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1 Introduction

In Sorrento #47bis and Riga #47 meetings, some companies like [1-2] drew the attention of dual-polarized antennas. Should precoding be considered for dual-polarized MIMO? Up to now, no codebook has been proposed in LTE for the case of multi-polarized antennas because it is not clear whether precoding is really helpful in this kind of configurations. As was explained in [1], "The use of pre-coding for this scenario has not been investigated, and the performance of such a system is not well known. Further, the choice of code-book also poses an interesting problem here." It is believed multi-polarization should deserve more consideration as it is a very attractive solution for practical implementation of applications covered by LTE. Indeed it allows to highly alleviate the space requirements, which is of particular importance in handsets. This contribution investigates the use of precoding for 4-Tx dual-polarized MIMO.

This contribution presents the link level simulation results of precoded single user MIMO (SU-MIMO) with various codebook designs. It is shown that precoding does help in dual-polarized 4-Tx scenarios but an appropriate codebook structure has to be defined in order to benefit from precoding.

2 Dual-Polarized Channels

Let us assume the following simple model to account for dual-polarized channels

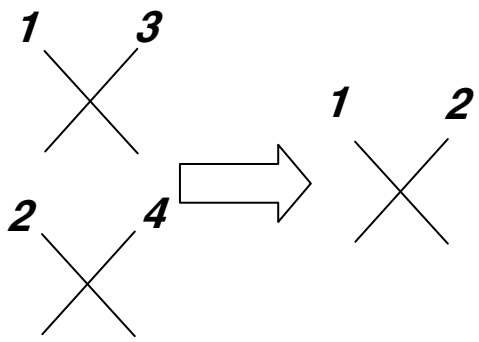
$$\mathbf{H} = \mathbf{X} \odot \mathbf{H}_p$$

where the use of orthogonal polarizations totally decorrelate all individual channels, such that $\mathbf{H}_p = \mathbf{H}_w$ with $\mathbf{H}_w$ the classical i.i.d. complex Gaussian matrix. Operator $\odot$ stands for Hadamard product or entrywise product. The co-polar imbalance (gain imbalance between $+45^\circ$ and -45° scattering amplitudes) is fixed to 1, that means that we are modeling a typical propagation between $\pm 45^\circ \rightarrow \pm 45^\circ$, i.e. the transmitter and receiver use the same $\pm 45^\circ$ polarization. This model has been extensively used in the past [8].

For 4-Tx 2-Rx, matrix $\mathbf{X}$ can be written as

$$\mathbf{X} = \begin{bmatrix} 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \\ \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \end{bmatrix},$$

which models the following scenario

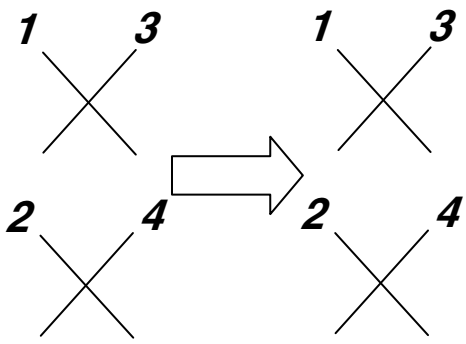


The parameter χ, called depolarization factor, can be thought of as the global XPD (cross polarization discrimination) of the antennas and the channel. The exact value of the depolarization factor is difficult to quantify as it depends on many factors and will vary from one environment to another. It can cover the wide range of values $0 \le \chi \le 1$. However in SCM model, it is chosen to be -7.2 dB for urban macro and -8 dB for urban micro, respectively.

Equivalently in 4-Tx 4-Rx configuration we can write

$$\mathbf{X} = \begin{bmatrix} 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \\ 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \\ \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \\ \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \end{bmatrix},$$

which models the following scenario



3 Codebook Designs for SU-MIMO

3.1 Codebook for uni-polarized channels

In Sorrento #47bis meeting, rank-specific codebooks have been discarded. Let us then only focus on matrix codebooks. Several matrix codebooks have been proposed in LTE for single-polarized MIMO. Among them we find Fourier Based codebook (Rotated DFT codebook [4], DFT codebook [3]), CDD based codebook [6-7], random codebook [5] etc… Examples of Fourier based codebooks are given below. They will be used later in the simulation results.

1) Rotated DFT codebook [4] is simply represented by $\{\mathbf{E}\ \mathbf{E}^2\ \cdots\ \mathbf{E}^{2^B}\}$, where

$$\mathbf{E} = \begin{bmatrix} e^{j\theta_0} & 0 & 0 & 0 \\ 0 & e^{j\theta_1} & 0 & 0 \\ 0 & 0 & e^{j\theta_2} & 0 \\ 0 & 0 & 0 & e^{j\theta_3} \end{bmatrix} * \mathbf{DFT}$$

and the set of $\{\theta_i\}$ can be optimized by given criteria. As an example, we can choose

{-2.51,-0.21} for a 2 transmit antenna system and {-1.24,2.72,1.52,-2.30} for a 4 transmit antenna system.

2) DFT codebook [3]

Let $\Upsilon = \{\mathbf{U}^{(0)} \cdots \mathbf{U}^{(2^B-1)}\}$ be the precoding matrix set, $\mathbf{U}^{(b)} = [\mathbf{u}_0^{(b)} \cdots \mathbf{u}_{M-1}^{(b)}]$ be the b-th precoding matrix and $\mathbf{u}_{m-1}^{(b)}$ be the m-th precoding vector in $\mathbf{U}^{(b)}$, the codebook is constructed as

$$\mathbf{u}_m^{(b)} = \frac{1}{\sqrt{M}}[u_{0m}^{(b)} \cdots u_{(M-1)m}^{(b)}]^T$$
$$u_{nm}^{(b)} = \exp\left\{j\frac{2\pi n}{M}(m+\frac{b}{M})\right\}$$

3.2 Codebook for dual-polarized channels

For multi-polarized MIMO, however, no codebook has been investigated up to now in LTE. It was only suggested in Riga #47 and Sorrento #47bis meetings to include an identity matrix to account for multi-polarization.

Therefore we investigate the performance gap between the identity matrix codebook, the DFT codebooks and another kind of codebook highlighting a block diagonal structure given by

$$\mathbf{U}^{(i)} = \begin{bmatrix} \mathbf{U}_2^{(i)} & \mathbf{0}_2 \\ \mathbf{0}_2 & \mathbf{U}_2^{(i)} \end{bmatrix} = \mathbf{I}_2 \otimes \mathbf{U}_2^{(i)}$$

where $\otimes$ is the Kronecker product and $\mathbf{U}_2^{(i)}$ is the ith precoding matrix in a codebook designed for single-polarized MIMO with 2 Tx. $\mathbf{I}_2$ is the 2x2 identity matrix. Hence the DFT codebook or the rotated DFT codebook may be used for example to build $\mathbf{U}^{(i)}$. This structure enables to perform beamforming on antennas having the same polarization.

4 Numerical Results

We assume 4x2 and 4x4 flat fading dual-polarized SU-MIMO channels and perform link level simulations. Both BS and UE have dual-polarized $\pm 45^\circ$ antennas so that the co-polar imbalance can be fixed to 1. We evaluate the gain achievable with several codebooks in the two extremes scenarios $\chi = 0$ and $\chi = 1$ (corresponding to i.i.d. Rayleigh fading channels) in order to cover the broad range of possible propagation conditions. In practice χ may evolve between those two values, suggesting that the codebook should be robust for all values of χ between 0 and 1. Naturally the performance for any χ different from 0 and 1 will lie in between the performance obtained with 0 and 1. We assume MMSE receivers and the achievable rates are calculated based on Shannon formula. Perfect channel estimation and ideal link adaptation are assumed. Rank adaptation is performed.

Figures 1 and 2 show the capacity achievable with different kinds of codebooks ('rotated DFT' codebook, 'identity matrix' codebook and the block diagonal matrix codebook used with the rotated DFT codebook for 2Tx and called 'blockwise rotated DFT' in the sequel) in 4x2 and 4x4 configurations, respectively.

From the simulation results in 4x2 and 4x4, we observe

1) For large χ ($\chi = 1$ corresponds to i.i.d. Rayleigh fading), the use of a block diagonal structure enables to outperform identity matrix based codebook by 0.8 dB when 8 rotated DFT matrices are used in the 'blockwise rotated DFT' codebook and by 0.6 dB when 4 matrices are used in 4x2 scenarios. In 4x4, the gains are equal to 0.5dB and 0.45dB for 8 and 4 matrices respectively. Due to the block diagonal structure, in the presence of large χ, the 'blockwise rotated DFT' cannot achieve the same performance as the original 4Tx 'rotated DFT' codebook because

precoding is only performed on a subset of antennas and never on 4Tx antennas simultaneously. However, the loss incurred by the block diagonal structure over the original 4Tx rotated DFT is limited to about 0.15 dB for 2^B=4 thanks to the combination of precoding and antenna subset selection on two polarizations. Note that even though this situation may occur in practice, SCM channel recommends the use of much lower values of χ.

2) For small χ, the use of a block diagonal structure enables to outperform identity matrix based codebook by 0.9 dB when 8 rotated DFT matrices are used in the 'blockwise rotated DFT' codebook and by 0.7 dB when 4 matrices are used. The gain over the original 4Tx 'rotated DFT' is even larger (more than 1 dB) because single-polarized codebooks do not spread energy efficiently across antennas in the presence of low channel depolarization factors. Single-polarized codebooks therefore result in poor performance when used in dual-polarized system with low depolarization factors. Note that if we rely only on the average values of XPD given by the SCM model (i.e. -7.2 dB for urban macro and -8 dB for urban micro), multi-polarized MIMO should only be investigated for very low values of χ.

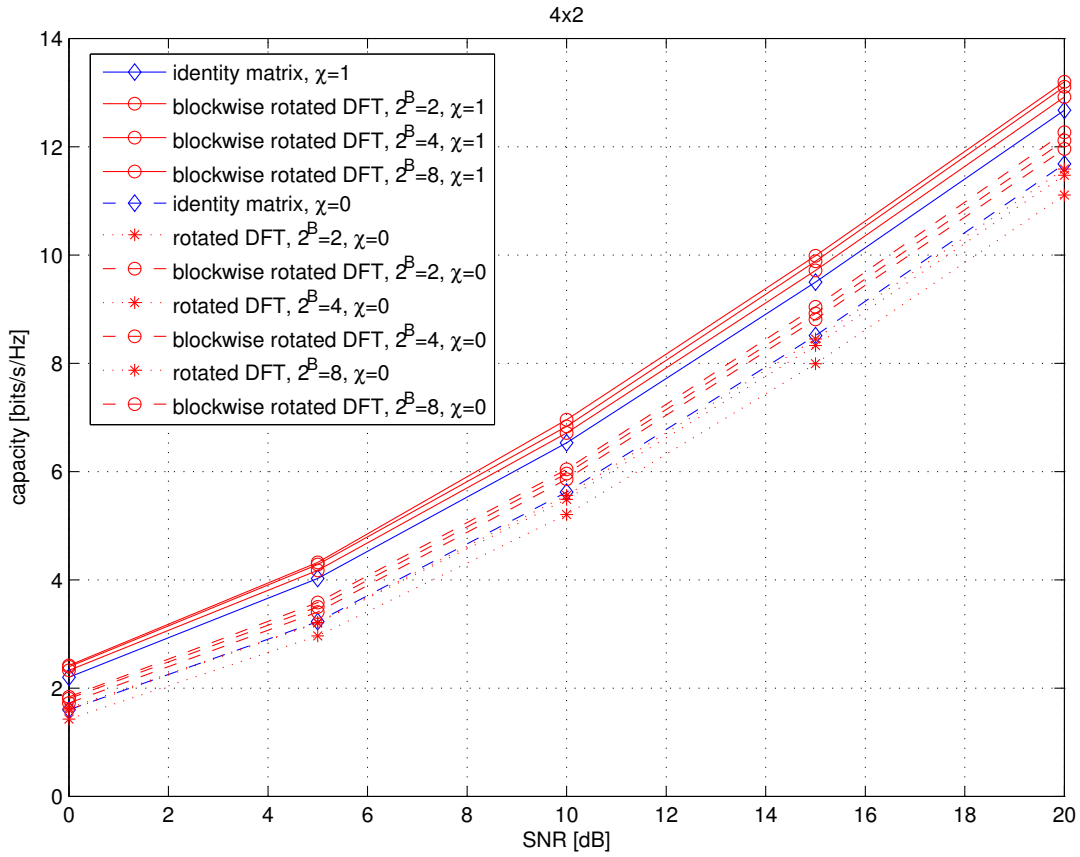


Fig.1 Capacity comparison of SU-MIMO with various codebooks ('rotated DFT', 'identity matrix' and 'blockwise rotated DFT' codebooks) in 4x2 dual-polarized MIMO channels.

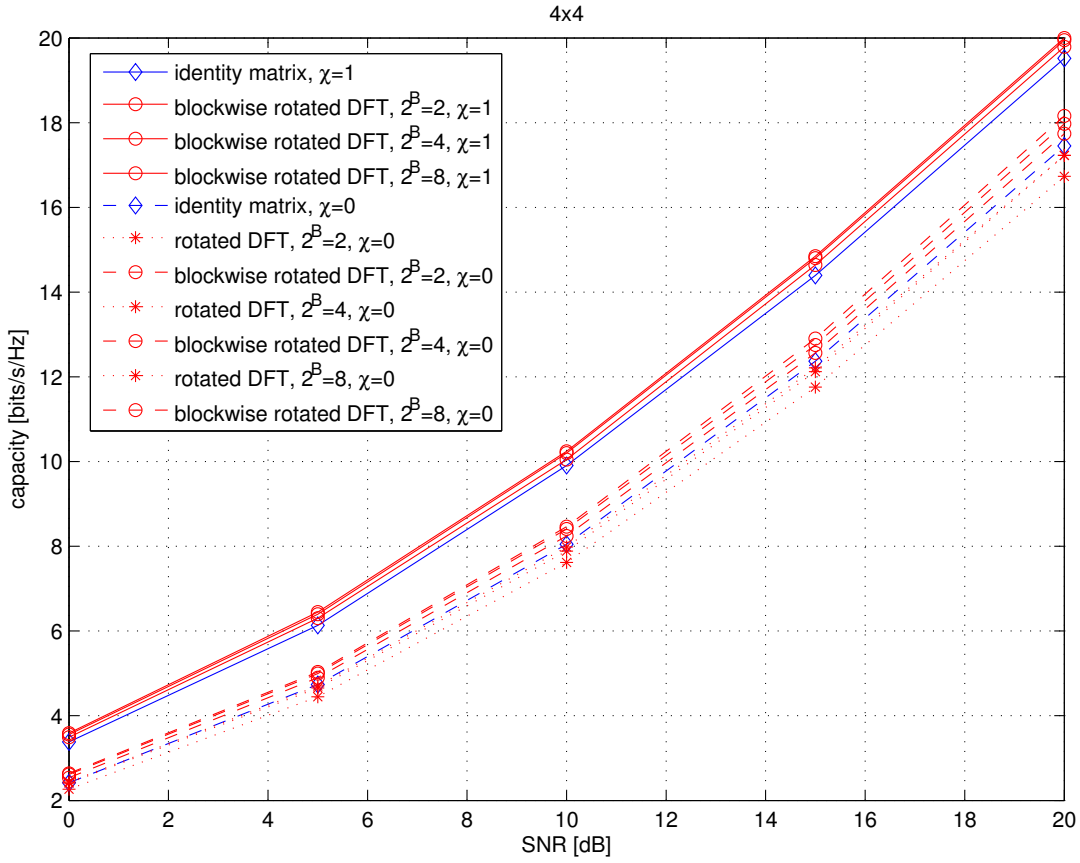


Fig.2 Capacity comparison of SU-MIMO with various codebooks ('rotated DFT', 'identity matrix' and 'blockwise rotated DFT' codebooks) in 4x4 dual-polarized MIMO channels.

Gains achievable in 4x2 scenarios with blockwise rotated DFT codebook over identity matrix codebook and single-polarized rotated DFT codebook are summarized in Table 1.

		Gains over identity matrix codebook	Gains over single-polarized rotated DFT codebook
$\chi = 0$ (SCM recommends $-7.2dB \le \chi \le -8dB$)	$2^B = 8$	0.9 dB	1dB
	$2^B = 4$	0.7 dB	1dB
	$2^B = 2$	0.5 dB	1.3 dB
$\chi = 1$	$2^B = 8$	0.8 dB	- 0.25 dB
	$2^B = 4$	0.6 dB	- 0.15 dB
	$2^B = 2$	0.35 dB	- 0.08 dB

Table 1. Gains of blockwise rotated DFT codebook over identity matrix codebook and single-polarized rotated DFT codebook for 2 codebook sizes ($2^B = 2$, $2^B = 4$ and $2^B = 8$) in 4x2 scenarios for $10 \le SNR[dB] \le 20$.

In Figure 3 and 4, we change the inner codebook and take the 2-Tx DFT codebook to build the dual-polarized 4-Tx codebook. The codebook is now called 'blockwise DFT' codebook. We illustrate the gain achievable with the 'blockwise DFT' codebook over identity matrix and 4-Tx DFT codebooks. Compared to the blockwise rotated DFT codebook, the same behavior is highlighted and similar gains are achieved over the identity matrix and single-polarized codebooks. The blockwise rotated DFT codebook achieves however some slight gains (0.2 – 0.3 dB) over the blockwise DFT codebook due to the improved distance properties between precoding matrices in the 2-Tx rotated DFT codebook compared to the 2-Tx DFT codebook.

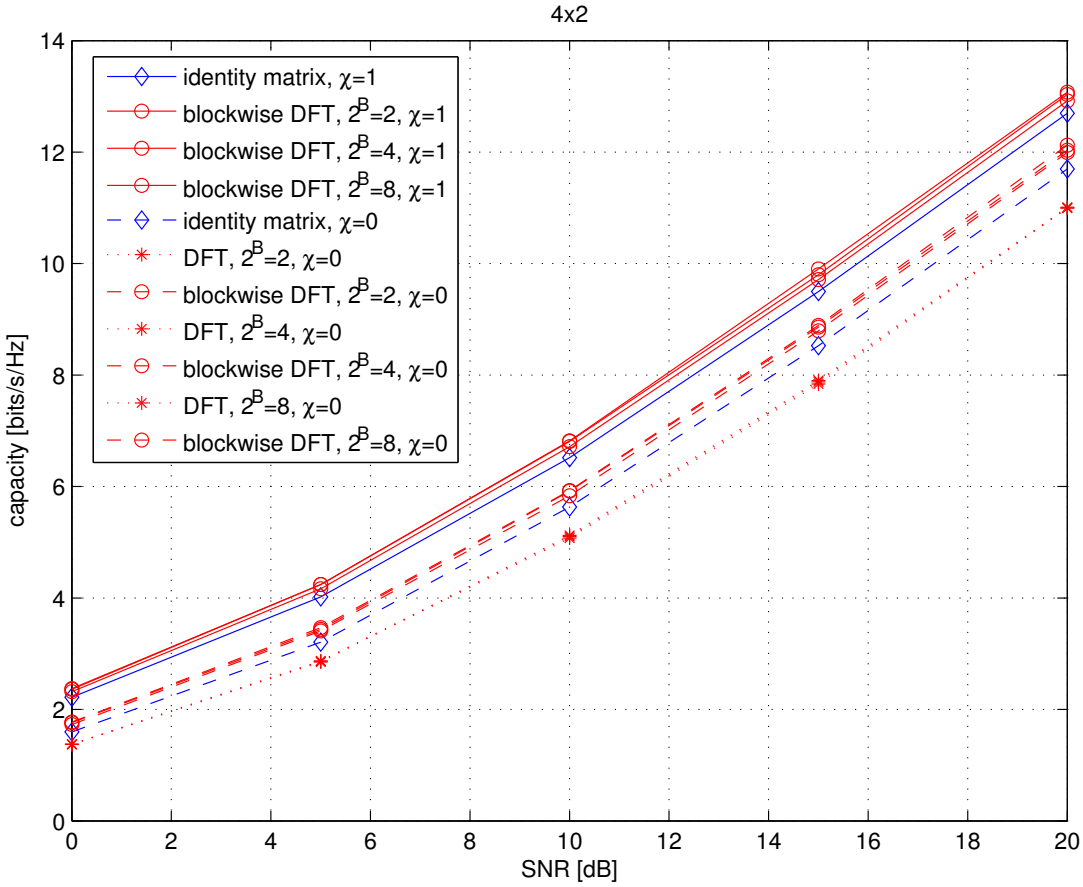


Fig.3 Capacity comparison of SU-MIMO with various codebooks ('rotated DFT', 'identity matrix' and 'blockwise DFT' codebooks) in 4x2 dual-polarized MIMO channels.

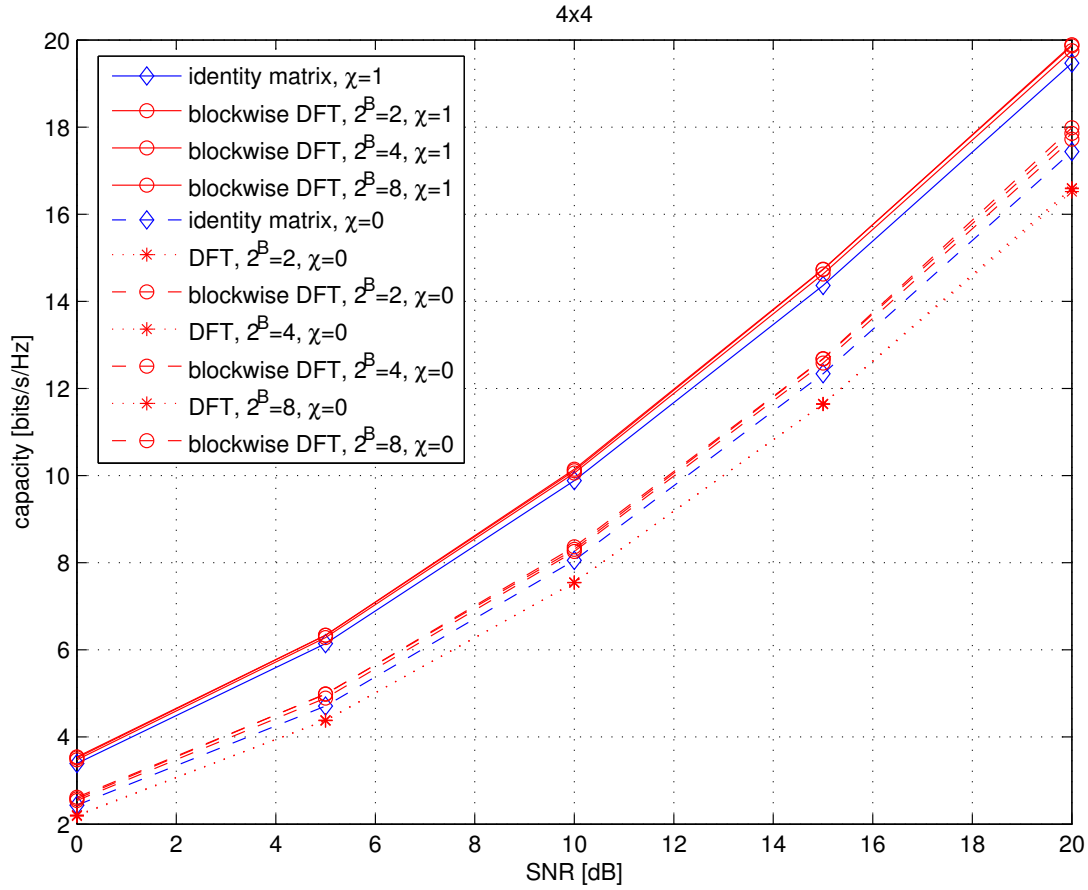


Fig.4 Capacity comparison of SU-MIMO with various codebooks ('rotated DFT', 'identity matrix' and 'blockwise DFT' codebooks) in 4x4 dual-polarized MIMO channels.

Gains achievable in 4x2 scenarios with blockwise DFT codebook over identity matrix codebook and single-polarized DFT codebook are summarized in Table 2.

		Gains over identity matrix codebook	Gains over single-polarized rotated DFT codebook
$\chi = 0$ (SCM recommends $-7.2dB \le \chi \le -8dB$)	$2^B = 8$	0.60 dB	1.65 dB
	$2^B = 4$	0.55 dB	1.6 dB
	$2^B = 2$	0.45 dB	1.5 dB
$\chi = 1$	$2^B = 8$	0.65 dB	- 0.03 dB
	$2^B = 4$	0.5 dB	0 dB
	$2^B = 2$	0.35 dB	0 dB

Table 2. Gains of blockwise rotated DFT codebook over identity matrix codebook and single-polarized rotated DFT codebook for 2 codebook sizes ($2^B = 2$, $2^B = 4$ and $2^B = 8$) in 4x2 scenarios for $10 \le SNR[dB] \le 20$.

Those results show that an appropriate structure of the codebooks enables to achieve beamforming gain in dual-polarized MIMO. This justifies the use of precoding in dual-polarized environments. Recall that the block diagonal structure may be applied to any single-polarized codebooks. Examples have been provided for DFT and rotated DFT matrices but can of course be applied to any other codebook. Similar gains can be expected. The better the inner single polarized 2-Tx codebook, the better the block diagonal dual-polarized 4-Tx codebook.

5 Conclusion

Based on the simulation results, we propose to adopt the block diagonal structure for dual-polarized codebooks in 4 by 2 and 4 by 4 antenna configurations. As for the inner codebook used in the block diagonal structure, we recommend the use of the DFT codebook. Naturally other codebooks could be used instead as inner codebooks, like precoded CDD. Non negligible gains of about 1 dB have been shown to be achievable over identity matrix based codebooks or single-polarized codebooks by the use of this block diagonal structured codebook.

For 2 by 2 configuration, it is believed that simple identity matrix should be enough as no possible beamforming gain can be exploited when the depolarization factor is small.

6 Conclusion

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