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Experimental Investigation of the Temporal Variation of MIMO Channels

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Abstract – **The measurement and characterisation of multiple-input multiple-output (MIMO) channels has gained increasing attention over recent years. Previous analysis of MIMO measurements has generally focussed on the evaluation of the capacity of such systems in differing locations and configurations. In this paper we present measurements made in an indoor environment at 5.2GHz, specifically to investigate temporal channel variation. Line-of-sight and non-line-of-sight situations are compared by means of an analysis of the rate of variation in the powers of the 'orthogonal spatial channels' comprising the overall MIMO channel. The conclusions are extended to encompass the rate of variation in performance of MIMO channels under different environmental conditions.**

I. INTRODUCTION

The potential of Multiple-Input Multiple-Output (MIMO) communication systems to realise huge spectral efficiencies [1] has aroused much interest in the use of these techniques for future wireless communication standards in order to help meet the anticipated demand for high bit-rate, real-time services within limited bandwidths.

The creation of accurate models for MIMO channels has therefore become an increasingly important area of research, both for indoor and outdoor environments. This work has been aided and complemented by various measurement campaigns [2]-[6] that have sought to both verify initial assumptions and to provide a resource for channel model development. These channel sounding activities have largely focused on the spatial capacity variation of such channels, and have hence either ensured a stationary measurement environment or viewed it as being quasi-static.

The investigation of temporal channel variation is equally important, since this can also have a large impact on the performance and reliability of digital communication systems. Even in an indoor office or laboratory environment, the relatively slow (compared to speeds encountered outdoors) movement of people and objects can cause significant channel variation. Measurement and analysis of these effects have been reported in [7]-[13] for a variety of frequencies and environments, although only for single-input, single-output (SISO) systems. An initial investigation of the temporal variation of MIMO channels was reported in [14], where it was shown that the rate of variation of the overall MIMO channel characteristics was much slower than that of the constituent SISO channels.

This paper presents an extension of the results in [14] and compares the temporal variation of measured MIMO channels in indoor line-of-sight (LOS) and non-line-of-sight (NLOS) situations at 5.2GHz. In Section II, the characteristics of MIMO channels are described and methods for their numerical evaluation outlined. Section III describes the measurement system and procedure employed. Results of the temporal analysis are presented in Section IV, followed by the conclusions in Section V.

II. MIMO CHANNELS

For a narrowband system, the complex channel response between a single element at the transmitter and receiver can be represented as a single complex number. The full channel response of a system comprising of n_T transmit elements and n_R receive elements, can therefore be described by an n_R-by-n_T matrix, G, (where element G_{ij} is the response between receive element i and transmit element j).

The comparison and performance evaluation of these MIMO channels is usually achieved through the calculation of the channel's information theoretic capacity. For fixed numbers of antenna elements it has been shown [1] that this capacity is a function of both the average received signal to noise ratio at each receive element, ρ, and the normalised channel response matrix, H, as shown in (1). (Where I_n is the n-by-n identity matrix and * is conjugate transpose). This assumes that the transmitter does not have knowledge of the channel response, and hence distributes its power equally amongst the n_T elements.

$$C = \log_2\left[\det\left(I_{n_R} + \frac{\rho}{n_T} HH^*\right)\right] \quad \text{bits/s/Hz} \qquad (1)$$

The normalised channel matrix, H, is obtained from the absolute, instantaneous, (measured) channel response, G, by removing the average path loss component [1], as follows,

$$H = \left(\hat{P}/P\right)^{1/2} \cdot G \qquad (2)$$

where $\hat{P}$ is the total transmitted power and P is the average power taken over all receive elements.

Although (1) provides one metric for evaluating the performance of a MIMO channel, it is often useful to view a MIMO channel as several 'orthogonal spatial channels', each with it's own path gain [15]. These *absolute* path (power) gains can be identified as the eigenvalues, λ_i (for $i = 1,\ldots,n_R$), of the matrix GG^*. From these, both the variations in channel path loss and correlation between elements can be investigated. Similarly, in common with other studies, the

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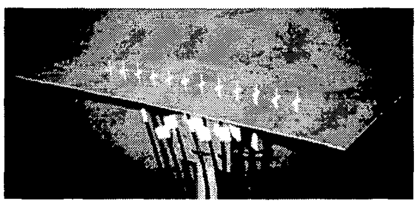
relative path (power) gains can be obtained from the normalised channel matrix, H, as the eigenvalues, ε_i (for $i = 1,\ldots,n_R$), of the matrix HH^*.

III. Measurement System and Procedure

A. *Measurement Equipment*

The measurement platform used for these measurements is based on a Medav RUSK BRI vector channel sounder [16]. This employs a periodic multi-tone signal with a maximum bandwidth of 120MHz, centred at 5.2GHz. The receive antenna is a uniform linear array composed of eight vertically polarised dipole-like elements separated by 0.5λ (Fig. 1a). A fast multiplexing system switches between each of these elements in turn in order to take a SIMO 'snapshot' of the channel in 12.8μs.

a) RX array



b) TX array

Fig. 1. Antenna arrays employed for 5.2GHz MIMO channel measurements

MIMO channel sounding is achieved through the use of additional switching and synchronisation circuitry to control a second eight-element uniform linear array at the transmitter (Fig. 1b). This array consists of 0.5λ-spaced, monopole elements so as to retain an omni-directional radiation pattern and therefore excite as much scattering as possible within the indoor environment.

For each transmit element in turn, a SIMO snapshot of the channel is taken at the receiver. In this way, eight consecutive SIMO snapshots contain the complex channel responses of all 64 combinations of the eight transmit and receive elements. Each complete 'MIMO snapshot' of the channel is therefore recorded in 102.4μs, which is fast enough in indoor environments to ensure that the channel remains stationary during each measurement.

Although wideband data is recorded, the results presented here only consider a subset of this data in order to analyse the narrowband channel response.

B. *Measurement Conditions*

The photographs in Fig. 2 show the two environments in which the measurements presented here were recorded. In the entrance foyer, measurements were taken for a variety of stationary mobile terminal (MT) positions, all located with LOS to the fixed 'access point' (AP). The arrays at the MT (measurement TX) and AP (measurement RX) were maintained at heights of 1.1m and 2.7m respectively. Throughout the duration of these measurements, between eight and eleven people moved around at walking pace in the vicinity of both the MT and AP.

Fig. 2. Measurement environments. (top) Open Foyer. (bottom) Cluttered Laboratory

The measurements in the laboratory were conducted in a similar manner, with the exception that the array at the AP was lowered to a height of 1.7m in order to bring it below the height of the shelves. All measurements were therefore recorded with both arrays being surrounded by a cluttered environment with no line-of-sight path between them.

For each location, in both environments, one MIMO snapshot was recorded every 4.096ms for a total period of 13s. Due to memory constraints of the current measurement hardware, these parameters were judged to be an acceptable compromise of repetition rate and overall duration.

IV. Results

The results presented here will concentrate on only three of the measurements recorded, since these are sufficient to illustrate the general characteristics shown by all locations. The first two of the chosen locations (herein referred to as A and B) were located in LOS to the AP in the foyer, whereas the third (location C) was in a NLOS position in the laboratory.

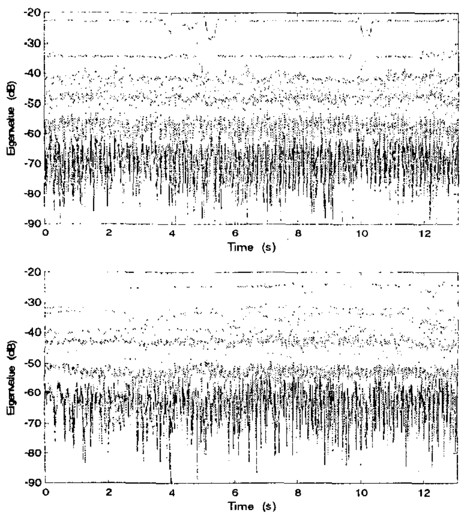


Fig. 3. Variation in λ_i, the eigenvalues of GG^*, with time, for (top) Location A, (bottom) Location B.

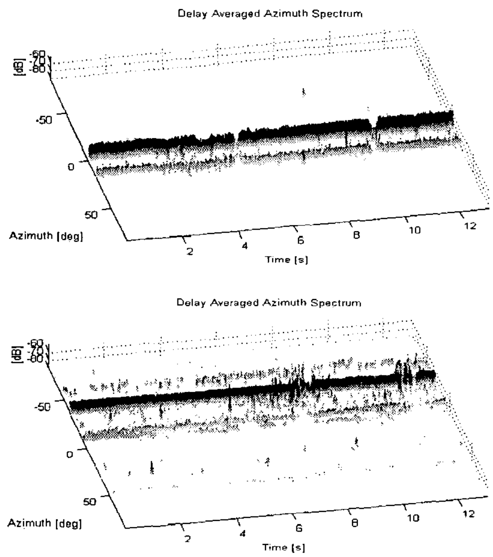


Fig. 4. Variation in multipath angle of arrival (estimated at the AP for one MT antenna element) for (top) Location A, (bottom) Location B. Both plots have had a threshold applied at –40dB from their peak components.

As described in Section II, a MIMO channel matrix can be decomposed by an operation such as an eigenvalue decomposition (EVD) in order to ascertain the gains of the 'orthogonal spatial channels' that it encompasses. The variation of these gains, with time, is shown in Fig. 3 for locations A and B. The reason for the noisy appearance of the lower eigenvalues is due to the lack of any averaging of consecutive snapshots. Since these eigenvalues represent subspaces containing low signal powers, they are therefore more susceptible to measurement noise. This is a consequence of the trade-off in requiring a high measurement repetition rate, although it does not affect the analysis herein since we are specifically interested in the relative variation of the larger eigenvalues.

The most significant artefact exhibited in Fig. 3 is that the eight eigenvalues (of GG^*) do not necessarily vary at the same time as each other. In particular, the variations in the eigenvalues for Location B appear to be almost totally independent of each other, with the third eigenvalue being seen to change whilst the first and second remain almost constant. Similarly, for Location A it can be seen that although the variations in the first two eigenvalues appear to be due to the same channel disturbances, the changes in the second eigenvalue occur about 0.25s before corresponding changes in the first eigenvalue.

An intuitive reasoning for the behaviour of the eigenvalues in Fig. 3 can be obtained from the plots of the estimated angles of arrival of the multipath components, as shown in Fig. 4. Here, it can be observed that for Location A (with direct LOS between the MT and AP) there are two dominant signals arriving at the AP. These are sufficiently separated in azimuth that the decomposition of the channel matrix has resulted in the two signals being almost completely contained in separate orthogonal subspaces (described by the basis vectors of the EVD). Any variation in either of the signals, for instance if the path is shadowed by a person, will therefore cause a noticeable variation only in the corresponding eigenvalue.

The variations of the two largest eigenvalues can now be explained as a person walking past the MT, first through one path to the AP and then 0.25s later, through the second path. This can also be noted from the characteristic shape of the eigenvalue variation being that of the envelope variation caused by a human body walking through a LOS signal [13]. This interpretation has subsequently been verified against a video taken of the environment during the measurement.

Similar effects can be seen from the lower plot in Fig. 4, for Location B, where the three dominant signals arriving at the AP are again sufficiently separated in azimuth for the energy to be mostly contained in orthogonal subspaces. In this case, the movement of people through the third strongest ray arriving at the AP gives rise to the variation in the third largest eigenvalue, but not the first two.

The results in Fig. 3 and Fig. 4 are specifically for a strong LOS scenario where only a few widely separated rays dominate the received signals. Hence, an orthogonal decomposition of the channel matrix easily separates these signals. The alternative situation, where a large number of scatterers (more than the number of array elements) exist is therefore of interest, since the above reasoning will no longer hold.

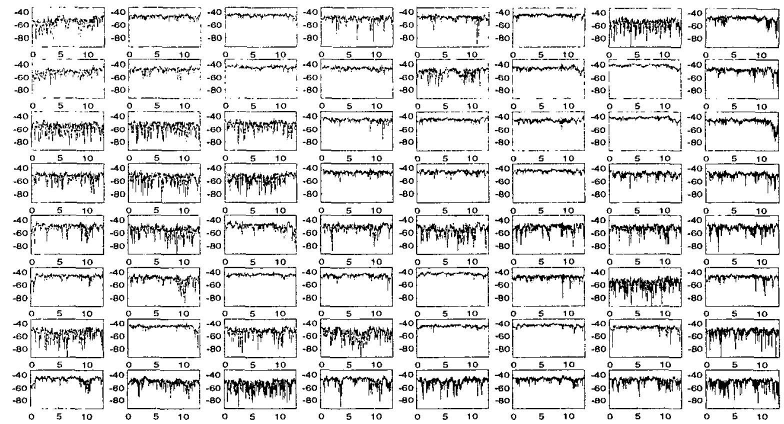


Fig. 5. Path gain (dB), versus Time (s), for each of the SISO channels between all 8 transmit and 8 receive elements in Location C. Each column corresponds to the paths for one transmit element, and each row corresponds to the paths for one receive element.

The multiple plots in Fig. 5 show the temporal variation of each of the path gains between all combinations of transmit and receive elements for the NLOS scenario in Location C. It is immediately apparent that there are large disparities between the SISO channel responses, with some exhibiting rapid variation whilst others show little change over the measurement period. An expanded view of a short period of the channel response between transmit element 7 and receive element 6 is shown in Fig. 6. Here, it can be verified that even with this rate of temporal variation, the measurement configuration is still sufficient to oversample the channel.

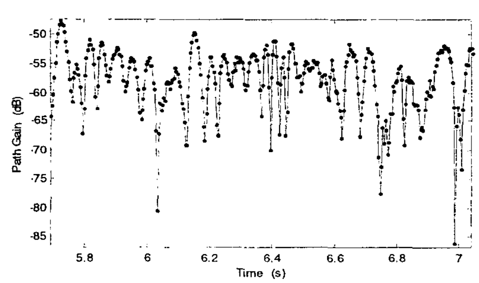


Fig. 6. Expansion of a period of the measured response between transmit element 7 and receive element 6 (Location C).

An explanation for the disparities observed in the behaviour of the different SISO channels can be inferred from a result reported in [9]. This showed that a receiver which experiences a high path gain under stationary environment conditions is affected less by the movement of people than one that is normally in a spatial fade. This will be true if the dominant signal(s) between the two arrays do not vary, since the effect of changes in the superposition of the smaller multipath components will make little difference to the elements already receiving a strong signal from the dominant component. Conversely, elements that receive less power from the dominant signal(s) will be influenced to a greater extent by changes in the other multipath components. This can be seen in Fig. 5, where the plots with the highest mean path gain show the least temporal variation. In effect, some elements experience a higher Rician K-factor than others.

Since the propagation environment for Location C was NLOS, it is assumed that the dominant path between the transmitter and receiver was a reflection from the ceiling. Hence, the movement of people only yielded changes in the smaller multipath components that were scattered around the laboratory shelves, as it would be much harder for the ceiling reflection to be shadowed.

The effect of temporal variation on the eigenvalues of GG^* for Location C is shown in Fig. 7. It can be seen that in this case, the largest eigenvalue remains relatively constant, while the other values vary more noticeably (ignoring the superposition of noise on each value). Even so, the range over which the eigenvalues vary is small compared to that seen in Fig. 3.

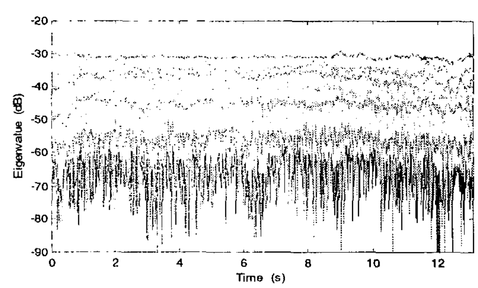


Fig. 7. Variation in λ_i, the eigenvalues of GG^*, with time, for Location C.

This is due to each eigenvalue now representing power received from several multipath components. An indication of this can also be seen from an improvement in the average condition (ratio of the largest and smallest eigenvalues) of the channel matrices.

An extension of the conclusion drawn in [14] can therefore be made with regard to the rate of change of the powers of the 'orthogonal spatial channels' (eigenvalues of GG^*) in different environmental conditions, compared with the rate of change of the complex response of the constituent SISO channels:

i) In the limiting case of a single path between the two arrays, or in the presence of a true 'keyhole' effect [17], only one eigenvalue will exist and will vary at the same rate as any change in the single path's response.

ii) For signals impinging on the arrays from suitably spaced angles of arrival (up to the same number as array elements), which can be uniquely separated by an orthogonal decomposition, any change in their response will affect the corresponding eigenvalue at the same rate.

iii) When the impinging signals are not suitably separated in azimuth, such that they cannot be resolved by an orthogonal decomposition of the channel matrix, or the number of elements is less than the number of impinging signals, some, or all, eigenvalues will represent power from more than one multipath component. These eigenvalues will therefore typically vary at a slower rate than the responses of the individual path gains between elements (changes in the superposition of the impinging waves).

iv) Finally, in the limit of Rayleigh fading, even though the constituent SISO channels may experience rapid fading, relative variation between the eigenvalues of GG^* will only be due to random momentary correlation between element path gains causing the lowest eigenvalue(s) to significantly decrease in value (as seen in [14]). Any significant environmental change, such as body shadowing of a terminal, will be observed as a joint variation in all eigenvalues.

V. CONCLUSION

This paper has reported the measurement of MIMO channels in both LOS and NLOS indoor channels at 5.2GHz. The temporal variation these channels due to the movement of people has been analysed with respect to changes in the powers of the 'orthogonal spatial channels' comprising the overall MIMO channel. The joint, and sometimes independent, variation of these channels has been described. Finally, it has been shown that the relative rate of variation in the powers of these channels, compared to that of the constituent SISO channels is dependent on the nature of the propagation environment.

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