INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. (2016)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/dac.3137

Joint scheduling and mapping in support of downlink fairness and spectral efficiency in ieee 802.16e OFDMA system

Nguyen Huu Thanh[1,*,†], Doan Van Tung[1], Ngo Quynh Thu[1], Nguyen Canh Nam[1] and Kumbesan Sandrasegaran[2]

[1]*Hanoi University of Science and Technology, Hanoi, Vietnam*
[2]*University of Technology Sydney, Sydney, Australia*

SUMMARY

The next generation broadband wireless networks deploy orthogonal frequency division multiple access (OFDMA) as the enabling technologies for broadband data transmission with QoS capabilities. In such broadband wireless systems, one major issue is how to utilize radio resource efficiently while maintaining fairness between sessions as well as providing adequate QoS. In this work, we propose an approach for OFDMA/time division duplex (TDD) downlink suitable for IEEE802.16e WiMAX systems that combines scheduling and burst mapping algorithms for a trade-off between session fairness, QoS, and spectral efficiency. While optimizing radio resources under QoS and fairness constraints is an *NP*-hard problem, we follow a heuristic approach that simplifies the complexity of the algorithm. Performance results show that while the new scheme outperforms the Proportional Fair algorithm in terms of fairness, it also improves the overall system spectral efficiency. Copyright © 2016 John Wiley & Sons, Ltd.

Received 28 April 2015; Revised 14 March 2016; Accepted 15 March 2016

KEY WORDS: OFDMA; scheduling; mapping; radio resource management; fairness; spectral efficiency

1. INTRODUCTION

Orthogonal frequency division multiple access (OFDMA) transmission scheme is becoming popular as it is the key technology for the fourth generation (4G) broadband wireless networks such as WiMAX and has been standardized by the WiMAX forum. OFDM/OFDMA technologies can meet the demands for high data rates, can operate in fading channels, and support line and non-line-of-sight operations with multipath mitigation. In combination with Medium Access Control (MAC) layer mechanisms, it can meet specific QoS requirements of active sessions. OFDMA can be considered as a joint Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) scheme, in which data can be transmitted in both *time domain* and *frequency domain* simultaneously. In the time domain, the channel is divided into *OFDM symbols*, while in frequency domain, data can be transmitted in multiple orthogonal *sub-carriers*. Thus, it provides possibilities to exploit diversity of a frequency selective fading channel as the number of sub-carriers and OFDM symbols allocated to a session can be dynamically and effectively reserved based on user's actual needs as well as the channel condition. However, the price for the efficiency gained at the Physical Layer is the increasing complexity at the MAC layer and several following related issues.

In wireline systems, the channel resources, such as time slots or channel frequency bandwidth, can be allocated proportionally to the requested user data rates because all user equipments (UEs) have the same channel condition. Contradictionally, performing bandwidth allocation while keeping fairness and QoS for users in wireless networks appears to be a much complexer task because of *pathloss*, *user mobility,* and *channel fading*. There are some requirements for the design of the wireless MAC layer:

*Correspondence to: Nguyen Huu Thanh, School of Electronics and Telecommunications, Hanoi University of Science and Technology, Hanoi, Vietnam.
†E-mail: thanh.nguyenhuu@set.hust.edu.vn

- *Spectral efficiency*: Wireless systems should efficiently utilize the radio resources, such as sub-carriers and time slots, so that the total channel capacity is maximized within a given allocated frequency bandwidth.
- *Fairness*: The wireless system needs to ensure that a reasonable level of fairness is maintained among users. Fairness measures the difference between users with respect to the service rates or resources allocated to them.
- *Quality-of-Service guarantees*: In order to make use of the broadband wireless channel to serve a wide range of wireless applications categorized in multiple classes of service, wireless systems should offer QoS mechanisms to satisfy QoS requirements from users.

From the *network operator point of view*, it is very important to utilize the channel resources effectively as the available radio resources become more and more scarce, while revenue should be maintained or increased. From the *user point of view*, it is more important to have fair resource allocation so that user's data sessions can avoid outage situations and the requested QoS is guaranteed. In general, there has been a tremendous opportunity to improve the spectral efficiency while providing fairness and meeting QoS requirements of all users at the same time [1, 2].

However, the aforementioned requirements are difficult to satisfy as user data rates exhibit both *time-varying* and *user-dependent* characteristics because of the dynamicity of the radio channels. Thus, in wireless systems, *radio resource management* (RRM) function of MAC-layer is designed to ensure *spectral efficiency*, *fairness,* and *QoS*. As mentioned in [3], RRM plays an important role in assuring resource utilization in OFDMA-based systems. As a consequence, new challenges and opportunities are created to keep up with the requirement of services and accelerated research related to RRM algorithms. RRM in any wireless system in general as well as in OFDMA/TDD systems in particular should face with the issues as the following:

- A common issue in any wireless system is *how to balance between on spectral efficiency, fairness and QoS guarantees*. As the overall system throughput is dynamic and time-varying depending on the channel condition of every user, the main objective of the RRM is to enhance the spectral efficiency of the radio channel, and hence maximizing the total system capacity. On the other hand, because the next generation broadband wireless networks should accommodate applications with various QoS requirements such as bandwidth, delay, or jitter, resources allocated to users should be fair and sufficient to meet specific QoS parameters. It is worthwhile to know that QoS, fairness, and spectral efficiency cannot be achieved at the same time [1–3]. Scheduling algorithms aiming at maximizing channel throughput are usually unfair to users under bad channel conditions. On the other hand, absolute fairness may lead to low spectral efficiency as more radio resources should be allocated to such users under bad channel conditions so that the required transmission rates can be met.
- Another specific issue of RRM in the OFDMA/TDD transmission scheme is *how to map user's data into the time-frequency OFDMA frame, so that radio resources are efficiently utilized*. As illustrated in [3], the concept of time domain scheduling and frequency domain scheduling is proposed for Long-term Evolution (LTE) systems, whereby time domain is responsible for adopting users and frequency domain is in charge of resource allocation. The OFDMA/TDD channel is organized in both *frequency* and *time* domains. An OFDMA/TDD frame is further divided into an *uplink* and a *downlink subframe*. As can be seen in Figure 1, user's data, which are called *data bursts* or *Service Data Units*[‡] (SDU) in IEEE802.16, are mapped into time-frequency rectangular regions in the subframe. The smallest time-frequency unit that user's data can use in the subframe is called *slot*. Based on the channel condition of each user, several *Adaptive Modulation and Coding* (AMC) schemes can be used for different user's data bursts. One important issue in the mapping phase is *the selection of best channels for each user to maximize the overall radio channel capacity*. Specific issues related to mapping data bursts to the OFDMA subframe will be discussed later on in the next section.

[‡]In this article, user's data or user packets coming from higher layer are interchangeably referred to as user's *data burst* of user's *SDU*

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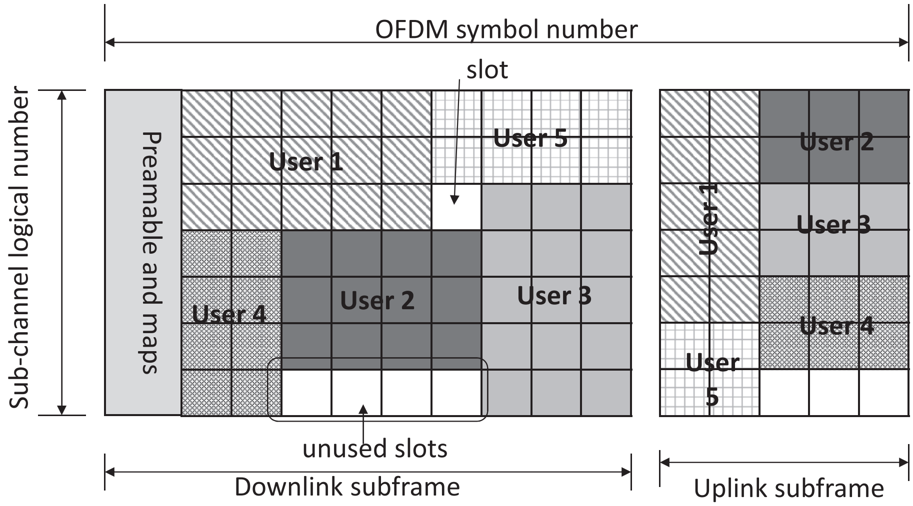

Figure 1. Orthogonal frequency division multiple access (OFDMA)/time division duplex (TDD) frame.

Until now, there are several efforts in the research community attempting to balance between spectral efficiency and fairness in wireless environments. However, we find that the research on these previous mentioned issues is not sufficient for OFDMA/TDD systems. In this article, we propose a new scheme for the trade-off between QoS, fairness, and spectral efficiency for IEEE802.16e OFDMA/TDD downlink. Optimizing spectral efficiency while meeting the fairness (and/or QoS) requirements simultaneously are a complex task, as it requires to resolve a multiple objective problem. In our approach, these objectives can be obtained by dividing the RRM in OFDMA/TDD into the *burst mapping* and *scheduling* components; each of these components has different objective function. The contributions of our work are the following:

- A new proposed scheduling algorithm suitable for OFDMA/TDD that can guarantee *bandwidth* and *resource fairness* between users with different channel conditions.
- A new mapping algorithm that maximizes the channel capacity of the OFDMA/TDD channel in WiMAX IEEE802.16e.
- By combining these two algorithms, simulation results show that our scheme outperforms Proportional Fair (PF) and reaches Weighted Fair Queuing (WFQ) in terms of fairness, while the spectral efficiency is also better than PF.

The article is organized as follows. In the next section, we firstly discuss some previous work on scheduling and RRM and their properties in terms of fairness, QoS guarantee as well as spectral efficiency. We also discuss unsolved issues on these areas. Section 3 describes the proposed algorithms in details. In Section 4, the new proposed schemes are investigated and evaluated. The last section concludes the works and outlines our future research direction.

2. RELATED WORK AND DISCUSSION

2.1. Design objectives of the MAC layer in wireless systems

As addressed previously, while in conventional TDMA wireless systems such as 3G/UMTS RRM is normally realized by *scheduling* algorithms, the RRM in OFDMA composes of two MAC-layer functions, namely, *scheduling* and *two-dimensional burst mapping* (Figure 6). While the scheduler operates in time domain, the burst mapping component is responsible for mapping user data selected by the scheduler into the OFDMA frame. Depending on the design objectives, these components are responsible for fairness or spectral efficiency or both.

DOI: 10.1002/dac

- *Spectral efficiency*: In any wireless system, improving spectral efficiency is an important objective as it allows optimizing the total system throughput. Spectral efficiency can be obtained by efficiently utilizing and allocating the radio resources to different users served by the system.
- *Bandwidth fairness* is a concept already well-defined in rate-controlled network systems. It expresses how fair the service rates are allocated to backlogged sessions in a network node. Bandwidth fairness is quantified by the *fairness index*, proposed firstly by Jain *et al.* [4]. Let us denote C as the output link capacity; Ω_B is the set of all backlogged sessions during time $[0, t]$; ϕ_i as a predefined weight assigned to session i ($\phi_i \in \Re, \quad \phi_i > 0 \quad \forall i \in \Omega_B$), which is understood as the proportion of nominated bandwidth allocated to i; R_i as the nominated rate of session i, that is, $R_i = C \frac{\phi_i}{\sum_{j \in \Omega_B} \phi_j}$; $r_i(0, t)$ as the actual average bandwidth allocation to session i during time $[0, t]$; $n(\Omega_B)$ as the number of backlogged sessions during $[0, t]$; and $x_j = r_i(0, t)/R_i$. The bandwidth fairness index is defined as the following:

$$F_b = \frac{\left[\sum_{i=1}^{n(\Omega_B)} x_i\right]^2}{n(\Omega_B) \sum_{i=1}^{n(\Omega_B)} x_i^2} \tag{1}$$

  Ideal fairness can be achieved if $F_b = 1$. This can be obtained when the service rates reach the nominated rates, that is, the required rates specified by users, or $r_i(0, t) = R_i \quad \forall i \in \Omega_B$.
- *Resource fairness*: In contradiction to wired networks, in wireless networks, the throughput of a session i is not necessarily in proportion to the allocated radio resources because of user diversity and radio channel dynamicity. Thus, from the resource allocation perspective, we argue that it is *fair* when a session i is allocated a portion of radio resource (such as OFDMA slots) proportionally to the total radio resources, that is, $\frac{\phi_i}{\sum_{j \in \Omega_b} \phi_j}$. A fair resource allocation ensures that a session cannot grasp more resources than it deserves to have, thus improves the overall system spectral efficiency. In an OFDMA system, let N_s be the total number of OFDMA slots in all downlink subframes because the session i is active; ω_i be the actual number of OFDMA slots allocated to session i and $\widehat{\omega_i}$ be the expected number of OFDMA slots that should be assigned to session i to guarantee resource fair, $\widehat{\omega_i} = N_s \times \frac{\phi_i}{\sum_{j \in \Omega_B} \phi_j}$, in this work, we introduce the notion of *Resource Fairness Index* as follows:

$$F_r = \frac{\left[\sum_{i=1}^{n(\Omega_B)} y_i\right]^2}{n(\Omega_B) \sum_{i=1}^{n(\Omega_B)} y_i^2} \tag{2}$$

  where $y_i = \frac{\omega_i}{\widehat{\omega_i}}$. Similar to the bandwidth fairness, absolute resource fairness is obtained when $F_r = 1$.

The next subsections outline related work on different approaches for scheduling and burst mapping.

2.2. *Wireless scheduling*

The main task of a scheduling algorithm in a wired network is often to maintain QoS requirements, such as delay, jitter, or to guarantee minimum traffic rates for active sessions. The resource management function is usually neglected in these schedulers, as users enjoy the same channel conditions; thus, network resources (such as bandwidth) are allocated in proportion to QoS requirements or requested service rates. In contradiction to wired networks, because of the nature of radio environments, data rates and the corresponding QoS parameters in wireless networks are usually not in proportion to the allocated radio resources, such as bandwidth or time slots. Therefore, there are a lot of discussions about functionalities of wireless scheduling. Generally, wireless scheduling algorithms are divided into the following categories.

2.2.1. Opportunistic scheduling. Algorithms belonging to this category are aware of channel conditions of each user. Based on the channel information, these algorithms aim at maximizing the total

DOI: 10.1002/dac

channel throughput by selecting the user with best channel conditions. A typical scheduling algorithm for this category is the *Maximum Carrier-to-Interference-and-Noise scheduling* (MaxCINR) [5]. MaxCINR is the optimal scheduler in terms of maximum spectral efficiency; however, it does not take into account fairness between users.

2.2.2. Fairness and QoS scheduling. The *fairness and QoS scheduling* algorithms, on the other hand, focus on providing fairness between sessions, guaranteeing minimum service rates so that they can satisfy the requested QoS parameters from users. Many of these algorithms stem from wired networks, such as the WFQ [6] and its family [7, 8], or the *Backlog Proportional Rate* scheduler and the *Waiting Time Priority* scheduler [9]. In this work, we use the term *fair scheduling* to denote all of these scheduling families. The basic principle of a fair scheduling algorithm is that it tries to maintain a predefined proportion of bandwidth allocated to each session (or user). More specifically, let $W_i(0,t)$ be the amount of session's i data in bits that is served by the scheduler during the backlogged time $[0,t]$, the following equation holds for fairness scheduling algorithms:

$$\frac{W_i(0,t)}{\phi_i} = \frac{W_j(0,t)}{\phi_j}; \quad \forall i, j \in \Omega_B \tag{3}$$

However, most of these algorithms do not suit wireless environments as they originally channel-unaware and utilize radio resources inefficiently. In fact, there are also efforts to deploy QoS/fairness schedulers in wireless environments by making use of the wireless channel information. Ali-Yahiya *et al.* [2] propose the *Adaptive Slot Allocation* and *Reservation-based Slot Allocation* algorithms, both are specifically designed for OFDMA schemes. Both algorithms prioritize radio resources based on IEEE 802.16e WiMAX classes of service. While Adaptive Slot Allocation assign all needed radio resources firstly to real-time (RT) traffic, the Reservation-based Slot Allocation algorithm tries to maintain a fair share between classes of service to avoid starvation of non-real-time (NRT) services.

2.2.3. Trade-off between fairness and spectral efficiency. There are other scheduling algorithms that attempt to strike a balance between spectral efficiency and fairness. A typical scheduling algorithm of this kind is the PF [10]. In PF, a user i is selected according to the following equation:

$$i = \arg_m \max[r_m(t)/R_m] \tag{4}$$

where $r_m(t)$ is the instantaneous rate of session m at time t and R_m is the average allocated rate for session m. As can be seen in Eq. (4), the better the channel condition of session i or the lower its average allocated rate, the more likely that session i is selected for transmission. Until now, there are many scheduling variants that are based on the PF algorithm. Rodrigues *et al.* [11] proposed a multi-carrier packet scheduling using utility functions based on average data rates.

In [12], authors proposed a joint of carrier load balancing and packet scheduling for LTE-advanced system. In this approach, the PF algorithm is modified to support resource allocation in frequency domain. This implies that PF can be flexibly used in both frequency and time domains.

Furthermore, the *Adaptive Modified Largest Weighted Delay First* (AMLWDF) algorithm [13] extends PF by considering other factors, such as delay and Channel Quality Indicator (CQI) priority to improve fairness and QoS performance while maintaining good spectral efficiency. Results show that the throughput of Adaptive Modified Largest Weighted Delay First is a little worse than PF. On the other hand, its delay performance is improved in comparison with PF.

Enhanced Proportional Fair (E-PF) [14] is yet another method, which is based on the PF scheme that supports QoS for multi-channel OFDMA system. Its aim is to improve the throughput performance for users in bad channel conditions. Performance results demonstrate that E-PF outperforms PF in terms of system throughput and mean delay. However, E-PF is specially designed for RT traffic. Throughput of high priority data increases with the increasing percentages of high priority data. Meanwhile, the system throughput is invariable and irrespective of the percentage of high priority traffic.

DOI: 10.1002/dac

In [15], the authors introduced a utility-based resource allocation scenario, where the number of NRT and RT users are kept satisfied in the downlink of the radio access network of an OFDMA system. In order to solve the mentioned problem, a radio resource allocation (RRA) framework is divided into two RRA policies, which has an ability to maximize the number of satisfied users in the system. A policy for NRT users, which is called the *throughput-based satisfaction maximization* (TSM) policy, has the main idea based on the user's throughput. Another policy for RT users, which is called the *delay-based satisfaction maximization* policy, has the main idea based on the users' HOL delay. The TSM technique is compared with other RRA techniques such as SORA-NRT, PF, and RM. Performance results show that TSM technique achieves the highest satisfaction, very high fairness. Furthermore, the TSM technique not only contributes to increase system capacity with the number of users due to multiuser diversity but also shows the low computational complexity. However, a drawback is that TSM has the lowest system capacity when the number of users is low. The reason is that the TSM technique tries to satisfy all users.

In [16], Rebekka *et al*. discussed a RRA scheme under the constraint of the minimum data rate requirement of each user. All users are particularized into Priority and Non Priority users. This algorithm is accomplished in a way to satisfy the priority users followed by allocating the radio resource for the remaining users. According to the results show in [16], the fairness index and throughput of the proposed method are lower than PF.

A new approach to the resource allocation in OFDMA system is presented in [17]. Accordingly, two cooperatives games implemented to improve fairness are in turns nontransferable utility game and transferable utility game. Meanwhile in [18], the authors attempt to maximize system capacity under transmission power and minimal rate constraints. However, the trade-off between fairness and spectral efficient should be considered ensuring the efficient utilization of radio resource.

After surveying the literature, we find that most of research work recently is based on the PF algorithm with some modifications to improve QoS, fairness, or spectral efficiency. However, solutions for the trade-off between these criteria are still not well established and need further research.

2.3. *Burst mapping*

As shown in Figure 1, once being selected for transmission by the scheduler, the task of the *burst mapping* function is to map data burst of users into *rectangular regions* or *data regions* in the subframe. Essentially, there are two problems associated with the burst mapping function:

- *Fragmented unused spaces in the subframe*: in WiMAX, it is required that data regions in the downlink subframe always be in rectangular shapes. Consequently, a data region is often reserved more slots than needed. Furthermore, as several user data regions with different sizes are packed into time-frequency areas of the OFDMA subframe, the mapping problem can be formulated as the *bin packing problem* [19]. As shown in Figure 4, some unused leftover slots

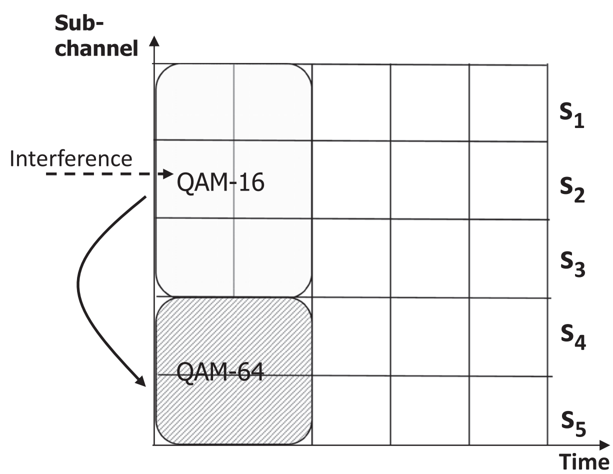

Figure 2. Selecting mapping sub-carriers affects the spectral efficiency.

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might be too small to be allocated to user's data. Thus, the leftover slots have negative impact on the spectral efficiency.

- *Suboptimal mapping of user data*: in OFDMA, subchannels assigned to UEs undergo fading (e.g., frequency selective fading) and interference (e.g., co-channel interference). For example, as illustrated in Figure 2, a UE is assigned a data region taking place in subchannels s_1, s_2, and s_3. Because the UE undergoes interference in s_2, only 16-QAM is applied for the whole data region. On the other hand, if the resource allocation takes place in the data region covering s_4 and s_5, 64-QAM modulation scheme can be used. In this case, less radio resource can be allocated to the same amount of user's data. That is, the spectrum efficiency of the system can be improved if each user is allocated its best subchannel in the subframe. However, this becomes more complicated in case there are more than one user contending the same subchannel. Based on the CQI provided by 4G systems, a *channel map* for each UE can be built that indicates the AMC schemes for each subchannel s_i as well as the corresponding available slots $\widehat{l}_{s_i}$. Figure 3 describes the channel maps of two users u_1 and u_2 with SDU lengths of l_1 and l_2, respectively. As can be seen in the figure, channel mapping priorities of u_1 and u_2 have the order from high to low as $(s_5, s_4, s_2, s_1, s_3)$ and $(s_5, s_1, s_4, s_2, s_3)$, respectively. In this given case, the both users have s_5 as the preferable mapping subchannel. If the number of available slots $\widehat{l}_{s_5}$ in s_5 cannot accommodate the mapping of both u_1 and u_2, contention occurs (Figure 4). This raises the question of *how to resolve the resource contention of multiple users to obtain optimal spectrum efficiency*.

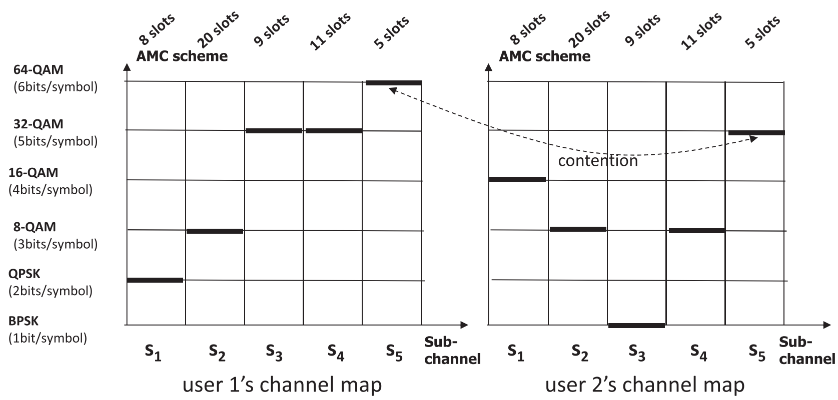

Figure 3. Subchannel mapping priorities of two users.

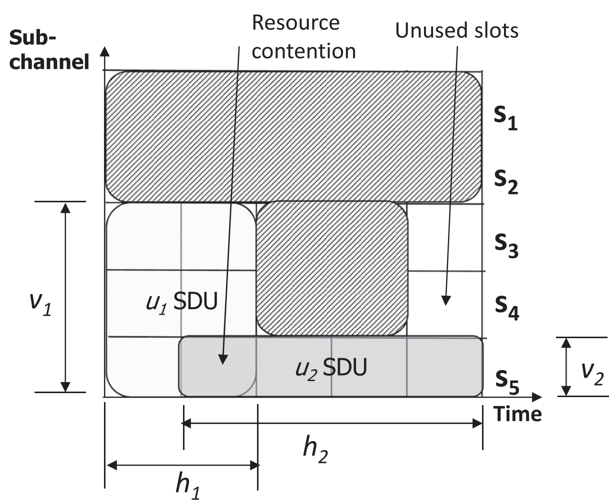

Figure 4. Resource contention between u_1 and u_2.

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We find that most of research in the recent years [19–27] focus on the former issue, while approaches for the later issue are rarely found in the literature. That is, most of recent approaches are to minimize wasted unused slots because of leftover spaces in the downlink subframe. By mapping users' SDUs *consecutively* instead of mapping the SDUs *concurrently* into the OFDMA subframe, these approaches omit the aforementioned resource contention issue.

In this work, we address the second issue. If radio resource of a subchannel cannot be sufficiently allocated to all contending users, it is the task of the mapping algorithm to select best suitable users, so that the downlink channel capacity can be maximized.

3. SYSTEM DESIGN REQUIREMENTS, ARCHITECTURE AND ALGORITHMS

3.1. System design requirements

The objectives of this research are to find an approach for the compromise between *fairness*, *QoS,* and *spectral efficiency* of 4G wireless systems using OFDMA/TDD schema, as these aforementioned objectives are often contradictory.

As illustrated in Figure 5, a new joint scheduling and RRM scheme is developed that should have the following requirements:

- On the one hand, the new scheme should provide a certain level of fair bandwidth share between active sessions, so that it can prevent data sessions with bad channel conditions from being

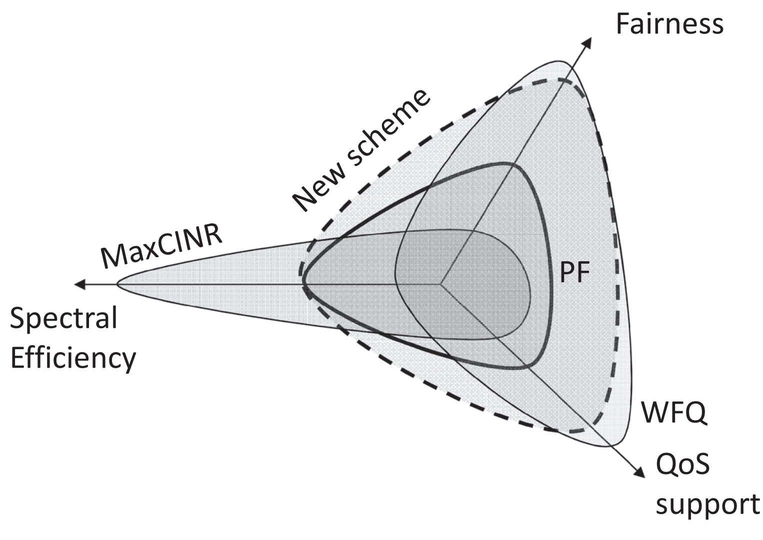

Figure 5. Design requirements of the new scheme.

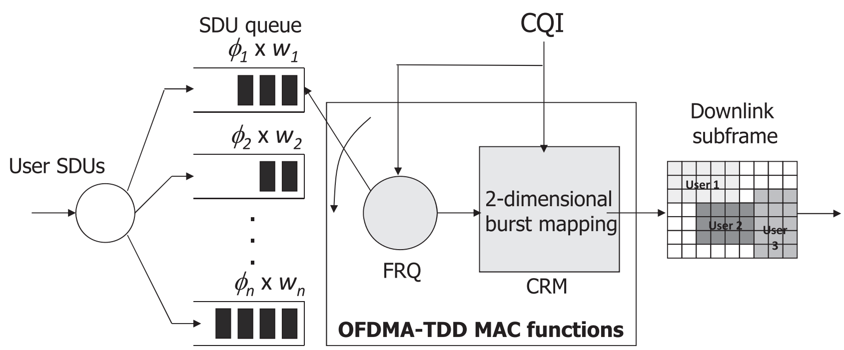

Figure 6. Orthogonal frequency division multiple access (OFDMA)/TDD scheduling and mapping.

DOI: 10.1002/dac

blocked. Thus, the joint scheme should be *as good as fair scheduling in terms of bandwidth fairness*;
- On the other hand, the new scheme should allow any session to only have its fair share of radio resources to avoid excessive resource allocation, which leads to the degradation of total channel capacity. In other words, the joint scheme should be the *best approach in terms of resource fairness compared to existing ones*;
- Furthermore, the joint scheduling–mapping approach should have *better spectral efficiency level compared with PF*.

3.2. System architecture

In order to satisfy the aforementioned objectives, the MAC-layer component in our approach is decomposed into two separated functions as described in Figure 6, namely the following:

- *Scheduling function in support of fairness*: a novel *Fair Resource Queuing* (FRQ) scheduling algorithm is proposed. Its main function is to select appropriate user SDUs from a list of candidates waiting at the SDU queues (Figure 6) with the objective of maintaining fair shares of radio resources between sessions. The FRQ algorithm creates a set of users' SDUs to be mapped to the current OFDMA downlink subframe.
- *Burst mapping in support of spectral efficiency*: beside the scheduler, we also propose the *Contention Resolution Mapping* (CRM) algorithm for improving spectral efficiency. Based on the set of users' SDUs that are pre-selected by the scheduling function, the CRM component maps these users' data into time-frequency areas within the downlink subframe. Its objective is to resolve resource contention between users and finds the best mapping solution, so that radio resources are best utilized and the channel capacity can be maximized.

WiMAX makes use of the *Channel Quality Information* (CQI) to exchange channel information between UEs and BS. Thus, as shown in Figure 6, we assume that the Base Station (BS) receives the update of channel conditions from all users in its coverage periodically. Based on CQI, the Base Station can maintain the modulation maps (e.g., the maps illustrated in Figure 3) and select a suitable AMC scheme for each user within a subframe. As discussed earlier in Section 2, the focus of this work is to resolve the suboptimal mapping of user data.

3.3. Fair Resource Queuing Algorithm

3.3.1. Scheduling Algorithm. The FRQ algorithm is developed based on the idea of the WFQ algorithm [6]. WFQ defines a weight ϕ_i ($\phi_i \in \Omega_B$) for every session i. It operates based on the notion of the *virtual time* $V(t)$, which is the normalized service in bits of all sessions served by the scheduler during a backlogged period $[0, t]$. Based on $V(t)$, it then calculates the *start tag* S_i^k and *finish tag* F_i^k of all incoming packets k in session i and serves the packets in the increasing order of finish tags. By doing that, WFQ allocates bandwidth to a backlogged session i proportionally to its weight ϕ_i. WFQ is a channel-unaware scheduling algorithm that is originally designed for wired networks.

Instead of allocating fair shares of bandwidth to users, FRQ tries to maintain resource fairness, which is defined as the amount of OFDMA slots allocated to a backlogged session. Furthermore, FRQ is a channel-aware algorithm by making use of the Channel Quality Index information periodically sent by UEs. The FRQ algorithm at the BTS makes use of that information to decide an appropriate modulation and coding scheme to raise the maximum bandwidth according to the temporary Signal-to-Noise Ratio (SNR).

In this work, three different modulation schemes supported by WiMAX are taken into consideration, namely, QPSK, 16-QAM, and 64-QAM. Table I represents some notations used in our scheduling and burst mapping algorithms. Let k be the number of bits per symbol in these schemes, $k = 2, 4, 6$, respectively. Let M_i^k be the number of subchannels that can accommodate k bit/symbol for user i. We define K_i as the average number of bits per symbol of user i over all subchannels at the given frame as following:

$$K_i = \frac{\sum k M_i^k}{N} = \frac{2 \times {M_i}^{(2)} + 4 \times {M_i}^{(4)} + 6 \times {M_i}^{(6)}}{N} \tag{5}$$

DOI: 10.1002/dac

Table I. Notations used in the algorithms.

Notation	*Meaning*
u_i	– user i
$S = \{s_1, s_2, ..., s_M\}$	– set of M sub-channels used in the downlink subframe
$T = \{t_1, t_2, ..., t_N\}$	– set of N OFDM symbols in the downlink subframe
M_i^k	– Number of OFDMA subchannels that can accommodate k bits per symbol for user i (e.g., $k = 2, 4, 6$ corresponding to QPSK, 16-QAM and 64-QAM).
L_i^p	– The length of SDU p belonging to session i.
$b_{k,m,n}$	– The amount of data in bits that session k can send if k is assigned a slot specified by subchannel m and OFDM symbol n at a given downlink subframe.
F_i^p	– Virtual Finish Tag of SDU p in session i.
S_i^p	– Virtual Start Tag of packet p in session i.
$V(t)$	– Virtual System Service at t.
$t_{a,i}^p$	– Arrival time of SDU p of session i.
$t_{a,i}^p$	– Departure time of SDU p of session i.
Ω_B	– Set of backlogged sessions.
Ω_{DL}	– Set of SDUs selected for transmission in a given downlink subframe.
$W(t_1, t_2)$	– Total amount of OFDMA slots utilized by the scheduler in $(t_1, t_2]$.
$W_i(t_1, t_2)$	– Total amount of OFDMA slots allocated to session i in $(t_1, t_2]$.
$B_i(t_1, t_2)$	– Total service in bits that session i is served in $(t_1, t_2]$.
W_{DL}	– Total OFDMA slots in the current downlink subframe.
ω_i^p	– Estimated number of OFDMA slots needed to map SDU p of session i.

	User1	User2	User3	User4	User5	User6	User7	User8	User9
Sub1	2	6	4	6	2	4	2	6	4
Sub2	2	4	4	6	4	6	6	6	2
Sub3	4	2	4	4	4	6	4	4	2
Sub4	4	2	2	2	4	2	2	4	2
Sub5	6	4	6	4	2	2	2	2	6
Sub6	2	4	2	2	6	4	4	2	6
Sub7	2	2	4	2	6	4	6	2	4
Sub8	4	2	4	2	4	4	4	4	6
Sub9	4	2	4	2	2	4	4	6	6
Sub10	4	2	2	2	2	4	4	2	4
	K_1= 3.4	K_2= 3.0	K_3= 3.6	K_4= 3.2	K_5= 3.6	K_6= 4.0	K_7= 3.8	K_8= 3.8	K_9= 4.2

Figure 7. Values of K_i depends on the channel condition of each user.

while N is the total of subchannels of current OFDMA frame. The coefficient K_i is calculated based on the CQI feedback from the UEs. The larger K_i is, the better is the channel condition of user i in the current downlink subframe. Thus, K_i is used as a channel-aware indicator in FRQ. As illustrated in Figure 7, we have the set of users $\{u_1, u_2, ..., u_9\}$ and their corresponding channel state information. The value of K_i is calculated for each UE. The UE, which has the maximum weight ($K_i = 4.2$), is the $9th$ user and the UE, which has the minimum weight ($K_i = 3.0$), is the $2nd$ user. It means that the $2nd$ user has the worst channel condition and the $9th$ user has the best channel condition.

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Each session in FRQ is also assigned a weight ϕ_i, $\phi_i \in \Re$. The objective of FRQ is to allocate radio resources in terms of OFDMA slots to any session i proportionally to its weight ϕ_i. That is, a session i will have a resource proportion of $\frac{\phi_i}{\sum_{j \in \Omega_B} \phi_j}$ of the total OFDMA slots in the downlink subframe.

Similar to WFQ, a *start tag* S_i^p and a *finish tag* F_i^p are assigned to each SDU p of session i in FRQ. The start tags and finish tags of different SDUs are calculated based on the *virtual system service* $V(t)$. In FRQ, the virtual system service is the normalized number of OFDMA slots (or the normalized amount of radio resources) that are served during a backlogged period $[0, t]$. F_i^p and S_i^p are calculated as follows:

$$S_i^p = \max\left[F_i^{p-1}, V\left(t_{a,i}^p\right)\right] \tag{6}$$

$$F_i^p = \max\left[F_i^{p-1}, V\left(t_{a,i}^p\right)\right] + \frac{L_i^p}{K_i}\frac{\sum_{j \in \Omega_B} \phi_j}{\phi_i} = S_i^p + \frac{L_i^p}{K_i}\frac{\sum_{j \in \Omega_B} \phi_j}{\phi_i} \tag{7}$$

$$V(t+\tau) = \begin{cases} 0 \\ \qquad \text{if} \quad \Omega_B(t_0) \in \emptyset \qquad \forall t_0 \in [t, t+\tau], \\ V(t) + W(t, t+\tau)\frac{1}{K_i}\frac{\sum_{i \in \Omega} \phi_i}{\sum_{j \in \Omega_B} \phi_j} \\ \qquad \text{if} \quad \Omega_B(t_0) \notin \emptyset \quad \forall t_0 \in [t, t+\tau]; \end{cases} \tag{8}$$

As expressed in Equation (7), the finish tag can be understood as the serving deadline for an SDU, which depends on the average number of OFDMA slots $\frac{L}{K_i}$ that should be allocated to user i, normalized by the proportion of its weight. Thus, our scheduling approach resolves the following issues: (i) by defining the finish tag that depends on the normalized number of OFDMA slots allocated to a session and serving user's SDU in the increasing order of the finish tags; the FRQ algorithm can maintain the resource fairness between sessions in the long term; and (ii) by using K_i as a channel-aware coefficient, the algorithm is able to adapt its resource allocation policy to users with better channel condition in the short term.

3.3.2. Subframe capacity estimation. Once selected by FRQ, a user's SDU is not directly forwarded to the output but is buffered to wait for the next eligible downlink subframe duration. The number of buffered SDUs depend on the capacity of the OFDMA/TDD downlink channel. However, the downlink channel capacity cannot be precisely evaluated in advance because of user diversity and channel dynamicity. Moreover, channel capacity also depends on the efficiency of the mapping algorithm. In FRQ, we estimate the number of SDUs to be mapped into the next downlink subframe as the following:

$$\omega_i^p = \left\lceil L_i^p \times \frac{W_i(t_1, t_2)}{B_i(t_1, t_2)} \right\rceil \tag{9}$$

Finally, the operations of FRQ can be summarized as follows. Upon arrival, an SDU p of a session i is firstly classified and enqueued in the corresponding session i's queue as described in Figure 6. Its start and finish tags S_i^p and F_i^p are calculated according to Eqs. (6) and (7). The FRQ algorithm then serves the head-of-line SDUs in the increasing order of the finish tags as described in Algorithm 1. In the algorithm, the finish tag of the head-of-line SDU belonging to session i is denoted as F_i^{HOL}; Ω_B and Ω_{DL} are the set of all backlogged sessions as well as the set of SDUs that are selected for transmission in the current downlink subframe, respectively; $\tilde{W}$ is the total estimated number of slots required to carry the selected SDUs in the given downlink subframe; and $B_i(t_1, t_2)$ is the total session's i service in bits served by the scheduler during time $[t_1, t_2]$.

3.4. Contention Resolution Mapping Algorithm

3.4.1. Formal analytical model. Firstly, we assume that the BS can select the best AMC scheme for each user based on CQI information (e.g., QPSK, 16-QAM, and 64-QAM). Thus, as denoted

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Algorithm 1 Fair Resource Queuing Algorithm

1: $\widetilde{W} \leftarrow 0$
2: **repeat**
3: $\quad j = \arg_i \min \{F_i^{HOL} \mid \forall i \in \Omega_B\}$
4: $\quad \omega_i^{HOL} = \left\lceil L_i^{HOL} \times \frac{W_i(t_1,t_2)}{B_i(t_1,t_2)} \right\rceil$ // Eq. 9
5: $\quad \Omega_B \leftarrow \Omega_B \backslash j$
6: $\quad \Omega_{DL} \leftarrow \Omega_{DL} \cup j$
7: $\quad \widetilde{W} \leftarrow \widetilde{W} + \omega_j^{HOL}$
8: $\quad$ update$[V(t)]$ // Eq. 8
9: **until** $\widetilde{W} \geq W_{DL}$

in Table I, the number of bits $b_{k,m,n}$ of session k that can be transmitted in a slot $\{m, n\}$ of the downlink subframe with subchannel m and OFDM symbol n can be calculated.

Let us define the function $x_{k,m,n}$ as follows:

$$x_{k,m,n} = \begin{cases} 1 & \text{if slot } \{m,n\} \text{ in the given subframeis allocated to flow } k, \\ 0 & \text{if slot } \{m,n\} \text{ in the given subframeis not allocated to flow } k; \end{cases} \tag{10}$$

Thus, in order to maximize channel capacity, we have the following objective function:

$$C_{max} = \max \left\{ \sum_{k \in \Omega_{DL}} \sum_{m \in M} \sum_{n \in N} x_{k,m,n} b_{k,m,n} \right\} \tag{11}$$

where C_{max} is the maximum bits that can be transmitted in the downlink subframe. Equation (11) should be resolved under three constraints.

- Firstly, there is maximum of *one* session that can be allocated to any slot, that means

$$0 \leqslant \sum_{k \in \Omega_{DL}} x_{k,m,n} \leqslant 1 \qquad \forall m, n \tag{12}$$

- Next, the number of slots that are allocated to an SDU of session k should be just enough to transmit that SDU. This constraint can be explained as the following:
  At an arbitrary OFDM symbol T, the number of bits that are already allocated to session k in the downlink subframe are as follows:

$$L_k^T = \sum_{n=1}^{T} \sum_{m=1}^{M} x_{k,m,n} b_{k,m,n} \tag{13}$$

$$\text{If } L_k^T \geqslant L_k \text{ then } \forall n > T : x_{k,m,n} = 0 \tag{14}$$

$$\text{Otherwise, if } L_k^T < L_k \text{ then } \exists n > T : x_{k,m,n} = 1 \tag{15}$$

  The Conditions (14) and (15) can be expressed by the following inequation:

$$\left|L_k - L_k^T\right| - \left[L_k - L_k^T\right] \geqslant \sum_{m=1}^{M} \sum_{n>T} x_{k,m,n}; \tag{16}$$

- Last, according to the requirements of some OFDMA schemes such as WiMAX, resource allocation can be defined as the mapping of two-dimensional rectangles of users' SDUs into an arbitrary downlink subframe j. In other words, consider the mapping of an SDU belonging to session k. As illustrated in Figure 8, if two slots $\{s_i, t_{l+e}\}$ and $\{s_{i+f}, t_l\}$ are two arbitrary slots belonging to the data burst of session k with $x_{k,i,l+e} = x_{k,i+f,l} = 1$, then any other

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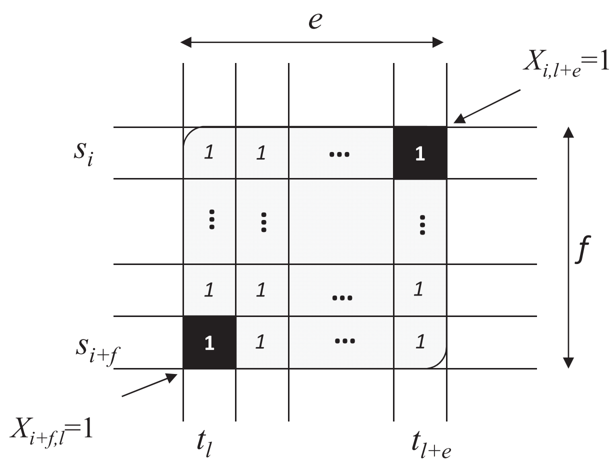

Figure 8. Rectangular mapping of data burst in downlink subframe.

slots located in the rectangular bounded by $\{s_i, t_{l+e}\}$ and $\{s_{i+f}, t_l\}$ will have the value of 1: $x_{k,o,p} = 1\ \forall o \in \overline{[i, i+f]}$ and $\forall p \in \overline{[l, l+e]}$. On the other hand, the slots outside the rectangular border are not necessary to have the value of 1. The aforementioned arguments can be expressed by the following inequation:

$$\begin{aligned} &ef + \textstyle\sum_{o=i}^{i+f} \sum_{p=l}^{l+e} x_{k,o,p} \geqslant ef\left[x_{k,i+f,l} + x_{k,i,l+e}\right] \\ &\forall o \in \overline{[i, i+f]} \text{ and } \forall p \in \overline{[l, l+e]}. \end{aligned} \tag{17}$$

Thus, the RRA in OFDMA/TDD schemes can be formulated as an optimization problem with the objective function described by Eq. (11) and three constraints as in Eqs. (12), (16), and (17). This is an *NP-hard* problem that is complex and cannot be resolved in RT.

3.4.2. Algorithm. In this section, we simplify the aforementioned formal optimization method by proposing a heuristic burst mapping mechanism, which is called the *Contention Resolution Mapping* algorithm (CRM).

The main properties of CRM are as the follows:

- *Subchannel re-ordering*: Firstly, we calculate the *average number of bits per symbol* e_i of subchannel i that the subchannel can accommodate for all users. The parameter e_i is defined as follows:

$$e_i = \frac{\sum_{i=1}^{S} \sum_{j=1}^{N} M_i^j}{N} \tag{18}$$

  where S is the number of subchannels; N is the number of users; and M_i^j is the number of bits per symbol of user j on subchannel i ($M = 2, 4, 6$ bit/symbol). As can be seen, e_i indicates the *contention level* of a subchannel i. The larger e_i is, the more users will contend for subchannel i to map their data. The set of $\{e_1, e_2, ..., e_k\}$ is then organized in their decreasing order. In CRM, subchannel with highest value of e_i will be considered first. By doing that, we try the resolve resource contention between users. Figure 9 illustrates this calculation according to Eq. (18). The boxes in the figure express the number of bits per symbol of users in given subchannels. Algorithm 2 represents the subchannel re-ordering procedure.
- *Contention resolution*: In a given subchannel, the next issue is how to choose multiple user's SDUs to be mapped into the subchannel's OFDMA slots, especially when there are several users contending the same resource, and the number of OFDMA slots in the subchannel do not suffice to accommodate all of them. It this while worthy to note that our mapping strategy is try to fit an user's SDU into one subchannel, that is, the height of the rectangular map

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	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9	User 10
Sub1	**2**	**6**	**4**	**6**	**2**	**4**	**2**	**6**	**4**	**6**
Sub2	**2**	**4**	**4**	**6**	**4**	**6**	**6**	**6**	**2**	**2**
Sub3	**4**	**2**	**4**	**6**	**4**	**6**	**4**	**4**	**2**	**2**
Sub4	**4**	**2**	**2**	**2**	**4**	**2**	**2**	**4**	**2**	**4**
Sub5	**6**	**4**	**6**	**4**	**2**	**6**	**4**	**6**	**6**	**6**
Sub6	**2**	**4**	**2**	**2**	**6**	**4**	**4**	**2**	**6**	**4**
Sub7	**2**	**2**	**4**	**2**	**6**	**4**	**6**	**2**	**4**	**4**
Sub8	**4**	**6**	**4**	**2**	**4**	**4**	**4**	**4**	**6**	**4**
Sub9	**4**	**2**	**4**	**2**	**4**	**4**	**4**	**6**	**6**	**6**
Sub10	**4**	**2**	**2**	**4**	**4**	**2**	**4**	**4**	**2**	**4**

Priority Level: $\mathrm{e_i} = \dfrac{\sum matrix\_level}{\sum users}$

Sub 1: **4.2**
Sub 2: **4.2**
Sub 3: **3.8**
Sub 4: **2.8**
Sub 5: **5.0**
Sub 6: **3.6**
Sub 7: **3.6**
Sub 8: **4.2**
Sub 9: **4.2**
Sub 10: **3.2**

=>E={Sub5,Sub1,Sub2,Sub8,Sub9,Sub3,Sub6,Sub7,Sub10,Sub4}

Figure 9. Subchannel re-ordering based on the value of e_i.

(Figure 8) is 1. We call this mapping as *horizontal mapping*. Assume that there is a set of users $\{u_1, u_2, ..., u_N\}$ contending radio resource in subchannel i. A procedure is performed to vote for the next SDU of user u_i to map to the given subchannel as follows:

$$u_i = \arg_i \min \left\{ \frac{L_i}{M_i} \right\} \tag{19}$$

Algorithm 2 Subchannel re-ordering

```
i ← 1
j ← 1
repeat
    repeat
        e_i ← e_i + M^i_j / N
    until j = N
until i = M
// Arrange subchannels in order of decreasing priority.
// PS is the set of subchannels which are arranged
PS ← ∅
l ← 1
while l ≤ M do
    ps = arg_j max{e_j | ∀j ∈ S}
    PS ← PS ∪ {ps}
    S ← S\{ps}
    l ← l + 1
end while
```


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Algorithm 3 Contention resolution

$\widehat{N} \leftarrow N$
$i \leftarrow 1$
while $i \leq M$ **do**
  $\widehat{i} \leftarrow PS_i$
  // Let $\widehat{i}$ be the prior subchannel which is got from PS
  $j \leftarrow 1$
  while $j \leq \widehat{N}$ **do**
    $A_j^{\widehat{i}} \leftarrow [\frac{L_j}{M_j^{\widehat{i}}}]$
    // Let $A_j^{\widehat{i}}$ be the required number of slots of user j
    // on subchannel $\widehat{i}$
    $j \leftarrow j + 1$
  end while
  // Step 1. Resolve resource contention
  // Let $A^{\widehat{i}}$ be the number of available slots of
  // subchannels $\widehat{i}$
  while $U \neq \emptyset$ **do**
    $\widehat{j} = \arg_j \min\{A_j^{\widehat{i}}\}$
    if $A^{\widehat{i}} - A_{\widehat{j}}^{\widehat{i}} \geq 0$ **then**
      $A^{\widehat{i}} \leftarrow A^{\widehat{i}} - A_{\widehat{j}}^{\widehat{i}}$
      $U \leftarrow U \backslash \{\widehat{j}\}$
      $\widehat{N} \leftarrow \widehat{N} - 1$
    else
      break
    end if
  end while
  $i \leftarrow i + 1$
end while
// Step 2. If there are non-served users and frame is
// not fully utilized, the rest of users will be mapped with a
// rectangle burst.
// Let A_r be available area which is the rest of frame.
if $(U \neq \emptyset) \cap (frame\_status \neq full)$ **then**
  $j \leftarrow 1$
  $N_r \leftarrow \widehat{N}$
  while $j \leq N_r$ **do**
    $M_j \leftarrow \chi(j)$
    // χ is any choice which user j can be
    // mapped with a rectangle burst.
    $A_j \leftarrow \frac{L_j}{M_j}$
    if $A_j < A_r$ **then**
      $A_r \leftarrow A_r - A_j$
      $\widehat{N} \leftarrow \widehat{N} - 1$
      $U \leftarrow U \backslash \{j\}$
    end if
    $j \leftarrow j + 1$
  end while
end if

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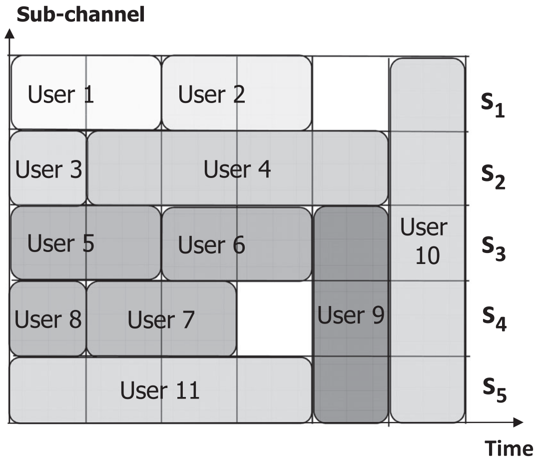

Figure 10. Mapping strategy in Contention Resolution Mapping.

Table II. Simulation parameters.

Parameter	*Value*
Number of BSs	7
Number of UEs per border cell	20
Number of UEs per center cell	30–70
Radius of cell coverage	$1500m$
Antenna height of BS	$80m$
Antenna height of UE	$2m$
Physical layer	OFDMA
Permutation model	ACM
WiMAX frame	TDD
DL/UL ratio	1:1
Radio channel	Releigh
Channel bandwidth	$5MHz$
Carrier frequency	$2.5GHz$
FFT size	512
Bandwidth of a subcarrier	$10.94kHz$
Number of null subcarriers	92
Number of pilot subcarriers	60
Number of subcarriers for user data	360
Number of subchannels	16
Symbol duration	$102.9\mu s$
Frame duration	$5ms$
Modulation schemes	4-QAM, 16-QAM, 64-QAM
Code rate	3/4
Average UE velocity	$40km/h$
Doppler shift	$90Hz$
Guard duration (G)	1/16

where L_i is the SDU length of user i and M_i is the number of bits per symbol of user i at the given subchannel. According to Eq. (19), user who utilizes the least radio resource in terms of the number of OFDMA slots, that is, user with higher modulation scheme or user with shorter SDU length, has higher priority. By doing so, a subchannel is given to 'better users'. Also, it can accommodate larger number of users, which consequently improves the fairness. On the other hand, if subchannel is full or not capable of meeting user's requirements, the next subchannel will be chosen by the order defined by Eq. (18). Algorithm 3 describes the contention resolution mapping.

- *Mapping other SDUs to leftover OFDMA slots*: If there are non-served users and there are still some unutilized OFDMA slots, the rest SDUs will be mapped with a vertical rectangle burst.

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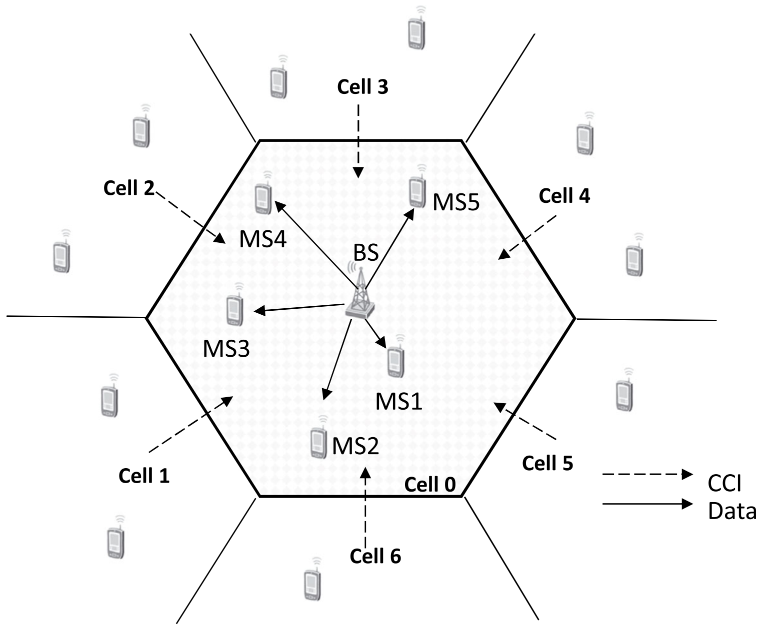

Figure 11. Simulation scenarios.

Figure 10 represents an example of the CRM mapping strategy. Firstly, it tries to fit a user's SDU in a single subchannel as the case of user $\{u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_{11}\}$, only users u_9 and u_{10} utilize the leftover OFDMA slots by forming vertical rectangular bursts.

4. PERFORMANCE EVALUATION

4.1. Simulation scenarios

In order to evaluate the performance of the proposed algorithms, simulation models based on MATLAB have been developed. Although the proposed approaches can generally be deployed to any OFDMA-TDD wireless systems, their performance is investigated under WiMAX technology with the corresponding IEEE 802.16e parameters described in Table II. Simulation scenarios are further described in Figure 11, which include 7 cells. We consider the center cell that undergoes *Co-Channel Interference* (CCI) emitted by BSs and UEs from six other cells. User devices are uniformly distributed in the given cells. All UEs are moving with the average velocity of 40 km/h. In the center cell, we measure and evaluate the bandwidth and resource fairness indices of all users as well as the total channel capacity of the downlinks.

In order to investigate the impact of each proposed component on overall system performance and to see whether these algorithms meet three design objectives addressed in Section 3.1, two test scenarios are considered, namely, (i) *scheduling* and *regular burst mapping* and (ii) *scheduling* and the proposed *Contention Resolution Mapping*. In *regular burst mapping*, user's SDUs are mapped *consecutively* to the downlink subframe. The mapping begins from the top-left corner of the subframe. User's SDUs are mapped from the left to the right and from the top to the bottom of the frame with the order selected by the scheduler. Four scheduling algorithms are chosen for the performance evaluation, namely, (i) *MaxCINR*, which is the best in terms of spectral efficiency and the worst in terms of fairness; (ii) *WFQ*, which is one of the fair scheduling algorithms and is the ideal scheduling in terms of fairness and the worst in terms of spectral efficiency; (iii) *PF*, which is the trade-off solution between WFQ and MaxCINR; and finally (iv) the newly proposed *Fair Resource Queuing* algorithm. Thus, there are totally seven combinations of the aforementioned scheduling–mapping schemes.

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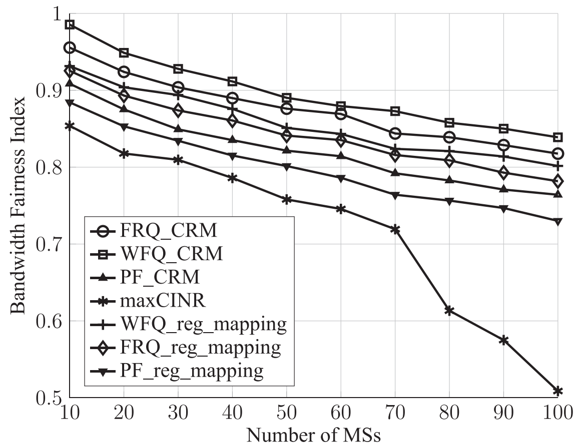

Figure 12. Bandwidth Fairness Index with different number of user equipments per cell.

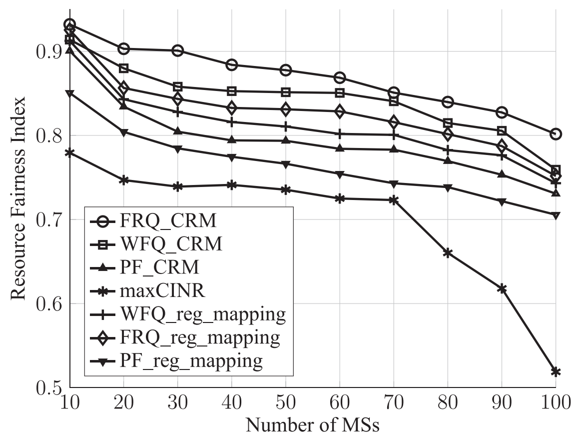

Figure 13. Resource Fairness Index with different number of user equipments per cell.

4.2. Fairness

In this paper, Eqs. (1) and (2) in turn are used to compute the bandwidth and resource fairness metrics. These measurements demonstrate how fair bandwidth and radio resources are allocated to users under different scheduling and mapping schemes. Figure 12 shows the bandwidth fairness indices of seven aforementioned mapping and scheduling combinations. Firstly, we investigate the performance of different scheduling algorithms without the deployment of CRM (i.e., with regular burst mapping). Results show that FRQ outperforms PF and MaxCINR in terms of bandwidth fairness. Only WFQ is superior to FRQ on this aspect.

Now that we evaluate the fairness of four different schedulers with the support of CRM. WFQ-CRM is the best overall scheduler in terms of bandwidth fairness; this is followed in the second place by the proposed FRQ-CRM combination. This implies that the CRM algorithm does not only maximize spectral efficiency but also improve the system bandwidth fairness. This finding is explained in Section 3.4.2 with Eq. (19).

Next, Resource Fairness is investigated (Figure 13). In contradiction to the previous case, where WFQ-CRM is the best in terms of fair bandwidth allocation, results shown in Figure 13 indicate that FRQ-CRM is the best one in terms of fair resource allocation. Moreover, from Figures 12 and 13, it is noted that without CRM, FRQ still allocates bandwidth and radio resources fairer than the conventional well-known PF scheduler.

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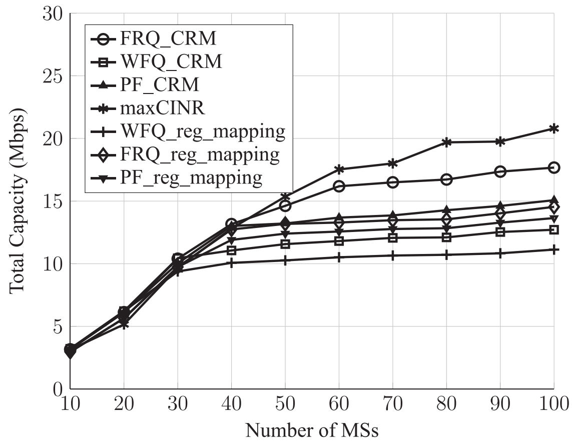

Figure 14. Spectral efficiency with different number of user equipments per cell.

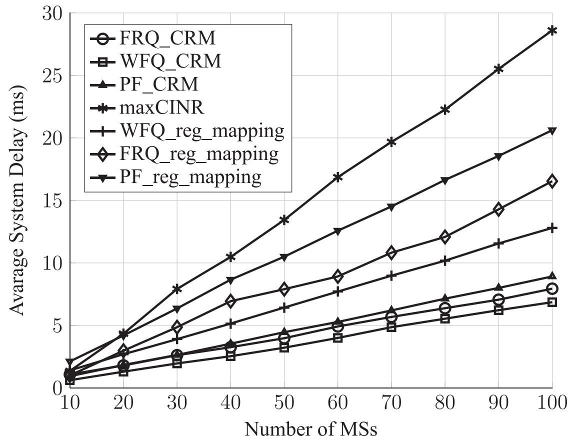

Figure 15. Average System Delay with different number of user equipments per cell.

4.3. Spectral efficiency

Figure 14 shows total downlink channel capacity of the seven scheduling–mapping combinations. As can be seen in the figure, without the present of CRM, spectral efficiency under the FRQ paradigm is still better than that under PF. This can be explained by the fact that the utility function of PF (Eq. (4)) does not deal directly with RRA. Moreover, PF is originally designed to operate only in the time domain. In OFDMA paradigm, if user's SDUs selected by PF do not efficiently mapped into the downlink subframe, channel capacity can deteriorate.

On the other hand, if CRM is used in combination with these scheduling algorithms, the overall spectral efficiency is significantly improved in comparison with conventional regular mapping. Especially, except the MaxCINR scheduler that is the ideal paradigm for maximizing channel capacity, the joint FRQ-CRM outperforms all other algorithms, including PF and PF-CRM.

4.4. Delay performance

Beside fairness and spectrum efficiency, now the performance of the system in terms of *mapping delay* is studied. Mapping delay is defined as the latency from the moment that an SDU becomes the head-of-line of a queue until it is completely mapped into a downlink subframe. Mapping delay is also an important factor that indicates the QoS of a wireless system. In our simulations, SDUs are always available for transmission in every output queue of the scheduler. As can be seen in Figure 15, WFQ-CRM is the best scheduler in terms of delay, while FRQ-CRM is in the second place. MaxCINR introduces worst delay compared with other scheme. This can be explained by the

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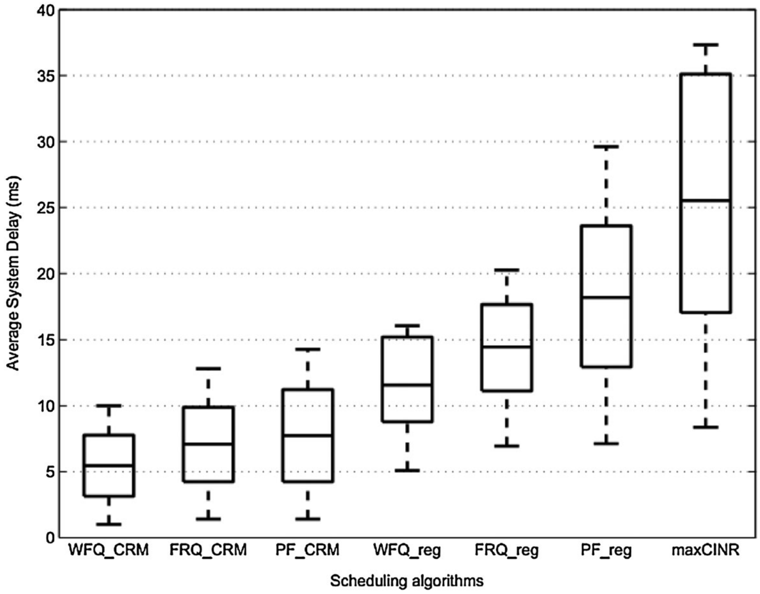

Figure 16. Delay performance – 90 users .

fact that MaxCINR only serves users with best channel conditions, while the ones with bad channels should refrain from transmission.

Now that delay performance of the different scheduling algorithms with and without CRM is investigated in more details. We measure the min, max, average, and 95-percentile delays of the system in case of 90 users. Figure 16 shows the detailed measurement. In the figure, the seven box-plots represent the seven scheduling–mapping schemes, where the two ends of the box-plot represent min, max delay; the horizontal line in the middle of the box represents the average delay; and the box shows the area of 95-percentile delay. Beside the average delay, the maximum and minimum delay, as the 95-percentile delay plays an important role in QoS guarantee. The higher the difference between max and min delays, the more unreliable and more unstable the scheme. Thus, MaxCINR is the worst scheduler, while FRQ-CRM is the second best after the WFQ-CRM.

4.5. Discussions

From the previous results, there are some conclusions and discussions as follows:

- The PF scheduler does not perform optimally in OFDMA paradigm. While it is one of the most referred scheduling algorithms in the literature and considered as the solution for the trade-off between spectral efficiency and fairness, PF has some drawbacks. Firstly, PF is specifically designed for operating in time domain, when working in such time-frequency environments as OFDMA, one issue is how PF can be integrated with a burst mapping strategy for a better spectral performance. Moreover, its utility function shows that PF tries to balance between fairness and spectral efficiency through allocating suitable momentary service rate to a session. However, as already discussed previously, in wireless networks, radio resources and service rate are not necessarily in proportion to each other. This leads to the fact that resource allocation might still be suboptimal in terms of fairness.
- On the other hand, as can be seen from the results, FRQ performs well with regard to bandwidth and resource fairness. It is the best scheduler in terms of fair resource allocation and outperforms PF. When combined with CRM, its property of fair resource and bandwidth allocation is even improved. Thus, CRM does not only maximize the spectral efficiency but also improves fairness. From the perspective of spectral efficiency, by resolving resource contention between multiple users, the Contention Resolution Mapping remarkably improves the channel capacity of the downlink. Besides the unrealistic MaxCINR, the joint FRQ-CRM is the best in terms of channel capacity. From the QoS perspective, FRQ-CRM is also suitable for user's service guarantees as it is better than PF.

DOI: 10.1002/dac

- Although in this paper, the performance of the CRM algorithm is investigated for IEEE802.16e WiMAX, we argue that CRM is also suitable for LTE. As the mapping algorithm tries to map user's SDUs in a single row, the constraint on rectangular burst in WiMAX can be eased.
- Another phenomenon observed from the results is that bandwidth and resource fairness decrease, while spectral efficiency is improved as the number of users increase. This is reasonable because user diversity usually increases with the number of UEs. The more diverse users are, the less the wireless system can guarantee fairness, and the more likely that the scheduling and mapping mechanisms can choose users with better channel condition for better spectrum efficiency.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a joint scheduling and burst mapping mechanism, which comprises (i) the Fair Resource Queuing scheduler and (ii) the Contention Resolution Mapping algorithm. The idea of the proposed approach is as the follows. First, we decompose RRM and allocation functions into two components. FRQ is responsible for fairness guarantees. We argue that it is fair when the radio resources allocated to a session be proportional to its required service rate. Instead of trying to allocating fair bandwidth to each session, the FRQ scheduler selects a set of candidates to be transmitted in the downlink OFDMA subframe based on the amount of allocated radio resources in terms of OFDMA slots, thus preventing a session from utilizing excessive resources to satisfy its bandwidth requirements. Next, CRM tries to optimize downlink spectral efficiency by resolving the resource contention between different users and mapping user's SDUs in appropriate places in the downlink subframe. In CRM, better subchannels with more contending users are likely to be considered first. In a given subchannel, CRM gives priority to users with better channel condition or shorter SDU length, so that more users can be served. Simulation results show that

- The joint FRQ-CRM scheme outperforms PF in terms of both fairness and spectral efficiency.
- In terms of fairness, FRQ-CRM performs as well as fair scheduling algorithms (such as WFQ).
- In terms of spectral efficiency, FRQ-CRM is one of the best schemes. Its performance is only worse than MaxCINR, which is considered as the ideal algorithm for maximizing channel capacity.
- In terms of delay performance, FRQ-CRM also performs well.

In conclusion, if taking fairness, spectral efficiency and QoS into account at once, our proposed FRQ-CRM approach performs well and is one of the best mapping/scheduling strategies.

As a future direction, it would be interesting to see how the new scheme can accommodate users with different QoS requirements. Especially it would be useful to study some advanced scheduling–mapping algorithms based on the proposed approach in support of user's *Quality of Experience* and optimized resource utilization in OFDMA-based wireless systems.

ACKNOWLEDGEMENTS

This research is partly supported by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under the grant number 101.01-2013.19.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

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DOI: 10.1002/dac