Acta Universitatis Sapientiae
Electrical and Mechanical Engineering, 9 (2017) 19-32

DOI: 10.1515/auseme-2017-0007

Game Theory Based Radio Resource Management Algorithm for Packet Access Cellular Networks

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Manuscript received September 10, 2017; revised October 19, 2017.

Abstract: The goal of Radio Resource Management (RRM) mechanisms is to allocate the transmission resources to the users such that the transmission requests are satisfied while several constraints are fulfilled. These constraints refer to low complexity and power consumption and high spectral efficiency and can be met by multidimensional optimization. This paper proposes a Game Theory (GT) based suboptimal solution to this multidimensional optimization problem. The results obtained by computer simulations show that the proposed RRM algorithm brings significant improvement in what concerns the average delay and the throughput, compared to other RRM algorithms, at the expense of somewhat increased complexity.

Keywords: game theory, cellular network, bargaining theory, radio resource management, quality of service, service class

1. Introduction

Today's wireless packet access communication networks have to deal with a challenging multi-user access issue: a large number of users located in the same geographical area use a large variety of services with various Quality of Service (QoS) requirements, such as voice, video, gaming, web browsing [1], and request high on-demand data rates in a finite bandwidth. Modern broadband wireless systems, such as 3GPP LTE, employ Orthogonal Frequency Division Multiple Access (OFDMA) as the basic multiple access scheme [2]. The OFDMA multiple access technique exploits both time and frequency diversity by allowing both time and frequency domain scheduling of the data packets [2] [3], [4]. Due to this, OFDMA presents the flexibility needed to accommodate many users with a broad range of services, bit rates, and QoS requirements. Several studies on time and frequency domain packet scheduling have been carried out in the last years [4], [5], [6]. Spatial multiuser OFDM based access techniques were considered also in [7].

The design of the RRM algorithms should consider that the traffic generated by the users is a mixture of Real-Time (RT) and Non-Real-Time (NRT) traffic, the parameters characterizing these types of traffic being presented in [8]. The purpose of these algorithms is to divide the network resources among the concurrent transmissions initiated by the users, subject to low complexity and power consumption, low call blocking probability, efficient spectrum usage, and high system capacity constraints. The mentioned issues are important both in cellular networks and in Wireless Local Area Networks [9]. The RRM entity also has to perform the selection of the Modulation and Coding Schemes (MCS). Adaptive MCS selection algorithms in fading affected and peak power limited radio channels are proposed in [10].

Assigning the transmission resources to the users of the network while fulfilling both network and service related performance criteria requires the definition of appropriate utility functions. The RRM entity will target the maximization of these functions and by this process, the optimal or close to optimal resource allocation to the users can be achieved. In [11] the authors propose a network utility maximization mechanism for optimizing multicast transmissions taking place in WLANs.

The design of RRM algorithms in OFDM cellular systems has attracted a lot of attention in the last years [4], [5]. The trade-off between spectral efficiency and fairness among users is one of the most challenging tasks and several papers propose RRM solutions for OFDMA networks based on "negotiation" strategies, thus transforming RRM into a game theory problem [12]. GT based RRM mechanisms have the potentials to achieve fairness between users while maximizing the overall system capacity [13], but its drawback is the increased complexity. The Nash Bargaining Solution (NBS) is considered in [14] together with coalition to find an optimal agreement among negotiating users.

This paper proposes a Bargaining Game (BG) theory based RRM algorithm for packet access cellular network, capable of ensuring the QoS requirements of RT and NRT type of services. Also, the appropriate utility functions are defined for each type of traffic considered. The paper is organized as follows: Section 2 presents the system model, Section 3 describes the modeling of the RRM process as a bargaining game and proposes the traffic dependent utility functions and Section 4 describes the proposed GT based RRM algorithm as well as the constrained optimization based RRM algorithm used as reference. The simulation scenarios, the numerical results obtained by the performed computer simulations and the analysis of these results are presented in Section 5, while Section 6 concludes the paper.

2. System model

The system model presented in *Fig. 1* consists of a cellular network with a variable number of users which access various RT and NRT services. The cell's access node (the eNB in 4G networks) runs the RRM algorithm responsible for the scheduling of the user's transmissions and the allocation of the transmission resources (divided into units called Resource Blocks (RB)) to the scheduled users. The scheduling process is executed during each Transmission Time Interval (TTI) and the link adaptation process, i.e. the selection of the modulation and coding scheme for each user, is a preliminary step of each scheduling round. The allocated RBs and the results of the link adaptation are signaled to the users on the specific control channels. Only due to evaluation reasons an OFDMA access technique is considered with transmission resources partitioned both in frequency and time domain and the RB represents the smallest time-frequency resource unit that the scheduler can assign.

It is considered that one user has only one running service at a given moment and that the type of the service is known by the scheduler. Note that a user device may run more than one service at a given moment and in this case, the system will consider each service, run by a given user, as a separate user having the same geographical position, the same speed, and motion pattern.

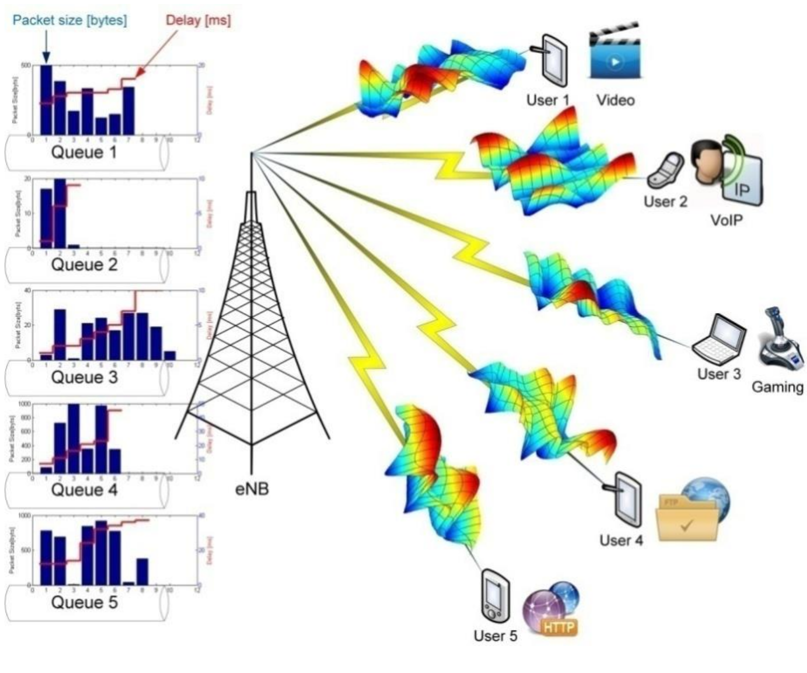

Figure 1: System model

In the cell's central node each user has an individual FIFO queue where the data packets are stored before transmission. The queue stores also information about the data packets (see *Fig. 1*) such as time stamp, packet length, type of service, information which constitutes the Queue State Information (QSI).

In order to perform the scheduling, the RB allocation, and the link adaptation the RRM process should exploit the information that characterizes the wireless links (Channel Quality Information (CQI)). The acquisition and representation of CQI are performed according to specifications given in [15].

3. RRM process modeling and definition of the utility functions

A. RRM process as a Bargaining Game

Let be $\mathbf{K}$ the set of indexes of the N active users located in a given cell, $|\mathbf{K}| = N$, and let be $k, k \in \mathbf{K}$, the index of an individual user. It is considered that each active user is represented by an *agent* which tries to fulfill the QoS requirements of the user's transmission while using the minimum number of RBs. By $\mathbf{RB} = \mathbf{RB_1} \ldots \cup \mathbf{RB_k} \ldots \cup \mathbf{RB_N}$ is denoted the set of available resource blocks and by $\mathbf{RB_k}$ the set of RBs assigned to user k. Let $\mathbf{A_K}$ denote the set of all possible agreement alternatives $\mathbf{a}$, each agreement being represented by the set of RBs allocated to each user, i.e. $\mathbf{a} = \{\mathbf{RB_1}, \ldots, \mathbf{RB_k}, \ldots, \mathbf{RB_N}\}$. Each agent has an upper bounded utility function $u_k(\mathbf{a}) : \mathbf{A_K} \rightarrow \mathbf{R}$ which describes the satisfaction of the user k if the negotiation result is agreement $\mathbf{a}$. The set of all utility functions that result from an agreement is denoted by $\mathbf{S_K} = \{u_1(\mathbf{a}), \ldots, u_i(\mathbf{a}), \ldots, u_N(\mathbf{a})\} \subset \mathbf{R}^N$, a non-empty convex and closed set [14]. If the agents fail to reach an agreement, then by $\mathbf{D}$ is denoted the outcome of this situation and by $\mathbf{d_0} = \{u_1(\mathbf{D}), \ldots, u_i(\mathbf{D}), \ldots, u_N(\mathbf{D})\} \subset \mathbf{R}^N$ the set of utilities achieved by the agents in this situation, referred as "*disagreement point*" [14]. The tuple $(\mathbf{S_K}, \mathbf{d_0})$ defines a bargaining problem. A mapping $f(\mathbf{S_K}, \mathbf{d_0}) \rightarrow \mathbf{A_K}$ is a Nash Bargaining Point (NBP) if some axioms presented in [14] are satisfied.

Let $\mathbf{A^0} = \{\mathbf{a} \in \mathbf{A_K} \mid \forall k, u_k(\mathbf{a}) \geq u_k(\mathbf{D})\}$ represent the set of agreements for which *all* agents achieve at least their minimum utilities (considered in this case to be the utilities from set $\mathbf{d_0}$. Let $\mathbf{J} = \{k \in \{1, \ldots, |\mathbf{K}|\} \exists \mathbf{a} \in \mathbf{A^0}, u_k(\mathbf{a}) \geq u_k(\mathbf{D})\}$ denote the set of users able to achieve a performance greater than or equal to their minimum performance. In this situation a unique NPB exists [14], [16]:

$$f(\mathbf{S_K}, \mathbf{d_0}) = \arg\max \prod_{k \in J} \left(u_k(\mathbf{a}) \geq u_k(\mathbf{D}) \right) \quad (1)$$

B. Utility functions for RT and NRT traffic

In the case of delay sensitive traffic, the time spent by a packet in the transmission chain is the main parameter which influences the QoS of the transmission. Let be $L(\mathbf{RB_k}, \mathbf{CQI_k})$ the function which returns the number of payload bits nb_k which can be carried by the set of $\mathbf{RB_k}$ resource blocks assigned to user *k*. The $\mathbf{CQI_k}$ parameters of the RBs select the MCS schemes.

We denote by $\mathbf{T_k} = \left\{ T_k^1, T_k^2, ..., T_k^{Np_k} \right\}$ the set of delays accumulated by the packets of user *k* in the transmission queue. Np_k represents the number of packets waiting in the queue and the set $\mathbf{B_k} = \left\{ B_k^1, B_k^2, ..., B_k^{Np_k} \right\}$ represents the lengths of these packets. If we suppose that during several consecutive TTIs (with duration t_{TTI}) the instantaneous bit rate remain constant, the expected values of the delay, Te_k^j, accumulated in the network by a packet *j* of user *k* is:

$$Te_k^j = T_k^j + \left\lceil \sum_{i=1}^{j} B_k^i \middle/ nb_k \right\rceil \cdot t_{TTI} \quad (2)$$

Denoting by $\tau_k = \max_{j=1,\ldots,Np_k}(Te_k^j)$ the maximum value of the expected delay we propose for delay sensitive (RT) traffic the following utility function:

$$u_k\left(\mathbf{RB_k}, \mathbf{CQI_k}, \mathbf{QSI_k}\right) = 10^{-\frac{\tau_k}{c_k}} \quad (3)$$

where $\mathbf{QSI_k} = (\mathbf{T_k}, \mathbf{B_k})$ represents the Queue State Information of user *k*, and c_k characterizes the priority of the service accessed by user *k*.

In the case of delay tolerant traffic, the main parameter which influences the satisfaction of the user is the average call throughput. Let R_k^{call} denote the number of bits received by user *k* during the current call and t_i^{call} is the time elapsed from the beginning of the call. The instantaneous value of the average call throughput is given by (4) and the proposed utility function is given by (5):

$$R_k(\mathbf{RB_k}, \mathbf{CQI_k}) = \frac{R_k^{call} + L(\mathbf{RB_k}, \mathbf{CQI_k})}{t_k^{call}} \quad (4)$$

$$u_k\left(\mathbf{RB_k},\mathbf{CQI_k},\mathbf{QSI_k}\right)=\tanh\left(\frac{R_k\left(\mathbf{RB_k},\mathbf{CQI_k}\right)}{R_k^{av}}\right) \tag{5}$$

where R_k^{av} represents the average bit rate.

4. RRM algorithms based on BG and constrained optimization

A. Initial resource allocation

The proposed initial resource allocation algorithm represents the starting point of the bargaining process. This operation is implemented as a modified Round Robin algorithm which assigns to each user a number of RBs proportional to the ratio between the number of bits in the user's queue and the total number of bits waiting to be transferred to all users. The initial allocation algorithm assigns each available RB, but ignores the CQIs associated to the RBs.

$$\left|\mathbf{RB_k}\right|\approx|\,\mathbf{RB}\,|\cdot\sum_{j=1}^{Np_k}B_k^j\Bigg/\sum_{i=1}^{|\mathbf{K}|}\sum_{j=1}^{Np_i}B_i^j \tag{6}$$

Algorithm 1 Initial resource allocation based on Round Robin algorithm

for i=1 to |**K**| **do**
  compute the initial number of RBs allocated to user i, rb_i, using (6)
  initialize $\mathbf{RB}_i=\varnothing$
end for
initialize i=1
for m=1 to |**RB**| **do**
  find an active user for which the number of allocated resource blocks is less than the computed number of initial resource blocks
  while $\left|\mathbf{RB}_i\right|\geq rb_i$ **do**
    $i=\left(i+1\right)_{\mathrm{mod}|\mathbf{K}|}$
  end while
  allocate resource block m to user i
  $\mathbf{RB_i}=\mathbf{RB_i}\cup RB^m$
  $i=\left(i+1\right)_{\mathrm{mod}|\mathbf{K}|}$
end for

B. The bargaining game based resource management algorithm

In the proposed algorithm, after the initial assignment, each user $i \in \mathbf{K}$ will negotiate with each of the other users $j \in \mathbf{K}; i \neq j$, thus resulting $|\mathbf{K}| \cdot (|\mathbf{K}|-\mathbf{1})/2$ negotiations. For every pair (i, j), the two users merge the *"owned"* RBs and the agents negotiate to re-divide this set, $\mathbf{RB_{i,j}}$, of resources. For each RB in the set the ratio CQI_i / CQI_j is computed and the set is sorted decreasingly according to this ratio, as presented in *Fig. 2*. The RBs with low indexes in the set have good propagation conditions for the first user and worse conditions for the second user. Vice versa, the RBs with high indexes in the set have better propagation conditions for the second user and worse conditions for the first user. On the RBs at the middle of the sorted set both users experience almost the same CQIs, so it doesn't matter to which user will be allocated. This sorted set is denoted as $\mathbf{R\hat{B}_{i,j}}$, the k^{th} element of this set being $RB_{i,j}^{k}$.

$$\begin{aligned}
&\mathbf{a_{i,j}^k} = \left\{\mathbf{RB_i^k} \cup \mathbf{RB_j^k}\right\}; k = 0,..,|\mathbf{R\hat{B}_{i,j}}| \\
&\mathbf{RB_i^k} = \left\{RB_{i,j}^{1}, RB_{i,j}^{2}, ..., RB_{i,j}^{k}\right\}; \mathbf{RB_j^k} = \left\{RB_{i,j}^{k+1}, RB_{i,j}^{k+2}, ..., RB_{i,j}^{|\mathbf{R\hat{B}_{i,j}}|}\right\}
\end{aligned} \quad (7)$$

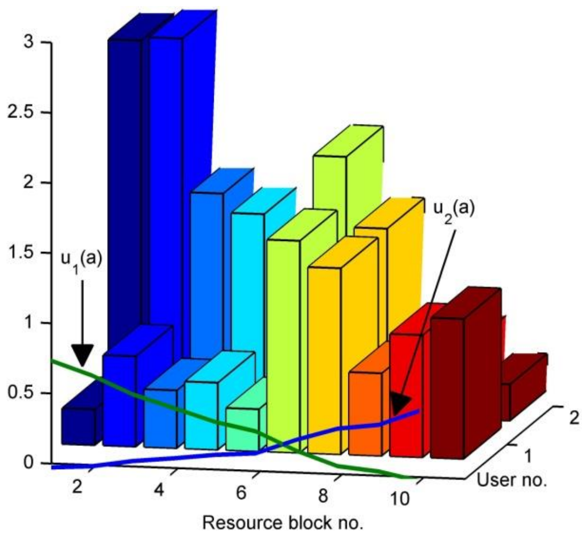

Figure 2: The bargaining process

C. The constrained resource management algorithm

This RRM algorithm adaptively assigns the RBs to the $|\mathbf{K}|$ active users and distributes the total power P_{tot} in order to maximize the ergodic weighted sum rate (8), satisfying the user's minimum rate and fairness requirements [17].

$$U_\gamma = E_\gamma \left\{ \sum_{i=1}^{|\mathbf{K}|} \frac{1}{\left(R_i\right)^\alpha} \sum_{m=1}^{|\mathbf{RB}|} \rho_{\mathrm{i},m} \log_2 \left(1 + p_{\mathrm{i},m}\gamma_{\mathrm{i},m}\right) \right\} \tag{8}$$

where $\boldsymbol{\gamma} = \left[\boldsymbol{\gamma}_\mathbf{1}^\mathbf{T}, \ldots, \boldsymbol{\gamma}_{|\mathbf{K}|}^\mathbf{T}\right]^\mathbf{T}$ with $\boldsymbol{\gamma}_\mathbf{i} = \left[\gamma_{i,1}, \gamma_{i,2}, \ldots, \gamma_{i,|\mathbf{RB}|}\right]$ and $\gamma_{i,j}$ is the effective SNR of user i at the j^{th} resource block. $p_{\mathrm{i},m}$ denotes the power allocated to the user i on resource block m, $\rho_{\mathrm{i},m} \in \{0,1\}$ is an indicator which shows whether resource block RB^m is allocated to user i or not. Note that each RB can be assigned to at most one user at a given time, i.e. $\sum_{i=1}^{|\mathbf{K}|} \rho_{\mathrm{i},m} \in \{0,1\}$ for all m. The function $E_\gamma\{\cdot\}$ represents the statistical expectation with respect to γ, R_i is the user's average call throughput and α is an adjustable fairness parameter. Setting $\alpha = 1$ results in proportional fair allocation, while setting $\alpha = 0$ results in maximum throughput allocation of the available resources.

The constrained optimization problem can be stated as follows [17]:

$$f = \max_{\rho_{i,m}, p_{i,m}} \left(U_\gamma\right) \tag{9}$$

Subject to:

$$E_\gamma \left\{ \sum_{m=1}^{|\mathbf{RB}|} \rho_{\mathrm{i},m} \log_2 \left(1 + p_{\mathrm{i},m}\gamma_{\mathrm{i},m}\right) \right\} \geq R_i^{av} \ \& \ E_\gamma \left\{ \sum_{i=1}^{|\mathbf{K}|} \sum_{m=1}^{|\mathbf{RB}|} \rho_{\mathrm{i},m} p_{\mathrm{i},m} \right\} \leq P_{tot} \tag{10}$$

Algorithm 2 Bargaining game based RRM algorithm

1: Run Algorithm 1 to perform the initial resource allocation to each user
2: **for** i=1 to $|\mathbf{K}|$ **do**
3: **for** j=i+1 to $|\mathbf{K}|$ **do**
4: merge user's i and j resource blocks: $\mathbf{RB_{i,j}} = \mathbf{RB_i} \cup \mathbf{RB_j}$
5: sort $\mathbf{RB_{i,j}}$ decreasingly according to $CQI_\mathbf{i} / CQI_\mathbf{j}$ ratio to obtain $\hat{\mathbf{RB}}_\mathbf{i,j}$
6: **for** k=0 to $\left|\mathbf{RB_{i,j}}\right|$ **do**
build a possible agreement $\mathbf{a_{i,j}^k}$ according to (7)

$\mathbf{RB_i} = \varnothing \cup RB_{i,j}^{1} \cup \cdots \cup RB_{i,j}^{k}$; $\mathbf{RB_j} = \varnothing \cup RB_{i,j}^{k+1} \cup \cdots \cup RB_{i,j}^{|\mathbf{\hat{RB}_{i,j}}|}$

compute the difference between the utility functions for $\mathbf{a_{i,j}^{k}}$

$\psi_k = \left| u_i\left(\mathbf{RB_i}, \mathbf{CQI_i}, \mathbf{QSI_i}\right) - u_j\left(\mathbf{RB_j}, \mathbf{CQI_j}, \mathbf{QSI_j}\right) \right|$

end for

determine the NBS $k = \arg\min\left(\psi_k\right)$

$\mathbf{RB_i} = \mathbf{RB_i^{NBS}} = \varnothing \cup RB_{i,j}^{1} \cup \cdots \cup RB_{i,j}^{k}$

$\mathbf{RB_j} = \mathbf{RB_j^{NBS}} = \varnothing \cup RB_{i,j}^{k+1} \cup \cdots \cup RB_{i,j}^{|\mathbf{\hat{RB}_{i,j}}|}$

end for

end for

By solving the problem described by (9), based on the Lagrange dual decomposition framework [17], block RB^m should be assigned to user k_m:

$$k_m = \arg\max_i \left(G_{i,m}\left(\tilde{p}_{i,m}\right)\right) \tag{11}$$

where $\tilde{p}_{i,m}$ is the optimal power allocation (12) and $G_{i,m}\left(\tilde{p}_{i,m}\right)$ is given by (13).

$$\tilde{p}_{i,m} = \max\left(0, \frac{\left(R_i\right)^{-\alpha} + \lambda_i}{\mu \ln 2} - \frac{1}{\gamma_{i,m}}\right) \tag{12}$$

$$G_{i,m}\left(\tilde{p}_{i,m}\right) = \frac{\left(R_i\right)^{-\alpha} + \lambda_i}{\mu \ln 2} \mathrm{e}^{\left(\frac{1}{\tilde{p}_{i,m}\bar{\gamma}_{i,m}}\right)} \cdot \int_1^{\infty} \frac{e^{-\frac{t}{\tilde{p}_{i,m}\bar{\gamma}_{i,m}}}}{t} dt - \tilde{p}_{i,m} \tag{13}$$

where λ_i and μ are the Lagrangian multipliers computed according to:

$$\lambda_i\left(\mu\right) = 2^{R_i^{av}} \frac{\mu \ln 2}{\bar{\gamma}_{i,m}} - \frac{1}{\left(R_i\right)^{\alpha}} \tag{14}$$

The optimum value of μ can be obtained through a one-dimensional search with a geometrical convergence of the convex function:

$$L_{\gamma}\left(\mu\right) = \frac{R_i^{av}}{\left(R_i\right)^{\alpha}} - \frac{2^{R_i^{av}}}{\bar{\gamma}_{i,m}} + \frac{\mu}{\bar{\gamma}_{i,m}} + \mu P_{tot} \tag{15}$$

Algorithm 3 Constrained optimization based RRM algorithm

1: Compute the optimal value of μ via one dimensional search
1: **for** *m*= 1 to |**RB**| **do**
2: **for** *i*=1 to |**K**| **do**
3: compute $\tilde{p}_{i,m}$ using (12) and compute λ_i using (14)
4: **end for**
5: find user k_m based on (11) to assign RB^m
6: **end for**

5. Numerical results

The evaluation scenario consists of an LTE cellular network (see *Fig. 1*) with 20MHz bandwidth allocated for downlink transmission [15]. An OFDM transmission scheme with 2048 subcarriers is used, out of which 1201 are modulated. The RB is represented by a frequency-time bin of 12 subcarriers and 7 OFDM symbols. The total number of RBs for downlink transmissions is $100/t_{TTI}$. The average speed of the users is 5km/h and each user follows a random walk movement pattern. The used channel model is the WINNER+ urban model [18] [19]. The parameters of the simulation scenarios are presented in Table 1 and the simulations were performed for 10^5 TTIs. As performance indicators, the Cumulative Density Function (CDF) of the packet delays (for RT services) and the CDF of the average instantaneous throughput (for NRT services) are used.

Table 1: The simulation scenarios

	Scenario 1	Scenario 2	Scenario 3
No. of users per cell	100	250	500
Traffic type / users	50% RT (VoIP&Video), 50% NRT (HTTP&FTP)		
R_i^{av} NRT traffic	1Mbps		
c_i RT traffic	10ms		

The CDFs of the delays suffered by the RT type traffic in the considered test scenarios and RRM algorithms are presented in *Fig. 3*. In all cases, the inserted delay has small and moderate values if the GT based RRM algorithm is used, even for a large number of active users in the cell. The constrained RRM algorithm has worse performance in all cases, compared to the GT algorithm.

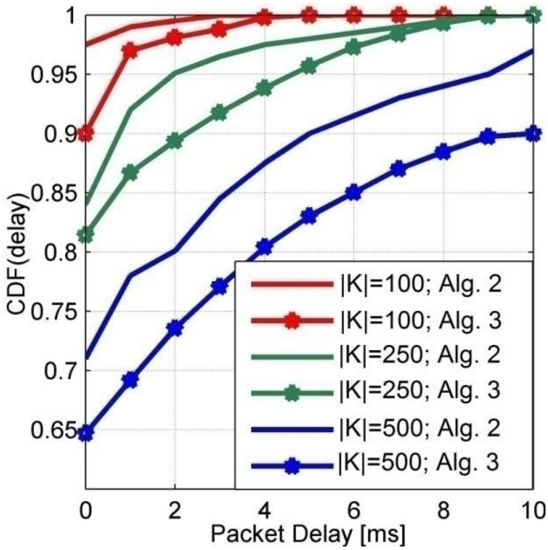

Figure 3: CDF of the packet delays for delay sensitive traffic

In *Fig. 4* it is presented the CDFs of the instantaneous throughput of the NRT type transmissions. The maximum achievable throughput depends on the number of users in the cell. The obtained results show that the GT based RRM algorithm ensures better performance, i.e. larger throughput, for the NRT transmissions.

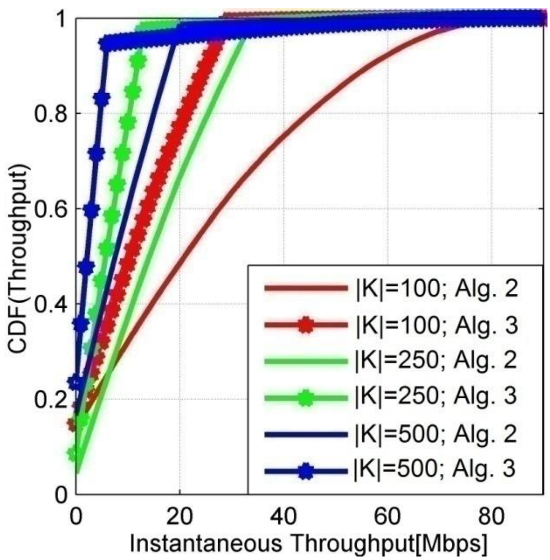

Figure 4: CDF of the instantaneous throughput for best effort traffic

A. Complexity analysis of the RRM algorithms

The RRM algorithm based on constrained optimization needs to run a one-dimensional search to compute the value of μ. After this step, for each user the value of multiplier λ_i and for each RB the power allocation $\tilde{p}_{i,m}$ has to be computed. This means that for every frame $|\mathbf{K}|\cdot|\mathbf{RB}|$ values of λ_i and $\tilde{p}_{i,m}$ should be computed using (14) and (12). Assuming that the search for μ requires I_μ operations the complexity of this algorithm is $O\left(|\mathbf{K}|\cdot|\mathbf{RB}|\cdot I_\mu\right)$.

The proposed GT based RRM algorithm involves $|\mathbf{K}|\cdot(|\mathbf{K}|-\mathbf{1})/2$ negotiations and the negotiating agents in each negotiation process share and sort $2|\mathbf{RB}|/|\mathbf{K}|$ RBs, operation which has a complexity of $O\left(\left(2|\mathbf{RB}|/|\mathbf{K}|\right)^2\right)$. The values of the utility functions have to be computed for all agreements during the negotiation process and the computation of these functions has a linear variation with the number of RBs $O\left(2|\mathbf{RB}|/|\mathbf{K}|\right)$. Another search with complexity $O\left(2|\mathbf{RB}|/|\mathbf{K}|\right)$ is also necessary to find the NBS point, i.e. the best agreement between negotiating users. The overall complexity can be expressed as:

$$O\left(\left(2\frac{|\mathbf{RB}|^2}{|\mathbf{K}|}+|\mathbf{RB}|\right)\left(|\mathbf{K}|-1\right)\right) \tag{16}$$

The variation of the required number of operations as a function of the number of active users and the number of resource blocks is presented in *Fig. 5*.

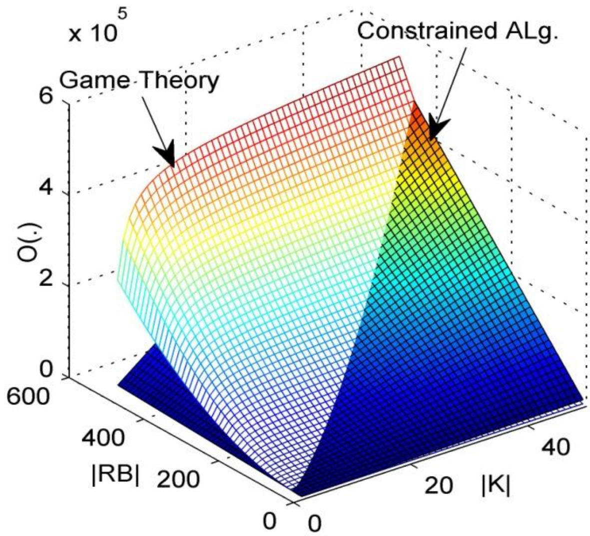

Figure 5: Complexity of the GT RRM and of the constrained RRM algorithms

Conclusion

The paper proposes a game theory based RRM algorithm which targets to find a close to optimal allocation of the transmission resources in cellular networks with OFDMA type multiuser access. The RRM problem in discussion is an NP-hard multidimensional optimization problem. The paper also proposes utility functions for the GT approach, separately for RT and NRT type traffic. The proposed RRM algorithm can ensure the QoS requirements of the user's services while providing high spectral efficiency of the wireless transmissions.

The results obtained using computer simulations show that the proposed RRM algorithm brings significant improvement in terms of average delay and throughput compared to other algorithms, like the constrained optimization based RRM algorithm, at the expense of somewhat larger complexity.

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