A Tri-Polarized Ultra-Wideband MIMO System

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Abstract— **We investigate the performance of an ultra-wideband multiple-input multiple-output (UWB-MIMO) system that employs three co-located, orthogonally polarized antennas at both ends of the communications link. Results show that at 1% outage probability, such a system can achieve 24 b/s/Hz spectral efficiency, which indicates a predicted capacity of up to 180 Gb/s for a full-band (3.1-10.6GHz) UWB-MIMO communications system.**

Index Terms— **Channel capacity, MIMO, polarization, signal correlation, ultra-wideband (UWB).**

I. Introduction

Owing to the large spreading bandwidths, ultra-wideband (UWB) technology enables very high data throughputs [1]. The promised high-speed makes UWB an ideal technology for high-volume wireless applications such as multimedia content delivery and high speed short-range computer communications.

Another very promising technique for improving capacity is the use of multiple antennas at both ends of the communications technique, dubbed multiple-input multiple-output (MIMO) systems[2-4] . MIMO systems improve capacity by supporting several independent information channels concurrently, without extra use of channel bandwidth. This is achieved by spacing antennas apart (usually half-wavelength), in order to decorrelate the transmitted and received signal, since the signals impinge on different scatterers in space.

Initial work on MIMO was investigated in narrowband flat-fading channels, using the spatial technique. In [5] wideband spatial MIMO channels were characterized. MIMO systems employing dual-polarized antennas were investigated in [6, 7]. A tri-polarized MIMO system was reported for narrowband in [8] and wideband in [9].

A system that would employ both the MIMO technique and UWB technology would achieve spectacular data-rates. But there is very limited reported research on UWB-MIMO. This paper's main contribution is an investigation of the performance of a system that simultaneously employs the compact tri-polarized MIMO technique and UWB technology. This is based on indoor radio channel measurements conducted in the Engineering Science Department at the University of Oxford (UK). We investigate the independence of UWB-MIMO signals in a tri-polarized system. We also compare the performance of the tri-polarized MIMO technique in UWB and in narrowband in terms of the capacity gains referenced to the traditional single-input single-output (SISO) systems.

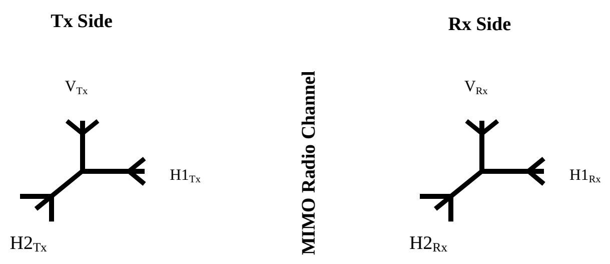

Fig. 1. Tri-polarized MIMO antenna configuration

II. Channel Measurements

At the transmitter, a tri-polarized antenna configuration was constructed by placing one antenna in the vertical position V_{Tx} and two orthogonal elements in the horizontal plane $H1_{Tx}$ and $H2_{Tx}$ [10]. Similarly, the receiving antenna set was constructed using V_{Tx}, $H1_{Tx}$ and $H2_{Tx}$, see Fig. 1. The UWB-MIMO channels measurements were conducted in a typical office environment using a vector network analyzer (VNA), see Fig. 2 [11, 12]. Using identical omni-directional antennas, 1601 discrete frequencies were sampled in the 3.1-10.6 GHz band, with a frequency resolution of $\Delta_f = B/(n_f - 1) = 4.7$ MHz.

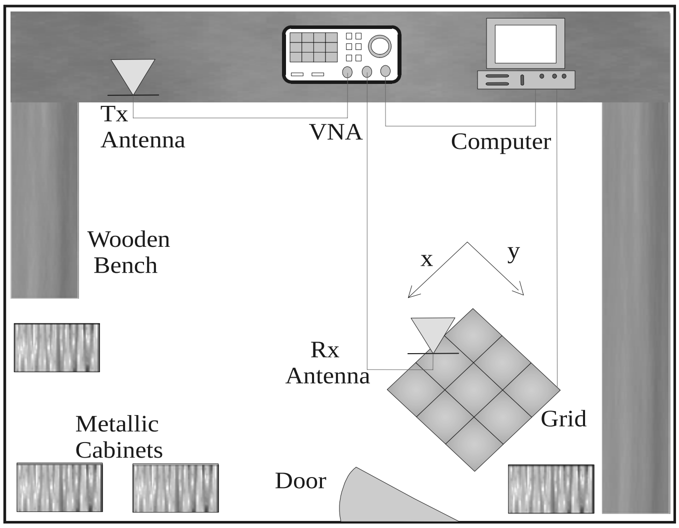

Fig. 2 Schematic of VNA measurement system

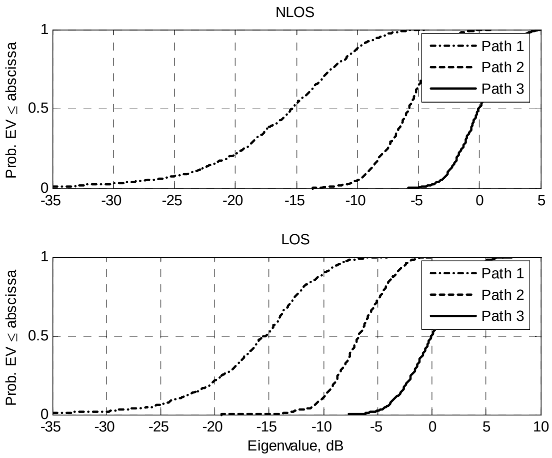

Fig. 3. Eigenvalues

The receive antennas scanned a spatial grid of 30 rows and 30 columns with 3 cm resolution. Measurements were conducted in both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. A 3x3x900x1601 UWB-MIMO channel transfer matrix $G(f) = g_{r,t}(f)$ was obtained, where $r,t = \{1,2,3\}$. In order to suppress the pathloss effects, this matrix was normalized over the whole band, resulting in $H(f)$.

III. EIGENVALUE ANALYSIS

Eigenvalue decomposition (EVD) is usually used to predict the number of independent (orthogonal) MIMO subchannels[13, 14]. EVD uses the MIMO correlation matrix

$$R = HH^H \tag{1}$$

where H is the normalized channel transfer matrix and $[.]^H$ represents Hermitian transposition. The eigenvalues, $\lambda_i (i = 1,\ldots,k)$ of R are the power gains of the k = 3 orthogonal subchannels. Fig. 3 shows the CDF plots for the eigenvalues for both the NLOS and LOS UWB MIMO channels, normalized to the mean of the strongest path. As can be observed three distinct eigenvalues were obtained in both the NLOS and LOS, indicating that the tri-polarization system can support three independent information-carrying UWB MIMO subchannels even in clutter-limited environments. This owes to the inherent independence between signals transmitted in orthogonal channels.

TABLE I
MAXIMUM RECEIVE & TRANSMIT CORRELATION

	RxCorr H_1&H_2	RxCorr H_1&V	RxCorr H_2&V	TxCorr H_1&H_2	TxCorr H_1&V	TxCorr H_2&V
NLOS	0.17	0.14	0.19	0.24	0.27	0.24
LOS	0.33	0.24	0.15	0.43	0.27	0.19

IV. SIGNAL CORRELATION COEFFICIENTS

Correlation coefficients are often used to assess the independence of signals in multi-antenna systems because correlation limits the achievable channel capacity [15]. In order to ascertain that the subchannels were orthogonal to each other, the correlation coefficient between any two signals *x(f)* and *y(f)* was computed as follows [16]:

$$r_{xy} = \frac{E[xy] - E[x]E[y]}{\sqrt{\{(E[x^2] - E[x]^2)(E[y^2] - E[y]^2)\}}} \tag{2}$$

where E[.] denotes the expectation operator. Both receive and transmit correlation coefficients were analyzed. Receive correlation is the independence between signals received at any two antennas R_i and R_j, both transmitted from a single antenna T_m. Transmit correlation is the measure of independence between two signals transmitted from any two antennas T_m and T_n, received at a single antenna R_i.

In diversity system performance analysis, a correlation coefficient of 0.7 is commonly used as the threshold value below which signals are considered independent [9, 10, 17]. Figs. 4 and 5 show CDF plots for transmit and receive correlation coefficients respectively, for both the NLOS and LOS channels. It can be observed that all values are well below 0.7. Table I gives a summary of the maximum correlation coefficients. The low correlation coefficients indicate that the tri-polarized MIMO technique should perform well in UWB systems. From the figures and the table, it can also be observed that the NLOS values are slightly lower than the LOS ones, due to the added clutter in the former case. It can also be observed that in the LOS channel, the correlation between the two horizontal signals in slightly higher than that between the vertical and either of the

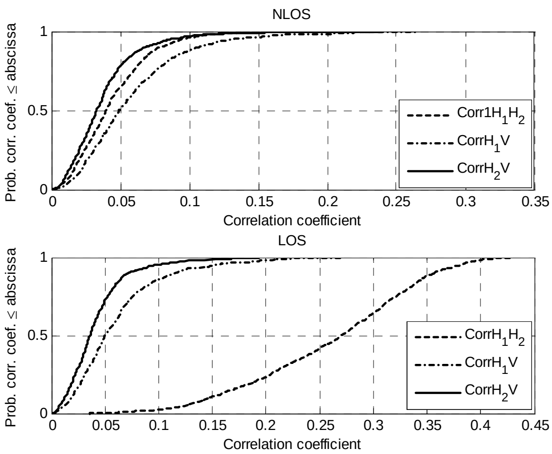

Fig. 4. Transmit correlation

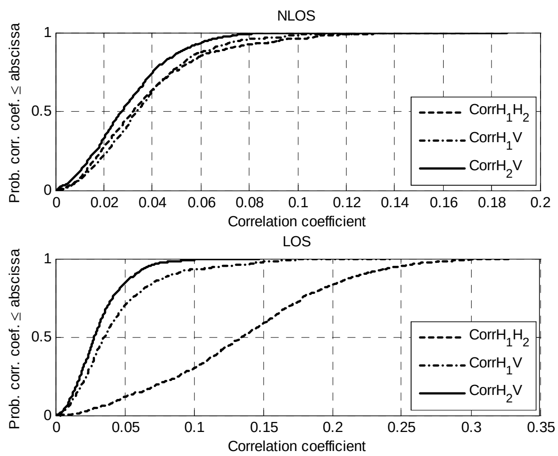

Fig. 5. Receive Correlation

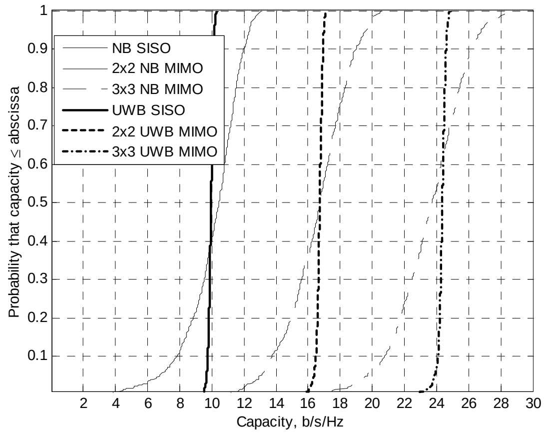

Fig. 6 Capacity of narrowband and UWB SISO and MIMO for NLOS

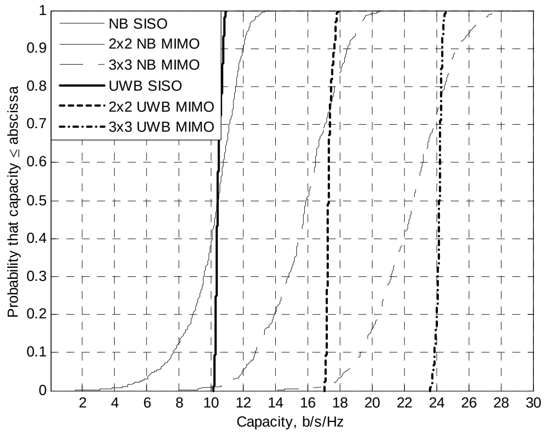

Fig. 7 Capacity of narrowband and UWB SISO and MIMO for LOS

horizontal signals.

V. CAPACITY RESULTS

In order to quantify the benefit of using the MIMO technique in UWB, we computed the Shannon capacity. The capacity C_{NB} of a narrowband MIMO system with uniform power allocation is given by [2]

$$C_{NB} = \log_2 \det\left[I + \frac{\rho}{N_T} H(f)^H H(f) \right] \qquad (3)$$

where ρ is the average SNR at the receiver and I is the identity matrix of size $N_R \times N_T$, $H(f)$ is the normalized complex channel matrix at frequency f, superscript H represents Hermitian transposition and 'det' is the determinant of a matrix. In the case of a wideband or UWB MIMO channel, (3) is integrated over the entire measurement bandwidth, as follows [5]:

$$C_B = \frac{1}{B}\int_B \log_2 \det\left[I + \frac{\rho}{N_T} H(f)^H H(f) \right] df \qquad (4)$$

Since the measured MIMO channel data is discrete, (4) can be approximated to

$$C_B \approx \frac{1}{B}\sum_{f=1}^{F} \log_2 \det\left[I + \frac{\rho}{N_T} H(f)^H H(f) \right] \Delta f \qquad (5)$$

where F is the number of discreet frequency points (1601 in this case). In order to make fair comparisons, average SNR at the receiver was fixed at 30 dB for all MIMO capacity calculations. Figs. 6 and 7 show the CDFs for the capacities of the narrowband (NB) and UWB systems with single-input single-output (SISO) and MIMO configurations in the NLOS and LOS scenarios, respectively. It can be observed that the capacity CDFs for UWB-SISO and UWB-MIMO are much steeper than their narrowband counterparts. This difference can be attributed to the fact that a UWB channel is much more stable than a narrowband channel, as a result of its resistance to small-scale fading [1]. In [18], it was shown that in frequency-selective channels, the outage capacity approaches the mean.

Fig. 9 shows capacity of narrowband and UWB SISO and MIMO in the LOS scenario capacity due to frequency selectivity [18]. Our results confirm this for frequency-selective UWB channels. Tables II and III show summaries of the 1% outage capacity values for the NLOS and LOS channels respectively, based on results plotted in Figs. 6 and 7. UWB gives an improvement of up to 6 and 7 b/s/Hz over NB in the NLOS and LOS channels respectively. The 3x3 UWB-MIMO achieves 15 and 14 b/s/Hz gain over UWB-SISO in the S and LOS channels respectively.

TABLE II
1% OUTAGE CAPACITY – NLOS

Antenna Elements	Narrowband	Ultra-Wideband
1x1 SISO	4 b/s/Hz	9 b/s/Hz
2x2 MIMO	12 b/s/Hz	16 b/s/Hz
3x3 MIMO	18 b/s/Hz	24 b/s/Hz

TABLE III
1% OUTAGE CAPACITY – LOS

Antenna Elements	Narrowband	Ultra-Wideband
1x1 SISO	4 b/s/Hz	10 b/s/Hz
2x2 MIMO	11 b/s/Hz	17 b/s/Hz
3x3 MIMO	17 b/s/Hz	24 b/s/Hz

The overall gain over NB-SISO is 20 b/s/Hz in both the NLOS and LOS channels. For a UWB system using a 7.5 GHz bandwidth with 3x3 MIMO, the available capacity is as high as 180 Gbps at a 30 dB SNR.

VI. CONCLUSIONS

Performance of the tri-polarized MIMO technique has been experimentally investigated in UWB systems. Eigenvalue analysis shows that such a technique can support three separate information channels in the UWB. This has been confirmed by the low correlation coefficients. The overall maximum correlation coefficients were 0.27 and 0.43 in the NLOS and LOS channels respectively. Capacity CDFs for UWB-SISO and UWB-MIMO were observed to be much steeper than their narrowband counterparts. The overall gain of UWB-MIMO over NB-SISO was 20 b/s/Hz in both the NLOS and LOS channels. For a UWB system using a 7.5 GHz bandwidth with 3x3 MIMO, the available capacity would be as high as 180 Gbps at a 30 dB SNR. Such high capacities are unprecedented in radio communications. Furthermore, this capacity can be achieved without necessarily increasing device size because of the compact tri-polarized antenna configuration.

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