# Capacity of Measured Ricean and Rayleigh Indoor MIMO Channels at 2.4 GHz with Polarization and Spatial Diversity

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***Abstract*— In this paper, we analyze the impact of polarization diversity on the capacity of multiple-input multiple-output (MIMO) channels in indoor environments. A channel measurement campaign was conducted at $2.4$ GHz to measure the co-polarized and cross-polarized subchannels under line-of-sight (LOS) and non-line-of-sight (NLOS) channel conditions. We analyze the measured data in terms of Ricean K-factor, cross-polar discrimination (XPD) and subchannel correlations. A major contribution of this paper is that in these measured channels, we observe a coincidence of low K factors and high XPD. In such channels, MIMO systems employing polarization diversity incur SNR and diversity deficits, when compared to spatial configurations. On the other hand, our results indicate that polarization diversity can substantially lower the subchannel correlations for compact configurations, even in a LOS scenario. We draw a fair comparison in terms of capacity, between spatial MIMO configurations and systems using polarization diversity. We analyze the performance of $2 \times 2$ and $4 \times 4$ MIMO configurations for a range of values of inter-element spacing.**

***Index Terms*— Polarization diversity, MIMO, dual-polarized antennas, inter-element spacing, indoor channels.**

## I. Introduction

Multiple-input multiple-output (MIMO) architecture has the potential to dramatically improve the performance of wireless systems. Much of the focus of research has been on uni-polarized spatial array configurations, which require an inter-element spacing of the order of $\lambda/2$ to achieve significant gains; even larger spacing is required for LOS channels as is shown in [1]. Such wide spacing would lead to impractical form factors for portable devices. Also, having multiple antennas separated far apart in space could complicate the physical design of devices. In this regard, polarization diversity presents an attractive alternative for realizing MIMO architectures in compact devices. Polarization diversity can be exploited by using the following configurations: (1) an array of dual-polarized elements, and (2) an array of spatially separated orthogonally polarized elements, which will be referred to as the hybrid configuration in this paper.

MIMO channels with polarization diversity cannot be modeled like pure spatial channels, because the subchannels of the MIMO channel matrix are not identically distributed [2]. They differ in terms of average received power, Ricean K-factor, cross-polar discrimination (XPD) and correlation properties. The aim of this paper is to investigate the performance of MIMO systems employing polarization diversity, in comparison with spatial configurations taking into account these differences in the channel structure. Indoor channel measurements with dual-polarized or hybrid array configurations have been reported in the literature [3]–[5]. However, all these measurement campaigns are restricted to a fixed array geometry, i.e. they do not take into account the spacing between the antenna elements at the transmitter and receiver. Since the main motivation behind using dual-polarized antennas is to achieve compactness, we note that inter-element spacing should be an important factor, while comparing spatial MIMO with dual-polarized/hybrid systems.

We report on an indoor channel measurement campaign conducted at 2.4 GHz using dual-polarized antennas. We analyze the measured data in terms of the Ricean K-factor, subchannel correlations and cross-polar discrimination (XPD). We highlight the differences between vertically polarized and horizontally polarized transmissions in the course of our analysis. An important contribution of this paper is that, our measurements indicate a coincidence of low K-factors and high XPD values. In such channels, MIMO configurations employing polarization diversity incur a diversity and an SNR loss when compared to spatial configurations. Using the measured capacity distributions, we draw a fair comparison between dual-polarized, hybrid and spatial array configurations. We consider $2 \times 2$ and $4 \times 4$ MIMO systems for a range of values of inter-element spacing, under LOS and NLOS channel conditions.

This paper is organized as follows: Section II presents the system model and section III describes the MIMO channel measurement process in detail. Section IV presents data analysis, in terms of K-factor, subchannel powers and correlation. Different array configurations are analyzed and compared in terms of achieved capacity in section V and finally section VI concludes the findings of this paper.

## II. System Model

The input-output relation for a narrowband MIMO channel with $n_t$ inputs and $n_r$ outputs can be expressed as:

$$\mathbf{r} = \sqrt{E_s}\mathbf{H}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{r}$ and $\mathbf{s}$ are the baseband complex received and transmitted vectors respectively. $\mathbf{n}$ represents the complex circular Gaussian

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noise vector with autocorrelation $R_{nn} = \sigma^2 \mathbf{I}_{\mathbf{n_r}}$. Here, $\mathbf{I}_{\mathbf{n_r}}$ is an identity matrix of size $n_r \times n_r$. $E_s$ denotes the transmit signal power on each input. $\mathbf{H} = [h_{ij}]$ is $n_r \times n_t$ channel transfer matrix with its entries $h_{ij}$ representing the complex subchannel gain between the $j$th input and the $i$th output.

For spatial MIMO configurations, all the subchannels of $\mathbf{H}$ are identically distributed. However, when antennas with different polarizations are employed, the properties of the co-polar subchannels differ significantly from those of the cross-polar subchannels. Hence for hybrid and dual-polarized MIMO configurations, the channel matrix can be conveniently written as:

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}^{VV}_{(n_r^V \times n_t^V)} & \mathbf{H}^{VH}_{(n_r^V \times n_t^H)} \\ \mathbf{H}^{HV}_{(n_r^H \times n_t^V)} & \mathbf{H}^{HH}_{(n_r^H \times n_t^H)} \end{bmatrix}_{(n_r \times n_t)} \tag{2}$$

Here $n_t^V, n_t^H$ are the number of vertically and horizontally polarized elements at the transmitter respectively. Similarly $n_r^V, n_r^H$ are the number of vertically and horizontally polarized elements at the receiver respectively. The elements of the submatrices $\mathbf{H}^{VV}$ and $\mathbf{H}^{HH}$ correspond to the co-polar subchannels in $\mathbf{H}$, while $\mathbf{H}^{VH}$ and $\mathbf{H}^{HV}$ correspond to the cross-polar subchannels.

## III. Measurement Process

### A. Measurement Equipment and Settings

The MIMO-channel measurement system that is illustrated in Figure 1, is composed of two parts: (1) the HP 85301B stepped-frequency antenna pattern measurement system, which, because of its coherent reference signal, can measure the channel frequency response directly, and (2) the actuator positioning system, which creates the virtual array by moving the antenna to arbitrary pre-programmed locations. Figure 2 shows one of the mobile platforms and one of the actuator positioning systems. There were two of the setups shown in Figure 2, one for each end of the MIMO channel. This virtual array approach has been validated in [6] and offers great flexibility to experiment with different antenna configurations. But it requires the environment to be kept still throughout the measurement process.

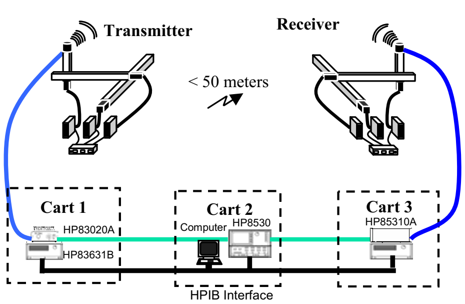


Fig. 1. MIMO channel measurement system

The antennas used at both ends were dual-polarized narrow-band antennas with a frequency range of 2.400 - 2.483 GHz (model number: SPDPG-4O-H2O, Superpass Company Inc.). The vertically and horizontally polarized elements differ in their antenna patterns [1]. A multi-channel controller HP 85330 and HP 85332 PIN switches were incorporated into the measurement system to measure the co-polar (VV and HH) and the cross-polar (VH and HV) channels successively. The transmitter (Tx) and the receiver (Rx) were kept at a height of 1.35 m. A virtual 50 element ($5 \times 5 \times 2$) cubicle array with a minimum inter-element spacing of $\lambda/2$, was used at both ends. Previous measurements in the same environment had indicated that the coherence bandwidth of the channel is about 15 MHz. Hence corresponding to each pair of transmit and receive antenna locations, we collected six uncorrelated channel samples in the frequency range of operation.

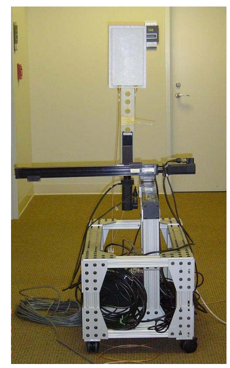

Fig. 2. Dual-polarized antenna mounted on the actuator system

### B. Measurement Scenario

The measurement campaign was conducted in the Georgia Centers for Advanced Telecommunication Technologies (GCATT) building in Atlanta, GA. The walls of the building are made of plasterboard with metal-studs in them. The ceiling and the floor are made of reinforced concrete. The LOS measurements were taken in the hallway on the fifth floor, which is lined by offices on one side and laboratories on the other as shown in Figure 3. The distance between the transmitter and the receiver was approximately 14 m in the LOS scenario. For the NLOS measurements the receiver array was moved into the adjoining laboratory and the door leading to it was closed.

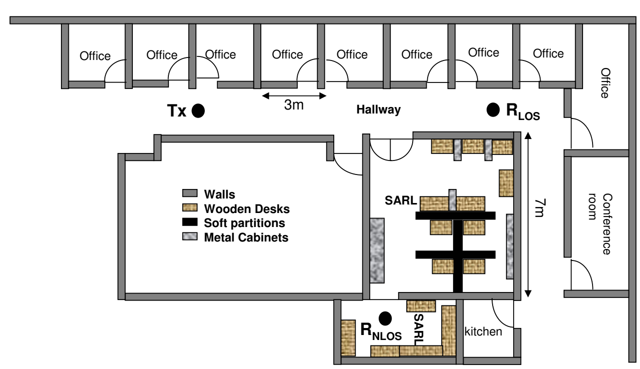


Fig. 3. Floor plan of the measurement location

[1] http://www.superpass.com/SPDPG-4O-H2O.html

## IV. Data Analysis

### A. Ricean K-factor

Under LOS channel conditions, the subchannels of $\mathbf{H}$ have a non-zero mean due to the presence of a direct component. For such channels, the envelope of the subchannel gains is well modeled by a Ricean distribution [7]. The Ricean factor ($K$), characterizes the Ricean distribution and is the ratio between the average powers of the deterministic and the random components of the channel. In the absence of any dominant paths, $K = 0$ and the Ricean distribution reduces to a Rayleigh distribution.

Using the channel samples collected, the K-factors for the co-polar and cross-polar subchannels were computed using the distribution fitting tool available in MATLAB. Under LOS channel conditions, as shown in Figure 4, it is observed that the co-polar subchannels follow a Ricean distribution, whereas the cross-polar subchannels follow a Rayleigh distribution. This is expected due to the fact that the cross-polar subchannel gains result from depolarization of the transmitted signal, which in turn is because of diffuse scattering and oblique reflections. Thus the subchannels of a MIMO channel employing polarization diversity are not identically distributed. In the hallway, the measured K-factors are 0.78 and 1.30 for VV and HH co-polar subchannels, respectively. Although counterintuitive, such low K-factors have been observed in previous measurements in the hallway environment [8], [9]. Under NLOS channel conditions, as expected all the subchannels follow a Rayleigh distribution.

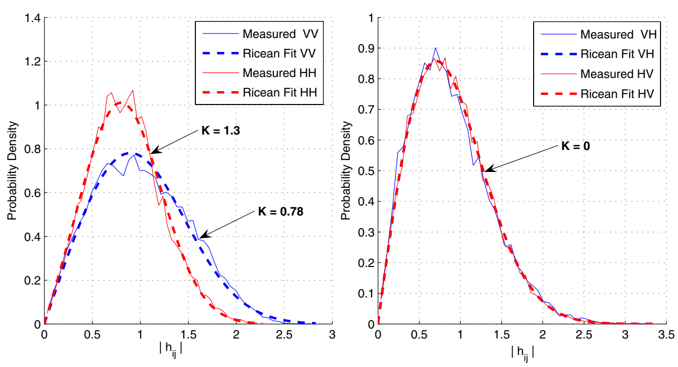


Fig. 4. Empirical PDFs of the envelopes of: a) co-polar subchannels b) cross-polar subchannels in the hallway

### B. Average Power and XPD

A vertically polarized antenna with good isolation properties can transmit and receive vertically polarized waves while suppressing horizontally polarized waves and vice versa. However, the transmitted radio signal as it traverses through the wireless channel undergoes multiple reflections and scattering resulting in a coupling into the orthogonal state of polarization. This phenomenon is referred to as depolarization and is a characteristic property of wireless channels. As a result the subchannels of the channel matrix differ in the average received power. We consider a $2 \times 2$ MIMO system using a dual-polarized antenna at both ends to study these power imbalances between the various subchannels. The channel matrix in (2) reduces to:

$$\mathbf{H} = \begin{bmatrix} h^{VV} & h^{VH} \\ h^{HV} & h^{HH} \end{bmatrix}. \tag{3}$$

Cross-polar discrimination (XPD), which is a measure of depolarization in a wireless channel is defined as:

$$\begin{aligned} X_V &= E\{|h^{VV}|^2\}/E\{|h^{HV}|^2\} \\ X_H &= E\{|h^{HH}|^2\}/E\{|h^{VH}|^2\} \end{aligned} \tag{4}$$

Most authors assume that $X_V \approx X_H$, but we note that this is not always true owing to the fact that depolarization not only depends on the environment, but also on the antenna patterns of the V and H elements [3]. The measured XPD values for both LOS and NLOS cases are tabulated in Table I. The XPD values in the LOS scenario are very high indicating very little cross-coupling between the orthogonal states of polarization. In the NLOS scenario, increased scattering results in a greater degree of depolarization. However, the XPD values in our NLOS scenario are not as low as the XPD values reported in [4], but values comparable to ours have been reported in [3].

TABLE I
Measured XPD values

| | $X_V$ | $X_H$ |
|---|---|---|
| LOS | 16.96 dB | 14.50 dB |
| NLOS | 8.58 dB | 8.29 dB |

The propagation characteristics of vertically polarized waves are significantly different from those of horizontally polarized waves [10]. It is observed from our measurements that $E\{|h^{VV}|^2\} > E\{|h^{HH}|^2\}$. This is because of the Brewster angle phenomenon for horizontally polarized transmission [10]. This power imbalance could also be attributed to the differences in the antenna pattern of vertically polarized and horizontally polarized elements. In the LOS scenario, the average received power on the VV subchannel is 1.6 dB greater than the HH subchannel. In the NLOS scenario this difference was found to be 2.2 dB.

As a result of these subchannel power losses, the average squared Frobenius norm, which represents the total energy in the channel, is diminished for dual-polarized MIMO channels. Furthermore, when the K-factor is low, the subchannel power losses would imply reduced degrees of diversity for these channels. For example, the available degrees of diversity for a $(n_r \times n_t)$ i.i.d. Rayleigh MIMO channel are $\eta_s = n_r n_t$ [7]. But for dual-polarized NLOS channels with a very high XPD, $\eta_p \approx n_r^V n_t^V + n_r^H n_t^H < \eta_s$. Thus MIMO systems employing polarization diversity incur SNR and diversity penalties, when compared to spatial configurations.

### C. Subchannel Correlations

The subchannel correlations effect the diversity performance of a MIMO channel [7], [11]. They depend on the scattering environment and the antenna configuration deployed at the transmitter and receiver. In this section we evaluate the subchannel correlations, for the measured spatial and dual-polarized/hybrid MIMO channels.

For a spatial MIMO channel, subchannel correlations are a strong function of the inter-element spacing at the transmitter and receiver. In order to analyze the impact of inter-element spacing on correlation, we consider a $2 \times 2$ uni-polarized spatial MIMO configuration. The spacing between the elements at the transmitter and the receiver is kept the same. We consider both vertically polarized and horizontally polarized spatial configurations. According to the Kronecker product model [12], under the assumption that all the antenna elements in a MIMO configuration have the same polarization and antenna pattern, the correlation between the elements at the transmitter can be considered independent of the receiver element chosen as the reference and vice versa. We have verified that this model is valid for our measurements. We can thus define the receive and transmit correlation coefficients as:

$$\begin{aligned} \rho_{i,j}^{R} &= <h_{i,m}, h_{j,m}> \\ \rho_{i,j}^{T} &= <h_{m,i}, h_{m,j}>, \end{aligned} \quad (5)$$

where $<a, b>$ is the power correlation coefficient between the complex random variables $a$ and $b$ and is defined as [12]:

$$<a, b>= \frac{E\left[|a|^2 \ |b|^2\right] - E\left[|a|^2\right]E\left[|b|^2\right]}{\sqrt{E\left[|a|^4 \ - \left(E\left[|a|^2\right]\right)^2\right]E\left[|b|^4 \ - \left(E\left[|b|^2\right]\right)^2\right]}}. \quad (6)$$

Shown in Figure 5 is the measured transmit and receive correlation values, for LOS and NLOS channel conditions, as a function of the inter-element spacing.

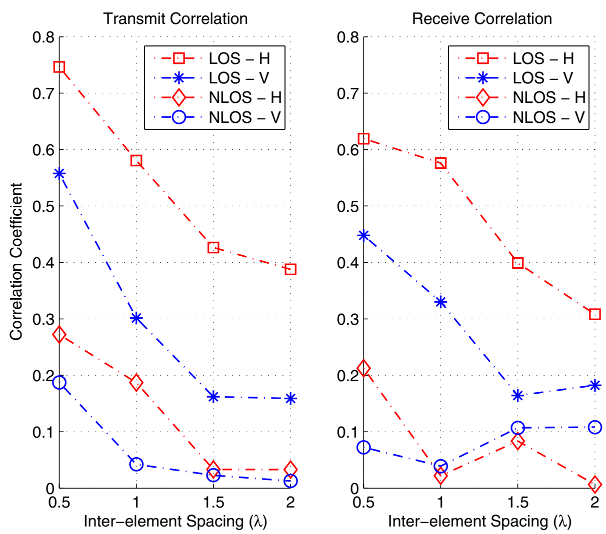


Fig. 5. Transmit and receive correlation for spatial MIMO in LOS and NLOS scenarios

The general trend suggests that increasing the spacing between the elements decorrelates the subchannels. An inter-element spacing of $d = 3\lambda/2$ is required to sufficiently decorrelate the subchannels in the LOS scenario and any further increase does not significantly decrease the correlation. As expected for NLOS scenarios, correlation values are significantly lower than their corresponding values in LOS. Although a definitive trend can be observed for transmit correlation in the NLOS scenario, there is no trend in the receive correlation values. This is because the transmitter is placed in the hallway, whereas the receiver is kept inside an adjoining laboratory where the angular spread is uniform.

We also note that the horizontally polarized spatial configuration achieves higher correlation values when compared to its vertically polarized counterpart for both LOS and NLOS scenarios. This could be attributed to the Brewster angle phenomenon, which results in a more narrow angular spread for horizontally polarized waves when compared to vertically polarized waves. Hence owing to the higher correlation values and the loss of power, there is no motivation to use horizontally polarized spatial MIMO configurations.

As noted above, increasing the inter-element spacing can improve the capacity of spatial MIMO channels in LOS scenarios. However this would lead to impractical form factors for portable devices. Hence a natural alternative would be to use dual-polarized configurations, which could use the additional dimension of polarization to sufficiently decorrelate the channel even for small inter-element spacing.

It should be noted that the Kronecker product model is not valid for dual-polarized configurations [13]. We have calculated the correlation between the elements of the channel matrix for $2 \times 2$ dual-polarized and hybrid configurations. The correlation values for these configurations were found to be significantly lower than their spatial counterparts, and were upper bounded by $0.25$ in LOS and $0.15$ in NLOS scenarios. Further, no definitive trend was observed, as the spacing between the V and H elements was increased. Thus a dual-polarized configuration with co-located antennas is sufficient to achieve low correlation values even in LOS scenarios.

## V. Capacity Analysis

In this section we compare the capacity obtained by dual-polarized/hybrid configurations with spatial systems for different values of inter-element spacing. We consider $2 \times 2$ and $4 \times 4$ MIMO configurations. On one hand, polarization diversity helps in dramatically reducing subchannel correlations for compact configurations in LOS scenarios. But on the other hand these systems suffer from subchannel power losses because of high XPD and horizontally polarized transmissions. When the K-factor is low, these subchannel power losses would imply reduced degrees of diversity, which negatively effects capacity. Thus both these opposing aspects need to be taken into consideration while evaluating MIMO channels in the presence of polarization diversity.

### A. Channel Normalization

In order to isolate the small scale characteristics of the channel from the effects of shadowing and path-loss in the measured channel samples, we need to normalize the measured channel matrix $\bar{\mathbf{H}} = [\bar{h}_{ij}]$ as $\mathbf{H} = \bar{\mathbf{H}}/N$. Then we can evaluate the capacity at different signal-to-noise ratios (SNR). The normalization factor $N$ is generally defined as [4]:

$$N = \left(\frac{1}{n_r n_t} \sum_i \sum_j E\{|\bar{h}_{ij}|^2\}\right)^{\frac{1}{2}} \quad (7)$$

For a spatial array configuration, this normalization would result in an average SISO SNR of unity on all the subchannels. On the other hand, hybrid or dual-polarized configurations suffer from subchannel power losses, which need to be accounted for in their capacity calculations. If the the normalization in (7) is used, the performance of these systems is overestimated. Thus in order to make a fair comparison with spatial configurations, we normalize the channel so as to achieve an average SISO SNR of unity on the elements of $\bar{\mathbf{H}}^{VV} = [\bar{h}_{ij}^{VV}]$. The normalization factor is calculated as:

$$N' = \left( \frac{1}{n_r^V n_t^V} \sum_i \sum_j E\{|\bar{h}_{ij}^{VV}|^2\} \right)^{\frac{1}{2}} \quad (8)$$

For a given reference SNR of $\rho$, the MIMO channel capacity can then be calculated as [4]:

$$C = \log_2(det(\mathbf{I}_{n_r} + \frac{\rho}{n_t}\mathbf{H}\mathbf{H}^H)), \quad (9)$$

### B. Capacity Results for $2 \times 2$ MIMO Channels

The measurement settings described in Section III provided us with enough uncorrelated channel samples to evaluate cumulative capacity distribution functions (CDF), for $2 \times 2$ spatial and hybrid MIMO systems with an inter-element spacing $d \in \{\lambda/2, \lambda, 3\lambda/2, 2\lambda\}$. Capacity CDFs are calculated as per (9) at $\rho = 20$ dB. The array configurations considered are illustrated in Figure 6. The capacity CDFs obtained under LOS and NLOS channel conditions are plotted in Figures 7 and 8 respectively.

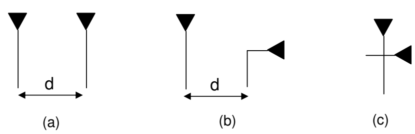


Fig. 6. $2 \times 2$ Array configurations (a) Spatial (b) Hybrid (c) Dual-polarized

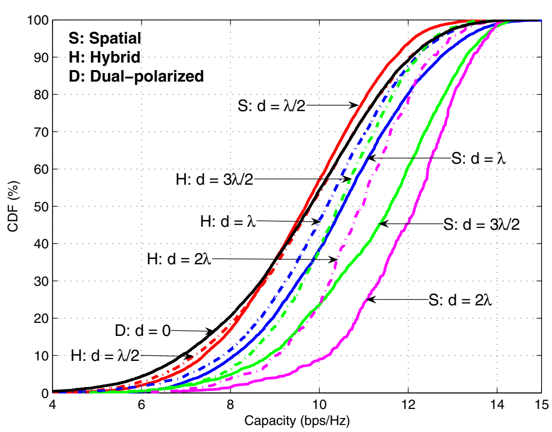


Fig. 7. Capacity CDFs for $2 \times 2$ LOS MIMO channels with different array configurations

Under LOS channel conditions, it is evident that as the inter-element spacing $d$ is made larger, the capacity of spatial and hybrid MIMO systems increases. This can be attributed to the decreasing subchannel correlation as observed in Figure 5 and to the spherical wavefront effects [1]. Comparing the various array configurations we can make the following observations:

- For $d = \lambda/2$, spatial and hybrid configurations achieve similar capacities. Furthermore, the dual-polarized configuration ($d = 0$), also performs equally well. We know from Section IV-C that for small inter-element spacing, polarization based configurations achieve much lower subchannel correlation when compared to the spatial system. As a result they achieve higher capacity, despite the loss in subchannel powers.
- For higher values of $d$, even the spatial systems achieve lower subchannel correlation. As a result they outperform the hybrid systems, owing to the subchannel power losses incurred by the latter configuration.

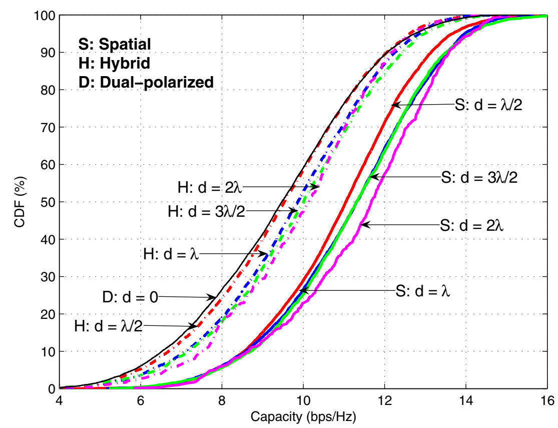


Fig. 8. Capacity CDFs for $2 \times 2$ NLOS MIMO channels with different array configurations

Under NLOS channel conditions, as seen in Figure 5, the correlation between the subchannels is low even for an inter-element spacing of $\lambda/2$. Hence the capacity does not significantly increase, as the spacing between the antenna elements is increased for both spatial and hybrid configurations. From our measurements, the correlation values for dual-polarized/hybrid configurations are also very low. But these systems suffer from subchannel power losses because of high XPD values and horizontally polarized transmissions. Thus in NLOS scenarios with limited depolarization, dual-polarized and hybrid configurations achieve lower capacities when compared to their spatial counterparts.

### C. Capacity Results for $4 \times 4$ MIMO Channels

With our measurement settings, we are limited to $d = \lambda/2$, when evaluating $4\times4$ spatial and hybrid MIMO systems. We consider dual-polarized configurations with $d \in \{\lambda/2, \lambda, 3\lambda/2, 2\lambda\}$. Note that a $4 \times 4$ dual-polarized configuration can be considered as a special case of the hybrid configuration. Figures 10 and 11 depict the measured capacity CDFs under LOS and NLOS channel conditions respectively.

As expected, for all configurations, the $4 \times 4$ systems achieve higher capacity when compared to their corresponding $2 \times 2$

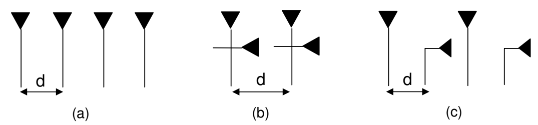


Fig. 9. $4 \times 4$ Array configurations (a) Spatial (b) Dual-polarized (c) Hybrid

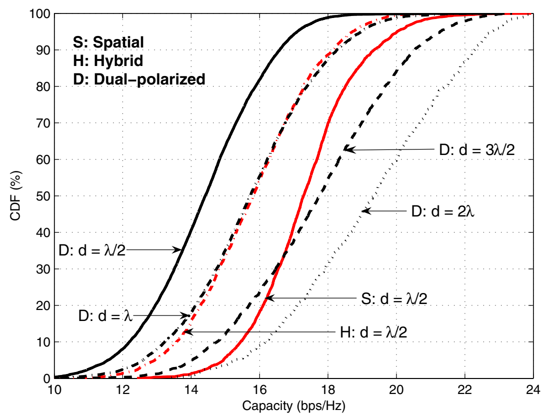


Fig. 10. Capacity CDFs for $4 \times 4$ LOS MIMO channels with different array configurations

counterparts. Further in the LOS channel, as observed with $2 \times 2$ systems, an increase in $d$ improves the capacity significantly. The following observations can be made:

- The spatial configuration performs better than the hybrid configuration owing to the loss in subchannel powers in the latter case.
- For the dual-polarized configuration the performance improves by increasing the inter-element spacing. This is because of the decreasing correlation between the elements of the co-polar submatrices. Further for $d = 3\lambda/2$, dual-polarized configuration performs slightly better than the spatial configuration with the same array length.

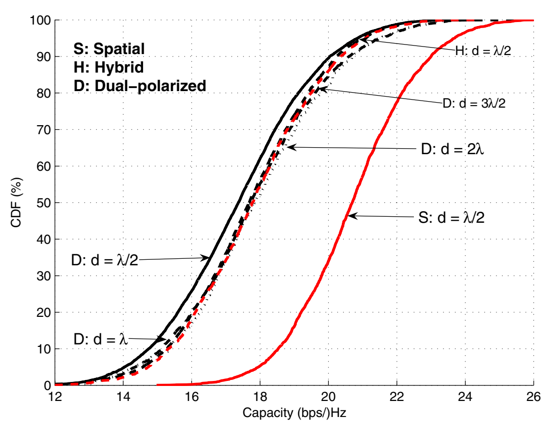


Fig. 11. Capacity CDFs for $4 \times 4$ NLOS MIMO channels with different array configurations

In the NLOS scenario, the capacity does not scale linearly with $d$. As for the 2x2 channels, the spatial system significantly outperforms both hybrid and dual-polarized configurations, once again owing to the subchannel power losses for the latter configurations.

## VI. Conclusion

We have analyzed MIMO systems under LOS and NLOS conditions in indoor environments, based upon the co-polar and the cross-polar channel measurements taken at 2.4 GHz in the GCATT Building in Atlanta, GA. We have characterized the measured channels in terms of Ricean K-factors, subchannel correlations and XPD. We have observed the coincidence of low K-factors and high XPD values in our measurements. For such scenarios, MIMO configurations employing polarization diversity incur a loss in SNR and diversity, when compared to spatial configurations. We have drawn a fair comparison in terms of capacity between spatial MIMO configurations and systems employing polarization diversity. Our results indicate that when space is not a constraint, spatial configurations should be preferred over dual-polarized or hybrid, especially in scenarios with low K-factors and high XPD.

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