An Optimized Resource Allocation Scheme Based on a Multidimensional Multiple-choice Approach with Reduced Complexity

Giulio Bartoli*, Andrea Tassi*, Dania Marabissi*, Daniele Tarchi*†, Romano Fantacci*
*Department of Electronics and Telecommunications
University of Florence
Firenze, Italy
†Department of Electronics, Computer Sciences and Systems
University of Bologna
Bologna, Italy

***Abstract*—Long Term Evolution (LTE) is considered one of the main candidate to provide wireless broadband access to mobile users. Among main LTE characteristics, flexibility and efficiency can be guaranteed by resorting to suitable resource allocation schemes, in particular by adopting adaptive OFDM schemes. This paper proposes a novel solution to the sub-carrier allocation problem for the LTE downlink that takes into account the queues length, the QoS constraints and the channel conditions. Each user has different queues, one for each QoS class, and can transmit with a different data rate depending on the propagation conditions. The proposed algorithm defines a value of each possible sub-carrier assignment as a linear combination of all the inputs following a cross-layer approach. The problem is formulated as a Multidimensional Multiple-choice Knapsack Problem (MMKP) whose optimal solution is not feasible for our purposes due to the too long computing time required to find it. Hence, a novel efficient heuristic has been proposed to solve the problem. Results shows good performance of the proposed resource allocation scheme both in terms of throughput and delay while guarantees fairness among the users. Performance has been compared also with fixed allocation scheme and round robin.**

I. INTRODUCTION

Broadband wireless communications have gained in the last years even more importance in both the consumer and research world, due to their ability of enabling high-data rate connections and broad area coverage even in the case of user mobility. This is also reflected in the presence of several communication standards (e.g., IEEE 802.16, IEEE 802.22, UMTS or LTE) that are already deployed or in an advanced standardization phase.

Among others we have focused our attention to the 3GPP's Long Term Evolution system , whose most important characteristics reside in the fact that it allows high data rate connections with mobile users, and that, from the implementation point of view, it can exploit the already present UMTS core network infrastructure. This is one of the main reason that let us to consider the LTE as one of the most viable alternative for implementing 4G services.

The LTE system proposes the use of Orthogonal Frequency Division Multiplexing (OFDM) in order to lower the effects of the frequency distortion events across the channels and make equalization process in a multi-path fading mobile channel easier. The multiple access scheme adopted in an LTE system is the Orthogonal Frequency Division Multiple Access (OFDMA) where not overlapped sets of subcarriers are assigned to different users within the same OFDM symbols. To have more flexibility and higher efficiency, adaptive OFDM schemes are adopted in order to increase the system capacity and match the desired user QoS performance.

Aim of this paper is to address the sub-carrier allocation problem for the downlink phase of an LTE TDD system through a cross-layer approach, to achieve an optimal resource allocation of traffics with different QoS constraints in a multiuser environment. The sub-carrier allocation problem is addressed in the literature with different approaches; among others, the most important are the resource allocation methods based on the maximization of the instantaneous (or ergodic) rates [1], the approaches that aim to maximize the system throughput and fairness [2], the techniques that perform the sub-carriers allocation in order to minimize the interferences among users in a multicellular environment [3], [4], and the methods based on the cross-layer principle that jointly consider channel quality, QoS constraints and fairness [5].

However, the strategies described in [1]–[5] perform a sub-carrier allocation optimizing just for one QoS class at time or does not take in account any QoS constraints for the traffic. Our approach is to consider that problem as a whole, by taking into account either the users needs in terms of amount of data to be transmitted and QoS contraints or the propagation condition. Different traffic types and different QoS classes are considered.

The resource allocation problem has been modeled in terms of a Multidimensional Multiple-choice Knapsack Problem (MMKP, [6]); a novel efficient heuristic has been also considered for solving the resource allocation problem. It should be noted that, at the best of our knowledge, the downlink resource allocation problem in a multi-user OFDMA system (taking in account different QoS traffic classes) has never been modeled before as a MMKP. The presented results clearly highlight the better behavior of the proposed approach in comparison with different alternatives.

The organizations of this paper is the following: the description of the considered system model is presented in Sec. II, Sec. III presents the problem formulation and the developed resource allocation algorithm and in Sec. IV numerical results obtained by computer simulations are given. Finally conclusions are drawn in Sec. V.

II. SYSTEM MODEL

In this paper an OFDMA TDD system compliant with the LTE specifications has been considered. In particular, LTE uses a downlink Scalable-OFDMA (S-OFDMA), which divides the entire available bandwidth in a variable number of subchannels with fixed width, and an uplink Single Carrier OFDM transmission, in order to reduce peak-to-average power ratio, thus enabling less complex and/or higher-power terminals. In this paper we focus on the LTE downlink and, hence, on the S-OFDMA scheme.

At the LTE physical layer, data incoming from MAC layer are turbo coded and mapped using one of the following schemes: quadrature-phase shift keying (QPSK), 16-QAM, or 64-QAM, the resulting symbols are mapped in the subcarriers by resorting to a OFDM modulation. Subcarrier spacing is $15\ \mathrm{kHz}$ while two cyclic-prefix lengths are assumed in uplink: normal cyclic prefix suitable for most deployments by discriminating the first symbol of each Resource Block ($5.21\ \mu\mathrm{s}$ time long) by the others ($4.69\ \mu\mathrm{s}$ time long); the extended cyclic prefix for highly dispersive environments with duration $16.67\ \mu\mathrm{s}$. A Resource Block (RB) is the minimal allocable unit: it is a time-frequency slot, made up of 12 sub-carriers of 7 or 6 OFDM symbols, depending on whether normal or extended cyclic prefix is used. Thus RB duration is fixed and assumed here equal to $0.5\ \mathrm{ms}$.

The transmitted signal is organized in frames of $10\ \mathrm{ms}$ duration. Even if LTE supports FDD, we focus here on the TDD structure due to its higher flexibility in managing variable data streams.

For what concerns the QoS management, the LTE specifications foresee the presence of two types of bearer: the Guaranteed bit rate (GBR) and the Non-guaranteed bit rate (non-GBR). They differs in the resource allocation management during the data communication. Moreover within each bearer it is possible to define a Quality Channel Indicator (QCI) that defines different packet forwarding treatments in terms of scheduling weights, admission thresholds, queue management thresholds, and link layer protocol configuration.

In this paper it has been considered a system composed by one Base Station (BS) and N active users, that can receive data belonging to M QoS classes. For these reasons the BS has been modeled in order to have for each active user a set of M outgoing queues holding traffics belonging to several QoS classes.

The downlink scheduler in the BS will send in the downlink slots the amount of desired data taking into account both the wireless channel conditions and the length and priority of the outgoing queues.

TABLE I
QI VALUES

Modulation order	QI
QPSK ($SER < 10^{-3}$)	0
QPSK ($SER \geq 10^{-3}$)	2
16-QAM	4
64-QAM	6

III. RESOURCE ALLOCATION BASED ON THE KNAPSACK PROBLEM

This section deals with the description of the proposed resource allocation scheme. According to the LTE specifications, we assume that the minimal resource unit that can be allocated in downlink is the RB. As stated before in order to match the QoS constraints requested by each user, an appropriate amount of resources has to be allocated according to the queue lengths, the priority and radio channel quality. This problem can be modeled as a MMKP, a variant of the classic Knapsack Problem (KP [7]) proved to be an $\mathcal{NP}$-hard problem [6].

In Sec. III-B a novel heuristic approach will be proposed aiming to produce a sub-optimal solution of the MMKP introduced to model the resource allocation problem formulated in Sec. III-A.

A. Problem formulation

Let's now consider a system composed by one BS, and a set $\mathcal{U} = \{u_1, u_2, \ldots, u_N\}$ of N active users that need to receive several downlink streams with different QoS classes (forming the QoS set $\mathcal{Q} = \{q_1, q_2, \ldots, q_M\}$ of M items); each stream can belong to only one QoS class. Each element of the set $\mathcal{B} = \{b_1, b_2, \ldots, b_T\}$ of T downlink RBs can carry elements coming from just one stream at a time. The Resource Allocation Problem (RAP) can be formalized as follows:

$$\max_{x_{i,j,l}} \left\{ \sum_{i=1}^{T} \sum_{j=1}^{N} \sum_{l=1}^{M} x_{i,j,l} v_{i,j,l} \right\} \tag{1}$$

subject to

$$\sum_{i=1}^{T} c_{i,j} x_{i,j,l} \leq w_{j,l} \quad j = 1, \ldots, N,\ l = 1, \ldots, M \tag{2}$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} x_{i,j,l} \leq 1 \quad i = 1, \ldots, T \tag{3}$$

$$x_{i,j,l} \in \{0, 1\} \quad j = 1, \ldots, N,\ l = 1, \ldots, M, \quad i = 1, \ldots, T \tag{4}$$

where the binary variable $x_{i,j,l} = 1$ means that the RB b_i contains traffic belonging to the QoS class q_l and directed to the user u_j, otherwise, $x_{i,j,l} = 0$; the RB capacity ($c_{i,j}$) is the amount of data (expressed in bits) that the i-th RB can carry according to the modulation scheme adopted by the BS in the considered RB for transmitting data to the j-th user, and $w_{j,l}$

Procedure 1 Greedy Resource Allocation Scheme

```
$x_{i,j,l} = 0, \quad i = 1,\dots,T,\ j = 1,\dots,N,\ l = 1,\dots,M$
for $i = 1$ to $T$ do
    $tui \leftarrow no\_user$
    $tuc \leftarrow no\_class$
    $tuv \leftarrow 0$
    for $j = 1$ to $N$ do
        $tv \leftarrow 0$
        $tc \leftarrow no\_class$
        for $l = 1$ to $M$ do
            if $tv < ef_{i,j,l}$ and $w_{j,l} - c_{i,j} \geq 0$ then
                $tv \leftarrow ef_{i,j,l}$
                $tc \leftarrow l$
            end if
        end for
        if $tc \neq no\_class$ and $tuv < tv$ then
            $tui \leftarrow j$
            $tuc \leftarrow tc$
            $tuv \leftarrow tv$
        end if
    end for
    if $tui \neq no\_user$ and $tuc \neq no\_class$ then
        $x_{i,j,l} = 1$
        $w_{tui,tuc} = w_{tui,tuc} - c_{i,tui}$
    end if
end for
```

is the queue length concerning the l-th traffic class and the j-th user. The constraint (3) of the RAP states that one RB can be assigned only to one pair (user, class) $\in \mathcal{U} \times \mathcal{Q}$, while (2) allows that a queue belonging to the j-th user and the l-th QoS class can not be reduced by more than its total length. The profit that the BS earns of transmitting on the i-th RB, data belonging to the l-th QoS class and directed to the j-th user, can be defined as:

$$v_{i,j,l} = \alpha g_{i,j} + \beta p_l w_{j,l} \tag{5}$$

where $g_{i,j}$ is the the QI (Quality Index) of the i-th RB perceived by the j-th user, according to the modulation order used in the RB itself (Tab. I), p_l is the priority of the l-th QoS class, and α and β are non-negative coefficients of the linear combination. The two terms of the linear combination are normalized respect to their maximum values in order to avoid that one is greater than the other; the wanted resource allocation policy can be defined by choosing properly α and β.

It should be noted that at a beginning of each frame a new RAP has to be solved in order to perform the resource allocation because the user queue lengths could change; for this reason the $p_l w_{j,l}$ products must be normalized by taking in account this aspect.

With the maximization process of the objective function in (1), we want to assign, at the same time, more resources to the users characterized by a higher RB capacity and longer data queues. However, it should be considered that the queue lengths belonging to a certain user could be quite full while the radio channel between the BS and that user could be not good (resulting in an low overall RB capacity), or, on the other hand, the users overall RB capacity could be good but the queue empty.

In the first case, the number of RBs assigned to the user must be appropriate in order to avoid the queue saturation, while in the second case assigning a number of RBs too high to the user is a waste of resources; in order to mediate between these two cases, the objective function of the RAP is defined in terms of a linear combination between the RB QIs and the queue lengths weighted with a coefficient expressing the priority of the QoS classes.

The RAP can be classified as a particular type of MMKP [6] because, through the definition the bijective function

$$F : \{1,\dots,(N \cdot M)\} \longrightarrow \{1,\dots,N\} \times \{1,\dots,M\}$$

it can be rewritten as:

$$\max_{x_{i,h}} \left\{ \sum_{i=1}^{T} \sum_{h=1}^{N \cdot M} x_{i,h} v_{i,h} \right\}$$

subject to

$$\sum_{i=1}^{T} \sum_{h=1}^{N \cdot M} x_{i,h} r_{i,h,k} \leq w_k \quad k = 1,\dots,(N \cdot M) \tag{6}$$

$$\sum_{h=1}^{N \cdot M} x_{i,h} \leq 1 \quad i = 1,\dots,T$$

$$x_{i,h} \in \{0,1\} \quad i = 1,\dots,T,\ h = 1,\dots,(N \cdot M)$$

where, for $\hat{i} = 1,\dots,T$, $\hat{j} = 1,\dots,N$, $\hat{l} = 1,\dots,M$, $\hat{h} = 1,\dots,(N \cdot M)$ and $\hat{k} = 1,\dots,(N \cdot M)$, we have:

- $x_{\hat{i},\hat{h}} = x_{\hat{i},\hat{j},\hat{l}}$, for $F(\hat{h}) = (\hat{j},\hat{l})$;
- $w_{\hat{k}} = w_{\hat{j},\hat{l}}$, for $F(\hat{k}) = (\hat{j},\hat{l})$;
- through the definition of the $r_{\hat{i},\hat{h},\hat{k}}$ parameter as follows

  $$r_{\hat{i},\hat{h},\hat{k}} = \begin{cases} c_{\hat{i},\hat{j}} & \text{if } F(\hat{h}) = F(\hat{k}) = (\hat{j},\hat{l}) \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

  the (2) constraint can be equivalently rewritten as the (6) one.

B. Resource allocation algorithm

In order to realize an efficient resource allocation, the BS has to solve a RAP before transmitting the data in downlink. The RAP, being an MMKP problem, belong to a class of so-called $\mathcal{NP}$-hard optimization problems; there are algorithms [8] that lead to an exact solution of that problem at the expense of a too long execution time.

As a consequence, there are also heuristics that lead to sub-optimal solutions through different approaches as that can be summarized as follows: heuristics based on the dimensional reduction of the problem admissible solution set [9], methods relying on the graceful degradation concept [10], techniques adopting genetic algorithms [11] and strategies based on greedy approaches [12]. It has been reported in Procedure 1

TABLE II
MAIN SYSTEM PARAMETERS

Parameter	**Setting**
LTE system duplexing type	TDD
radio frequency carrier	2.6 GHz
bandwidth	10 MHz
maximum delay spread	2.51 µs
channel model	vehicular ITU-R A with 6 paths [14]

the proposed heuristic that allow a greedy approach for solving the RAP.

Procedure 1 implicitly relies on the set $\mathcal{F} = \mathcal{B} \times \mathcal{U}$; for all the pairs (RB, user) in $\mathcal{F}$ the maximum, among all the QoS classes, is computed for the efficiency value defined as:

$$ef_{i,j,l} = \frac{v_{i,j,l}}{1 + \hat{c} - c_{i,j}}$$

Each element in $\mathcal{F}$ is labeled with the QoS class index associated to the maximum efficiency computed (satisfying the condition at line 10).

Due to the strong correlation in the RAP between profit and cost, it is not convenient to express the efficiencies as a ratio between them (as in the classical greedy approaches based on the modular dominance [7]). In this case the efficiencies has been defined in order to be greater for those elements with a bigger cost; for these reasons the value of the (i, j)-th element of $\mathcal{F}$ has been divided by $1 + \hat{c} - c_{i,j}$ ($i = 1, \ldots, |\mathcal{B}|$ and $j = 1, \ldots, |\mathcal{U}|$), where $\hat{c}$ is the maximum capacity of a RB.

For every RB b_a, we have to search the element $f_{a,s}$ of $\mathcal{F}$ with the maximum efficiency, by iterating on the $\mathcal{U}$ set; b_a is then assigned to the u_s user and designated to hold the traffic of the QoS class index according to the label of $f_{a,s}$. If the condition at line 21 is satisfied, $x_{a,s,d}$ is fixed to one, and $c_{a,d}$ elements are taken from the (s, d)-th queue (i.e., $w_{s,d}$ is decremented of value equal to $c_{a,s}$).

The cardinality of $\mathcal{B}$ and $\mathcal{Q}$ sets can be considered fixed because both are given by the considered communication standard; for these reasons the Procedure 1 has a computational complexity of $O(|\mathcal{U}|)$.

IV. NUMERICAL RESULTS

In this section the numerical results will be presented to validate the proposed cross-layer resource allocation strategy by resorting to computer simulations [13]. We will refer to the proposed scheme as Greedy Resource Allocation Scheme (GRAS).

It has been considered an LTE system composed by one BS and a variable number of users ($3\div13$). The system parameters values considered in our analysis are reported in Tab. II. It has been considered also an AMC (Adaptive modulation and Coding) schema, accordingly to the 3GPP's LTE standard, adopting the QPSK, 16-QAM or 64-QAM modulation type.

It has been considered five QoS traffic classes (Tab. III), from the 0th class (the highest priority) to the 4th class (the lowest priority), where the first three have a constant bitrate. All the traffic to an active user is produced independently by a traffic generator in order to have, for the same QoS class, different amounts of data to transmit to the various users.

TABLE III
QoS TRAFFIC CLASSES AND PROFILE ADOPTED

QoS class	**Average bitrate** [Mbit/s]	**Relevance**	**GRAS Priority**
0	1.39	5	4.0
1	0.83	4	3.33
2	0.67	3	2.08
3	2.04	2	0.36
4	0.73	1	0.48

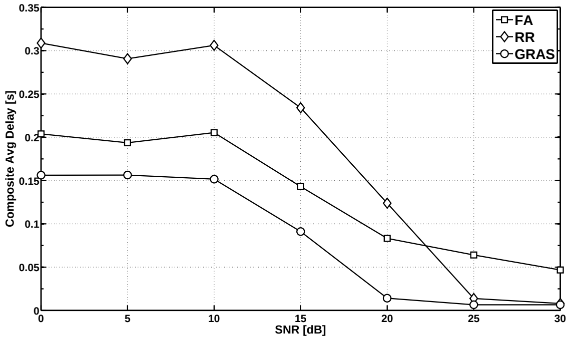

Fig. 1. Composite average delay comparison (of a given user) between the FA, RR and GRAS methods, for different SNR levels

The parameters of the proposed resource allocation scheme (see Sec. III-A), according to the traffic profiles adopted, have been set as: $\alpha = 0.4$, $\beta = 0.6$ and the GRAS priority of the QoS classes are reported in Tab III.

GRAS has been compared to a fixed allocation (FA) and round robin (RR) scheme:

- in the FA scheme the available downlink RBs are deterministically divided in a number of sets equal to the active users number. The RBs belonging to the same set will hold data coming from the different outgoing queues relative to the considered user, to each QoS class is assigned a number of RBs proportional to its relevance. A QoS class will receive RBs even if the corresponding queue is empty;
- in the RR schema considered we have assumed that the BS for each user holds just one outgoing queue (called data queue) filled periodically (before the resource allocation process) by the data elements coming from the user's QoS queues; the data elements pushed in a data queue are taken from the user's QoS queues according to the principle of the WFQ (Weighted Fair Queuing). According to the round robin principle the downlink RB will hold data coming from the data queues.

The resource allocation schemes have been compared in terms of average delay and throughput of the most relevant QoS class (holding traffic directed to a given user u); moreover, a combined average delay and a combined throughput

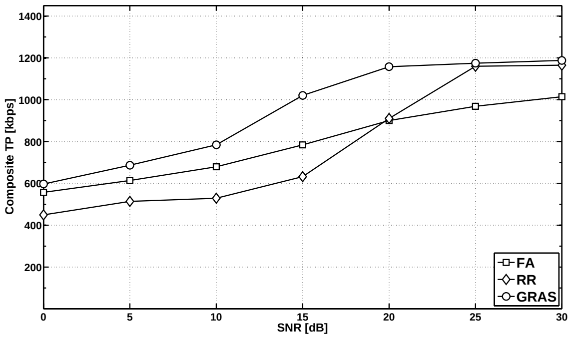

Fig. 2. Composite throughput comparison (of a given user) between the FA, RR and GRAS schemes, for different SNR levels

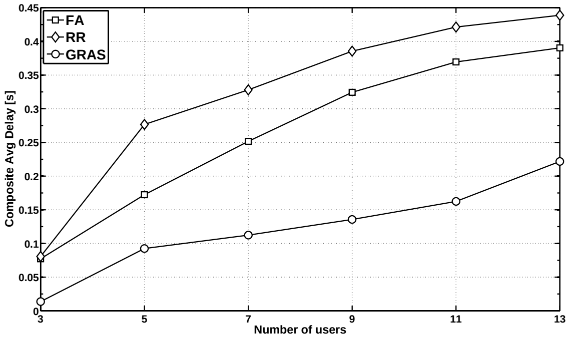

Fig. 3. Composite average delay comparison between the FA, RR and GRAS schemes, for different active users

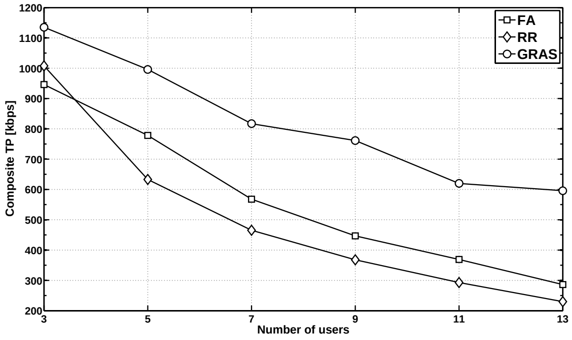

Fig. 4. Composite throughput comparison between the FA, RR and GRAS schemes, for different active users

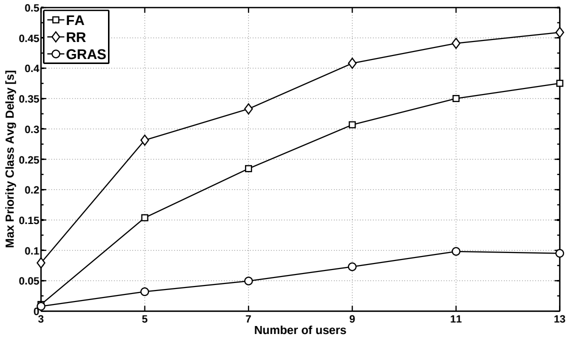

Fig. 5. Average delay of 0th QoS class comparison between the FA, RR and GRAS schemes, for different active users

has been defined:

$$\hat{d_u} = \frac{\sum_{l=1}^{m} d_{u,l} y_l}{\sum_{l=1}^{m} y_l} \tag{8}$$

$$\hat{t_u} = \frac{\sum_{l=1}^{m} t_{u,l} y_l}{\sum_{l=1}^{m} y_l} \tag{9}$$

where m is the number of QoS classes considered, y_l the priority of the l-th QoS class, $d_{u,l}$ and $t_{u,l}$ represent, respectively, the average delay and throughput of the l-th QoS class of the u-th user.

In Fig. 1 and 2, respectively, the combined average delay and throughput are reported of a given user for different SNR values in a scenario formed by one BS and 5 active users. It can be noted that the GRAS performances are always the best.

Fig. 3 and 4 show the same performance indexes of different active users in a scenario where the user's SNR has been fixed to 15 dB. It is not a surprise to note that the performance decrease with increasing number of active users but should be noted how the GRAS performances dominates the other schemes.

It is also relevant to analyze the performances of the resource allocation schemes in terms of average delay and throughput (of a given user) for the 0th QoS class, as reported in Fig. 5 and 6. It is important to note that also in this case the GRAS achieves the performance indexes respect to the other resource allocation schemes.

Lastly in Fig. 7 has been reported, for different active user numbers (and for a fixed SNR value of 15 dB), the performances of the three resource allocation schemas in terms of composite system throughput, defined in a scenario composed by U active users as follows:

$$\hat{T_U} = \sum_{j=1}^{U} \hat{t_j}$$

The weighted system throughput represent a global index of the transmitted traffic quality for different user numbers; Fig. 7 shows that the performances of the FA or of the RR scheme tend to be insensitive to the user number variations, this means that also for reduced datarates the partition among the service class maintains constant; in this context high priority class could not have enough downlink bandwidth. GRAS scheme overcomes these limits, giving resources taking in account both the outgoing queues priority and length.

V. CONCLUSION

This paper considered a LTE system based on an adaptive multiple access scheme that permits an efficient exploitation of the available resources.

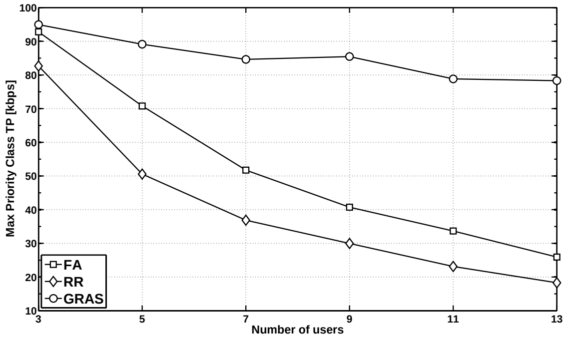

Fig. 6. Average throughput of 0th QoS class comparison between the FA, RR and GRAS schemes, for different active users

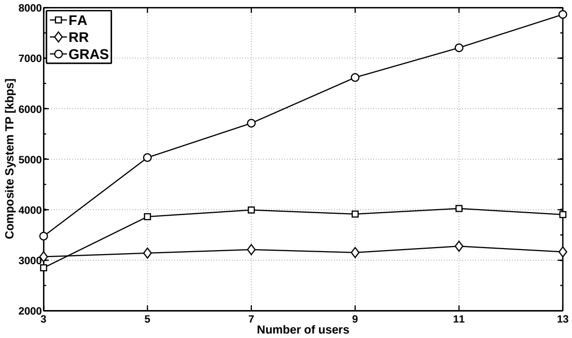

Fig. 7. Composite system throughput

In particular channel quality, QoS constraint and queue length have been jointly integrated in the proposed approach that dynamically assigns OFDM subcarriers to the users. The resource allocation problem has been formulated as a MMKP problem and due to the complexity of the optimal solution a novel heuristic that allow greedy approach to solve the problem has been presented. The proposed allocation scheme has good performance in terms either of throughput or delay with a good trade-off between fairness and bandwidth efficiency. The performance has been compared with other alternatives showing the significant gain achievable.

References

[1] K. Seong, M. Mohseni, and J. M. Cioffi, “Optimal resource allocation for OFDMA downlink systems,” in *Proc. of IEEE ISIT 2006*, Seattle, WA, USA, Jul. 2006, pp. 1394 –1398.

[2] C. Yue-yun and D. Xiao-hui, “A novel sub-carrier allocation algorithm in 3G LTE system,” in *Proc. of CCWMSN07*, Shanghai, China, Dec. 2007, pp. 474–477.

[3] X. Yang, Y. Wang, D. Zhang, and L. Cuthbert, “Resource allocation in LTE OFDMA systems using genetic algorithm and semi-smart antennas,” in *Proc. of IEEE WCNC 2010*, Sydney, NSW, Australia, Apr. 2010.

[4] F. D. Calabrese, C. Rosa, K. I. Pedersen, and P. E. Mogensen, “Performance of proportional fair frequency and time domain scheduling in LTE uplink,” in *Proc. of EW 2009*, Aalborg, Denmark, May 2009, pp. 271–275.

[5] H. Luo, S. Ci, D. Wu, J. Wu, and H. Tang, “Quality-driven cross-layer optimized video delivery over LTE,” *IEEE Commun. Mag.*, vol. 48, no. 2, pp. 102–109, Feb. 2010.

[6] H. Kellerer, U. Pferschy, and D. Pisinger, *Knapsack Problems*. Berlin, Germany: Springer-Verlag, 2004.

[7] S. Martello and P. Toth, *Algorithms for knapsack problems*. Amsterdam, Netherlands: Elsevier Science Publisher, 1987, pp. 213–258.

[8] R. D. Armstrong, D. S. Kung, P. Sinha, and A. A. Zoltners, “A computational study of a multiple-choice knapsack algorithm,” *ACM Trans. Math. Softw.*, vol. 9, no. 2, pp. 184–198, Jun. 1983.

[9] O. H. Ibarra and C. E. Kim, “Fast approximation algorithms for the knapsack and sum of subset problems,” *Journal of the ACM*, vol. 22, no. 4, pp. 463–468, Oct. 1975.

[10] S. Khan, K. F. Li, E. G. Manning, and M. M. Akbar, “Solving the knapsack problem for adaptive multimedia system,” *Studia Informatica Universalis*, vol. 1, no. 1, pp. 157–178, 2003.

[11] J. Zhao, T. Huang, F. Pang, and Y. Liu, “Genetic algorithm based on greedy strategy in the 0-1 knapsack problem,” in *Proc. of WGEC ’09*, Guilin, China, Oct. 2009, pp. 105–107.

[12] H. Shojaei, A.-H. Ghamarian, T. Basten, M. Geilen, S. Stuijk, and R. Hoes, “A parameterized compositional multi-dimensional multiple-choice knapsack heuristic for CMP run-time management,” in *Proc. of ACM/IEEE DAC ’09*, San Francisco, CA, USA, Jul. 2009, pp. 917–922.

[13] The MuDiSP++ tool. [Online]. Available: http://mudisp3.sourceforge.net

[14] *Guidelines for evaluation of radio transmission technologies for IMT-2000*, ITU-R Rec. M.1225, Feb. 1997.