TIME VARIATION CHARACTERISTICS OF MIMO-OFDM BROADBAND CHANNELS IN POPULATED INDOOR ENVIRONMENTS

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***Abstract*—In this paper, the results and analysis of the measured data for multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) channels in indoor environment, in presence of pedestrian, are reported. The experiment used 4 sending and 4 receiving antennas and 114 OFDM sub-carriers for each transmission. The mean channel capacity and the dynamic range of the received power increased with the number of pedestrians present within the indoor environment . Each transmitter-to-sender sub-channel had a Signal to Noise Ration (SNR) of 15 db. With three pedestrians, the mean channel capacity rose by up to 2 bps/Hz compared to the vacant room scenario due to the increase in multipath conditions caused by body-shadowing effects. This demonstrates that the use of MIMO in the indoor environment is effective in compensating for the presence of pedestrians.**

Keywords- multiple-input multiple-output (MIMO), channel capacity, multipath channels.

I. INTRODUCTION

In recent years, there has been an increased interest in the study of multiple-input multiple-output (MIMO) systems in multipath environments as an approach that can offer significant bandwidth efficiency in broadband wireless applications. The MIMO approach can yield significant gains for both link and network capacities, with no additional energy or bandwidth consumption when compared to conventional single-array diversity methods [1], [2]. When MIMO systems are deployed in suitable rich scattering environments such as indoor environments, a significant capacity gain can be observed due to the assurance of multipath propagation. However, temporal channel variations can occur as a result of personnel, industrial machinery, vehicles and different equipment moving within the indoor environment. Recent studies have modeled pedestrian traffic effects on MIMO channels [3], [4]. The time varying effects on the propagation channel within populated indoor environments depends on different pedestrian traffic conditions, and is related to the particular type of environment considered [5]. Sufficiently rich multipath signal propagation has been found in MIMO channels operating within indoor environments [6], [7]. Notwithstanding previous studies, a systematic measurement campaign to characterize pedestrian movement effects in MIMO channels has not yet fully investigated. Measuring channel variations caused by the relative positioning of pedestrians is essential in the study of indoor MIMO broadband wireless networks.

This paper investigates the time variation characteristics of a 4x4 Multiple Input Multiple Output – Orthogonal Frequency Division Multiplexing (MIMO-OFDM) broadband channel within two populated indoor environments through systematic experimental measurements. Following, Section 2 presents an overview of the fundamentals of MIMO-OFDM systems. The description of the measurement equipment and measurement sites are presented in Section 3. Section 4 provides the time-varying results and analysis for the 4x4 MIMO-OFDM channels, followed by the conclusions in Section 5.

II. MIMO-OFDM CHANNEL CAPACITY

The MIMO-OFDM channel is characterized by its coefficient, $g(i, j, k, l)$, where, g is the MIMO-OFDM channel coefficient of *ith* receiving antenna, *jth* transmitting antenna, *kth* OFDM sub-carrier and *lth* receiving antenna array location. The number of transmitting antennas, receiving antennas, OFDM sub-carriers, and the receiving antenna array locations is n_t, n_r, n_f, and n_x, respectively. To obtain the Shannon capacity of the MIMO channel as a function of average signal to noise ratio (SNR) per receiving antenna, it will be convenient to work on the normalized channel coefficient, $h(i, j, k, l)$ [6]. As follows:

$$h(i,j,k,l)=\frac{g(i,j,k,l)}{\sqrt{\frac{1}{n_r n_t n_f}\sum_{i=1}^{n_r}\sum_{j=1}^{n_t}\sum_{k=1}^{n_f}\left|g(i,j,k,l)\right|^2}} \tag{1}$$

If we perform normalization at each of the receiving antenna location, the rule is to vary the transmitting power accordingly.

The normalized channel matrix at the kth OFDM sub-carrier at the lth receiving antenna array location is given by the channel coefficient matrix, $\mathbf{H}(k, l)$, whose ith row and jth column element is $h(i, j, k, l)$. When the MIMO channel is completely known by the receivers but is unknown to the transmitters, the Shannon capacity of the MIMO channel at the kth OFDM sub carrier at the lth receiving antenna array location is given by

$$C(k.l) = \sum_{m=1}^{n_t} \log_2\left(1 + \frac{\rho}{n_t}\lambda_m(k,l)\right) \tag{2}$$

where ρ is the average SNR per receiver over MIMO sub-channels and OFDM sub-carriers, λ_m is the mth eigenvalue of $\mathbf{HH^*}$, and superscript * denotes complex conjugate transpose. In the following, the MIMO channel capacity at each OFDM sub-carrier is calculated using the above equation while the analysis is performed using averaged results over the operational bandwidth.

It is important to have a detailed understanding of the characteristics of MIMO channels in various indoor environments, where high data rate systems are expected to be utilized. The structural understanding will play a key role to that as the performance of MIMO system depends on the actual structure of the MIMO channels formed at the time of transmission.

In indoor environments, moving pedestrians can intersect the direct path of the wave between the transmitting and receiving antenna, potentially blocking the line-of-sight (LoS) path. Often, the communication link can be maintained by the contribution of reflected waves in the environment, as the propagation conditions become non-line-of-sight (NLoS). Another important source of variation in signal quality is the effect of reflections from the body itself. All biological tissues have a relatively high reflection coefficient at UHF and microwave frequencies. For example, taking the transverse electric case at 5.2 GHz, the minimum reflection coefficient for muscle is 0.759, assuming a relative permittivity of 49.8 and a conductivity of 4.53 S/m for the tissue [8]. Doppler effects are not significant when considering pedestrian movement due to the low speeds involved: for example, even with a subject almost running, at 2 m/s, the resultant Doppler shift at 5.2 GHz is only 34.5 Hz, causing slow-fading effects. A more typical walking speed is around 0.5 m/s with a resultant Doppler shift of only 8.6 Hz.

III. MEASUREMENT EQUIPMENT AND SITES

The measurements reported were performed using the MIMO channel sounder developed by CSIRO ICT Centre currently equipped with four transmitters and four receivers [6]. It operates at a carrier frequency of 5.24 GHz and has an operational bandwidth of 40 MHz. The channel sounder has 4 transmitters with maximum power of 23 dB per channel and 4 receivers with 3 dB noise figure over the 40 MHz bandwidth. Commercially available omnidirectional antennas were 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 PC client. Users can generate, via software, signals which are simultaneously sent from the transmitters, and captured as multiple signal streams at the receivers.

The aggregate MIMO-OFDM channel consists of 16 MIMO antenna to antenna sub-channels each using 114 OFDM sub-carriers. Four Digital to Analog Converters (DACs) and 4 Analog to Digital Converters (ADCs) were also used, each using 12 bit resolution sampling at 112 Mega samples per second. The DACs and ADCs are designed to process signals at intermediate frequency (IF) which are converted to and from the radio frequency (RF) signals by the multi-channel transmitter (Tx) and the receiver (Rx). A photograph of the equipment is shown in Figure 1.

Figure 1: CSIRO ICT center MIMO-OFDM channel sounder (Left: Tx, Right Rx)

A. Measurement Sites

Measurements were performed on the ground floor in the CSIRO ICT Centre, Marshfield, Sydney. All measurement rooms were furniture free. Two different Rx locations were considered (1) LoS, were Tx and Rx are located inside the same 57 m^2 laboratory, and (2) NLoS, were Rx is located in an adjacent 30 m^2 office, see Figure 2.

During the experiments, both locations were cleared of furniture and obstructions to allow the free movement of pedestrians. The Tx cart was placed at 1 m and 5.5 m from the walls in two separate experiments as shown in Figure 2. The transmitter was fixed for all of the measurements reported in this paper.

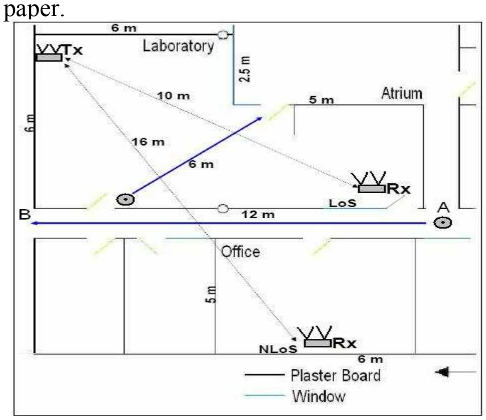

Figure 2: Measurement sites.

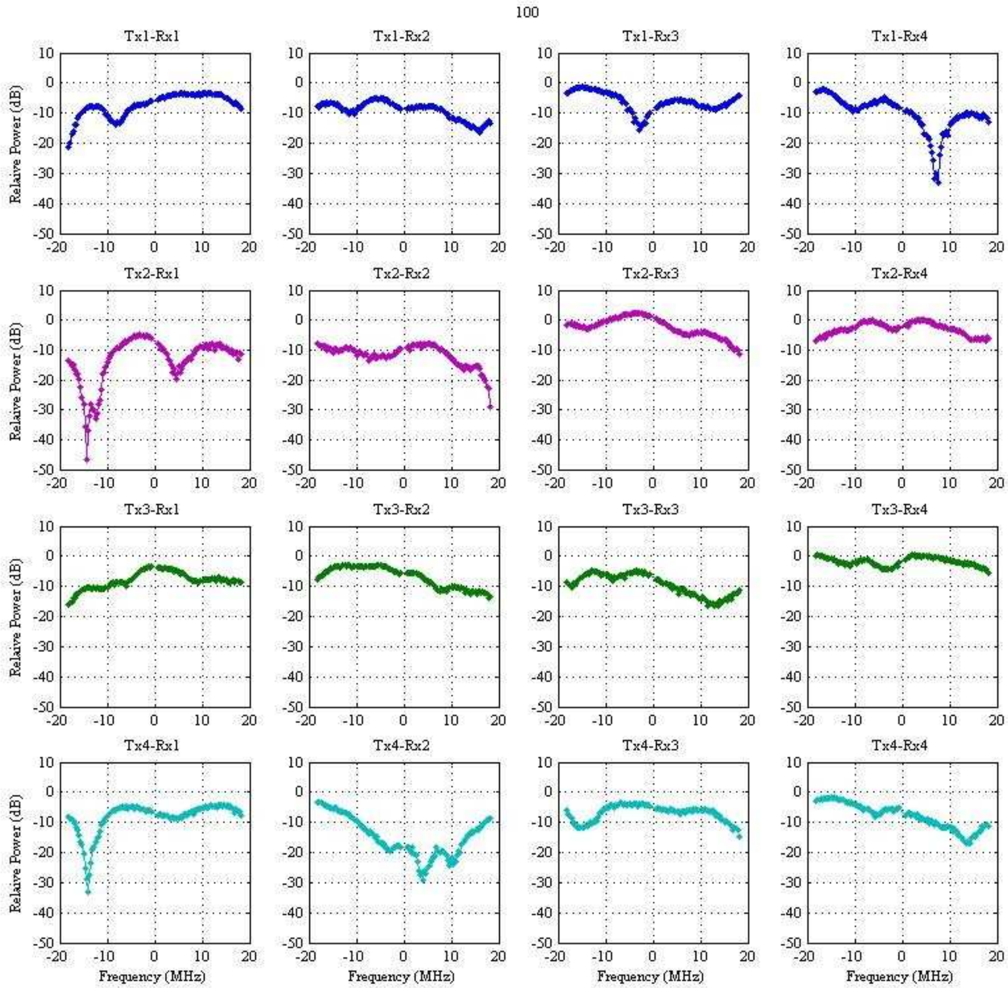

Figure 3. A sample of the 4X4 MIMO-OFDM sub-channels

In all adjacent locations, the walls were constructed from painted concrete blocks and plywood and the floor was cement based. The ceiling was suspended at a height of 5 m and was composed of mineral tiles and fluorescent lights.

IV. EXPERIMENT DESCRITPION

Pedestrian trajectories for LoS and NLoS experiments are shown in Figure 2. During the LoS scenario pedestrians walked along a 6 m trajectory within the laboratory while during the NLoS scenario pedestrians walked along the adjacent 12 m corridor.

Data have been collected under controlled pedestrian traffic conditions. Four different scenarios were considered: vacant, one, two and three person walking along the indicated trajectories. Additionally, as the performance of MIMO-OFDM system can dramatically change due to a small shift of the antenna array [6], two data sets have been collected for each scenario by placing the Rx antenna array in two different locations 4 λ (approximately 25 cm) apart. Wide band relative power was collected for the 4x4 antenna-to-antenna channels. For each scenario 100 samples were collected. Each sample has 16 antenna-to-antenna channels and each of these is made up of 114 OFDM sub carrier samples.

A. Line of Sight (LoS) Measurements:

During the LoS experiments Tx and Rx were placed within the same laboratory. The distance between the Rx and Tx was 10 meters. For the first data set, the Rx was placed within the laboratory, as shown in Figure 2. Received power was recorded for the four different pedestrian traffic scenarios: vacant, one, two, and three pedestrians walking along the trajectory. The second data set was collected after moving the Rx antenna 4 λ apart. Received power for the same four pedestrian scenarios was recorded.

B. Non Line of Sight (NLoS) Measurements:

During the NLoS measurements, Rx was located in an adjacent office and pedestrians walked along the 12 m corridor shown in Figure 2. The Tx was fixed at the same location as for the LoS measurements. Received power values were recorded for the four different pedestrian scenarios.

V. RESULTS

Figure 3 shows a sample of relative received power for the 16 MIMO-OFDM sub-channels. Figure 4 shows the total relative received power for the LoS measurements. There is a significant decrease in the received power when pedestrians are present in the measurement site due to body-shadowing effects.

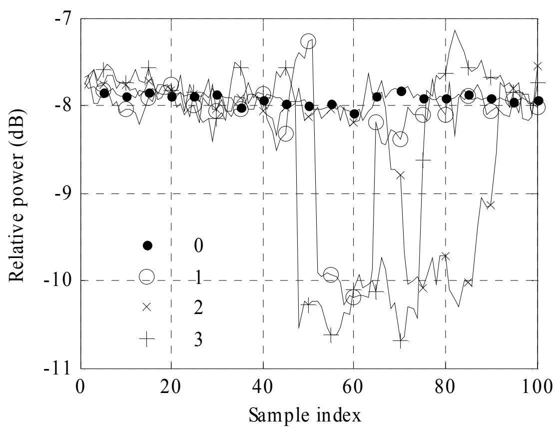

Figure 4. Relative received power for LoS measurements.

Table 1 summarizes the received power dynamic range for all the four different pedestrian scenarios in both LoS and NLoS measurements.

	Scenario	Dynamic Range [dB]
LOS	Vacant	0.44
	One Person Walking	3.03
	Two Person Walking	2.74
	Three Person Walking	3.55
NLOS	Vacant	1.17
	One Person Walking	1.49
	Two Person Walking	1.83
	Three Person Walking	2.02

Table 1: Dynamic range for received power.

For both, LoS and NLoS measurements, an increase in dynamic range was observed in conjunction with an increase in the number of pedestrians present in the measurement locations, with LoS scenarios recording larger variations than NLoS scenarios. Received power dynamic range increased approximately 3 dB from the vacant scenario compared to the three pedestrians scenario in LoS. While for the NLoS measurements an increase of 0.8 dB was recorded from the vacant scenario in comparison to the three pedestrians' scenario. In the NLoS scenarios, low variation in dB due to pedestrian activity was observed.

Figure 5 shows the dynamic MIMO channel capacity for LoS experiments, assuming a fixed SNR of 15 dB. There is a significant variation in channel capacity with the number of pedestrians present in the environment. Variations in channel capacity are more noticeable at sample index 60-80 when pedestrians were directly obstructing the LoS between Tx and Rx. During this time when there were three pedestrian present, an increase of 2 bps/Hz of channel capacity was observed relative to the vacant scenario due to the increase in multipath conditions caused by body-shadowing effects. This shows that the use of MIMO is effective in compensating for the presence of pedestrian.

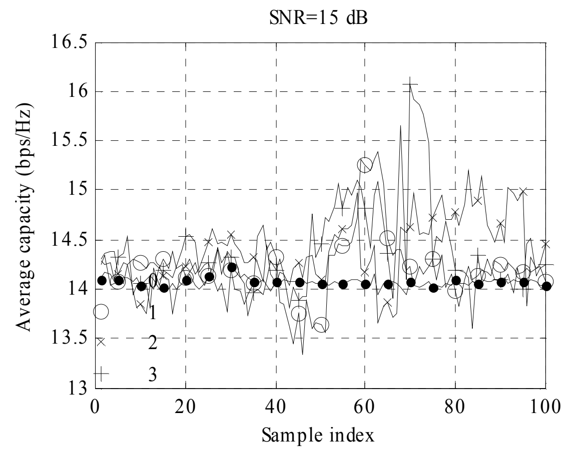

Figure 5. MIMO channel capacity for LoS measurements.

VI. CONCLUSIONS

The time-varying effect of nearby pedestrian traffic on the channel capacity of an indoor MIMO-OFDM system was measured. From the study of LoS and NLoS scenarios with up to three pedestrians, the results presented demonstrate that pedestrian effects significantly affect the theoretical maximum channel capacity of indoor MIMO systems. The mean channel capacity increased with the number of pedestrians present within the indoor environment. With three pedestrians, the mean channel capacity rose by up to 2 bps/Hz compared to the vacant room scenario due to the increase in multipath conditions caused by body-shadowing effects.

Future effort should be directed at the analysis of different types of environment and pedestrian traffic conditions, including corridors and larger populated areas such as malls.

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