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# Resource allocation with multicell processing, interference cancelation and backhaul rate constraint in single carrier FDMA systems☆

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ABSTRACT

We consider a cellular system where base stations (BSs) cooperate to receive data from mobile terminals (MTs) using single carrier frequency division multiple access (SC-FDMA). This yields a distributed multiantenna system, with corresponding multicell processing gain. Moreover, the exchange of information among BSs is limited due to the rate constraint on the backhaul network. A first contribution of the paper is a scheduler of the signals shared among BSs on the backhaul with the objective of maximizing the SC-FDMA system sum rate. A greedy algorithm is proposed as a viable solution of the problem. A fundamental feature of the scheduler is that BSs may share received signals only within a subset of the subcarriers of each SC-FDMA block. As a further contribution of the paper, to increase the system sum rate, we also consider interference cancelation, where BSs detect some messages without cooperation, and transmit on the backhaul a suitable linear combination of received and detected signals. The scheduling problem is suitably modified to take into account interference cancelation, thus selecting the MTs for which detection occurs before sharing the signal on the backhaul. Numerical results for typical cellular configurations are presented.



## 1. Introduction

The use of multiple antennas for reception of wireless signals has proven to provide benefits with respect to the use of single antenna devices. The concept has found applications also in the uplink of cellular systems, where not only each base station (BS) may be equipped with multiple antennas, but also BSs may share signals received from the mobile terminals (MTs). In this latter case, we obtain a distributed multiantenna system – which goes also under the names of *multicell processing* (MCP), *coordinated multipoint* (CoMP), cooperative multiple input multiple output (MIMO) system, or *network MIMO* [1,2] – that has been considered for the long term evolution (LTE) of the 3rd generation partnership project (3GPP) [3]. The benefits of MCP are: (a) a better coverage, obtained by improved decoding capabilities of cell-edge MTs, (b) mitigation of the interference that can be efficiently avoided or subtracted, and (c) an improved spectral efficiency, due to the MIMO channel obtained with the MTs [4,5]. The drawback of MCP is that it requires exchange of information among the BSs, which usually is performed on the backhaul network. However, the backhaul network was designed to support only the data traffic with the radio network controller (RNC) rather than the MCP traffic, thus there is a constraint on the amount of information that can be exchanged among BSs.

The first studies from a information theoretic point of view [6–8] have derived rate regions (or bounds on the regions) for the backhaul constrained MCP, and more recently the effect of imperfect channel estimation has been considered [9]. It turns

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out that scheduling of both MT transmissions and backhaul resources is of paramount importance in these systems, in order to exploit at best the potentials of MCP. Various approaches have been proposed in the literature. In [10] a trade-off between the rate of the wireless link and the backhaul occupation is achieved by scheduling the MT transmissions. In [11,12] the set of BSs that cooperate for the decoding of signals is selected based on the outage probability assuming that transmissions use a hybrid automatic repeat request (HARQ) protocol. The maximization of the network rate for a given MT deployment is considered as objective in the selection of cooperating BSs in [13]. When linear beamforming is used by BSs equipped with multiple antennas, in [14] the selection of cooperating BSs is performed by a dynamic greedy algorithm. A related problem is the allocation of resources in relay-assisted networks, where the connection from the relay to the base stations can be seen as a backhaul network [15–17]. However in this case the backhaul network structure is simplified with respect to that of cooperating BSs.

All of the above cited studies focus on achievable rates and scheduling (on the wireless link and the backhaul) for MCP, assuming that transmissions occur on a set of parallel additive white Gaussian noise (AWGN) channels as in orthogonal frequency division multiplexing (OFDM). However, the LTE of 3GPP, in the uplink, has adopted single carrier frequency division multiple access (SC-FDMA) [18], where a single carrier signal is allocated to a specific band by use of discrete Fourier transforms (DFTs). Moreover, the addition of a cyclic prefix yields a simplified receiver architecture since equalization of dispersive channels can be performed in the frequency domain by means of efficient DFTs [19]. In practice, linear equalizers are used in order to limit complexity, at the expense of reduced performance with respect to non-linear equalizers [20]. For SC-FDMA systems, scheduling of MT transmission for interference mitigation is considered in [21,22], but among the BSs no sharing of signals received from MTs is considered. To the best of the authors' knowledge, the problem of MCP with a backhaul rate constraint for the SC-FDMA system has never been addressed before in the literature.

In this paper we consider MCP for the uplink of a SC-FDMA based cellular system, under a backhaul rate constraint. The main objective of the paper is a scheduling algorithm for transmission on the backhaul network in order to maximize the system sum rate achieved on the wireless link while satisfying a constraint on the maximum rate on the backhaul. To limit backhaul rate, we propose that on the backhaul the BSs share the received samples only within a subset of the SC-FDMA subcarriers. In turn this set is selected dynamically according to the channel conditions of each MT–BS link and considering the backhaul rate constraint. The shared samples are then suitably gathered by each BS in order to reconstruct an improved version of the received signal from the served MTs. In particular, before data detection two equalization approaches are considered, both in the frequency domain: signal selection and combining. In the first approach the serving BS may substitute the signals received directly from the MTs with those shared on the backhaul. In the combining approach instead each BS performs a combining of the signals received directly and those shared on the backhaul. Inter-cell interference (ICI) is taken into account both in the model and in the MCP. In both cases, the weighting of the useful signal against noise plus interference is carried out by both a zero forcing and mean square error criterion. Since scheduling turns out to be a non-linear integer programming problem, a greedy algorithm is proposed for an efficient implementation. Lastly, to further increase the system performance, we propose that BSs detect messages from some MTs without cooperation, then adjust the amplitude and phase of the detected signals before transmitting them on the backhaul. This adjustment allows a perfect cancelation of the interference caused by the detected signals at the cooperating BSs. The scheduling problem is suitably modified in order to take into account the benefits of interference cancelation, thus shaping the ordering of decoding of the various messages. To assess the merits of the proposed solutions, numerical results in a realistic LTE scenario allow a comparison between the proposed greedy algorithm and an upper bound given by a backhaul with no constraint.

The rest of the paper is organized as follows. In Section 2 we present the system model by describing the SC-FDMA modulation and the backhaul infrastructure. In Section 3 we describe our proposals and formulate the optimization problems. In Section 4 a greedy algorithm is presented to solve the scheduling problems. In Section 5 we numerically evaluate the proposed schemes in an cellular network in terms of the system sum rate and draw conclusions in Section 6.

*Notation*: We use $(\cdot)^T$ to denote transpose and $(\cdot)^H$ to denote complex conjugate transpose. $\mathbf{0}_{N\times M}$ denotes the $N \times M$ matrix with all zero entries and $\boldsymbol{I}_N$ the identity matrix of size $N$.

## 2. System model

We consider the uplink of a cellular system comprising a set $\mathcal{K} = \{1, 2, \ldots, K\}$ of MTs transmitting to a set $\mathcal{J} = \{1, 2, \ldots, J\}$ of BSs. Both MTs and BSs are assumed to have one antenna each. The generalization to the case of multiple antenna systems is left for future study. BSs are connected to a RNC node by a backhaul network. In the following we describe the transmission both from the MTs to the BSs on the wireless link and among the BSs over the backhaul.

### 2.1. Conventional SC-FDMA transmission

According to SC-FDMA, the available spectrum of $N$ subcarriers is divided into $S$ *resource blocks* (RBs) each of $M$ subcarriers, i.e., $N = MS$. In particular, let $\mathcal{S} = \{0, 1, \ldots, S-1\}$ be the set of available RBs and $\mathcal{N}_s = \{sM, sM+1, \ldots, sM-1\}$, $s \in \mathcal{S}$, the set of subcarriers associated to RB $s$. With reference to MT $k \in \mathcal{K}$ we define as $\mathcal{S}^{(k)} \subseteq \mathcal{S}$ the set of allocated RBs and $\mathcal{N}^{(k)} = \left\{n \in \mathcal{N}_s : s \in \mathcal{S}^{(k)}\right\}$ the corresponding set of subcarriers. Moreover, let $\mathcal{K}^{(j)} \subseteq \mathcal{K}$ be the