

Agenda Item: 7.9.1
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1 Introduction

In St Louis meeting #48, it was decided that precoding for different kinds of 4Tx-antenna configurations should be investigated and proposed for Malta meeting. In St Louis meeting some companies gave their opinions about an appropriate structure of codebooks for multi-polarized 4Tx antennas [1-3]. In [1], it was shown that precoding does help in dual-polarized 4-Tx scenarios but an appropriate block diagonal structure has to be defined in order to benefit from precoding. This block diagonal structure was also highlighted and proposed in [2-3]. In this contribution, we further address the problem of codebook design for multi-polarized MIMO and propose a way forward for the codebooks to be adopted in LTE.

2 Dual-Polarized Channels

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

$$\mathbf{H} = \mathbf{X} \odot \mathbf{H}_w \quad (1)$$

with \mathbf{H}_w the classical i.i.d. complex Gaussian matrix. Operator \odot stands for Hadamard product or entry-wise product. For 4 dual polarized Tx – 2 dual polarized Rx, matrix \mathbf{X} can be written as

$$\mathbf{X} = \begin{bmatrix} 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \\ \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \end{bmatrix}, \quad (2)$$

which models the following scenario shown in Figure 1.

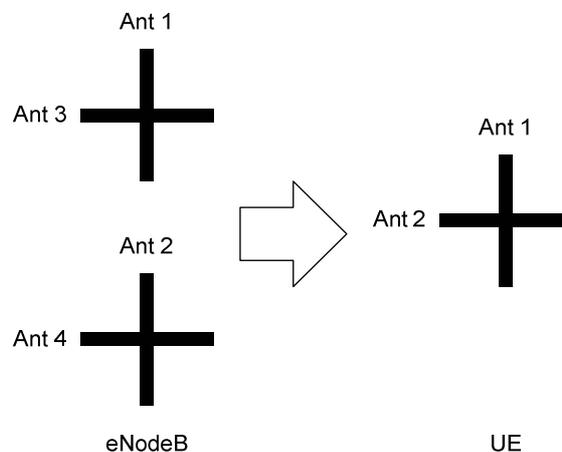


Figure 1: 4X2 polarized antenna configuration with dual polarized antennas at UE

The parameter χ , called depolarization factor, can be thought of as the inverse of 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 $0 \leq \chi \leq 1$. However in SCM model, it is chosen on average to be -7.2 dB for urban macro and -8 dB for urban micro, respectively.

In case the UE is single polarized, we can think of the matrix \mathbf{X} as

$$\mathbf{X} = \begin{bmatrix} \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \\ \sqrt{\chi} & \sqrt{\chi} & 1 & 1 \end{bmatrix} \quad (3)$$

for horizontal polarization at UE side illustrated in Figure 2 and

$$\mathbf{X} = \begin{bmatrix} 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \\ 1 & 1 & \sqrt{\chi} & \sqrt{\chi} \end{bmatrix} \quad (4)$$

for vertical polarization at UE side illustrated in Figure 3.

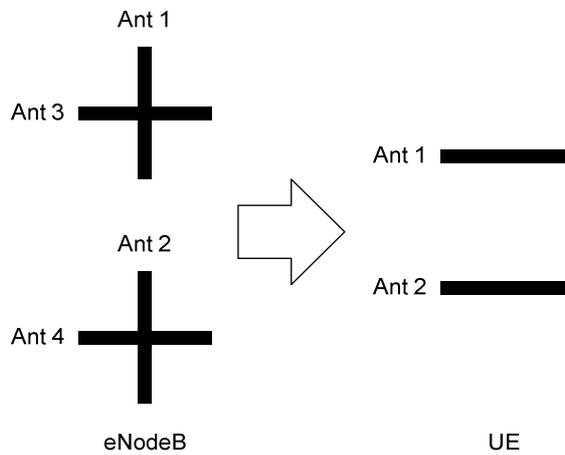


Figure 2: 4X2 polarized antenna configuration with horizontally polarized antennas at UE

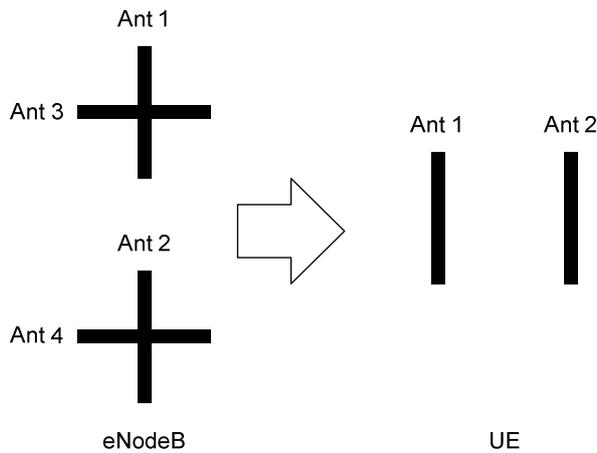


Figure 3: 4X2 polarized antenna configuration with vertically polarized antennas at UE

3 Codebook and Signaling for Multi-Polarized MIMO

We believe that the structure of codebook matrices should be dictated exclusively by the polarization of the node B. The UE's polarization may affect the columns subset selection and signaling. We address codebook structure and signaling in the sequel.

3.1 Codebook structure for dual-polarized channels

As far as the codebook structure is concerned, 3 kinds of codebook structure could be proposed:

- identity matrix \mathbf{I}_4
- codebook for single-polarized channels (e.g. DFT codebook [4], Rotated DFT codebook [5], random codebook [6], CDD based codebook [7-8], Householder codebook [9], etc...)
- block diagonal codebooks whose i^{th} matrix for 4Tx antennas is given by

$$\mathbf{U}^{(i)} = \begin{bmatrix} \mathbf{U}_2^{(i)} & \mathbf{0}_2 \\ \mathbf{0}_2 & \mathbf{U}_2^{(i)} \end{bmatrix} = \mathbf{I}_2 \otimes \mathbf{U}_2^{(i)} \tag{5}$$

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

As explained in [1], identity matrix codebook performs reasonably well for all possible propagation conditions (i.e. XPD). However, it lacks in exploiting any additional beamforming gains. On the other hand, codebooks designed for single-polarized antennas are very efficient in exploiting beamforming gains when the XPD is small (i.e. $\chi \approx 1$). However their performance is very weak when the XPD is large (i.e. $\chi \approx 0$), the transmit power being inefficiently spread among transmit antennas. Codebooks highlighting a block-diagonal structure have been shown to be particularly robust in all environments, as they are able to exploit beamforming gains both when the XPD is large and small, beamforming being performed only on antennas having the same polarization (beamforming on x-pol antennas may not be efficient).

The Block diagonal structure is therefore an appropriate structure for codebooks in multi-polarized channels. Regarding the inner 2-Tx codebook (the set of matrices $\mathbf{U}_2^{(i)}$) used in the block diagonal structure of eq. (5), several codebooks could be considered. However combining the identity matrix with constant modulus (CM) matrices (such as DFT matrices) is an efficient way to build a robust codebook for 2Tx antennas: the CM matrices being particularly useful in correlated channels, while the identity matrix improves performance in iid channels. This kind of codebook was selected for 2Tx configuration in St Louis meeting [10].

3.2 Signaling for dual-polarized channels

An important problem to be addressed is the fact that the UE may be single or dual-polarized. Therefore should the final codebook be UE's polarization dependent (i.e. the column subset selection would be different for single and dual-polarized UEs) and should the signaling account for this? The problem occurs for UEs with 2 or 4 antennas. Let us assume 2 antennas UEs for simplicity.

In [2-3], it is proposed to use matrices for rank 2 transmission of the kind (x refers to a non-zero entry)

$$\begin{bmatrix} x & 0 \\ x & 0 \\ 0 & x \\ 0 & x \end{bmatrix}, \tag{6}$$

i.e. two streams are transmitted on orthogonal polarizations. This is intuitive but makes sense only if the UE is dual-polarized and the XPD is large ($\chi \approx 0$). If the UE is single polarized and the XPD is large, this matrix structure would be catastrophic as a single polarized UE would never benefit from a rank 2 transmission. Indeed it is able to detect correctly only one stream: the one sent on the same polarization as its own polarization. In such scenarios (large XPD and single-polarized UE), it would be much more beneficial to transmit 2 streams on the same polarization as its own polarization, i.e. the codebook matrices for rank 2 should look like

$$\begin{bmatrix} x & x \\ x & x \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ x & x \\ x & x \end{bmatrix}. \quad (7)$$

Hence should a UE report to the node-B which polarization it holds or not?

- If a UE reports its polarization to the node-B:
 - pros*: - a lower feedback rate is required to signal precoder index as only precoders (6) or (7) are used.
 - cons*: - signaling to inform the kind of polarization is necessary.
 - if XPD becomes small, it may harm dual pol and single pol as they have less flexibility
 - in general, the UE's polarization may change a lot depending on the environment and the UE's orientation.
- If a UE selects the best column subset irrespective of its polarization, i.e. the codebook is independent of the UE's polarization:
 - pros*: - the node-B does not need to care about the polarization of the UE.
 - the UE always selects the best matrix structure depending on the channel conditions (and so the XPD)
 - the scattering environment may reverse the x-polarization effect either at the UE or at the Node B. In this case it is better that the UE can truly find the optimal precoder instead of choosing from a constrained subset.
 - cons*: - combinations (6) and (7) should be signalled.

For all the enumerated reasons, it is believed the final codebook should be independent of UE's polarization..

3.3 Proposed codebooks for dual-polarized channels

3.3.1 Two polarized antenna pairs with large separation

For a node-B having two polarized antenna pairs with large separation, the proposed codebook for 4x2 configuration is build based on the 2-Tx codebook decided in St Louis meeting

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ j & -j & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & j & -j \end{bmatrix}.$$

Bear in mind that in all the codebook presented here, a power normalization factor $1/\sqrt{2}$ should be applied to some matrices. It is omitted in this text for brevity.

As proposed in Section 3.2, rank adaptation with column subset selection should be performed over all combinations. Therefore the codebook for rank 1 and 2 is given by

$$\text{rank 1: } \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ j \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -j \end{bmatrix}$$

$$\begin{aligned}
\text{rank 2: } & \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \\
& \begin{bmatrix} 1 & 1 \\ 1 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 1 \\ 1 & -1 \end{bmatrix}, \\
& \begin{bmatrix} 1 & 1 \\ j & -j \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ j & 0 \\ 0 & 1 \\ 0 & j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ j & 0 \\ 0 & 1 \\ 0 & -j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -j & 0 \\ 0 & 1 \\ 0 & j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -j & 0 \\ 0 & 1 \\ 0 & -j \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 1 \\ j & -j \end{bmatrix}
\end{aligned} \tag{8}$$

This is a 5bits codebook.

For 4x4 configuration, the codebook can be constructed by the following matrices:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 0 & 0 \\ e^{j\frac{\pi}{3}} & -e^{j\frac{\pi}{3}} & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & e^{j\frac{\pi}{3}} & -e^{j\frac{\pi}{3}} \end{bmatrix} \begin{bmatrix} 1 & 1 & 0 & 0 \\ e^{j\frac{2\pi}{3}} & -e^{j\frac{2\pi}{3}} & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & e^{j\frac{2\pi}{3}} & -e^{j\frac{2\pi}{3}} \end{bmatrix} \tag{9}$$

All the precoders in the codebook are generated in the manner that rank adaptation with column subset selection within each matrix is performed over all combinations and over all ranks. This requires 6 bits FBI.

3.3.1 Two closely located polarized antenna pairs

Regarding the case where two polarized antenna pairs are closely located, this configuration may be extremely harmful as the largest multiplexing rate would be 2 for a dual-polarized UE (which remains acceptable) but 1 for a single polarized UE when the XPD is large, irrespective of the number of receive antennas.

However in case this configuration is implemented, we recommend the use of the following codebooks.

A suggested 4 bits codebook would be

$$\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ j & -j & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & j & -j \end{bmatrix}$$

with transmission performed only on orthogonal polarizations. Due to small spacing, we can expect that the maximum rank will 2, for 4x2 and 4x4 configurations. Therefore the 4 bits codebook is given

$$\text{rank 1: } \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ -j \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ j \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ -j \end{bmatrix} \tag{10}$$

$$\text{rank 2: } \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ j & 0 \\ 0 & 1 \\ 0 & j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ j & 0 \\ 0 & 1 \\ 0 & -j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -j & 0 \\ 0 & 1 \\ 0 & j \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -j & 0 \\ 0 & 1 \\ 0 & -j \end{bmatrix}$$

If a 5 bits codebook is chosen, we propose the use of

$$\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ e^{j\frac{\pi}{4}} & -e^{j\frac{\pi}{4}} & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & e^{j\frac{\pi}{4}} & -e^{j\frac{\pi}{4}} \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ j & -j & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & j & -j \end{bmatrix}, \begin{bmatrix} 1 & 1 & 0 & 0 \\ e^{j\frac{3\pi}{4}} & -e^{j\frac{3\pi}{4}} & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & e^{j\frac{3\pi}{4}} & -e^{j\frac{3\pi}{4}} \end{bmatrix}$$

where transmission should also be performed only on orthogonal polarizations. We believe however that 4 bits codebook is enough.

4 Numerical Results

We assume 4x2 flat fading SU-MIMO channels with dual and single polarized UEs and perform link level simulations. The node B is assumed dual polarized. We evaluate in Figure 4 the gain achievable with the proposed codebook and the identity matrix codebook 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. 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. In Figure 4, ‘dual→dual’ and ‘dual→single’ refer to a transmission from a dual-polarized node-B to a dual-polarized UE and to a single-polarized UE, respectively. Full CSS refers to the use of column subset selection over all possible combinations. Partial CSS refers to the case where only matrices like (6) are used for rank 2 transmission (as proposed in [2-3]).

From the simulation results in 4x2, we observe

- The proposed codebook (5 bits FBI) significantly outperforms the identity matrix codebook (4 bits FBI) in both small and large XPD environments
- The use of partial CSS is extremely detrimental to single polarized UE but does not affect the performance of dual-polarized UE, when χ is small.

In Figure 5, we illustrate the performance gain by using the proposed block diagonal codebook (8) over DFT codebook with 3 matrices and identity matrix codebook in 4x2 environment when we account for the distribution of the XPD (contrary to Figure 4 where the XPDs were fixed to two extreme values). Full column subset selection is used. Narrowband transmission over SCM “urban micro” channel with 6 clusters is performed. Vertical and horizontal polarized antennas are assumed at the node-B and the UE. Inter-element spacing of 10λ between the two polarized antenna pairs is used at the node-B. Polarized antennas are assumed to be co-located. The average capacity is calculated for each channel profile over a fading distance of 50λ . In Figure 5, the CDF of the average capacity over 1000 channel profiles is displayed. The SNR is fixed to 10 dB. Results are in accordance with the behavior highlighted in Figure 4 and [1]. The proposed codebook with a block diagonal structure has a non negligible performance gain over identity matrix and codebook designed for single-polarized antenna, e.g. the DFT codebook.

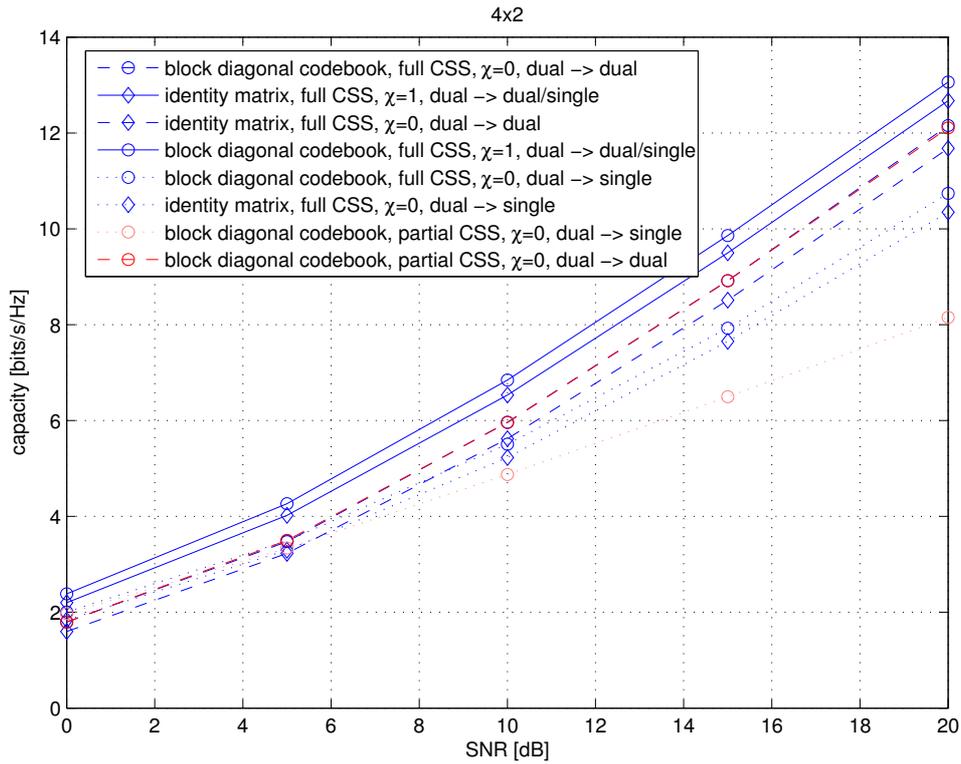


Figure 4: Capacity comparison of SU-MIMO with the proposed codebook (8) and the ‘identity matrix’ codebook in 4x2 dual-polarized MIMO channels.

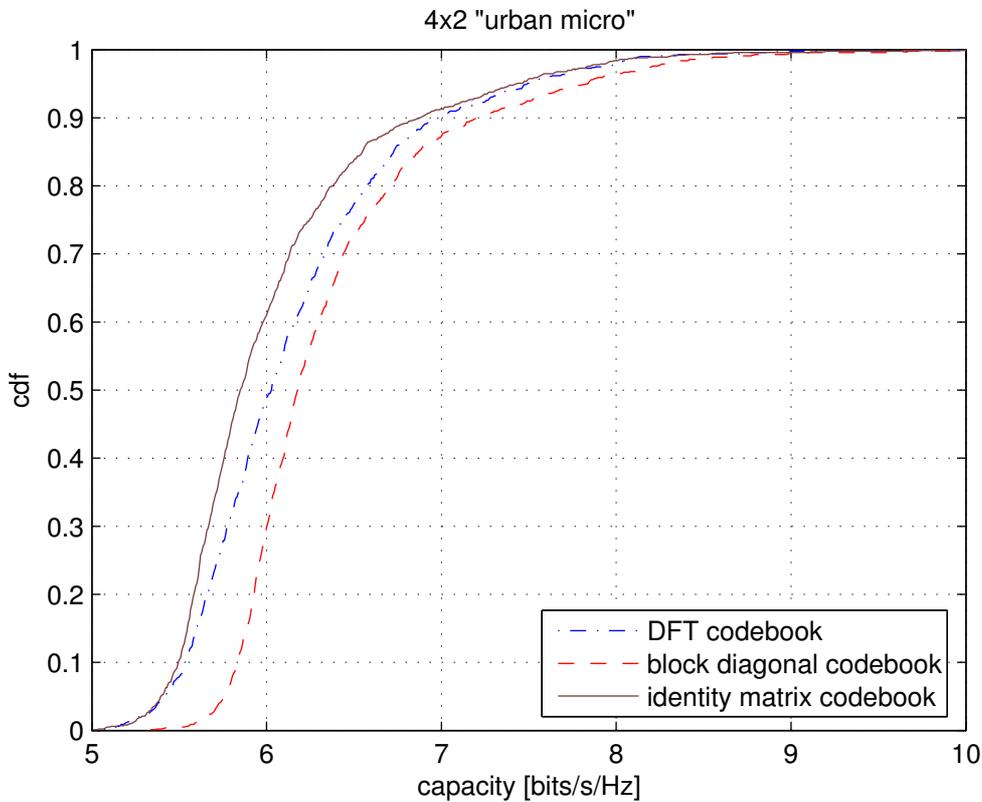


Figure 5: Capacity comparison of SU-MIMO with the proposed codebook (8), the ‘identity matrix’ codebook and DFT codebook in 4x2 dual-polarized MIMO channels.

5 Conclusions

This contribution proposes and justifies the use of

- codebooks with block diagonal structure for dual-polarized MIMO transmissions.
- column subset selection over all possible combinations in order to cope with the fact that UEs may have different polarizations.
- 5-bit codebook given in (8) for 4x2 configurations where the spacing between antenna pairs is large.
- 6-bit codebook generated by (9) for 4x4 configurations where the spacing between antenna pairs is large.
- 4-bit codebook given in (10) for 4x2 and 4x4 configurations where the spacing between antenna pairs is small.

6 References

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