Effect of Fading Correlation on the Performance of Spatial Multiplexed MIMO systems with circular antennas

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ABSTRACT

In this paper the performance of the Vertical Bell Laboratories Space-Time (V-BLAST) detection that is used in spatial multiplexed MIMO system is investigated when fading correlation effects is included. Simulations of MIMO systems are developed employing accurate stochastic spatial channel model for both the uniform linear array (ULA) and uniform circular array (UCA) geometries. Systems applying VBLAST detection and utilizing UCA are compared with the other existing ULA antenna. Recently, A realistic spatially and temporally clustered channel model is developed to be applied in the simulation of UCA based MIMO systems applying IEEE 802.11n standard. This model accounts for six various real propagation scenarios that are applied in IEEE 802.11n channel model. These models represent a variety of indoor environments. Therefore in this paper the impact of applying IEEE802.11n channel model and the effect of the channel model selection on the link performance of spatial multiplexed MIMO systems is presented.

Keywords: UCA, ULA, MIMO, VBLAST, IEEE802.11n

1. INTRODUCTION

Practical MIMO channels exhibit spatial correlations between Channel paths to or from different antenna elements. It is therefore important to study the effect of spatial correlations on the system performance since this helps in optimally designing the transmit and receive antenna arrays.

For such spatial multiplexing MIMO systems, maximum-likelihood (ML) detection is optimum however it has a prohibitive complexity which grows exponentially with the number of antennas and the signal constellation size. On the other hand V-BLAST detection technique [1]–[2] offers a good tradeoff between performance and complexity. It uses a combination of linear and nonlinear detection techniques: first nulling out the interference from undetected signals, then canceling out the interference using already detected signals. In order to approach the near-optimal performance, this successive interference cancellation (SIC) based detection scheme is complemented by maximum likelihood detection.

The receiver is based on the multi-user detection algorithms which detect the symbols through ordering, linear nulling, and symbol cancellation. Zero Forcing (ZF) and Minimum Mean Squared Error (MMSE) criterion can be used for nulling. The V-BLAST detection algorithm is based on the successive interference cancellation (SIC) and/or parallel interference cancellation (PIC) methods. Most of previously published studies for different VBLAST schemes assumed an uncorrelated Rayleigh fading channel between each pair of transmit and receive antennas. Here in this paper, the objective is to study the effect of fading correlation and compare between different VBLAST detection techniques and antenna geometries when considering correlated channel models.

Channel realizations for MIMO systems employing UCA at either the transmitter or the receiver were developed and studied before in papers [3], [4]. In [3] a general analysis of fading correlation as a function of antenna spacing and angle of arrival distribution was carried out for the UCA. While in [4] a more realistic spatial and temporally clustered channel model was presented to be applied in the simulation of UCA-MIMO systems applying IEEE 802.11n standard. The proposed model accounts for six various real propagation scenarios that are applied in IEEE 802.11n channel model. These models represent a variety of indoor environments. The impact of channel model selection on channel capacity of MIMO systems employing uniform linear array (ULA) and UCA configurations were given.

The paper unfolds as follows: Section II present the VBLAST system based on the SIC algorithms and MMSE nulling principles that will be examined numerically with fading correlation effect. Followed by presentation of the channel models in section III. Section IV, Presents the numerical results of a comparative study between different channel models and antenna geometries of VBLAST detection receivers. The paper is concluded in section V.

2. SPATIAL MULTIPLEXED MIMO SYSTEMS

The V-BLAST high-level block diagram is shown in Fig.1 There are \( M_t \) transmit antennas and \( M_r \) receive antennas, where \( M_t \geq M_r \). The vector encoder is a demultiplexer followed by independent bit-to-symbol mapper, the data is demultiplexed into layers, or parallel sub-streams, and each layer is transmitted from a different antenna. The receivers operate co-channel, each receiver antenna receives a superposition of faded signals radiated from all \( M_t \) transmit antennas.
The received vector, at time $k$, can be represented as [2]

$$ r_k = H a_k + v $$  \hspace{1cm} (1)$$

Where $H$ is the channel matrix, $a_k$ denotes the vector of the transmitted symbols during the $k$-th time interval and $v$ is the noise vector that are given by

$$ a_k = [a_1, a_2, ..., a_{M_t}]^T $$  \hspace{1cm} (2)$$

$$ v = [v_1, v_2, ..., v_{M_r}]^T $$  \hspace{1cm} (3)$$

The V-BLAST detection algorithm employs interference suppression and symbol cancellation to successively detect symbols from each transmit antenna. When detecting the $i$-th symbol, all other symbols are treated as interferes. Linear nulling is used in interference suppression by weighting the received vector to satisfy a performance criterion, such as ZF or MMSE. The nulling matrix $W$ for the ZF and MMSE criteria with the form of Moore-Penrose pseudo-inverse of the channel matrix $H$ as follows

$$ W = (H^H H)^{-1} H^H $$  \hspace{1cm} (4)$$

$$ W = \left( H^H H + \frac{\sigma_n^2}{\sigma_d^2} I \right)^{-1} H^H $$  \hspace{1cm} (5)$$

Where $(\sigma_n^2 / \sigma_d^2)$ is the inverse of signal-to-noise ratio at each receive antenna. The MMSE receiver suppresses both the interference and noise components, whereas, the ZF receiver removes only the interference components. This implies that the mean square error between the transmitted symbols and the estimate of the receiver is minimized. Hence, MMSE is superior to ZF in the presence of noise. The V-BLAST detection scheme based on SIC and PIC is discussed in [3-6]. The ordered SIC scheme that is used in this paper is shown in Fig. 2.

3. REALISTIC FADING CHANNEL MODEL FOR SYSTEMS WITH ULA/UCA

A correlated fading channel is considered for MIMO system with $M_t$ transmit antennas and $M_r$ receive antennas in [7] as shown if Fig. 3. Assuming $H$ is the $M_r \times M_t$ complex channel matrix at one instance of time. It can be modeled as a fixed (constant, LOS) matrix and a Rayleigh (variable, NLOS) matrix.

$$ H = \sqrt{\frac{K}{1 + K}} H_f + \sqrt{\frac{K}{1 + K}} R_{r}^{1/2} H_w R_{t}^{1/2} $$  \hspace{1cm} (6)$$

Where $H_f$ represents the fixed LOS channel matrix and $H_w$ is zero mean and unit variance complex Gaussian random variables that presents the coefficients of the variable NLOS matrix, $K$ is the Rician $K$-factor. $R_r$ and $R_t$ are the $M_r \times M_r$ and $M_t \times M_t$ receiver and transmitter spatial correlation matrices respectively and are obtained as in [7] for both ULA-MIMO and UCA-MIMO configurations.

A more realistic model was presented in [8] and it is also utilized in this paper. In this model the $H$ channel matrix is presented as follows.
\[ H_1 = \sqrt{p_1} \left( \frac{K_i}{K_i+1} \left( e^{\frac{j2\pi f_{\text{LO}}}{\lambda}} \cos(\frac{\theta}{r}) \right)^2 + \frac{1}{K_i+1} \left( R_{\text{spatial}} B \right) \right) H_1 \quad (7) \]

The first term represents \( H_1^{\text{LOS}} \) and the second accounts for \( H_1^{\text{NLOS}} \). \( p_1 \) is the total power of the \( l \)-th channel tap that is the sum of the fixed LOS power and the variable NLOS power of the \( l \)-th tap defined in the power delay profiles. \( K_i \) is the Rician K-factor of the \( l \)-th tap that represents the relative strength of the LOS component, \( S \) is the steering matrix, \( R_{\text{spatial}} \) is spatial fading correlation shaping matrix, \( B \) is a vector that is obtained by passing \( H_{\text{id}} \) independent identically distributed complex Gaussian random samples with zero mean and unit variance through a filter that is shaped based on the Doppler model as in [8]. For the developed model, the clusters and taps exponential decays used are the power delay profiles that are in compliance with the standard IEEE 802.11n channel models as shown in [8].

4. NUMERICAL RESULTS

Without loss of generality, the numerical studies are performed for 4x4 MIMO channel. VBLAST receiver is simulated with Quadrature Phase-Shift Keying (QPSK) modulation, and 125000 channel realizations. In the simulation the channel is modeled with spatial correlation model [7] or IEEE802.11n channel [8] is used in this simulation. In the subsequent figures 5, 6, 7 and 8 the performance of ordered SIC-MMSE detection algorithm is studied for 4x4 MIMO channel employing ULA with inter-element spacing (spacing between array elements) of \( D_e=0.5\lambda \) for the transmit antennas and ULA with inter-element spacing of \( D_e=0.5\lambda \) or UCA with radius of \( R_e=3/2\times D_e \) at receive antenna. The channel model assumes truncated Laplacian PAS distribution with angular spread (\( \sigma \)) and angle of arrival (\( \theta_0 \)), and one cluster as in [7]. However for Fig. 9 the spatio-temporal channel model of IEEE802.11n [8] is used. The performances of the ZF and MMSE / SIC detectors for V-BLAST are shown in Fig. 4. It compares the average BER for different versions of the SIC algorithm. It can see that, the ordering of layers improves performance considerably in view of the fact that the ordered algorithm detects the strongest signal first. As a result, the strongest interference is cancelled first. On average, this leads to improved BER performance in the sequentially detected layers. The figure shows that the ordered scheme obtains a performance gain compared with that of unordered scheme for both ZF and MMSE nulling techniques. In addition, MMSE nulling criteria outperforms ZF, even if both of them suffer from poor energy efficiency caused by error propagation problem. Since, the MMSE utilizes the knowledge of the signal to noise ratio to improve performance.

![Fig 4: BER performance of SIC V-BLAST, ZF vs. MMSE, with and without ordering.](http://www.cisjournal.org)

Fig. 5 shows the performance of the ULA and UCA receiver as a function of the angle of arrival (\( \theta_0 \)) for various SNR, SNR= \{0, 10, 20\} dB, and fixed angular spread, \( \sigma =20^\circ \). Also, the performance of uncorrelated \( H_{\text{id}} \) is presented for comparison. It can be seen that at low SNR the channel spatial fading correlation has less effect on the reliability of the system. In turn, at moderate and high SNR the spatial correlation reduces the BER performance. As seen, the ULA receiver obtains 8 dB and 16 dB, UCA receiver attains 2 dB and 6 dB performance loss compared with uncorrelated channel case at SNR=10 dB and SNR=20 dB, respectively. Moreover, the presented result reveals that the system performance in general is more affected by the correlation in the ULA unlike the UCA. As shown, the UCA significantly outperforms the ULA at endfire (\( \theta_0=90^\circ \)). However, at central angle of arrival values less than approximately 45° and greater than 135° (i.e., approaching the broadside of the ULA), the linear array performs similarly to or even better than the UCA.

![Fig 5: VBLAST BER performance of ULA and UCA receiver as a function of central \( \theta_0 \) for various SNR, SNR= \{0, 10, 20\} dB, and \( \sigma=20^\circ \).](http://www.cisjournal.org)
Fig. 6 shows the performance of the ULA and UCA receiver as a function of the angle of arrival (θ) for various angle spread, σ = {1°, 5°, 20°} and fixed SNR= 20 dB. As shown, the variability in the performance of ULA and UCA arrays is more pronounced at moderate and high angle spreads. It can be noticed that at small and moderated angle spreads the UCA performs similarly to or even better than the linear array. At high angular spread, the ULA outperforms the ULA by an order of magnitude at endfire. While, the ULA provides an order of magnitude improvement over the UCA near the broadside of the ULA (θ = 90° and 180°). This variability in the ULA performance is due to the fact that the correlation between elements is high for the ULA when the central θ is near endfire. The worst case for the UCA is (θ = 45° and 135°) since in these cases two elements are directly behind and parallel to the other two elements (strongly correlated).

Fig. 7 compares the BER performance of the ULA and UCA receiver versus the angle spread (σ) at SNR=20 dB, and various angle of arrival, θ = {0°, 45°, 90°}. As shown, for both antenna arrays as the angle spread increases (correlation decreases) the reliability of the system is improved. Again, the performance of the ULA is poor for (θ = 90°) since the correlation across the array is high. Therefore, there is little diversity advantage. As well, the worst performance of the UCA is at θ = 45°. Since, in this case the correlation is high in view of the fact that elements three and four are directly behind elements one and two. In addition, as can be noticed the all curves (except, the ULA at θ = 90°) approach the same performance as σ increases. Because for large σ, the angle of arrival distribution approaches a uniform distribution which will provide low correlation among antennas for any value of θ.

Fig. 8 illustrates the BER performance of ULA and UCA receiver versus the receive antenna spacing (D/R) for σ = 20°, SNR = 20 dB, and various θ = {0°, 45°, 90°}. Note that D/R is the inter-element spacing for ULA and also it is related to the UCA radius since (R/R = 3/2 × D/R) as shown in Fig. 3, with R, is held constant. It can be seen that as the array size increases, the BER performance improves and floors at a certain value that is about one wavelength. Although, this behavior can’t be seen for the ULA at θ = 90°. Again this is because all four elements are in-line with the central angle of arrival leading to high correlation between elements. However, for other values of θ, the ULA does approach the BER floor (P_c = 6 × 10^{-4} in this case) since the four elements eventually become uncorrelated. The UCA also shows improving for θ = 0°, 45°, 90° with increasing D/R. As expected, the worst case is θ = 45°. Again, in this case elements three and four are directly behind elements one and two and thus, will be highly correlated with those elements. However, as D/R increases the correlation is gradually diminished and the performance is close to the BER floor, unlike the worst case of ULA. At θ = 0°, elements three is directly behind (and, thus, highly correlated with) element one. Consequently, as D/R increases the performance quickly approaches the BER floor. At θ = 90°, all four elements become decorrelated as D/R is increased. Thus, the performance approaches the BER floor.
Finally, the BER performance is examined for WLAN 802.11a system utilizing VBLAST (SIC-MMSE) for 4x4 MIMO system employing UCA configurations at both ends considering Binary Phase Shift Keying (BPSK). Two radii $R=0.5\lambda$ and $0.75\lambda$ are considered at AP receiver. The channel is modeled as in [8] in this channel selection scenarios. Table 1 shows the parameters of six different environment profiles that are included in the developed channel model.

Table 1: IEEE802.11a TGn Channel Models [4]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Environment</th>
<th>$K$ (dB)</th>
<th>$\text{LOS/NLOS}$</th>
<th>Delay (rms)</th>
<th>Clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flat fading</td>
<td>0/∞</td>
<td>∞</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>Residential</td>
<td>0/∞</td>
<td>15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Residential</td>
<td>0/∞</td>
<td>30</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>Typical Office</td>
<td>0/∞</td>
<td>50</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Large Office</td>
<td>0/∞</td>
<td>160</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Large Space, In-out-door</td>
<td>0/∞</td>
<td>150</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Fig.9 illustrates a comparison of BER performance curves under different TGn models. Corresponding BER of an iid. Channel (uncorrelated fading channel) is also included for comparison. As can be seen that the link has its best performance for Model ‘F’ conditions, in this case it is the nearest performance curve to the uncorrelated fading channel independent identically distributed ‘iid’ curve. Model ‘F’ performance curve is followed by model ‘B’ then model ‘A’ with the lowest performance. Also, as expected, that the link performance improves as the radius of UCA at AP end increases from $0.5\lambda$ to $0.75\lambda$. In general, the results show that the BER performance of uniform circular diversity array depends on the main angle of arrival.

5. CONCLUSION

In this paper, the V-BLAST architecture and detection algorithms have been presented and compared under different antenna array geometries with different channel models. The impact of channel spatial correlation on the V-BLAST system based on the ordered SIC scheme with MMSE nulling criteria has been investigated. The investigations have been compared the diversity performance of ULA and UCA. The results have been showed that the UCA outperforms the ULA for small and moderate angle spreads for similar aperture size. However, at high angle spread the ULA outperforms the UCA for certain angles-of-arrival (e.g., near broadside of the ULA). Furthermore, the worst performance for ULA can be occurred at the endfire angle. Given that, all elements are in-line with the central angle of arrival that leads to high correlation between elements. As well, the worst performance for UCA occurs at $\theta_r = 45^\circ$ and $135^\circ$. Because, in these cases the correlation is high in view of the fact that elements three and four are directly behind elements one and two. Hence, the central angle of arrival has a significant impact on the BER performance of both the UCA and ULA. In addition, with small values of angle spread, there is little diversity advantage from either array; while for large angle spreads both arrays provide enhancement to the performance. Moreover, VBLAST system BER performance has been investigated under realistic IEEE802.11n different channel scenarios. The results show that with a proper selection of UCA radius and number of elements the performance of uncorrelated channel can be achieved. On the other hand, it has been shown that the uniform circular array MIMO system best performance is obtained with model F profile of IEEE802.11n channel model which is a simulation of large space indoor environment conditions.
ACKNOWLEDGEMENTS

The author would like to thank the Deanship of Scientific Research at University of Bahrain, Kingdom of Bahrain, for their financial support of this research work.

Also, thanks to Mrs. Zahra Mahdi for her help in producing the numerical results of this paper.

REFERENCE


