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Analysis of Compensation Network in a Correlated-based Channel using Angle of Arrivals

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***Abstract*—We explore combined effect of spatial correlation and mutual coupling matrix, and its subsequent effects on performance of multiple input multiple output (MIMO) systems After the decoupling process. We will also look at a correlation based stochastic channel model with the linear antenna arrays as the signal source. For the purpose of understanding, it is assumed that fading is correlated at both transmitter and receiver sides, in spite of the fact that the decoupling network enhances isolation between Receiving antenna array. In this paper, we model the transmit the antenna array in CST Microwave Studio, as a uniform linear Array with monopoles as antenna elements. On the receiving side, the scattering parameters of the coupled and decoupled monopole Array are measured in an anechoic chamber. The theoretical analysis and simulation results show the joint dependency of the system capacity on an angle of arrival (AoA) and antenna element spacing, with enhanced system performance at reduced AoAs with Increased antenna element separation. Consequently, essential benefits of MIMO system performance can be achieved with an efficient decoupling network while boosting the signal sources by adding further antenna elements.**

Keywords—Angle of arrival (AoA); channel correlation; decoupling network; mutual coupling; MIMO

I. INTRODUCTION

One of the challenges of MIMO antenna design is the task of enhancing the isolation between ports nearly located within restricted space in the mobile handset. This is because of the way the array elements have to be contained in a reduced volume, which brings about substantial pattern/spatial correlation and Strong mutual coupling effect between the elements. It is the common conclusion that mutual coupling influences the performance of antenna arrays, as the increase in correlation Restricts the channel capacity. Moreover, if mutual coupling is solid, a massive portion of the power fed into one port will be coupled to the other port rather than radiating to free space; consequently diminishing the signal-to-noise ratio, radiation Sufficiency and channel capacity. Some of works have investigated the effect of mutual coupling on the performance of communication system [1]-[10]. For this reason, building a successful decoupling technique to balance the performance degradation in MIMO antennas by mutual coupling effects has attracted the attention of the academic society recently.

In [11] researchers separates decoupling strategies into four classes: *1) Eigen-mode Decomposition Scheme:* Its guideline is to diagonalize the scattering matrix of a compact array using 90° and or 180° [12]-[16]. *2). The Inserted Component Scheme*: It works on the concept of inserting a section of transmission-line between the coupled antenna ports [17]-[21]. *3). Artificial Structure Decoupling Scheme:* This method uses sub-wavelength EM structures such as electromagnetic band gap (EBG) structure [22], defected ground structures (DGS) [23], and magnetic meta-materials [24], [25]. *4). Coupled Resonator Decoupling Scheme:* This method was proposed for the first time in 2014, and has the concept of decoupling pair of coupled elements using coupled resonators [11] and [26]-[29].

Various works have examined the impact of spatial correlation on the performance of communication systems by means of experimentation [30], [31], modeling [32], [33] and theoretical analysis [34]-[40]. Numerous works have characterized the effect of channel correlation in the performance and capacity of the wireless channels by mathematical analysis [34], [35], further focusing on linear receivers [36], [37], [40] using mainly random matrix theory [41], [42], [43]. In [33] and [44]-[48] precoder designs Specifically tailored for correlated channels are derived. An interesting channel model with transmitting correlation, based on the angular spread of the transmits antenna elements emission, was shown by the authors of [33], [49].

The above discussions focus on studying the influence of antenna separation on a set number of antennas and effects on The communication performance. The purpose of compensation or decoupling network, however, is to enhance the isolation between ports jointly located within restricted space in mobile handset. It is, therefore, reasonable to investigate the combined effect of spatial correlation and mutual coupling matrix on correlation-based stochastic channel coefficients, and subsequent effects on system capacity and transmit diversity After the decoupling process. To recognize user equipment (UE) channels and enhance channel estimation, the correlation channel model introduces angle of arrivals (AoAs).

For this reason, we investigate the system performance of a user equipment (UE) channels at different orientations for the uniform linear antenna arrays at diverse antenna separations, while increasing the signal sources by adding the further antenna elements. For the purpose of demonstrating the effectiveness of the research, we utilized a prototype of two-element compensation network with insertion losses between input and Output ports better than 11dB. Using the spatial correlation model [33] and incorporating the effects of mutual coupling matrix before and after the decoupling process, the results reveal different system performances for the user equipment (UE) channels at reduced AoAs and antenna physical separation while adding more elements.

The paper is organized as follows: Section II presents the formulation of operating matrix and the design of the compensation network. Part III focuses on the system model. Analytical results and discussions are presented in Section IV. Finally, we give concluding remarks in Section V.

II. OPERATING MATRIX AND DESIGN OF COMPENSATION NETWORK

The Operating pattern for two-element receiving array for the remittance network is expressed as [54]

$$\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} 1 & -\dfrac{Z_{12}}{Z_L} \\ -\dfrac{Z_{21}}{Z_L} & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} V_1 - \dfrac{Z_{12}}{Z_L} V_2 \\ V_2 - \dfrac{Z_{21}}{Z_L} V_1 \end{bmatrix} \tag{1}$$

Where V_1 and V_2 are the coupled voltages and the inputs to the network from the monopole terminals and the output voltages are U_1 and U_2, also known as the compensation voltages. The compensation network is designed using a power divider of unequal power-dividing ratio with no active circuit elements to minimize extra circuit noise and two rat-race couplers. The power divider has three transmission lines (Z_A, Z_B and Z_C), each having impedance of $\sqrt{2}Z_o$, where Z_o is the system's characteristic impedance, but unequal electrical Lengths ϕ, Ψ and θ [55]. The electrical length ϕ can be defined as $\phi = \cos^{-1}\left(\left|Z_M / Z_L\right|\right)$, whereas Ψ and θ are 90° and $\left(90^\circ + \phi\right)$ respectively and Z_M representing the mutual impedance. We fabricate the circuit by using the substrate FR4 with dielectric constant 4.8 at operating frequency of 2.4 GHz as shown in Figure 1. The measured insertion losses between input and output ports of the decoupling network are shown in Figure 2.

III. SYSTEM MODEL

In this paper, we examine the theoretical performance of MIMO system in the correlation-based stochastic channel Models with the decoupling network. It has been accounted for in [50] that the correlation-based stochastic channel models could be applied to cases that the user equipment (UE) with multiple antennas work at millimeter wave, in any case, we experiment the performance of the MIMO systems at 2.4 GHz. For the purpose of understanding, it is assumed fading is correlated at both transmitter and receiver sides, in spite of the fact that, the decoupling network enhances isolation between antenna arrays at the user equipment (UE). When the linear the antenna array is assumed, the steering matrix R_k is expressed as [50], [51]

$$R_k = \frac{1}{D_k}\left[a(\theta_{k,1}), a(\theta_{k,2}), \ldots, a(\theta_{k,\mathrm{D}_k}) \right] \tag{2}$$

$$a(\theta_{k,\mathrm{i}}) = [1, e^{(j2\pi d/\lambda)\sin\theta_{k,\mathrm{i}}}, \ldots, e^{(j2\pi d(N-1)/\lambda)\sin\theta_{k,\mathrm{i}}}]^T \tag{3}$$

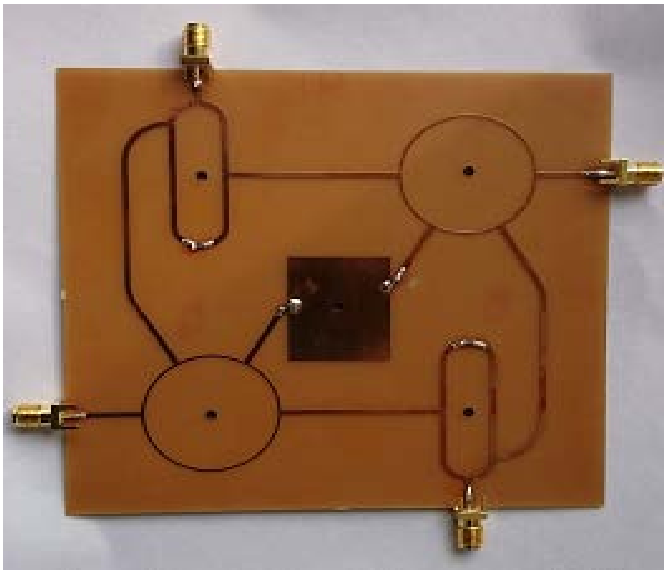

Fig. 1. Photograph of the fabricated inserted decoupling network

Where d is the distance between the adjacent antennas, λ is the carrier wavelength and N the number of elements. Incorporating mutual coupling the channel vector UE can be written as follows

$$h_k = ZR_k v_k, k = 1, 2, \ldots, k \tag{4}$$

Where, $Z \in \mathfrak{M}^{N \times N}$ represents the mutual coupling matrix, $R_k \in \mathfrak{M}^{N \times D_k}$ denotes the steering matrix containing D_k steering vectors of the receiver array, $v_k \sim \mathfrak{M}\,\mathrm{N}(0, I_{D_K})$. The mutual coupling matrix is defined as [51], [52]

$$Z = (Z_A + Z_L)(\Gamma + Z_L I)^{-1} \qquad (5)$$

with

$$\Gamma = \begin{bmatrix} Z_A & Z_m & 0 & \cdots & 0 \\ Z_m & Z_A & Z_m & \cdots & 0 \\ 0 & Z_m & Z_A & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_m & Z_A \end{bmatrix} \qquad (6)$$

Where, Z_A, Z_L, Z_m are the antenna impedance, load impedance and mutual impedance respectively. For theoretical approximation of bilateral coupling (4) we assume that Z_A and Z_L have a value of $50\,\Omega$ each. Z_m is calculated using the EMF method [7] using d.

A. S-parameter Based Mutual Coupling

Regarding scattering parameters the mutual coupling the Matrix in (5) of the linear array is expressed as [53]

$$Z_t = (I + S_t)(I - S_t)^{-1} * Z_o \qquad (7)$$

Where Z_o represent the reference antenna impedance, and $S_t \in \mathfrak{M}^{N \times N}$ is the S-parameter matrix of the antenna array. The voltage and current on the $m-the$ antenna element are given as

$$v_m = \sqrt{Z_o}\,(a_m + b_m) \text{ and } i_m = \frac{1}{\sqrt{Z_0}}(a_m - b_m) \qquad (8)$$

Where vectors *a* and *b*, are the complex envelopes of the inward-propagating and outward-propagating waves from the antenna elements respectively. In this paper, we model the transmit antenna array in CST Microwave Studio, as a uniform linear array with monopoles as antenna elements. For the receiving antenna array, the scattering parameters of the coupled and decoupled monopole array are measured in an anechoic chamber.

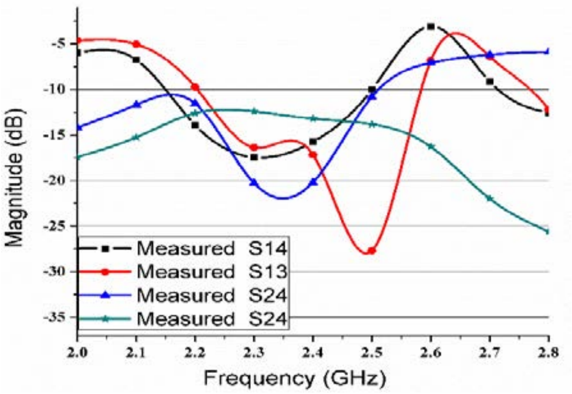

Fig. 2. Measured insertion losses between input and output ports of the Decoupling Network

IV. NUMERICAL RESULTS

This section illustrates the analytical performance and results according to the modeling of mutual coupling matrix at the Receiving side. The simulation assumes a uniform linear array With monopoles as antenna elements at the source. The compact antenna array consists of two parallel monopoles operating at 2.4 GHz and placed on a metallic ground. The monopoles have the length of 30 mm, a radius of 0.5 mm and fixed element separation of $\lambda/8$. The S-parameters for the receiving array are determined in two different conditions. Firstly, the scattering parameters of the coupled monopole array are measured in order to determine the coupled voltages (V_1 and V_2) and coupling matrix. Secondly, the monopole antennas in the array are connected to the decoupling network through equivalent length coaxial links, and scattering parameters of the output ports of the decoupling network are measured to determine the coupling matrix for the compensated voltages (U_1 and U_2).

The simulated channel is according to the channel model (1)-(6) and the angle of arrival is between 0° and $360.^\circ$ For the purpose of demonstrating the effectiveness of the decoupling network, there are three different types of voltages listed in Table I. The last row in Table I is a ratio of the voltage obtained with monopole B to the voltage achieved with monopole A. It can be seen that the ratio of the compensated voltage is very close to the uncoupled voltages, demonstrating that the compensated voltages have successfully taken off from the coupling effect.

A. Fixed Number of Antennas- Traditional View

We investigate the effect of antenna spacing on performance according to coupling matrix model at the receiving side. For reasons of reference, first, we analyze the performance of the uncorrelated channel when the receiving antenna array are closely spaced with a separation of $\lambda/8$. We do this for an angle of arrival at the receiving end as 360° for SNR of 10 dB, to illustrate the behavior of system performance regarding dependency between antenna spacing and average capacity. Figure 3 reveals that capacity of the decoupled receiving array is statistically better than that of the coupled receiving array. In order words, the results demonstrate the promising potentials of an efficient decoupling scheme in a correlated-based stochastic channel. However, system performance is restricted to antenna element spacing. With the decoupling network at the receiving end, therefore, results show the performance benefits that can be achieved by increasing the separation between antenna elements.

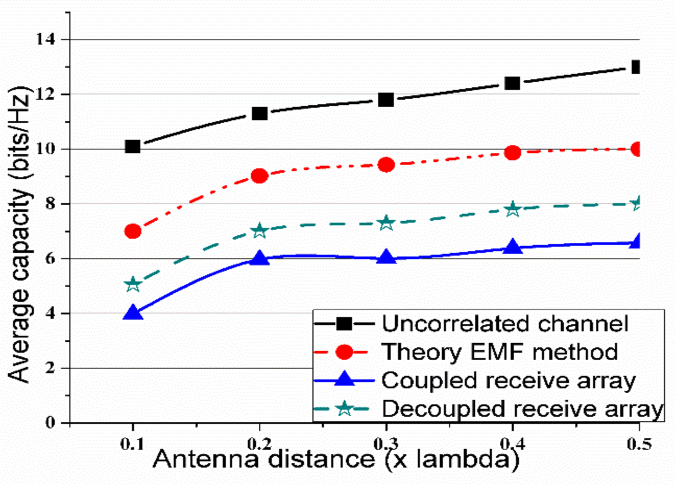

Fig. 3. Average capacity vs. antenna spacing d with SNR=10 dB, AoA= 360°

B. Effects of AoA on System Performance

We now move forward to investigate the behavior of channel capacity with different AoAs at various antenna Elements separations at the transmitter. In Figure 4 we compare the performances for 2×2 systems for AoAs of 60° and 360° at element separation of at $dt=\lambda/8, \lambda/4, \lambda/2$. We repeat the process with increasing number of transmit antennas for AoAs Of 90° and 120° in figure 5 for 4×2 MIMO system. The graphs reveal that system performance at reduced AoAs with the increase antenna element separation outperformed that with increased AoA and reduced antenna separation. The results also demonstrate the dependency of channel capacity on an antenna separation. We note that reducing the distance between antenna elements affect system performance, however, the larger number of antenna elements at the signal source improves system performance. It is interesting to observe in Figure 5 that even though the channel is modeled with spatial correlation and mutual coupling at both ends, the performance for AoA of 60° at $\lambda/2$ a uncorrelated Mutual coupling at SNR=10 dB. The result demonstrates the advantage of decoupling system in a correlated channel with reduced AoA

C. Transmit Diversity

For larger performance gain of almost 20 dB at error rate of 10^{-2} figure 6 indicates no match between decoupled and coupled receive arrays for AoA $=360^\circ$. However, a close observation in Figure 7 reveals an improvement in the BPSK performance. In spite of the fact that there was little change in the QPSK performance, we take note of that after an increase of 10 dB, the performance for coupled array with both modulations remains Nearly the same. In general, our analysis indicates a close match between QPSK and BPSK diversity performances under both conditions. We include theoretical performance based on the EMF method which outperformed the simulation results.

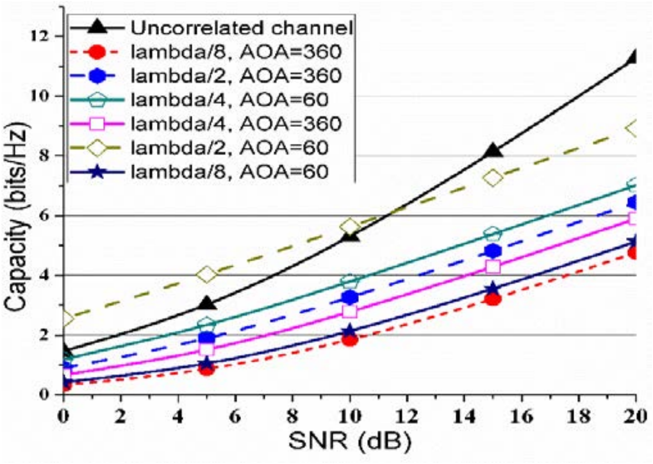

Fig. 4. Capacity vs. SNR for decoupling array for 2×2 MIMO at different AoAs (degrees) and antenna separation

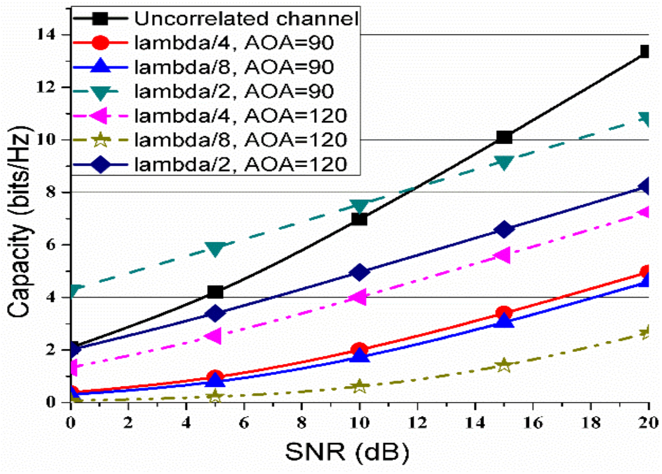

Fig. 5. Capacity vs. SNR for decoupling array for 4×2 MIMO at different AoAs and antenna element separation

V. CONCLUSION

In this paper, we have analytically explored the performance of decoupling network in the correlation-based stochastic model With uniform linear array at the transmitter. Performance evaluation indicates the joint dependency of system capacity on the angle, angle of arrival and antenna separation. Results show that an important benefit of system performance can be achieved for reduced AoA with increase antenna element separation at the transmitter. Our analysis demonstrates the promising potentials when mutual coupling matrix is modeled with efficient Decoupling network for a compact antenna array. Further work can be carried out towards investigating the performance the behavior of rectangular and circular arrays with decoupling network for MIMO spatially correlated transmitters.

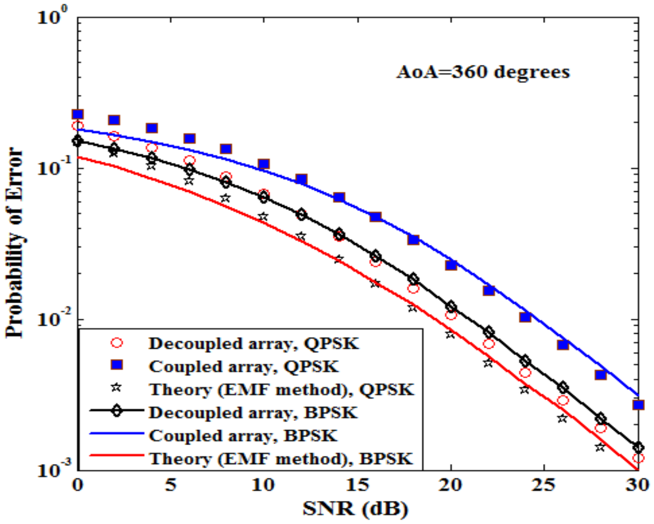

Fig. 6. Transmit diversity for decoupled and coupled array in correlated based stochastic model with linear array

TABLE I. DIFFERENT MEASURED VOLTAGES

		Uncoupled Voltages (reference)	Coupled voltages	Compensated voltages
Monopole A	mag (mV)	16.64	12.4	11.55
	angle (°)	-160.64	-166.67	34.967
Monopole B	mag (mV)	16.54	15.42	12.30
	angle (°)	-139.56	-141.46	55.16
B/A	mag (mV)	0.9939	1.2199	1.065
	angle (°)	21.08	25.208	20.193

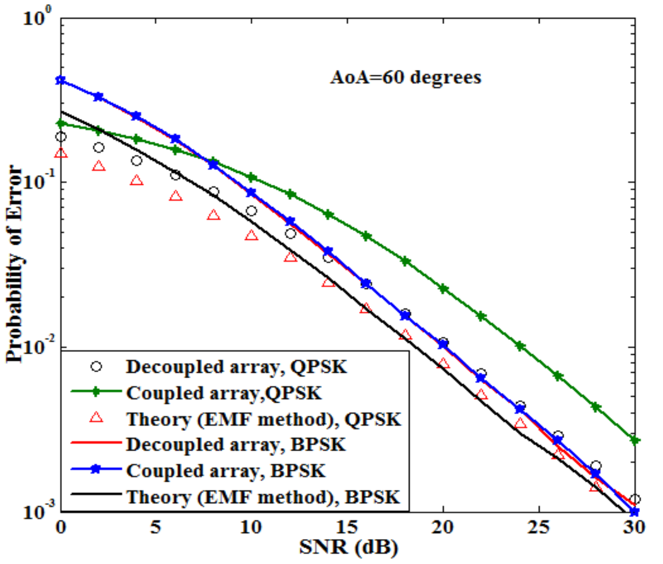

Fig. 7. Transmit diversity for decoupled and coupled array in correlated-based stochastic model with the linear array

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