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# Performance of Waterfilling-based Schemes for Interference Cancellation in 4G networks

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***Abstract*—In this work we consider the optimization of the power assigned to the user streams in a coordinated base station downlink environment with Orthogonal Frequency Division Modulation (OFDM). In this scenario the base stations perform distributed cooperative processing with a block diagonalization scheme to remove interference among users. Two schemes based on the waterfilling technique are proposed and compared to the optimal solution, which can be obtained numerically, by using convex optimization.**

**We show that the proposed schemes achieve a performance, in terms of weighted sum rate, very close to the optimal, without the heavy computational complexity required by the numerical solution. These sum rates are compared in a simplified scenario consisting of two-user and two-cell. Other more realistic multicell scenario and some examples of achievable rates are presented too.**

## I. Introduction

Following the increasing demand of higher data rates and mobility in wireless communications, Orthogonal Frequency Division Multiplexing (OFDM) has become a solution to the problem of transmitting data over wireless channels with large delay spread [1]. This technology has been adopted in several wireless standards such as Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB-T), IEEE 802.11a or the IEEE 802.16a, and it has become fundamental in the downlink of 4G systems as Long Term Evolution (LTE) and LTE-Advanced.

OFDM may be combined with antenna arrays at the transmitter and receiver in frequency-selective channels in order to increase the system capacity and/or achieve additional diversity without using additional bandwidth [2]. However, achieving a capacity increase through MIMO techniques in actual celullar networks requires significant Signal-to-Noise-plus-Interference Ratios (SINR) values which can be found only in the proximity of base stations (BS). In current OFDM-based cellular networks users with same frequency assignment in nearby cells will experience large inter-cell interference (ICI), particularly at cell boundaries, leading to a decreased capacity. Hence ICI becomes a major performance limiting factor in cellular OFDM systems so that it can be concluded that processing techniques which successfully lower interference levels would automatically increase the usefulness of MIMO processing in these environments.

Lately interference mitigation techniques have been studied in order to improve the capacity in 4G networks [3]. According to standards and literature, the ICI mitigation techniques include ICI coordination, ICI randomization, and ICI cancellation techniques [4]. We focus here on ICI cancellation schemes, which have been proposed as another approach for improving both system throughput and cell-edge performance. In [5]-[7] downlink transmission schemes with ICI cancellation processing based on the joint detection of desired and interference signals for MIMO/OFDM cellular systems was introduced. The inconvenience of these joint detection based ICI cancellation algorithms is the extremely heavy computation loads on the Mobile Stations (MS) due to nonlinear signal processing of the algorithms used. Sphere and Dirty Paper Decoding are two decoding algorithms potentially applicable to 4G systems [3]. The interest of Sphere Decoding is based on its potential to provide close to a Maximum Likelihood (ML) decoding result at significantly lower complexity than an ML decoder. Dirty Paper Coding (DPC) has been proposed as an approach to eliminate interference in systems where joint decoding is not possible. The idea is to precode each transmission such that the desired signal is mapped into a known code space. The receiver will have knowledge of the precoding code space which can be employed to decode the desired signal in presence of ICI. However, this approach has a high implementation complexity. Recently, Coordinated Multi-Point transmission/reception (CoMP) has received significant attention in academic literature and it has been considered by 3GPP as a tool to mitigate ICI and hence improve coverage, cell-edge throughput, and/or system efficiency in 4G networks [9]. The main idea of CoMP is as follows: when the same spectrum resources are used, a user equipment placed in the cell-edge region may receive signals with similar power from multiple cell sites. If the signalling transmitted from the multiple cell sites is coordinated, the ICI can be mitigated and consequently the downlink performance can be increased significantly. This coordination can be simple as in the techniques that focus on interference avoidance or more complex as in the case where the users' distributed data is cooperatively processed and then transmitted coherently from multiple cell sites.

In [2] [8] several coordinated strategies based on DPC and Block Diagonalization (BD) schemes are proposed where both schemes achieve the interference cancellation initial step and then the transmit powers for each base station antenna must be obtained. The optimal power assignment is solved by convex optimization to maximize the minimum transmission rate for all users and important improvements in spectral-efficiency are shown by simulation.

In this paper, we focus on BD-based CoMP with the aim of maximizing the weighted sum rate (WSR) of the users of multiuser OFDM systems in a downlink transmission. We will formulate the cooperative processing for interference cancellation and the power optimization problem when OFDM is used. We will derive two power allocation schemes that resemble the well-known waterfilling distribution. These schemes based on the waterfilling technique were initially proposed by the authors in [10], but only for narrowband modulations. In this work, we will extend the interference cancellation scheme and the power allocation strategies when OFDM systems are employed and we will study its behaviour using different channel models and BS-MS deployment scenarios. To that end, we will examine the achievable rates in a 2-user simplified scenario and the distribution of the rates obtained in a more realistic system emulating a 16-cell cellular network. The channel models used for the study include the standardised Spatial Channel Model (SCM) developed by 3GPP for evaluating MIMO system performance in outdoor environments and usually used in 3G and 4G networks' simulation [11]. In the results, we will show that the schemes that we are proposing, although suboptimal, perform close to the optimum power allocation – obtained by convex optimization – with a reduced complexity.

The remainder of this paper is structured as follows. In section II the system model is presented, in section III the proposed power allocation schemes are developed and section IV discusses some numerical results. The paper finishes with some concluding remarks.

## II. System Model

The system model assumes a coordinated transmission downlink cellular scenario based on OFDM, where $M$ cooperating BS serve $N$ users or MS. Each base station has $t$ transmit antennas and each user has $r$ receive antennas, being also $r$ the number of streams of information addressed to each user. In the following, the analysis will be applied to BS-user pairs, therefore the case $M=N$ will be considered.

The principle of OFDM is to split a high-rate data stream into a number of lower rate streams, which are then simultaneously transmitted on a number of orthogonal subcarriers. Hence, each subcarrier experiences approximately frequency-flat fading and it can be dealt with independently from the others. We consider a CoMP system with OFDM where the whole channel is known to all BS. This is usually the case for a bidirectional transmission system where Channel State Information (CSI) is available at the receiver side after channel estimation and a signalling channel can be used to forward the CSI to the transmitter. We assume a linear time-invariant channel with frequency selective fading and additive Gaussian noise. Provided that the length of the cyclic prefix is chosen longer than the longest impulse response, the channel seen by each user can be decomposed into $N_{OFDM}$ independent flat subchannels with frequency response $\mathbf{H}_k^p$ for the user $k$ and the subchannel $p$.

Despite there seems to be a pairing between BS and users being served in the system, it should be noted that in a CoMP scheme, where cooperative processing is used to avoid interference, all BS serve all users. Thus we will consider that the transmitted signal from a particular BS arrives, with different propagation conditions (path loss and fading), to all the users in the cellular system. Under this assumption, the channel on each subcarrier $p$ $(p=1\dots N_{OFDM})$ may be modelled by a $Nr\times Mt$ matrix $\mathbf{H}^p$ where each matrix coefficient represents the fading from each transmit antenna in the BS to each receive antenna at the user side.

The received signal model is, on the $p$-th subcarrier, as follows

$$\mathbf{y}^p=\mathbf{H}^p\mathbf{x}^p+\mathbf{n}^p \tag{1}$$

where $\mathbf{y}^p$ is the received $Nr\times 1$ signal vector on the $p$-th subcarrier, $\mathbf{x}^p$ is the $Mt\times 1$ signal vector transmitted from all the BSs on the $p$-th subcarrier, and $\mathbf{n}^p$ is the $Nr\times 1$ i.i.d complex Gaussian noise vector on the $p$-th subcarrier, with variance $\sigma^2$. If we define $\mathbf{H}_k^p$, with $k=1\dots N$, as the $r\times Mt$ channel matrix seen by user $k$ on the $p$-th subcarrier, then $\mathbf{H}^p=\left[\mathbf{H}_1^{p\mathrm{T}}\mathbf{H}_2^{p\mathrm{T}}\dots\mathbf{H}_N^{p\mathrm{T}}\right]^{\mathrm{T}}$.

For this scenario we define $\mathbf{x}^p$ as follows

$$\mathbf{x}^p=\sum_{i=1}^{r}b_{1i}^p\mathbf{w}_{1i}^p+\sum_{i=1}^{r}b_{2i}^p\mathbf{w}_{2i}^p+\cdots+\sum_{i=1}^{r}b_{Ni}^p\mathbf{w}_{Ni}^p=\mathbf{W}^p\mathbf{b}^p \tag{2}$$

where $b_{ki}^p$ represents the symbol of the $i$-th stream $(i=1\dots r)$ of user $k$ with power $P_{ki}^p$ on the $p$-th subcarrier, and $\mathbf{w}_{ki}^p=\left[w_{ki}^{p,1},\dots,w_{ki}^{p,(m-1)t+j},\dots,w_{ki}^{p,Mt}\right]^{\mathrm{T}}$ are the precoding vectors being $w_{ki}^{p,(m-1)t+j}$ the weight of $j$-th transmit antenna $(j=1\dots t)$ of the $m$-th base station for the $i$-th symbol of the user $k$ transmitted on the $p$-th subcarrier. The precoding matrix $\mathbf{W}^p=\left[\mathbf{w}_{11}^p,\dots,\mathbf{w}_{1r}^p,\dots,\mathbf{w}_{k1}^p,\dots,\mathbf{w}_{kr}^p,\dots,\mathbf{w}_{N1}^p,\dots,\mathbf{w}_{Nr}^p\right]$, will be obtained under a BD criteria as in [8], to guarantee that

$$\begin{aligned}&\mathbf{H}_k^p\left[\mathbf{w}_{q1}^p,\mathbf{w}_{q2}^p\dots\mathbf{w}_{qr}^p\right]=\begin{cases}\mathbf{0} & : \quad k\neq q\\ \mathbf{U}_k^p\mathbf{S}_k^p & : \quad k=q\end{cases},\\ &\parallel\mathbf{w}_{ki}^p\parallel^2=1,\quad k=1,\dots,N,\ i=1,\dots,r,\ p=1,\dots,N_{OFDM}\end{aligned} \tag{3}$$

where $\mathbf{U}_k^p$ is a unitary matrix and $\mathbf{S}_k^p=\mathrm{diag}\{(\lambda_{k1}^p)^{1/2},(\lambda_{k2}^p)^{1/2},\dots,(\lambda_{kr}^p)^{1/2}\}$ is a diagonal matrix that contains the square roots of the nonzero eigenvalues of the matrix $\mathbf{Q}_k^p\mathbf{Q}_k^{p\dagger}$, being $\mathbf{Q}_k^p$ the part of the channel matrix $\mathbf{H}_k^p$ orthogonal to the subspace spanned by other users' channels $\mathbf{H}_q^p$ $(q\neq k)$

Then, the received signal on $p$-th subcarrier can be expressed as

$$\mathbf{y}^p = \begin{bmatrix} \mathbf{U}_1^p\mathbf{S}_1^p & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{U}_2^p\mathbf{S}_2^p & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{U}_N^p\mathbf{S}_N^p \end{bmatrix} \mathbf{b}^p + \mathbf{n}^p \qquad (4)$$

Each user may independently rotate the received signal and decouple the different streams. Thus, the signal obtained by $k$-th user on $p$-th subcarrier can be expressed as

$$\widetilde{\mathbf{y}}_k^p = \mathbf{U}_k^p\mathbf{S}_k^p\mathbf{b}_k^p + \widetilde{\mathbf{n}}_k^p = \begin{bmatrix} \left(\lambda_{k1}^p\right)^{1/2} b_{k1}^p \\ \vdots \\ \left(\lambda_{kr}^p\right)^{1/2} b_{kr}^p \end{bmatrix} + \widetilde{\mathbf{n}}_k^p \qquad (5)$$

where the noise $\widetilde{\mathbf{n}}_k^p$ remains white with the same covariance because of the unitary transformation.

## III. Power allocation schemes

Under the BD-based CoMP strategy it can be observed from (5) that the overall system is then a set of parallel noninterfering channels. Therefore, in a MIMO-OFDM scenario based on BD-based CoMP, the achievable rates per user are as follows

$$R_k = \frac{1}{N_{OFDM}} \sum_{p=1}^{N_{OFDM}} \sum_{i=1}^{r} \log_2\left(1 + \frac{\lambda_{ki}^p P_{ki}^p}{\sigma^2}\right) \qquad (6)$$

We would like to maximize a weighted sum of the rates $R_k$ for the set of users, that requires solving the following optimization problem in terms of the power $P_{ki}^p$ allocated to the $i$-th stream of user $k$

$$\max\left\{\frac{1}{N_{OFDM}} \sum_{j=1}^{N} \alpha_k \sum_{p=1}^{N_{OFDM}} \sum_{i=1}^{r} \log_2\left(1 + \frac{\lambda_{ki}^p P_{ki}^p}{\sigma^2}\right)\right\} \qquad (7)$$

subject to a constraint on the maximum available power for transmission from each base station $m$ $P_{max}$

$$P_{BS_m} = \sum_{j=1}^{t} \underbrace{\sum_{p=1}^{N_{OFDM}} \sum_{k=1}^{N} \sum_{i=1}^{r} P_{ki}^p \left|w_{ki}^{p,\,((m-1)\cdot t+j)}\right|^2}_{j\ transmit\ antenna\ power} \leq P_{max} \qquad (8)$$

$$\forall m = 1 \dots M$$

In (7) the values $\alpha_k \in [0,1]$, ($\sum_{k=1}^{N} \alpha_k = 1$), can be seen as indicating the priorities of the users: the closer $\alpha_k$ is to 1, the higher the priority given to user $k$. In the particular case of $\alpha_k = 1/N$, for all $k$, the solution of the above problem maximizes the sum rate.

The problem above is convex since the logarithmic function is concave in the power assignments, the addition operation preserves concavity and the constraints (8) are linear. Therefore it can be solved by standard convex optimization techniques [13]. However, closed-form solutions, even if suboptimal, would be desirable in order to reduce the computational time and resources required for the optimization. Application of the Lagrange multiplier technique leads to solve this convex problem (see [10] for details). Thus, the general solution is given by:

$$\begin{cases} P_{ki}^p = \sigma^2\left[\dfrac{\alpha_k}{\ln(2) L_{ki}^p} - \dfrac{1}{\lambda_{ki}^p}\right]^+ \\ L_{ki}^p = -\displaystyle\sum_{m=1}^{M} \sum_{j=1}^{t} \mu_m \left|w_{ki}^{p,\,(m-1)t+j}\right|^2 \\ \displaystyle\sum_{j=1}^{t} \sum_{p=1}^{N_{OFDM}} \sum_{k=1}^{N} \sum_{i=1}^{r} P_{ki}^p \left|w_{ki}^{p,\,(m-1)t+j}\right|^2 = P_{max} \end{cases} \qquad (9)$$

where $k = 1,\dots,N$, $i = 1,\dots,r$, $p = 1,\dots,N_{OFDM}$ and $\mu = [\mu_1,\dots,\mu_M]$ is the vector of the Lagrange multipliers. This solution resembles the well-known waterfilling distribution. However, here the waterlevel is given by $\sigma^2\alpha_k/(\ln(2)L_{ki}^p)$, that is, the waterlevel is different for each symbol $i$ to be transmitted to each user $k$ on each subcarrier $p$. Even though the values of the waterlevels can be found again by convex optimization techniques, we still have a similar computational complexity that we would like to reduce.

### A. Modified waterfilling

By considering the most stringent of the constraints in (8) we can reduce the problem to an "equivalent" base station $m_0$ having for each symbol transmitted to each user the precoding weights whose sum of squared values is maximum among all the BSs, that is

$$\Omega_{ki}^p = \max_{m=1,\dots,M}\left(\sum_{j=1}^{t} \left|w_{ki}^{p,\,(m-1)t+j}\right|^2\right) \qquad (10)$$

Application of the Lagrange multiplier technique gives the new function whose solution is given by

$$P_{ki}^p = \left[K\frac{\alpha_k}{\Omega_{ki}^p} - \frac{\sigma^2}{\lambda_{ki}^p}\right]^+ \qquad (11)$$

with

$$K = \frac{-\sigma^2}{\ln(2)\mu} \qquad (12)$$

where $[\cdot]^+$ denotes the maximum between zero and the argument. This corresponds again to a waterfilling distribution with variable waterlevel. However, for given user priorities $\alpha_k$ and channel realization determining $\lambda_{ki}^p$ and $\Omega_{ki}^p$, the problem reduces to finding a constant $K$ that can be solved with the same algorithms that solve standard waterfilling (see for example [14]).

### B. Waterfilling

In order to further simplify the solution to the optimization problem we may consider the fact that in a practical realization the values of $\Omega_{ki}^p$ are close to each other for all $k$, $i$ and $p$. Then we can simplify the solution (11) to give

$$P_{ki}^p = \left[K\alpha_k - \frac{\sigma^2}{\lambda_{ki}^p}\right]^+ \qquad (13)$$

which corresponds to a waterfilling distribution with the waterlevel modified only by the user priorities. In particular for equal priorities $\alpha_k = 1/N$ it corresponds to a standard waterfilling.

## IV. Numerical results

In this section we compare the performance of the power allocation schemes in the cooperative processing for interference cancellation in terms of achievable rates of the proposed waterfilling (WF), modified waterfilling (MWF) and the optimum solution found by convex optimization (CVX). For the sake of comparison we also include the rates achieved when using a uniform power distribution (UP). In this last case the power allocated to each user transmission is the same and corresponds to the maximum value that fulfils the constraints in eq. (8).

The proposed algorithms are studied in different BS-MS deployment scenarios where users can be randomly placed in the cell with a uniform distribution, or are within a fixed radio of their paired BS. In the first case the cumulative distribution function (CDF) of the achievable rates of the users gives the distribution of rates considering any possible position in the cell, however in this scenario the influence of the user position is diluted. For this reason two fixed configurations are studied in a two-BS two-user scenario ($M = N = 2$). In *Configuration 1* both users are within the same radio of its paired BS, close enough to the BS so that the dominant received signal from the base stations is the one that is paired to that particular user. In *Configuration 2* one of the users is placed near its BS and the other one is placed in between the two cell boundaries. This last user will in average receive the same power from both BS in the system.

The channel models studied are a simple frequency-selective channel with an exponential power-delay profile (PDP) and the SCM channel specified by 3GPP for evaluating MIMO system performance in 4G networks [11]. The exponential model accounts for $N_{path} = 6$ paths and does not take into account any correlation in space or in time. The power of the $n$-th path can be written as

$$\mathrm{PDP}(n) = \frac{e^{-\beta n}}{\left(\sum_{c=1}^{N_{path}} e^{-2\beta c}\right)^{1/2}} = \left(\frac{1-e^{-2\beta}}{1-e^{-2\beta N_{path}}}\right)^{1/2} e^{-\beta n} \tag{14}$$

where $\beta$ is the factor which indicates the decreasing decay of the power. The SCM channel is a ray-based model based on stochastic modelling of scatterers. It defines three environments: Suburban Macro, Urban Macro, and Urban Micro. Besides, in Urban Micro environment can be identified Line-of-Sight (LOS) and non-LOS (NLOS) propagation. All environments are frequency selective with up to six dominant paths taken into account. Path powers, path delays, and angular properties for both sides of the link are modelled as random variables with cross-correlations as specified in [11], [12].

Other parameters for the simulations are $N_{OFDM} = 8$ and signal-to-noise ratio (SNR) values of SNR= 10 dB and SNR= 20 dB. The SNR are defined in the fixed scenarios (*Configuration 1* and *Configuration 2*) as the average SNR perceived by both users taking into account the channel fading and path loss and in the case of the uniform distribution of users as the SNR perceived by 90% of the users computed also taking into account the channel fading and path loss.

### *A. Achievable rates in a two-user scenario with different priorities*

The achievable rates of the interference cancellation scheme with the proposed power allocations is studied for a two user scenario $M = N = 2$ where the users are assigned different priorities (fig. 1). Each of the achievable rates pairs correspond to a pair of values of $\alpha_1$ and $\alpha_2$ that $\sum_{k=1}^{2} \alpha_k = 1$. The channel for this study follows the simple exponential model with an SNR= 10 dB and the users are randomly placed in the cell.

The fig. 1 shows that the achievable rates obtained with WF and MWF are very close to the optimal solution CVX and in most cases far from the performance of the UP. However, it is interesting to note the comparative behaviour of UP algorithm in the scenarios where $r < t$. For the configurations $t = 2$, $r = 1$ and $t = 4$, $r = 2$, WF and MWF performs similar to UP. The reason for that is that in these cases the values of the channel eigenvalues $\lambda_{ki}^{p}$ are similar, that is $\lambda_{k1}^{p} \approx \lambda_{k2}^{p} \approx \cdots \approx \lambda_{kr}^{p}$ and therefore the WF based solutions tend to a UP allocation scheme.

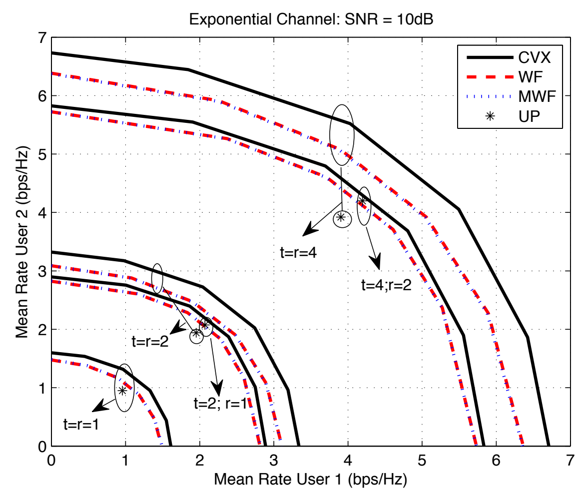
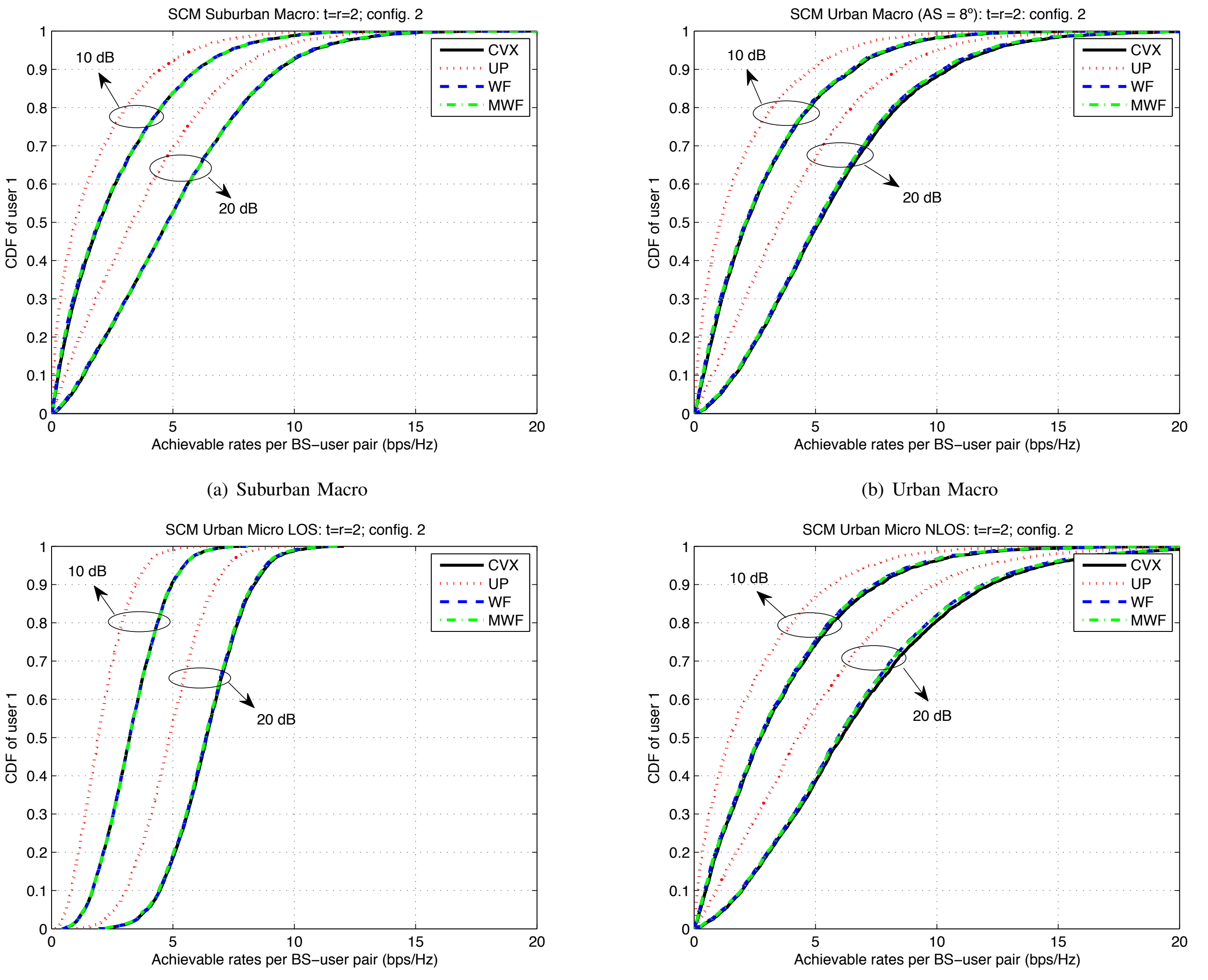



Fig. 1. Mean achievable rates with exponential channel ($\beta = 0.1$), $M = N = 2$ and several values of the number of transmit $t$ and receive $r$ antennas.

### *B. SCM performance in a two-user scenario*

The different environments specified by 3GPP to analyse 4G networks are studied for the two particular BS-MS deployments explained before. The motivation for that is to highlight the dependence of the user position within the cell in the performance of the interference cancellation strategy and its power allocation schemes. All users are given the same priority $\alpha_k = 1/N$. In a first stage, all SCM environments are studied with $M = N = t = r = 2$ and SNR= 10 dB providing the CDFs of the achievable rates (fig. 2). In a second stage, the mean




(a) Suburban Macro

(b) Urban Macro

(c) Urban Micro LOS

(d) Urban Micro NLOS

Fig. 2. Achievable rates of user 1 in different environments of SCM channel (Urban Micro, Suburban Macro, Urban Macro) with $M = N = t = r = 2$, configuration 2, and SNR = 10dB.

achievable rates are obtained for one of the SCM scenarios, $M = N = 2$, SNR= 10 dB and different antenna configurations (fig. 3).

In fig. 2 it is shown that, again, the proposed power allocation schemes perform very close to the CVX. The results shown are for *Configuration 2* for the user closest to its cell BS. In this configuration, the performance of the user in the cells boundaries will be analysed later (see fig. 3). The results for *Configuration 1* are similar to the ones provided in fig. 2, however they are not included due to space constraints.

The comparative performance of the users in different positions is given in fig. 3. It should be noted that due to the optimization criteria, where the sum rate of all users is maximized, the power allocation schemes assigns most of the available power in each BS to serve the user in the best situation and this leads to the user in the boundary to get very low rates. In this figure it is also observed the effect of the values of the channel eigenvalues in the power allocation schemes detailed in section IV-A. As an example it should be noted that the UP power allocation scheme in the *Configuration 2* with $t = 4$, $r = 2$ performs very similar to $t = r = 4$ in terms of achievable mean rate. The reason for that is that the distribution of eigenvalues in the case of $t = r = 4$ is very uneven. That is, strictly there are two dominant eigenvalues (like in the case of $t = 4$, $r = 2$) and the two other very close to zero values; when the power is uniformly assigned to each of them, the effective power assigned is reduced to half given that the power assigned to the almost zero eigenvalues is wasted.

### *C. Micro Urban NLOS SCM performance in a multi-cell scenario*

Considering now a more realistic scenario we set up a cellular system defined by $M = N = 16$ hexagonal cells

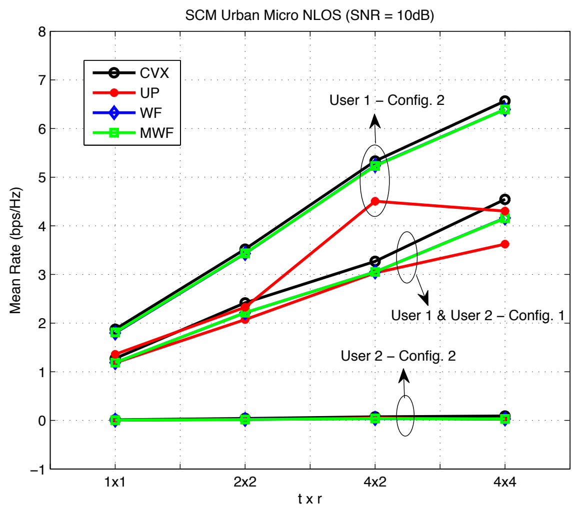



Fig. 3. Mean achievable rates in a Micro Urban NLOS SCM channel with $M = N = 2$, SNR = 10dB and different configurations and values of $t$ and $r$.

arranged to form a torus as in [10]. This particular shape avoids the boundary effect that causes cells at the border of the cellular deployment to receive less interference. The users are randomly deployed and an SNR= 10 dB is guaranteed for 90% of the users. In fig. 4 it is shown the CDF of the achievable rates in the different antenna configurations, showing that the proposed algorithm perform close to the optimal and outperforms an uniform power allocation scheme.

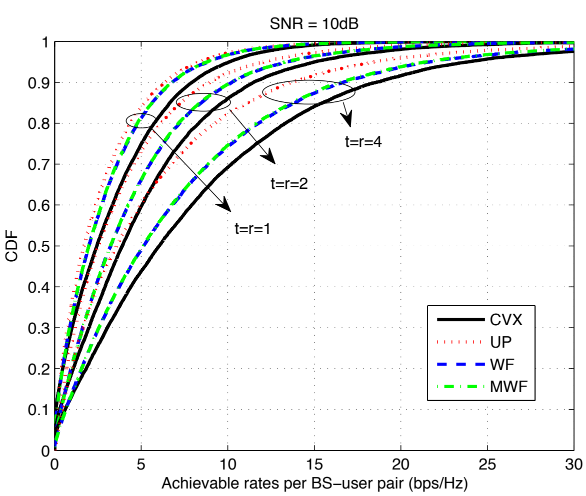



Fig. 4. Achievable rates in a realistic scenario with $M = N = 16$, Micro Urban NLOS SCM channel, SNR = 10dB and different values of $t = r$.

## V. Conclusion

In this paper, we have studied a BD-based interference cancellation algorithm and two waterfilling-based power allocation strategies (MWF and WF) in a OFDM transmission. We have studied the performance using different channel models: an exponential channel and the standardised SCM developed by 3GPP for 3G and 4G networks. Two scenarios with 2BSs-2MSs and 16BSs-16MSs deployments respectively have been considered. In the first one, several BS-MS deployments have been studied. In the second one, users' uniform distribution around the cells have been taken into account. We have shown that the two proposed power assignment schemes achieve the same performance in terms of weighted sum rate and very close to the optimal - obtained by convex optimization - but with an important reduction in the computational complexity.

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