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Design and Performance Assessment of High-Capacity MIMO Architectures in the Presence of a Line-of-Sight Component

Ioannis Sarris and Andrew R. Nix

Abstract—In this paper, the capacity of multiple-input multiple-output (MIMO) communication systems is investigated in the presence of a Line-of-Sight (LoS) component. Under this scenario, the channel-response matrix is usually rank deficient due to the high correlation between the LoS responses. Previous studies have shown that this problem can be overcome by the use of specifically designed antenna arrays. The antenna elements are positioned to preserve orthogonality and, hence, maximize the LoS-channel rank. To help in the design of such architectures, we derive a 3-D criterion for maximizing the LoS MIMO capacity as a function of the distance, the orientation, and the spacing of the arrays. The sensitivity of these systems to imperfect positioning and orientation is examined using a geometric MIMO model. The spectral efficiency is also investigated in the presence of scattered signals in the environment using a stochastic channel model and a Monte Carlo simulator. To demonstrate the validity of our predictions, we present the results of two MIMO measurement campaigns in an anechoic and an indoor environment where the measured capacities are compared with the capacities obtained from our models. All experimental results validate our predictions and, hence, confirm the potential for superior MIMO performance (when the developed criterion is applied) in strong LoS channels.

Index Terms—Antenna arrays, channel capacity, K-factor, line-of-sight (LoS), multiple-input multiple-output (MIMO), Ricean channel.

I. INTRODUCTION

COMMUNICATION systems with multiple-element arrays at both ends of the communication link have drawn considerable research interest in recent years. This trend was driven by the potential for considerable capacity enhancement compared to the conventional single-input single-output (SISO) systems. Given the scarcity and, thus, the rising value of radio spectrum, multiple-input multiple-output (MIMO) technology is considered as a necessity in future high-bandwidth communication systems.

MIMO research was initiated by the mathematical derivation of the MIMO channel capacity assuming independent identically distributed (i.i.d.) Rayleigh fading [1]. It was shown that, in this scenario, MIMO technology can, in principle, offer a linear increase in capacity that is proportional to the minimum number of transmit and receive elements. This ca-

capacity enhancement is attributed to the utilization of multiple spatial subchannels between the transmit and receive elements. Evidently, in practical systems, the spectral efficiency is limited by the number of uncorrelated communication paths between the transmitter and the receiver, and also by the relative powers of the corresponding communication subchannels. In systems with highly correlated channel responses, only a few subchannels effectively contribute to the total capacity of the system, and therefore, the performance of the system is lower than that predicted by the i.i.d. Rayleigh fading model.

For the case where the transmit and receive arrays are not in Line-of-Sight (LoS), the number of uncorrelated communication paths is usually directly related to the number of active scatterers in the environment. In the ideal scenario, where an infinite number of scatterers exists, the capacity increases linearly with the minimum number of transmit and receive elements following the i.i.d. Rayleigh model. However, in reality, the finite number of active scatterers imposes a limit on the spectral-efficiency gains that are possible using MIMO. As a result, the spectral-efficiency gain saturates rapidly with increasing numbers of transmit and receive elements and, in particular, when the number of elements exceeds the number of active scatterers [2].

If a LoS component is present, this is usually thought to limit the spectral efficiency of the system due to the high amounts of spatial correlation introduced. This can be attributed to the fact that, in most conventional MIMO systems, the transmit and receive arrays are in the far field.¹ Under this condition, the LoS signals can be seen as plane waves, and as a result, the LoS response is rank one, and the channel is rank deficient. This effect has been verified by the results of various information theoretic studies and measurement campaigns in the literature [3]–[5].

Contrary to these observations, a number of studies have shown that the LoS response is not inherently correlated and that by using specifically designed antenna arrays, the orthogonality of the received signals can be preserved [6], [7]. A number of configurations that achieve high-rank MIMO channels were previously reported in [8]–[13]. In this paper, we investigate the theoretical performance of such systems in LoS via analysis, simulation and measurement, and compare them

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¹That is, $D \gg (2s^2/\lambda)$, where D is the distance between the arrays, s is the largest dimension of the array, and λ is the wavelength.

with conventional systems that make use of electrically small antenna arrays.

The main contribution of this paper is the derivation of a simplified 3-D maximum capacity criterion for MIMO systems employing uniform linear arrays (ULAs) in LoS. Using this new criterion, array architectures can be designed that overcome the problem of reduced capacity in a LoS scenario and, thus, offer superior performance compared to conventional MIMO systems. The capacity sensitivity of systems designed to satisfy this criterion is investigated, and the theoretic predictions are validated experimentally using MIMO channel measurements taken in the 5.2-GHz band.

The remainder of this paper is organized as follows. Section II introduces the system model and the capacity equation employed throughout this paper. In Section III, the design criteria for maximizing the capacity of LoS MIMO channels are derived. Next, in Section IV, the sensitivity of the capacity performance for a LoS MIMO system is investigated by means of geometric and stochastic channel modeling. In Section V, the measured capacities of a MIMO system in an anechoic chamber and an indoor office environment are presented and compared with the capacities found from our channel models. Finally, Section VI discusses the conclusion of this paper and summarizes the key findings.

II. SYSTEM MODEL AND MIMO CAPACITY

The system model employed throughout this paper involves a communication system with n_t transmit elements and n_r receive elements (which is, from now on, referred to as an $n_t \times n_r$ MIMO system) impaired by additive white Gaussian noise (AWGN). The complex baseband input–output relationship for this system can be represented mathematically by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

where $\mathbf{y} \in \mathcal{C}^{n_r}$, $\mathbf{H} \in \mathcal{C}^{n_r \times n_t}$, $\mathbf{x} \in \mathcal{C}^{n_t}$, and $\mathbf{n} \sim \mathcal{CN}(0, \sigma_n^2)$ correspond to the received signal vector, the channel-response matrix, the transmitted signal vector, and the AWGN noise vector, respectively.

In the aforementioned system, the receiver is assumed to have perfect channel knowledge, whereas no such prior knowledge is available at the transmitter. Note that the transmit power is equal to P_t/n_t (at all transmit elements) and that P_t is independent of n_t . The capacity of such a system is given by

$$C = \log_2 \left(\det \left(\mathbf{I}_{n_r} + \frac{\rho}{n_t} \mathbf{H}\mathbf{H}^H \right) \right) \quad (2)$$

where \mathbf{I}_{n_r} is the $n_r \times n_r$ identity matrix, ρ corresponds to the average received signal-to-noise ratio (SNR) at the input of the receiver, and $[\cdot]^H$ denotes the (Hermitian) conjugate transpose [1].²

Throughout this paper, our purpose is to compare the MIMO gains of a number of architectures, and therefore, the capac-

²In this equation and throughout this paper, we assume that $n_t > n_r$. However, similar results can be obtained for systems with $n_r > n_t$ by replacing n_t with n_r and $\mathbf{H}\mathbf{H}^H$ with $\mathbf{H}^H\mathbf{H}$.

ities are analyzed independently of the average SNR. This is achieved by normalizing the channel-response matrices so that they satisfy the following constraint:

$$E \{ \|\mathbf{H}\|_F^2 \} = n_t n_r \quad (3)$$

where $\|\cdot\|_F$ corresponds to the Frobenius norm. In physical terms, this assumption corresponds to a system with perfect power control.

A. Dynamic Range of MIMO Capacity

Before deriving the design criteria for high-capacity LoS MIMO architectures, it is useful to determine the mathematical conditions for achieving the minimum and maximum capacities in a time-invariant MIMO channel. Using (2), it is trivial to show that the minimum capacity is obtained for $\mathbf{H}\mathbf{H}^H = n_t \mathbf{I}_{n_r}$, where \mathbf{I}_{n_r} is an $n_r \times n_r$ all-ones matrix. This corresponds to an entirely correlated (rank one) MIMO channel, and the associated capacity is equivalent to that of a single-input multiple-output channel as follows:

$$C_{\min} = \log_2(1 + n_r \rho). \quad (4)$$

At the other extreme, the capacity in (2) is maximized for $\mathbf{H}\mathbf{H}^H = n_t \mathbf{I}_{n_r}$, i.e., when \mathbf{H} is orthogonal. This response corresponds to a system with perfectly orthogonal MIMO subchannels, and the capacity of the MIMO channel is then equivalent to that of n_r independent SISO channels as follows:

$$C_{\max} = n_r \log_2(1 + \rho). \quad (5)$$

III. MAXIMUM LOS MIMO CAPACITY CRITERIA

As mentioned previously, in a LoS scenario, the LoS component affects the rank of the total channel response. In this section, we investigate the design requirements for maximizing the rank of the LoS channel response (ignoring any scatter components at this stage), hence, formulating the design criteria for high-rank MIMO systems in LoS.

A. Channel Model

In free space, the complex response between a transmit element m and a receive element n (assuming isotropic elements) is equal to $e^{-jkd_{n,m}}/d_{n,m}$, where $k = 2\pi/\lambda$ is the wavenumber corresponding to the wavelength λ , and $d_{n,m}$ is the distance between the two elements. Assuming that the relative differences in path loss are negligible, the normalized free-space channel-response matrix of an $n_r \times n_t$ MIMO system can be written as

$$\mathbf{H} = \begin{bmatrix} e^{-jkd_{1,1}} & e^{-jkd_{1,2}} & \dots & e^{-jkd_{1,n_t}} \\ e^{-jkd_{2,1}} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ e^{-jkd_{n_r,1}} & \dots & & e^{-jkd_{n_r,n_t}} \end{bmatrix} \quad (6)$$

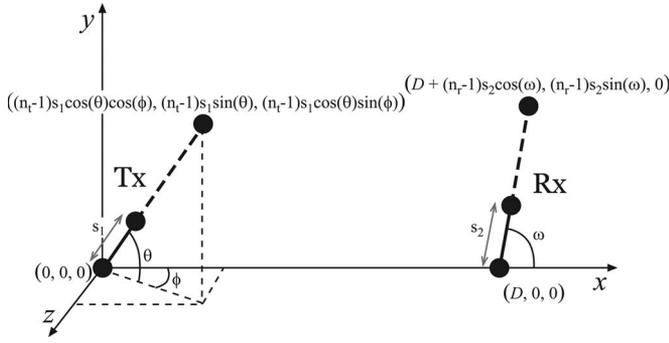


Fig. 1. Positioning of the elements in a $n_t \times n_r$ MIMO system.

and the correlation matrix is equal to

$$\mathbf{H}\mathbf{H}^H = \begin{bmatrix} n_t & \dots & \sum_{m=1}^{n_t} e^{-jk(d_{1,m}-d_{n_r,m})} \\ \vdots & \ddots & \vdots \\ \sum_{m=1}^{n_t} e^{-jk(d_{n_r,m}-d_{1,m})} & \dots & n_t \end{bmatrix}. \quad (7)$$

Clearly, the aforementioned matrices are deterministic and depend only on the distances between the transmit and receive elements [14].

B. Maximum 2×2 Capacity Criterion

A 2×2 MIMO system is now used as the basis of our derivation of the maximum capacity criterion. Using the mathematical condition of Section II-A, it is clear that the capacity of a 2×2 MIMO system is maximized for $\mathbf{H}\mathbf{H}^H = 2\mathbf{I}$, i.e., when the condition in (8), shown at the bottom of the next page, is met.

The solution to the aforementioned equation can be written as

$$k(d_{1,1} - d_{2,1}) - k(d_{1,2} - d_{2,2}) = (2p + 1)\pi \quad \forall p \in \mathbb{Z} \quad (9)$$

where \mathbb{Z} represents the set of integers. This is equivalent to

$$d_{1,1} - d_{2,1} - d_{1,2} + d_{2,2} = (2p + 1)\frac{\lambda}{2} \quad \forall p \in \mathbb{Z}. \quad (10)$$

Assuming the 3-D geometric configuration shown in Fig. 1 and $n_t = n_r = 2$, the Euclidean distance between each pair of elements can be calculated. If we define the distance between the first element of each array to equal D and the interelement spacing of the two arrays to equal s_1 and s_2 , then the conditions in (11)–(14), shown at the bottom of the next page, are met.

These equations can be simplified using the following first-order Taylor series approximation as follows:

$$\begin{aligned} \sqrt{(D + \alpha)^2 + \beta^2} &= (D + \alpha)\sqrt{1 + \frac{\beta^2}{(D + \alpha)^2}} \\ &\approx (D + \alpha) + \frac{\beta^2}{2(D + \alpha)}. \end{aligned} \quad (15)$$

This approximation is valid for $(D + \alpha)^2 \gg \beta^2$, which is true for all systems of interest since D is much larger than s_1 and s_2 .

Then,

$$d_{1,1} = D \quad (16)$$

$$d_{1,2} = D - s_1 \cos \theta \cos \phi + \frac{(s_1 \sin \theta)^2 + (s_1 \sin \phi \cos \theta)^2}{2(D + s_1 \cos \theta \cos \phi)} \quad (17)$$

$$d_{2,1} = D + s_2 \cos \omega + \frac{(s_2 \sin \omega)^2}{2(D + s_2 \cos \omega)} \quad (18)$$

$$d_{2,2} = D - s_1 \cos \theta \cos \phi + s_2 \cos \omega + \frac{(s_2 \sin \omega - s_1 \sin \theta)^2 + (s_1 \sin \phi \cos \theta)^2}{2(D - s_1 \cos \theta \cos \phi + s_2 \cos \omega)}. \quad (19)$$

Finally, to simplify these equations further, we can assume without any loss of accuracy³ that the denominators in (17)–(19) are equal to $2D$.

By substituting the simplified distance equations into (10), the maximum capacity criterion becomes

$$\frac{s_1 s_2 \sin \omega \sin \theta}{D} = (2p + 1)\frac{\lambda}{2} \quad \forall p \in \mathbb{Z} \quad (20)$$

or equivalently

$$s_1 s_2 = (2p + 1)\frac{\lambda D}{2 \sin \omega \sin \theta} \quad \forall p \in \mathbb{Z}. \quad (21)$$

Physically, the approximate maximum capacity criterion corresponds to systems where the sum of the path differences $(d_{1,1} - d_{1,2})$ and $(d_{2,2} - d_{2,1})$ is an odd integer multiple of a half wavelength. The importance of the simplified maximum 2×2 MIMO capacity criterion lies in the fact that it is expressed in terms of the interelement spacings, the transmitter-to-receiver (T–R) distance, the orientation of the arrays, and the carrier frequency. Thus, by knowing the carrier frequency and the T–R distance, the optimal spacings can be easily calculated. It is interesting to note that since this criterion is a function of the products of the interelement spacings, it indicates the potential to achieve high capacities in systems with small array sizes at one end of the link by compensating with large array sizes at the other end. This is particularly useful for distributed MIMO applications where larger array sizes can be accommodated in the access point, while the size of the mobile terminal is kept to practical levels.

C. Maximum $n_t \times n_r$ Capacity Criterion

Following a similar approach to that used in Section III-B, the maximum capacity criterion for an $n_t \times n_r$ MIMO system

³Note that the error introduced from all the aforementioned simplifications is minor for all practical systems. For example, in a system with $s_1 = s_2 = 20$ cm and $D = 3$ m, the maximum error for all values of θ , ϕ , and ω is less than $3 \cdot 10^{-5}$ (the error is even smaller for higher values of D or lower values of s_1 and s_2).

can be derived. It is trivial to show that $\mathbf{H}\mathbf{H}^H = n_t \mathbf{I}_{n_r}$ is equivalent to

$$\sum_{m=1}^{n_t} e^{-jk(d_{a,m} - d_{b,m})} = 0 \quad \forall a, b \in \{1, 2, \dots, n_r\}. \quad (22)$$

In the special case of ULAs at both ends of the communication link, and for all practical values of T-R distance and interelement spacing, the phase difference $k(d_{a,m} - d_{a,m+1})$ is almost constant for all $m \in \{1, 2, \dots, n_t - 1\}$. Therefore

$$k(d_{a,m} - d_{b,m}) - k(d_{a,m+1} - d_{b,m+1}) \quad (23)$$

is also constant for all $m \in \{1, 2, \dots, n_t - 1\}$. Thus, the solution to (22) (substituting $m = 1$) becomes

$$\begin{aligned} k(d_{a,1} - d_{b,1}) - k(d_{a,2} - d_{b,2}) \\ = \frac{2\pi}{n_t} + 2p\pi \quad \forall a, b \in \{1, 2, \dots, n_r\}, p \in \mathbb{Z}. \end{aligned} \quad (24)$$

Again, since the array elements at both ends are uniformly distributed and $D \gg s_1, s_2$, the following approximation can be used:

$$\begin{aligned} d_{a,m} - d_{b,m} \approx (a - b)(d_{1,m} - d_{2,m}) \\ \forall a, b \in \{1, 2, \dots, n_r\}, m \in \{1, 2, \dots, n_t\} \end{aligned} \quad (25)$$

and (24) can be further simplified to

$$k(d_{1,1} - d_{2,1}) - k(d_{1,2} - d_{2,2}) = \frac{2\pi}{n_t} + 2p\pi \quad \forall p \in \mathbb{Z}. \quad (26)$$

Finally, the maximum capacity criterion can be expressed as

$$d_{1,1} - d_{2,1} + d_{2,2} - d_{1,2} = \lambda \left(\frac{1}{n_t} + p \right) \quad \forall p \in \mathbb{Z}. \quad (27)$$

Using the derivation for the 2×2 criterion, the simplified $n_t \times n_r$ criterion can be written as

$$s_1 s_2 \approx \lambda \left(\frac{1}{n_t} + p \right) \frac{D}{\sin \omega \sin \theta} \quad \forall p \in \mathbb{Z}. \quad (28)$$

It is interesting to note that the product of the required interelement spacings at the two arrays reduces with increasing n_t , resulting in a higher space efficiency (i.e., smaller spacing per element) for arrays with a large number of elements. This feature can potentially be very attractive for future communication systems since, in these systems, multiple elements can be accommodated in a compact array without the problem of mutual coupling and signal correlation. Such architectures are attractive for future communication systems since their performance (contrary to non-LoS systems) does not depend on the existence of a rich-scattering environment. Therefore, the capacity enhancement with increasing element number in environments with a strong LoS signal will always be linear.

IV. SENSITIVITY STUDY

The maximum capacity criterion in Section III corresponds to very specific array geometries and only considers the LoS component of the channel response. In this section, the sensitivity of these systems is studied under more realistic deployment and propagation conditions. The performance of a MIMO system is investigated with imperfectly positioned arrays using the geometrical MIMO channel model from Section III-A. Furthermore, the performance of full-rank and rank-one LoS systems is studied in the presence of scatter by means of a stochastic channel model.

A. Displacement

The criterion for full-rank MIMO architectures defines a number of MIMO architectures for systems with antenna arrays fixed at optimal locations. However, in almost all practical situations, there is a need for high capacity over an area, rather than to a fixed point. To examine the sensitivity of the performance of maximum capacity architectures under these

$$\begin{bmatrix} 2 & e^{-jk(d_{1,1} - d_{2,1})} + e^{-jk(d_{1,2} - d_{2,2})} \\ e^{-jk(d_{2,1} - d_{1,1})} + e^{-jk(d_{2,2} - d_{1,2})} & 2 \end{bmatrix} = 2\mathbf{I} \quad (8)$$

$$d_{1,1} = D \quad (11)$$

$$d_{1,2} = \sqrt{(D - s_1 \cos \theta \cos \phi)^2 + (s_1 \sin \theta)^2 + (s_1 \sin \phi \cos \theta)^2} \quad (12)$$

$$d_{2,1} = \sqrt{(D + s_2 \cos \omega)^2 + (s_2 \sin \omega)^2} \quad (13)$$

$$d_{2,2} = \sqrt{(D - s_1 \cos \theta \cos \phi + s_2 \cos \omega)^2 + (s_2 \sin \omega - s_1 \sin \theta)^2 + (s_1 \sin \phi \cos \theta)^2} \quad (14)$$

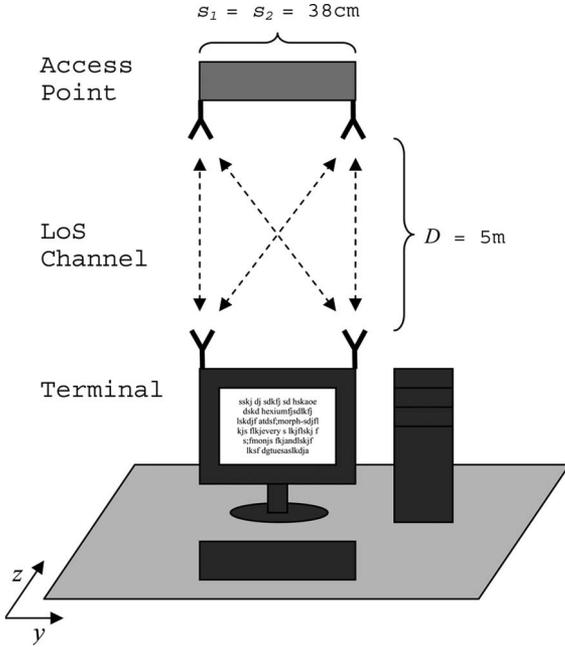


Fig. 2. Example 2×2 full-rank MIMO deployment scenario.

conditions, the capacity is now evaluated as a function of the array displacement from the optimum point. For our investigation, a 2×2 MIMO indoor system is assumed with one of the arrays mounted on the ceiling and the other at desk level (Fig. 2). This arrangement corresponds to the system of Fig. 1 with $\phi = 0^\circ$ and $\theta = \omega = 90^\circ$. If a T-R distance of 5 m and a carrier frequency of 5.2 GHz are assumed, a number of full-rank configurations can be defined from (10). Here, we use the solution of equal interelement spacings of 38 cm at both arrays.

To examine the sensitivity of this system to displacements from the optimum point, the free-space channel-response matrix is calculated using the geometric model from Section III-A. The corresponding capacity is then calculated using (2) for a displacement of d_z in the direction of the z -axis of Fig. 1 and a displacement of d_y in the direction of y , where $0 < d_z, d_y < 5$ m. The variation of capacity with d_z and d_y (assuming an SNR of 20 dB) is shown in Fig. 3. From this figure, it is clear that the capacity is relatively insensitive to displacements of a few meters from the optimum point. In detail, the capacity at $d_y = 5$ m was 15.6% lower than the maximum capacity, whereas for $d_z = 5$ m, the capacity was only 2.4% lower than the maximum.

It is interesting to note that the system outperformed the i.i.d. Rayleigh capacity derived in [1] for the same SNR. In detail, it was found that for a MIMO system with an i.i.d. Rayleigh channel-response matrix, the ergodic capacity is 11.4 b/s/Hz, whereas the proposed system achieved a minimum of 11.6 b/s/Hz in the aforementioned displacement range.

B. Orientation

From the simplified maximum capacity criterion of (28), it is clear that there is a dependence of the LoS MIMO capacity to the orientation of the two arrays (angles θ and ω). This dependence is now examined using the same geometric MIMO channel model as before. The capacity is evaluated for the same

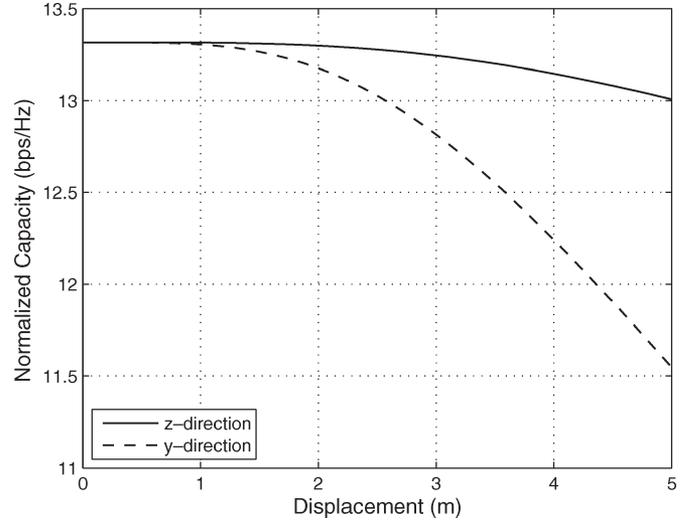


Fig. 3. Capacity as a function of the displacement from the optimum point ($\rho = 20$ dB).

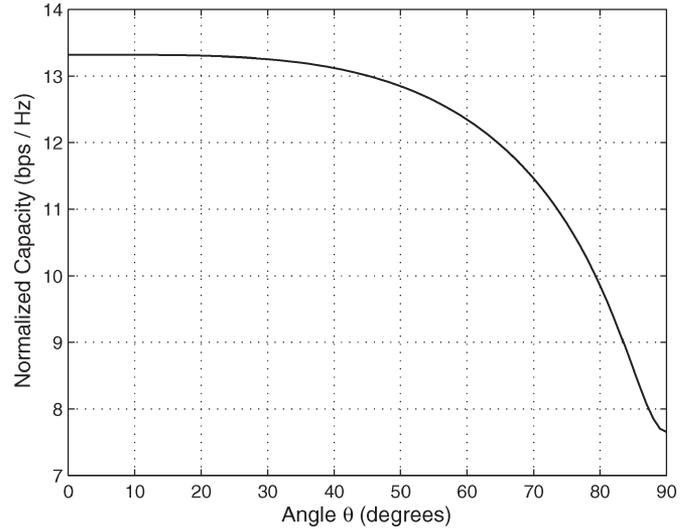


Fig. 4. Capacity as a function of the angle deviation from the optimum angle ($\rho = 20$ dB).

system configuration as in the previous section for $\phi = \omega = 90^\circ$ and $0^\circ \leq \theta \leq 90^\circ$ [from (28), it is clear that the same results apply for $\phi = \theta = 90^\circ$ and $0^\circ \leq \omega \leq 90^\circ$].

The variation of capacity as a function of the angle θ is shown in Fig. 4. The results show a large sensitivity (in terms of capacity) to the orientation of the arrays. In detail, the channel capacity is seen to vary between the minimum ($C_{\min} = 7.65$ b/s/Hz) and the maximum ($C_{\max} = 13.32$ b/s/Hz) values found from (4) and (5) (for an SNR of 20 dB). This sensitivity needs to be taken into account in the design of any practical MIMO system and is discussed more thoroughly in the following section.

C. Scattering

In the previous section, only the LoS component of the channel response was considered. In reality, some degree of scattering is always present in the radio channel, and hence, its effect must be accounted for in the design of the MIMO system.

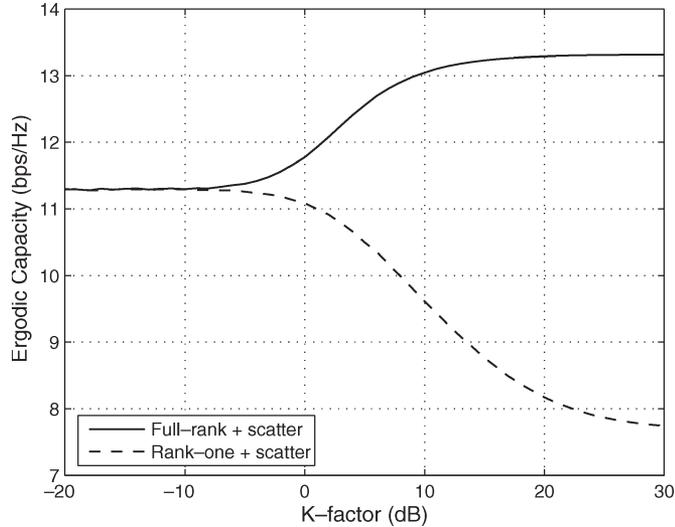


Fig. 5. Ergodic capacity as a function of the Ricean K factor for a full-rank and a rank-one configuration ($\rho = 20$ dB).

To investigate the MIMO capacity in the presence of scatter, a stochastic channel model is now employed. It is common for the MIMO channel-response matrix to be modeled as

$$\mathbf{H} = \sqrt{\frac{K}{K+1}} \mathbf{H}_L + \sqrt{\frac{1}{K+1}} \mathbf{H}_N \quad (29)$$

where \mathbf{H}_L is the matrix containing the free-space (LoS) responses between all elements, and \mathbf{H}_N accounts for the scattered (non-LoS) signals [15]. In the aforementioned equation, K represents the Ricean K factor, which is equal to the ratio of the specular signal power to the multipath signal. Contrary to the LoS response, the response of the scattered signals is not deterministic and is usually modeled by a stochastic process. In detail, we model \mathbf{H}_N as a $\mathcal{C}^{n_r \times n_t}$ matrix with i.i.d. elements $h_{n,m} \sim \mathcal{CN}(0, \sigma^2)$.

To assess the performance of this stochastic channel, the notion of ergodic capacity must be employed. This is equal to the expectation of the channel capacity and can be evaluated from a large number of channel realizations. The ergodic capacity of a MIMO system is given by

$$C_{\text{erg}} = E \left\{ \log_2 \left(\det \left(\mathbf{I}_{n_r} + \frac{\rho}{n_t} \mathbf{H} \mathbf{H}^H \right) \right) \right\}. \quad (30)$$

Using this metric and the stochastic model, we assess the performance of two 2×2 MIMO systems, namely, a system with full rank \mathbf{H}_L and a system with rank-one \mathbf{H}_L response. The first system corresponds to an architecture that satisfies (10), and therefore, $\mathbf{H} \mathbf{H}^H = 2\mathbf{I}_2$. The second is a conventional MIMO system where the arrays are in the far field (i.e., the T-R distance is much larger than $2s^2/\lambda$), and therefore, $\mathbf{H} \mathbf{H}^H = \mathbf{21}$. In both cases, 10^6 channel realizations are generated for each value of K factor, and from these, the ergodic capacity is calculated. The results for the two systems as a function of the K factor are shown in Fig. 5.

This result reveals that the K factor influences the dynamic range of the capacity values. The substantial difference in the capacity of the two configurations at high values of K factor

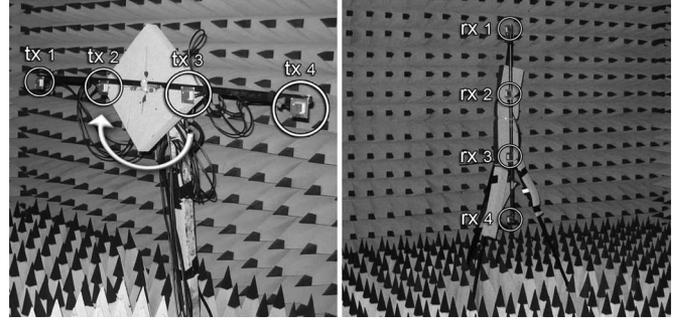


Fig. 6. Transmit (rotating) and receive (fixed) arrays in the anechoic chamber.

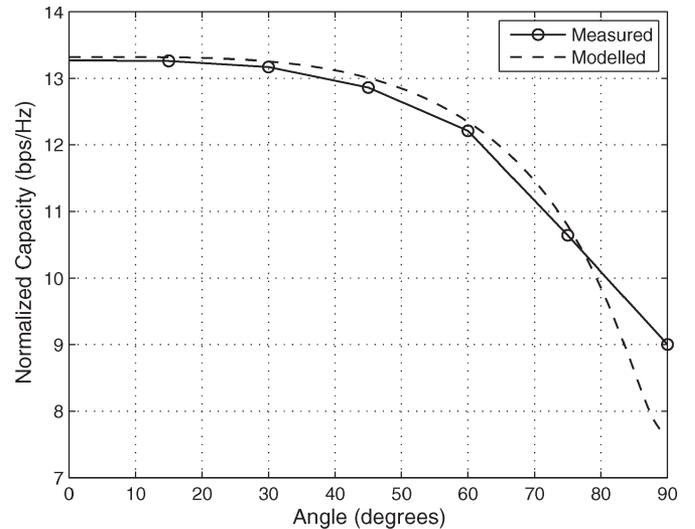


Fig. 7. Measured and modeled 2×2 MIMO capacity in the anechoic chamber ($\rho = 20$ dB).

demonstrates the effect of the array geometry on the capacity of LoS MIMO systems. The rank-one scenario validates the common belief that a strong LoS signal results in poor MIMO capacity performance. However, it is shown that specifically designed antenna arrays [such as those that satisfy (28)] can offer a higher (or at least equal) capacity than the i.i.d. Rayleigh case (11.4 b/s/Hz) at all values of K factor.

V. MIMO MEASUREMENTS

In order to verify the theoretical predictions made in the previous sections, two measurement campaigns were conducted at the University of Bristol. The first campaign was performed inside an anechoic chamber, while the second campaign took place in an indoor office environment. Both measurements were based on the same platform, which is a customized MEDAV RUSK vector channel sounder. A detailed description of this sounder can be found in [16] and [17].

A. Anechoic Measurement

In an anechoic environment there is (ideally) no scatter, and therefore, the channel response is equal to the free-space case discussed in Section III-A. In that environment, it is expected that the maximum capacity of Section II-A can be achieved with an optimum interelement spacing and alignment.

TABLE I
CAPACITY AS A FUNCTION OF THE ANGLE θ (FOR $\phi = \omega = 90^\circ$), ($\rho = 20$ dB)

Angle θ	Anechoic (modelled)	Anechoic (measured)	Indoor (modelled)	Indoor (measured)
0°	13.32	13.27	13.31	13.08
15°	13.31	13.26	13.31	12.82
30°	13.25	13.17	13.25	12.90
45°	13.01	12.86	13.00	12.68
60°	12.34	12.21	12.31	12.25
75°	10.78	10.64	10.76	10.41
90°	7.65	9.00	10.07	10.54

The transmit and receive arrays used for this measurement were ULAs composed of four dual-polarized patch elements separated by 38 cm, as shown in Fig. 6 (note that, for this paper, only elements 2 and 3 are used).⁴ Each measurement was performed at a T-R distance of 5 m with the receive array fixed, while the transmit array was rotated through seven different angles between the vertical and horizontal positions.⁵ A total of 1024 MIMO channel snapshots were recorded at each angle, and via postprocessing, the capacity was calculated using (30). By rotating the array to these angles, it was possible to experimentally study the sensitivity of the system to array rotation and to compare the results with the theoretic study of Section IV-B. The results are shown in Fig. 7 and Table I.

It is obvious that the measured capacities show very close agreement with the modeled capacity. In detail, for $0^\circ \leq \theta \leq 75^\circ$, the largest deviation from the geometric model prediction was only 1.2%. For $\theta = 90^\circ$, however, a deviation of 17.6% was observed. This can be accounted for by the polarization mismatch of the antenna elements at this angle (which limited the power of the LoS signal) and minor inaccuracies in the positioning and orientation of the antenna elements. Despite these inaccuracies, capacities of around 99.7% of the maximum LoS capacity predicted by (5) were achieved.

B. Indoor Measurement

A similar measurement campaign is now performed in an indoor office environment (Fig. 8) using the same channel sounding equipment and the same methodology as that reported in Section V-A. The purpose of this measurement was to assess the performance of the system in a realistic environment with

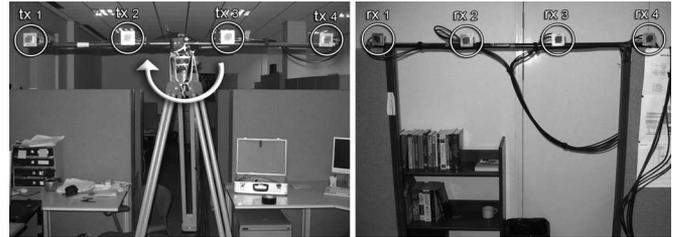


Fig. 8. Transmit (rotating) and receive (fixed) arrays in the indoor office environment.

some degree of scatter. The existence of scatter was expected to limit the dynamic range of the capacity proportionally to the K factor as predicted in Fig. 5. For example, in the extreme case where the K factor is equal to zero (non-LoS), the capacity would be independent of the orientation of the arrays and equal to that of the i.i.d. Rayleigh model.

To verify the effect of the K factor on the capacity, this value was extracted from the measurement data during post-processing using the method of [18] for all angles. The results are shown in Fig. 9. The K factor was found to decrease with increasing angle between the arrays due to the polarization mismatch between the elements. By obtaining the LoS-response matrix from the geometric model of Section III-A and by using these values of K with the stochastic channel model of Section IV-C, it was possible to model the ergodic capacity of the system. The measured and modeled capacities are compared in Fig. 10.

As expected, the angular sensitivity of the system was reduced due to the existence of scattering. This agrees with the results of Section IV-C, where it was shown that the geometry and the orientation of arrays have less influence on the total capacity when the K factor is small (less than 5 dB). As far as the accuracy of our combined geometric and stochastic model is concerned, it should be noted that the predicted capacities showed very close agreement with the measurements at all angles, with the largest deviation being only 4.7%.

It is interesting to note that at $\theta = 90^\circ$, where the free-space component is rank one, the ergodic capacity was around 40%

⁴The fact that our theoretic investigation is based on the assumption of isotropic elements does not affect the applicability of our derived criterion. Providing approximately equal gains are observed between all pairs of transmit and receive elements, our criterion can be used for nonisotropic antenna elements. For the measurement system, it was found that the maximum difference between the gains of the four subchannels was 1.39 dB.

⁵This geometry corresponds to the angles $\phi = \omega = 90^\circ$ and $0^\circ \leq \theta \leq 90^\circ$ of Fig. 1.

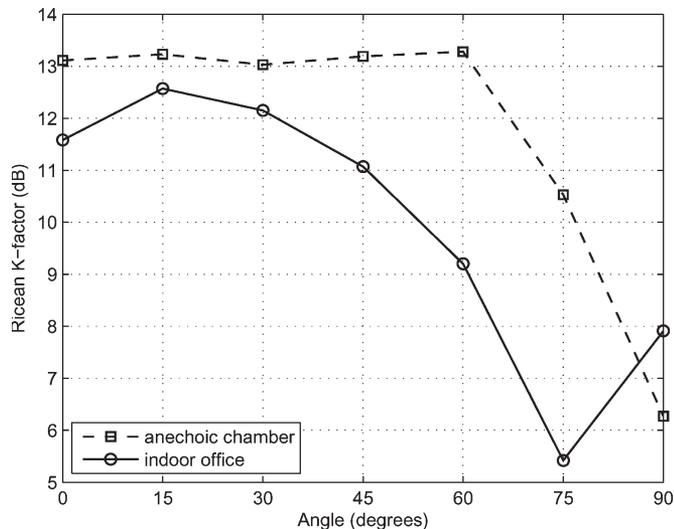


Fig. 9. Measured K factors in the anechoic chamber and the indoor environment.

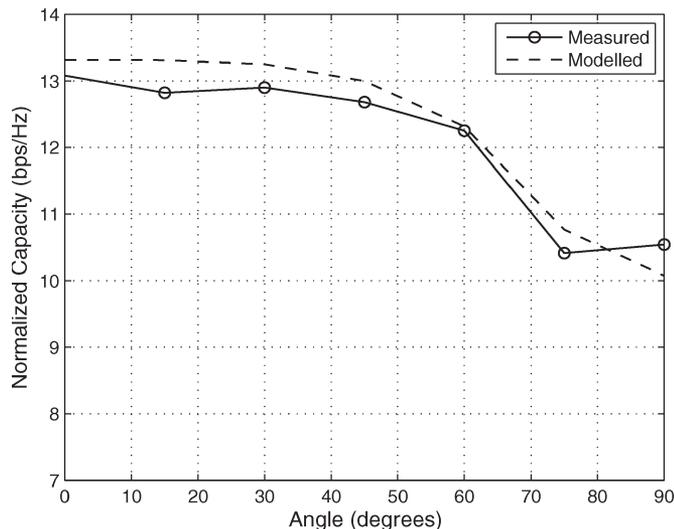


Fig. 10. Measured and modeled 2×2 MIMO capacity in the indoor environment ($\rho = 20$ dB).

higher than the free-space capacity and only 6.5% lower than the i.i.d. Rayleigh capacity. This can again be attributed to the polarization mismatch between the transmit and receive elements, which reduces the K factor and, consequently, reduces the effect of the LoS on the ergodic capacity [19]. This feature of polarized elements is beneficial for LoS-based MIMO systems since it reduces the sensitivity of the capacity in suboptimum orientations while maintaining a capacity close to the maximum limit at optimal angles (e.g., 98% of the maximum capacity was measured at $\theta = 90^\circ$).

VI. CONCLUSION

This paper presented a method to achieve orthogonality between the spatially multiplexed MIMO signals in LoS channels by employing specifically designed antenna array geometries. A new criterion for achieving the maximum LoS MIMO ca-

capacity was presented, therefore, formulating a design methodology for structures that can achieve high spectral efficiency in LoS. The sensitivity of the performance to the positioning and orientation of the arrays was discussed and evaluated. The performance of the proposed structures was investigated in the presence of scatter using a stochastic MIMO model. For high values of K factor (e.g., for $K = 10$ dB), the proposed system was seen to achieve a significant capacity enhancement (36.8% improvement) compared to conventional MIMO systems. Our theoretic work was experimentally validated using measurements from an anechoic and an indoor environment, where the theoretical and measured capacities showed very close agreement. For most configurations, deviations of less than 5% from the modeled capacities were observed.

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