Das Gupta, Jishu and Ziri Castro, Karla (2009) *Pedestrians Effects on Indoor MIMO-OFDM Channel Capacity*. In: The 5th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2009), September 24-26, 2009, Beijing.

Pedestrians Effects on Indoor MIMO-OFDM Channel Capacity

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Abstract— **Temporal variations caused by pedestrian movement can significantly affect the channel capacity of indoor MIMO-OFDM wireless systems. This paper compares systematic measurements of MIMO-OFDM channel capacity in presence of pedestrians with predicted MIMO-OFDM channel capacity values using geometric optics-based ray tracing techniques. Capacity results are presented for a single room environment using 5.2 GHz with 2x2, 3x3 and 4x4 arrays as well as a 2.45 GHz narrowband 8x8 MIMO array. The analysis shows an increase of up to 2 b/s/Hz on instant channel capacity with up to 3 pedestrians. There is an increase of up to 1 b/s/Hz in the average capacity of the 4x4 MIMO-OFDM channel when the number of pedestrians goes from 1 to 3. Additionally, an increment of up to 2.5 b/s/Hz in MIMO-OFDM channel capacity was measured for a 4x4 array compared to a 2x2 array in presence of pedestrians. Channel capacity values derived from this analysis are important in terms of understanding the limitations and possibilities for MIMO-OFDM systems in indoor populated environments.**

MIMO; OFDM; Channel characterization; Channel capacity

I. INTRODUCTION

With the expanding demand of indoor Wireless LAN systems, recent research have been focused on Multiple-Input Multiple-Output (MIMO) as an alternative technology that can offer significant bandwidth efficiency in broadband wireless applications. Conventional single-array diversity methods have limitations that can be overcome without additional energy or bandwidth consumption by using the MIMO approach for both link capacity and network usages [1, 2]. In addition, MIMO is currently one of the top listed technologies for the Next generation wireless communication system [3, 4]. However, channel capacity of indoor MIMO systems experience significant variations due to the presence of pedestrians in the indoor environment, as reported in our previous work [5-6]. Temporal variation in the Wireless LAN channel can also be due to movement of industrial machinery, various equipment and florescent lights [7-9]. The time varying effects on the propagation channel of populated indoor environments depend on the instant pedestrian traffic conditions and the particular type of environment considered [10-11]. Our previous research demonstrates that measured temporal variations caused by pedestrian movement in indoor MIMO channels are significant [5,12]. Nevertheless, the effect of pedestrians on indoor MIMO-OFDM channel capacity is not completely considered by current channel models [13]. Accurate analysis and modeling of practical Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) channels is necessary for the design and optimization of this transmission scheme. This paper investigates measured and simulated MIMO-OFDM channel capacity in a populated indoor environment. Measurements were conducted using an in-house built MIMO channel sounder, while simulations used ray tracing to replicate the measurement scenarios.

The remaining of this paper presents an overview on MIMO-OFDM channel capacity in Section II. Section III describes the measurement locations and equipment. In Section IV the simulation techniques are described. MIMO channel capacity results are discussed in Section V followed by conclusions and suggestions for further work.

II. MIMO-OFDM CHANNEL CAPACITY

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. The MIMO-OFDM channel is characterized by its coefficient, $g(i,j,k,l)$ where, g is the MIMO-OFDM channel coefficient of i th receiving antenna, j th transmitting antenna, k th OFDM sub-carrier and l th receiving antenna array location. The number of transmitting antennas, receiving antennas, OFDM sub-carriers, and the receiving antenna array locations is nt, nr, nf and nx, respectively. To obtain the Shannon capacity of the MIMO channel as a function of average signal to noise ration (SNR) per receiving antenna, it will be convenient to work on the normalized channel coefficient, $h(i,j,k,l)$ as follows:

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

The normalized channel matrix at the k th OFDM sub-carrier at the l th receiving antenna array location is given by the channel coefficient matrix, $H(k,l)$, whose i th row and

j th 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 k th OFDM sub carrier at the l th receiving antenna array location is given by

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

where ρ is the average SNR per receiver over MIMO sub-channels, OFDM sub-carriers, and a local area, λm is the m th eigenvalue of 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.

III. MEASUREMENTS: EQUIPMENT, LOCATION AND SCENARIOS

The measurements reported were performed using the MIMO channel sounder developed by CSIRO ICT Centre currently equipped with four transmitters and four receivers [7]. 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. The aggregate MIMO-OFDM channel consists of 16 MIMO antenna to antenna sub-channels each using 114 OFDM sub-carriers. Commercially available omni-directional 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. 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. Users can generate, via software, signals that are simultaneously sent from the transmitter array, and captured as multiple signal streams at the receiver array.

A. Measurement Locations

Measurements were performed on the ground floor in the CSIRO ICT Centre at Marshfield, Sydney. All measurement rooms were furniture free. During the measurements both the Tx and Rx are located inside the 57-m2 laboratory separated by a distance of 10 meters. The Tx cart was placed at 1 m and 5.5 m from the walls as shown in Figure 1. The transmitter was fixed for all of the measurements reported in this paper.

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.

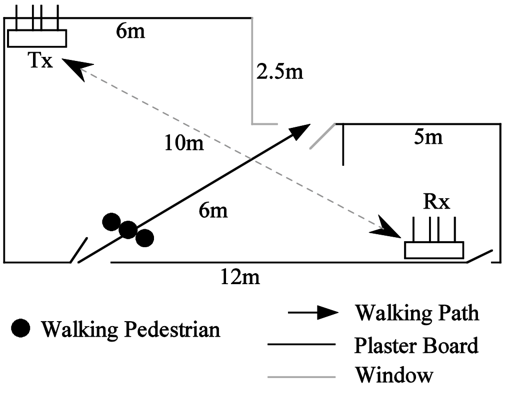


Figure 1. Measurement location and pedestrians trajectory

B. Measurement Scenarios

Pedestrians walked along a 6 m trajectory within the laboratory, as shown in Figure 1. Data have been collected under controlled pedestrian traffic conditions. Received power was recorded for four different pedestrian traffic scenarios: vacant, one, two and three pedestrians walking along the indicated trajectory. Additionally, as the performance of MIMO-OFDM system can dramatically change due to a small shift of the antenna array [7], two data sets have been collected for each scenario by placing the Rx antenna in two different locations 4 λ (approximately 25 cm) apart. Wideband 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.

IV. SIMULATION TECHNIQUES

The measurements scenarios have been replicated using ray tracing. We have used two different simulation techniques. The first one replicates the wideband measurements using 2x2, 3x3 and 4x4 arrays. The second one simulates a MIMO narrowband channel using an 8x8 array in presence of pedestrians. Details of these two approaches are described in the following sections.

A. 2x2, 3x3 and 4x4 MIMO channels simulation technique

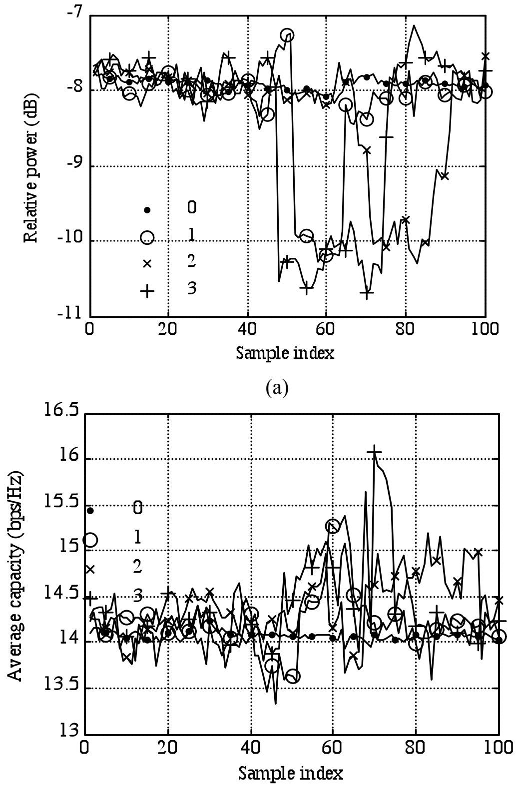
A Matlab® based frustum ray tracing technique was used to simulate the 2x2, 3x3 and 4x4 MIMO-OFDM indoor channels. The technique utilizes a fast line-clipping algorithm [14] instead of the conventional time-consuming ray intersection test. The measurement scenarios have been replicated in the simulation by incorporating a new module to the existing ray tracing algorithm. The new module simulates the permittivity and conductivity characteristics of a real human body, as considered in [6]. The geometric optics ray tracing technique considers 4 reflections, providing maximum temporal variation in capacity due to a moving human body in a single room environment. The software simulates moving human bodies along specified trajectories within the indoor environment. The four measurement scenarios, vacant, one, two and three pedestrians, have been simulated. For each scenario, 400 receiver locations, 16 antenna-to-antenna channels and 117 OFDM sub carrier were considered.

B. 8x8 MIMO channel simulation technique

An ANSI-C based program that combines Radar Cross Section (RCS) values for an anatomically realistic upright human body with conventional three-dimensional image-based geometrical optics was used to simulate an 8x8 MIMO array. This ray-tracing code includes the effect of human bodies within the indoor environment, as reported in [6]. The use of RCS is an improvement on the pedestrian's effect simulated using the technique in Section A, where the human body is represented as a finite dielectric block. However, it should be noted that the RCS approach is still only an approximation and, as with geometrical optics, becomes more accurate as the distances involved become larger with respect to the wavelength considered. All image-based ray contributions are checked for intersection with pedestrians, represented initially as 1.8 m high cylinders of 0.16 m radius. All geometrical optics rays, including the direct ray, that intersect bodies are considered 'blocked' and are excluded from the summation process. However, the RCS contribution for each pedestrian in the environment is considered as an additional ray. The RCS value for the incident angle and outgoing angle is interpolated from a previously generated database.

V. RESULTS

Figure 2 shows an example of measured relative received power and dynamic range of MIMO-OFDM channel capacity for 0 to 3 pedestrians using a 4x4 array. There is a significant variation in channel capacity and received power with the number of pedestrians present in the environment.



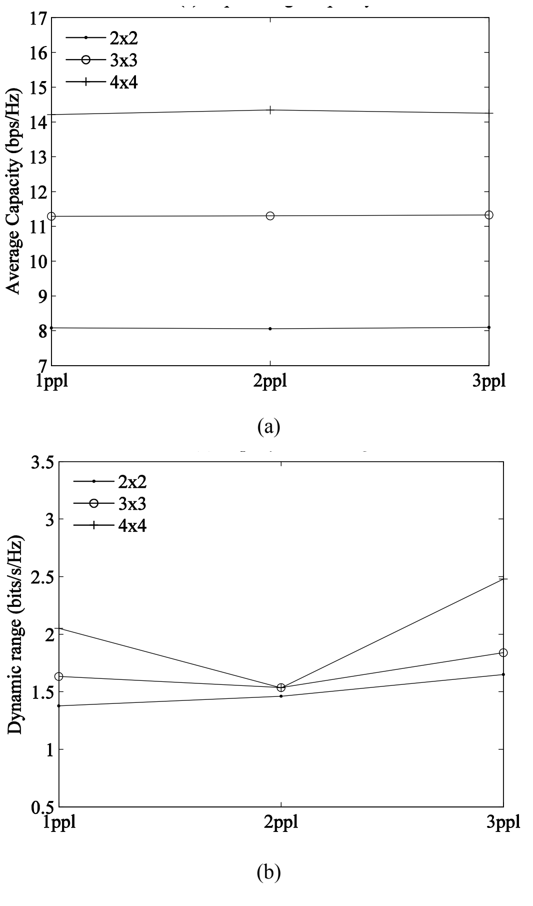
(a)

(b)

Figure 2. Measured results for a 4x4 array : (a) relative received power, and (b) capacity time variation in presence of pedestrians

Variations in channel capacity and received power 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 in the room, a fading of 2.8dB in the received power and an increase of 2 bps/Hz of channel capacity relative to the vacant scenario were observed 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.

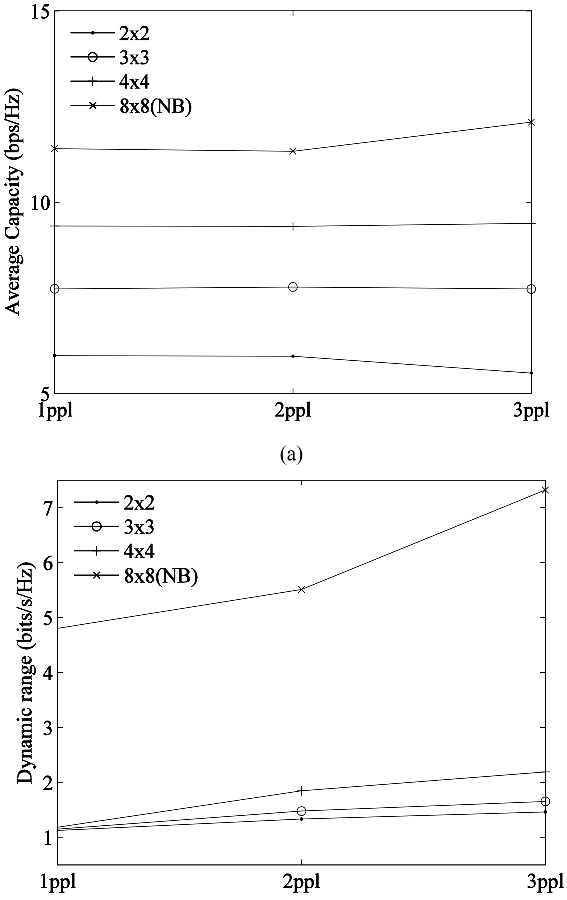
Figure 3 shows the average measured MIMO-OFDM channel capacity and dynamic range for the 2x2, 3x3 and 4x4 MIMO-OFDM arrays. The 4x4 array shows the highest average measured channel capacity compared to the 2x2 and 3x3 arrays as a higher number of parallel channels are created in a MIMO system with larger arrays. The increase in multipath conditions due to a higher number of pedestrians causes a general increase in average channel capacity and capacity dynamic range for all the array sizes, 2x2, 3x3 and 4x4. The highest measured average capacity, 14.2 b/s/Hz, corresponds to the 4x4 array with 3 pedestrians walking.



(a)

(b)

Figure 3. Measured capacity in presence of pedestrians: (a) average theoretical channel capacity and (b) capacity dynamic range.



(a)

(b)

Figure 4. Predicted capacity in presence of pedestrians: (a) average theoretical channel capacity and (b) capacity dynamic range

Simulated results are shown in Figure 4. In general, simulations tend to underestimate measured channel capacity values due to an inaccurate prediction of multipath conditions generated by pedestrians in the indoor environment. Generally, as the number of pedestrians and the size of the array increase the predicted average capacity and its dynamic range also increases. Therefore, simulation techniques are able to predict the trend of measurement results with relative accuracy.

VI. CONCLUSION

The effect of nearby pedestrian traffic on the channel capacity of indoor MIMO-OFDM systems was both measured and simulated. From the study of LoS scenarios with up to three pedestrians, the results demonstrate that pedestrian effects significantly affect the theoretical 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 of a 4x4 array by up to 2 bps/Hz compared to the vacant room scenario due to the increase in multipath conditions caused by body-shadowing effects.

Measured and simulated results show similar trends reaching higher theoretical capacity values as the number of pedestrians and the size of the MIMO arrays increase. 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.

ACKNOWLEDGMENT

The authors would like to acknowledge the CSIRO ICT center personnel at Marshfield, Sydney, for providing the MIMO-OFDM channel sounder and measurement sites. Special thanks to Dr. Hajime Suzuki for his invaluable support during the experimental trials and his contribution to this manuscript and its results.

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