R and N_R . This selection algorithm serves an upper bound of the performance for any other antenna selection algorithms.

SM 2: Minimum ratio of maximum and minimum channel eigenvalues: For each channel matrix, define a parameter as the ratio between the maximum and the minimum channel eigenvalues:

$$G = \lambda_{max} / \lambda_{min} \quad (5)$$

where λ_{max} and λ_{min} are the largest and smallest channel eigenvalue. This parameter reflects the spread between the best and the worst eigenmodes of a MIMO link. For equal power spatial multiplexing MIMO systems, smaller G corresponds to higher performance. It is used as a criterion for adaptive transmission between beamforming and spatial multiplexing in [8, 9]. In this paper the parameter is adopted for selecting

antenna elements. For MIMO-OFDM antenna selection, the subset of transmit/receive antennas is firstly determined for each OFDM tone. Then the subset, which is chosen with the largest number of OFDM tones, is selected.

SM 3: Maximum minimum channel eigenvalue. In [10], it is shown that the minimum channel eigenvalue affect the error performance of the spatial multiplexing with maximum likelihood and zero-forcing receivers. Using the minimum eigenvalue as selection criterion, about 6 dB BER improvement is found for MIMO-OFDM with selecting 2 over 3 transmit antennas over channel 'A' defined for HIPERLAN/2 [5]. Here, we use this criterion for MIMO-OFDM antenna selection to pursue capacity gain. It is to choose the transmit and/or receive antenna set, whose corresponding channel matrix has the largest minimum eigenvalue, λ_{min} with the highest number of OFDM tones.

SM 4: Maximum SNR method: This criterion was proposed for flat fading MIMO channels in [3, 6, 10]. This method is performed by maximizing the receive SNR, which is equivalent to maximizing the Frobenius norm of the channel matrix, and hence to improve capacity and the instantaneous error performance [10]. Instead of directly calculating Frobenius norm for all possible subsets of transmit/receive antennas, the method here is simplified by firstly choosing a subset of transmit antennas that maximize the Frobenius norm using all receive antennas. Then choose a subset of receive antennas that maximize the Frobenius norm using all transmit antennas. For OFDM subcarriers, the antenna subset, which has the largest Frobenius norm with the highest number of OFDM tones, is selected.

The complexity of SM 2 and SM 3 are similar since both involve the calculation of eigenvalues, with SM 3 being slightly simpler. SM 4 is the simplest which uses channel gain only. The used channel data include both standardized channel models and real MIMO-OFDM channel data obtained in an office environment.

IV. INDOOR CHANNEL MODELS FOR MIMO WLAN

The IEEE 802.11n standard is an upcoming WLAN standard, which is being specified for adopting the MIMO-OFDM technique to provide high data rate up to 600 Mbps. The standardization body has defined a group of indoor channel models as standard models for indoor WLANs [11]. These double directional MIMO models were defined as a benchmark for development and evaluation of MIMO-OFDM WLAN algorithms and systems. A total of six clustering channel models have been defined to incorporate various indoor propagation environments, including different offices and open space. The frequency-selectivity of a propagation channel is reflected from its RMS delay spread. Table 1 tabulates the RMS delay spreads for the six indoor propagation scenarios that were standardized. Generally, a large RMS delay spread indicates severe fluctuation of channel frequency response. For example, channel F has the most frequency selective characteristic which has a largest RMS delay spread of 150 ns. In this work, the performance of MIMO-OFDM antenna selection will be first investigated for the defined six channel conditions. In 20 MHz bandwidth at 5.25 GHz, 64

MIMO-OFDM subcarrier correlated channel matrices have been generated for antenna selection.

TABLE I. CHANNEL MODELS FOR IEEE 802.11N

Channel Models	A	B	C	D	E	F
RMS delay spread [ns]	0	15	30	50	100	150
Taps	1	2	2	3	4	6

V. INDOOR MIMO-OFDM CHANNEL MEASUREMENT

In addition to using the standardized MIMO channel models to investigate MIMO-OFDM antenna selection, real MIMO-OFDM channel data are also utilized to evaluate these antenna selection algorithms. The MIMO-OFDM channel data used in this study have been acquired using a MIMO-OFDM channel sounder developed at the CSIRO ICT Centre. The channel sounder is equipped with four transmitters and four receivers consisting of full RF chains. It operates at the carrier frequency of 5.24 GHz and supports an operational bandwidth of up to 40 MHz. A uniform square array arrangement is used both for Tx and Rx with antenna spacing of three and two wavelengths for Tx and Rx, respectively.

For MIMO-OFDM channel sounding purposes, typically a packet consists of a preamble and a channel training sequence is sent. The channel training sequence is designed to estimate the frequency response over 117 OFDM subcarriers in a 40 MHz bandwidth with a sub-carrier spacing of 312.5 kHz. The MIMO-OFDM channels are measured by moving the receiving antenna array within an area of four wavelengths \times four wavelengths with 0.05 wavelength increment, resulting in 6400 locations per local area. More details of the measurement can be found in [12].

The measurement was performed at the CSIRO's Radiophysics Laboratory in Marsfield, Sydney. Four different propagation scenarios are considered as follows:

- Lab LoS: Both Tx and Rx are located in the Laboratory with line-of-sight (LoS). The RMS delay spread for this measurement case is 23 ns.
- Atrium LoS: Both Tx and Rx are located in the Atrium with LoS. The measured RMS delay spread is 23 ns.
- Lab NLoS: Rx is located in the Laboratory while Tx is located in a different room with no LoS. The measured RMS delay spread is 26 ns.
- Atrium NLoS: Rx is located in the Atrium while Tx is located in a different room with no LoS. The measured RMS delay spread is 32 ns.

VI. PERFORMANCE OF MIMO-OFDM ANTENNA SELECTION

In this paper, antenna selection is to be carried out by choosing two out of four antenna elements for both transmitter and receiver. It is assumed that the transmitter obtains selection results through a feedback loop [3]. For the generation of IEEE

TGn channel data, the same antenna array configurations as in the measurements are considered.

Figs. 1 and 2 present results of MIMO-OFDM antenna selection at both sides for indoor NLoS channels A and F with 20 MHz bandwidth. The reason for presenting NLoS data is that the frequency selectivity of NLoS channels is more significant than the LoS case. For the sake of comparison, all our plots include 2 \times 2 MIMO capacity with randomly selected Tx and Rx antennas, which represents the performance with no antenna selection.

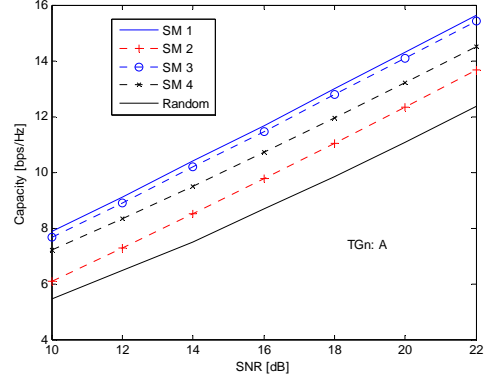


Fig. 1. Performance in TGn Channel A.

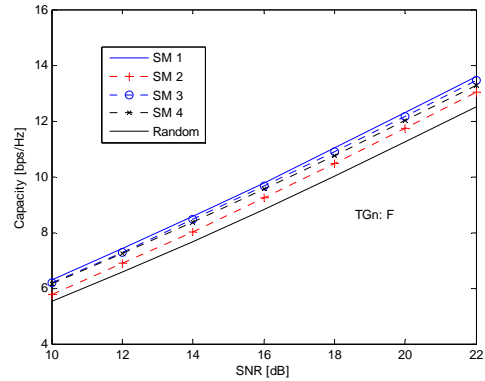


Fig. 2. Performance in TGn Channel F.

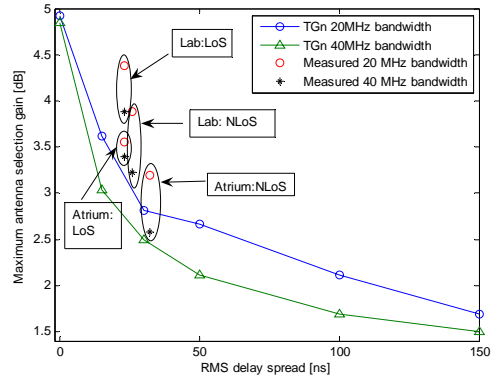


Fig. 3. Maximum achievable antenna selection gain for TGn Channels.

Firstly, the gain of optimal antenna selection at both sides over random selection for NLoS channels can be observed. For TGn channel A, which is a flat fading channel with only one signal path, about 4.9 dB gain can be achieved for antenna selection at both sides. This gain is almost equal to the gain for iid flat fading channels (5.1 dB). And only about 1.7 dB gain can be achieved for the most frequency selective channel F, as shown in Fig. 2. For the propagation scenarios modeled by channels B, C, D and E, about 3.6, 2.8, 2.7 and 2.1 dB gain can be achieved respectively, as shown in Fig. 3, which show the maximum achievable gain in TGn channels and measurement channels with 20 and 40 MHz bandwidth. The achievable gain for MIMO-OFDM antenna selection decreases with the increase of channel frequency selectivity (increasing RMS delay spread) for all channels. Comparing the achievable gain between the two different bandwidth, the gain for Channel B, C, D, E and F with 40 Mhz bandwidth is lower than their corresponding 20 MHz counterpart. The similar gain for Channel A is due to its flat fading.

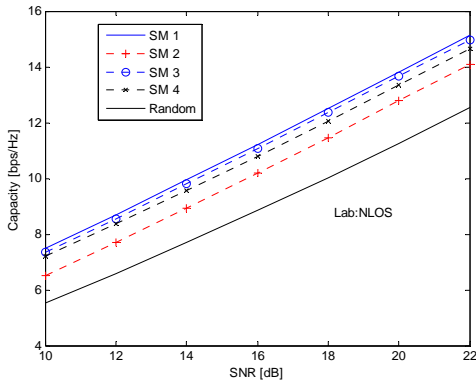


Fig. 4. Performance in Laboratory for NLoS condition.

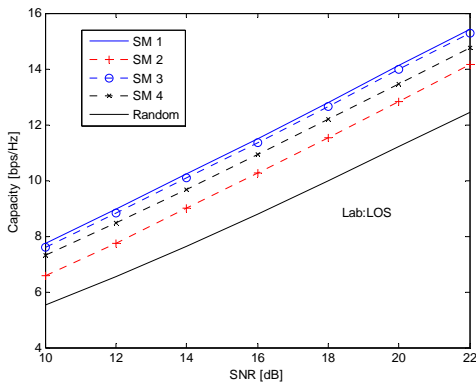


Fig. 5. Performance in Laboratory for LoS condition.

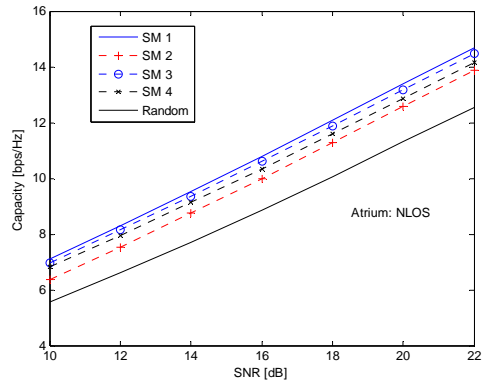


Fig. 6. Performance in Atrium for NLoS condition.

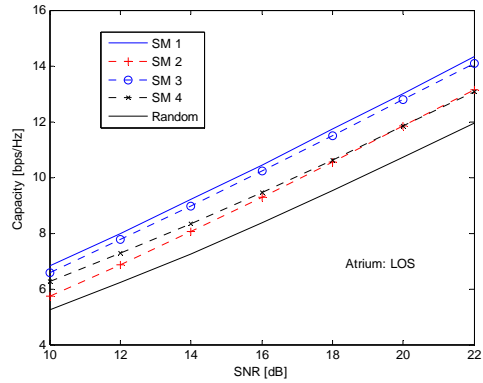


Fig. 7. Performance in Atrium for LoS condition.

There are about 3.2 and 3.6 dB gains for NLoS and LoS cases in Atrium scenario. This gain is similar to that for TGn Channel B. For the four measurement scenarios, the achievable gain from real channel data is better than using simulated TGn frequency selective channels. This may attribute to that, some practical factors, such as mutual coupling, are not appeared in the IEEE TGn models. Note that, the performance of antenna selection for the measured LoS cases in Laboratory and Atrium differ, although they have similar RMS delay spread values. This can be attributed to the higher spatial correlation for Atrium LoS case [12, 13]. In highly correlated channels antenna separation of three wavelengths used may not reduce correlation.

Further comparing the achievable gain for measurement channels with 20 MHz and 40 MHz bandwidth, about 0.5-0.6 dB loss is observed for the two Laboratory scenarios and NLoS atrium case due to the increase of channel bandwidth. This loss is similar to the loss for TGn channels B. It is interesting that only about 0.2 dB loss is observed for the LoS case in atrium. This is understandable since this measurement channel has the largest Ricean K factor of 2.4 which mean less frequency selective.

Secondly, for the four antenna selection methods under study, they all can achieve certain gain over random selection

in all channel conditions, as shown in Figs. 8 and 9. However, the achieved gain differs for them in different propagation conditions. SM 1 always plays a role as an upper bound. The performance of SM 3 is very close to that of SM 1 (less than 0.2 dB loss with respect to SM 1) and better than SM 2 and SM 4 for all propagation scenarios. The performance of SM 4 is better than SM 2 for all channel conditions. But it seems SM 4 itself performs better in NLoS channels (about 0.6 dB loss with respect to SM 1) than it in LoS conditions (about 1.6 dB loss with respect to SM 1). This is due to SM 4 utilize signals power only which discard the spatial correlation effect. It performs better in lower correlated channels.

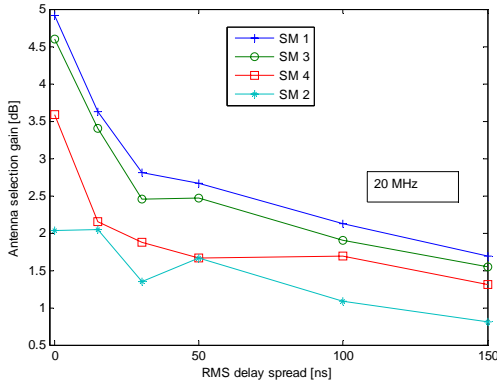


Fig. 8. Performance in antennas selection algorithms for TGN channels.

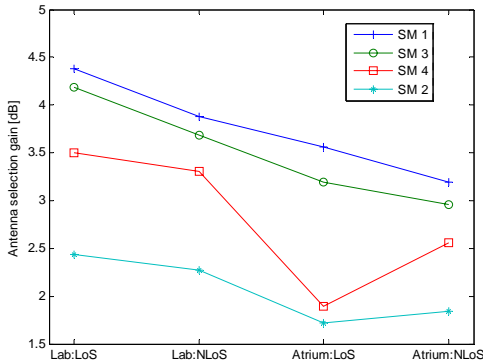


Fig. 9. Performance in antennas selection algorithms for real channels.

VII. CONCLUSION

Antenna selection for MIMO-OFDM systems is studied using both standardized indoor MIMO channel models and measured indoor MIMO-OFDM channel data. The performance of four different selection algorithms is

evaluated. Our results reveal that, the achievable capacity gain using MIMO-OFDM antenna selection decreases with the increase of channel frequency selectivity and channel bandwidth. For the practical indoor scenarios under investigation, the advantage of MIMO-OFDM antenna selection (over 3 dB) still can be achievable with 20 MHz bandwidth. The gain for real channels is higher than that for simulated channels. Among the three studied suboptimal algorithms, the maximum minimum eigenvalue method outperforms the other two in both LoS and NLoS, uncorrelated and correlated indoor channels.

REFERENCES

- [1] G. L. Stuber, J.R. Barry, S.W. McLaughlin, Ye Li, M.A. Ingram, and Pratt, T.G., "Broadband MIMO-OFDM wireless communications," *Proc. IEEE*, vol. 92, pp. 271-294, Feb. 2004.
- [2] A. F. Molisch et. al., "Capacity of MIMO systems with antenna selection," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1759-1772, Jul. 2005.
- [3] A. Gorokhov, D. Gore and A. Paulraj, "Receive antenna selection for MIMO flat-fading channels: theory and algorithms," *IEEE Trans. Inform. Theory.*, vol. 49, pp. 2687 – 2696, Oct. 2003.
- [4] M.A. Jensen and J.W. Wallace, "Efficient Capacity-Based Antenna selection for MIMO systems," *IEEE Trans. Veh. Technol.* vol. 54, no. 1, pp. 110-116, Jan. 2005.
- [5] X. Shao, J. Yuan, P. Rapajic, "Antenna selection for MIMO-OFDM spatial multiplexing system" *Proc. IEEE Inter. Symp. Information Theory*, pp. 90, 2003.
- [6] A. Gorokhov, M. Collados, D. Gore, and A. Paulraj, "Transmit/Receive MIMO antenna subset selection," *Proc. IEEE Inter. Conf. Acoustics, Speech, and Signal Processing*, vol. 2, pp. 13-16, May 2004.
- [7] H. Bolckei, D. Gesbert and A.J. Paulraj, "On the capacity of OFDM-based spatial multiplexing systems" *IEEE Trans. Commun.* Vol. 50, pp. 225-234, Feb. 2002.
- [8] A. Forenza, A. Pandharipande, H. Kim, R. W. Heath, Jr., "Adaptive MIMO transmission scheme: exploiting the spatial selectivity of wireless channels," *Proc. VTC 2005*, vol. 5, pp. 3188-3192, May 2005.
- [9] A. Forenza, M. R. McKay, A. Pandharipande, R. W. Heath Jr. and I. B. Collings, "Adaptive MIMO Transmission for Exploiting the Capacity of Spatially Correlated Channels", *IEEE Trans. Vehicular Technology*, accepted to appear.
- [10] R. W. Heath, Jr., S. Sandhu, and A. J. Paulraj, "Antenna selection for spatial multiplexing systems with linear receivers," *IEEE Commun. Letters.*, vol. 5, pp. 142 – 144, 2001.
- [11] V. Erceg, L. Schumacher, P. Kyritsi, A. Molisch and et al. "TGN channel models," IEEE 802.11-03/940r4, <http://www.802wirelessworld.com:8802/>. May 2004.
- [12] H. Suzuki, "Characteristics of 4x4 MIMO-OFDM channels in indoor environments," *Proc. ClimDiff '05*, Diff 13, Sept. 2005.
- [13] Z. Tang and A. S. Mohan, "Experimental Investigation of Indoor MIMO Ricean channel Capacity," *IEEE Antennas and Wireless Propagation Letters*, vol. 4, pp. 55- 58, 2005.