Joint STBC and Pre-Filtering Technique for MISO TDD Downlink MC-CDMA Systems

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Abstract—**The paper considers downlink space-time block coding with a pre-filtering technique for time division duplex MC-CDMA. We consider the use of antenna arrays at the base station (BS) and a single antenna at the mobile terminal. The space-time block codes allow that the spatial diversity be efficiently exploited and the multi-user pre-filtering technique allows to format the transmitted signals so that the multiple access interference at mobile terminals is reduced without enhancing the noise power, allowing to transfer the most computational complexity from mobile terminal to the base station. Simulations results are carried out in scenarios with spectral efficiency equal 2, 3 and 4 bps/Hz without channel coding and 1.5, 2 bps/Hz with UMTS channel turbo code, to demonstrate the effectiveness of the proposed joint STBC and multi-user pre-filtering algorithm in a high data rate context.**

I. INTRODUCTION

As demand for wireless services increases, more capacity is needed, and since the spectrum is a very scarce resource, the development of efficient techniques regarding the usage of this resource are mandatory. MC-CDMA is one the most promising multiple access scheme for achieving high data rates, in order to meet the quality of service requirements of the future multimedia application [1]. This scheme combines efficiently Orthogonal Frequency Division Multiplex (OFDM) and CDMA. Therefore, MC-CDMA benefits from OFDM characteristics such as high spectral efficiency and robustness against multi-path propagation, while CDMA allows a flexible multiple access with good interference properties for cellular environments [2]. However, the user capacity of MC-CDMA system is essentially limited by the Multiple Access Interference (MAI). MC-CDMA is for example studied within the European IST-MATRICE and 4MORE projects [3][4].

It is consensual that provision of the broadband wireless component will probably rely on the use of multiple antennas at transmitter/receiver side. For the DL using multiple antennas at the BS is more feasible than at the MT. Thus, transmit diversity schemes relying on multiple transmit antennas are very attractive. Space-time coding schemes, such as space-time block coding (STBC), relying on multiple antenna at transmitter side and appropriate signal processing in the receiver were proposed [5][6]. Recently, the combination of STBC with MC-CDMA has been proposed using conventional single user equalizers at the MT [7][8]. In [7], it has been shown that for the same throughput Alamouti's STBC MC-CDMA outperforms Tarokh's MC-CDMA because the latter has a rate lower than one and therefore an higher order modulation is mandatory to get the same spectral efficiency. However, the performance of these STBC MC-CDMA combined with single user equalization is still far way from channel capacity limits.

Since low complexity is required at MTs, only simple and single user equalizers techniques can be implemented, limiting the MAI cancellation capability. Motivated by this constraint at the MT, this paper proposes a joint space-time coding and pre-filtering technique for the downlink of MC-CDMA systems. This technique use Time Division Duplex (TDD) channel reciprocity between alternative uplink and downlink transmission periods. The knowledge of the channel state information (CSI) from the uplink can be used to improve the performance in the downlink. The crucial assumption is that channel dynamics are sufficiently slow so that the multi-path profile remains essentially constant over the block of transmitted symbols. Normally, this principle is valid for indoor and pedestrian environments, i.e. in low mobility scenarios. STBC allows that the spatial diversity be efficiently exploited and the multi-user pre-filtering technique allow to format the transmitted signal so that the MAI at mobile is completely removed without enhancing the noise power, keeping it at very low complexity. The pre-filtering processing is performed in the frequency domain and the algorithm is designed using as criterion the minimization of the transmitted power at the BS. This issue is very important because it avoids excessive transmit power allocation.

The paper is organized as follows: In section II we present the proposed downlink MC-CDMA system. In section III, we analytically derive the joint STBC and pre-filtering algorithm which we call joint multi-user constrained zero forcing (*J*-MCZF). In section IV, we present some simulation results obtained with the *J*-MCZF for several modulations schemes, such as, QPSK, 8-PSK and 16-QAM in order to assess the pre-filtering algorithm in a high data rate context. We also compare the *J*-MCZF with conventional STBC schemes using single user equalizer techniques such as, Zero Forcing Combining (ZFC) and Minimum Mean Square Error Combining (MMSEC). Finally, the main conclusions are presented in section V.
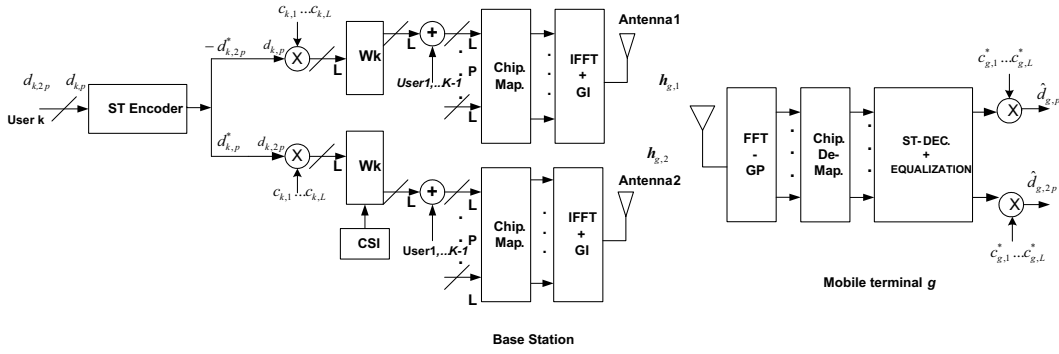
Figure 1: Transmitter and receiver schemes proposal for downlink MC-CDMA

II. SYSTEM MODEL

Figure 1 shows the proposed downlink MC-CDMA transmitter and receiver of the kth user based on joint Alamouti's space-time coding and pre-filtering with $M=2$ transmit antennas and $N=1$ receive antenna. After channel coding and interleaving, the bit streams are mapped into a QPSK, 8-PSK or 16-QAM constellations, which for simplicity are omitted in Figure 1. Each user k transmits $P= N_c/L$, (where N_c is the number of carriers and L the length of the spreading code) data symbols per OFDM symbol, from two antennas the data symbol $d_{k,p}$ and $d_{k,2p}$ at time t, and the symbols $-d_{k,2p}^*$ and $d_{k,p}^*$ at time $t+T$, where T is the OFDM symbol duration. Then the encoded data symbols are spread into L chips using the orthogonal Walsh-Hadamard code set. We denote the code vector of user k as $\boldsymbol{c}_k = \left[c_{k,1},...,c_{k,q},...,c_{k,L}\right]^T$,where $c_{k,q}$ is the qth chip and $(.)^T$ denotes the transpose operator. Thus the chips are weighted by a vector $\boldsymbol{w}_k = \left[w_{k,1},...,w_{k,q},...,w_{k,L}\right]^T$ of size L, where $w_{k,q}$ is the qth weight chip of the kth user. The same vector weight is applied to $d_{k,p}$, $d_{k,2p}$, $-d_{k,2p}^*$ and $d_{k,p}^*$ spreaded space-time encoded data symbols, i.e, we compute a vector weight for each four space-time encoded data symbol, which are calculated using the CSI according the criterion presented in next section. After that, the signals of all users on each sub-carrier and antenna branch are added to form the muti-user transmitted signal. Finally, the chips are frequency interleaved and a guard interval is inserted to avoid ISI interference. We consider frequency non-selective Rayleigh fading channel per subcarrier. However, due to the frequency interleaving operation, each data symbol experiences L uncorrelated frequency complex channel fading coefficients increasing the frequency diversity gain.

The received signal at mobile g, for symbols p and $2p$ at the instants t and $t+T$ is given by,

$$x_g(t) = \sum_{k=1}^{K} (d_{k,p}\boldsymbol{c}_k \circ \boldsymbol{w}_k \circ \boldsymbol{h}_{g,1} + d_{k,2p}\boldsymbol{c}_k \circ \boldsymbol{w}_k \circ \boldsymbol{h}_{g,2}) + \boldsymbol{n}_g(t)$$
$$x_g(t+T) = \sum_{k=1}^{K} (d_{k,p}^*\boldsymbol{c}_k \circ \boldsymbol{w}_k \circ \boldsymbol{h}_{g,2} - d_{k,2p}^*\boldsymbol{c}_k \circ \boldsymbol{w}_k \circ \boldsymbol{h}_{g,1}) + \boldsymbol{n}_g(t+T)$$

(1)

where $\boldsymbol{h}_{g,m} = \left[h_{g,m,1},...,h_{g,m,q},...,h_{g,m,L}\right]^T$ is the channel frequency response between antenna m and mobile g and each

components $h_{g,m,q}$ represents the frequency complex fading channel for mobile g, antenna m and subcarrier q; $\boldsymbol{n}_g(t)$ is the additive white Gaussian noise and (o) denotes the element wise vector product. We consider the channel response constant over two adjacent OFDM symbols.

At the receiver side we propose a very simple single user equalizer, with the coefficients given by:

$$z_{g,m,q} = h_{g,m,q}^* / \sum_{m=1}^{M}|h_{g,m,q}|$$

(2)

These equalization coefficients are slightly different from the ones used by an EGC equalizer, which are given by,

$$CoefEgc_{g,m,q} = h_{g,m,q}^* / \left|h_{g,m,q}\right|$$

(3)

The reason to use the equalization coefficients of (2) instead of (3), is due to the fact that with the coefficients of (2) we do not get intersymbol interference in the ST decoding process contrarily to what would arise using (3).

After space-time decoding and equalization with the coefficients presented in (2), we obtain the decision variable for symbol p or $2p$,

$$\hat{d}_{g,p} = \underbrace{\boldsymbol{c}_g^H (\boldsymbol{f}_g \circ \boldsymbol{w}_g \circ \boldsymbol{c}_g)d_{g,p}}_{DesiredSignal} +$$
$$\underbrace{\sum_{k=1,k\neq g}^{K} \boldsymbol{c}_g^H (\boldsymbol{f}_g \circ \boldsymbol{w}_k \circ \boldsymbol{c}_k)d_{k,p}}_{MAI} + \underbrace{\boldsymbol{c}_g^H (\boldsymbol{z}_{g,1} \circ \boldsymbol{n}_g(t)) + \boldsymbol{c}_g^H (\boldsymbol{z}_{g,2} \circ \boldsymbol{n}_g(t+T))}_{Noise} \quad (4)$$

where $\boldsymbol{f}_g$ is a vector of size L, and each elements given by,

$$\boldsymbol{f}_g = \left[\sum_{m=1}^{M}\frac{|h_{g,m,1}|^2}{|h_{g,m,1}|},...,\sum_{m=1}^{M}\frac{|h_{g,m,q}|^2}{|h_{g,m,q}|},...,\sum_{m=1}^{M}\frac{|h_{g,m,L}|^2}{|h_{g,m,L}|}\right]$$

(5)

The signal of (4) involves the three terms: the desired signal, the MAI caused by loss of code orthogonality among the users, and the residual noise after despreading. As it can be seen from (4) using the equalization coefficients of (2) we have only MAI, the intersymbol interference is removed from the ST decoding process. The pre-filtering algorithm proposed in the

next section completely removes the MAI component and eliminate the deep fades of (4).

III. PRE-FILTERING ALGORITHM

The use of pre-filtering algorithms has the following main advantages: reduce the MAI at mobile terminals by pre-formatting the signal so that the received signal at the decision point is free from interferences without enhancing the noise power at receiver side and allow to move the most computational burden from MT to BS, keeping the MT at a low complexity level. The multi-user pre-filtering algorithm is based on zero forcing criteria. This algorithm is designed in frequency domain in order to remove the MAI term of (4) at all MTs. Furthermore, it takes into account the transmitted power at BS, reason why we call this algorithm the joint multi-user constrained zero-forcing (*J-MCZF*).

The interference that the signal of a given user g produces at an other MT k is from (4) given by

$$MAI(g \rightarrow k) = \boldsymbol{c}_k^H (\boldsymbol{f}_k \circ \boldsymbol{w}_g \circ \boldsymbol{c}_g) = \boldsymbol{v}_{k,g}^T \boldsymbol{w}_g \qquad (6)$$

with $\boldsymbol{v}_{k,g} = \boldsymbol{c}_k^* \circ \boldsymbol{f}_k \circ \boldsymbol{c}_g$.

The weight vector for user g is then obtained by constraining the desired signal part of its own decision variable to a constant while cancelling its MAI contribution at all other mobile terminals at same time. This leads to the following set of conditions,

$$\begin{cases} \boldsymbol{c}_g^H (\boldsymbol{f}_g \circ \boldsymbol{w}_g \circ \boldsymbol{c}_g) = \alpha_g \\ \boldsymbol{c}_k^H (\boldsymbol{f}_k \circ \boldsymbol{w}_g \circ \boldsymbol{c}_g) = 0 \qquad \forall k \neq g \end{cases} \qquad (7)$$

Hence, to compute the weights for user g we have to solve a linear system of K equations given by,

$$A_g \boldsymbol{w_g} = \boldsymbol{b} \qquad (8)$$

where A_g is a matrix of size KxL and $\boldsymbol{b}$ a vector of size K, given by,

$$A_g = \begin{bmatrix} \left[\sum_{m=1}^M \frac{|\boldsymbol{h}_{g,m,1}|^2}{|\boldsymbol{h}_{g,m,1}|}, \dots, \sum_{m=1}^M \frac{|\boldsymbol{h}_{g,m,q}|^2}{|\boldsymbol{h}_{g,m,q}|}, \dots, \sum_{m=1}^M \frac{|\boldsymbol{h}_{g,m,L}|^2}{|\boldsymbol{h}_{g,m,L}|} \right] \\ \boldsymbol{v}_{0,g}^T \\ \vdots \\ \boldsymbol{v}_{g-1,g}^T \\ \boldsymbol{v}_{g+1,g}^T \\ \vdots \\ \boldsymbol{v}_{K-1,g}^T \end{bmatrix} \quad \boldsymbol{b} = \begin{bmatrix} \alpha_g \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

As stated above the pre-filtering algorithms should take into account the minimization of the transmitted power. Here, the transmitted power must be minimized under the K constraints given by (8). It can be seen from (7) that we only need to know the modulus of the channel frequency at the BS. Basically, we just perform a pre-amplitude equalization. This problem can be solved using the method of Lagrange multipliers [9] [10].

After same mathematical manipulations, we obtain the *J-MCZF* based pre-filtering vector,

$$\boldsymbol{w}_g = \alpha_g A_g^H (A_g A_g^H)^{-1} \boldsymbol{b} = A_g^H \psi_g^{-1} \boldsymbol{b} \qquad (9)$$

where $\psi_g = A_g A_g^H$ is a square and Hermitian matrix of size *KxK* and α_g is a constant used to normalize the vector according,

$$|\boldsymbol{w}_k|^2 = \boldsymbol{w}_k^H \boldsymbol{w}_k = 1 \quad \forall k = 1...K \qquad (10)$$

ensuring that the pre-filtering weight vector always has unit norm in order to compare with systems without pre-equalization.

Observing equation (9) it easy to see that the most computational intensive task to obtain the weights, comes from matrix Ψ_g inversion. However, the size of this real matrix is just *KxK* independently of the spreading factor and the number of antennas, which makes this algorithm very attractive for real time applications.

IV. NUMERICAL RESULTS

To evaluate the performance of the proposed pre-equalization algorithm, we used a pedestrian Rayleigh fading channel, whose system parameters are derived from the European BRAN Hiperlan/2 standardization project [11]. We extended this time model to a space-time, assuming that the distance between antenna elements is large enough, to consider for each user M independents channels, i.e, we assume independent fading processes. The main parameters used in the simulations are presented in Table 1.

Table 1: Main simulation parameters.

Number of Carriers	1024
Spreading factor	32
Guard period samples/time	256 / 6.4μs
Number of users	32 (full load)
Total OFDM symbol duration (T_s)	32μs
Modulation	QPSK/8-PSK/16-QAM
Sampling frequency	40Mz
Frame duration	32*Ts
Channel profile	BRAN E
Maximum delay	1.76μs
Number of paths	18

It is assumed that the receiver and transmitter have perfect knowledge of the channel. We considered a DL synchronized transmission using Walsh-Hadamard spreading sequences of length 32 scrambled by a pseudo-random code. The channel is

considered to be constant during a number of OFDM symbols equal to the length of the space-time code considered, that is two OFDM symbols for Alamouti's STBC, or eight and four for Tarokh's code of rate 1/2 and 3/4 respectively. The transmitter power is normalized to one in all presented schemes

We compare the joint multi-user pre-filtering with Alamouti's and Tarokh's STBC using conventional single user equalizers at the MT, such as MMSEC and ZFC. We present results for three different spectral efficiencies η=2,3,4 bps/Hz when no channel coding is used and η=1.5,2 when a half rate channel code is applied, in order to assess the proposed scheme in high data rate context scenario. The channel coding scheme is the turbo-code defined for UMTS, combined with a puncturing process and an interleaver to have an overall coding rate of 1/2.

Figure 2, 3, 4 show the performance results obtained without channel coding, while figures Figure 5 and Figure 6, show the performance considering the referred channel turbo-code. The metric used is the average bit error rate (BER) as function of Et/No, the transmitted energy (assuming a normalized channel) per bit over the noise spectral density.
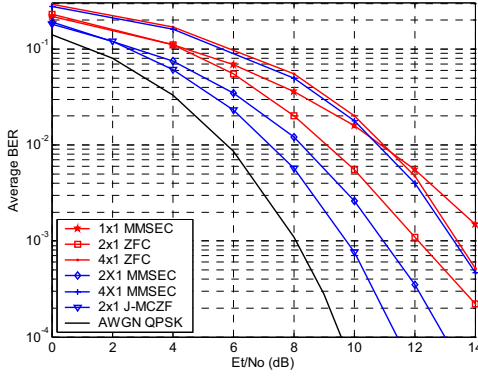

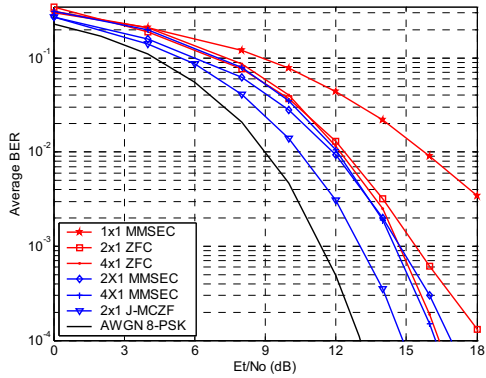Figure 2: Schemes comparison of η=2 bps/Hz without channel coding.

Figure 3: Schemes comparison of η=3 bps/Hz without channel coding
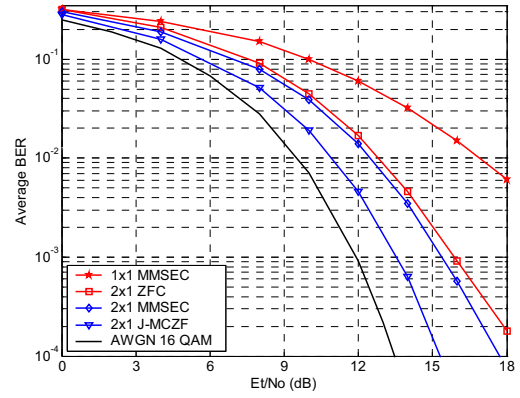

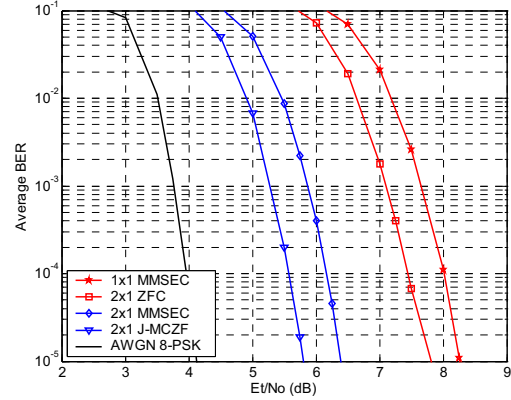Figure 4: Schemes comparison of η=4 bps/Hz without channel coding.

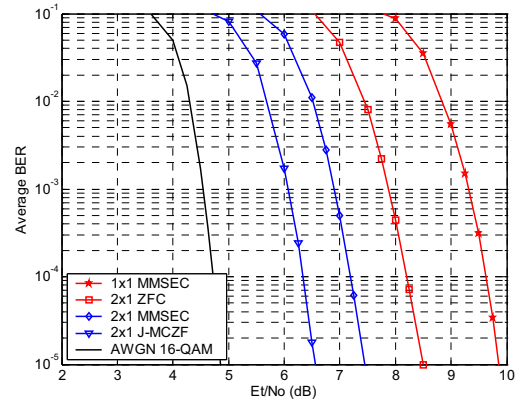Figure 5: Schemes comparison of η=1.5 bps/Hz with half rate channel turbo coding.

Figure 6: Schemes comparison of η=2 bps/Hz with half rate channel turbo coding.

Figure 2 shows the performance of the proposed *J*-MCZF algorithm against STBC schemes employing two and four antennas and using ZFC and MMSEC equalization. To have the same spectral efficiency of 2 bps/Hz in all cases, the modulation schemes are:

- QPSK for MMSEC single antenna, *J*-MCZF and STBC schemes with two antennas, since these techniques have unity-rate.

- 16-QAM for STBC with four antennas and 1/2 rate.

As can be observed from this figure the performance of the *J*-MCZF outperforms all STBC schemes. For a BER=1E-3, we get approximately 1.2dB and 2.3 dB gain, when compared with STBC with two antennas and using MMSEC and ZFC equalization, respectively. When we use Tarokh's STBC with half rate, to keep the same spectral efficiency we need to use a high order modulation, which is more prone to errors and hence the performance is degraded. It must be noted that when MMSEC equalization is applied the noise power must be estimated at the MT thus increasing the complexity. However, with the *J*-MCZF algorithm we obtain better performance without the need to estimate the noise power. We also can observe that all schemes with a multiple-antenna array at the BS side outperform the conventional SISO single user MMSEC. Figure 3 shows the performance of the proposed *J*-MCZF algorithm against STBC schemes with two and four antennas using ZFC and MMSEC equalization. To have the same spectral efficiency of 3 bps/Hz in all cases, the modulation schemes are:

- 8-PSK modulation for *J*-MCZF, single antenna MMSEC and STBC schemes with two antennas.

- 16-QAM for STBC with four antennas and 3/4 rate.

In this scenario we also can observe that the performance of the *J*-MCZF outperforms all STBC schemes. For a BER=1E-3, we get approximately 1.8dB gain, as compared with STBC schemes using MMSEC and ZFC equalization. As the performance of Gaussian SISO systems with 8-PSK and 16-QAM are closer, there is less difference between Tarokh's codes with four antennas associated with QAM modulation and 8-PSK associated with Alamouti´s codes with two antennas.

Figure 4 shows the performance of the proposed *J*-MCZF algorithm against STBC schemes for two antennas using ZFC and MMSEC equalization. All schemes considered in this figure have unity-rate, and we consider for all cases a 16-QAM modulation, resulting in a theoretical spectral efficiency of 4 bps/Hz. In this scenario we can see that the performance of the *J*-MCZF outperforms all STBC schemes. For BER=1E-3, we get approximately 2dB and 2.2 dB gain, when compared with STBC schemes using MMSEC and ZFC equalization, respectively. Observing the three considered scenarios the relative performance of the J-MCZF against the one obtained with STBC improves as the modulation order increases which makes this algorithm very interesting for high data rate context.

Figure 5 and Figure 6 compare the performance of the *J*-MCZF against Alamouti's MMSEC and ZFC schemes for spectral efficiencies of 1.5 and 2.0 bps/Hz. Basically, we applied a half channel turbo code to the curves presented in

Figure 3,4. As expected, the BER performance with turbo code mainly depends on performance at low Et/No without channel coding. From Figure 5 we can observe that the *J*-MCZF outperforms STBC Alamouti's MMSEC and ZFC single user equalizers. For a BER=1.0E-5, we get approximately 0.7dB and 2.0dB gain when compared with MMSEC and ZF, respectively. From Figure 6 we can take the same conclusions. However in this case, we get approximately 1.0dB and 2.0dB gain when compared with MMSEC and ZFC, respectively. Thus, we show that even for low values of Et/No the *J*-MCZF outperforms STBC codes using single user equalizers, with lower complexity than MMSEC STBC.

V. CONCLUSION

We proposed a joint STBC with a pre-filtering algorithm for downlink TDD MC-CDMA, using antenna arrays at BS and single antenna at mobile terminal. We analytically derived the proposed pre-filtering algorithm, based one a constrained zero-forcing criterion. The performance was assessed for scenarios with spectral efficiency equal 2, 3 and 4 bps/Hz with no channel coding and 1.5 and 2 bps/Hz with UMTS channel turbo codes. We compared the performance of proposed *J*-MCZF against STBC using MMSEC and ZFC single user equalization. We demonstrated that *J*-MCZF algorithm allows a significant improvement of the user capacity, outperforming the STBC schemes using single user equalizer, keeping the mobile terminal at low complexity.

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