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Dynamic radio resource and interference management for MIMO–OFDMA mobile broadband wireless access systems

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ABSTRACT

A multi-user multi-cell Multiple-Input Multiple Output/Orthogonal Frequency Division Multiple Access (MIMO/OFDMA) system for next generation Broadband Wireless Access (BWA) networks is studied, in which the Base Station (BS) or evolved Node B (eNB) has only knowledge of the statistics of the channel. A combination of MIMO and OFDMA could increase the spectral efficiency in a high speed network. We investigate methods with scalable channel feedback and we analyze the trade off between the amount of Channel State Information (CSI) to the transmitter and the system performance. The proposed schemes with limited feedback are combined with other cell interference reduction strategies based on cooperation for improving the performance of a coordinated multi-cell system under very dynamic conditions like high velocity and fast fading. Simulation results demonstrate that substantial gain is obtained by the proposed schemes which take advantage of the statistical information of the highly dynamic channel.

1. Introduction

Wireless Metropolitan Area Networks (MANs) are under extensive investigation over the last years as they are envisaged to support broadband services and Internet Protocol (IP) connectivity over wide geographical areas. New service providers wishing to offer traditional and novel mobile services may select Worldwide interoperability for Microwave Access (WiMAX) or 3rd Generation Partnership Project-Long Term Evolution (3GPP-LTE) as their technology for mobile broadband access. 4G networks target mobile/portable markets and operate in Non Line Of Sight (NLOS) environments by introducing MIMO technology and Adaptive Antenna Systems (AASs) [1,2]. OFDMA with data transmission on parallel narrow-band subcarriers is the basis of the LTE downlink radio transmission. The basic unit for data transmission is referred to as physical resource block (PRB) which has both a time and frequency dimension. LTE supports both the Frequency Division Multiple Access (FDD) and Time Division Multiple Access (TDD) modes of operation. In FDD, during each frame duration of 10 ms there are 10 downlink subframes, each of 1 ms duration. In the case of TDD operation, seven different uplink-downlink configurations are supporting providing downlink periodicities of 5 and 10 ms [3]. Each subframe is divided into two slots, each of 0.5 ms duration. Each slot consists of 7 symbols, separated by the OFDM cyclic prefix. A PRB consists of 12 consecutive subcarriers for one slot duration. It's the smallest resource allocation element. In order to reduce Intercell interference in LTE, the ICIC feature (Inter-cell Interference Coordination) is proposed. This is a Radio Resource Management (RRM) function with the goal to keep interference under control. The ICIC is located in the evolved Node B (eNB) and the communication between neighboring eNBs is based on the X2 interface. Despite the attractive features and capabilities of the current generation of LTE systems, achieving higher data rates and Quality of Service (QoS) will require further evolution.

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The LTE-Advanced amendment provides an advanced air interface that can ensure higher mobility, throughput and spectral efficiency, essential characteristics for a packet-based wireless system. The LTE-Advanced technology introduces the coordinated multipoint transmission/reception by joint exploitation of multiple cell information.

The influence of user mobility in a multi-path propagation environment can be modeled by an individual Doppler shift on each signal path. Information about the channel quality cannot be instantaneous and is outdated to some degree. Second order statistics describe the fluctuation of channel parameters with time. We define the covariance matrix of channel gain $H(t)$ as $R = \varepsilon\{H(t)H^H(t)\}$. The symbol $\varepsilon\{\cdot\}$ denotes the expected value. The channel is fast fading and the feedback information could be only low rate. Therefore, feedback is used for the next transmission process. The mobiles perform channel estimation, averaged over N PRBs and send back the covariance matrix by explicit feedback. This technique has been referred in the literature as covariance feedback. Our design is based on the short-term CSI at the transmitter by averaging the channel covariance matrix over the duration of one half frame or ten slots (to be compliant with the TDD and FDD operation). In a MIMO system, the application of multiple antennas at the transmitter and the receiver increases the number of channel state parameters. The feedback requirements grow with the product of the number of transmitter antennas, receiver antennas, the delay spread and the number of users. Statistical feedback in a channel that varies rapidly reduces the feedback requirements. Given a low-rate feedback channel, this information may be easily obtained at the eNB. The number of PRBs may be considerably large, e.g. for one LTE system with a total available frequency bandwith 20 MHz, in each slot, the bandwidth is subdivided into 100 PRBs. Aiming to reduce the feedback load, we group the PRBs in a set of consecutive PRBs in time a frequency domain named Group PRBs (GPRBs). The number of GPRBs Q is scaled down until it gets the value $Q = 1$ when the channel varies rapidly and is scaled up to exploit strong channel modes associated with a static or slowly varying channel (stationary, pedestrian users). Additionally, in the downlink direction, when the eNB transmits over the same channel to multiple users, inter-user Multiple Access Interference (MAI) is present. The eNB constructs appropriate beams in order to mitigate MAI, if CSI is available at the transmitter. In our case, where the channel is changing rapidly, accurate CSI is difficult to obtain. Therefore, second order statistical information can be used to form beams at each PRB but not to separate users in the spatial domain. Beamforming seeks to improve the total throughput or minimize the total transmitted power. Our approach is robust and non risky taking into account the coarse estimation of CSI at the transmitter. Statistical information can be used for scheduling the users in a multiuser Time-Division MIMO–OFDM system. We optimize the number of PRBs allocated to the User Equipments (UEs) in order to achieve maximum overall throughput or minimize the emitted power guaranteeing the QoS for all users.

Based on our previous works in dynamic radio resource allocation for a single-cell WiMAX systems reported in [4,5], we extend our studies in a cellular system, assuming B neighboring eNBs. We consider a network infrastructure based on cooperative processing. Our approach applies adaptive beamforming and exploits the possibility of neighboring eNBs to dynamically schedule their transmissions in a cooperative fashion. Beamforming is used to maximize the signal energy sent to the desired users, while it minimizes the interference sent toward interfering users. We reduce inter-cell interference indirectly, since statistical interference knowledge for the neighboring eNBs is not necessary. Universal frequency reuse is used for the central users and cooperative scheduling transmission for edge users to share dynamically the radio resources in the frequency and time domains. Cooperative scheduling requires minimal information among neighboring eNBs. Our paper addresses the design of a dynamic radio resource and interference management for 4G systems. Our novelty is a complete and practical dynamic management in both Physical (PHY) and Medium Access Control (MAC) layers by integrating techniques such beamforming, frequency allocation and scheduling to high speed users in a multi-cell environment. The proposed intercell interference management, through the use of limited feedback mechanisms, reduces the signaling overhead and does not require any sharing of feedback information among neighboring eNBs. Hence, the cost of coordination is reduced. We expect practical eNB cooperation techniques to be implemented in the LTE-Advanced systems.

The organization of this paper is as follows: In Section 2, we address how this work is related to the existing literature. Section 3 describes the system model. In Section 4 feedback strategies are presented while in Section 5 the weights of the beams at the eNB for each GPRB sending as feedback information are designed. In Section 6 an algorithm which finds the PRB assignment solution is proposed. Section 7 investigates the scenario with one central and six neighboring hexagonal cells. Simulation results are presented in Section 8. Finally, Section 9 concludes the paper.

2. Related work

2.1. Radio resource management with partial feedback

For an OFDMA air-interface combined with MIMO technologies, performance improvement may basically be obtained through proper radio resource management schemes, e.g. beamforming, packet scheduling algorithms, fast link adaptation at the eNB side. The UE mobility poses several limitations on the observed CSI reported from UE and hence to the overall system performance. The reported feedback may not be reliably to following the fast fading dynamics. In literature, advanced multi-user radio resource management algorithms studied the benefits considering time, frequency and spatial domain metrics and identified the limitations of imperfect feedback.

In [6], an optimization problem is solved for a MIMO point to point system. The transmitter has partial channel knowledge (mean or covariance of the channel coefficient). It was found that the capacity improvement can be

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significantly high and that beamforming performs close to the optimal strategy. A similar problem is studied in [7], where it's shown that transmitting to the direction of the eigenvectors of the correlation matrix is the optimal transmission strategy. The statistical model depends on the time scale. In short term, the correlation of channel matrix $H(t)$ reflects the geometry of a particular propagation environment. Over a longer term, the channel coefficients may be uncorrelated due to the averaging over several propagation environments. According to [8], the transmitter antenna with the best PRB towards the receiver antenna could be selected to transmit non-zero information. In [9], closed-loop feedback is used to enable the diversity mode for two adaptive transmit antennas. Two schemes are proposed for the feedback design: (a) Quantized phase information where a set of bits is used to quantize the phase angles needed to perform equal gain beamforming and (b) Direct channel quantization with a set of bits for the gain and the phase of the channel. In this case, the feedback consists of sending back the unquantized channel coefficients transmitted as real and imaginary parts of a complex modulation symbol.

Our approach is based on feedback of statistical channel information. The computed channel covariance at each downlink half frame is quantized using a limited number of bits. Statistical feedback cannot be used when the channel is static or varying slowly. In [10], the goal is not the reconstruction of the channel but the mapping of possible precoding matrices to a codebook. The optimal codeword is based on achieving the spatial diversity by quantization of the beamforming direction. Each single codebook is optimized for one specific user. In LTE systems, a single precoding matrix for one user could be applied to the whole band over the period of one or more frames. The precoding matrix is computed from the covariance matrix. In [11], a multi-code book is utilized for beamforming and multi-user scheduling in order to exploit both spatial diversity and multi-user diversity. One single codebook is utilized for each PRB but it switches for different PRBs. The design of limited feedback codebooks cannot be applied to our proposed strategy because we construct beams for a set of users. In [12] the design of codebooks for unit vectors instead of matrix codebooks is proposed to reduce the feedback overhead. This paper focus on the unitary matrix V which is addressed at a single user and derived from Singular Value Decomposition (SVD) of the channel matrix H as $H = U\Sigma V^H$. The columns of V are recursively parameterized column by column. Each column of V is quantized by a unit vector codebook that decrease the computational complexity. Taking into account that the adjacent OFDM subcarriers are correlated, the beamforming of adjacent feedback subcarriers downsampled in frequency domain are interpolated with almost no performance degradation. This feedback technique could not be applied in the proposed scheme because the beamforming matrix is designed for multiple users and therefore it is not a unitary matrix (derived from SVD) to compute the Householder transformation. The interpolation scheme reduces the feedback load but increases the receiver complexity for a large number of subcarriers, as is the case in LTE systems with 20 MHz bandwidth.

In [13], the authors deal with a joint multiuser time-sharing and power allocation problem assuming that the transmitter knows only the statistical information about the channel. The initial problem is not convex and is modified into a sub-optimal convex optimization problem. An advanced multi-user Proportional Fair (PF) packet scheduling technique based on LTE considering up to 120 km/h user velocities was studied [14]. The scheduling metric considered the instantaneous quality of each user radio channel and the achievable throughput of individual UEs. The performance in terms of throughput, coverage and fairness distribution was investigated. Mutual effective SINR mapping (MIESM) was introduced as an effective adaptive spatial and modulation selection process [15]. By using four bits feedback, the system switched between tree different spatial modes, i.e. spatial multiplexing (MUX), space–time block coding (STBC) and beamforming (BF). The system supported a single user with two transmitted and two received antenna elements and generated two orthogonal fixed beams for MUX and STBC mode while in BF mode it selected the best beam among three fixed beam candidates.

2.2. Interference management

The most challenging problem to maximize the capacity is the co-channel interference generated among neighboring cells. The studies addressing this problem could be classified into three groups: randomization, interference cancellation and interference coordination (avoidance).

In the first group of studies, it was found that scrambling and frequency hopping methods are not efficient and must be combined with other intercell interference management techniques. Interference cancellation techniques as the Interleave Division Multiple Access (IDMA) reduces the power of the strongest interfering signals by applying different interleaving patterns. However, this method introduces a great amount of computational load. Interference Coordination/Avoidance techniques apply restrictions on the time/frequency resources and the power attached to them.

In [16], interference control is provided by combining an interference coordination technique with an adaptive subcarrier and power allocation. This interference coordination technique uses cell-based power masks by applying different transmit power limits along the frequency resources. The difference with our work is that we apply beams to different radio resources in order to suppress (not avoid) interference. Also, QoS requirements are not included as in our study. Another semi-dynamic inter-cell interference coordination scheme is proposed in [17], where intercell negotiation is employed for heavy-load networks. UEs are categorized in groups based on their geometric locations and orthogonal radio resources are reallocated among neighboring groups through leasing/returning agreements. The distributed algorithm in [18] divides the frequency resources into a 'high power' region (for allocation to cell-edge users) and 'low power' region (for allocation to cell-center users). Each cell adjusts the power step by step and tries to allocate the low power regions to cell-edge UEs. The combination of intercell interference coordination at the superframe level (a number of consecutive frames) and opportunistic scheduling at frame level is discussed in [19]. Additionally, the architecture and protocol support for ICIC in the LTE standard are described. In [20] the authors deal with the frequency allocation problem for inter-sector/cell interference management. The conventional frequency reuse technique, where user transmissions are restricted to separate orthogonal narrowband channels leads to inefficient use of the bandwidth. Frequency reuse factor $1/n$ ($n = 3$, 7, 12) means that the same spectrum is used in 1 out of n sectors/cells. In the case of universal frequency reuse techniques, the same spectrum is used in every sector/cell and that increases cell edge interference. The study develops a frequency partitioning method that divides the frequency band into partitions to create some interference immunity. The UEs at the edge of the sector/cell suffer from higher interference as well as higher path loss than the terminal at the center. Therefore, a dynamic scheduler allocates frequency partitions considering various interference levels while maintaining fairness among terminals.

2.3. Interference management with limited feedback

A multicell MIMO-based scheme with limited feedback by applying different precoding vectors from a codebook to BS is proposed to partially or completely cancel intercell interference [21]. A distance-based threshold together with a reference precoding vector is used to further reduce the signaling overhead. In this scheme, cell-edge users send information to both serving and interfering BSs. However, as opposed to our proposed work, this reduced feedback/overhead scheme (a) is not flexible to adapt to varying channel quality and (b) does not profit from multi-user diversity.

3. System model

The downlink scheduler is assumed to select K UEs. Each UE $k \in \{1,2,\ldots,K\}$ has M_r receiver antennas while the eNB has M_t transmitter antennas with a maximum power constraint P_{max}. We assume that a matrix H_k^n of size $M_r \times M_t$ represents the channel between the user k and eNB at PRB $n \in \{1, 2, \ldots, S\}$. Finally, we suppose that the channel is frequency-flat due to OFDM modulation, V_n is the beamforming vector (of size $M_t \times 1$) operated to the transmitter antennas at PRB n and σ_0 is the variance of the Gaussian noise applied at the input of the receiver. In our design, the signals received from M_r antenna elements are linearly combined to improve SNR. Also, CSI is available at the receiver. The received signals are multiplied by a coefficient vector U_k^n of size $M_r \times 1$. According to the Maximum Ratio Combining (MRC) technique, the antenna is aligned to the Rx direction of $H_k^n V_n$ and therefore the MRC weights are given by Proakis [22]

$$\boldsymbol{U}_k^n = \frac{\boldsymbol{H}_k^n \boldsymbol{V}_n}{\|\boldsymbol{H}_k^n \boldsymbol{V}_n\|} \tag{1}$$

The SNR_k^n calculated at the receiver k is given by

$$\boldsymbol{SNR}_k^n = \frac{\boldsymbol{H}_k^n \boldsymbol{V}_n}{\|\boldsymbol{U}_k^n\|^2 \boldsymbol{\sigma}_0^2}$$

$$\boldsymbol{SNR}_k^n = \frac{\left|\boldsymbol{V}_n^H (\boldsymbol{H}_k^n)^H \boldsymbol{H}_k^n \boldsymbol{V}_n\right|^2}{\boldsymbol{\sigma}_0^2} \tag{2}$$

Statistical feedback contains information $R_{k,c}$ about the covariance channel gains that correspond to GPRB $c \in \{1, 2, \ldots, Q\}$.

$$\boldsymbol{R}_{k,c} = \mathrm{E}\{\boldsymbol{H}_{k,c}(\boldsymbol{H}_{k,c})^H\} \tag{3}$$

Eq. (2) could be transformed as

$$\boldsymbol{SNR}_{k,c} = \frac{\left|\boldsymbol{V}_c^H \boldsymbol{R}_{k,c} \boldsymbol{V}_c\right|^2}{\boldsymbol{\sigma}_0^2} \tag{4}$$

Assuming that the transmitted signal Sc, of dimension $M_t \times 1$, that is directed to receivers in GPRB is zero mean, with unit variance ($\varepsilon\{|S_c|^2\} = 1$), the total radiated power at eNB is

$$\sum_{c=1}^{Q} \|\boldsymbol{V}_c\|^2 \leqslant \boldsymbol{P}_{\max} \tag{5}$$

A frame structure applicable to the TDD mode is considered. The DL one half-frame has duration $T_f = 5ms$. If the number of GPRBs c, allocated to UE k, is $S_{k,c}$, the total number of PRBs must be at least N = S/Q with $S = 50$ the total number of PRBs and Q the total number of GPRBs

$$\sum_{k=1}^{K} \|\boldsymbol{S}_{k,c}\|^2 \leqslant \boldsymbol{N} \tag{6}$$

One PRB in time domain consists of 6 or 7 OFDM symbols S_{OFDM}, depending on whether extended or normal Cyclic Prefix (CP) is configured respectively. For our simulation we select

$$\boldsymbol{S}_{OFDM} = 7 \text{ symbols} \tag{7}$$

A modulation level with $b_{k,c}$ bits per symbol is selected from a set $\mathcal{M} = \{1, 2, 4, 6\}$ of available QAM constellations. For M-QAM modulation with M equal to $2^{b_{k,c}}$, $b_{k,c} \in \mathcal{M}$, the minimum required SNR $\gamma(b_{k,c})$ to achieve a BER lower than a pre-specified value ϵ is given in [23]

$$\gamma(\boldsymbol{b}_{k,c}) = -\frac{\ln 5\varepsilon}{1.5}(2^{b_{k,c}} - 1) \tag{8}$$

Given that $SNR_{k,c} = \gamma(b_{k,c})$, $b_{k,c}$ is computed from Eq. (8). The rate of UE k, calculated for one half frame duration is

$$\boldsymbol{R}_k = \frac{\boldsymbol{S}_{OFDM} \sum_{c=1}^{Q} \boldsymbol{b}_{k,c} \boldsymbol{S}_{k,c}}{\boldsymbol{T}_f} \tag{9}$$

The transmitted power at GPRB c can be written now as

$$\boldsymbol{P}_c = \sum_{k=1}^{K} \frac{\|\boldsymbol{V}_c\|^2 \boldsymbol{S}_{k,c}}{\boldsymbol{N}} \tag{10}$$

4. Reduced feedback scheme

The solution of operating CSI per PRB is suboptimal since it does not take advantage of the fact that channel

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vectors at different PRBs are correlated. In this paper, we consider that the feedback channel is error- and delay-free. We propose the simplified feedback design based on grouped PRBs. We consider, N adjacent OFDM PRBs are grouped into Q GPRBs so that $S = QN$. Each user feeds back information only about the GPRBs. This technique greatly reduces the amount of uplink control information. In situations when the channel changes rapidly, the channel information feedback to the transmitter is outdated. Only the statistics of the channel coefficient would be of significant benefit to the system design. We have defined the covariance matrix of the channel gain as

$$\boldsymbol{R}_{k,c}^{n} = \mathrm{E}\left\{\boldsymbol{H}_{k,c}^{n}\left(\boldsymbol{H}_{k,c}^{n}\right)^{H}\right\} \quad (11)$$

that is derived from averaging the PRB n in the frequency and time domain. The idea to feedback the covariance comes from the fact that it changes at a slower rate, e.g. second order statistics have a longer coherence time compared to that of fast fading. Additionally from (4), the channel covariance is the only metric that is representative of the received SNR and is better than feeding back the channel autocorrelation. The following two feedback strategies are proposed:

4.1. Mean over PRB covariance metric (MPC)

The estimated covariance matrix from user k $R_{k,c}^{n}$ is indicative of gain variations of PRB n belonging to GPRB c. The representative value is obtained from averaging the covariance matrix of all PRBs containing to GPRB c

$$\boldsymbol{R}_{k,c} = \frac{1}{L}\sum_{n=1}^{N}\boldsymbol{R}_{k,c}^{n} \quad (12)$$

4.2. Minimum effective SNR covariance metric (MEC)

Each user calculates the effective SNR at each PRB $n \in \{1, 2, \ldots, N\}$, where n is the total number of PRBs that construct a GPRB.

$$\boldsymbol{ESNR}_{k,c}^{n} = \mathrm{E}\left\{\boldsymbol{SNR}_{k,c}^{n}\right\} \quad (13)$$

$SNR_{k,c}^{n}$ is computed from Eq. (2) taking into account that each receiver k has perfect knowledge of the channel in all PRBs and for all antennas. In this scheme, the covariance matrix $R_{k,c}$ corresponds to PRB n^* with the minimum effective SNR.

$$\begin{aligned} \boldsymbol{R}_{k,c} &= \mathrm{E}\left\{\boldsymbol{H}_{k,c}^{n^*}\left(\boldsymbol{H}_{k,c}^{n^*}\right)^{H}\right\} \\ \boldsymbol{n}^* &\leftarrow \arg\min_{\forall n\in N}\left\{\boldsymbol{ESNR}_{k,c}^{n}\right\} \end{aligned} \quad (14)$$

Both schemes offer a considerable reduction in the amount of feedback and complexity of the allocation process but also decrease the system throughput. The scheduling is not done for each PRB individually because our scheme proposes the same value of supportable throughput for all PRBs of the GPRB. This considerably reduces the allocation complexity especially for a small number of GPRBs Q. It's clear that when having small GPRBs, many users achieve their throughput target but the feedback load is not much reduced. The choice of large GPRBs reduces feedback but increases the risk of achieving lower data rates than those required. If the size of GPRBs is of the order of the channel coherence bandwidth, no degradation in the system throughput occurs. The channel variations over PRBs are small and thus we achieve the optimum capacity. This GPRBr size is the optimum in the case that users move with low speeds and large amount of feedback is feasible. In order to reduce the feedback load even more in situations where the channel changes rapidly, each user sends back only the covariance matrix of the strongest GPRB c_{max}. c_{max} corresponds to the GPRB with the greatest minimum ESNR. Therefore

$$\begin{aligned} \boldsymbol{R}_{k,c_{\max}} &= \mathrm{E}\left\{\boldsymbol{H}_{k,c_{\max}}^{n^*}\left(H_{k,c_{\max}}^{n^*}\right)^{H}\right\} \\ \boldsymbol{c}_{\max} &\leftarrow \arg\max_{\forall c}\left\{\boldsymbol{ESNR}_{k,c}^{n^*}\right\} \end{aligned} \quad (15)$$

This approach can lead to many users not reaching their target rate. The amount of feedback could be scaled for higher speeds. The users estimate the set $\left\{ESNR_{k,c}^{n^*}\right\}_{c=1,\ldots,Q}$ of the effective SNR on the weakest PRB at each GPRB c. The GPRBs are sorted in increasing order. Let $C_{\pi(1)}, C_{\pi(2)}, \ldots, C_{\pi(Q)}$ be the sorted GPRBs. Each UE k sends to the eNB information only for $\pi(\alpha)$ GPRB with $\alpha \in \{1,2,\ldots,Q\}$. The PRB – size α is scaled according to mobility-speed classes. It takes the maximum value for the stationary users where optimum performance is required and the minimum value equal to one for the high speed users in order to ensure baseline performance. No transmission will be scheduled on the PRB that $ESNR_{k,c}^{n^*} \leqslant \overline{ESNR}$, where $\overline{ESNR}$ is a predefined threshold.

The Adaptive Modulation and Coding (AMC) schemes exploit better the UE feedback in case where the channel fading rate is sufficiently slow. This requires the channel coherence time to be as long as the time spent between the UE measurements and the reception of the subframe containing the corresponding – adapted downlink transmission on the Physical Downlink Shared Channel (PDSCH). This time is typically 7–8 ms assuming a UE speed equal to 16 km/h at 1.9 GHz [24]. A trade-off exists between the amount of feedback information and the accuracy with which the AMC schemes can match the channel variations. Frequent reporting of the CSI in the time domain allows better matching to the channel variations and co-channel interference changes, while fine resolution in frequency domain exploits better frequency-domain diversity. LTE can configure the CSI update rate in both the time and frequency domains. In the time domain, both periodic and aperiodic CSI reporting are supported. The Physical Uplink Shared Channel (PUSH) is used for periodic and the Physical Uplink Shared Channel (PUSCH) for aperiodic reporting respectively. The UE reports a wideband CSI value named Wideband feedback. In addition, the UE reports a CSI value for each PRB or GPRB. This information is encoded differentially with respect to the Wideband feedback using 2 or 4 bits. In periodic reporting mode, the period could be equal to 2, 5, 10, 16, 20, 32, 40, 64, 80, 160 ms or the mode could even be disabled.

5. Beamforming weights among GPRBs

A downlink beamforming method is proposed that uses a common transmission weighting vector for each GPRB. This technique utilizes feedback information and assumes flat-fading with a modified covariance channel matrix $R_{k,c}$ derived from section 4. Our proposed scheme consists of simultaneously designing downlink beamformers to multiple GPRBs in order to maximize the total throughput or minimize the transmit power, under the constraints on providing at least a specified received SNR to each intended receiver keeping also the total eNB transmit power (sum power) upper bounded. In this section, we first give a formal description of the optimization problem studied in [25]. We extend this multicast scenario with full CSI available at the transmitter to a multi-GPRBs, where the transmitter receives second order statistics from the receiver. In the following, we transform the transmit power optimization problem into a throughput maximization target problem. Given the covariance matrix $R_{k,c}$ calculated from user k and γ_k the guaranteed specified SNR for user k at each GPRB c and also considering that the low rate feedback channel is error and delay free, the objective is to generate an optimal downlink beamforming vector for each GPRB c at the eNB, minimizing the total transmit power while satisfying at the same time the prescribed SINR constraints γ_k at each user.

$$\begin{aligned} C \quad & \min \|\boldsymbol{V}_c\|_2^2 \\ \text{s.t.} \quad & \frac{\left|\boldsymbol{V}_c^H \boldsymbol{R}_{k,c} \boldsymbol{V}_c\right|^2}{\boldsymbol{\sigma}_0^2} \geqslant \gamma_k \\ & \forall k \in \{1,2,\ldots K\} \quad \forall c \in \{1,2,\ldots Q\} \end{aligned}$$

The above problem is NP-hard but it can be relaxed into a convex optimization problem. Towards this end, we define $U_c = V_c V_c^H$ of size $M_t \times M_t$ and we denote that $V_c^H R_{k,c} V_c = trace\left(R_{k,c} V_c V_c^H\right) = trace(R_{k,c} U_c)$. Then problem $\mathcal{C}$ can be reformulated as

$$\begin{aligned} C' \quad & \min trace \boldsymbol{U}_c \\ \text{s.t.} \quad & trace(\boldsymbol{R}_{k,c}\boldsymbol{U}_c) \geqslant \gamma_k \\ & \boldsymbol{U}_c = \boldsymbol{U}_c^H (a) \\ & \boldsymbol{U}_c \geqslant 0 (b) \\ & \boldsymbol{rank} \boldsymbol{U}_c = 1 (c) \\ & \forall k \in \{1,2,\ldots K\} \quad \forall c \in \{1,2,\ldots Q\} \end{aligned}$$

The constraints (a) and (b) are applied from the fact that U_c is a symmetric, positive, semidefined matrix. The rank-one constraint derives from the definition of matrix U_c and is not convex. Dropping the constraint (c), the original problem is relaxed into a Semi Definite Programming (SDP) which can be solved by any SDP solver such SeDuMi [26], based on the interior point method. In optimization problem $\mathcal{C}'$, we have removed one of the problem constraints. Therefore, the solution $traceU_c^{opt}$ gives a lower power bound. We generate candidate beamforming vectors V_c with negligible cost by utilizing a randomization procedure described in the following way: The computed matrix U_c^{opt} is analyzed in $U_c^{opt} = U\Sigma U^H$ with the Singular Value Decomposition (SVD) technique. Feasible weight vectors can be found from equation. $V_c = U\Sigma w_g$, w_g is a Gaussian variable with $w_g \sim N(0,1)$ in order to achieve $U_c^{opt} = \varepsilon\{V_c V_c^H\}$. From the calculated beamforming vectors V_c, the vector with minimum $\|V_c\|^2$ is selected. In case that our goal is to maximize the total throughput under the transmit power constraint P_{max}, we introduce a transmit vector for each cluster $V_c' = \sqrt{P_c} V_c$. P_c denotes the power boost factor for GPRB c. The boost factor changes only the gain of the antenna weights. If the transmit power is distributed equally at all GPRBs then

$$\|\boldsymbol{V}_c\|^2 \boldsymbol{P}_c = \frac{\boldsymbol{P}_{\max}}{Q} \Rightarrow \boldsymbol{P}_c = \frac{\boldsymbol{P}_{\max}}{\|\boldsymbol{V}_c\|^2 Q} \tag{16}$$

An important issue is how to quantize the information needed at the transmitter. Instead of quantizing properties of the transmitted signal, we can quantize the channel matrix by using intelligent vector quantization (VQ) techniques [27]. The channel matrix at each user $k(H_k)$ is reformulated into a $M_r{\cdot}M_t \times 1$ complex vector h_k^{vec}.

$$\boldsymbol{h}_k^{vec} = vec(\boldsymbol{H}_k) \tag{17}$$

where vec denotes vectorization. The $vec(x)$ creates a long vector by stacking the columns of matrix x on top of each other to form a vector. The h_k^{vec} is then quantized to $\widehat{h_k^{vec}}$ by using a VQ algorithm. These algorithms map complex valued vector realizations by minimizing some functions such as the average mean squared error (MSE) $\varepsilon\left\{h_k^{vec} - \widehat{h_k^{vec}}\right\}$. Feeding back either the precoding matrices or the covariance channel matrix has almost exactly the same performance but the precoding matrix reduces the overhead compared to the covariance matrix over long periods (long term beamforming) [28].

6. Optimal number of PRBs assignment

This problem is especially crucial if the target rates of the users are predetermined. The minimum rate required R_{min}^k in bits per second and the maximum BER ϵ are related differently in the different classes of services for each UE k. The exact order of PRBs allocation in each GPRB is not important because only channel statistics for each PRB are known at the transmitter. Therefore, we are interested in the number of PRBs assigned to UEs at each GPRB. In addition, each PRB of the same GPRB supports the same modulation level. Therefore, we could use $N = S/Q$ PRBs and not require specific PRBs for each GPRB. Eqs. (6), (9) and (10) can be written

$$\sum_{k=1}^{K} \boldsymbol{S}_{k,c} \leqslant N \quad \forall c \in \{1,2,\ldots,Q\} \tag{18}$$

$$\boldsymbol{R}_k = \frac{\boldsymbol{S}_{OFDM} \sum_{c=1}^{Q} \boldsymbol{b}_{k,c} \boldsymbol{S}_{k,c}}{\boldsymbol{T}_f} \quad \forall \in \{1,2,\ldots,K\} \tag{19}$$

$$\boldsymbol{P}_c = \frac{\sum_{k=1}^{K} \|\boldsymbol{V}_c\|_2^2 \boldsymbol{S}_{k,c}}{N} \quad \forall c \in \{1,2,\ldots,Q\} \tag{20}$$

Our goal is to maximize the total throughput while ensuring the users' individual QoS by optimizing the PRB allocation S_k^c for all users. Mathematically, this optimization problem can be presented as

$$\begin{aligned} \mathcal{T} \quad & \max \boldsymbol{S}_{OFDM}\mathbf{T}_f \sum_{k=1}^{K}\sum_{c=1}^{Q} \boldsymbol{b}_{k,c}\boldsymbol{S}_{k,c} \\ \text{s.t.} \quad & \frac{\boldsymbol{S}_{OFDM}}{\boldsymbol{T}_f}\sum_{c=1}^{Q}\boldsymbol{b}_{k,c}\boldsymbol{S}_{k,c} \geqslant \boldsymbol{R}_{\min}^{k} \\ & \sum_{k=1}^{K}\boldsymbol{S}_{k,c} \leqslant N \\ & \boldsymbol{S}_{k,c} > 0 \\ & \forall k \in \{1,2,\ldots K\} \quad \forall c \in \{1,2,\ldots Q\} \end{aligned}$$

A simple approach is to schedule equal PRBs at each GPRB. If F_c is the number of users which sends back information for GPRB c then the number of PRBs allocated to each user is

$$\boldsymbol{S}_{k,c} = \left\lfloor \frac{\boldsymbol{N}}{\boldsymbol{F}_c} \right\rfloor \tag{21}$$

$\lfloor x \rfloor$ denotes the biggest integer that does not exceed x. Finally, we consider the problem of minimizing the overall transmit power guaranteeing a specified QoS by optimizing the PRB allocation $S_{k,c}$

$$\begin{aligned} \mathcal{P} \quad & \min \frac{\sum_{c=1}^{Q}\sum_{k=1}^{K}\|\boldsymbol{V}_c\|_2^2\boldsymbol{S}_{k,c}}{S} \\ \text{s.t.} \quad & \frac{\boldsymbol{S}_{OFDM}\sum_{c=1}^{Q}\boldsymbol{b}_{k,c}\boldsymbol{S}_{k,c}}{\boldsymbol{T}_f} \geqslant \boldsymbol{R}_{\min}^{k} \\ & \sum_{k=1}^{K}\boldsymbol{S}_{k,c} \leqslant \frac{S}{Q} \\ & \boldsymbol{S}_{k,c} > 0 \\ & \forall k \in \{1,2,\ldots K\} \quad \forall c \in \{1,2,\ldots Q\} \end{aligned}$$

Problems $\mathcal{T}$ and $\mathcal{P}$ are Linear Programming (LP) problems and they could be solved optimally by using SeDuMi [26].

7. Network deployment and adaptive radio resource management

FFR uses orthogonal frequency resources among neighboring cell edge users to mitigate inter-cell co-channel interference. In order to reduce the interference without under-utilizing the frequency resources in each cell, cell UEs may be partitioned into two classes, namely interior and exterior users. Frequency resources are universally used in all interior cell areas whereas users of exterior zones have a frequency reuse factor strictly higher than one. Fig. 1 illustrates different parts of spectrum (f1–f6) of the OFDMA band. Universal frequency reuse is realized for users close to the center. Static Fractional Frequency Reuse (FFR) suffers from loss of frequency selectivity gain and from a corresponding drop in the spectral efficiency due to the large reuse factor. It's widely accepted that cross-layer interactions between the MAC and PHY layers are necessary for the optimal usage of the limited wireless radio resources satisfying at the same time the QoS requirements. By having interactions between both the MAC and PHY layers, the optimum parameters can be obtained.

We consider a scenario that involves the coordination of eNBs assuming the capability of full frequency reuse. We investigate an alternative to the traditional static FFR scheme where neighboring eNBs dynamically schedule their transmissions to reduce inter-cell interference. By adaptively using different weights according to the channel conditions, the SINR may be improved and therefore higher order modulation modes may be employed. Dynamic scheduling and adaptive beamforming for mobile UEs are based on partial CSI. The combination of the above-mentioned techniques fully exploits the frequency selectivity gain and avoids deep fades for edge UEs without introducing more packet delays for related delay sensitive services. Suppose that $B = 7$ is the total number of co-channel adjacent eNBs as in Fig. 1.

(A) If $\mathbf{V}_{bc}$ are the beamforming weights applied at each eNB $b \in \{1,2,\ldots,B\}$, we calculate from problem $\mathcal{C}$ the beam vectors for all GPRBs without taking into account inter-cell interference for all UEs K.
(B) The K UEs are partitioned into K_{int} "interior" users for which the interference term satisfies the $\sum_{d\neq b}|\mathbf{V_{bc}H^H_{k,b,c}H_{k,b,c}V_{bc}}|^2 \ll \sigma_0^2$ for all GPRBs and thus does not contribute to the value of SINR and to the rest K -K_{int} of users that are considered as "exterior" (K_{ext}).
(C) We solve the optimization problem $\mathcal{P}$ only for the exterior users and we put the GPRBs in order of increasing $P_{c,b}$, (where $P_{c,b}$ is the power of GPRB c for eNB b) and form the following list (GPRBs in decreasing order of power), $C_b^{min} = \left\{C_{1b}^{min}, C_{2b}^{min}, \ldots, C_{Qb}^{min}\right\}$ where C_{ib}^{min} is the ith PRB of eNB b.
(D) We define the number of GPRBs M allocated for edge UEs as a function of the number of edge UEs, M = $\lfloor K_{ext}/K \rfloor$Q.

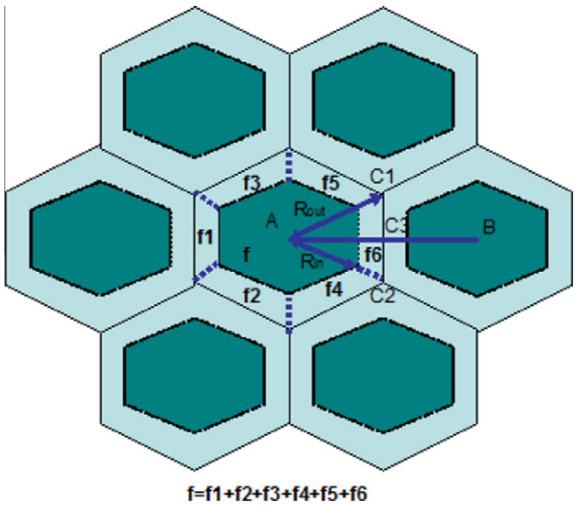

Fig. 1. Fractional frequency reuse.

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(E) We find the set of M GPRBs allocated to exterior users C_{min}^{ext} with the minimum $P_{c,b}$ for all eNB, e.g. $C_{min}^{ext} = \left\{C_1^{min}, C_2^{min}, \ldots, C_M^{min}\right\} = arg\min \sum_{b=1}^{B} P_{c,b}, \forall_c \in \{1, 2, \ldots, Q\}$.
(F) The rest of the GPRBs $C_{min}^{int} = \{1, 2, \ldots, Q\} - C_{min}^{ext}$ are allocated to interior users.
(G) Finally, optimization problems $\mathcal{C}$ and $\mathcal{T}$ are solved separately for interior and exterior users for each cell $b \in \{1, 2, \ldots, B\}$.

The advantages of our strategy are summarized in the following points:

I. The complexity and advanced signal processing is shifted to the eNB side that accommodates and processes the received partial CSI.
II. Our design does not require channel information for the neighboring eNB's. The monitoring of pilot channels from neighboring BS's is a complex process and requires complicated detectors built-in the mobile device, and also involves increased feedback load in order to update this extra information to the BS. Our method is based on a single cell downlink transmission with the goal to minimize the total transmitted power to the neighboring cells. This means that inter-cell interference is neglected.
III. In the literature, the eNB cooperation schemes assume that the desired and interfering signals arrive simultaneously at each mobile [29]. This is unrealistic especially for scenarios involving fast fading and highly mobile users. Our scheme does not require synchronization among different eNBs which could lead to complex signal processing based on an asynchronous system model. It's important to note that in cooperative transmission, even when the desired signal components arrive synchronously (perfect-timing), multi-user interference is asynchronous by nature and may lead to a significant performance degradation of the linear transmission strategies.

8. Simulation results

The advanced radio resource and interference management algorithms may be considered to be performed on two domains: on the Spatial Domain (SD) where beamforming is calculated for each PRB and on both the Time and Frequency Domains (TD/FD) where the actual PRB allocation takes place (Fig. 2). These two domains are affected in different ways by two specific elements. The first is the feedback load related to the channel quality and the second is the intercell interference which partitions the UEs into these located in the exterior cell area and those located within the interior cell area, close to the base station. The division among SD and TD/FD domains provides the flexibility to simulate the two optimization problems $\mathcal{C}$ and $\mathcal{T}$ independently. The goal is to examine how the feedback load and interference affect the total throughput, maintaining at the same time a guaranteed QoS.

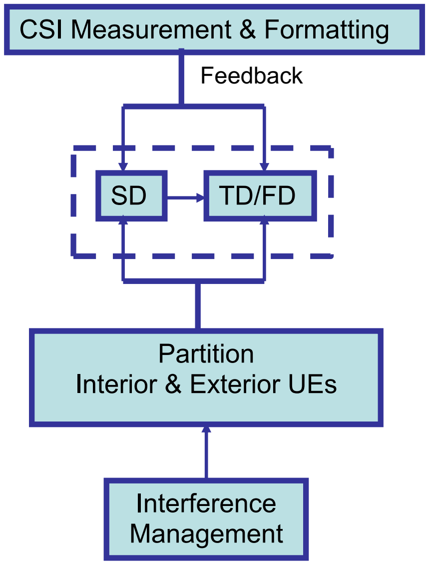

Fig. 2. Radio resource and interference management framework.

A network deployment with one cell of radius $R = 500$ m and one eNB at the center of the cell is considered. The number of eNB and UE antennas is four. Uniform Linear Arrays (ULAs) with half wave length spacing are used at both ends. The network is assumed to operate at 5.25 GHz with 10 MHz transmission bandwidth. All simulations, throughput and transmit power calculations were generated in the Matlab system. A summary of the system parameters is provided in Table 1. The channel model was related to the C2 Metropolitan area for typical urban macro-cell scenario from Wireless World Initiative NEwRadio II (WINNER II) [30]. The model is applicable for mobiles located in an outdoor environment at street level communicating with fixed eNBs installed above rooftops. Non Line Of Sight (NLOS) propagation is the typical case scenario in such cases. The modulation and coding rates were selected in relation to the received SNR-given in Table 2 – and the bit error rate requirement was set to 10^{-5}. Therefore, con-

Table 1
System model parameters.

Parameter	Value
Cell radius (m)	500
Frequency band (GHz)	5.25
Number of BS array antenna elements	4
Number of MS array antenna elements	4
Mobile velocity (km/h)	110
Channel bandwidth (MHz)	10
Half frame duration (ms)	5
Number of subcarriers per PRB	102.86
Number of available PRBs, S	50
eNB transmit power (dBm)	30
Channel profile	WINNER II C2 Metropol
UE distribution	Uniform, random positioning
Traffic model	Full buffer

Table 2
Type of modulation and coding rate according to SNR.

Modulation	Coding	SNR (dB)
BPSK	1/2	3
QPSK	1/2	6
QPSK	3/4	8.5
16 QAM	1/2	11.5
16 QAM	3/4	15
64 QAM	2/3	19
64 QAM	3/4	21

volutional codes of rates 1/2, 2/3, 3/4 and 5/6 that are supported in mandatory WiMAX modes were selected without FEC. In the following, the performance of optimization problem $\mathcal{C}$ is evaluated. The feedback scenario with 5-GPRBs for half frame period is used. All GPRBs are sent as feedback information from the 15 mobiles to the eNB. Furthermore, the total throughput of an omnidirectional transmit system at a eNB with four antennas at the receiver – Single Input Multiple Output – is also given to serve as a lower bound. This SIMO 1×4 system could be compliant to an 3GPP-LTE system in case of high mobility, where no CSI is available at the eNB and therefore the scheduler allocates randomly the PRBs to different UEs with 0.5 BPSK modulation and coding scheme.

The transmitted power as a function the number of UEs (cell load) guaranteeing an SNR = 10 dB for all mobiles is depicted in Fig. 3. For a number of mobiles, approximately equal to 15 and randomly distributed in the cell, an emitted power level of one Watt (30 dBm) could support the required SNR and a power level of lower than 6 W (38 dBm) would be adequate to have the same effect when 40 mobiles are located in the cell. Fig. 4 presents the average physical layer data rate as a function of distance for a UE that moves along the horizontal axis. We remark that our scheme improves the coverage area at about 45% over SIMO 1×4 system, when a minimum data rate of 4 Mbits/s is required over the air. Additionally, Fig. 5 shows that fairness is improved among the users with our GPRBs beamforming design. In this scheme 20% of users achieve an SNR lower than 10 dB while in SIMO 1×4 scheme only 50% of mobiles present SNR greater than 10 dB. Fig. 6

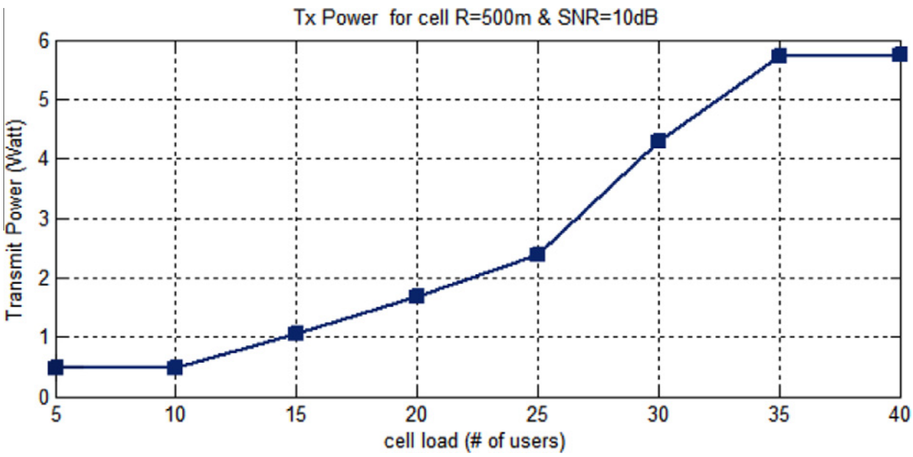

Fig. 3. Transmit power versus cell load.

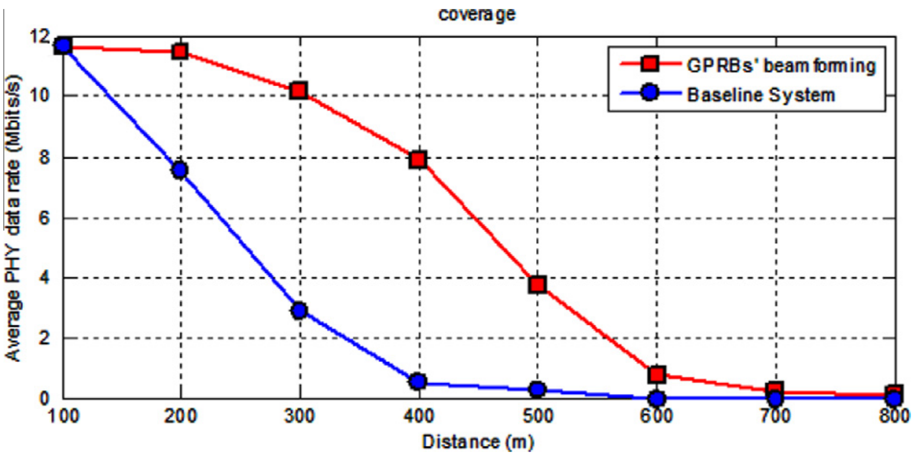

Fig. 4. PHY data rate versus distance.

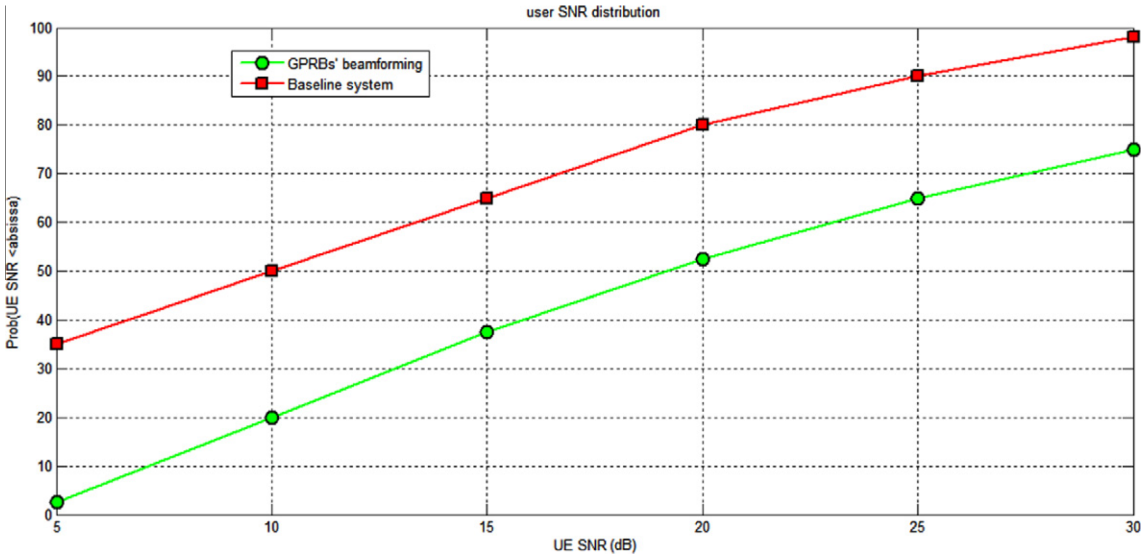

Fig. 5. UEs' SNR distribution.

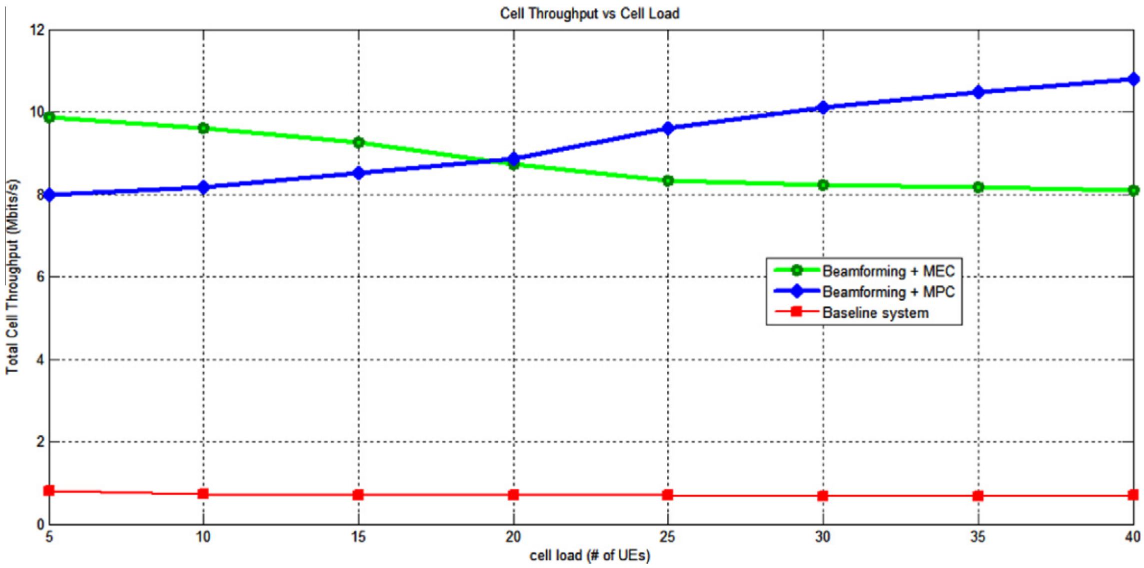

Fig. 6. Cell throughput versus cell load.

compares the Mean over PRB Covariance (MPC) statistical feedback strategy, the Minimum Effective SNR covariance (MEC) feedback scheme and the omnidirectional SIMO 1×4 system. As Fig. 6 indicates, the performance with feedback may be significantly enhanced, e.g. the total cell throughput is improved from 1 Mbits/s to more than 10 Mbits/s. The performance with MPC feedback is better when the number of mobiles grows than that with the MEC feedback scheme. This can be justified by the fact that a large number of users provide increased multiuser diversity. The large number of users involves large number of independent channels. The MEC scheme takes into consideration more reliable information about the correlated channel based on the weakest PRB. When a wider variety of different channels is present, the radio resource management algorithm with MEC has more chances to improve the efficiency of the system. Fig. 7 depicts the achievable system throughput as a function of feedback load if the 50 PRBs are divided into 20 GPBs (e.g. 15 GPRB contain 3 PRBs and 5 GPRBs 1 PRB) for a system with the MEC feedback scheme. The total cell throughput increases from 0.5 Mbits/s, when the strongest cluster is fed back to more than 7.5 Mbits/s in the case where the five GPRBs with bigger minimum ESNR are used. A degradation of the system performance of about 15% is observed if 5 PRBs instead of 20 are selected to be fed back. The performance starts to

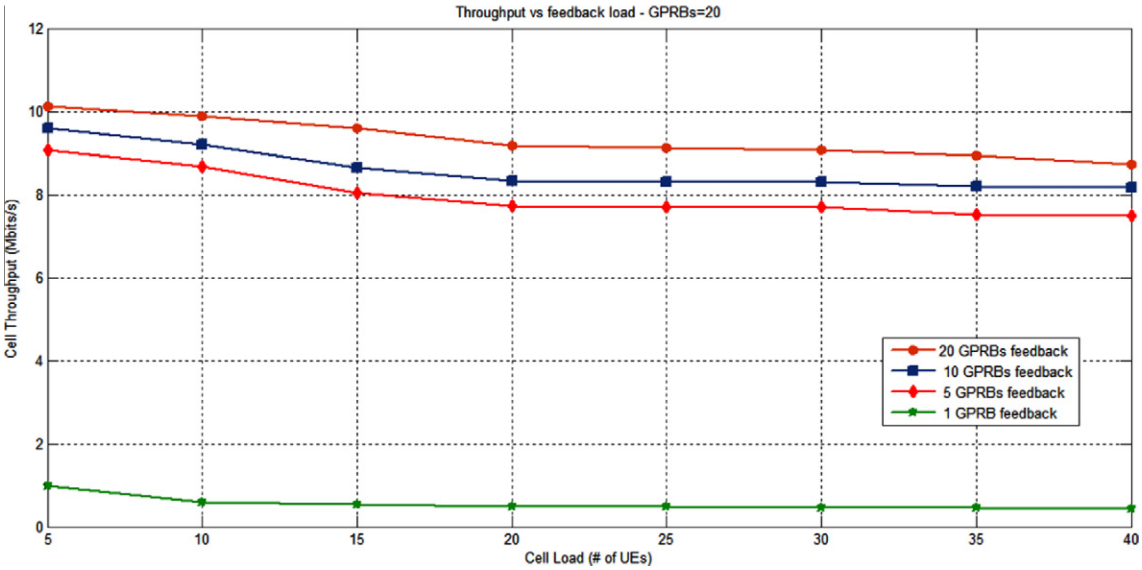

Fig. 7. Total cell throughput versus feedback load.

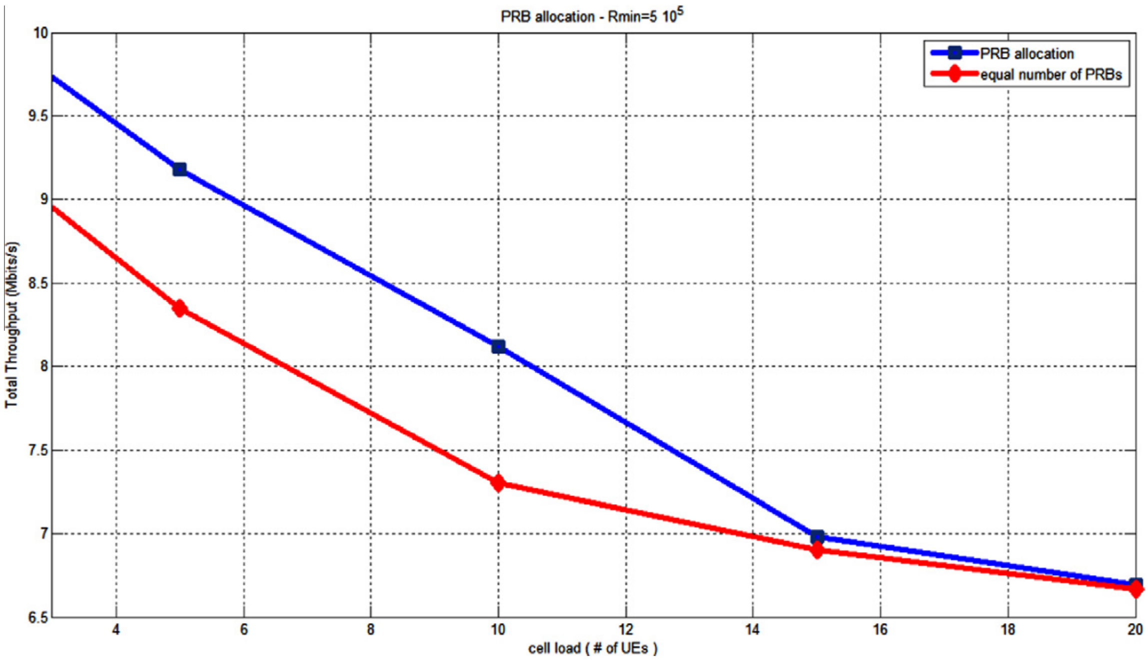

Fig. 8. Total throughput versus cell load for the PRB sharing problem.

degrade due to the fact that the same AMC scheme is used for a GPRB and therefore the CSI report is outdated, compared to the fast variation of the channel in the time and frequency domains.

Computer simulations have also been conducted to evaluate the performance of the optimization problem after the beamforming and frequency allocation problem $\mathcal{T}$ is solved for 5 GPRBs or 10 consecutive grouped PRBs. Our proposed algorithm for optimal PRB assignment is compared to the equal PRB method (equal number of PRBs is allocated to each UE) in Fig. 8. Target rates of UEs are predetermined to 500 Kbits/s. When the number of UEs is greater than 15, our optimal strategy tends to allocate similar number of PRBs with the equal-time method.

In the multi-cell environment, the results of two different scenarios are presented. The MEC feedback scheme with 3 GPRBs is applied. We assume that the eNB's are placed following the pattern depicted in Fig. 1 ($B = 7$),

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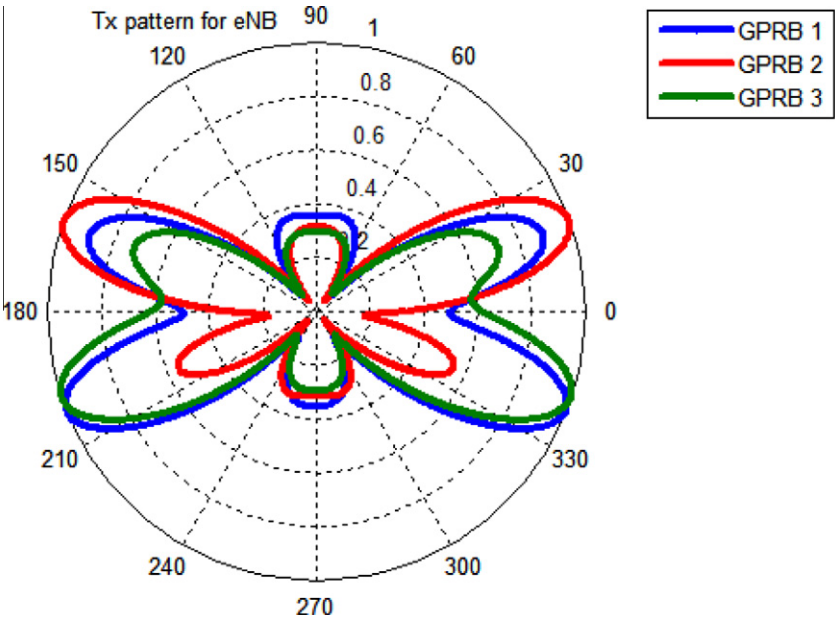

Fig. 9. Transmitted beams of eNB for a scenario with 3 GPRBs as feedback load.

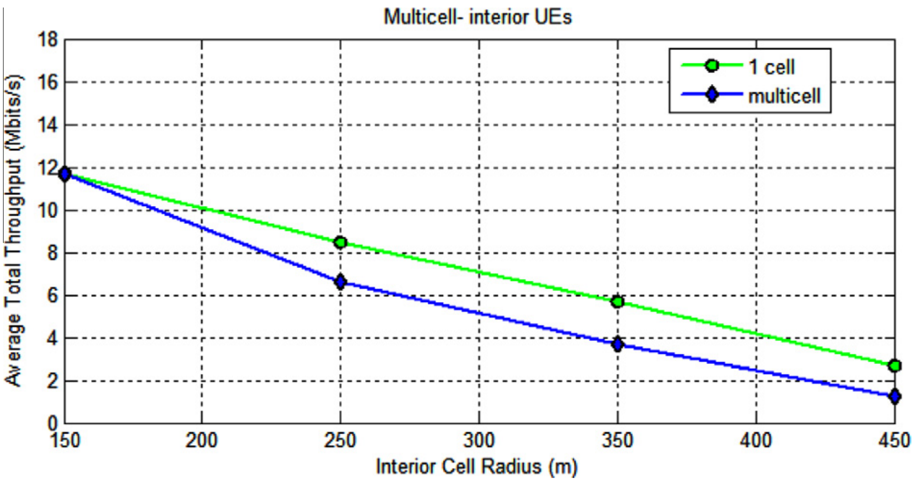

Fig. 10. Throughput degradation of interior UEs.

transmitting at full power (1 W). Transmitted beams for the 3 GPRBs are highlighted in Fig. 9 to show the effect of our approach. In the first scenario, six mobile users are distributed in the interior-cell edge. Each user moves along a line connecting neighboring sites, for example along the line connecting A and B in Fig. 1. Fig. 10 shows the variation of the PHY data rate of the six interior edge UEs versus the radius of the interior cell R_{in}. We remark that co-channel interference from other cells leads to a performance degradation compared to the single cell case without inter-cell interference. For R_{in} = 250 m, inter-cell interference causes an average cell throughput loss of 33% while for R_{in} = 150 m no degradation in throughput can be observed. Finally, we consider an external area with three users located at one edge with polar coordinates (R_{out}, 0°), (R_{out}, 30°) and (R_{out}, −30°). It can be seen by Fig. 11 that the throughput for this area can be improved by about 60% when R_{out} = 400 m and dynamic beamforming-scheduling is used instead of beamforming-static FFR by fully exploiting the frequency selectivity gain.

9. Conclusions

This paper has addressed the multiuser multi-cell MIMO/OFDMA problem of beamforming and scheduling in the frequency and time domains when the transmitter

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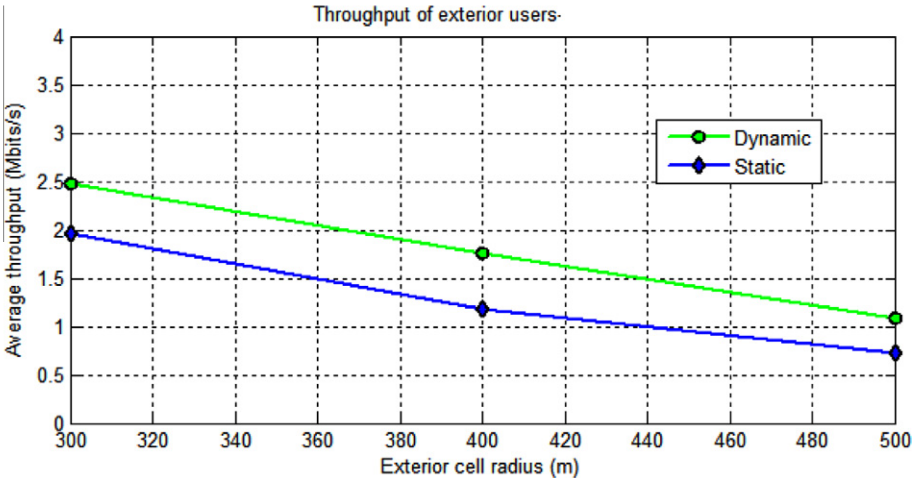

Fig. 11. Frequency diversity for exterior users.

has only the knowledge of channel statistics of the users. We proposed and developed two new, flexible and scalable low rate feedback schemes in a network with rapidly time-varying channels. We have proposed system-level techniques that can be combined with the advanced algorithms already proposed in literature to reduce intra-cell interference and to coordinate the user transmissions aiming at increased throughput and better spectrum exploitation. Our results indicated that the proposed strategies can meet the requirements of the promising the future IEEE 802.16m and LTE advanced standard technologies.

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