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# Performance of Pattern Diversity in Reconfigurable Antenna Arrays

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***Abstract*—In this paper, we investigate the benefits offered by radiation pattern diversity in reconfigurable antenna arrays and place these benefits in context with spatial diversity provided by conventional antenna arrays. These antennas provide pattern diversity that can improve capacity and offers a unique opportunity for antenna system miniaturization for portable wireless devices.**

**We use a common modeling framework to study the impact of spatial and pattern correlation on the performance of the multi-antenna array systems. We consider a geometry-based MIMO channel cluster model to investigate the effects of the channel spatial characteristics and antenna array geometry/radiation patterns on the spatial correlation and system performance. Our findings demonstrate relative diversity performance improvement of at least 3 dB from using pattern diversity over space diversity.**

***Index Terms*—Pattern Reconfigurable Antennas, MIMO Systems, and Pattern/Space Diversity, Smart Antennas**

## I. Introduction

Numerous information-theoretic studies in [1]–[5] have demonstrated the impact of spatial correlation on the capacity of multi-element antenna array (MEAs). Spatial correlation diminishes the diversity gain and spectral efficiency performance of these systems. Traditional MEAs arrays use antenna element spacing to combat the effects of spatial correlation and channel fading. This array element spacing is a constraint that makes these arrays impractical to deploy in portable wireless devices such as routers or access points. This limitation is the main motivation for research efforts in the design of a compact alternative solution using reconfigurable antenna arrays system (RAS). Reconfigurable antenna technology has been shown to offer performance gains in MIMO systems by increasing channel capacity [6] and Signal-to-Noise Ratio (SNR) [7] at the receiver. RAS antennas are capable of dynamically changing their radiation characteristics and enable MIMO systems to adapt to physical link conditions. These antennas also provide space and cost benefits in incorporating multiple elements in a single physical device by reducing the number of RF chains [8].

The main objective of this work is to explore this new class of adaptive antenna array systems in lieu of traditional MEAs arrays as a suitable solution to achieve the benefits of MIMO arrays in small wireless handheld devices. The design flexibility of reconfigurable antenna arrays enables us to exploit the antenna geometry and mutual coupling between radiating array elements to generate different uncorrelated radiation patterns [12]. These uncorrelated radiation patterns can produce uncorrelated channel realizations in a multipath rich wireless environment which improves link reliability and channel capacity [13].

We use a common modeling framework to study the impact of either spatial or pattern correlation on the performance of the multi-antenna array system. We consider a geometry-based MIMO channel cluster model to investigate the effects of the channel spatial characteristics and antenna array geometry/radiation patterns on the spatial correlation and system performance. This allows for the benchmarking of conventional antenna array techniques such as antenna grouping, and selection, against pattern reconfigurability. And, motivated us to study the benefits of pattern diversity derived from reconfigurable antennas arrays over spatial diversity from conventional arrays.

In Section II we present the MIMO channel model and briefly discuss the key features of the cluster model. In Section III, we discuss the antenna design and characterization of a reconfigurable antenna, and in Section IV, we analyze the performance of MEAs arrays in clustered MIMO channels and Section V gives a brief conclusion.

## II. MIMO Channel Model
## A Geometry-based MIMO Cluster Modeling

We consider a geometry-based stochastic channel model (GSCM) presented in [14]. This is a double-directional cluster model that uses advanced modeling techniques to capture the propagation characteristics of the wireless environment and the effects of antenna array patterns, their polarization and the mutual coupling between array elements. We chose the WINNER model because it covers a wide range of propagation scenarios and environments and is antenna independent; which makes it suitable for evaluating adaptive radio systems. This is a key distinction with other models such as the SCM/SCME models proposed for 3GPP systems in [15].

### *A. Channel Selectivity and Spatial Correlation*

The time-variant impulse response for a P×Q MIMO channel as modeled in [14] is given by (1). The channel matrix is composed of the antenna array response matrices $\mathbf{F}_{tx}$ and $\mathbf{F}_{rx}$ for the transmitter and receiver respectively. It defines the channel from the Tx antenna element q to the Rx element p, for a given cluster n with R number of rays (subpaths). The

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$$\mathbf{H}_{p,q,n}(t;\tau) = \sum_{r=1}^{R} \begin{bmatrix} \overrightarrow{F}_{rx,p,V}(\varphi_{n,r}) \\ \overrightarrow{F}_{rx,p,H}(\varphi_{n,r}) \end{bmatrix}^T \begin{bmatrix} \alpha_{n,r,VV} & \alpha_{n,r,VH} \\ \alpha_{n,r,HV} & \alpha_{n,r,HH} \end{bmatrix} \begin{bmatrix} \overrightarrow{F}_{tx,q,V}(\phi_{n,r}) \\ \overrightarrow{F}_{tx,q,H}(\phi_{n,r}) \end{bmatrix} \times exp(j2\pi\lambda_0^{-1}(\overrightarrow{\varphi}_{n,r} \,.\, \overrightarrow{\iota}_{rx,p})) \times exp(j2\pi\lambda_0^{-1}(\overrightarrow{\phi}_{n,r} \,.\, \overrightarrow{\iota}_{tx,q})) \times exp(j2\pi\upsilon_{n,r})\delta(\tau - \tau_{n,r}) \tag{1}$$

where

t is time, $\tau$ is the propagation delay;
$\overrightarrow{F}_{rx,p,V}$ and $\overrightarrow{F}_{rx,p,H}$ are the antenna element p field radiation patterns for vertical and horizontal polarization, respectively;
$\alpha_{n,r,VV}$ and $\alpha_{n,r,VH}$ are the complex gains of vertical-to-vertical and horizontal-to-horizontal polarizations of ray n,r respectively;
$\lambda_0$ is the wavelength of the carrier frequency;
$\overrightarrow{\phi}_{n,r}$ is the angle of departure (AoD unit vector;
$\overrightarrow{\varphi}_{n,r}$ is the angle of arrival (AoA) unit vector;
$\overrightarrow{\iota}_{rx,p}$ and $\overrightarrow{\iota}_{tx,q}$ are the location vectors of elements p and q, and;
$\upsilon_{n,r}$ is the Doppler frequency component of ray n, r.

$$\rho_{p,q} = \frac{\iint_{4\pi}[e^{-j2\pi\frac{d_{p,q}}{\lambda}sin(\Omega)}PAS(\Omega)|\overrightarrow{F}_p(\theta,\phi) \bullet \overrightarrow{F}_q(\theta,\phi)|^2]d\Omega}{\iint_{4\pi}PAS(\Omega)|\overrightarrow{F}_p(\theta,\phi)|^2 d\Omega \iint_{4\pi}PAS(\Omega)|\overrightarrow{F}_q(\theta,\phi)|^2 d\Omega} \tag{2}$$

where

$d_{p,q}$ is the distance between antenna elements p and q,
$\lambda$ is the wavelength corresponding to the carrier frequency of the system,
$\Omega = (\theta, \phi)$ is the solid angle for the elevation and azimuth angles respectively,
$PAS(\Omega)$ is the PAS of the scattered fields and
$\overrightarrow{F}_i(\theta,\phi)$ is the field radiation pattern of the antenna system when port $i$ is excited,
$\bullet$ denotes the Hermitian product.

spatial characteristics of the propagation channel are described by the angular parameters AoA/AoD, which are distributed according to a certain probability distribution function (PDF) that models the power angular spectrum (PAS).

The spatial correlation between the $q$th and $p$th antenna array elements, denoted by $\rho_{p,q}$, is defined by (2) as in [17] and [18]. It can be observed that the spatial correlation is a function of the channel or spatial characteristics through $PAS(\Omega)$, and antenna array parameters such as polarization, radiation patterns through $\overrightarrow{F}(\theta,\phi)$ as well as the array element spacing or geometry. This fact demonstrates the need to tune and optimize both channel and antenna array parameters to reduce spatial correlation. In this work, we exploit this dependence through a joint design approach that simultaneously tunes antenna array parameters as well physical layer algorithms that improve system performance in correlated MIMO channels.

## III. Antenna Design and Characterization

### A. Reconfigurable Alford Loop Antenna Design

Fig. 1 shows the reference antenna design first published in [20]. Each of these elements can be selectively connected or disconnected to the feed to generate different radiation patterns. When adjacent microstrip elements are excited through connection to a voltage on the feedline, a directional pattern is generated. The energy toward the disabled branches undergoes reflections that focuses the beam in the direction of the excited pair. Similarly, when all the branches are connected to the feedline, an omnidirectional pattern is generated from the uniform current distribution on the antenna surface. Therefore, one element is capable of generating at least eight different antenna patterns.

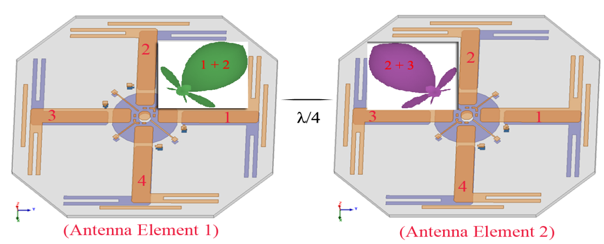


Fig. 1. Measurement Setup for the S-parameters (a) Configuration 1 (b) Configuration 2 [20]

### B. Antenna Characterization Setup

For this work, the reconfigurable alford loop antenna design was fine tuned to resonate at the frequency band 2.5 –3

GHz. The scattering parameters of the prototypes and the effects of mutual coupling between the elements of an antenna array of two reconfigurable alford loop elements are analyzed. This characterization enabled us to derive a relationship with the pattern antenna correlation between the alford loop array elements as discussed in the prior section. The antenna correlation is based on (2) without the PAS distribution since we are only concerned about the inter-element correlation. This analysis helps us to draw inferences on how the antenna array characteristics affect the performance of a MIMO system that employs this array.

Fig. 1 also illustrate the setup of the antenna array of two elements. The close proximity ($\lambda/4$) of the two elements have deliberately been selected so that there is strong mutual coupling between them. This coupling is effectively leveraged to generate different radiation patterns for each array's geometry. The antenna branches 1 and 2 of antenna element one and branches 2 and 3 of antenna element two are enabled or connected to the feedline –element one is in mode 1 and element 2 is in mode 2. The second configuration is obtained when branches 1 and 4 of antenna element one and 3 and 4 of antenna element two are enabled to generate the directional pattern. In this configuration, antenna element one is in mode 4 and element two is in mode 3, respectively. Note, the element is in mode 5 when branches 1 and 3 are activated, and in mode 6 when branches 2 and 4 are enabled. When all of the branches of the element are active, the antenna element is said to be in mode 7. When in mode 7, the antenna radiation pattern is omnidirectional and the rest of the modes are directional patterns. The two elements of the antenna array operate in configuration 8 –omnidirectional configuration– when both elements are in mode 7. This configuration is fixed and used as the reference non-reconfigurable state of the antenna array. The reconfigurability however, is achieved from switching between any of the 8 configurations of the antenna array.

## IV. Performance of MEAs in Clustered MIMO Channels

In this section we evaluate the capacity and diversity performance of both conventional MEAs and the proposed reconfigurable antenna arrays in clustered MIMO channels described above. To avoid any inconsistencies and for a fair comparison, we use the same antenna array structure for both conventional and reconfigurable array scenarios. The reconfigurable alford loop described above, generates both omnidirectional and directive radiation patterns. For the conventional array scenario, we fix the state of all the array elements in the omnidirectional mode, whereas in the reconfigurable scenario, the antenna array can switch between any of the 49 possible configurations. This ensures that the conventional array scenario solely relies on the space diversity between the elements while the reconfigurable array system leverages the pattern diversity of the antenna system. We analyze these two systems to demonstrate the benefits of pattern diversity relative to space diversity.

Using the correlated channel model described in [14], we generate the channel matrix as in (1) above. To define the ergodic capacity of the MIMO link, a Frobinius normalization of the channel matrix was computed to remove the differences in path loss among a number of channel matrices [6]. This normalization is necessary to preserve the relative antenna gain effects of each configuration. All the channel matrices for each receiver were normalized with respect to the channel matrix generated from the omnidirectional configuration. The normalization factor $\eta_F$ is given by

$$\eta_F = \sqrt{\frac{||H_{Omni}||_F^2}{P\ Q}} \tag{3}$$

The capacity of the $Q\times$ P MIMO system without transmitter channel knowledge and uniform power allocation across transmit antennas is then given by

$$C = E\left\{log_2\ det\left[I_P + \frac{SNR}{Q}\frac{H\ H^{\dagger}}{\eta_F^2}\right]\right\} \tag{4}$$

We use diversity gain as a performance metric to show the improvement of the diversity receiver. Theoretically, the diversity gain is maximal at the receiver when the different received antenna signals are uncorrelated and minimal when the signals are correlated. The performance of diversity systems is often based on the cumulative distribution functions of the output SNR for a given outage probability as analyzed in [21]. Based on the selection combining technique and the assumption that the AoAs of the the multipath waves are uniformly distributed, the probability that the instantaneous combiner output SNR $\gamma$ is below some value $\gamma_s$ is described by

$$Prob(\gamma < \gamma_s) = 1 - 2\ exp(\frac{\gamma_s}{\Gamma})Q(\sqrt{(\xi\gamma_s)}, |\rho_s|\sqrt{(\xi\gamma_s)}) + exp(-\xi\gamma_s)I_o\left[|\rho_s|\sqrt{(\xi\gamma_s)}\right] \tag{5}$$

where $\Gamma$ is the mean SNR and $\rho_s$ is the correlation coefficient between two channels. The functions Q and $I_o$–the modified Bessel function– are given in [21] and $\xi = \frac{2}{\Gamma(1-|\rho_s|^2)}$.

### A. Simulation Results

We simulate the MIMO channel for a typical indoor environment using the WINNER II model consistent with the WINNER II scenario A1 [14]. In this scenario, the Base station (BS) or Access Points(AP) are assumed to be in the corridors of an office setting, where the LOS case is realized in corridor-to-corridor and the NLOS in corridor-to-room. And, in the NLOS case, the basic path-loss is calculated into the rooms adjacent to the corridor where the AP is located. Wall-losses and floor losses are also appropriately modeled and added to the general path-loss model.

The channel parameters for each snapshot is determined stochastically, based on statistical distributions. Each cluster is approximated by a truncated Laplacian PAS distribution with each path in the cluster being modeled by a unique spatial distribution characterized by a fixed angular spread and variable mean AoAs/AoDs. Antenna patterns for each

MIMO radiating element are both simulated in Ansoft HFSS and directly measured in the anechoic chamber. The patterns are then added to the propagation and fading model in the WINNER simulation channel model.

The link capacity of the channel for the reconfigurable antenna system is computed using (4) for all possible configurations of the transmitting and receiving array per simulation scenario. The channel capacity from the reconfigurable antenna scenario is then compared with the capacity achieved from when the antenna system is used as a conventional array. For the diversity performance, we vary the spacing between the antenna elements when it is being used as a conventional array in order to study the effect of antenna spacing on performance.

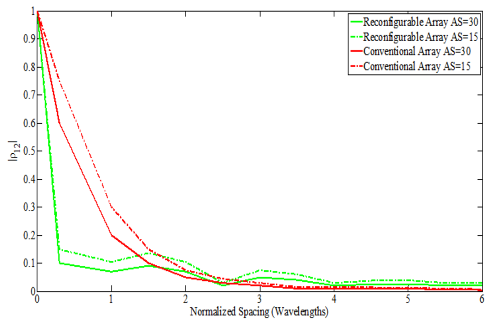


Fig. 2. Correlation Coefficient of two Antenna Elements for using Laplacian PAS

Fig. 2 illustrates the absolute value of the correlation coefficient as a function of antenna spacing for different antenna modes and azimuth angular spread. These curves assumed a single mode-Laplacian PAS with mean AoA of $20^o$ and $\Delta\theta$ set to $180^o$. It can be observed that the correlation coefficient decreases as the antenna spacing between the two elements increases as well as when the AS increases. The graphs also show the performance of the reconfigurable array relative to the conventional array. As shown, for a given antenna spacing and AS the conventional array elements tend to be more correlated than the reconfigurable array ones.

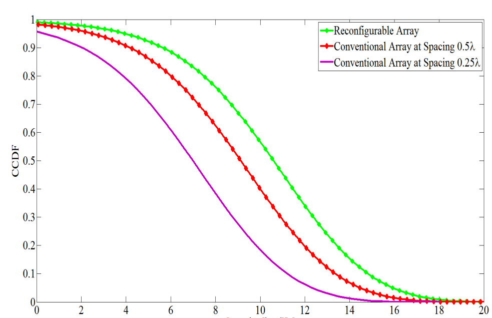


Fig. 3. The CCDF of Capacity for a $2 \times 2$ MIMO/MEA using Conventional and Reconfigurable Arrays for an SNR of 20dB

Fig. 3 shows the complementary cumulative distribution function (CCDF) performance of the capacity for the conventional and reconfigurable arrays for $AS = 15^o$ and antenna spacing of $0.25\lambda$. The CCDF shows the percentage of time that the capacity is at or above the values specified by the horizontal axis. The curves show improved performance with the MEA system using reconfigurable arrays relative to the conventional array structure. For the capacity of the reconfigurable array system, the capacity of the channel is found for each possible configuration of the transmitting and receiving array. And, the optimal solution of the reconfigurable antenna array was the one that guaranteed the highest channel capacity.

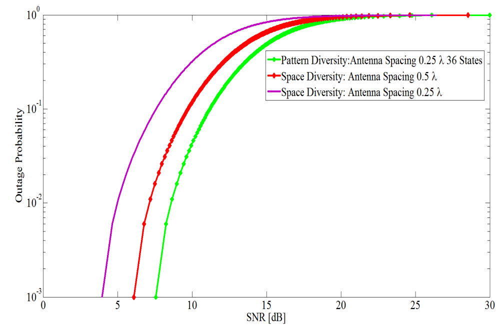


Fig. 4. The Diversity Gain CDFs for the a $2 \times 2$ MIMO/MEA System in Conventional and Reconfigurable Array Modes

Fig. 4 compares the diversity gain from space diversity derived from the conventional array structure versus the antenna-pattern diversity derived from reconfigurable antenna arrays. The pattern diversity is realized from using 49 combined states for each array pair –each element is capable of generating 7 different patterns, therefore, with a 2 element array we are able to realize $7 \times 7$ radiation pattern configurations. If the receiver uses a reconfigurable array as well, a total of 2401 combined states are realizable. But for this study we only consider the case when only the transmitter uses the reconfigurable array. We only use the top 6 configurations since using all 49 antenna states is impractical. This reduction in the number of configurations was obtained by finding the states with the lowest correlation between the two antenna signals. The curves show that for a given antenna spacing of $0.25\lambda$, antenna-pattern diversity outperforms the space diversity by more than 3dB at an outage probability greater than 0.01. This performance gain may increase with the number of patterns used but at the cost of antenna selection complexity.

## V. CONCLUSION

In this paper, an analysis of the benefits of a new radiation pattern diversity system is presented. We characterize spatial correlation in a clustered MIMO channel using a geometry-based stochastic model to motivate these benefits. Through this study, we have shown the complex dependence of spatial correlation on both spatial characteristics and antenna array geometry and radiation patterns. And, subsequently, its adverse impact on systems capacity and diversity performance. Our findings show, that for fixed antenna placement or spacing conventional antenna arrays experience high spatial correlation relative to reconfigurable antenna arrays. This difference is attributable to the fact that RAS array designs integrate spatial geometry and spatial effects such as mutual coupling and polarization to reduce element correlation. Conversely, conventional antenna arrays only rely on greater antenna spacing to low correlation between array elements.

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