Investigation of Polarization Deficiencies in SIMO Systems in Random-LOS Propagation Channels

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***Abstract*—We study the probability of detecting the bitstream of a 2×1 SIMO polarization-diversity system with co-located orthogonally polarized antenna ports on the receiving side of a free-space propagation environment with arbitrary angle-of-arrival, i.e., in so-called Random-Line-Of-Sight (Random-LOS) propagation environments. We show how the diversity gain degrades in directions where the two orthogonal ports have non-orthogonal far-field functions or an amplitude imbalance. We also show that the system performance is better when one side of the link is circularly polarized and the other side is linearly polarized.**

I. Introduction

MIMO (Multiple-Input Multiple-Output) algorithms can improve the throughput performance of a communication system by using the independent fading measured at two orthogonal receiving antenna ports, referred to as polarization diversity [1]. The present paper investigates the polarization diversity in environments where there is no multipath. The received signal is then entirely determined by a pure Line-Of-Sight (LOS) contribution with an arbitrary polarization and angle-of-arrival (AoA), i.e., a random-LOS environment. The term Random-LOS has been introduced to describe such a new representative OTA test scenario [2], [3].

In general, the Over-The-Air (OTA) testing of wireless devices can be performed in both anechoic chambers (with absorbers on the walls) and reverberation chambers (with reflecting walls) [4], [5]. The reverberation chamber emulates a Rich Isotropic Multi-Path (RIMP) environment [5], and is suitable for environments with a lot of scatterers, such as indoor and urban environments. The complementing pure LOS environment can be reproduced in the well-known anechoic chamber that has been used for decades for testing the performance of antennas for fixed installations. However, the user side of a wireless communication link is subjected to randomness due to usage of a wireless device and changes in location and orientation. Therefore, the MIMO antenna system must be designed to account for such slow fading that is characteristic to Random-LOS.

It has been shown that by using two antenna ports with orthogonal polarizations and equal gains on the receiving side of the link, the Maximal Ratio Combination (MRC) of the two receiving antenna ports will cause the receiving antenna to align its polarization to any polarization of the incident wave [6, Sec. 3.10]. Hence, the envelope of the combined signal will be constant independently of the polarization of the incident wave (provided the incident power density is constant). However, this is not the case if the far-fields of the two receiving antenna ports are unbalanced or non-orthogonal in the direction of arrival.

The current paper aims to provide new insights into the requirements on two parameters, polarization orthogonality and received power balance, for 2×1 SIMO antenna systems operating in the Random-LOS channels. These parameters depend on far-field functions of the two ports. The far-field functions are deterministic. However, the AoA is random relative to the orientation of the antennas. Hence, the aforementioned parameters will affect the system performance in a random way. To this end, we investigate how the amplitude imbalance and non-orthogonality of the far-fields affect the figures of merit for the system performance. The figure of merit is the degradation of the diversity gain at 5% CDF level, corresponding to the 95% level of the Probability of Detection (PoD).

II. Deficiencies

Generally, the two ports of a dual-polarized antenna do only provide orthogonal far-field functions in its symmetry planes. There can be significant cross-polar field levels appearing between the symmetry planes, (see, e.g., the BOR_1 antenna relations in [6, Sec. 2.4.2]). Furthermore, the amplitudes of the far-fields of the two ports may not be equal everywhere either. This appears in particular if the E- and H-planes are different, because the E-plane of one port will coincide with the H-plane of another. These two deficiencies will affect the system performance in a Random-LOS environment, due to the randomness of the angle of arrival and polarization of the incident wave.

Assuming that the far-field functions of the two receiving antennas are defined as $\boldsymbol{G_1}(\theta,\phi)$ and $\boldsymbol{G_2}(\theta,\phi)$ at any point in space, we can define the *polarization non-orthogonality factor* in a direction (θ,ϕ) as

$$I_\mathrm{p}(\theta,\phi) = \frac{|\boldsymbol{G_1} \cdot \boldsymbol{G_2}^*|}{|\boldsymbol{G_1}|\,|\boldsymbol{G_2}|}. \quad (1)$$

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The *amplitude imbalance factor* is defined as

$$I_{\mathrm{a}}\left(\theta,\phi\right)=\frac{\max\left\{|\boldsymbol{G}_1|,|\boldsymbol{G}_2|\right\}}{\min\left\{|\boldsymbol{G}_1|,|\boldsymbol{G}_2|\right\}}, \tag{2}$$

which is the ratio of the amplitudes of the two far-field functions, greater than or equal to 1.

Thus the polarization non-orthogonality and amplitude imbalance vary with AoA, even if the antennas themselves are orthogonal. Actually, it is known that rotationally symmetric antenna structures generally will have crosspolar sidelobes in the 45° planes. This is shown in, e.g., section 3.4.2 in [6] about the so-called BOR_1 antennas. Exceptions are the incremental Huygens source [6, Sec. 4.4.3], and corrugated horn antennas [6, Sec. 8.8].

III. Figures of Merit

Here we focus on two figures of merit in order to investigate the effect of the imbalances on system performance: the degradation of the *Diversity gain* at the 5% CDF level, and the degradation at the *95% PoD level*. We will first assume that the AoA is fixed, and find the CDF and PoD when the polarization is random. We know from [6, Sec. 3.10] that the MRC algorithm used in MIMO systems will always align the polarization of the receiving side with that of the transmitting side if the receiving antenna ports have orthogonal far field functions and amplitude balance. Therefore, we use this polarization-aligned case as a reference for both figures of merit.

The first figure of merit, the diversity gain, is defined at the 1% CDF level for RIMP channels [7] (see also the compact formulas in [8]). However, we have here chosen the definition at 95% PoD level (corresponding to 5% CDF level) because this can in practical situations be determined much more accurately than at 99% level. The degradation of the diversity gain relative to the i.i.d. case is in [6, Sec. 3.4.4] referred to as a decorrelation efficiency. We do not have any i.i.d. reference in Random-LOS environments, so we will instead use a polarization-aligned single-port isotropic antenna with 100% radiation efficiency as a reference.

The second figure of merit, is the power degradation at the 95% probability of detection (PoD) level. The PoD is obtained using the threshold receiver model [9]. The power corresponding to the 95% PoD level shows the amount of power that is required at the receiver in order for 95% of the data packets to be received with no error for a fixed coding and modulation scheme when the polarization and AoA are random.

IV. One bitstream in Diversity System

A simple model is used to investigate the effects of imbalances on a receiving diversity system. Since the transmitting and receiving antennas are typically located in each other's far-field region, we can assume the incoming signal as a plane wave with random linear or circular polarization. The linearly polarized receiving antennas are modeled by their corresponding far-field functions, $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$. In the case of linearly polarized incoming wave, the $\boldsymbol{E}_i$ and $\boldsymbol{G}_1$ vectors make a random angle β with each other, corresponding to the random polarization of the plane wave as shown in Fig. 1. The

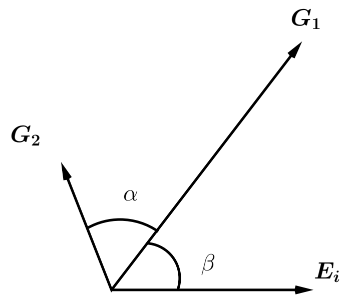


Fig. 1: Two receiving antennas with polarization non-orthogonality and amplitude imbalance in a 2×1 diversity system.

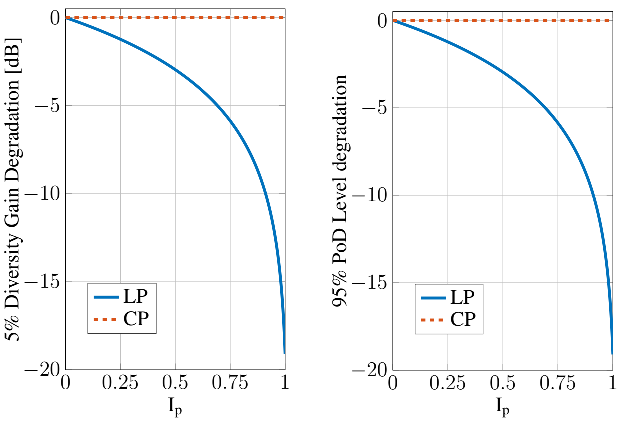
received signals are then combined using the MRC-algorithm. The imbalances are defined in (1) and (2) and are dependent on the AoA, i.e., on the far-field function.

Assuming that the two antennas have equal gains but non-orthogonal polarizations in the direction of the AoA, one can see the effect of polarization non-orthogonality on the diversity gain. If the two receiving antennas are orthogonal, the MRC-algorithm will act such that the combined polarization of the receiving antenna ports is aligned with that of the incident wave, regardless of the polarization of the incident field [6]. Fig. 2(a) shows the degradation in diversity gain at 5% CDF level, vs. polarization non-orthogonality factor I_{p}. We observe that the diversity gain has its maximum when $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$ are orthogonal ($I_{\mathrm{p}}=0$), whereas it will decrease with the increase in the polarization non-orthogonality until it reaches its minimum when the two are parallel ($I_{\mathrm{p}}=1$). For the incident circular polarization, the diversity gain is independent from I_{p}. In this case, the two antennas will each receive half of the radiated power and the MRC power will be optimal regardless of I_{p}. For the dual linear polarization, the improvements in the diversity gain can be up to 19dB at 5% CDF level, corresponding to 95% of the users, which is a significant improvement.

Fig. 2(b) shows the calculated degradation of 95% PoD level vs. I_{p}. It can be observed that 3 dB more power is required to achieve 95% PoD when $I_{\mathrm{p}}=0.5$, compared to the case where the far-field patterns are orthogonal to each other. For the circular incident polarization there is no dependence on the polarization non-orthogonality as described earlier. It is observed that since the reference CDF level for the diversity gain is independent of I_{p}, the effect of polarization non-orthogonality is the same on both 5% CDF level and 95% PoD level.

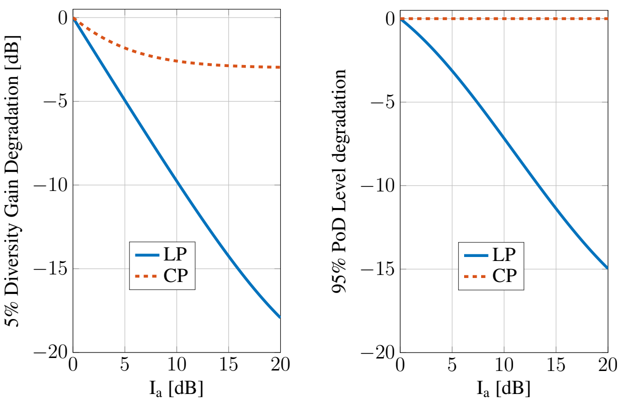
A similar study can be performed on the effects of the amplitude imbalance I_{a} on the two figures of merit. For this purpose, we assume that the two far-field patterns are orthogonal and I_{a} varies between 0 and 20dB, while the combined power of the two antennas is constant, i.e., $|\boldsymbol{G}_1|^2+|\boldsymbol{G}_2|^2=constant$.

The diversity gain degradation at 5% CDF level is plotted vs. amplitude imbalance factor I_{a} in Fig. 3(a). We observe that the MRC diversity gain at 5% CDF level can vary as much as 18dB when the amplitude imbalance of the two antennas changes between 0 and 20dB. Fig. 3(b) shows the degradation of 95% PoD level, vs. the amplitude imbalance I_{a}. Here again we can see that the amplitude imbalance between



(a) (b)

Fig. 2: 1-bitstream degradation of the (a) diversity gain at 5% CDF level, and (b) 95% PoD level, vs. the polarization non-orthogonality factor.



(a) (b)

Fig. 3: 1-bitstream degradation of the (a) diversity gain at 5% CDF level, and (b) 95% PoD level, vs. the amplitude imbalance factor.

the two receiving antennas requires almost the same increase in power in order to maintain 95% probability of detection. For circular polarization, it can again be observed that the required power for 95% PoD, is independent of the deficiency, i.e., the amplitude imbalance in the present case, due to the fact that the combined power of the two antennas is kept constant as mentioned earlier. It should be noted that unlike the case of the variations in I_p, the two degradation graphs in Fig. 3(a) and (b) do not have similar dependence on I_a because the reference CDF level for the diversity gain is I_a-dependent.

V. Conclusion

Definitions are provided for the polarization non-orthogonality and the amplitude imbalance between two co-located orthogonal linearly polarized antenna ports. The performance degradation of a 2×1 single-bitstream SIMO system have been investigated in Random-LOS due to the two polarization deficiencies. We have shown that we need to keep the polarization non-orthogonality within 0.5, i.e., the angle between the far-field vectors should be at least 60° in order to keep the reduction in diversity gain within 3 dB, and the power imbalance must be kept within 3 dB, both for a linearly polarized incident wave. We have shown that if we use circular polarization at the transmitter side, the degradation due to the polarization deficiencies will be reduced to a large extent.

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