Personal Area Networks with Line-of-Sight MIMO Operation

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Abstract— **In this paper, the results of an on-body, line-of-sight (LOS), multiple-input, multiple-output (MIMO) channel sounding investigation are reported. Transmission takes place between on-body antennas and a uniform linear array, positioned at close range and within line-of-sight of each other. Due to the on-body location of the antennas, the influence of actual radio channel can no longer be separated from the effects of user behaviour and body proximity. This paper therefore argues that the composite channel must be considered. Post-processing of the recorded channels shows that their capacities outperform those from equivalent Rayleigh channels. Taking into account the clear LOS in the experiment, this appears counter-intuitive to the well-known fact that uncorrelated scattering results in high capacity. An analysis of the results highlights some less familiar facts and leads to an overview of capacity generating mechanisms in MIMO systems. The paper adds an analysis of the sensitivity of the capacity to the properties of the channel matrix, which is used for a discussion of the practical use of MIMO in personal and body area networks.**

I. Introduction

Since [1], the potential capacity increases offered by multiple-input, multiple-output (MIMO) antenna systems are well-known and have been studied extensively, mainly for outdoor and wireless local area network (WLAN) applications. It is well known that in these applications, uncorrelated scattering allows MIMO systems to extract a significant diversity gain. As a result, line-of-sight (LOS) and correlated channels are usually assumed to have an adverse effect on MIMO performance [2].

In this paper, the results of a wideband MIMO measurement campaign in a body area network are reported. The measurements were made in 120 MHz bandwidth centred around 5.2 GHz. The experiment highlights the difficulties of measuring these channels due to the influence of the user on antenna characteristics. Evaluation of the capacity shows that despite line-of-sight and gain imbalance, the measured channels exceed the capacity of equivalent Rayleigh fading channels. Analysis of these results emphasises some subtleties in the literature. This paper adds an investigation of the sensitivity of the capacity to the properties of the channel matrix, which is used to demonstrate the practical potential for MIMO in body and personal area networks (BAN and PAN).

The measurement campaign on which this paper is based is presented in section II. The results are analysed and discussed in the following section, while section V draws conclusions for the use of MIMO in BAN and PAN.

II. Channel Measurement Campaign

The results presented in this paper are based on measurements that took place in a small room (5 by 4 metre), part of the Wireless and Networks Research Lab on level 1 of the University of Bristol's Merchant Venturers Building (UK). These measurements are a sub-set of the campaign previously reported in [3]. Apart from two people, the measurement equipment and some furniture, the room was empty. For the measurements used in this paper, one of the two people present has two, transmitting, stacked patch antennas [4] mounted at chest height. These represent devices in a chest pocket or antennas integrated in the user's clothing. The user is facing the array and standing about 1 metre away from it. The receiving array is an eight plus two passive elements 5.2 GHz uniform linear array with half wavelength antenna spacing. For 2-by-2 MIMO system evaluation below, antenna elements 1 and 7 are used.

For channel measurements for cellular or WLAN scenarios, careful calibration of the antennas makes it possible to extract the actual radio channel from the measured transmission responses. For BAN or PAN applications where some of the antennas are body-mounted, this is no longer possible. The proximity of the body will change the antenna characteristics [5], while user actions [6], [7] and arbitrary antenna orientation will lead to further unpredictable changes to the recorded transmission response. Therefore, in this type of situations, it is necessary to extend the definition of the radio channel to a system level perspective that includes the antennas and user effects.

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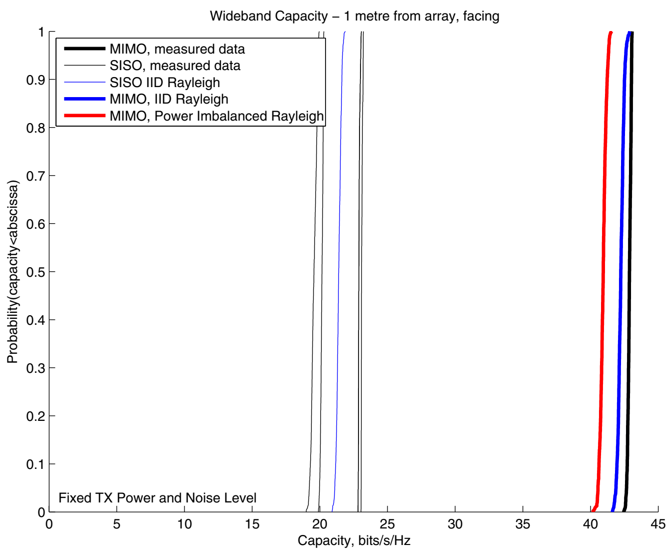

Fig. 1. Wideband Capacity Comparison

III. Post-Processing Results

Fig. 1 compares the wideband capacities of the measured SISO and MIMO links with equivalent independent, identically distributed (IID) Rayleigh channels. In order to do this, the capacity has been averaged over the 120 MHz measurement bandwidth.

The differences between the SISO capacities are due to a gain imbalance caused by body mounting, which results in antenna orientation and polarisation alignment differences. In the measured data, up to 10 dB power difference is observed. Therefore, fig. 1 also includes the capacity of an equivalent MIMO system with Rayleigh fading channels that have the same power imbalance as observed in the measured channels.

Despite the power imbalance and the clear line-of-sight, the measured channels outperform both the IID and power imbalanced Rayleigh fading MIMO systems. This is due to the deterministic effect of the LOS. Since there is no fading, the capacity will be constant over the measurement bandwidth and time period, while the Rayleigh wideband average is taken over a number of narrowband frequency bins that fade arbitrarily. For the measurements presented here, the measured data has a capacity equal to that of the highest narrowband Rayleigh fading channels over the whole measurement bandwidth.

The latter is still surprising because it is well known that uncorrelated channels result in high MIMO capacity. Since the system is operating in line-of-sight and short-range, it is unlikely that scatterers provide the necessary decorrelation. Indeed, analysis of the spatial correlation coefficients shows that they are all high:

$$abs(R) = \begin{bmatrix} 1.0000 & 0.9726 & 0.9155 & 0.9082 \\ 0.9726 & 1.0000 & 0.9240 & 0.9666 \\ 0.9155 & 0.9240 & 1.0000 & 0.8794 \\ 0.9082 & 0.9666 & 0.8794 & 1.0000 \end{bmatrix} \quad (1)$$

According to some papers, e.g. [2], this would imply that the MIMO capacity collapses to SISO case.

IV. Analysis and Discussion

As the measurement results demonstrate, high correlation coefficients don't necessarily lead to low MIMO capacity. In the narrowband case, the capacity equation is given by [1]:

$$C = log_2\left[det\left[I_{N_R} + \frac{\rho}{N_T}HH^\dagger\right]\right] \quad bps/Hz \qquad (2)$$

Hence, the capacity is determined by the properties of $HH^\dagger$, which, for 2-by-2 MIMO can be extended as[1]:

$$\begin{aligned} HH^\dagger &= \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} h'_{11} & h'_{21} \\ h'_{12} & h'_{22} \end{bmatrix} \\ &= \begin{bmatrix} h_{11}h'_{11} + h_{12}h'_{12} & h_{11}h'_{21} + h_{12}h'_{22} \\ h_{21}h'_{11} + h_{22}h'_{12} & h_{21}h'_{21} + h_{22}h'_{22} \end{bmatrix} \end{aligned} \qquad (3)$$

The entries on the diagonal will be real valued and equal to sum of the power of the respective channels. For a particular location, this will be dependent on the path loss. The value of the determinant, and hence the MIMO capacity, is determined by the sum of $h_{21}h'_{11}$ and $h_{22}h'_{12}$. The capacity will be maximal when these off-diagonal values are zero. Since $h_{21}h'_{11} + h_{22}h'_{12}$ is the inner product of the rows of H, maximal capacity is achieved when channel matrix H is orthogonal [8].

Note that $h_x h'_y$ is proportional to the correlation coefficient. In most scenarios, the channel coefficients are out of the designer's control and hence uncorrelated scattering is required to minimise the values of the off-diagonal entries. In pure LOS, however, the channel coefficients become deterministic. The phase difference between the channel coefficients is fixed and dependent on the operating frequency, array geometry and positions [9]. Since the coefficients are complex valued, even highly correlated channel coefficients can add destructively, and result in orthogonal rows. In order for this to happen, a significant phase difference between the channel coefficients is required. This is possible when the spherical nature of the wavefronts has to be taken into account, i.e. for systems operating over a short distance or with significant antenna spacings [10]. In [11], this has been used to derive a design criterion that maximises the channel capacity under LOS conditions.

In order to get an appreciation of the sensitivity of the capacity to orthogonality, consider the following normalised, LOS channel matrix:

$$H = \begin{bmatrix} e^{-jkd_{11}} & e^{-jkd_{12}} \\ e^{-jkd_{21}} & e^{-jkd_{22}} \end{bmatrix}$$

where d_{xy} is the distance between transmit and receive antennas a and b and it is assumed that this distance is such that

[1] In this paper, † will be used to indicate the Hermitian of a matrix, while ′ is used to indicate the complex conjugate of a number

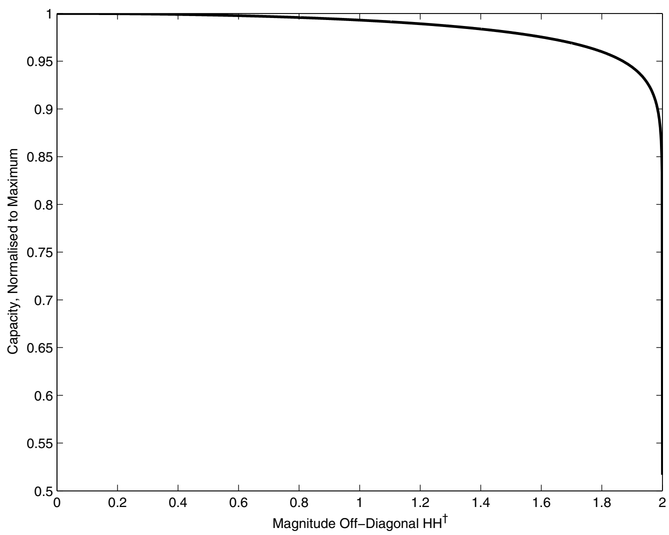

Fig. 2. Relation between orthogonality and capacity

the path loss differences are negligible. As shown in [11], in this case, $HH^\dagger$ equals:

$$HH^\dagger = \begin{bmatrix} 2 & e^{jk(d_{21}-d_{11})} + e^{jk(d_{22}-d_{12})} \\ e^{jk(d_{11}-d_{21})} + e^{jk(d_{12}-d_{22})} & 2 \end{bmatrix}$$

where the magnitude of the off-diagonal sum varies between 0 and 2 depending on the antenna spacing. Since the entries on the diagonal are constant, the magnitude of the off-diagonal entry is a measure for the orthogonality of the channel matrix. The closer to zero, the closer to orthogonal the rows of the matrix are and the higher the capacity will be. The exact relation between this value and the resulting capacity for a system operating in the high SNR region is given in fig. 2. Due to the logarithmic relation between the two, the magnitude of the off-diagonal entries has to rise up to 1.98 for the capacity to drop below 90 percent of its maximum value.

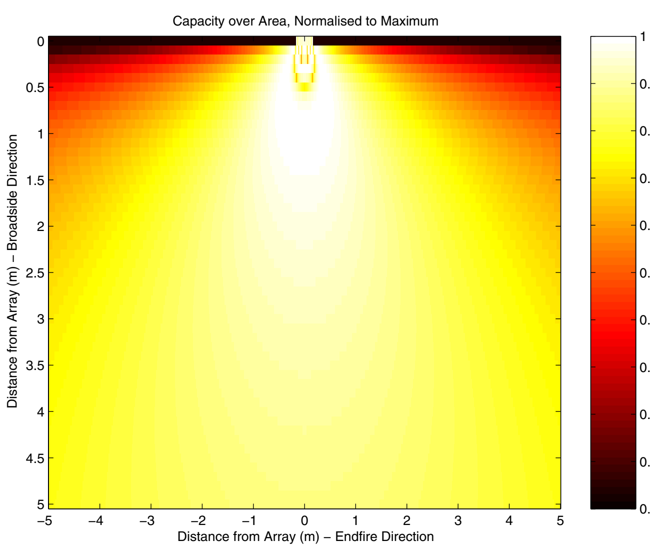

Fig. 3. Capacity in area in front of array

Therefore, a MIMO system can still offer significant capacity increases in LOS conditions even if the conditions are not ideal. Indeed, in the recorded channels, 2-by-2 MIMO achieves an 85 percent capacity increase compared to SISO systems despite 10 dB gain imbalance. In fig. 3, the capacity achieved by a 5.2 GHz MIMO system optimised for a separation of 1 metre is shown over an area of 10-by-5 metres. As can be seen, the MIMO system is able to extract a significant capacity increase in most of this area. Therefore, it can be concluded that despite the probable presence of a LOS, it is worth considering MIMO for PAN applications.

V. Conclusions

This paper has reported on the results of a channel measurement campaign in a body area network. Difficulties to the proximity of the body have been discussed and it was proposed to extend the channel definition to include the influence of the user. It was explained how, despite a clear line-of-sight, the capacity of the measured channels could outperform equivalent Rayleigh fading channels. Relevant references were highlighted to show that orthogonality of the channel matrix is required to achieve high capacity and how, under LOS conditions, careful antenna placement can lead to such an orthogonal channel matrix. The paper added an analysis of the sensitivity of capacity to orthogonality. It was shown that despite significant deviations from orthogonality, MIMO can still offer significant capacity gains. This knowledge was then applied to a personal area network scenario where it was shown that this capacity increase can occur over a significantly big area to consider MIMO for personal area network applications.

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