Tri-polarized MIMO systems in real-world channels: channel investigation and performance analysis

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Abstract

Polarized multi-antenna systems are an effective solution for reducing inter-antenna spacing while still maintaining low inter-antenna correlation. Traditionally, only dual-polarized antenna systems are used for polarized transceivers. In this paper, tri-polarized antenna systems are investigated. Starting from the polarization mechanisms in the wireless propagation channel, it is shown that dual-polarized MIMO systems show high sensitivity to the transmitter and receiver orientation. Tri-polarized MIMO systems are introduced as a solution to obtain a robust MIMO performances, which are independent of the transmitter and receiver orientation. The performances of dual- and tri-polarized MIMO systems are evaluated on real-world measured channels, and the limits of each of these systems is highlighted.

Keywords: wireless, propagation, MIMO, polarization

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1. Introduction

By using multiple antennas at the transmitter and at the receiver, Multiple-Input Multiple-Output (MIMO) systems are able to exploit spatial diversity induced by the multi-path environment, increasing data rates and improving quality of wireless transmission [1, 2]. One major issue with classical MIMO systems is that the inter-antenna spacing has to be sufficiently large to have low inter-antenna correlation, which limits the number of antennas that one can place on a mobile terminal. Polarized MIMO systems use co-located perpendicular antennas, thereby obtaining low inter-antenna correlation while maintaining compact equipment size. Despite the fact that the electromagnetic medium is fundamentally polarization-sensitive, the design of MIMO system did not take polarization into account. Early work on dual-polarized MIMO systems was performed by Vaughan in [3]. As a result, a lot of subsequent work focused on the modeling, performances and design of dual-polarized MIMO systems [4, 5, 6, 7]. The idea of using all three components of the electrical field was proposed in [8], where it was shown that in theory it is possible to triple the data rate by using tri-polarized antennas. Several paper focused on the design and the modeling of tri-polarized MIMO systems [9, 10, 11]. However, most of these paper focus on particular scenarios (anechoic chamber, static environments etc.), and to the best of the author's knowledge, no results have been published to assess the performances of tri-polarized MIMO systems in realistic situations. The aim of this paper is to investigate the evaluate the benefits and feasibility of tri-polarized MIMO system in realistic indoor environments, based on the particular characteristics of the tri-polarized MIMO channel. The paper is organized as follows: Section 2 describes the fundamental characteristics of polarized MIMO channels, and addresses the limits of dual-polarized MIMO systems. Section 3 presents a tri-polarized MIMO measurement campaign, and investigates the differences between dual-polarized and tri-polarized MIMO systems. Finally, Section 4 evaluates the benefits of tri-polarized MIMO systems and compares these ben-

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efits with traditional dual-polarized MIMO systems.

2. Polarized MIMO channels

Wireless channels can be described with their complex baseband transfer function $H(f,\tau)$, where f represents baseband frequency and τ represents the propagation delay. The inverse Fourier transform of $H(f,\tau)$ yields the impulse response $h(\tau,t)$ of the channel. For a narrowband system, only one frequency is considered ant the impulse response reduces to $h(t)$. A MIMO channel is then described with the $N_r \times N_t$ MIMO channel matrix $\mathbf{H}(\tau,t)$. Each element $h_{ij}(\tau,t)$ of $\mathbf{H}(\tau,t)$ represents the channel from transmitter j to receiver i at propagation delay τ and time instant t.

2.1. Polarization mechanisms

Let's consider a dual-polarized MIMO system with a vertical and a horizontal antenna at the transmitter and at the receiver. When the vertical antenna transmits, most of its power will be transmitted to the vertical receive antenna. However, some of its power will leak to the horizontal receive antenna. The same holds when the horizontal antenna is used as a transmitter. This leakage is mainly caused by three mechanisms: antenna polarization, antenna orientation and channel depolarization. Each of these three mechanisms will be detailed in the following subsections.

2.1.1. Antenna polarization

Most antennas are designed to capture a given polarization. Nevertheless, no matter how well designed the antenna is, it will always capture some of the perpendicular polarization. This phenomenon, well-known by antenna designers, can be characterized by the antenna's *polarized radiation pattern* [12]. Figure 1 shows a polarized radiation pattern of three perpendicularly-oriented short linear antennas. The upper subfigures shows in how much power is transmitted in the θ-polarization for each direction, the lower subfigures show how much power is transmitted in the ϕ-polarization for each direction. It can be observed that for a vertical antenna, the doughnut-shape radiation pattern is obtained for the θ-polarization, while only low power is transmitted on the ϕ-polarization. For the horizontal antennas, it can be observed that the antenna transmits most power on the ϕ-polarization, but in some directions the antenna will also transmit power on the θ-polarization.

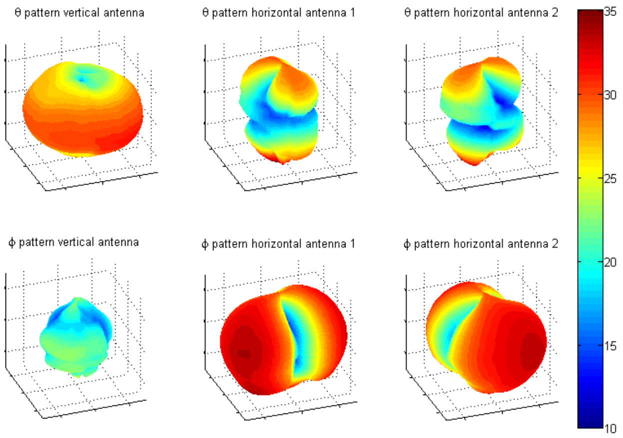

Figure 1: Polarized radiation patterns for three perpendicularly-oriented short linear antennas.

2.1.2. Antenna orientation

The effect of antenna orientation is very intuitive: when a vertical antenna is rotated, it will start transmitting on the ϕ-polarization as well. When an antenna is rotated, the polarized radiation pattern of the antenna changes. Some of the gain of the θ-polarization will be moved to the ϕ-polarization and vice-versa. For a half-wavelength dipole antenna, the polarized radiation pattern is given by [13, 14]

$$F^{\theta}(\varphi,\vartheta) = \left|(\cos\vartheta\cos\varphi\sin\gamma - \sin\vartheta\cos\gamma)\frac{\cos(\pi\zeta/2)}{1-\zeta^2}\right| \tag{1}$$

$$F^{\phi}(\varphi,\vartheta) = \left|\sin\varphi\sin\gamma\frac{\cos(\pi\zeta/2)}{1-\zeta^2}\right| \tag{2}$$

where $\zeta = \sin\vartheta\cos\varphi\sin\gamma + \cos\theta\cos\gamma$.
In these equations, φ and ϑ represent the azimuth and co-elevation in spherical coordinates respectively, and γ represent the inclination of the antenna in the yz-plane. It can be noted that for a vertical antenna ($\gamma = 0$), the ϕ-component of

the polarized radiation pattern is zero and the θ-component of the radiation pattern results in the doughnut-shape radiation pattern.

2.1.3. Channel depolarization

When multipath components (MPCs) interact with their environment, the polarization of the MPCs change. This can be taken into account by considering the MPC cross-polarization matrix [15], which determines the amount of leakage between the different polarizations of the MPCs:

$$\begin{bmatrix} \alpha_\theta^{(2)} \\ \alpha_\phi^{(2)} \end{bmatrix} = \begin{bmatrix} \gamma_{\theta\theta} & \gamma_{\theta\phi} \\ \gamma_{\phi\theta} & \gamma_{\phi\phi} \end{bmatrix} \begin{bmatrix} \alpha_\theta^{(1)} \\ \alpha_\phi^{(1)} \end{bmatrix} \tag{3}$$

where $\alpha_\theta^{(1)}$ and $\alpha_\phi^{(1)}$ are the baseband complex amplitudes of the θ- and ϕ-components of the MPC before interaction with the environment, $\alpha_\theta^{(2)}$ and $\alpha_\phi^{(2)}$ are the baseband complex amplitude of the θ- and ϕ-components of the MPC after interaction with the environment, and matrix $\boldsymbol{\gamma}$ is the MPC cross-polarization matrix.

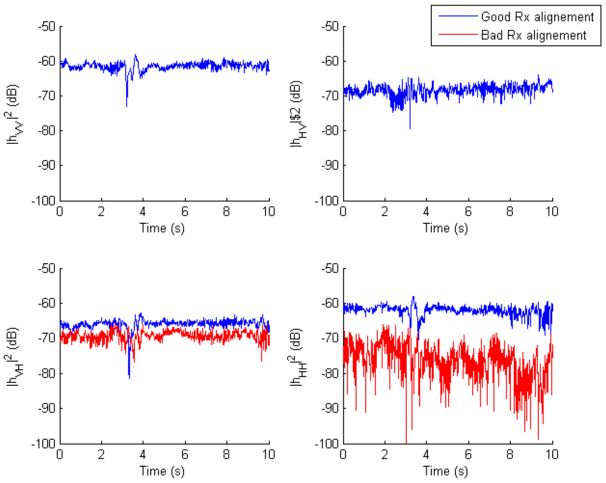

Figure 2: Four channels of a dual-polarized MIMO system. The blue curves are the case with a good relative orientation of Tx and Rx, the red curves are a case with a receiver is rotated 90° around the vertical axis.

2.2. Dual- and tri-polarized MIMO systems

Dual-polarized MIMO systems have gained lots of attention in literature. Several stochastic channel models have been developed for dual-polarized MIMO systems [4, 5, 6, 7], and signal processing techniques specific to dual-polarized MIMO systems have also been developed [16, 17]. One major drawback of dual-polarized MIMO systems is the antenna system misalignment of dual-polarized MIMO systems, which causes the signal power of certain links to drop drastically. The measurement in Figure 2 shows the power of the four channels of a dual-polarized MIMO channel with a vertical-horizontal transmitter and a vertical-horizontal receiver. The blue curves represent the case where transmitter and receiver have a good relative orientation, and the red curves represent the case with a receiver rotated by 90° in the azimuth plane (around the axis of the vertical receive antenna). Fist, looking at the blue curves, it can be observed that the co-polar channels (h_{VV} and h_{HH}) have higher power than the crossed channels (h_{HV} and h_{VH}), due to the mechanisms explained before. When considering a rotated receiver, it can be seen that the power the HH-channel drops drastically. This is due to a change in the radiation pattern: the nulls of the horizontal receiving antenna are now pointing towards the main direction of arrival of the MPCs, which causes a serious drop in the received power signal level. This drop in received power will result in a significant mutual information loss [1], as can be seen in Figure 3. The mutual information of a MIMO system is in this case defined as:

$$MI\left(t\right) = \log_2 \left\{ \det \left(\mathbf{I}_{n_t} + \frac{\rho}{n_t} \mathbf{H}_n\left(t\right) \mathbf{H}_n^H\left(t\right) \right) \right\} \tag{4}$$

where n_t is the number of transmit antennas, ρ is the receive SNR, set to 10 dB in this case and $\mathbf{H}_n\left(t\right)$ is the time-variant normalized channel matrix. In conclusion, it can be seen that dual-polarized systems are very sensitive to the relative transmitter-receiver orientation. One way to have more reliable communications over polarized MIMO channels is to use tri-polarized transmitters and receivers. A tri-polarized transceiver is composed of three perpendicularly polarized antennas (a compact realization of tri-polarized antennas has been presented in [9]). Intuitively, it

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[1] note that the term "capacity" is often used to describe the mutual information in literature

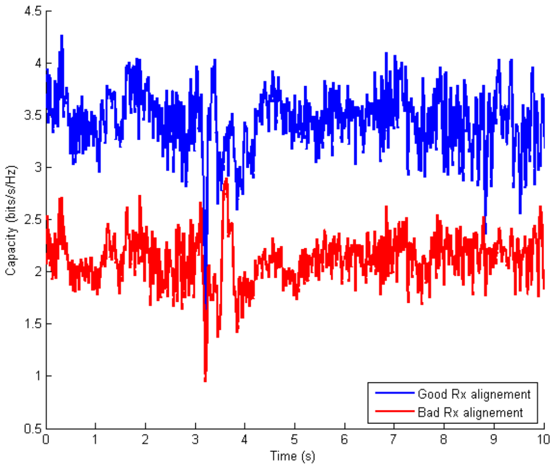

Figure 3: Difference in mutual information when considering a well-aligned and a poorly-aligned dual-polarized MIMO system.

can be understood that tri-polarized MIMO systems will not present a great capacity improvement compared to a well-aligned dual-polarized system. However, when rotating the transmitter or the receiver, the performances of a tri-polarized MIMO system will not drop as in the case of a dual-polarized MIMO system: if one antenna of the tri-polarized system receives less power, another antenna of the tri-polarized system will see its received power increase.

3. Polarized channel measurements

3.1. Measurement setup

A measurement campaign has been performed using the ULB/UCL Elektrobit MIMO channel sounder to measure tri-polarized MIMO channels. The working frequency was 3.6 GHz with a 100 MHz bandwidth. The transmitter and receiver unit of the sounder were connected using a 32-meter N-cable, to run the sounder on a unique clock to avoid phase drift. Both the transmitter and the receiver were tri-polarized antennas, composed of three perpendicular short linear antennas (in the rest of the paper, antenna 1 will stand for the vertical antenna, and antennas 2 and 3 will stand for the two perpendicular horizontal antennas). Each cycle recorded the complete 3×3 channel matrix. The channel sample rate was 291.212 Hz and a total of 30000 cycles were recorded (a little over 100 s recording time). Three cases corresponding to three different usages were considered:

- static receiver and static transmitter, with people moving in between (SS),
- static receiver and transmitter moving in a local area (SSmSc),
- static receiver and transmitter moving along a route (SR).

When moving the receiver, the vertical antenna stays vertical, while the antenna may be rotated in the azimuth plane to simulate a realistic user movement. The measurements were performed in three scenarios, shown in Figure 4:

- Corridor-2-Office (C20): the transmitter was moving in an office room (between 11 and 24 m^2) and the receiver remained static in the corridor.
- Corridor-2-Lab (C2L): the transmitter was moving in a meeting room (between 25 and 75 m^2) and the receiver remained static in the corridor.
- Corridor-2-Corridor (C2C): the transmitter was moving in a corridor and the receiver remained static in the corridor.

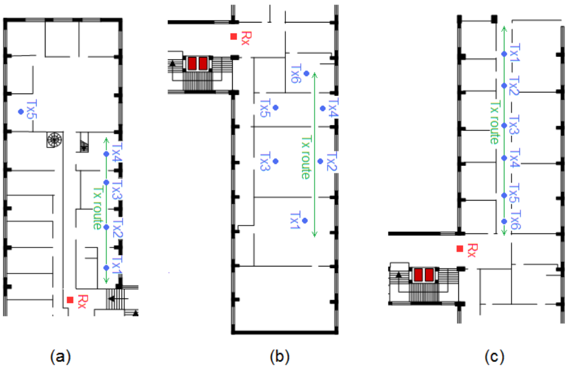

Figure 4: Floor plan of the measurements for (a) C2O scenario (b) C2L scenario and (c) C2C scenario. The square represents the receiver location, the dots and line the transmitter locations and route, respectively.

The measured impulse responses were averaged over 3 successive impulse responses to increase the measurement SNR, yielding a final channel sampling rate of 97.07 Hz. Finally, the narrowband MIMO matrices were obtained by summing the wideband impulse responses in the delay domain. These narrowband MIMO matrices will be used in the further data treatment.

3.2. Channel characteristics

The main parameter of cross-polarized MIMO system is the channel cross-polarization discrimination (XPD), which is defined as the power ratio of the different elements of the channel matrix:

$$\mathrm{XPD}_{XY/WZ} = \frac{\mathcal{E}\{|h_{XY}|^2\}}{\mathcal{E}\{|h_{WZ}|^2\}} \qquad (5)$$

where $\mathcal{E}\{X\}$ is an averaging operator over a stationarity interval. In the case of tri-polarized MIMO systems, 8 different XPDs are needed to fully characterize the polarimetric behavior of the channel. These 8 XPDs can be defined in several ways. Figure 5 presents the histogram of the measured channel XPDs for a receiver moving in a local area. The stationarity interval estimation was estimated using variographic analysis, as explained in [18]. The positive XPDs (in dB) show that the vertical-to-vertical channels are higher than the horizontal-to-vertical channels, and that the horizontal-to-horizontal channels are higher than the horizontal-to-vertical channels. The horizontal-to-horizontal channels $\mathrm{XPD}_{22/32}$ and $\mathrm{XPD}_{33/23}$ may however exhibit negative XPD (in dB), depending on the relative orientation of the transmitter and the receiver. The statistics over all measurements of the XPDs (averaged over each measurement) are shown in Table 1.

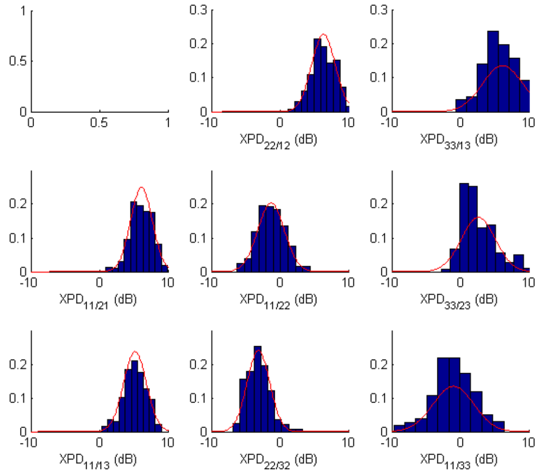

Figure 5: Measured XPDs for a receiver moving in a local area. Antenna 1 is the vertical antenna and antennas 2 and 3 are the horizontal antennas.

Table 1: Measured average XPDs statistcs in the SS- and SSmSc-case. Antenna 1 is the vertical antenna and antennas 2 and 3 are the horizontal antennas.

	SS		**SSmSc**	
	Mean	Std	Mean	Std
$\langle \mathrm{XPD}_{11/21} \rangle$ (dB)	4.29	3.29	4.28	2.30
$\langle \mathrm{XPD}_{11/31} \rangle$ (dB)	3.67	2.90	3.74	1.72
$\langle \mathrm{XPD}_{22/12} \rangle$ (dB)	3.64	4.72	3.59	1.83
$\langle \mathrm{XPD}_{22/32} \rangle$ (dB)	-2.50	6.45	-2.10	3.09
$\langle \mathrm{XPD}_{33/13} \rangle$ (dB)	6.05	6.00	6.01	2.27
$\langle \mathrm{XPD}_{33/23} \rangle$ (dB)	2.73	4.51	1.91	3.17
$\langle \mathrm{XPD}_{11/22} \rangle$ (dB)	0.82	5.35	0.09	1.96
$\langle \mathrm{XPD}_{11/33} \rangle$ (dB)	-1.43	5.71	-1.73	2.83

The correlation coefficients between all channels have been measured, and as expected from a polarized MIMO system, the correlations are very low. An example is given in Figure 6. The somewhat higher correlation coefficients are the ones of the horizontal channels: the antennas of these channels have overlapping radiation patterns, and will therefore have some common MPCs, which will increase the correlation coefficients. Nevertheless, for all measurements, the correlation coefficients are all below 0.5 and can be neglected.

4. Tri-polarized MIMO systems robustness evaluation

The channel properties described in Section 3 will have an important impact on the performances of communication schemes. In this section, the performances of dual- and tri-polarized communication systems will be compared by using three metrics: mutual information, Demmel condition number and ellipticity. Each of these

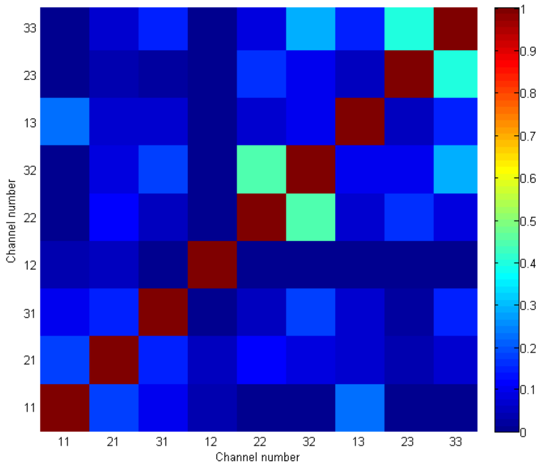

Figure 6: Measured correlation coefficients for a receiver moving in a local area. The x-label indicates channel ij with transmitter j and receiver i, the y-label indicates channel kl with transmitter l and receiver k, and the color indicates the correlation between h_{ij} and h_{kl}. Antenna 1 is the vertical antenna and antennas 2 and 3 are the horizontal antennas.

metrics will be explained and their importance in the context of polarized communications will be highlighted, and each of these metrics will be evaluated on the real-world measured channels of Section 3. Finally, the specificities of tri-polarized communications will be discussed.

In the following the measured 3×3 channel matrices are normalized to constant transmit power for the evaluation of all metrics [19]:

$$\mathbf{H}_n\left(t\right) = \frac{1}{\frac{1}{T}\sum_{t=1}^{T}\left\|\mathbf{H}\left(t\right)\right\|_F^2}\mathbf{H}\left(t\right) \qquad (6)$$

where T represents the total number of time samples of one measurement. When using 2×2 channel matrices in the following, 2 rows and 2 columns of $\mathbf{H}_n\left(t\right)$ are selected. For the SISO cases, one element of $\mathbf{H}_n\left(t\right)$ is selected.

4.1. Mutual information

The mutual information (MI), defined in (4), defines the upper bound of information that can reliably be transmitted over a noisy communication channel. It shows how much information (in bits/s/Hz) can be transmitted over the MIMO channel for a given SNR. It has been shown previously for co-polar systems, where all elements of the channel matrix have equal power, that correlation is detrimental to the mutual information [20]. It has also been observed that a dual-polarized system will perform worse than a co-polar 2×2 system, due to the power loss on the anti-diagonal elements of the channel matrix [16]. The MI is thus sensitive to inter-channel correlation and to channel powers. In the case of polarized MIMO systems, low correlation is obtained at the price of reduced power on the crossed channels.

The cumulative distribution function (CDF) of the MI has been computed for each measurement presented in Section 3, for a SISO system, a dual-polarized MIMO system and a tri-polarized MIMO system. When considering SISO and dual-polarized system, the MI for all possible combination of antennas has been computed. This permits to have best and worse case scenarios (cases with good antenna alignment and bad antenna alignment). Figure 7 shows the areas in which the CDFs of the MI are located. All MI CDFs of the SISO system are located in the green area, all the MI CDFs of the dual-polarized MIMO system are located in the red area, and all the MI CDFs of the tri-polarized MIMO system are located in the blue area. Several conclusions can

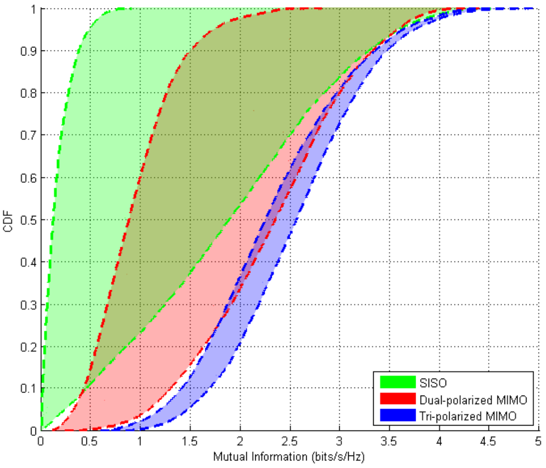

Figure 7: Mutual information CDFs for a SISO, dual-polarized MIMO and tri-polarized MIMO system in the SSmSc-case.

be drawn from Figure 7. First, it can be seen that the MI CDF of a SISO system and dual-polarized MIMO system varies greatly, while the MI CDF of a tri-polarized MIMO system remains fairly constant. This is due to the fact that SISO and dual-polarized MIMO systems may have very good Tx-Rx alignment, but can also have very bad Tx-Rx alignment. In consequence, the performances of the SISO and dual-polarized MIMO systems may show big differences from case to case. The tri-polarized MIMO system has performances which are independent of the Tx-Rx alignment: if the Tx or Rx is rotated, one antenna may receive less power, but another antenna will receive more power. A second conclusion is that the MI of the tri-polarized system is not significantly higher that the best achievable MI of a dual-polarized system. This means that a tri-polarized system will have similar performances than a dual-polarized system with optimal Tx-Rx alignment. Section 4.4 will discuss an architecture with a tri-polarized antenna system and dual-feeds to benefit from the advantages of tri-polarized MIMO while maintaining a low RF design complexity.

4.2. Demmel condition number

The Demmel condition number κ_D was first introduced in [21] to validate experimental channel models. It is defined as:

$$\kappa_D = \frac{\|\mathbf{H}_n\|_F}{\sigma_{\min}(\mathbf{H}_n)} \tag{7}$$

where $\sigma_{\min}(\mathbf{H}_n)$ is the smallest singular value of matrix $\mathbf{H}_n$. It was shown in [22] that if the Demmel condition number is below a certain threshold, the channel is more suitable for spatial multiplexing than for diversity transmission. The threshold is defined by the Euclidian distance between the space-time codewords of the diversity scheme and the Euclidian distance between the different received space-time codewords when using spatial multiplexing [22]. For a dual-polarized MIMO system, the fact that the system will use spatial multiplexing or diversity transmission depends on the XPD of the channel. Channel with high XPD will be more suitable for multiplexing, and channel with low XPD will be more suitable for diversity transmission. Therefore, the Demmel condition number can be considered as a very fundamental metric for polarized communication systems. Figure 8 shows the bounds for the CDFs of κ_D for the SISO, dual-polarized MIMO and tri-polarized MIMO measurements. It can be observed that the dual-polarized MIMO system has a lower κ_D, and is thus more suitable for spatial multiplexing. However, the variation of the CDF of κ_D is lower for tri-polarized systems than for dual-polarized systems, showing that tri-polarized system benefit from higher stability.

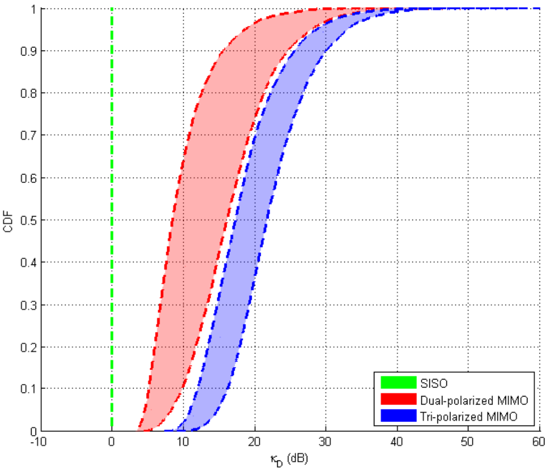

Figure 8: Demmel condition number CDFs for a SISO, dual-polarized MIMO and tri-polarized MIMO system in the SSmSc-case.

4.3. Ellipticity

The ellipticity of a MIMO channel was introduced in [23] and is defined as:

$$\log(\gamma) = \log\left[\frac{\left(\prod_{i=1}^{N}\sigma_i\right)^{1/N}}{\frac{1}{N}\sum_{i=1}^{N}\sigma_i}\right] \tag{8}$$

where $N = \min(n_r, n_t)$ and σ_i are the singular values of the MIMO channel matrix. This metric indicates the information loss of the channel compared to a purely diagonal channel due to the singular value dispersion. Therefore, $\log_2(\gamma)$ is always negative and gives the information loss in bits. The closer $\log(\gamma)$ is to zero, the lower the loss compared to a diagonal channel. If all eigenvalues are equal, then $\log(\gamma) = 0$. This metric has the advantage of being independent of SNR and dynamic range (as long as the singular values can be estimated accurately). Compared to other validation metrics (such as the Demmel condition number), it has the great advantage of including all the singular values of the channel [23]. Therefore, it is a good validation metric to estimate the spatial multiplexing capability of a channel, and thus a natural measure of multipath richness. For a dual-polarized MIMO system, this metric indicates the loss compared to a dual-polarized MIMO system with infinite XPD.

Figure 9 shows the bounds for the ellipticity CDFs of a dual- and tri-polarized MIMO system. The ellipticity of a tri-polarized system is slightly lower than for a dual-polarized system. This is due to the four horizontal-to-horizontal channel in a tri-polarized system, which do not *per se* have a diagonal structure, but may have very similar powers. Again, it can be observed that the CDF region is smaller for tri-polarized systems, and thus have higher stability.

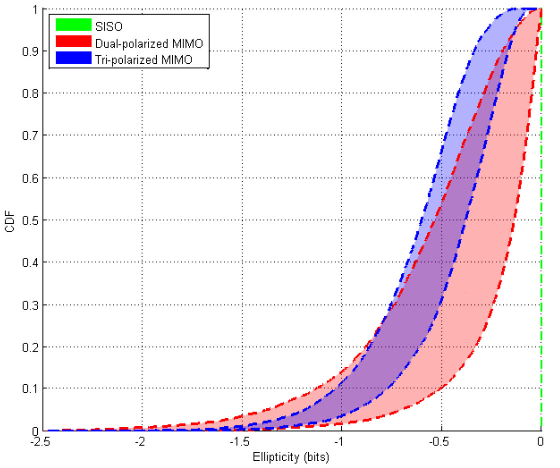

Figure 9: Ellipticity CDFs for a SISO, dual-polarized MIMO and tri-polarized MIMO system in the SSmSc-case.

4.4. Overview of tri-polarized MIMO system performances

From Figures 7-9, it can be concluded that the performance improvement of tri-polarized systems compared to dual-polarized systems is quite limited. However, the performances of dual-polarized systems are very unstable: if the transmitter and receiver are badly aligned, the performances will become very bad. Tri-polarized systems are much more stable, the performances of the system stay fairly constant, independently of the Tx-Rx alignment.

This renders the idea of using antenna selection [24, 25] to reduce the cost of the hardware associated with each additional antenna. In antenna selection, only a sub-set of the available antennas is used for the communication. This permits to reduce the number of RF chains that has to be implemented in the hardware. In the case of tri-polarized communications, it is sufficient to select two out of the three antennas as shown in Figure 10, limiting the number of RF chains to two. The algorithm to decide which antenna are selected depends on the signaling scheme, the transmitter and receiver architecture and the available knowledge at the transmitter. However, given that the main problem of dual-polarized systems is the SNR of certain channels at the channel matrix, a fairly simple solution is to select two out of the three antennas at the transmitter and at the receiver that contribute to the four most powerful channels of the 3×3 $\mathbf{H}$-matrix. Figure 11 shows the mutual information of a dual-RF tri-polarized transmission system. At each instant, the two

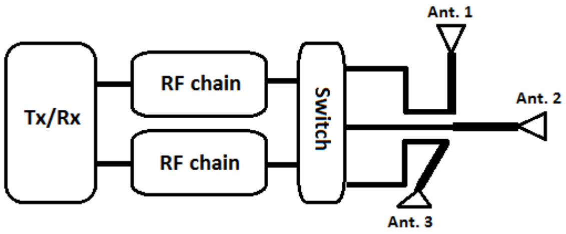

Figure 10: Schematic of a dual-RF chain, tri-polarized transceiver.

transmit and the two receive antennas who contribute to the four most powerful channels of the **H**-matrix are selected. It can be seen that the performances of such a system are almost as good as the performances of a tri-polarized antenna system, but with a significantly reduced hardware implementation.

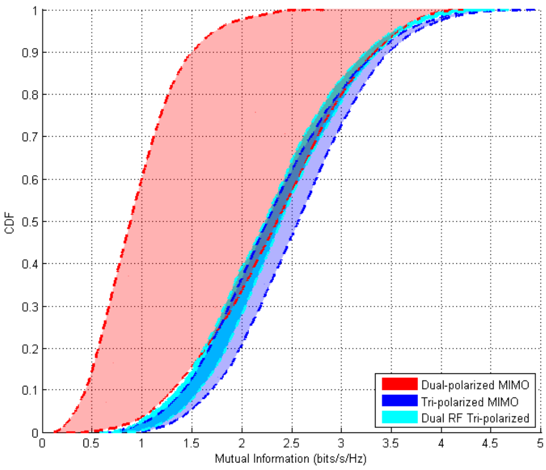

Figure 11: Mutual information CDF of a dual-RF chain, tri-polarized system for the SSmSc-case.

5. Conclusions

Tri-polarized MIMO systems were analyzed in this paper. An overview of the different polarization mechanisms was presented, and the robustness issues of dual-polarized MIMO systems with respect to the transmitter-receiver alignment was presented. It is observed that when the transmitter and the receiver of a dual-polarized MIMO system are not well oriented, the performances of the system tend to break down. The idea of using tri-polarized MIMO systems to improve the robustness of polarized MIMO was proposed. First, the channel characteristics of tri-polarized MIMO systems were investigated. All cross-polarization ratio were measured and presented in several indoor environments. The correlation coefficients between all channels was also measured, and observed to be low. A performance evaluation of tri-polarized MIMO systems was presented. It was observed that the capacity tri-polarized MIMO system is not much higher than conventional dual-polarized MIMO systems, but that the reliability and the robustness of the performances was much more stable in the case of tri-polarized MIMO. From the Demmel condition number and ellipticity it could be concluded that dual-polarized MIMO are more suitable for spatial multiplexing, while tri-polarized MIMO might need space-time coding to perform well. Finally, a simplified architecture with antenna selection was proposed. It was observed that this system performs almost as well as a full tri-polarized system, but with only two RF chains instead of three, which substantially simplifies the front-end design.

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