Measurement of the MIMO UWB OFDM Channel

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***Abstract*— The designation of the 3-10 GHz frequency band for ultra-wideband (UWB) communications has led to the emergence of competing standards designed to facilitate high data-rate personal area networks (PAN). In particular, the IEEE 802.15.3 standard provides a multi-band physical layer to use all of the wide bandwidth while avoiding the frequency selective fading common to UWB channels. None of the proposed UWB techniques make use of spectrum efficient multiple input multiple output (MIMO) techniques in part because the characteristics of MIMO UWB OFDM channels are not well understood. This paper presents the results of measurements that characterize the MIMO UWB OFDM wireless channel over the frequencies from 3-6 GHz. Analysis of these measurements demonstrates the clear benefit of incorporating MIMO techniques into UWB OFDM communications to increase network capacity and system reliability.**

***Index Terms*— Ceramics, coaxial resonators, delay filters, delay-lines, power amplifiers.**

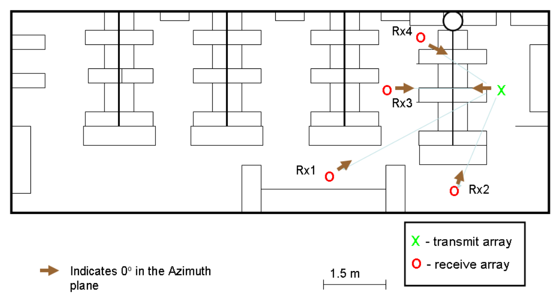

Fig. 1. Tx and Rx locations for channel measurements in indoor office cubicle environment

I. Introduction

In February of 2002 the FCC authorized use of the 3.1-10.6 GHz band for UWB communications [1]. The FCC constrained the power spectral density (PSD) of wireless emissions in this band to -41 dBm/Hz, making it ideal for high data-rate, short range communications, such as multi-media PAN's. The designation of this band motivated the development of two competing standards [2], [3]. Both the IEEE and ECMA standards employ a multi-band physical layer, such as orthogonal frequency division multiplexing (OFDM) to exploit the wide bandwidth mitigate and frequency selective fading, that would be excited in such a wideband channel [4]. This motivates the use of adaptive algorithms to optimize throughput. This type of communication has been considered in [5]. Attempts to measure the single-input single-output (SISO) UWB channel have been discussed in [6].

There is also potential to increase spectral efficiency through the use of multiple-input multiple-output (MIMO) techniques to exploit the spatially varying nature of the wireless channel. The capacity of such MIMO communications links for narrowband channels has been estimated in [7]. These results show that the capacity of the wireless channel can be greatly improved in uncorrelated MIMO channels. This paper builds upon our previous effort to model the MIMO UWB channel using computational electromagnetic simulations [8].

The goal of this paper is to measure representative 2x2 MIMO UWB OFDM channels through the use of controlled hardware experimentation. Channel estimates were obtained with a 4 port network analyzer over the first UWB channel (3.1 GHz - 3.6 GHz), and the resulting estimates were evaluated to measure channel capacity and validate our previous results using computational electromagnetic models. Provided is preliminary analysis of mutual coupling effects for UWB antenna arrays at various frequencies as well as measurement based validation of computational electromagnetic models for simulated channels and additional metrics for characterizing the MIMO UWB OFDM channel.

II. UWB Channel Model

The channel being evaluated is for short range (5-10 m) communications in a rich scattering environment. OFDM modulation is useful for channels with frequency selective fading, because of its ability to break the channel into orthogonal flat fading channels. Both standards for

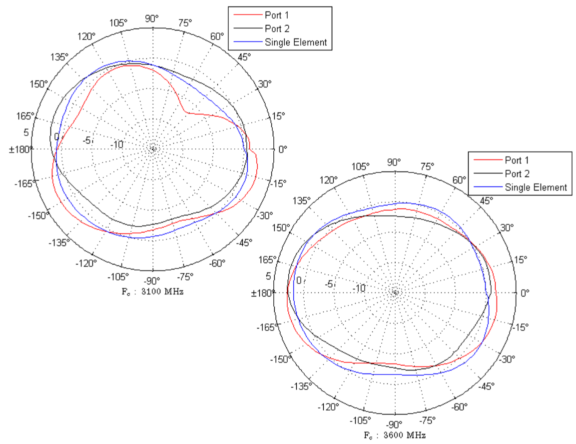

Fig. 2. Antenna radiation patterns in the azimuth plane at 3.1 GHz and 3.6 GHz

UWB currently divide the 528 MHz channel in to 128 subcarriers, spaced evenly at 4.125 MHz.

The 2x2 MIMO channel model defines the channel input/channel output relation between the transmitter and receiver. In the MIMO channel model, the separate signals transmitted, $\mathbf{x} \in [x_1, x_2]^T$, $(x_i \in \mathbb{C})$, on each element of the transmitter are combined linearly at each element of the receiver, $\mathbf{y} \in [y_1, y_2]^T$, $(y_i \in \mathbb{C})$. The individual channel gains of the path between each transmitter and receiver element are determined by the multi-path channel $\mathbf{H} \in \mathbb{C}^{2\times 2}$, with each element $h_{i,j} \in \mathbf{H}$ being a circularly symmetric, zero-mean, independent, identically distributed Gaussian random variable. In addition combined signals will also be distorted by the presence of additive thermal noise $\mathbf{n} \sim \mathcal{N}(0, \sigma_n^2)^{1\times 2}$ with noise power σ_n^2. The OFDM modulation technique synthesizes the wireless signal with memory from a series of orthogonal memoryless signals, that can be deconstructed at the receiver. The input output relationship for each signal on each subcarrier, k, can be seen in (1).

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{n}_k \tag{1}$$

The measurement campaign obtained complex gain estimates for H at each of the $k \in 128$ subcarriers. Since the purpose of the measurements is to evaluate the capacity of the link with regard to channel geometry, all channel matrices were normalized with regard to their Frobenius norm. This makes is possible to isolate the effect of path loss on capacity and the effect of channel geometry on link capacity.

III. Instrumentation and Hardware

The channel sounding measurements are collected to approximate a 2x2 MIMO physical layer with both the transmitter and receiver implementing a linear antenna array with $\lambda/2$ separation at the center frequency, 3.3 GHz. This corresponds to a spacing of 4.5 cm.

The test includes one transmit array (BS) and four receive arrays (MU) at different locations for a total combination of 4 total links. The locations of the transmitter are varied, by an automated x-y positioner, on a grid of 25 locations in the vertical plane over a square of size 1.5m by 1.5m. At each location in the grid a total of 100 channel estimate samples are collected. The channel estimates are captured with Agilent's N5230A 4-port PNA-L Network Analyzer. The network analyzer collects both magnitude and phase samples at each subcarrier.

The antennas used for the measurements are FR05-S1-P-0-107 designed by Fractus. The antennas are linearly polarized and designed for operation in the first band group of the UWB spectrum over the range of frequencies from $3.1GHz$ to $5GHz$. The radiation patterns of the MIMO antenna arrays for both ports, measured in an anechoic chamber, are shown for both the elevation and azimuth plane in figure 2. These patterns were measured at 3.36 GHz with an antenna spacing of $\lambda/2 = 4cm$ The antennas radiates omni-directionally making them an ideal candidate for measuring the multi-path channel. In addition, mutual coupling is apparent in the distortion of the radiation pattern by supression of the lobes at 90^o for port 1 and -90^o for port 2.

IV. Channel Metrics

The following channel metrics provide a means of characterizing the wireless channel with regard to wireless communications and evaluating the value of different physical and MAC layer configurations.

A. Open Loop Capacity

Without the use of link feedback to estimate the channel, the transmitter is unable to adapt its transmit parameters according to the varying channel. Instead, the transmitter uses equal power across all subcarriers and MIMO streams. The capacity of this channel has been derived in [7]. The equation for this capacity can be seen in (2), where P_{Tx} is the transmitted power per subcarrier, $\mathcal{N}_o$ is the noise power per subcarrier and $\mathbf{H_k}$ is the channel matrix for each of the $k \in \{1, \ldots, 128\}$ subcarriers.

$$C = \frac{1}{128} \sum_{k=1}^{128} \log_2 \left[\det \left(\mathbf{I}_{2\times 2} + \frac{P_{Tx}}{2\mathcal{N}_o} \mathbf{H_k} \mathbf{H_k}^* \right) \right] \tag{2}$$

B. Closed Loop Capacity

Making use of channel state information (CSI), it is possible for the transmitter to further optimize communication over the MIMO OFDM channel. The optimal method of transmission in this scheme is a water filling scheme where power is allocated to each subcarrier proportionally according to the channel gain. The capacity of the channel with waterfilling is shown in (3).

$$C = \frac{1}{128}\sum_{k=1}^{128} \quad \log_2 \quad \left[det\left(\mathbf{I}_{2\times 2} + \frac{P_{Tx}}{2\mathcal{N}_o}\mathbf{USU}^* \right) \right] \tag{3}$$

$$\begin{aligned} \text{SVD}(\mathbf{H}) &= \mathbf{UDV}^* \\ s_{i,j} \in \mathbf{S} &= \begin{cases} (\mu - \frac{1}{d_{i,j}}) & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \end{aligned}$$

1) MIMO Waterfilling: The MIMO waterfilling method, from here on referred to as waterfilling 1 (WF1), allocates equal power among all subcarriers and instead waterfills power along the separate MIMO streams. The power allocated to each MIMO stream is according to (4), where λ_j^k is the j^{th} singular value of the matrix, D, for subcarrier k.

$$P_{Tx}^k \quad = \quad \sum_{j=1}^{2}\left(\mu_k - \frac{1}{(\lambda_j^k)^2} \right)^+ \tag{4}$$

Using this equation, the waterlevel can be set for each subcarrier so that all available power is allocated and then the capacity can be calculated from (3).

2) MIMO OFDM Waterfilling: The MIMO OFDM waterfilling method, from here on referred to as waterfilling 2 (WF2), allocates the total power along OFDM subcarriers as well as MIMO streams. The power for WF2 is allocated according to (5).

$$P_{Tx} \quad = \quad \sum_{j=1}^{2}\sum_{k=1}^{128}\left(\mu_k - \frac{1}{(\lambda_j^k)^2} \right)^+ \tag{5}$$

The capacity can again be determined by selecting the waterlevel for the OFDM symbol and then allocating all power and substituting in to (3).

C. Reciprocal Condition Number

The reciprocal condition number (RCN) is defined as the ratio of the smallest singular value of the matrix $\mathbf{HH}^*$ to the largest. The smaller the RCN of the channel matrix the more highly correlated the antenna streams favoring transmit diversity or beamforming to improve signal reliabiltiy. The higher the RCN the less correlated the streams [9].

V. Results

A histogram of the RCN numbers of all channel matrices, shown in figure 3, indicates that the RCN is less than 0.5 with probability near 1. This would suggest that the MIMO streams of the MIMO UWB OFDM channel have a relatively high degree of correlation. In the event of highly correlated MIMO channels, the waterfilling algorithm is likely to allocate all energy to the single MIMO stream with the highest channel gain magnitude. Transmit diversity schemes, like Alamouti coding, may be more applicable to transmissions in highly correlated channels to improve transmission reliability [10].

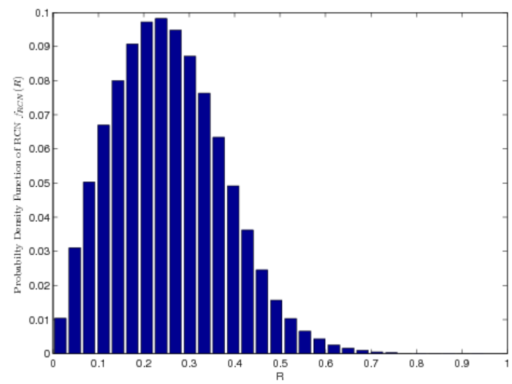

Fig. 3. Histogram of RCN for all collected channel samples

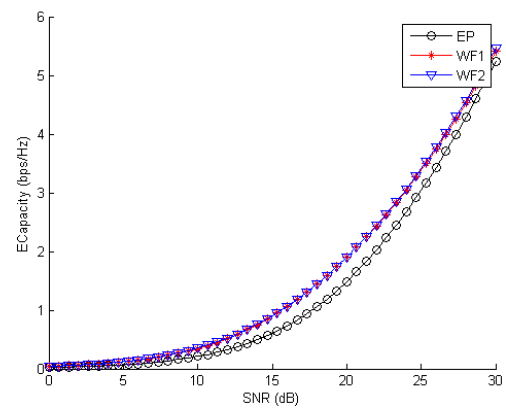

Fig. 4. Capacity vs. SNR for equal power and waterfilling algorithms

The plot of expected capacity vs. SNR, shown in figure 4, demonstrates the effectiveness of the waterfilling algorithms over the equal power allocation for various channel conditions. At high SNR, both waterfilling schemes perform near equally. This is due to the fact that the distance between the inverse of the subcarrier singular values is small relative to the available power. As a result most subcarriers are allocated relatively equally. The benefit of the second waterfilling algorithm can be seen more clearly at low values of SNR where allocating power efficiently with regard to MIMO streams and OFDM subcarriers provides a more pronounced gain in capacity.

These measured capacity measurements match closely to simulated results from channels generated by computational electromagnetic models, at lower SNR values [8]. At higher SNR values the expected capacity of measured channels shows convergent performance of equal power allocation and waterfilling schemes, while modeled channels show greater performance improvement from waterfilling over equal power allocation. Figure 4 demonstrates that link adaptive modulation can provide capacity improvements over equal power for a range of SNR values between 10 and 25 dB. This would indicate that using MIMO link adaptive modulation can improve spectral efficiency over the working ranges for UWB standards.

VI. Conclusions

Channel measurements of the MIMO UWB OFDM channels demonstrate a clear benefit from intelligent use of multiantenna techniques to exploit the spatially and spectrally non-flat channel. Additionally, the MIMO OFDM waterfilling physical layer demonstrates better performance at lower link qualities as related by SNR. For short range communications the maximum link range can be improved through the use of waterfilling to better allocate link resources. Finally, statistical analysis of the RCN of the channel matrix demonstrates a high degree of correlation between MIMO streams. This would lead tothe conlclusion that either transmit diversity or beamforming would be the best ways to improve channel capacity.

Acknowledgement

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References

[1] FCC, "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," in *ET Docket 98-153*, 2002, pp. 98–153.

[2] Standard, "IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements part 15.3:," *IEEE Std 802.15.3-2003*, pp. 1 – 315, 2003.

[3] ——, "ECMA-368: High rate ultra wide-band PHY and MAC standard," in *Available: http://www.ecmainternational.org/publications/standards/Ecma-368.htm*, 2008.

[4] E. Arikan, "Capacity bounds for an ultra-wideband channel model," Oct. 2004, pp. 176 – 181.

[5] G. Wang, J. Zhu and J. Jin, "Optimal power allocation for space-time coded OFDM UWB systems," vol. 1, Sept. 2005, pp. 189 – 192.

[6] Q. Liang and X. Cheng, "Wireless channel modeling in foliage environment: UWB versus narrowband," Nov. 2008, pp. 1 –6.

[7] I. E. Telatar, "Capacity of multi-antenna gaussian channels," *European Transactions on Telecommunications*, vol. 10, pp. 585–595, Feb 1999.

[8] R. Dragone, J. Kountouriotis, P. Mookiah, and K. Dandekar, "Modeling MIMO-UWB OFDM systems with computational electromagnetics," Nov. 2007, pp. 4527 –4531.

[9] D. Piazza, J. Kountouriotis, M. D'Amico, and K. Dandekar, "A technique for antenna configuration selection for reconfigurable circular patch arrays," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 3, pp. 1456 –1467, March 2009.

[10] S. Alamouti, "A simple transmit diversity technique for wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 16, no. 8, pp. 1451 –1458, Oct 1998.