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Abstract - This paper presents a MIMO throughput performance analysis of dynamic wideband double-directional channel measurements that were recently obtained by the University of Bristol. Identical 16-element Uniform Circular Arrays (UCAs) were employed at both ends of the link and the parameters of the multipath components (MPCs) were extracted. In this paper, the performance analyses of several 4×4 subarrays of the 16×16 measurement arrays are presented. The MIMO response of these channels was synthesised from the extracted MPCs. A comparison is then made between the capacity estimates from the directly measured and synthesised MIMO channels. This was found to show good agreement.

Keywords - antenna arrays, multiple-input multiple-output, indoor propagation, channel models

I. INTRODUCTION

The theoretical performance benefits of deploying multiple antennas at both ends of a wireless communications link and the effect of channel correlation on MIMO capacity are well known [1-2]. However, accurate modelling of the wireless channel is needed for the development of practical MIMO applications, such as that needed for Wireless LANs. The so-called “double-directional” approach of modelling the MIMO wireless channel is a well accepted method of providing a full description of the channel [3]. It can describe fading in the spectral, doppler, and spatial domains of the multi-dimensional signal vectors. This is achieved by making use of the joint distributions of radiated power in time, delay, directions of arrival (DOA) and direction of departure (DOD). The development of such models requires channel data in the form of multipath parameters from numerous propagation environments. This is ideally obtained from the extraction of multipath components (i.e. DOA, DOD, delay, power of each ray) from multi-element channel measurements.

In this paper, we present a capacity-based analysis of MIMO channels obtained from dynamic wideband channel measurements and double-directional multipath parameter extraction. The measurements were conducted with identical 16-element UCAs in indoor environments at 5.2 GHz. To the best of our knowledge, measurements of this scale have not yet been conducted elsewhere. This is probably due to the hardware complexity of the measurement campaigns, and also the large computation time required for parameter extraction. Fortunately through UK Government funding under JERI 98 for measurement equipment facilities, and Toshiba TREL providing a state-of-the-art computer cluster, these difficulties have been overcome to a large extent at Bristol. The extracted multipath data allows us to investigate the interaction of different array geometries and element patterns within the measured environments. This type of knowledge is much needed to aid the design of antennas and antenna array topologies for future terminals employing MIMO capacity enhancement techniques. As an alternative to direct measurements, double-directional channel data can also be obtained from site specific models such as ray-tracing [4], or synthesised from power delay profiles (PDPs), Doppler power spectra (DPS) and power distributions in DODs and DOAs [5].

This paper is structured as follows. Section II gives a brief overview of the measurement campaign and the associated multipath parameter extraction. Section III contains a capacity based analysis of several 4×4 subarrays of the 16×16 measured channels, highlighting the importance of power normalisation. Section IV describes how MIMO wideband channel responses were calculated from the extracted MPCs using a plane-wave model, and a comparison between these values and the directly measured MIMO channels is also presented. Section V concludes the document.

II. CHANNEL MEASUREMENTS

A. Measurement Equipment

This measurement campaign was conducted alongside the Mobile VCE [6] campaign at the University of Bristol. The channel measurements were conducted using a Medav RUSK BRI channel sounder [7] capable of supporting multi-element wideband channel characterisation. The transmitter employs a periodic multi-tone signal with a bandwidth of 120 MHz, centred on 5.2 GHz and a repetition tone period of 0.8 µs. The signal is constructed such that all tones have equal power and are evenly spaced over the measurement bandwidth. The patch antennas for the two identical 16-element UCAs were dual-polarised (horizontal and vertical), and were designed by the EM Group at Bristol [8]. Although these elements were dual-polarised facets,
only the vertical polarisation was considered during these measurements. Figure 1 shows the azimuth gain pattern of one of the antenna elements. The UCAs had a radius of 1.28h.

Figure 1: Azimuth gain pattern (dB) of an antenna

B. Measurement Environments

Dynamic measurements were conducted by slowly pushing the receiving UCA on a trolley, while the transmitting UCA was fixed at a certain location. Measurements were taken under different propagation conditions. This includes line-of-sight (LOS), obstructed LOS, non-line-of-sight (NLOS), populated scenario, unpopulated scenario, and different antenna heights at either end. Measurements were conducted in several indoor environments, including the foyer, corridor, research lab, open plan office and outdoor court yard. A full account of the measurement campaign and description of the environments can be found in [9].

C. Parameter Extraction

The newly developed hybrid-space Space Alternating Generalised Expectation-maximisation (HS-SAGE) algorithm [10] was used to extract multipath parameters of the channel, i.e. Direction of Arrival, Direction of Departure, time delay of arrival and complex amplitude of each ray from the transmit array to the receive array. Much of the development of the algorithm was conducted under the UK Mobile VCE Core 2 programme. In addition to being suitable for use with a circular array, it also enhances the effective processing speed of the classical SAGE algorithm [11] without sacrificing accuracy and resolution.

III. MIMO ANALYSIS OF MEASURED CHANNELS

A. Selected Antenna configurations

The purpose behind conducting measurements with 16-element circular arrays was to accurately characterise the multipath properties for the entire azimuth domain at both transmitting and receiving ends of a wireless link. For the purpose of capacity analysis, only certain 4×4 subsets of the 16×16 measurements have been used. A description of the chosen 4×4 sectors is now given below.

1) Facing and Non-Facing MIMO sectors

Most measurements were conducted with the circular arrays placed in line of sight. However, due to the shape and construction of the arrays and the relatively narrow beamwidth of the patch antennas deployed, some of the transmit-receive antenna pairs experienced a dominant LOS component, while other Tx-Rx pairs were effectively NLOS links. These were shielded by the ground planes of the arrays. See pictures of UCAs in [9] for further details.

Figure 2: labelling of patch antennas in the 16-element measurement UCAs

From Figure 2, an example of a facing sector is (Tx 15,16,1,2 and Rx 7,8,9,10), whereas (Tx 7,8,9,10 and Rx 15,16,1,2) forms a non-facing MIMO sector. As expected, the non-facing channels were found to exhibit Rayleigh fading, aided by the large number of scatterers present in the indoor environment. The channels observed between facing arrays were found to follow a Ricean distribution with K-factors varying between 2-6 dB for the different environments considered. This justifies the use of facing and non-facing sectors to simulate LOS and NLOS MIMO scenarios respectively in the capacity analysis presented here.

2) Co- and Cross-oriented Antenna Arrays

It would be almost impossible to deploy an array comprising of omni-directional elements in any practical device, especially for a mobile terminal. It is likely that directional antennas such as the patch antennas (Figure 1) used in these measurements will be used in real MIMO application [12]. Due to their relatively narrow beamwidth, the effect of orientation of these elements must be taken into account.

The facing and non-facing sectors described in III.A.1) are co-oriented sectors. Since all 4 elements are facing a similar direction, the array is more likely to be entirely “shadowed” or “illuminated”. For contrast, we also observe the 4×4 MIMO channel for cross-oriented sectors, as given by elements 1,5,9,13 from each array in Figure 2. We define the “power spread” of a MIMO channel as the difference (dB) between the strongest and the weakest constituent SISO subchannels. This was found to be much greater for cross- than co-oriented sectors (Figure 6), indicating that cross-oriented channels were more likely to contain at least one strong constituent subchannel link.
The average power spread of the 4x4 cross-oriented channels was greater than 18 dB for all environments, including those where the UCAs were in NLOS (foyer loc 1, lab). As expected, power spread was even larger for smaller angular spreads, which was the case when a dominant LOS component existed (foyer loc 2, foyer loc 3, office). In either case, we observe that the orientation of the deployed antennas have a significant effect on the strength of the link in indoor propagation at 5.2 GHz.

Channel Normalisation

The normalisation factor for each wideband measurement snapshot $T_i$ ($i$ is the time or snapshot index) was calculated separately. This removed the effect of large-scale spatial fading, which can be significant for dynamic measurements, and ensured that only the small-scale spatial fading was observed. $T_i$ has dimensions of $N_R \times N_T \times N_F$, where $N_R$, $N_T$, and $N_F$ are the number of receive antennas, transmit antennas and frequency components respectively.

Since adjacent elements in the UCAs are spaced at 0.5λ, constituent single-input single-output (SISO) channels could be assumed to experience sufficiently independent fading. Each 4x4 measured channel snapshot had dimensions of $(4 \times 4 \times 97 = 1552)$, thus providing a sufficient number of independent samples for normalisation. The normalised wideband channel $\mathbf{H}_i$ was calculated from (1) and (2), where $\bar{n}_k$ is the normalisation factor estimate.

$$\bar{n}_k^2 = \frac{1}{n_R n_T N_F} \sum_{f=0}^{N_F} \sum_{j=1}^{N_R} \sum_{k=1}^{N_T} |T_{i,f,j,k}|^2$$  \hspace{1cm} (1)$$

$$\mathbf{H}_i = \frac{T_i}{\bar{n}_i}$$  \hspace{1cm} (2)$$

The goal of channel normalisation is usually to scale the channel response so that the expectation of its power is unity. This can be achieved by taking the summation in Equation (1) over only the 4x4 channel response that is being analysed. We refer to this as unity-gain normalisation.

However, when comparing of performance of arbitrarily oriented directional antenna arrays at given locations of the transmitting and receiving arrays, we should ideally normalise for only the “omni-directional pathloss” between the two locations. This is equivalent to the pathloss measured when single omni-directional antennas are placed at the same transmit and receive locations. The unity-gain normalisation does not necessarily achieve this, especially for co-oriented directional antennas. Therefore, we introduce a pathloss normalisation factor.

Since the measurement UCAs propagate and receive over the entire azimuth range, the pathloss normalisation factor could be estimated from the average over all 16x16 constituent channels in Equation (1). However, the resulting normalised 4x4 channel is unlikely to have average gain of unity. The difference between the two normalisation techniques is demonstrated in Figure 4. The unity-gain normalisation can be used to observe that the 4x4 facing (LOS) channel is more correlated than the 4x4 non-facing (NLOS) channel at the same locations of the UCAs. On the other hand, pathloss normalisation shows better performance for the LOS channel despite higher correlation, simply because antenna sectors in line-of-sight receive more power. Thus, the two normalisation techniques deliver very different results, and either might be preferred depending on the purpose of the analysis.

The omni-directional pathloss information may not always be available for measurements with directional antennas. In such cases, if transmit power across the transmit antennas is equal, the normalisation factor can be taken to be the gain of the strongest constituent SISO channel. This method gives
similar performance results as the pathloss normalisation for
cross-oriented antennas.

C. Capacity Calculation
Since power was allocated equally to each transmit element
and frequency sub-channel, and the frequency components
were equally spaced, the capacity of the frequency selective
channel was calculated using [1]

$$C_i = \frac{W}{N_f} \sum_{f=1}^{N_f} \log_2 \left( 1 + \frac{P}{N_T} H_{i,f} H_{i,f}^* \right)$$

(3)

where $H_{i,f}$ is the normalized channel response at frequency
component $f$, $*$ is the complex conjugate, and $\rho$ is the
average signal-to-noise ratio (SNR) at each receiver branch
over the entire bandwidth $W$. The normalised capacity of the
wideband channel, given by $C/W$, will be presented in the
remaining analysis.

IV. MIMO CHANNELS FROM EXTRACTED
MULTIPATH PARAMETERS
A. Calculating MIMO response from extracted MPCs
Each snapshot of extracted MPCs describes the channel
from the transmit origin to the receive origin as a joint
function of the delays, DOAs and DODs. A summation of
these electromagnetic wave components gives rise to the
channel response. Applying the plane-wave propagation
assumption allows us to predict the channel response for
transmit and receive antennas placed at arbitrary locations
that are close to their respective origins. In order to allow
the plane-wave assumption to apply, the antenna arrays
during measurements were placed at a sufficient distance
from the nearest scatterers. Any effects of mutual coupling
have been ignored. Equation (4) gives the channel response
at each delay tap $l$ ($l = 1, N_l$), $N_l$ was chosen to be equal to
the number of frequency tones employed in the
measurements. The subscript $l$ has been omitted in the rest
of the equation (from $h_{i,l}$ and $\theta_{i,l}$) for clarity. For each
snapshot, the multipath components were assigned to the
nearest delay tap, according to their excess delay. The
impulse response from the $k$th transmit to the $j$th receive
channel is given by

$$h_{i,k,l} = \sum_{s=1}^{N_s} P_s e^{j\phi_s} \sqrt{G_{R_i}(\vec{\theta}_s^A, \vec{\phi}_s)} \sqrt{G_{T_i}^*(\vec{\theta}_s^D, \vec{\phi}_s)}$$

$$\times e^{j2\pi (\vec{x}_i^D \cdot \vec{\phi}_s)} e^{j2\pi (\vec{x}_i^D \cdot \vec{\phi}_s)}$$

(4)

where $N_s$ is the number of MPCs within each delay bin, $P_s$ is
the power of each path, and $\phi_s$ is the overall phase. Vectors
$\vec{x}_i^D$ and $\vec{x}_i^A$ are the locations of the antenna elements
defined with respect to the centres of the respective UCAs.
$\vec{\phi}_j$ and $\vec{\phi}_k$ give the directions of orientation of antennas at
the Rx and Tx respectively. The locations and orientations
were assigned to correspond to the 4x4 arrays described in
III.A. Vectors $\vec{\theta}_s^A$ and $\vec{\theta}_s^D$ represent the DOAs and DODs
respectively. Since DOAs and DODs were extracted as
angles in the azimuth plane, elevation angles had to be
assigned from a truncated statistical distribution. This
was needed because angular spread in elevation can be expected
to be significant due to reflections from the ceiling and the
ground. $G_{R_i}(\vec{\theta}_s^A, \vec{\phi}_s)$ and $G_{T_i}^*(\vec{\theta}_s^D, \vec{\phi}_s)$ are the antenna
pattern gains, which account for the arbitrary patterns and
orientations of the antennas. The wideband channel response
was calculated from windowed discrete-Fourier transform
(DFT) of the tap-delay response $h_{i,k,l}$ and unity-gain
normalisation was used for calculation of capacity.

B. Measured channels vs. extracted MPCs
Figure 5 shows a capacity comparison between MIMO
channels from extracted MPCs and directly measurements
for the 4x4 facing (LOS) and non-facing (NLOS) co-
oriented sectors. The capacities of channels calculated from
extracted MPCs were found to be lower than the measured
channels for both LOS and NLOS scenarios. This has been
found to be the case in similar studies conducted elsewhere
[13]. This can be partly attributed to the limitations of the
parameter extraction process. For instance, the total power
of extracted parameters for any snapshot was typically about
70% of the measured power, as only a finite number (~50)
multipath components were extracted for each snapshot.
Significantly larger computation time would have been
necessary to extract a greater number of components.
The unextracted energy might be expected to consist mainly
of a large number of low-power diffuse components and
second/third bounce reflections. When the unextracted
power was compensated for by adding low-power randomly
distributed components (as suggested in [13]), there was
much better agreement between the extracted MPCs and the
measured channels (Figure 5). It can also be seen that the
difference between the measured and estimated capacities is
similar for the two antenna configurations, especially after
addition of the "unextracted" components. The use of
extracted parameters along with the plane wave model may
not precisely predict the actual theoretical capacity.
However, this approach may be potentially useful for
comparing performances of different antenna types and
array configurations. This has relevance to evaluation of
candidate MIMO array designs [12], since extensive MIMO
measurements are not easily realisable.

Figure 6 confirms that whilst the extraction process might
fail to extract the low-power diffuse components, it
accurately extracts the stronger MPCs, which make a greater
contribution to the fading and the power of constituent SISO
links. There is excellent agreement between the power
spread of the MPC-based and measured channels, for both
cross- and cross-oriented antenna arrays.
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