Channel Characteristics Analysis of the Dual Circular Polarized Land Mobile Satellite MIMO Radio Channel

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Abstract – **This paper analyses the characteristics of the dual circular polarized land mobile satellite MIMO radio channel using measured and modeled channel data. To describe the small scale fading observed in the measured channel, the model makes use of three parameters, which respectively represent the mean LOS, specular reflected and diffuse multipath signals. The model is validated by comparing the CDF plots of the received signal power and eigenvalues with that of the measured channel. Furthermore, the effects of channel correlation on the capacities of equal power allocation MIMO and dual circular polarization multiplexing (DCPM) is investigated. It is found that only the capacity of the LOS-friendly DCPM is negatively affected by a reduction in channel correlation.**

1 INTRODUCTION

Research has shown that multiple-input multiple-output (MIMO) can increase the capacity of wireless communication and broadcast systems without the need for additional spectrum [1]. This increase relies on the presence of a rich scattering environment to de-correlate the signals between the multiple transmit and receive antennas. However, the satellite link-end of all land mobile satellite (LMS) channels is completely devoid of scatterers, thus making the implementation of traditional MIMO challenging. Some solutions, including the use of multiple satellites placed in hugely separated orbital slots have been proposed in [2]. Given the huge distances between orbiting satellites and land mobile terminals, this MIMO implementation is beset with many problems including the need for perfect transmission synchronization and scheduling among others. A more viable MIMO solution for the LMS scenario, and which lends itself to easy implementation in line with the standards for Digital Video Broadcast to Small Handhelds and to the Next Generation of Handhelds (DVB-SH and DVB-NGH) [3], is the use of a single satellite and orthogonal circular polarizations to separate and/or de-correlate the multiple channels. Pioneering work in this area has been performed by [2][4], however, more detailed knowledge of the dual circular polarized LMS MIMO channel characteristics is needed.

Direct channel measurements provide the best way to study the characteristics of wireless propagation channels. Hence, several measurements [2][5] have been undertaken in order to produce good quality dual circular polarized LMS MIMO channel data. Apart from getting a true picture of the measured channel, measurement campaigns are expensive, time consuming and difficult to carry out. Also, measured channel data can only provide insights into the particular environment in which the measurements were performed. These disadvantages make the use of channel models more attractive. Hence, based on the measured channel data, a simple stochastic channel model has been developed. The tractability of this model allows it to be used in investigating the effects of channel correlation on the capacities of MIMO and dual circular polarization multiplexing (DCPM) in the LMS MIMO channel.

2 CHANNEL MEASUREMENT AND MODELLING

In addition to the channel data derived from King's measurements [2], data for this analysis is obtained from two measurement campaigns carried out in the summer of 2009 and 2010 to accommodate higher elevation angles. Parameters extracted from the measured channel have been used in generating and validating a simple stochastic channel model.

2.1 Measurement Campaign Description

The two measurement campaigns relied on an Elektrobit Propsound wideband channel sounder to sample the dual polarized LMS MIMO channel. In the 2009 measurement, a satellite transmitting at a frequency of 2.43 GHz to a vehicular mobile receiver was emulated by mast mounted right hand circular polarized (RHCP) and left hand circular polarized (LHCP) antennas placed on a hill. Signals from this emulated satellite were received using omnidirectional RHCP and LHCP antennas mounted on the roof of a vehicle driven along preselected routes in a rural environment close to the town of Guildford, UK. This measurement provided high Ricean line of sight (LOS) and obstructed LOS (OLOS) channel data. The second measurement campaign was conducted in a suburban area of Guildford. Here, a 2.5 GHz carrier frequency was

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used and the receive antenna configuration was the same as in the previous measurement. The satellite in this case was emulated by mast mounting two (RHCP and LHCP) directional antennas on a tower block. This setup allowed for satellite elevation angles as viewed from the mobile receiver to range 15^{o} to 37^{o}.

The measured channel data was stored in the form of complex valued wideband channel impulse response and extensive post processing had to be performed to reduce the data down to its representative narrowband component. This, in addition to simplifying the analysis, was necessary because present and future LMS systems are inherently narrowband. The dual polarized LMS MIMO channel is thus represented by:

$$\mathbf{H} = \begin{bmatrix} h_{RR} & h_{RL} \\ h_{LR} & h_{LL} \end{bmatrix} \tag{1}$$

Due to the antenna pairs at the transmit and receive link-ends being RHCP and LHCP, h_{RR} in equation (1) represents the co-polar channel between an RHCP transmitter and an RHCP receiver. The other channels (h_{RL}, h_{LR} and h_{LL}) follow the same naming convention.

To preserve the power ratio between the time sampled MIMO channels and to remove the large scale fading effects, **H** was Frobenius normalized and then de-meaned one time-series section at a time by dividing through with the mean value of the same sections of the h_{RR} channel. Elimination of large scale fading effects allowed for the very important small scale fading to be analyzed.

2.2 Channel Modeling

As a first step towards channel modeling, it is assumed that the MIMO sub-channels are independent of each other; hence the single input single output (SISO) approach of [6] is followed. The mean signal levels of the measured co- and cross-polar channels denoted α and β are first extracted. A third parameter, σ representing multipath components, is the standard deviation extracted separately for the co- and cross-polar channels. Thus, without yet considering the interdependence between sub-channels, the dual polarized LMS MIMO channel is given as:

$$\begin{bmatrix} h_{RR} & h_{RL} \\ h_{LR} & h_{LL} \end{bmatrix} = \begin{bmatrix} \alpha + \sigma \exp(j\theta_{RR}) & \beta + \sigma \exp(j\theta_{RL}) \\ \beta + \sigma \exp(j\theta_{LR}) & \alpha + \sigma \exp(j\theta_{LL}) \end{bmatrix} \tag{2}$$

where θ_{ij} are zero mean randomly distributed elements with unit standard deviation representing the phase angles of the individual channels. All the other elements are as previously defined.

For simplicity, only the channel correlation between the two co-polar channels, C_{CP}, and the correlation between the cross-polar channels, C_{XP} are considered. Cholesky factorization is then employed to impose correlation on the modeled channel. Thus we have:

$$\mathbf{H}_{COR} = \begin{bmatrix} h_{RR|COR} & h_{RL|COR} \\ h_{LR|COR} & h_{LL|COR} \end{bmatrix} \tag{3}$$

$$\text{where} \quad \begin{bmatrix} h_{RR|COR} & x \\ x & h_{LL|COR} \end{bmatrix} = \mathbf{C}_{CP}^{T} \begin{bmatrix} h_{RR} & 0 \\ 0 & h_{LL} \end{bmatrix} \mathbf{C}_{CP} \tag{4}$$

$$\text{and} \quad \begin{bmatrix} h_{RL|COR} & x \\ x & h_{LR|COR} \end{bmatrix} = \mathbf{C}_{XP}^{T} \begin{bmatrix} h_{RL} & 0 \\ 0 & h_{LR} \end{bmatrix} \mathbf{C}_{XP} \tag{5}$$

In equations (4) and (5), the $h_{ij|COR}$ ($i,j = R,L$) terms on the left represent the correlated co- and cross-polar channels of the overall $\mathbf{H}_{COR}$ channel matrix. The off-diagonal x terms are unwanted products of the matrix multiplication on the right. Superscript T indicates matrix transposition. Observe that (4) and (5) use a variant of the Cholesky factorization, defined in [7] as:

$$\mathbf{A} = \mathbf{R}^{T}\mathbf{D}\mathbf{R} \tag{6}$$

where **A** is a symmetric matrix to be cholesky factorized, **R** is a Cholesky factorized product of **A** and and **D** is a diagonal matrix. Thus co-polar and cross-polar correlation matrices to be Cholesky factorized are respectively formulated as:

$$\mathbf{C}_{CP} = \begin{bmatrix} 1 & C_{CP} \\ C_{CP}^{*} & 1 \end{bmatrix} \text{ and } \mathbf{C}_{XP} = \begin{bmatrix} 1 & C_{XP} \\ C_{XP}^{*} & 1 \end{bmatrix} \tag{7}$$

The above channel model represents a departure from the popular Kronecker model which uses transmit and receive end correlation matrices to render Rayleigh distributed MIMO channels. For the proposed model, the values of α, β and σ differ for different levels of signal obstruction. Alongside the three parameters, a Markov process can be used to model the switching between the different large scale fading levels.

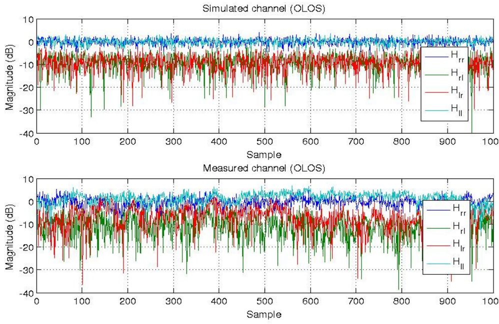

Figure 1: Time series plots of received signal power for the measured and simulated channels

3 MODEL VALIDATION

For model validation purposes, the cumulative distribution (CDF) plots of branch powers and eigenvalues have been used.

3.1 Branch Power Distribution

Branch power distribution of the 2×2 dual polarized LMS MIMO channel is a function of both the antenna and channel cross-polar discrimination. In the LOS channel, where there are few interacting objects to cause massive depolarization, the received cross-polar signal power is mostly scaled by the antennas ability to reject oppositely polarized signals. In the case of the OLOS channel where interacting objects cause a lot of depolarization, the received power level of all the channels are usually at similar levels.

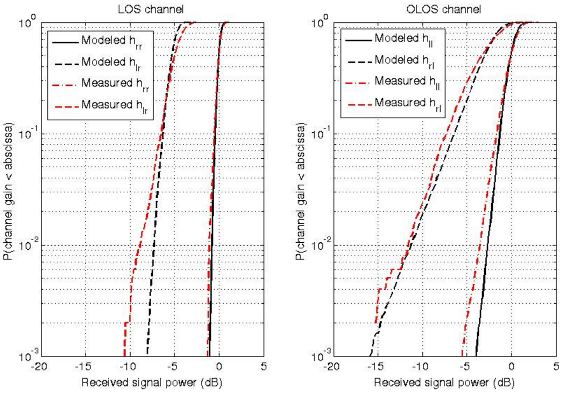

Figure 2: CDF plots of received signal power for LOS and OLOS channels

Figure 2 shows CDF plots of the measured and modeled channels for LOS and OLOS conditions. The very close fit between them indicate the accuracy of the model in representing the small scale fading characteristics of the channel.

3.2 Eigenvalue Distribution

The distribution of eigenvalues of a MIMO channel indicates what transmission modes–whether multiplexing or diversity–can be reliably supported by such a channel. Eigenvalues are defined as:

$$\boldsymbol{\lambda} = \mathrm{EVD}(\mathbf{H}\mathbf{H}^{H}) \tag{8}$$

where $\boldsymbol{\lambda}$ is a matrix containing the eigenvalues(λ_i) of the MIMO channel and in this case i = 1,2. EVD indicates an eigenvalue decomposition operation on $\mathbf{HH}^H$. The superscript represents Hermitian transposition.

The CDF plots of the measured and modeled channel are shown in Figure 3, where there is a very good match between both. This provides further proof of the accuracy of the proposed model. The right plot of Figure 3 represents an OLOS channel where at a probability value of 10^{-3}, the second eigenvalue is about 30dB less than the first eigenvalue. This represents a scenario where diversity-combining would be more beneficial. The left side of the same figure shows an LOS scenario. Here, the first and second eigenvalues are closely spaced and similarly distributed. It would be more efficient to transmit independent bit streams through these two available channels and multiplex them at the receiver. A scheme for implementing such multiplexing has been proposed in [4].

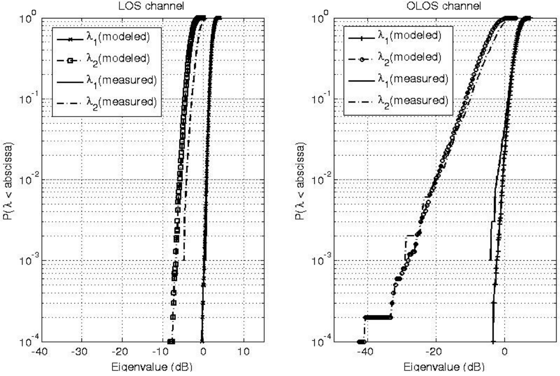

Figure 3: CDF plots of channel eigenvalues

In light of the promise of increased LOS channel capacity and given that MIMO was not originally conceptualized for such channels, the next section investigates how the capacity of the dual circular polarized LMS MIMO channel is affected by channel correlation.

4 CHANNEL CHARACTERISTICS ANALYSIS

Capacity is a very important metric to characterize the MIMO channel and in our context of LOS LMS MIMO, two capacity definitions are used. The first being the traditional MIMO channel capacity more suitable for Rayleigh channels and the second is the DCPM capacity which is more suitable for polarized LOS MIMO channels. Also investigated is the relationship between the Rice factor and channel correlation.

4.1 Rice-Correlation Characteristics

The relationship between Rice factor and correlation among MIMO channels is a very important one for LMS systems. Data from several measurement campaigns have been analyzed to uncover this relationship, which is shown in Figure 4. Using Figure 4 as a guide, the effects of correlation on channel capacity is next analyzed.

4.2 Effects of Channel Correlation on Capacity

In terms of eigenvalues, MIMO channel capacity without channel state information at the receiver is given by:

$$C_{MIMO} = \sum_{i=1}^{n_t} \log_2 \left(1 + \frac{\rho}{n_t}\lambda_i\right) \quad \text{b/s/Hz} \tag{9}$$

where ρ is the average SNR at the receive antenna and n_t is the number of transmit antennas.

DCPM capacity is defined in [4] as:

$$C_{DCPM} = \left(\begin{array}{c} \log_2\left[1+\left(\frac{|h_{RR}w_{11}+h_{RL}w_{12}|^2}{|h_{LR}w_{11}+h_{LL}w_{12}|^2+\sigma_n^2}\right)\right]+ \\ \log_2\left[1+\left(\frac{|h_{LR}w_{21}+h_{LL}w_{22}|^2}{|h_{RR}w_{21}+h_{RL}w_{22}|^2+\sigma_n^2}\right)\right] \end{array} \right) \quad (10)$$

where w_{ij} (i,j = 1,2) are the complex channel weights applied to enhance/attenuate the wanted/unwanted channels. σ_n^2 is the noise term and is defined as:

$$\sigma_n^2 = \frac{|h_{RR}|^2}{SNR} \quad (11)$$

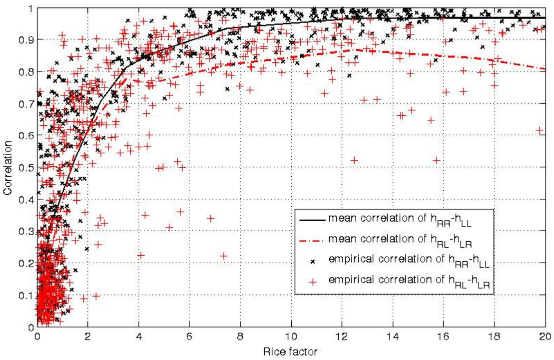

Figure 4: Rice–channel correlation relationship for the dual circular polarized LMS MIMO channel

By inserting the channel model into equations (9) and (10), we have uncovered the effects of channel correlation on the capacity per SNR of the dual polarized LMS MIMO channel. This is shown in Figure 5, where it can be observed that at high correlation (co-polar and cross-polar correlation values being 0.95 and 0.7 respectively) and with SNR values less than 10dB, the LOS-friendly DCPM provides slightly better channel capacity than equal power allocation MIMO. However, at SNR values above 12dB, MIMO gives better performance and the effect of a reduction in correlation (co-polar 0.5, cross-polar 0.3) is further reduced. DCPM does not fare well when channel correlation reduces.

Capacity wise, the good performance of DCPM at low receiver SNRs in highly correlated LOS MIMO channels makes it a suitable technique for implementing the complementary satellite coverage aspects for DVB-SH and DVB-NGH systems.

5 CONCLUSION

The dual circular polarized LMS MIMO channel has been analyzed and the relationship between its Rice factor and channel correlation was found to follow an exponential growth pattern. A model for the channel has also been generated and used in investigating the effects of channel correlation on the capacity of such channels. It was found that low channel correlation negatively affects the capacity of DCPM but has negligible effects on the capacity of equal power allocation MIMO.

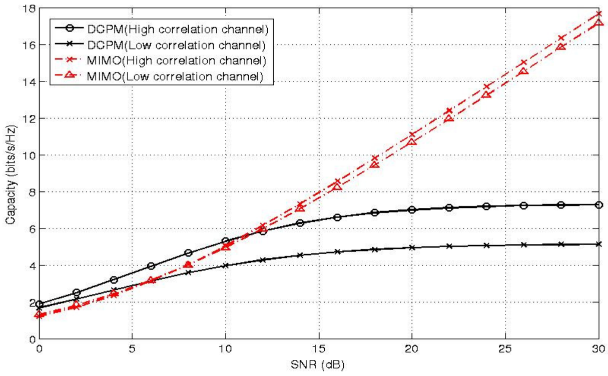

Figure 5: Mean channel capacity per SNR for DCPM and equal power allocation MIMO

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