

Performance Evaluation of Polarization Effects on 5G Clustered Delay Line Channels

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Abstract—The majority of the vast literature using state-of-art MIMO transmission schemes present evaluations on simplified propagation models using simplified antenna arrays. However, such a model neglects channel polarization effect, which could result in severe signal degradation. In this paper, we quantify the impact of channel polarization for arrays with co-polarized and cross-polarized antennas. We focus on the usage of the recently standardized 3GPP 38.901 clustered delay line channel for 5G New Radio. Evaluations have shown that while traditional co-polarized array can lead to better performance, in a realistic scenario of mutual transmitter-receiver, tilting channel polarization can cause severe degradation. This has motivated the use of cross-polarized antennas that are invariant to these tilts. Extensive simulations show that polarization causes 2-6dB degradation for traditional co-polarized arrays, while for cross-polarized arrays, this value is 1-3dB.

Index Terms—Channel polarization, clustered delay line, cross-polarized arrays, co-polarized arrays, 5G New Radio.

I. INTRODUCTION

Wireless data volume has explosively grown for the fifth-generation (5G) and sixth-generation (6G) communication systems [1], [2]. Of numerous proposals and techniques from a signal processing point of view, multiple-input multiple-output (MIMO) antennas keep playing an important role in meeting more stringent data-hunger applications. Thus, the number of antennas needed for 5G increases correspondingly as compared with previous generation systems. Antenna polarization further offers extra degrees of freedom for MIMO processing. Both diversity and beamforming gains can be obtained simultaneously [3], [4]. On the other hand, accurate channel models for 5G are of great importance for evaluation purposes. The 3rd Generation Partnership Project (3GPP) has reported two kinds of channel models, tapped-delay-line (TDL) and clustered-delay-line (CDL) models for 5G New Radio (5G NR). TDL is easy to use for conventional link-level simulations. In contrast, CDL is a geometry-based channel model, which comprises angle and polarization effects. It is more suitable for angle-dependent analysis, such as antenna array processing. However, little research uses the CDL model due to its complicated parameter settings. Pioneering work in this direction is presented [5] with focus on implementation

of switchable dual-polarized array antennas. Although some studies on antenna polarization and CDL channel model have been done separately, additional investigation is needed to ascertain the effects of antenna polarization based on CDL model. The contribution of this work lies in investigating how antenna polarization influences link performance using the actual CDL channel models, which allows a more precise quality of service (QoS) provisioning. To the best of the authors knowledge, it was the first work that explores the effects of polarization based on CDL channel model. Simulation results reflect performance gaps between the different polarization scenarios, which can serve as a reference design for 5G communication products.

II. SYSTEM, CHANNEL, AND SIGNAL MODELS

A. System Model

The system depicted in Fig. 1 is considered herein. The transmitter side (Tx) and receiver side (Rx) are equipped with n_{TX} and n_{RX} antennas, respectively. During wireless transmission, it is common that one side is static, while the other side has mobility. Without loss of generality, assume that Tx is fixed while Rx can move freely and, therefore, can have different antenna array orientation to Tx. Particularly, there exists a Tx-Rx slant, which is the angle difference between orientations of Tx and Rx, denoted by ζ . For instance, if the Tx array is placed vertically and Rx array is placed horizontally, then $\zeta = 90^\circ$. In this work system with $n_{TX} = n_{RX} = 2$ is considered; however, the analysis is valid for configurations with a larger number of antennas, which is likely to happen for mmWave communications [6], [7]. Without loss of generality, a simple configuration of 2×2 MIMO allows to show polarization effects since one of the

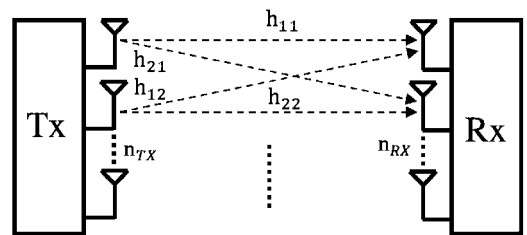


Fig. 1. System model

This material is based upon work supported by Industry-Academia R&D Cooperation between Foxconn Inc. and National Chiao Tung University (Taiwan)

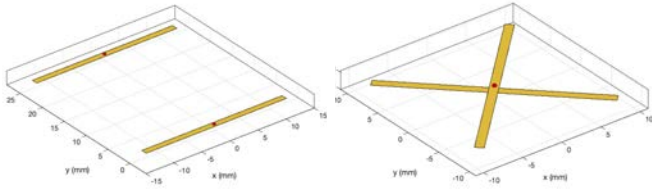


Fig. 2. Structure of antenna arrays with co-polarized (left) and cross-polarized (right) dipole elements

main goals of the work is to show the advantage of cross-polarized arrays over co-polarized arrays, both of which are described below.

Two different antenna array configurations are considered herein. One is shown on the left side of Fig. 2, where both antennas are co-polarized, i.e., antenna elements are placed in parallel and spaced by half-wavelength of the signal. Another, shown on the right side of Fig. 2, is a cross-polarized array, i.e., antenna elements are placed perpendicular to each other. Throughout the work, the channel polarization effect is investigated and evaluated for different Tx-Rx pairs.

Assuming OFDM transmission, a frequency-domain channel between the i th Rx antenna and the j th Tx antenna on q th subcarrier is denoted as h_{ij}^q . h_{ij}^q follows the 3GPP cluster-based definition of the mmWave propagation channel from [8]. Index for subcarrier is omitted here for brevity. The signal model can be written as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \triangleq \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (1)$$

where x_i is a transmitted symbol at the i th transmit antenna. y_i and n_i are received signal and noise at the i th receive antenna, respectively.

MIMO technologies, such as space-time diversity, array processing, and multiplexing, are popular schemes to obtain performance gain, and hence it is imperative to evaluate degradation caused by channel polarization effect. Particularly, we consider zero-forcing (ZF), minimum mean square error (MMSE) channel equalizers for spatial multiplexing and Alamouti space-time block coding (STBC) [9] for diversity. These techniques are briefly reviewed below.

- For signal model (1), the decoded signal via ZF equalizer $\mathbf{W}_{ZF}$ is written as

$$\hat{\mathbf{x}}_{ZF} = \mathbf{W}_{ZF}\mathbf{y} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H\mathbf{y}. \quad (2)$$

While doing ZF equalization, there can be an amplification of noise. Hence, the ZF equalizer is inadequate equalizer for noise-limited systems. However, it is simple and intuitive to apply in current 3GPP standards.

- For signal model (1), the decoded signal via MMSE equalizer $\mathbf{W}_{MMSE}$ is written as

$$\hat{\mathbf{x}}_{MMSE} = \mathbf{W}_{MMSE}\mathbf{y} = (\mathbf{H}^H\mathbf{H} + \sigma^2\mathbf{I})^{-1}\mathbf{H}^H\mathbf{y}, \quad (3)$$

where σ^2 denotes noise power. Considering noise effects, MMSE can achieve about 3dB of improvement compared to ZF equalizer.

- Alamouti STBC is widely used in point-to-point multi-antenna channels to enhance transmission reliability in terms of the diversity gain. For two-transmit antenna system, the coding matrix is given as

$$\tilde{\mathbf{X}} = \begin{bmatrix} x_1 & -x_2 \\ x_2 & x_1^* \end{bmatrix}. \quad (4)$$

Now, the received signal in the first time slot (denoted by superscript) is

$$\begin{bmatrix} y_1^1 \\ y_2^1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \end{bmatrix} \quad (5)$$

The received signal in the second time slot

$$\begin{bmatrix} y_1^2 \\ y_2^2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \begin{bmatrix} n_1^2 \\ n_2^2 \end{bmatrix} \quad (6)$$

Let us define

$$\tilde{\mathbf{H}} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix} \quad (7)$$

Then, the estimate of the transmitted symbol is,

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2^* \end{bmatrix} = (\tilde{\mathbf{H}}^H\tilde{\mathbf{H}})^{-1}\tilde{\mathbf{H}}^H \begin{bmatrix} y_1^1 \\ y_2^1 \\ y_1^2 \\ y_2^{2*} \end{bmatrix}. \quad (8)$$

More details can be found in [9]

In Sec. III the performance of the three schemes mentioned above is evaluated for various Tx-Rx configurations and the impact of channel polarization effect is investigated along with the CDL channel model in a sequel.

B. CDL channel model

CDL channel model was proposed in 3GPP TR38.901 [8] for link-level simulations. The full carrier frequency ranges from 500 MHz to 100 GHz with a maximum channel bandwidth of 2 GHz. It was a geometry-based stochastic MIMO channel model. It was designed for the small-scale fading process. TR38.901 offers five channel profiles named CDL-A, CDL-B, CDL-C, CDL-D, and CDL-E. The first three represent Non-Line-Of-Sight (NLOS) scenarios while the rest correspond to Line-Of-Sight (LOS) scenarios.

The importance of the CDL channel model has been proven in technical report R1-165974 3GPP, which consists of calibration results from leading 5G pioneers such as Ericsson, Huawei, Samsung and Nokia to name a few.

CDL is a comprehensive channel model that encompasses time, frequency, space, and polarization dimensions. It is continuous in time as the transmitter or receiver is moving, which gives time selectivity by Doppler spread. It further contains diffuse phenomena by including subpaths around the dominant path. CDL has rich resolvable multipath components for 5G wideband transmission, which characterizes frequency selectivity. Delay spreads for various scenarios from indoor to outdoor cases are tabulated. Considering radio

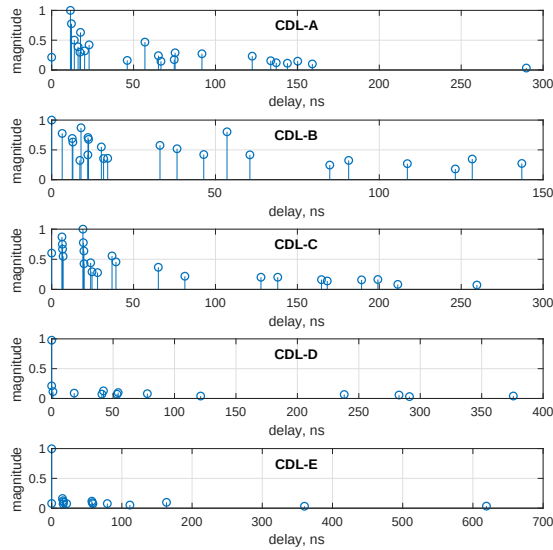


Fig. 3. CDL-A – CDL-E channel realizations

wave propagation, CDL models incoming paths (also known as rays) on a cluster-wise basis. Besides, angular spreads for both azimuth and zenith directions are also included. Antenna polarization is defined through the cross-polarization power ratio for each ray in a cluster, which is explained in more detail in the next section. Moreover, CDL supports a large antenna array for which the power pattern for each antenna is accompanied. All the rest details can be found in [8]. Fig. 3 shows a typical realization of CDL-A – CDL-E.

C. Channel Polarization Effects

In wireless communication, the antenna radiates in desired polarization it was designed to, but in addition to that it has *leakage* that radiates in the perpendicular polarization to a desired one [10]. Moreover, the wireless channel between Tx and Rx would have its additional effect on polarization leakage, so that resulted pattern at Rx would contain a degraded version of a signal in designed polarization. The ratio between desired polarization to the undesired polarization is called *cross-polarization ratio* or XPR. While technology advance in antenna engineering allows reducing antenna XPR to as good as 20dB [11], a typical value for mmWave CDL channel XPR is varying between 3 and 15dB according to Table 7.5-6 in [8] and therefore cannot be neglected. Dependency between channel response and polarization effect is described mathematically by Eq. 7.5-22 (not repeated here due to its size) of [8], which is complicated due to its dependency on both azimuth and zenith angles of arrival (AoA and ZoA, respectively) for each ray and is hard to link to any of performance metrics directly. To put light on this issue empirical evaluation of channel polarization effect is given in this work in the following section.

III. NUMERICAL RESULTS

Presented in this section are simulations and evaluations of CDL channel polarization effects for different antenna array

TABLE I
SIMULATION PARAMETER SETTINGS

System Parameter	Value
Channel type	CDL-A – CDL-E
Carrier frequency	28GHz
Sampling rate	122.88MHz
Channel bandwidth	100MHz
Subcarrier spacing	30kHz
Delay spread	10ns
Cross-polarization ratio (XPR)	10dB
Number of used subcarriers	3276
FFT size	4096
Modulation	QPSK
Antenna polarization	Co/cross-polarized
MIMO scheme	ZF/MMSE/STBC

configurations described in Sec. II. Table I gives summary of all simulation parameters.

As was mentioned in Sec. II-B, the polarization effect depends on the orientations of both Tx and Rx. There are two main antenna configurations considered by 5G equipment manufacturers and shown in Fig. 2, which is expected to behave differently within a polarized environment. This is illustrated in Figs. 4 and 5, where three different configurations of the Tx-Rx pair are tested: co-polarized Tx – co-polarized Rx, cross-polarized Tx – cross-polarized Rx, cross-polarized Tx – co-polarized Rx. Due to no essential difference with the latter, configuration with co-polarized Tx – cross-polarized Rx is not considered. On figures below co-polarized antenna array is labeled as *Cpol*, and cross-polarized – *Xpol*. The first label corresponds to Tx and second – to Rx. In addition, Tx orientation is fixed, while Rx is mobile, so that slant angle ζ varies from 0° to 180° . For all test channels, delay profiles are randomly picked.

Fig. 4 shows average channel power between each antenna links. Notice that when both arrays are co-polarized, there is a big difference between peaks at 0° and 90° for each link. For a blue line, each Rx antenna receives one stronger and one weaker channel from different Tx antennas. This illustrates the fact that cross-polarized arrays are invariant to mutual slant and their performance does not depend on slant angle. Similar behavior can be observed for green line. However, its receive power has strong dependency from Tx antennas. It can be seen that $|h_{11}|^2$ has the same variations as $|h_{12}|^2$, and it does so for $|h_{21}|^2$ and $|h_{22}|^2$. As seen later, this power dependency creates certain problems as a signal from either one of Tx antennas is severely degraded. Despite being invariant to slant angle, Fig. 5 shows that both cross-polarized Tx-Rx pair has lower peak power (blue and green lines) than co-polarized (red line). The reason is that in co-polarized arrays signal at each Rx antenna consists of the sum from two Tx antennas polarized in the same direction for the case of $\zeta = 0^\circ$, leading to a maximum channel power around the value of four. Given the effect of polarization of channel strength, next, BER performance analysis is conducted. Figs. 6–8 show BER performance for ZF, MMSE and STBC MIMO schemes, respectively. Different Tx-Rx pairs are compared.

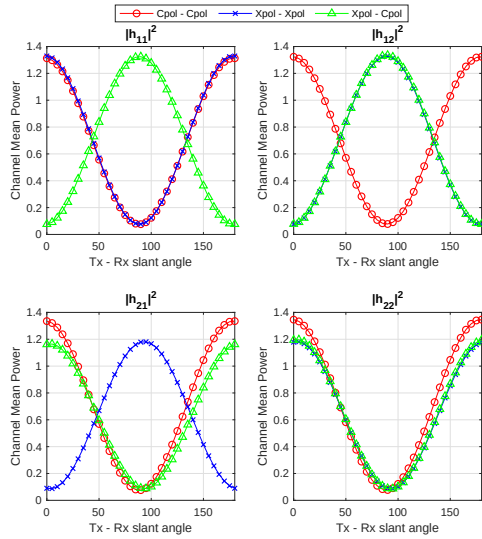


Fig. 4. Mean Channel power per antenna

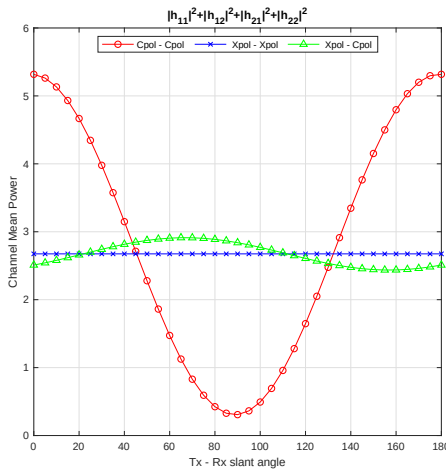


Fig. 5. Mean Channel aggregated power

Due to the strong dependency of signal power from the slant angle, when both Tx and Rx are co-polarized, three different scenarios are considered. Label *best* corresponds to both vertically oriented Tx and Rx while, label *worst* corresponds to vertically oriented Tx and horizontally oriented Rx ($\zeta = 90^\circ$). Labels *best* and *worst* refer to maximum and minimum aggregated channel strength in Fig. 5, respectively. Label *rand* corresponds to fixed Tx orientation, while the orientation of Rx is random and uniformly distributed between 0° and 90° . Moreover, “idealized” Rayleigh channel that does not incorporate polarization effect for all antenna pairs is used as a performance benchmark.

Fig. 6 and Fig. 7 show that *Cpol-Cpol, best* can match results of Rayleigh channel. However, for random slant there is a loss about 3dB and 5dB for MMSE and ZF equalizers, respectively. *Xpol-Cpol, rand* has even poorer performance due to power dependency discussed above. *Xpol-Xpol, rand*

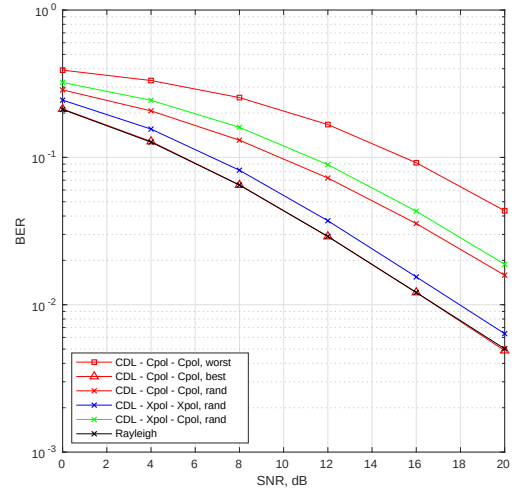


Fig. 6. BER for ZF receiver for CDL-A,B,C scenarios

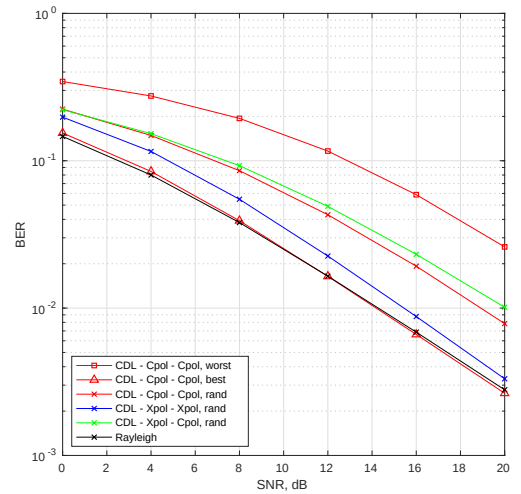


Fig. 7. BER for MMSE receiver for CDL-A,B,C scenarios

has superior performance with nearly 0.5dB loss for ZF and 2dB loss for MMSE compared to idealized Rayleigh channel.

A slightly different situation can be observed for STBC transmission on Fig. 8. The performance gap between *Cpol-Cpol, best* and *Rayleigh* is caused by antenna correlation in CDL channel model. This is a known phenomenon and is well-described in [12], [13]. Performance of the *Xpol-Xpol, rand* matches *Xpol-Cpol, rand* due to the nearly equal mean channel aggregated power drawn in Fig. 5. This is the essential property of Alamouti STBC that exploits each channel power when channel from TX is unknown.

Figs. 9 and 10 plot respective BERs in LOS channels, i.e., CDL-D and CDL-E. *Xpol-Xpol, rand* and *Cpol-Cpol, worst* result in the best and the worst BERs, respectively. Similarly, *Xpol-Xpol, rand* is better than *Xpol-Cpol, rand* as in the NLOS channels. *Xpol-Cpol, rand* suffers from the same TX power dependency effect that degrades the performance. On the other hand, *Cpol-Cpol, best* performs worse than *Xpol-Xpol, rand*. It is due to the LOS Rician fading such that no multipath diversity can be attained. Fig. 11 shows BER with

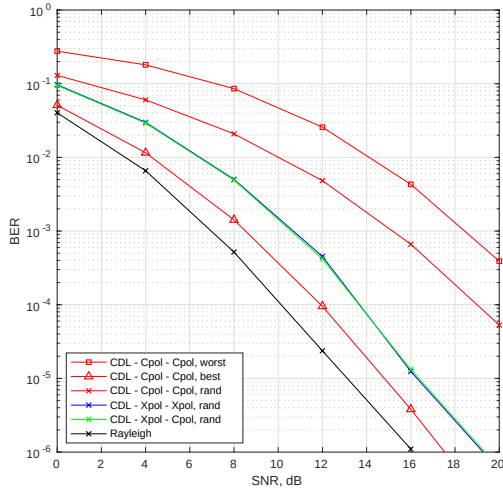


Fig. 8. BER for Alamouti STBC for CDL-A,B,C scenarios

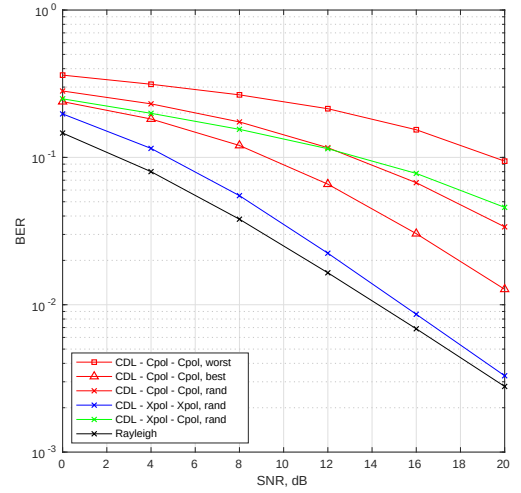


Fig. 10. BER for MMSE receiver for CDL-D,E scenarios

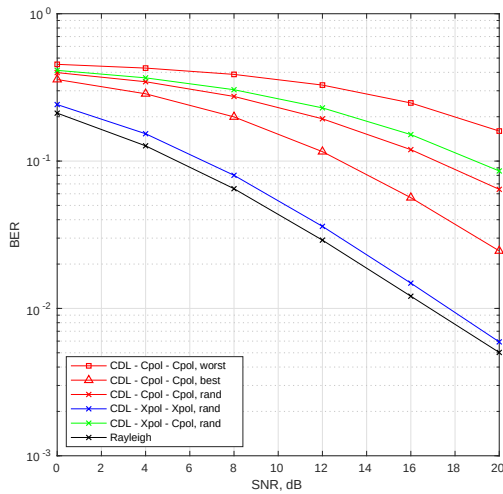


Fig. 9. BER for ZF receiver for CDL-D,E scenarios

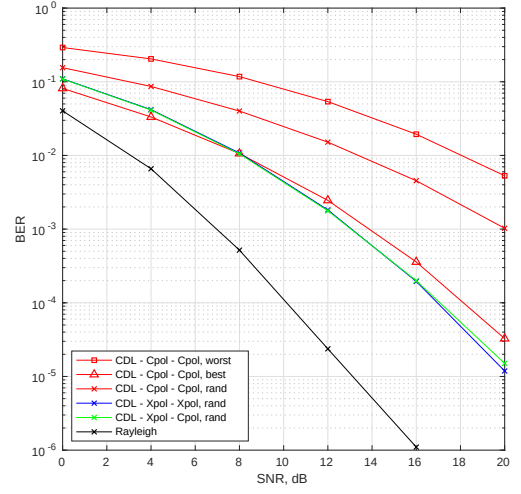


Fig. 11. BER for Alamouti STBC for CDL-D,E scenarios

Alamouti STBC in LOS channels. *Xpol-Xpol, rand* and *Xpol-Cpol, rand* have the similar performance owing to the same reason as discussed in Fig. 8. *Cpol-Cpol, best* also performs worse than *Xpol-Xpol, rand* and *Xpol-Cpol, rand* due to the LOS Rician fading. Figs. 6-11 discussed above all assumed antenna separation distance of half wavelength. In order to exploit antenna diversity for *Cpol-Cpol, best* in LOS channels, Fig. 12 explores the relationship between BER and antenna separation distance. Generally, the more the separation, the better the BER performance. It is attributed to the lower correlation between antennas for longer separation distance. It is noted that the case of half wavelength is better than that of 1 and 2 wavelengths. This is because antenna correlation is in fact a Bessel function of the separation distance as detailed in [14]. Thus, the case of half wavelength has lower correlation than that of one and two. To examine it more closely, Fig. 13 simulates BERs from 0.5 to 30 wavelengths with step size of 0.1 wavelength for SNR 12, 16 and 20 dBs. It is clear that BERs also exhibit fluctuations due to Bessel function for antenna correlation. Nevertheless, all of them

converge to certain BER values after 20 wavelengths. Lower SNR case converges to higher value since noise dominates the performance. In brief, the performance gets improved in LOS scenarios by increasing the separation distance from which antenna diversity can be benefited.

To summarize, there are two important observations from BER figures. First, for CDL channel model, there is 1-5dB degradation compared to Rayleigh channel. Second, cross-polarized array has a 2-4dB advantage over co-polarized arrays for random Tx-Rx orientation. This is a motivation for equipment manufacturers to consider the production of cross-polarization arrays on a larger scale.

IV. CONCLUSION

In this paper, we evaluate the impact of channel polarization of the CDL channel model for arrays with co-polarized and cross-polarized antennas on MIMO transceivers for ZF, MMSE and Alamouti STBC. The result is 1-3dB degradation in the BER curve for cross-polarized arrays and 2-6dB – for co-polarized arrays for the case when Tx and Rx have a

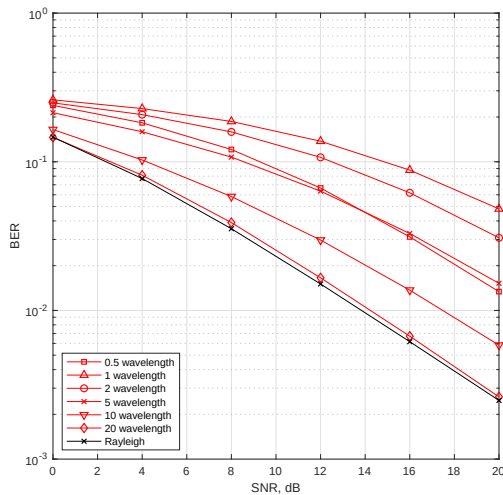


Fig. 12. BER for MMSE receiver with copolarized antennas for different antenna spacing

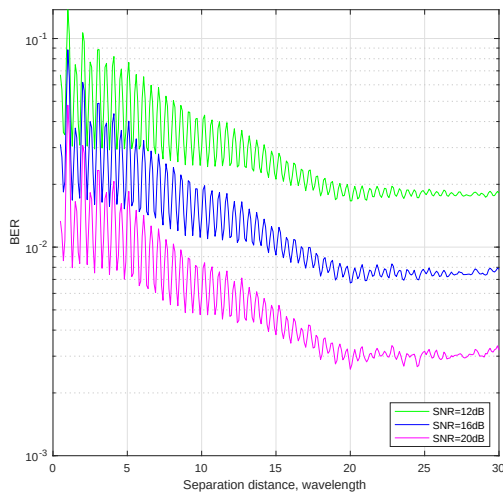


Fig. 13. BER for MMSE receiver with copolarized antennas for different antenna spacing

random slant angle. The aforementioned results have importance for channel model calibration and motivation for using cross-polarized arrays. Given cross-polarized antenna arrays invariant to slant angle, it is able to provide better and stable QoS and likely to be extensively used in 5G NR.

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