Maximizing LoS MIMO Capacity Using Reconfigurable Antenna Arrays

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***Abstract*—The presence of line-of-sight (LoS) components is usually regarded as a limiting factor for multiple-input multiple-output (MIMO) systems due to the lower multiplexing gains compared to the prevalent independent and identically (i.i.d.) Rayleigh fading model. In this paper, we present a versatile methodology for maximizing LoS-MIMO capacity at any operating signal-to-noise ratio (SNR) by capitalizing on some recent results in two areas: i) design of optimized LoS MIMO configurations and ii) MIMO capacity maximization with reconfigurable antenna arrays. Our theoretical and numerical results demonstrate that by simply adjusting the antenna spacing as a function of SNR, significant capacity gains are achievable. In the following, the implications of the model parameters on the system performance are also assessed.**

***Index Terms*—MIMO systems, Ricean fading, antenna arrays, reconfigurable configurations.**

I. Introduction

The development of MIMO systems over the past decade, has relied on the assumption of i.i.d. Rayleigh fading where no LoS path is present and a high number of multipath components is created by the surrounding environment [1]–[3]. In this case, channel capacity can asymptotically increase in a linear way with the minimum number of uncoupled receive and transmit antennas. Although the assumption of independent Rayleigh fading simplifies extensively the performance analysis of MIMO systems and the design of space-time codes, its validity is often violated due to either a specular wavefront or a strong direct component; then, the entries of the channel matrix can be more effectively modeled by the Ricean distribution. Conceptually, LoS propagation is viewed to limit MIMO advantages because the channel matrix is normally rank deficient due to the linear dependence of the LoS' rays phases [4]–[7]. This makes the differentiation of the received signals at the MIMO detector difficult, thereby causing a high percentage of erroneously detected transmitted signals.

Some recent investigations though have questioned this belief and proposed design methodologies in order to achieve subchannel orthogonality which is a key condition for capacity maximization [8]–[13]. This is realized by placing the antenna elements sufficiently far apart so that the spatial LoS responses become unique with a phase difference of $\pi/2$. Then, the LoS correlation matrix becomes full-rank and delivers equal eigenvalues. For a performance analysis of these optimized topologies, please refer to [14]–[16] and references therein.

The common characteristic of the above mentioned works is the fact that the transmitter (Tx) has no channel state information (CSIT), in which case a sensible choice is to split the total amount of power equally amongst all data streams, i.e. uniform-power allocation (UPA).[1] While this scheme is optimal for full-rank configurations with equal LoS eigenvalues [18, Proposition 1], it can cause a substantial loss in channel throughput when the channel is rank-deficient [18]–[20]. This loss is more pronounced at low SNRs. The sub-optimality of a uniform input for arbitrary Ricean channels was quantified in [21], where it was demonstrated that isotropic input is asymptotically optimal only when $N_t \geq N_r$ and for infinitely high SNR.

In light of these facts, the primary goal of the present paper is to explore the use of reconfigurable antenna arrays in order to maximize LoS MIMO capacity. We emphasize the fact that our approach is inspired by a capacity-maximizing framework for reconfigurable antenna array proposed in [22], [23] for sparse MIMO channels. This is realized by recalling that the antenna spacing is inherently related with the rank of the LoS component. As such, we can systematically adapt the inter-element spacing at both the transmitter (Tx) and receiver (Rx) so that the rank of the LoS channel matrix is matched to the rank of the input covariance matrix. By doing so, it is demonstrated that significant capacity gains are attained especially at low SNRs. In the following, we propose a theoretical framework which encompasses an entire family of configurations that can offer maximum capacity at any given SNR. More importantly, it is shown that by introducing three benchmark canonical configurations, we can still achieve near-optimum performance across the entire SNR range.

The remainder of this paper is organized as follows: In Section II, the system model used throughout the paper is outlined and the MIMO capacity expression is analyzed assuming CSIT. In Section III, the concept of agile LoS MIMO systems for capacity maximization is introduced while a set of numerical results illustrating the performance of the proposed configurations is given in Section IV. Finally, Section V concludes the paper and summarizes the key findings.

[1]This choice is justified via the so-called 'max-min' property which is a robust transmission scheme to maximize MIMO capacity, when no CSIT is available [17].

A note on notation: We use upper and lower case boldfaces to denote matrices and vectors, respectively while the identity matrix of size n is expressed as $\mathbf{I}_n$. The symbol $(\bullet)^\dagger$ corresponds to Hermitian transposition while $\mathcal{E}(\bullet)$ represents the expectation operation. Finally, $\det(\bullet)$ and $\mathrm{tr}(\bullet)$ return the matrix determinant and trace respectively.

II. MIMO System Model and Capacity

We consider a MIMO system with N_t transmit and N_r receive antennas respectively. In the free-space, the deterministic LoS component, $\mathbf{H}_\mathrm{L} \in \mathcal{C}^{N_r \times N_t}$, can be modeled as

$$\mathbf{H}_\mathrm{L} = \begin{bmatrix} e^{-jkd_{1,1}} & e^{-jkd_{1,2}} & \dots & e^{-jkd_{1,N_t}} \\ e^{-jkd_{2,1}} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ e^{-jkd_{N_r,1}} & \dots & & e^{-jkd_{N_r,N_t}} \end{bmatrix} \quad (1)$$

where $k = 2\pi/\lambda$ is the wavenumber corresponding to the carrier wavelength λ and $d_{m,n}$ is the distance between a receive element $m \in \{1, \dots, N_r\}$ and a transmit element $n \in \{1, \dots, N_t\}$. Please note that we have assumed, without loss of generality, that the relative differences in path loss are negligible. As was previously mentioned, when the inter-element spacings at the Tx (s_1) and Rx (s_2) are of the order of wavelength, the LoS correlation matrix $\mathbf{T} \triangleq \mathbf{H}_\mathrm{L}\mathbf{H}_\mathrm{L}^\dagger$ becomes rank-deficient due to high correlation between the LoS' rays phases. On the other hand, it has been demonstrated that the deterministic LoS component becomes orthogonal, i.e. $\mathbf{T} = N_t \mathbf{I}_{N_r}$, when the following criterion is fulfilled

$$s_1 s_2 \approx \lambda D \left(\frac{1}{N_t} + r \right), \; r \in \mathbb{Z} \cup \{0\} \quad (2)$$

where D is the Tx–Rx distance [10, Eq. (11)], [11, Eq. (28)]. A schematic illustration of a conventional rank-1 and optimized LoS MIMO system is given in Fig. 1.

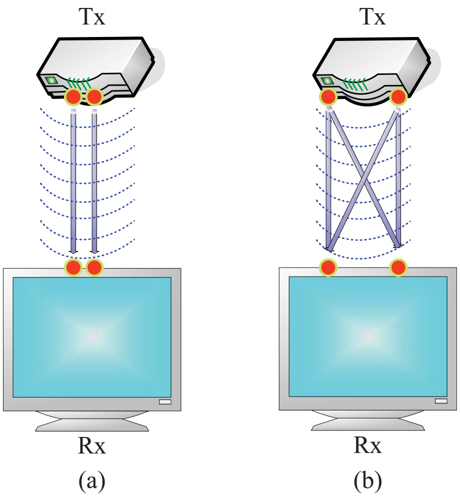

Fig. 1. Schematic illustration of (a) conventional and (b) optimized MIMO systems in LoS. The former configuration offers minimum multiplexing gains due to the high correlation between the LoS responses whereas the latter delivers orthogonal LoS subchannels.

Assuming statistical CSIT, the capacity (in bits/s/Hz) of a static MIMO channel (i.e. $\mathbf{H} = \mathbf{H}_\mathrm{L}$) is expressed as

$$C = \max_{\mathbf{Q}:\mathrm{tr}(\mathbf{Q}) \le \rho} \log_2 \left(\det \left(\mathbf{I}_{N_r} + \mathbf{H}\mathbf{Q}\mathbf{H}^\dagger \right) \right) \quad (3)$$

where ρ denotes the physically measured SNR at each receiving antenna and $\mathbf{Q}$ is the transmit covariance matrix. It has been recently shown that the capacity-maximizing rank of the channel matrix, and hence the rank of $\mathbf{Q}$, depends on the operating SNR. In particular, at low SNRs a rank-1 (beamforming) input is optimal while at high SNRs a full-rank input is optimal and consequently UPA takes place, or $\mathbf{Q} = (\rho/N_t)\mathbf{I}_{N_t}$ [18], [24], [25]. As the SNR grows, the rank of the optimal $\mathbf{Q}$ increases from 1 to N_t. More importantly, the channel rank can be shaped by reconfiguring the transmit and receive antenna arrays, as was originally shown in [22]. This leads to the concept of agile LoS MIMO systems for maximizing capacity as a function of SNR, which is introduced in the following section. Please note that, for the sake of notation, we hereafter consider a symmetric MIMO system with $N_t = N_r = N$.

III. Reconfigurable Antenna Arrays for Maximizing LoS MIMO Capacity

The theoretical framework of reconfigurable antenna arrays in order to maximize the ergodic capacity in sparse MIMO channels was recently developed by Sayeed and Raghavan in [22], [23]. The main idea is to adaptively match the rank of channel matrix to the rank of the input covariance matrix which, in the general case of stochastic MIMO channels, is equal to $\mathcal{E}\left(\left(\mathbf{H}^\dagger \mathbf{H} \right) \right)$. In this case, the power is allocated only to the p non-zero transmit spatial subchannels, where p is the rank of the deterministic LoS component. The latter can be parametrized as $p = N^\alpha$, with $\alpha \in [0, 1]$. It is also worth mentioning that the eigenvectors of the capacity-achieving input coincide with those of $\mathbf{H}_\mathrm{L}^\dagger \mathbf{H}_\mathrm{L}$, as was demonstrated in [18, Theorem 2] and also for ULAs in [22], [23], [26].

A. Optimum input and three canonical configurations

As was previously highlighted, in the case of LoS propagation the inter-element distance has a direct impact on the channel rank. This implies that the concept of reconfigurability can be directly applied to this problem of interest. To this end, using [22, Corollary 2], the capacity-achieving input, $\mathbf{Q}_\mathrm{opt}$, should allocate power only to the non-zero spatial dimensions of $\mathbf{T}$, so that $\mathbf{Q}_\mathrm{opt} = (\rho/p)\mathbf{\Lambda}$ where

$$\mathbf{\Lambda} \triangleq \begin{bmatrix} \mathbf{I}_p & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \in \mathbb{R}^{N_t \times N_t}. \quad (4)$$

We can then rewrite the MIMO capacity as

$$C = \sum_{k=1}^{p} \log_2 \left(1 + \frac{\rho}{p} \lambda_k \right) \quad (5)$$

$$\approx p \log_2 \left(1 + \frac{\rho}{p} \lambda_\mathrm{ave} \right) = p \log_2 \left(1 + \frac{\rho}{p^2} \mathrm{tr}(\mathbf{T}) \right) \quad (6)$$

$$= N^\alpha \log_2 \left(1 + \rho N^{\gamma - 2\alpha} \right) = N^\alpha \log_2 (1 + \rho_{rx}) \quad (7)$$

with λ_k being the k-th eigenvalue of $\mathbf{T}$ and $\rho_{rx} = \rho \mathrm{tr}(\mathbf{T})/p^2$ is the received SNR expressed as a function of the total channel power $\mathrm{tr}(\mathbf{T}) = N^{\gamma}$, $\gamma \in [0,2]$. The second expression approximates the marginal eigenvalues with the average eigenvalue, λ_{ave}. We note that although from (1), it is clear that $\mathrm{tr}(\mathbf{T}) = N^2$ (i.e. $\gamma = 2$), any power normalization can be accommodated within the proposed framework. The last formula (7) reveals a fundamental tradeoff between the channel rank p and the received SNR which was originally identified in [22], [23]. This tradeoff can be optimized to maximize MIMO capacity as function of SNR. That is, increasing the antenna spacing (and consequently the rank of LoS component) comes at the expense of SNR and vice versa. This is depicted in Fig. 2, where the ergodic capacity of a 9×9 system has been plotted against the SNR for ten uniformly sampled values of α in $[0,1]$ and $\gamma = 2$.

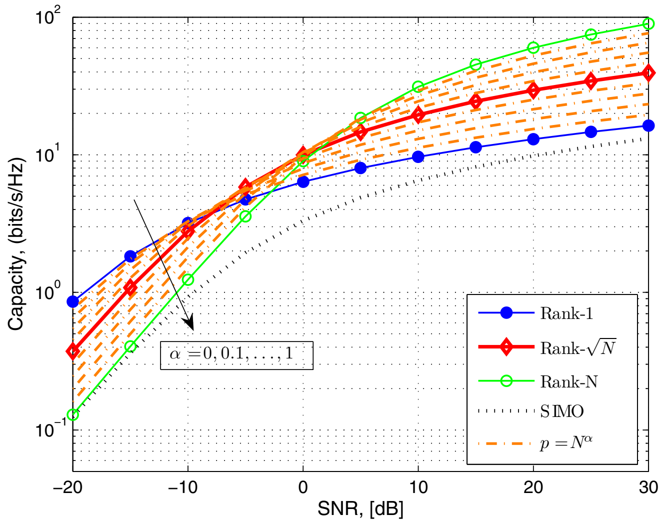

Fig. 2. Ergodic capacity for different MIMO configurations against the SNR ($N = 9$, $\gamma = 2$).

More importantly, only three canonical configurations suffice to achieve near-optimum performance across the entire SNR range, as was first proposed for sparse MIMO channels in [22], [23]. The first one is rank-1 and realized by small spacings at both ends (i.e. $s_1, s_2 \leq \lambda/2$) while it becomes optimal at low SNRs.[2] The full rank (FR) configuration is realized by sufficiently large spacings as determined by the criterion in (2) while its performance is optimal at high SNRs.[3] The last configuration is of rank-$\sqrt{N}$ and is realized by setting the antenna spacings equal to the square root of (2) (medium spacing) and at the same time is optimal at medium SNRs while it offers the fastest capacity scaling [23].

The characteristics of the above mentioned configurations can now be summarized as[4]

$$\text{Rank-1}: \quad s_1 = s_2 = \lambda/8 \tag{8}$$

$$\text{Rank-}N: \quad s_1 = s_2 = s_{\max} = \sqrt{\lambda D/N} \tag{9}$$

$$\text{Rank-}\sqrt{N}: \quad s_1 = s_2 = s_{\max}/\sqrt{N}. \tag{10}$$

In Fig. 3, the ergodic capacity of the above mentioned configurations is evaluated against the number of antennas for $\rho = 0, 5$ and 15 dB. The graph clearly depicts the fastest capacity scaling of the rank-$\sqrt{N}$ configuration as a function of N. In the low-SNR regime, the rank-1 configuration outperforms the other two configurations for low number of antennas while the FR yields the best performance in the large system limit. On the contrary, in the high-SNR regime the FR initially dominates but as N gets higher, the rank-$\sqrt{N}$ configuration eventually outperforms it. For moderate SNR values, the rank-$\sqrt{N}$ configuration is systematically superior for all possible values of N.

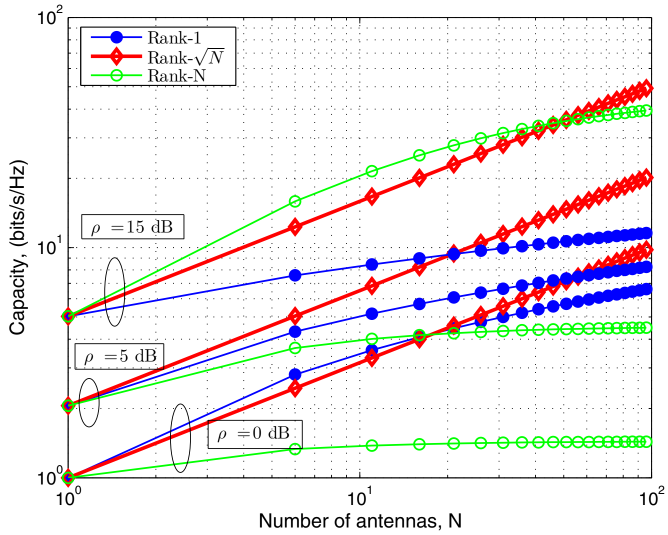

Fig. 3. Ergodic capacity for different MIMO configurations against the number of antennas N ($\gamma = 1$).

B. Optimum antenna spacing and capacity gains

The concept of agile MIMO systems can be fully characterized after defining the optimum antenna spacings that offers the maximum capacity at any given SNR. To this end, we compute the first and second-order derivatives with respect to p of the approximating capacity formula in (7)

$$C'(N,\rho,p) = \frac{dC}{dp} = \frac{1}{\ln 2}\left(\ln(1+\rho_{rx}) - \frac{2\rho_{rx}}{1+\rho_{rx}}\right) \tag{11}$$

$$C''(N,\rho,p) = \frac{dC^2}{dp^2} = \frac{1}{\ln 2}\frac{2\rho_{rx}(1-\rho_{rx})}{p(1+\rho_{rx})^2}. \tag{12}$$

[2]This is expected since at low SNRs the optimum strategy is to allocate power only to the dominant subchannel of the channel matrix (beamforming regime) [18], [24].

[3]At high SNRs, the optimal power allocation scheme becomes uniform and as such a FR configuration is optimal (multiplexing regime).

[4]For the rank-1 configuration we have empirically set $s_1 = s_2 = \lambda/8$ in order to minimize the effects of leakage. In fact, any value below the critical spacing of $\lambda/2$ should be appropriate. Hence, coupling between closely spaced antennas has been neglected.

It can be shown that $C'(N,\rho,p)=0$ when $\rho_{rx}\approx 4$ while $C''(N,\rho,p)>0$ for $\rho_{rx}<1$ and $C''(N,\rho,p)<0$ for $\rho_{rx}>1$ [22], [23]. Hence, we can consider that the capacity obtains its maximum value when $\rho_{rx}\approx 4 \Rightarrow \rho N^{\gamma}/p^2\approx 4$, which leads to the following condition for the optimum rank as a function of SNR

$$p_{\text{opt}}(\rho)\approx \frac{\sqrt{\rho}N^{\gamma/2}}{2} \overset{\gamma=2}{\Rightarrow} p_{\text{opt}}(\rho)\approx\frac{\sqrt{\rho}N}{2}. \tag{13}$$

As such, the *ideal MIMO channel* at any SNR ρ can now be defined according to

$$p_{\text{opt}}(\rho)\approx \begin{cases} 1, & \text{if} \quad \rho<\rho_{\text{low}} \\ \sqrt{N}, & \text{if} \quad \rho\in[\rho_{\text{low}},\rho_{\text{high}}] \\ N, & \text{if} \quad \rho>\rho_{\text{high}} \end{cases} \tag{14}$$

where ρ_{low} and ρ_{high} are the solutions of the following set of equations

$$\log_2(1+N^2\rho_{\text{low}})=\sqrt{N}\log_2(1+N\rho_{\text{low}}) \tag{15}$$

$$N\log_2(1+\rho_{\text{high}})=\sqrt{N}\log_2(1+N\rho_{\text{high}}) \tag{16}$$

We can now quantify the capacity gains due to reconfigurable antenna arrays in the low and high SNR regimes. Using the well-known asymptotic approximations $\log_2(1+x)\approx x, x\to 0$ and $\log_2(1+x)\approx\log_2(x), x\to\infty$, the capacity expressions in (7) yield

$$\lim_{\rho\to 0}\frac{C_{(\text{rank}-1)}}{C_{(\text{rank}-\sqrt{N})}}=\lim_{\rho\to 0}\frac{C_{(\text{rank}-\sqrt{N})}}{C_{(\text{rank}-N)}}=\sqrt{N} \tag{17}$$

$$\lim_{\rho\to \infty}\frac{C_{(\text{rank}-N)}}{C_{(\text{rank}-\sqrt{N})}}=\lim_{\rho\to \infty}\frac{C_{(\text{rank}-\sqrt{N})}}{C_{(\text{rank}-1)}}=\sqrt{N} \tag{18}$$

The above equations indicate that there is a dramatic capacity gain in the low-SNR regime (analogous to $\sqrt{N}$) where all power is allocated to the dominant eigenvalue. This effect is more pronounced when compared with UPAs which are inherently suboptimal for rank-deficient channels, especially at low SNRs [18]–[20].

IV. Numerical Results

In this section, we evaluate the performance of the three proposed configurations in (8)-(10) assuming a practical propagation scenario. For this reason, we explore an 9×9 MIMO system operating at 5.2 GHz with a Tx-Rx separation distance of $D=5$ m.[5] For these settings we have $s_{\text{max}}=17.90$ cm. In Fig. 4, the ergodic capacity is plotted as a function of SNR, ρ. The simulated curves are generated according to (3) while the analytical curves via (7).

It can be easily seen that the match between theory and simulation is perfect in the case of rank-1 and rank-N configurations; in the case of rank-$\sqrt{N}$ the match is getting looser at medium SNRs due to leakage effects but becomes tighter at low and high SNRs. This finding is in agreement with [22]. Please note that for smaller MIMO setups which are also of higher practical importance, the match is even better.

[5]For the emerging 60 GHz mm-wave applications, the required spacings, and consequently the array aperture, will be smaller.

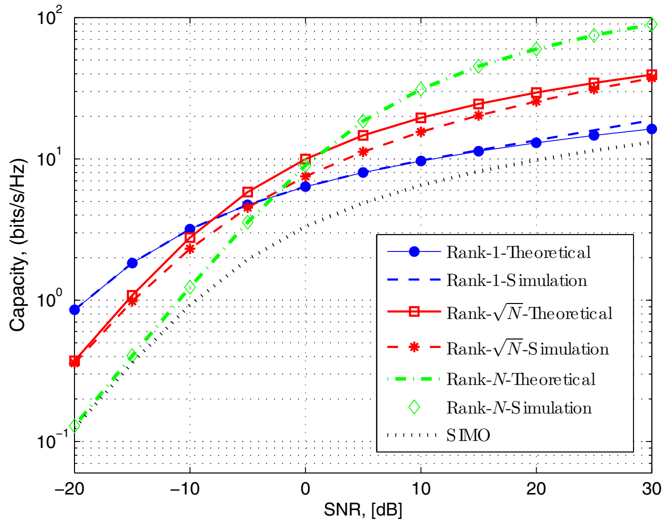

Fig. 4. Analytical and simulated capacity of three different LoS MIMO configurations against the SNR ($N=9$).

A. Scattering

In a realistic communication system, a degree of scattering is always presented as a result of the surrounding environment which creates multipath components. In this case, the MIMO channel model can be extended as follows

$$\mathbf{H}=\sqrt{\frac{K}{K+1}}\mathbf{H}_{\text{L}}+\sqrt{\frac{1}{K+1}}\mathbf{H}_{w} \tag{19}$$

where K is the Ricean K-factor expressing the ratio of powers of the free-space signal and the scattered waves. The random component, $\mathbf{H}_w$, accounts for the scattered signals with its entries being modeled as i.i.d. $\sim\mathcal{CN}(0,1)$ random variables (Rayleigh fading). Consequently, the coherent MIMO capacity becomes a stochastic process with its mean (ergodic capacity) given by [1], [2]

$$C_{\text{erg}}=\max_{\mathbf{Q}:\text{tr}(\mathbf{Q})\le\rho}\mathcal{E}_{\mathbf{H}}\left[\log_2\left(\det\left(\mathbf{I}_{N_r}+\mathbf{HQH}^{\dagger}\right)\right)\right] \tag{20}$$

where the expectation is taken across all realizations of $\mathbf{H}$. Please note that the approximating capacity expression in (7) holds also for C_{erg} [22], [23]. In order to comprehend better the advantages of reconfigurability, we now compare the capacity performance of the three reference configurations with UPA, as assumed in [10]–[12], [16], with that predicted by (7). In Fig. 5 and 6, the ergodic capacity is plotted against the Ricean K-factor and overlaid with the analytical formulae of (7) for each case under consideration and different SNR values.

We can now make the following important observations from inspection of Fig. 5 and 6:

- As expected, the FR configuration benefits from the presence of LoS components and attains its maximal capacity in the high K-factor regime, which is also identical with the predicted value of (7) (i.e. $C_{\text{erg}}=N\log(1+\rho)$). In the high-SNR regime this configuration is consistently superior compared to the other two configurations.

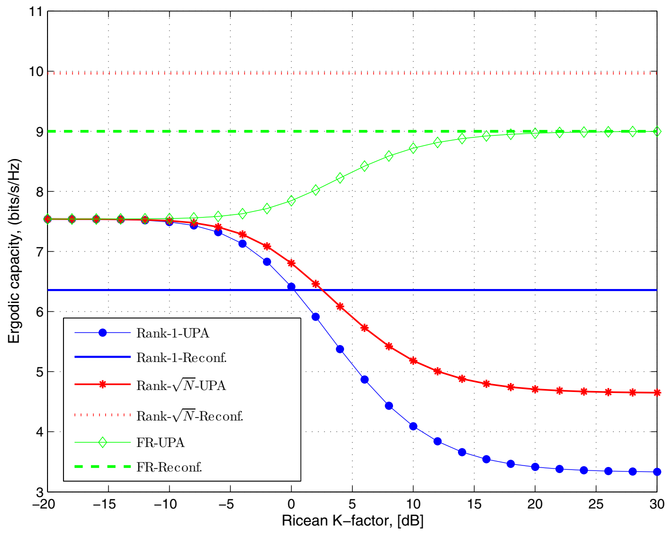

Fig. 5. Ergodic capacity of three different LoS MIMO configurations against the Ricean K-factor ($N = 9$ and $\rho = 0$ dB).

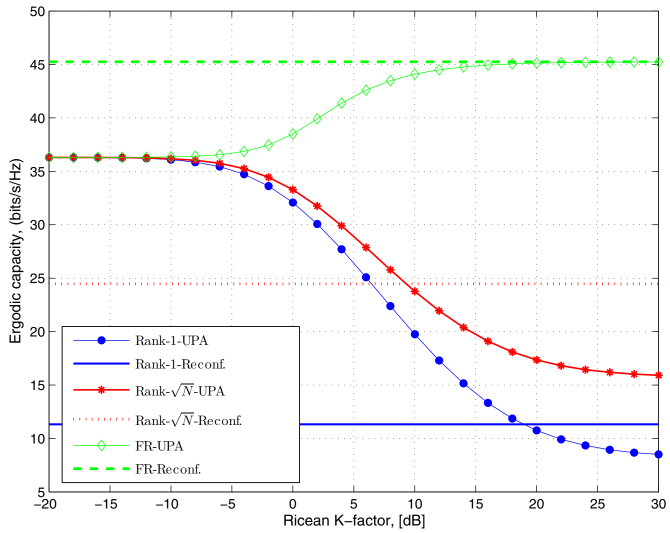

Fig. 6. Ergodic capacity of three different LoS MIMO configurations against the Ricean K-factor ($N = 9$ and $\rho = 15$ dB).

- At low and moderate SNRs, the advantages of reconfigurability become more pronounced. In particular, when the LoS component dominates, UPA becomes quite sub-optimal for the rank-1 and rank-$\sqrt{N}$ configurations since an amount of power is inevitably wasted to the vanishing spatial dimensions. In fact, it is clearly seen that at $\rho = 5$ dB the rank-$\sqrt{N}$ configuration can afford a 3dB gain when the power is allocated only to the dominant dimensions.
- In the case of UPA and for $K \leq 0$ dB, the impact of the inter-element spacing on MIMO capacity diminishes and in the limit, $K \to -\infty$ dB, the LoS component vanishes and we end up with a pure i.i.d. Rayleigh channel, whose ergodic capacity for the same number of antennas is 7.54 ($\rho = 0$ dB) and 36.3 bits/s/Hz ($\rho = 15$ dB), respectively. We point out that these results are consistent with the findings in [8]–[12], [14].

V. Conclusion

In this paper, the concept of reconfigurable antenna arrays has been applied to the problem of MIMO systems exhibiting Ricean fading. Using some recent results on agile sparse MIMO systems, we herein proposed a versatile methodology which adaptively adjusts the antenna spacings at both the transmitter and receiver in order to obtain the maximum capacity at any given SNR value. This is achieved by matching the rank of the LoS correlation matrix to the rank of the input covariance matrix.

Although the proposed methodology encompasses an entire family of configurations that can be easily implemented, it was shown that only three canonical topologies suffice to achieve near-optimum performance. In addition, we proposed a tractable capacity formula which not only reveals a fundamental tradeoff between the received SNR and channel rank but also remains tight across the entire SNR range. Finally, a set of numerical results was used to assess the implications of the model parameters on the capacity performance of the proposed configurations.

Acknowledgments

The authors would like to thank Dr. Vasanthan Raghavan, University of Melbourne, Australia for a number of stimulating discussions on the concept of reconfigurability.

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