An efficient and adaptive resource allocation scheme for next generation cellular systems

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Abstract—[1] **A dynamic and distributed multiuser radio resource allocation scheme for a FDMA-TDMA based multicellular system is proposed. User interference measurements and channel estimation at the mobiles are used in order to exploit the multiuser diversity of the system. Basic information bearers (i.e. the subcarrier/time-slot pairs) are efficiently allocated and power loaded to accommodate the users rate-demands and dynamically adapt to the interference produced by neighboring cells. Our solution leverages on the possibility to feed the RRM algorithm with parameters coming from different layers, following a cross-layer approach.**

Keywords: Cellular networks, radio resource management, dynamic distributed allocation.

1. Introduction

4G systems are expected to overcome 3G systems in terms of data rate, efficiency of the band usage, reconfigurability and QoS provisioning. A promising approach to realize such a vision consists in designing cross-layer solutions, which allow the exchange of information among different protocols layers to maximize the overall system performance. Improvements are expected by feeding the radio resource management (RRM) module with physical layer information, like radio links conditions and interference levels. Such information can be used to exploit the multiuser diversity of the system, while providing the requested QoS.

In this paper, we focus on the cellular system proposed within the framework of the P.R.I.M.O. project [9]. The radio interface is based on a OFDM modulation, which allows for a FDMA–TDMA medium access mechanism. The elementary radio resource that can be independently allocated is the subcarrier/time–slot couple, which will be called Physical Basic Unit (PBU). In the perspective of maximizing the use of the radio resources, avoiding static and a priori frequency planning, the project requires a complete reuse of the radio resources among adjacent cells. Furthermore, at this stage of the work, no direct communication is assumed among cells. On the one hand, these requirements promote the definition of a flexible and reconfigurable system which can dynamically adapt to traffic load and interference conditions. On the other hand, effective resource allocation algorithms, able to adapt to traffic and interference dynamics, are required to avoid very high interference among neighboring cells [1].

According to the scenario proposed in [9], we assume the algorithm is performed by the basestation (BS) of each cell, while no explicit signalling among cells is considered. We assume that the BS has a clear vision of the channel status and interference levels perceived by each user, for each allocable resource. Such information is passed to the allocation algorithm that allocates the PBUs, setting power and bit loads, to the mobiles in order to satisfy the rate-demands of the users. So far, only downlink allocation is considered.

The rest of the paper is organized as follows. Section 2 overviews the related works. Section 3 describes the system model considered in the study. Section 4 presents the allocation algorithm and the related heuristic. Results and comments are reported in Section 5. Finally, Section 6 concludes the paper and describes possible evolution of the work.

2. Related works

The definition of the allocation algorithm requires the identification of the objective to be optimized and the constraints to be guaranteed. Many algorithms have been proposed in literature. In [2] the objective is to maximize the minimum rate allocated to each user, subjected to a limit in the total power that can be allocated. A different approach is followed in [3], [6] and [4], where the optimization problem aims at minimizing the total transmitted power, while guaranteeing a minimum rate for each user. Another approach is proposed in [5], where the objective is the maximization of the allocated capacity under the constraint of satisfying the rate-demand of each user. Since the problem turns out to be nonlinear, a simplified approach is proposed, where the power is allocated in advance, leading to a linear problem.

Starting from this approach, we propose a new allocation algorithm that aims at maximizing an efficiency function in the PBU allocation, while guaranteeing the

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rate-demand of each user. This scheme, as all the previously cited approaches, presents a very high computation effort. Therefore, heuristics are needed to solve the problem in a reasonable time. A way to reduce the complexity of the resource allocation problem is to separately perform the PBU allocation and the bit loading [7,8]. According to this strategy, we will also provide an efficient heuristic for the proposed allocation algorithm.

3. System model

Although the design of the allocation algorithm has been referred to the system model described in [9], which encompasses a OFDM modulation [4], the algorithm can be adopted in any system that provides orthogonal PBUs within each cell, so that intra–cell interference can be neglected. For the sake of comparison with other algorithms proposed within the P.R.I.M.O. project, however, in the following we will refer to the scenario considered in [9].

The system model consists of a cluster of cells with the classical hexagonal cell disposition [9]. Each user is connected to the nearest BS. The radio access is organized in a hybrid FDMA–TDMA fashion. We assume that the downlink channel is obtained by reserving a frequency band B, which is divided in N_s orthogonal subcarriers. Furthermore, we assume that time axis is partitioned in successive frames of duration T_f and that N_t consecutive slots of each frame are devoted to downlink transmissions. Each Physical Basic Unit (PBU), represented by a subcarrier/Time–slot pair, will be identified by the couple (s,t), where $s \in \{1,\ldots,N_s\}$ denotes the subcarrier and $t \in \{1,\ldots,N_t\}$ the time slot index inside the considered frame. We assume PBUs are mutually orthogonal, so that self-interference produced by users in the same cell can be neglected. The PBU is the minimum allocable physical resource and the RRM algorithm can set the transmission power, and the bit load for each PBU independently. Only a finite set $b_j \in \{1 \geq j \geq J\}$ of bit loads is allowed.

At the beginning of each frame, each BS invokes the allocation algorithm by passing both the actual rate-demands of the users in the cell and the interference levels and channel quality perceived by each mobiles. We suppose that this information transfer from mobiles to the BS is performed over a separate error–free signalling channel. Also the channel estimation and interference measurement are supposed to be perfect. However, such values are updated only at the end of each downlink frame. Therefore, they may not reflect the actual condition that the users will face during the upcoming frame, since traffic and channel dynamic in the adjacent cells may change the current interference scenario.

On the basis of the information passed by the BS, the algorithm determines the PBUs, and the related power and bit load, that have to be allocated to each user in the next frame.

At this stage of the work, we assume a stationary channel, so that signal attenuation can be perfectly predicted on the basis of a simple path loss model, where the attenuation is proportional to d^4, being d the distance between BS and mobile. On the contrary, the interference depends on the resource allocation of the neighboring cells and can change frame by frame. Therefore, to improve the quality of the interference estimation, the RRM algorithm shall be designed to maintain the resource allocation matrix as static as possible. Following this policy, PBUs allocated to a flow will generally persist on successive frames, as will be described later.

Each cell is populated by uniformly scattered and static users. The traffic offered to the system by each user follows a dynamic and random pattern. Flows requests are generated at exponentially distributed time intervals with mean T_i and remains active for an exponentially distributed time with mean T_a. Each flow requires a minimum rate r_k to be allocated in each frame. When a request ends, the allocated resources are deallocated. This dynamic traffic pattern models a realistic situation where the variation of the traffic offered to the different cells reflects into variations of the interference scenario perceived by each user. The allocation algorithm has to dynamically adapt the allocation to the variable interference conditions and offered traffic.

The following section describes in detail the proposed algorithm.

4. The Radio Resource Allocation algorithm

The allocation process consists in assigning to each flow k one or more PBUs and to set the related transmission power and bit load. The allocation algorithm has to guarantee the rate demand r_k of each flow. To this end, rate-requests are grouped in two sets, OLD and NEW. The set OLD contains the flows that have already been allocated in some previous frame and that are still active. The PBUs allocated to the flows in this set are maintained in the successive frames. However, the power of each allocated PBU is independently adapted to follow the channel and interference variations. If the total mean power needed to satisfy the minimum rate requirement of the flows turns out to be greater than a specified threshold, all the related PBUs are deallocated and the corresponding flows are moved in the NEW set.

The NEW set contains the rate-requests corresponding to the new flows originated within the previous frame or the flows that need to be reallocated. Rate-requests belonging to NEW are allocated as follows.

By considering a common power level p_{tx}^i, the BS computes the capacity associated to each PBU and for each user. It is supposed that each PBU can be loaded with the highest allowable bit load, that, in this first analytical formulation, is assumed to equal the Shannon capacity.

Let C_k be the capacity matrix for the k-th user, i.e., the user that has generated the k-th rate-request ($1 \leq k \leq K$). Furthermore, let $c_{k,s,t}$ denote the element of C_k, which represents the Shannon capacity associated to the PBU (s,t), for the k-user, with the given transmission power p^i_{tx}.

Hence, we define the efficiency matrix E_k for the k-th request as the $N_s \times N_t$ matrix whose element $e_{k,s,t}$ are given by:

$$e_{k,s,t} = \frac{c_{k,s,t}}{\sum_{k=1}^{K} c_{k,s,t}} \; .$$

Notice that, $e_{k,s,t}$ gives an indication about the efficiency of the allocation of (s,t) PBU to the k–th user with respect to any other user.

Let us denote the outcome of the resource allocation for the k–th request as a $N_s \times N_t$ boolean matrix A_k, where $a_{k,s,t} = 1$ if the (s,t) PBU is assigned to user k, and $a_{k,s,t} = 0$ otherwise. Since we assume that a PBU can be allocated to one user only, the condition $\sum_{k=1}^{K} a_{k,s,t} \leq 1$ must hold.

The optimization problem can, then, be formulated as follows:

Objective:

$$\min \sum_{k=1}^{K} \sum_{s=1}^{N_s} \sum_{t=1}^{N_t} a_{k,s,t}(1 - e_{k,s,t}) \; ;$$

Constraints:

$$\frac{1}{T_f} \sum_{s=1}^{N_s} \sum_{t=1}^{N_t} c_{k,s,t} a_{k,s,t} \geq r_k,$$

$$\sum_{k=1}^{K} a_{k,s,t} \leq 1 \quad \forall (s,t) \; ,$$

where T_f is the frame duration.

If the rate request is not satisfied, the optimization problem is repeated using an higher power level $p^{i+1}_{tx} = p^i_{tx} + \delta p$ for each PBU. The procedure starts setting $p^i_{tx} = p^{min}_{tx}$ and it is repeated until all rate requests are satisfied or the maximum allowable power p^{max}_{tx} is reached.

The exact solution of such minimization problem is hard to be obtained, so a new greedy heuristic has been developed. Simulations of the heuristic behavior have proven that it is very near to the optimal solution, obtained using linear programming tools.

4.1. Heuristic

The heuristic method we adopt for the allocation strategy is described by the following operations.

The algorithm subsequently chooses a request k and then allocates a PBU to this request. Hence, rate requests and available resource set are refreshed accordingly. The criteria for the selection of the request and the related PBU are the following.

First, the capacity matrix for each user is computed by assuming a transmission power p^i_{tx}, equal for all the PBUs. At each stage of the algorithm, all users requests are sorted using the metric

$$\eta_k = \frac{c_{k,av}}{r_{k,rem}}.$$

Here, $r_{k,rem}$ is the bitrate the flow k still need in order to reach the minimum rate request r_k for the current frame. It is calculated by subtracting the already allocated capacity to the request r_k. $c_{k,av}$ is the total capacity that might be allocated to the k-th flow, in the case all the remaining PBUIs were assigned to that flow:

$$c_{k,av} = \sum_{n,s} c_{k,n,s}(1 - a_{k,n,s}).$$

The user with minimum η_k is chosen for the allocation of a PBU. This policy aims at serving first the user with the highest rate request with respect to the available resources. Once selected the flow to be served, it will be assigned the PBU with the highest efficiency $e_{k,s,t}$ among those not yet allocated. The quantization of allowable bit loads is accounted by associating to the chosen PBU the highest bit load b_j smaller than the Shannon capacity. The power is then recomputed based on the allocated bit load, adding an extra power nedded to overcome the error in interference estimation.

At the end of each step, the value of $r_{k,rem}$ and $c_{k,av}$ are recomputed and the process is repeated until all user rate requests r_k are satisfied or all the PBUs have been allocated.

If some requests remain unsatisfied, the entire procedure is repeated with a higher value of power p^{i+1}_{tx}. The increment of the power is limited by the maximum power p^{max}_{tx}. After this limit, the power cannot be further increased and the algorithm fails to allocate all the required flows.

A key point in the behavior of the algorithm is the choice of the starting power p^0_{tx}. A particular case is represented by the choice of $p^0_{tx} = p^{max}_{tx}$.

5. Simulation Results

The algorithm is tested on a 7-cells scenario. The system parameters are taken from [9]. Here a frame time of $T_f = 10$ms is assumed. The bandwidth of the system is $B = 20$MHz. The number of time slots is $N_t = 16$ and the number of subcarriers is $N_s = 33$. The channel model accounts only for deterministic pathloss due to the distance. The cell radius is fixed to 100m. The behavior of our RRM is evaluated in terms of the total mean power used by the base station, the throughput of a cell and the mean reuse factor of a PBU.

The throughput is simply evaluated in the following approximate way. It is assumed that the data allocated to a request in each frame can be thought as a single data packet. At the end of each frame the new values of interference perceived by each PBU are measured. The new Shannon capacity associated with each PBU is computed. If any of the PBU allocated to a packet results to have a capacity lower than the loaded bits, it is assumed that the packet has been lost. In Figure 1 it is plotted the throughput of the central cell (in order to avoid border effects) as a function of the requested traffic, for two different values of p_{tx}^0.

In Figure 2 it is plotted the total mean power transmitted by the BS of the central cell as a function of the requested traffic, for the same two different values of p_{tx}^0. It is also shown the power level in the case the neighboring cells where unloaded so that no interference is present.

In order to understand the behavior of the proposed algorithm and the impact of the choice of p_{tx}^0, for each PBU used by the central cell it is computed the number of BSs which are using the same PBU. In Figure 3 it is shown such value averaged over all allocated PBUs and divided by the maximum number of possible BS (7). This metric can be interpreted as a reuse factor.

Comparing the behavior of the two policies it can be seen that the choice of $p_{tx}^0 = p_{tx}^{max}$ lead to a lower reuse factor. This can be explained considering that each PBU is loaded with an high power so the corresponding PBUs of neighboring cells are highly interfered. In this case the algorithm allocates a small number of PBUs per request and tends to orthogonalize the allocated PBUs among cells. On the contrary, starting with a low level of power, many low power PBUs are used for each request, but PBUs can be used by more BSs at the same time. This behavior leads to a higher throughput while using a lower power than in the former approach.

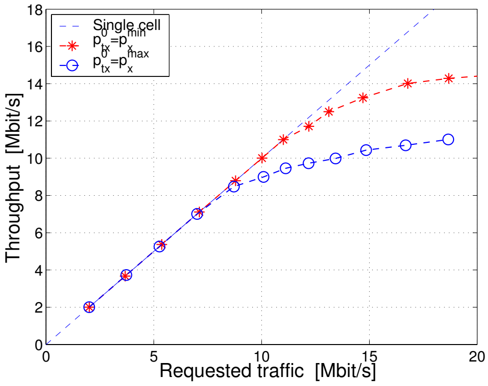

Fig. 1. Throughput

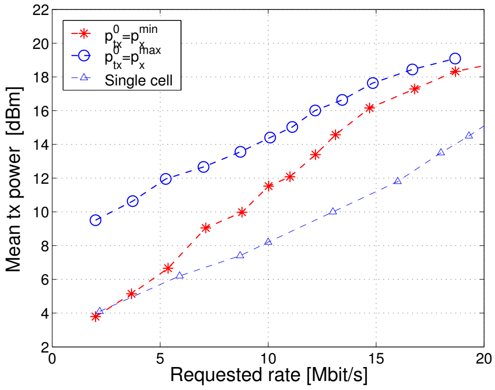

Fig. 2. Mean total power vs requested rate

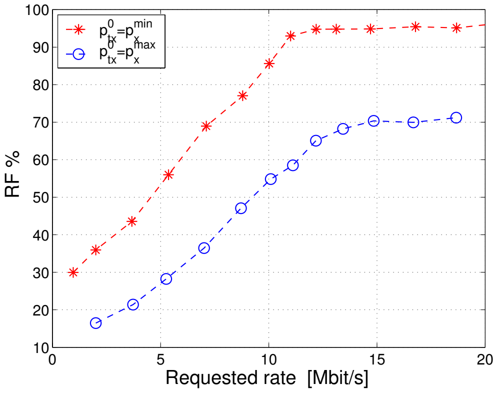

Fig. 3. Mean reuse factor

6. Conclusions and future work

In this paper a resource allocation algorithm suited for an FDMA-TDMA multicellular system has been presented. The mechanism is formulated as a liner programming problem, where the objective is the maximization of a function accounting for the efficiency of the allocation. The constraint is represented by the rate requested by each user. In order to reduce the computation complexity an efficient heuristic is also developed. The system is tested under a dynamic traffic scenario. The behavior of the algorithm shows the ability to provide an high reuse of the resources among neighboring cells.

Future investigations will aim at comparing the proposed algorithm with other mechanisms, in order to gain insights in the strengths and drawbacks of each approach.

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