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A Cross-Layer Radio Resource Management in WiMAX Systems

Sondes Khemiri Guy Pujolle[1] and Khaled Boussetta Nadjib Achir[2]
[1]LIP6, University Paris 6, Paris
[2]L2TI, University Paris 13, Villetaneuse
France

1. Introduction

This chapter addresses the issue of a cross layer radio resource management in IEEE 802.16 metropolitan network and focuses specially on IEEE 802.16e-2005 WiMAX network with Wireless MAN OFDMA physical layer. A wireless bandwidth allocation strategy for a mobile WiMAX network is very important since it determines the maximum average number of users accepted in the network and consequently the provider gain.

The purpose of the chapter is to give an overview of a cross-layer resource allocation mechanisms and describes optimization problems with an aim to fulfill three objectives: (i) to maximize the utilisation ratio of the wireless link, (ii) to guarantee that the system satisfies the QoS constraints of application carried by subscribers and (iii) to take into account the radio channel environment and the system specifications.

The chapter is organized as follows: Section 1 and 2 describe the most important concepts defined by IEEE 802.16e-2005 standard in physical and MAC layer, Section 3 presents an overview of QoS mechanisms described in the literature, Section 4 gives a guideline to compute a physical slot capacity needed in resource allocation problems, the cross-layer resource management problem formalization is detailed in section 5. Solutions are presented in section 6. Finally, section 7 summarizes the chapter.

2. Mobile WiMAX overview

This section presents an overview of the most important concepts defined by IEEE 802.16e-2005 standard in physical and MAC layer, that are needed in order to define a system capacity.

2.1 WiMAX PHY layer

We will give in this section details about PHY layer and we will focus specially on specified concepts that must be taken into account in allocation bandwidth problem namely, the specification of the PHY layer, the OFDMA multiplexing scheme and the permutation scheme for sub-channelization from which we deduce the bandwidth unit allocated to accepted calls in the system and the Adaptive Modulation and Coding scheme (AMC).

2.1.1 Generality

The IEEE 802.16 defines five PHY layers which can be used with a MAC layer to form a broadband wireless system.

These PHY layers provide a large flexibility in terms of bandwidth channel, duplexing scheme and channel condition. These layers are described as follows:

1. WirelessMAN SC: In this PHY layer single carriers are used to transmit information for frequencies beyond 11GHz in a Line of sight (LOS) condition.

2. WirelessMAN SCa: it also relies on a single carrier transmission scheme, but for frequencies between 2 GHz and 11GHz.

3. WirelessMAN OFDM (Orthogonal Frequency Division Multiplexing): it is based on a Fast Fourier Transform (FFT) with a size of 256 points. It is used for point multipoint link in a non-LOS condition for frequencies between 2 GHz and 11GHz.

4. WirelessMAN OFDMA (OFDM Access): Also referred as mobile WiMAX , it is also based on a FFT with a size of 2048 points. It is used in a non LOS condition for frequencies between 2 GHz and 11GHz.

5. Finally a WirelessMAN SOFDMA (SOFDM Access): OFDMA PHY layer has been extended in IEEE 802.16e to SOFDMA (scalable OFDMA) where the size is variable and can take different values: 128, 512, 1024, and 2048.

In this chapter we will focus only on the WirelessMAN OFDMA PHY layer. As we saw in previous paragraph many combination of configuration parameters like band frequencies, channel bandwidth and duplexing techniques are possible. To insure interoperability between terminals and base stations the WiMAX Forum has defined a set of WiMAX system profiles. The latter are basically a set of fixed configuration parameters.

2.1.2 OFDM, OFDMA and subchannelization

The WiMAX PHY layer has also the responsibility of resource allocation and framing over the radio channel. In follows, we will define this physical resource. In fact, the mobile WiMAX physical layer is based on Orthogonal Frequency Multiple Access (OFDMA), which is a multi-users extension of Orthogonal Frequency-Division Multiplexing (OFDM) technique. The latter principles consist of a simultaneous transmission of a bit stream over orthogonal frequencies, also called OFDM sub-carriers. Precisely, the total bandwidth is divided into a number of orthogonal sub-carriers. As described in mobile WiMAX (Jeffrey G. et al., 2007), the OFDMA sharing capabilities are augmented in multi-users context thanks to the flexible ability of the standard to divide the frequency/time resources between users. The minimum time-frequency resource that can be allocated by a WiMAX system to a given link is called a slot. Precisely, the basic unit of allocation in the time-frequency grid is named a slot. Broadly speaking, a slot is an *n* x *m* rectangle, where *n* is a number of sub-carriers called sub-channel in the frequency domain and *m* is a number of contiguous symbols in the time domain.

WiMAX defines several sub-channelization schemes. The sub-channelization could be adjacent i.e. sub-carriers are grouped in the same frequency range in each sub-channel or distributed i.e. sub-carriers are pseudo-randomly distributed across the frequency spectrum. So we can find:

- Full usage sub-carriers (FUSC): Each slot is 48 sub-carriers by one OFDM symbol.

- Down-link Partial Usage of Sub-Carrier (PUSC): Each slot is 24 sub-carriers by two OFDM symbols.
- Up-link PUSC and TUSC Tile Usage of Sub-Carrier: Each slot is 16 sub-carriers by three OFDM symbols.
- Band Adaptive Modulation and Coding (BAMC) : As we see in figure 1 each slot is 8, 16, or 24 sub-carriers by 6, 3, or 2 OFDM symbols.
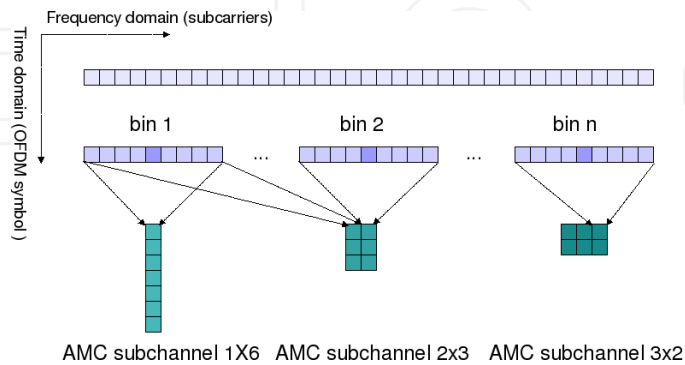

Fig. 1. BAMC slot format

In this chapter we will focus on the last permutation scheme i.e BAMC and we will explain how to compute the slot capacity.

2.1.3 The Adaptive Modulation and Coding scheme (AMC)

In order to adapt the transmission to the time varying channel conditions that depends on the radio link characteristics WiMAX presents the advantage of supporting the link adaptation called Adaptive Modulation and Coding scheme (AMC). It is an adaptive modification of the combination of modulation, channel coding types and coding rate also known as burst profile that takes place in the physical link depending on a new radio condition. The following table 1 shows examples of burst profiles in mobile WiMAX, among a total of 52 profiles defined in IEEE802.16e-2005 (IEEE Std 802.16e-2005, 2005): In fact when a subscriber station tries to

Profile	Modulation	Coding scheme	Rate
0	BPSK	(CC)	$\frac{1}{2}$
1	QPSK	$(RS + CC/CC)$	$\frac{1}{2}$
2	QPSK	$(RS + CC/CC)$	$\frac{3}{4}$
3	16 QAM	$(RS + CC/CC)$	$\frac{1}{2}$
6	64 QAM	$(RS + CC/CC)$	$\frac{3}{4}$

Table 1. Burst profile examples: (CC) Convolutional Code, (RS) Reed-Solomon

enter to the system, the WiMAX network undergoes various steps of signalization. First, the Down-link channel is scanned and synchronized. After the synchronization the SS obtains information about PHY and MAC parameters corresponding to the DL and UL transmission from control messages that follow the preamble of the DL frame. Based on this information negotiations are established between the SS and the BS about basic capabilities like maximum transmission power, FFT size, type of modulation, and sub-carrier permutation support.

In this negotiation the BS takes into account the time varying channel conditions by computing the signal to noise ratio (SNR) and then decides which burst profile must be used for the SS.

In fact, using the channel quality feedback indicator, the downlink SNR is provided by the mobile to the base station. For the uplink, the base station can estimate the channel quality, based on the received signal quality.

Based on these informations on signal quality, different modulation schemes will be employed in the same network in order to maximize throughput in a time-varying channel. Indeed,when the distance between the base station and the subscriber station increases the signal to the noise ratio decreases due to the path loss. Consequantely, modulation must be used depending on the station position starting from the lower efficiency modulation (for terminals near the BS) to the higher efficiency modulation (for terminals far away from the BS).

2.2 WiMAX MAC layer and QoS overview

The primary task of the WiMAX MAC layer is to provide an interface between the higher transport layers and the physical layer. The IEEE 802.16-2004 and IEEE 802.16e-2005 MAC design includes a convergence sublayer that can interface with a variety of higher-layer protocols, such as ATM,TDM Voice, Ethernet, IP, and any unknown future protocol.

Support for QoS is a fundamental part of the WiMAX MAC-layer design. QoS control is achieved by using a connection-oriented MAC architecture, where all downlink and uplink connections are controlled by the serving BS. Before any data transmission happens, the BS and the MS establish a unidirectional logical link, called a connection, between the two MAC-layer peers. Each connection is identified by a connection identifier (CID), which serves as a temporary address for data transmissions over the particular link. WiMAX also defines a concept of a service flow. A service flow is a unidirectional flow of packets with a particular set of QoS parameters and is identified by a service flow identifier (SFID). The QoS parameters could include traffic priority, maximum sustained traffic rate, maximum burst rate, minimum tolerable rate, scheduling type, ARQ type, maximum delay, tolerated jitter, service data unit type and size, bandwidth request mechanism to be used, transmission PDU formation rules, and so on. Service flows may be provisioned through a network management system or created dynamically through defined signaling mechanisms in the standard. The base station is responsible for issuing the SFID and mapping it to unique CIDs. In the following, we will present the service classes of mobile WiMAX characterized by these SFIDs.

2.2.1 WiMAX service classes

Mobile WiMAX is emerging as one of the most promising 4G technology. It has been developed keeping in view the stringent QoS requirements of multimedia applications. Indeed, the IEEE 802.16e 2005 standard defines five QoS scheduling services that should be treated appropriately by the base station MAC scheduler for data transport over a connection:

1. Unsolicited Grant Service (UGS) is dedicated to real-time services that generate CBR or CBR-like flows. A typical application would be Voice over IP, without silence suppression.

2. Real-Time Polling Service (rtPS) is designed to support real-time services that generate delay sensitive VBR flows, such as MPEG video or VoIP (with silence suppression).

3. Non-Real-Time Polling Service (nrtPS) is designed to support delay-tolerant data delivery with variable size packets, such as high bandwidth FTP.

4. Best Effort (BE) service is proposed to be used for all applications that do not require any QoS guarantees.

5. Extended Real-Time Polling Service (ErtPS) is expected to provide VoIP services with Voice Activation Detection (VAD).

Note that the standard defines 4 service classes for Fixed WiMAX: UGS, rtPS, nrtPS and BE.

In order to guarantee the QoS for these different service classes Call Admission Control (CAC) and resource reservation strategies are needed by the IEE 802.16e system.

2.2.2 QoS mechanisms in WiMAX

To satisfy the constraints of service classes, several QoS mechanisms should be used. Figure 2 shows the steps to be followed by the BS and SSs or MSSs to ensure a robust QoS management. To manage the QoS, we distinguish between the management in the UL and DL. For UL, at the
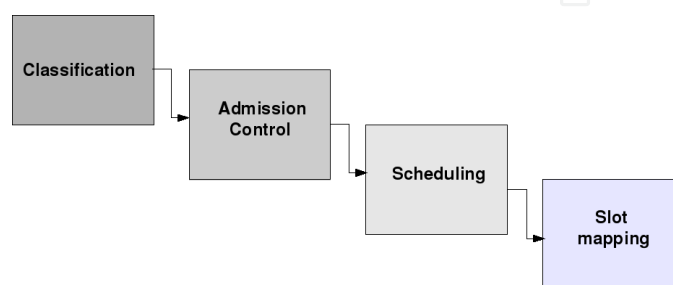

Fig. 2. QoS mechanisms

SS, the first step is the traffic classification that classifies the flow into several classes, followed by the bandwidth request step, which depends on service flow characteristics. Then the base station scheduler can place the packets in BS files, depending on the constraints of their services, which are indicated in the CID (Connexion IDentifier). The bandwidth allocation is based on requests that are sent by the SSs. The BS generates UL MAP messages to indicate whether it accepts or not to allocate the bandwidth required by the SSs. Then, the SS or MSS processes the UL MAP messages and sends the data according to these messages.

For the downlink, the base station gets the traffic, classifies it following the CID and generates the DL MAP messages in which it outlines the DCD messages that determine the burst profiles.

The following section will describe each step. It should be noted that the standard does not define in detail each mechanism. But it is necessary to understand some methods that are used to satisfy the QoS for each mechanism.

1. **The classification** The classifier matches the MSDU to a particular connection characterized by an CID in order to transmit it. This is called CID mapping that corresponds to the mapping of fields in the MSDU (for example mapping the couple composed of the destination IP address and the TOS field) in the CID and the SFID.

   The mapping process associates an MSDU to a connection and creates an association between this connection and service flow characteristics. It is used to facilitate the transmission of MSDU within the QoS constraints.

   Thus, the packets processed by the classifier are classed into the diffrent WiMAX service classes and have the correspondant CID. The standard didn't define precisely the classification mechanism and many works in the literature have been developed in order to define the mapping in QoS cross layer framework. Once classified the connection requests are admitted or rejected following the call admission control mechanism decision.

2. **Call admission control (CAC) and Bandwidth Allocation** As in cellular networks, the IEEE 802.16 Base Station MAC layer is in charge to regulate and control bandwidth allocation. Therefore, incorporating a Call Admission Control (CAC) agent becomes the primary method to allocate network resources in such a way that the QoS user constraints could be satisfied. Before any connection establishment, each SS informs the BS about its QoS requirements. And the BS CAC agent have the responsability to determine whether a connection request can be accepted or should be rejected. The rejection of request happens if its QoS requirements cannot be satisfied or if its acceptance may violate the QoS guarantee of ongoing calls.

To well manage the operation of this step, the WiMAX standard provides tools and mechanisms for bandwidth allocation and request that is described briefly as follows:

(a) **Bandwidth request** At the entrance to the network, each SS or MSS is allocated up to 3 dedicated CID identifiers. These CIDs are used to send and receive control messages. Among these messages one can distinguish Up-link Channel Descriptor, Downlink Channel Descriptor, UL-MAP and DL-MAP messages, plus messages concerning the bandwidth request. The latter can be sent by the SS following one of these modes:

- Implicit Requests: This mode corresponds to UGS traffic which requires a fixed bit rate and does not require any negotiation.
- Bandwidth request message: This message type uses headers named *BW request*. It reaches a length of 32 KB per request by CID.
- Piggybacked request: is integrated into useful messages and is used for all service classes, except for UGS.
- Request by the bit *Poll-Me*: is used by the SS to request bandwidth for non-UGS services.

(b) **Bandwidth Allocation modes**

There are two modes of bandwidth allocation:

- **The Grant Per Subscriber Station (GPSS):** In this mode, the BS guarantes the aggregated bandwidth per SS. Then the SS allocates the required bandwidth for each connection that it carries. This allocation must be performed by a scheduling algorithm. This method has the advantage of having multiple users by SS and therefore requires less overhead. However, it is more complex to implement because it requires sophisticated SSs that support a hierarchical distributed scheduler.
- **The Grant Per Connection (GPC):** In this type of allocation the BS guarantes the bandwidth per connection, which is identified thanks to the individual CID (Connection IDentifier). This method has the advantage of being simpler to design than the GPSS mode but is adapted for a small number of users per SS and provides more overhead than the first mode.

Thus, based on SS and MSS requests the base station can satisfy the other QoS application constraints by employing different allocation bandwidth strategies and call admission control policies. Recall that the latters have not been defined in the standard.

3. **Scheduling** In WiMAX, the scheduling mechanism consists of determinating the information element (IE) sent in the UL MAP message that indicates the amount of the allocated bandwidth, the allocated slots etc... A simplified diagram of the scheduler in the standard IEEE 802.16 is illustrated in the following figure:

The scheduler in the WiMAX has been defined only for UGS traffic. Precisely for this class, the BS determines the IEs UL MAP message by allocating a fixed number of time slots in
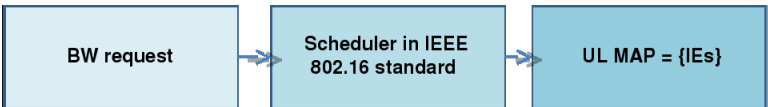
Fig. 3. Scheduler in IEEE 802.16 standard

each frame interval. The BS must take into account the state of queues associated to traffic and all queues among the SS, corresponding to UL traffic. For the remaining traffic classes the standard does not specify a particular scheduling algorithm, and left the choice to the operator to implement one of the algorithm that was described in the literature (Jianfeng C. et al., 2005) (Wongthavarawat K. et al, 2003).

4. **The mapping**

This is the final step before sending user data in the radio channel. The idea is to assign sub-carriers in the most efficient possible way to scheduled MPDUs in order to satisfy QoS constraints of each connection. The mapping mechanism is left to the choice of the provider.

3. State of the art

3.1 Bandwidth sharing strategies: background

To maintain a quality of service required by the constraining and restricting services, there are different strategies of bandwidth allocation and admission control. Many bandwidth allocation policies have been developed in order to give for different classes a certain amount of resource. Among the classical strategies, one can citeComplete Sharing (CS), Upper Limit (UL), Complete Partitioning (CP), Guaranteed Minimum (GM) and Trunk Reservation (TR) policies. These policies are illustrated in figure 4 and will be introduced in the following sections. To this end, and in a seek of simplicity of the presentation, we will suppose in these sections that system defines only two service classes 1 and 2 (instead of the 5 classes defined in Mobile WiMAX). Moreover, we will also suppose that if a system accepts a call of class $i \in \{1,2\}$ it will allocate to this call a fixed amount of bandwidth denoted by d_i. Finally, let n_i denotes the number of class $i \in \{1,2\}$ calls in the system.
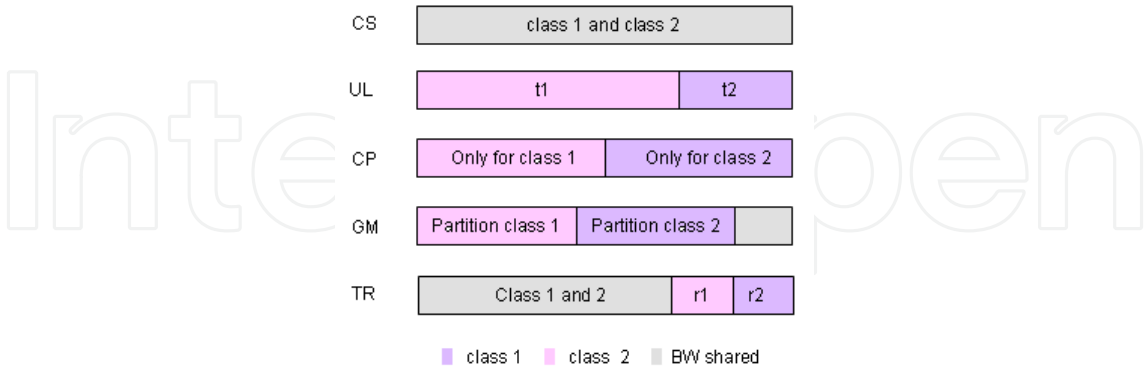

Fig. 4. Heuristic CAC policies

3.1.1 Complete Sharing (CS)

In this strategy, the bandwidth is fully shared among the different service classes. That is all classes are in competition. In other words, if we consider an offered capacity system equal to C and 2 types of service class (class 1 and 2). If class 1 (i.e. aggreagted calls) uses I units then

the remained bandwidth $C - I$ could be allocated either to class 1 or to class 2. Formally, a call of class $i \in \{1, 2\}$ is accepted if and only if:

$$d_i + \sum_{k=1}^{2} n_k d_k \leq C \tag{1}$$

3.1.2 Upper Limit (UL)

This policy is very similar to CS except that it aims to eliminate the case where one class can dominate the use of the resource, through the use of thresholds-based bandwidth occupation strategy. Precisely, thresholds t_1 and t_2 are associated to class1 and class 2, respectively. These thresholds represent the maximum numbers of bandwdith units that each class can occupy at a given time. So, a call of class $i \in \{1, 2\}$ is accepted if and only if:

$$(1 + n_i)d_i \leq t_i \; and \; \sum_{k=1}^{2} n_k d_k \leq C \tag{2}$$

Note that this relation is not excluded :

$$\sum_{k=1}^{2} t_k > C$$

3.1.3 Complete Partitioning (CP)

This policy allocates a set of resources for every service class. These resources can only be used by that class. To this end the bandwidth is divided into partitions. Each partition is reserved to an associated service class. In this figure the capacity is divided into 2 partitions denoted by C_1 for class 1 and C_2 for class 2. Then, a call of class $i \in \{1, 2\}$ is accepted if and only if:

$$(1 + n_i)d_i \leq C_i \tag{3}$$

Note that contrarily to the UL strategy the following relation must always be verified:

$$\sum_{k=1}^{2} C_k = C$$

3.1.4 Guaranteed Minimum (GM)

As illustrated in figure 4 the resource is divided into different partition. The policy gives each classes their associated partition of bandwidth, which we note M_1 for class 1 and M_2 for class 2. If this partition is fully occupied, each class can then use the remaining resource partition that is shared by all other classes. This is clearly an hybrid strategy between CP and CS. Formally, the CAC rule to follow in order to accept a call of class $i \in \{1, 2\}$ is:

$$\sum_{k=1}^{2} max(d_k(n_k + 1_i(k)), M_k) \leq C, \; where \; 1_i(k) = 1 \; if \; k = i, 0 \; otherwise \tag{4}$$

Note that the following relation must always be verified:

$$\sum_{k=1}^{2} M_k \leq C.$$

3.1.5 Trunk Reservation (TR)

As illustrated in figure 4, there are not dedicated partitions per classes in this policy. In fact, class $i \in \{1, 2\}$ may use resources in a system as long as the amount of remaining resources is equal to a certain threshold $r_i \in \{1, 2\}$ bandwidth units. Thus each service class will protected thank to thresholds, which will avoid that any class occupies the totality of resource units. So a call of class $i \in \{1, 2\}$ is accepted if and only if:

$$d_i + \sum_{k=1}^{2} n_k d_k \leq C - r_i \qquad (5)$$

This rule guarantees that after applying this CAC policy and accepting the class i the remaining bandwidth is equal to r_i. Several comparison have been made between these policies and with optimal solution. One important challenge is to explain the method that thresholds imposed by GM, UL and CP strategies are computed or determined which is explained in (Khemiri S. et al., 2007).

So the main challenge is to setup these policy in an optimized way. This is could be done by choosing the optimal partition sizes or reservation thresholds in order to 1) guarantee the QoS constraints of the application provided by the system and in the other words to satisfy subscribers and 2) to provide a good system performance which satisfies the provider.

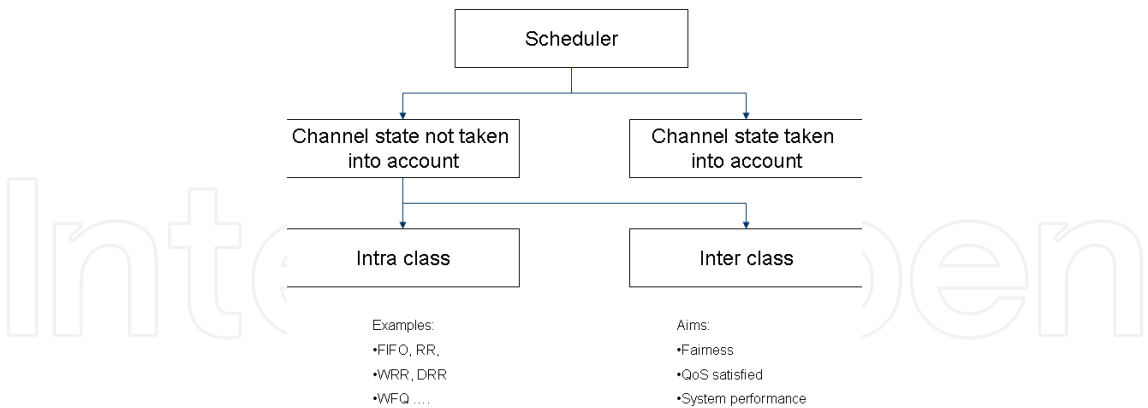### 3.2 Scheduling and mapping in the literature

Fig. 5. Scheduler classification

In literature few studies have focused on both the scheduling and the selection of MPDUs and choice of OFDMA slots to be allocated (called mapping) to send the data in the frame.

Regarding scheduling, we can distinguish, as shown in Figure 5, two types of schedulers: a) the non-opportunistic schedulers are those who do not take into account the state of the channel we cite the best known, the RRs that ensure fairness and WRRs based on fixed weights and b) the opportunistic schedulers are those that take into account the channel state (Ball et al., 2005)(Rath H.K. et al., 2006)(Mukul, R et al.)(Qingwen Liu and Xin Wang and Giannakis,

G.B. et al.)(Mohammud Z. et al., 2010) an example is the MAXSNR which first selects the MSSs that have the maximum SIR. In (Ball et al., 2005), the authors present an algorithm called TRS that removes from queues MSSs with the SNR that is below a certain threshold. Further works (Rath H.K. et al., 2006) (Laias E. et al., 2008) improve conventional schedulers like DRR to make opportunistic one and this by introducing the SNRs threshold as a criterion for selecting MSSs to serve. Others are based on the prediction of the packets arrival like in (Mukul, R et al.).

Regarding the mapping, in (Einhaus, M. et al 2006), the authors propose an algorithm that uses a combined dynamic selection of sub-channels and their modulation with a power transmission allocation in an OFDMA packets but this proposal does not take into account the constraints of QoS packets. (Einhaus, M. et al) made a performance comparison between multiple resource allocation strategies based on fairness of transmission capacity in a multi-user scenario of a mobile WiMAX network that supports an OFDMA access technology. These compared policies are the MAXSNR, the maximum waiting time and the Round Robin strategies. The performance metrics analyzed are the delay and the rate. The evaluation was conducted using a WiMAX simulator based on OFDMA mechanism developed in NS2 simulator. The results presented indicate the significant impact of these policies on the tradeoff between rate and delay. Indeed, this work shows that a strategy based on taking into account to the radio channel conditions gives a better performance in term of capacity utilization than that of the delay. Thus the slot allocation strategies aiming to minimize the delay has resulted in reducing the efficiency of resource use. However, this work does not address the specifics in terms of QoS traffic and didn't provide any service differentiation between classes UGS, rtPS, and nrtPS Ertps. This work was improved in (Khemiri S. et al., 2010) by applying this strategy to a mobile WiMAX network: authors compared it to MAXSNR well known as a conventional mapping techniques. The results showed an improvement of a channel utilization.

In (Akaiwa, Y. et al 1993) and (katzela I. et al, 1996) Channel segregation performance has been examined by applying it to FDMA systems. This paper discusses its application to the multi-carrier TDMA system. Spectrum efficiency of the TDMA/FDMA cellular system deteriorates due to the problem of inaccessible channel: a call can be blocked in a cell even when there are idle channels because of the restriction on simultaneous use of different carrier frequencies in the cell. This solution shows that channel segregation can resolve this problem with a small modification of its algorithm. The performance of the system with channel segregation on the call blocking probability versus traffic density is analyzed with computer simulation experiments. The effect of losing the TDMA frame synchronization between cells on the performance is also discussed.

In (Wong et al., 2004) Orthogonal Frequency Division Multiple Access (OFDMA) base stations allow multiple users to transmit simultaneously on different subcarriers during the same symbol period. This paper considers base station allocation of subcarriers and power to each user to maximize the sum of user data rates, subject to constraints on total power, bit error rate, and proportionality among user data rates.

These works did not consider the double problem of MPDUs selection for transmission and the channel assignment technique.

4. Slot capacity

As we seen before, the PHY layer provides different parameter settings which leads to interoperability problems. This is why *WiMAX forum* creates the WiMAX profiles which

describes a set of parameters of an operational WiMAX system. These sets of parameters concerns: The System Bandwidth, the system frequency and the duplexing scheme. This section gives a computational method of slot capacity based on two WiMAX system profiles: 1) The Fixed WiMAX system profile and 2) The mobile WiMAX system profile.

This slot capacity, computed in term of bits, depends on permutation type and parameters which depends on the radio mobile environment like burst profile and defined by the SINR (Chahed T. et al, 2009) (Chahed T. et al, 2009). To compute this capacity its is needed to know system parameters, so we distinguish:

1. The OFDM slot capacity compute in case of Fixed WiMAX profile system.

2. The OFDMA slot capacity compute in case of Mobile WiMAX profile system.

The following table describes the parameters of each system profile:

Parameters	definition	Fixed	Mobile
B	System Bandwidth	3.5 MHz	10 MHZ
L_{FFT}	Subcarrier number or FFT size	256	1024
L_d	Data subcarrier number	192	720
G	Guard time	12.5%	12.5%
n_f	Oversampling rate	8/7	28/25
$(DL:UL)$	Duplexing rate	3 : 1	3 : 1
(c,M)	Modulation and coding scheme $c = coding\ rate$ $M = Constellation\ of\ the\ modulation$	depending on channel	depending on channel
TTG and RTG	transition Gap between UL and DL	$188\mu s$	$134.29\mu s$
T	Frame length ms	5 ms	5 ms
N	Number of user	N	N
Perm	Permutation mode	-	BAMC 1X6

Table 2. Mobile and fixed WiMAX system parameters

4.1 Fixed WiMAX case

Lets consider an SS n and one subcarrier f, we can determine the corresponding $SINR_{n,f}$ and then the modulation and coding scheme $(c_{n,f}, M_{n,f})$. One subcarrier can transmit the following number of bits (Wong et al., 2004) (Chung S. et al, 2000):

$$b_{n,f} = c_{n,f} log_2 \left(M_{n,f} \right) \qquad (6)$$

An OFDM slot, denoted by s, is composed by L_d data subcarriers. The channel state of a user n described by $SINR_{n,s}$ can be deduced by computing the mean SINR of all data subcarriers. Once this SINR is determined we can deduce the MCS (c_n, M_n) and we can compute the SINR as follows:

$$SINR_{n,s} = \frac{1}{L_d} \sum_{f=1}^{L_d} SINR_{n,f} \qquad (7)$$

So the number of bits that can transmit the minimum time-frequency resource or a the OFDM slot is defined as follows:

$$b_n = c_n \log_2 (M_n) L_d \tag{8}$$

Where $\frac{(1+G)L_{FFT}}{n_f B}$ corresponds to time duration of the OFDM symbol of L_{FFT} length, so the rate in bps provided by an OFDM frame for a modulation and coding scheme (c, M) is given by:

$$C = c \log_2 (M) L_d \frac{n_f B}{(L_{FFT}(1+G))} \tag{9}$$

In addition, the total number of OFDM symbols per frame is computed as follows:

$$nb_s = T \frac{n_f B}{(1+G)L_{FFT}} \tag{10}$$

We deduce the number of symbols dedicated to the UL noted nb_{UL} and the DL noted nb_{DL} using the ratio $(DL : UL)$:

$$nb_{DL} = \frac{D}{D+U} nb_s \tag{11}$$

$$nb_{UL} = \frac{U}{D+U} nb_s \tag{12}$$

The DL throughput is given by the following formula:

$$C_{DL} = \frac{C T_{useful} \frac{1}{T}}{nb_s} nb_{DL} \tag{13}$$

where $T_{useful} = T - (TTG + RTG)$ is the usable size of the frame by removing periods reserved for the UL and DL transmission gap and $\frac{1}{T}$ is the number of frames sent per second. The total number of OFDM slots in a mobile WiMAX frame corresponds to $S \times T$ where $S = L_d$ is the number of data subcarriers and $T_s = nb_s$ is the number of OFDM symbol in the frame, we obtain a frame with the format $((S = 192) \times (T_s = 69))$ OFDM slots.

4.2 Mobile WiMAX case

In mobile WiMAX, the slot format depends on the permutation scheme supported by the system. In the rest of this chapter, we chose to take an interest in the permutation BAMC 1×6. This choice is not limiting, but for reasons of clarity and simplification of the presentation.

Considering the permutation BAMC 1×6, the format of the OFDMA slot is 8 data subcarriers of 6 OFDM symbols. The total number of OFDMA slots in a mobile WiMAX frame corresponds to $S \times T_s$ where $S = \frac{L_d}{8}$ and T_s is the number of OFDM symbol in the frame which is equal to $T_s = \frac{nb_s}{6}$. So we get a frame whose size is $((S = 90) \times (T_s = 6))$ OFDMA slots.

To determine the capacity of this slot $s \in [1, S]$, it suffices to determine the burst profile $(c_{n,s}, M_{n,s})$ of OFDMA slot s for user n. To do this, simply determine the $SINR_{n,s}$ corresponding to:

$$SINR_{n,s} = \frac{1}{48} \sum_{f=1}^{8} \sum_{t \in 1}^{6} SINR_{n,f}(t) \tag{14}$$

Thus the number of bits provided by the OFDMA slot s is given by the following equation:

$$b_{n,s} = 6 * 8c_{n,s} \log_2 (M_{n,s}) \tag{15}$$

Finally, using the parameter presented in table 2 and the equations above we obtain the following table. It should be noted that the flow rates presented are calculated for the modulation and coding scheme $(64 - QAM, \frac{3}{4})$

Parameters	definition	Fixed	Mobile
(SxT_s)	Frame size (Total slot number)	(192×69)	(90×6)
C_{DL}	DL frame rate (Mbps)	8.51117	23.0905
C_{UL}	UL frame rate (Mbps)	2.83706	7.69682
C	Total frame rate (Mbps)	11.348	30.787
$b_{n,s}$	**Number of bit per slot (bits)**	869	219

Table 3. Mobile and Fixed WiMAX slot capacity

In the rest of this chapter we focus on the slot allocation problem combined with scheduling mechanism in mobile WiMAX OFDMA system which consists of how to assign PHY resource to a user in order to satisfy a QoS request in MAC layer.

5. Case study: System description and problem statement

5.1 System description

In this case study let's consider a WiMAX cell based on IEEE 802.16e 2005 technology supporting Wireless MAN OFDMA physical layer. The system offers a quadruple-play service to multiple mobile subscribers (MSS). These subscriber stations can have access anytime and anywhere to various application types like file downloading, video streaming, emails and VoIP. In this model let's suppose a typical downlink WiMAX OFDMA system and we consider that the system parameters corresponds to those of a mobile WiMAX profile, which is characterized by the second column of the table 3.

Recall that the minimum time-frequency resource that can be allocated by a WiMAX system to a given link is called a slot. Each slot consists of one sub-channel over one, two, or three OFDM symbols, depending on the particular sub-channelization scheme used. So a slot is an n x m rectangle, where n is a number of sub-channel in the frequency domain and m is a number of symbols in the time domain. The standard supports multiple *subchannelization* schemes (PUSC, BAMC, FUSC, TUSC, etc.), which define how an OFDMA slot is mapped over subcarriers. As we see in figure 6, the system frame is a matrix whose size is $((S = 90) * (T_s = 6))$ OFDMA slots, where S is the number of subchannels and T_s is the number of OFDMA symbols. So we can allocate up to $90 * 6 = 540$ OFDMA slots to a user n. Only the DL case will be studied. In order to model this system the physical and MAC layer characteristics will be presented in following.

5.1.1 QoS constraints

In order to guarantee the quality of service required by these applications, the service provider has to distinguish five service classes. Namely: UGS for VoIP, rtPS for video streaming, nrtPS for file downloading and ErtPS for voice without silence suppression. As BE for emails is not
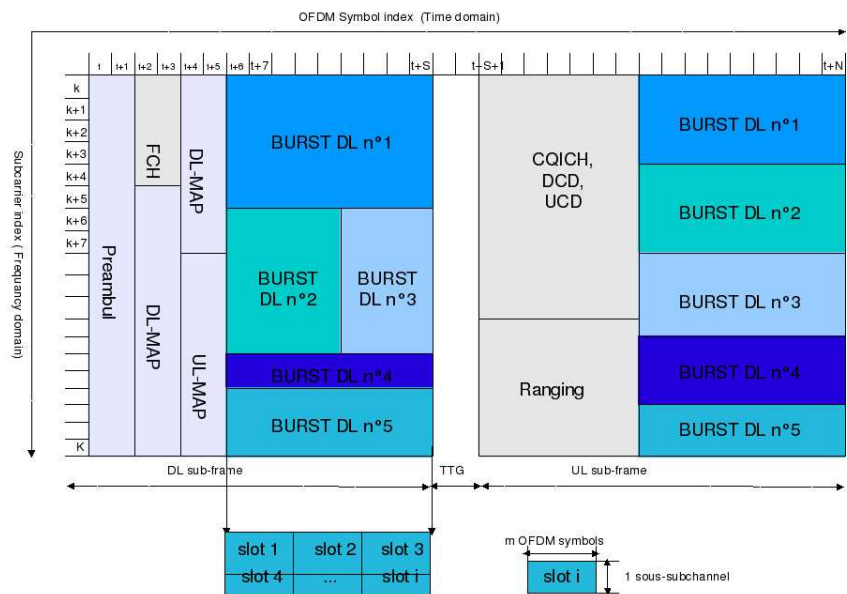
Fig. 6. OFDMA frame

constringent in term of QoS it will not be considered here. For notation simplicity, we will refer to UGS, rtPS, nrtPS and ErtPS as a class 1, 2, 3 and 4, respectively. Let $U = \{1, 2, 3, 4\}$. To satisfy application QoS constraints provided by the system, we assume that there is a classifier implemented in the BS that associates each traffic users to a class $i \in U$ and we also suppose that there is a call admission control mechanism that ensures that the newly admitted calls do not degrade the QoS of the ongoing calls, and there is enough available system resources for the accepted call and if not the call is rejected. We suppose that to satisfy the QoS of each user n supporting a traffic class i, it suffices to have:

$$C_n \in [\underline{s}_i, \overline{s}_i], \ \forall i \in U \tag{16}$$

Where $\underline{s}_i$ and $\overline{s}_i$, are respectively the minimum and maximum class i data rate. Since we consider a mobile radio environment this system capacity vary with channel condition. This is why a scheduling mechanism must be used in order to select which MPDUs must be transmitted in addition to a physical resource assignment strategy in order to select the best slot (physical resource) that satisfies the QoS constraints of the selected MPDUs.

5.1.2 Cell division for AMC

In order to adapt the transmission to the time varying channel conditions that depend on the radio link characteristics WiMAX presents the advantage of supporting the link adaptation called adaptive modulation coding (AMC). AMC consist of an adaptive modification of the combination of modulation, channel coding types and coding rate also known as burst profile, that takes place in the physical link depending on a new radio condition.

The following table 4 shows examples of burst profiles in mobile WiMAX there are 52 in IEEE802.16e-2005 (Jeffrey G. et al., 2007)(IEEE Std 802.16e-2005, 2005):

Profile	Modulation L	Coding scheme	Rate
3	16 QAM	$(RS + CC/CC)$	$\frac{1}{2}$
5	64 QAM	$(RS + CC/CC)$	$\frac{1}{2}$
6	64 QAM	$(RS + CC/CC)$	$\frac{3}{4}$

Table 4. Burst profiles: (RS) Reed Solomon, (CC) Convolutional Code

We will demonstrate in this section that we can divide the WiMAX cell into several areas where each of them corresponds to one modulation scheme.

Lets consider our system as a WiMAX base station with a total bandwidth B operating at a frequency f. The BS and SS antenna height in meters is respectively given by h_{BS} and h_{SS}. The SS has a transmission power P_{SS}. If we model our system in presence of path loss defined by the COST-231 Hata radio propagation model (Jeffrey G. et al., 2007) (Roshni S. et al., 2007), we can deduce a variation of the SNR while varying the distance d between SSs and BS (Chadi T. et al., 2007) (Chadi T. et al., 2007)(Chadi T. et al., 2007). This model is chosen because it is recommended by the WiMAX Forum for mobility applications in urban areas which is the case of our system.

In order to know the variation of the SNR with distance, the path loss for the urban system environment is needed. According to the COST-231 Hata model, the pathloss is given by:

$$P_{loss}[dB] = 46.3 + 33.9log_{10}(f) - 13.82log_{10}(h_{BS}) +$$
$$(44.9 - 6.55log_{10}(h_{BS}))log_{10}(d) - F_a(h_{SS}) + C_F \tag{17}$$

Where P_{loss} is the path loss, and $F_a(h_{SS})$ is the station antenna correction factor, C_F is a correction factor.

$$F_a(h_{SS}) = (1.11log_{10}(f) - 0.7)h_{SS} - (1.56log_{10}(f) - 0.8) \tag{18}$$

For illustration lets consider an example of a WiMAX system with total bandwidth $B = 20MHz$, operating at a frequency $f = 2Ghz$, with an SS transmission power $P_{SS} = 10Watt = 10dBm$, $h_{BS} = 30m$, $h_{SS} = 1m$. $d = 0$ to 20 Km, $C_F = 3dB$. The path loss is defined as:

$$P_{loss}[dB] = 41.17 + 35.26log_{10}(d) \tag{19}$$

By considering the following link budget :

$$SNR = P_{SS} - [P_{loss} + N] \tag{20}$$

Where N is the thermal noise equal to : $N[dBm] = 10log(\tau TB)$ here $\tau = 1.38 \cdot 10^{-23}W/KHz$ is the Boltzmann constant and T is the temperature in Kelvin ($T = 290$) as defined in (Chadi T. et al., 2007) $N[dBm] = -100.97dBm$. we can deduce the SNR as follows:

$$SNR = P_{SS} + 59.8 - 35.26log_{10}(d) \tag{21}$$

Using Matlab tool the variation of the SNR while varying the distance between SSs and BS from 0 to 20 Km is given by the figure 7 This figure shows that we can distinguish areas corresponding to the modulation region. We assume that our system supports only
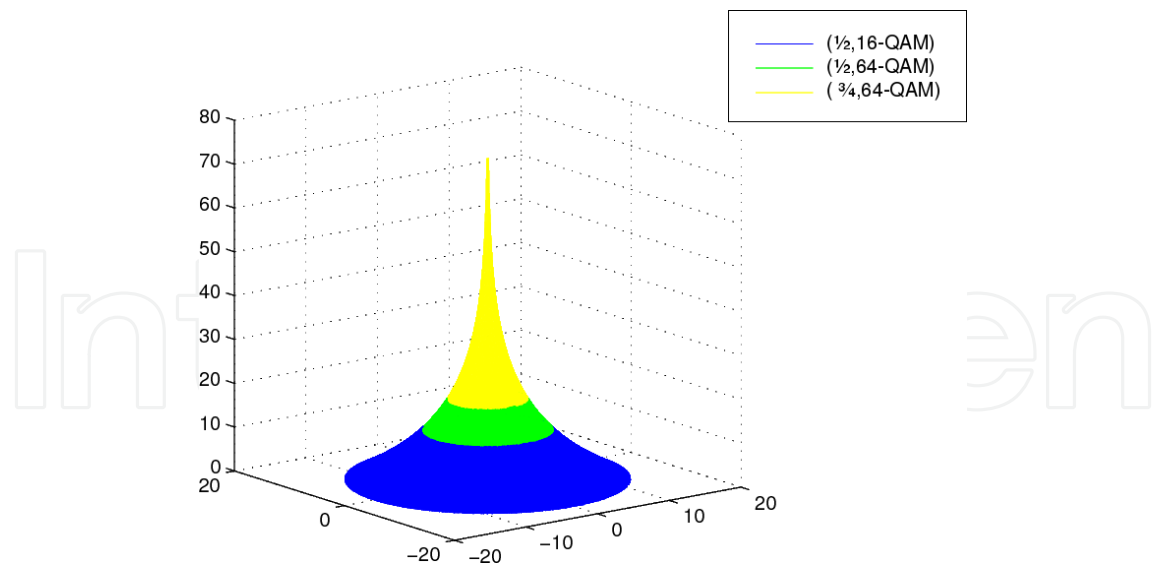
Fig. 7. SNR variation versus distance BS-SS

3 modulation schemes, so following SNR thresholds described in table 4 we obtain three modulation regions.

We assume that the cell's bandwidth is totally partitioned, so that each partition is adapted to a specific modulation scheme. According to the adaptive modulation and coding scheme, we can divide this cell into 3 uniform areas in which we suppose that only one modulation scheme is used. As figure 8 shows we choose 3 modulation and coding schemes as following:

1. $(\frac{1}{2}, 16QAM)$ corresponds to the SNR interval $I_1 = [0, 11.2[$ dB.

2. $(\frac{1}{2}, 64QAM)$ corresponds to the SNR interval $I_2 = [11.2, 22.7]$ dB.

3. $(\frac{3}{4}, 64QAM)$ corresponds to the SNR interval $I_3 =]22.7, +\infty[$ dB.

Note that the $(\frac{3}{4}, 64QAM)$ modulation (burst profile number 6) is used in the nearest area of the BS, then $(\frac{1}{2}, 64QAM)$ modulation (burst profile number 5) in the second area, finally $(\frac{1}{2}, 16QAM)$ (burst profile number 3) is employed in the third area.
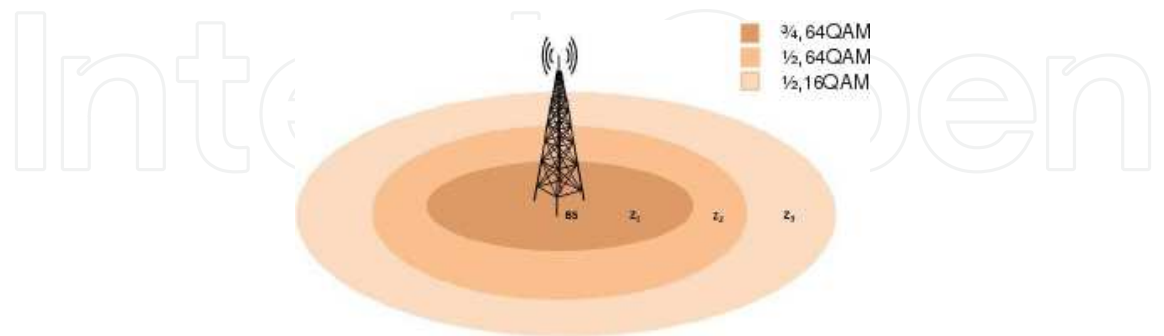

Fig. 8. The system partition areas

Thus at the BS transmitter, the station must select for each user $n \in [1, N]$ the MCS for each selected slot $s \in [1, S]$ using the signal to noise level $SNR_{n,s}$.

In figure 8, we designed three zones illustrated by three concentric perfect circles corresponding to the three types of modulation. It is just an example, because this obviously

does not square with reality since the channel undergoes disturbances other than the path Loss that vary the channel between two stations even they are at the same distance from the BS.

5.1.3 Mobility

In order to be close to a realistic WiMAX network, we take into account some assumptions. We assume that N users are MSSs whose trajectory is a perfect concentric circle with radius $n \in [1, N]$ km. The velocity of the MSS n corresponds to $V_n = n * V$ where n is the user index and V is a velocity expressed by m/s. Each signal will be transmitted through a slowly time-varying, frequency-selective Rayleigh channel with a bandwidth B. Each OFDMA slot s allocated to a user n will be sent with a power denoted by $p_{n,s}$. We will discuss here the choice of this power.

In this case study, let's consider that we allocate a fixed power $p_{k,s} = \frac{P}{5}$ for each subcarrier since we didn't focus on a power allocation problem. We assume that each user experiences an independent fading and the channel gain of user k in subcarrier s is denoted as $g_{k,s}$ We can easily deduce that the nth user's received signal-to-noise ratio (SNR) for the slot s which corresponds to the average signal to noise ratios of all sub-carriers that form this slot, is written as follows:

$$SNR_{n,s} = p_{n,s} \frac{g_{n,s}^2}{\sigma^2} \tag{22}$$

Where, $\sigma^2 = N_0 \frac{B}{L_{FFT}}$ and N_0 is power spectrum density of the Additive white Gaussian noise (AWGN). The slowly time-varying assumption is crucial since it is also assumed that each user is able to estimate the channel perfectly and these estimates are made known to the transmitter via a dedicated feedback channel. Specifically, the SNR will be sent periodically (once per frame) in control messages. Then they are used as input to the resource allocation algorithms. We suppose that the channel condition didn't change during the frame duration, i.e 5 ms.

5.2 Parameters and problem statement

As we consider a mobile WiMAX system supporting Adaptive Modulation and Coding we can deduce from (Wong et al., 2004) and (Chung S. et al, 2000) the OFDMA slot capacity denoted by $b_{n,s}$ corresponding to the number of bits that a given subcarrier s can transmit if we know channel condition for a given user n, so we have:

$$b_{n,s} = 48c_{n,s} \log_2 (M_{n,s}) \tag{23}$$

Where $(c_{n,s}, M_{n,s})$ is the modulation and coding scheme of a slot s allocated to the MSS n defined as follows: $(c_{n,s}, M_{n,s}) = (\frac{1}{2}, 16QAM)$ if $SNR_{n,s} \in I_1$, $(c_{n,s}, M_{n,s}) = (\frac{1}{2}, 64QAM)$ if $SNR_{n,s} \in I_2$ and $(c_{n,s}, M_{n,s}) = (\frac{3}{4}, 64QAM)$ if $SNR_{n,s} \in I_3$. As we see in 6 the OFDMA frame is a matrix with dimension $S \times T_S$. Let's have an allocation matrix of a nth user denoted by A_n, this matrix is expressed as following:

$$A_n = \left[a_{s,t}^n \right]_{(s,t) \in \{1,S\} \times \{1,T_s\}} \tag{24}$$

Where, $a_{s,t}^n = \mathbb{1}_{\{\mathbb{1}_{(s,t)} = n\}}$, ie, $a_{s,t}^n = 1$ if and only if $\mathbb{1}_{(s,t)}(i,j) = n$, 0 otherwise. By using equations 23 and 24, we can deduce the total capacity B_n which corresponds to the total bit

number provided to the user n after a slot allocation following the allocation matrix A_n:

$$B_n = \sum_{s=1}^{S} \sum_{t=1}^{T_s} a_{s,t}^n b_{n,s} \tag{25}$$

The total system capacity if the call admission controll mechanism accept N MSSs is:

$$C = \sum_{n=1}^{N} C_n = \frac{n_f B}{(1+G)L_{FFT}} \sum_{n=1}^{N} \sum_{s=1}^{S} \sum_{t=1}^{T_s} a_{s,t}^n c_{n,s} \log_2 (M_{n,s}) \tag{26}$$

It is clear that the choice of the matrix allocation is crucial for the optimal use of resources. The aim of this case study is to present an efficient cross-layer resource assignment strategy that takes into account two aspects: 1)the varying channel condition and 2) the QoS constraints of user's MPDUs scheduled to be transmitted into the physical frame.

Problems related to resource allocation and power assignment aim to solve the following mutli-constraints optimization problem (Wong et al., 2004) (Cheong et al., 1999):

Problem 1 Slot allocation problem

maximize: $\max\limits_{p_{n,s},a_{t,s}} C$

subject to:

$C1: \quad \sum\limits_{n=1}^{N} \sum\limits_{s=1}^{S} \sum\limits_{t=1}^{T_s} a_{t,s} p_{n,s} \leq P_{total}$

$C2: \quad C_n \in [\underline{s_i}, \overline{s_i}], \quad \forall i \in U$

$C3: \quad p_{n,s} \geq 0, \quad \forall (n,s) \in [1,N]X[1,S]$

$C4: \quad a_{t,s} \in {0,1}, \quad \forall (s,t) \in [1,S]X[1,T_s]$

Where C1 corresponds to the power constraint, C2 corresponds to the QoS constraint discribed in 16 , C3 and C4 ensure the correct values for the power and the subcarrier allocation matrix element, respectively.

This problem is NP-hard problem (Mathias et al, 2007) and was often treated by taking into account only the physical layer without respecting constraints related to quality of service. Generally, this problem is split into two subproblems: subproblem (1) consists on power assignment problem, where only the power will be considered as the variable of the problem, and subproblem (2) consists on maximizing the instantaneous system capacity C once the power is allocated. In our case study, we will not consider power allocation issues and we will assume that all subcarriers have the same transmit power, i.e, $p_{n,s} = p \forall (n,s) \in [1,N]X[1,S]$. The SNR variation is only related to the channel variation. So our problem statement is the following, if we consider the OFDMA frame is like a puzzle game with slots as game pieces, where the game rule is that these slots must be allocated to each MSSs according to their demand. The difficulty of this game is that of the slot capacity is variable and depends on the channel state. In the next we answer the two questions: Which MPDUs to serve? and which slot to assign to satisfy the bandwidth request of the selected MPDUs? In the next section, we propose solutions to both questions.

6. Solutions

In order to answer to questions asked in the previous section, one solution is to combine scheduling mechanism with a slots mapping while taking into account three aspects: 1) The QoS constraints of each traffic class, 2) the specific features of the system like Permutation scheme and 3) OFDMA access technology and the radio channel variation which results in the choice of modulation and therefore the variation of the allocated slots capacity.

To treat this problem five steps, as described in figure 9, are needed: step 1 for call admission control, step 2 for scheduling, step 3 for user selection, step 4 for the selection of the traffic granularity and step 5 for slots selection.
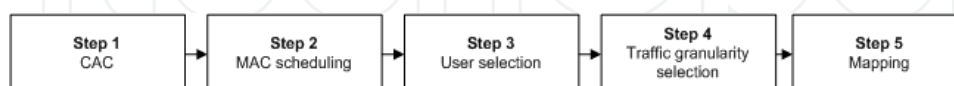
Fig. 9. The 5 steps solution

The main objective of these steps is to find a compromise between QoS constraints of service classes and the bandwidth utilization. We will describe in the following all these steps and we will present several proposals for step three, four and five.

6.1 Step 1: Call admission controll

One solution is to use a CAC block presented in (Khemiri S. et al., 2008) based on Complete Partitioning (CP) between service classes and we assume that all connections accepted in the system are the result of applying this CAC strategy. We also suppose that at the MAC layer all MPDUs of the traffic transported by the MSSs are fragmented so that a single frame can carry the largest MPDU in the traffic.

6.2 Step 2: Scheduling

Before presenting step 3, 4 and 5, it is important to choose the scheduler that guarantee the QoS constraints of applications provided to subscribers at the MAC layer. Several works have been proposed to efficiently schedule traffic in WiMAX (Jianfeng C. et al., 2005) (Wongthavarawat K. et al, 2003), one solution is to use a hybrid two-stage scheduler presented in figure 10.

Here the idea is to use two Round Robin (RR) schedulers in a first stair to provide fair distribution of bandwidth especially between ErTPS, UGS and rtPS classes since they are real time traffic. In the second stair we propose to use a Priority queuing scheduler in order to give a high priority for VoIP applications and real time traffic and a lower priority for video streaming and web browsing applications.

As we see in figure 10, we use two types of scheduler:

- **Priority Queuing (PQ)**: In this scheduler, each queue has a priority. A queue can be served only if all higher priority queues are empty.
- **Weighted Round Robin (WRR)**: In this discipline, each queue has a weight which defines the maximum number of packets that can be served during each scheduler round.

This hybrid scheduler handles differently real time and non real time traffic: In the first stage, each traffic class is associated to a queue. The classifier stores the packets in the queue that corresponds to the appropriate packet service class. Queues associated with real time flows
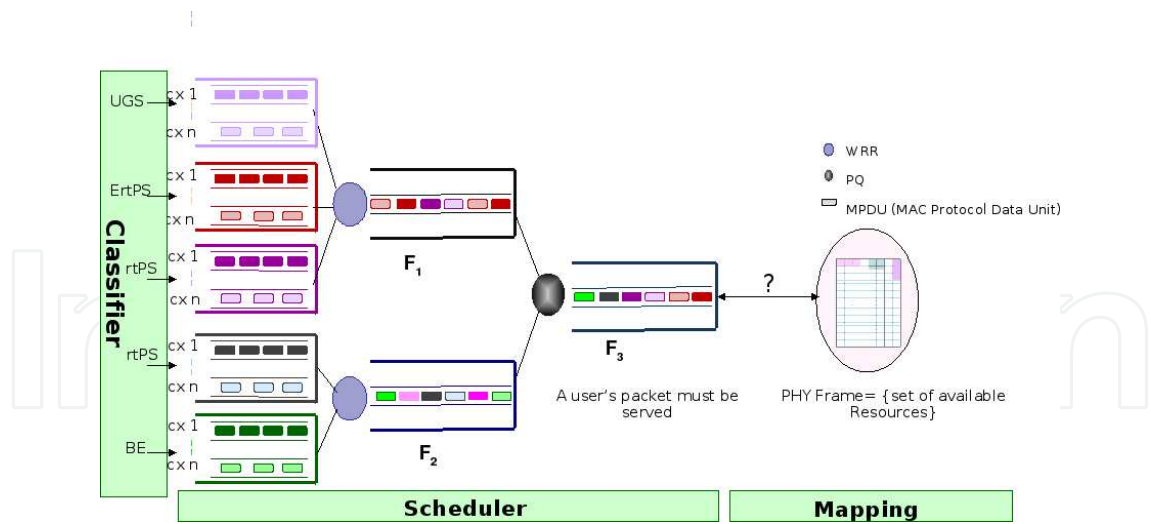
Fig. 10. DL hybrid scheduling block

(UGS, rtPS and ErtPS) are managed by the WRR scheduler and queues corresponding to non real time flows (nrtPS and BE) are managed by the same WRR discipline. This stage guarantees a fixed bandwidth for UGS and ErtPS classes and a minimum bandwidth for rtPS while ensuring fairness between flows because the rtPS packets have variable size and this flow could monopolize the server if the traffic is composed by packets with larger size than those of Class 1 and 2.

In the second stage, output of the two WRR schedulers are enqueued in two queues F1 and F2, packets of these queues are managed by a priority PQ scheduler which gives higher priority to real time stream (stored in F1) which are more constringent in term of throughput and delay than the non-real time traffic (stored in F2) which are less time sensitive.

Once scheduled the MPDUs are placed in a FIFO queue of infinite size. The next step is to choose the users and therefore MPDUs that must be served in this queue, it is also necessary to determine how much MPDUs will be served and what are the slots allocated to them?

6.3 Step 3: The users selection

We consider that for each source that transmitting a traffic class i a system have to allocate an $\underline{s_i}$ minimum required bandwidth to satisfy its QoS constraints. If we consider that this source has traffic with k service classes to send, the BS has to allocate a minimum required bandwidth denoted by $\underline{S_n}$ for each user n to satisfy its QoS constraints. If we assume that this user carries traffic with the five service classes $i \in U$, so this bandwidth $\underline{S_n}$ corresponds to:

$$\underline{S_n} = \sum_{i=1}^{5} \underline{s_i} \tag{27}$$

Where $\underline{s_i}$ is the required bandwidth to satisfy QoS constraints of class i. Note that these parameters varies periodical in time. Without loss of generality let's suppose that each user has only one type of traffic class to receive. So either it should be noted $\underline{S_n} = \underline{s_i}$. let's consider that for every user n in the system we can obtain the cumulative rate $S_n = \underline{s_i}$ which corresponds to the number of bits per seconds that the system has to allocate to this user. As before the mapping, all traffic are processed by a described scheduling mechanism, a weight ϕ_i that corresponds to the priority of a class i is assigned to each traffic class. Let's denote by

Q_i the following satisfaction parameter:

$$Q_i = \phi_i \frac{s_i}{\underline{s_i}} \tag{28}$$

This parameter will serve to select users that are not satisfied in order to serve them first. The user satisfaction is defined as follows: All users that verifying the condition $s_i \leq \underline{s_i}$, that we call QoS satisfaction condition (QSC), are called not satisfied users . To determine what user to choose, the algorithm selects the user that is least satisfied i.e the one that checks the least satisfaction condition QSC and thus satisfies the equation 29:

$$n = \arg\min_{u \in N} Q_u \tag{29}$$

If there are many that corresponds to the minimum several solutions are used: one solution is to choose randomly one of them or the user that request the maximum of bandwidth $\left(\underline{s_{(i)}}\right)$ or the user that corresponds to the maximum of the value $\left(s_i - \underline{s_i}\right)$ otherwise select the user that it has the prior service class ($UGS > ErtPS > rtPS > nrtPS > BE$).

In what follows, for simplicity the first option is used.

6.4 Step 4: The selection of the traffic granularity

Once the user is selected to be served, the next step is to know how much user MPDUs it will be served? Three solutions to choose the amount of MPDUs to be served are presented as follows:

1. All user MPDUs: All MPDUs belonging to the selected user that are in the queue will be served. The disadvantage is that a user could monopolize physical resources. We denote this method a **TP** strategy for Total user packets.

2. MPDUs by MPDUs: In this proposal, we process only one MPDUs by selected user. Once slots are allocated to it, we move to the next user. This avoids the disadvantage of the first proposal. We denote this method **PP** for Packet Per Packet.

3. Only the number of bits needed is treated in order to reduce the user delay: In this case, each user has a credit we will denote $Credit_n(t)$ which corresponds to the amount of bandwidth allocated until time t, (t is a multiple of the duration of the frame ($t = xT$, $T = Frame\ duration$)). This credit will be updated whenever the system allocates one or more slots by adding the amount of bits provided by each allocated slot. At time t, to guarantee the QoS constraints of the user n that receiving a traffic class i, the user will be allocated at least $B_n = x\underline{s_i}$. B_n is the number of bits that should be served to ensure the user's request. We can then define the delay or retard as follows:

$$Retard_n(t) = B_n - Credit_n(t) \tag{30}$$

   Two cases arise:
   - If $Retard_n(t) > 0$, i.e what we need to allocate to the user, is more than what we have allowed him, in this case the user is in retard and we must serve more than the $Retard_n(t)$ to retrieve the user n retard .
   - If $Retard_n(t) \leq 0$, in this case the user is not in retard and we serve only one MPDU of this user.

Lets note this strategy as **RR** for Retrieve Retard.

6.5 Step 5: Slots selection

The last step is the selection of slots to be allocated to MPDUs to be served by system. Two solutions are presented in this section:

1. Iterative solution: It is an instinctive idea. The BS allocates randomly the available slots in order to satisfy the selected user request in term of bits. We can call this solution as a FIFO strategy since the first user selected will be the first served.

2. MAXSNR solution: The basic idea is to select with a selfish behavior, so the BS choose the best slots in term of SNR for selected users and didn't care if the set of the allocated slots could be the best for other users. To determine if a slot is better or not, we proceed as follows: When we allocate a slot s to a given user n, that corresponds in term of bits to $b_{n,s}$. This parameter is easily deduced from the SNR of the allocated slot s to the user n and expressed by equation 23. Lets denote by $F_{n,s} = \frac{b_{n,s}}{b_n^{max}}$ the factor which indicates if a given slot s is the best one to be allocated to the user n. Here $b_n^{max} = \max_{l \in S_n} [b_{n,l}]$, where S_n is the set of free slots to be allocated to user n. More this factor is close to 1 more the slot is better.
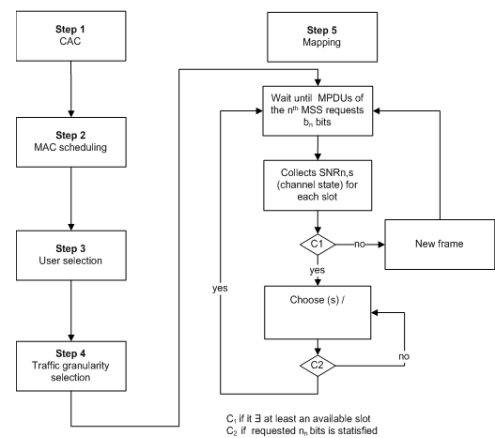

Fig. 11. Slot selection

7. Evaluation and discussion

7.1 Simulation parameters

This solution can be evaluated by using the following tools:

1. Opnet (Laias E. et al., 2008), (Shivkumar et al, 2000): This simulator is used to generate the traffic carried by the MSS and to implement the two stages of the scheduler block in step 2 9 that we described below.

2. Matlab: This mathematical tool is used to generate the MSSs signal at the physical layer and introduce the channel perturbation due to mobility and signal attenuation.

We then implement the steps 3, 4 and 5 of proposed block 9, using the programming language C++. These tools interact according to the following:

To evaluate the performance of the methods described above, we define three types of flows. Each flow models a service class: UGS, rtPS and nrTPS. This choice is justified by the fact
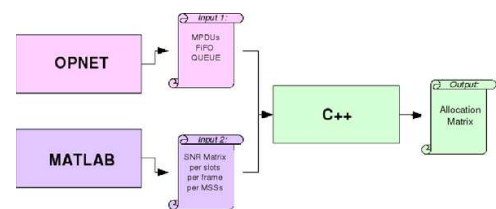
Fig. 12. Simulation tools

that classes UGS and ErtPS have same behavior and that the BE is a traffic which has no significant influence on the capacity as the BS allocate the rest of the remaining bandwidth. To characterize these streams, we set two parameters: the MPDUs size and the packet inter-arrival time. The following table shows the parameters used for the studied traffic :

Class	Application	Mean rate (Kbps)	Arrival time (s)	Distribution and packet size(bits)
UGS	VoIP(G711)	64	Constant: 0.02	Constant: 1280
rtPS	Video streaming (25 pictures/s)	$3.5 \, 10^3$	Constant: $2.2875 10^{-4}$	Geometric:mean=$12.5 10^{-4}$
nrtPS	FTP	$3.5 \, 10^3$	Constant: $2.2875 10^{-4}$	Geometric: mean=$12.5 10^{-4}$

Table 5. Traffic parameters

Note that we could easily introduce the packet loss due to the physical channel perturbation and assume that all the slots with $SNR_{n,s} \in I_0 = [0, 6.4[dB$ are considered as lost and no data will be sent in these slots. In fact, $6.4 dB$ corresponds to the sensitivity threshold of all MSSs receiving antennas, and therefore below this threshold, the received data will not be noticeable by these antennas. However, as we do not introduce retransmission mechanisms, we assume that the BS affects the least efficient modulation in terms of spectral efficiency to the user whose SNR is in I_0 which corresponds to MCS $(\frac{1}{2}, QPSK)$.

The topology of the simulated network consists of a BS with system capacity equal to 7.4 Mbps which serves for the first scenario 3 MSSs with 3 traffics classes UGS, rtPS and nrtPS and for the second scenario 6 MSSs where 2 MSSs receives UGS traffic, 2 other receives rtPS traffic and the rest receives nrtPS traffic.

These SS are randomly distributed around the BS, and they turn around a BS. The mobile SS velocity vary from 0.1 to 20 m/s and the trajectory is a perfect circle with radius varying from 1m to 2 km. The duration time of our simulation is 20s.We choose system parameters corresponding to the mobile WiMAX profile, with 10 MHz bandwidth and an FFT size of 1024. The mobile WiMAX frame with 5ms duration provides 69*4 units of physical resource or OFDMA slots. The base station provides the following applications to MSS: We apply a slowly time-varying, frequency-selective Rayleigh channel that we described in 5.1.3. Each MSS n moves with velocity $V_n = n * V$ where n is the user index and $V = 10 m/s$. Thus the MSS $n = 6$ will move with speed $V_6 = 60 m/s = 216 Km/h$ and the MSS $n = 1$ will move with a velocity $V_1 = 36 Km/h$.

We then varied the SNR channel for only one MSS and we kept the SNR fixed and equal to 11 dB, then we varried the channel for all MSSs, we studied a total of 5 scenarios which we summarized in the following table:

The channel variation is given by the figure 13 which corresponds to Cumulative Distribution Function CDF of the modulation schemes.

We then apply the different methods of choosing the granularity of traffic TP, RR and PP to which we added the FIFO method which corresponding to serve MPDUs as they arrive in

scenario: 6 MSSs					
Channel state	UGS(1)	UGS(2)	rtPS(1)	rtPS(2)	nrtPS(1)	nrtPS(2)
1	F	F	F	F	F	F
2	P	P	P	P	P	P
3	P	F	F	F	F	F
4	F	F	P	F	F	F
5	F	F	F	F	P	F

Table 6. Studied scenarios, F: SNR fixed 11 dB, V: SNR varied, (1): MSS_1, (2): MSS_2
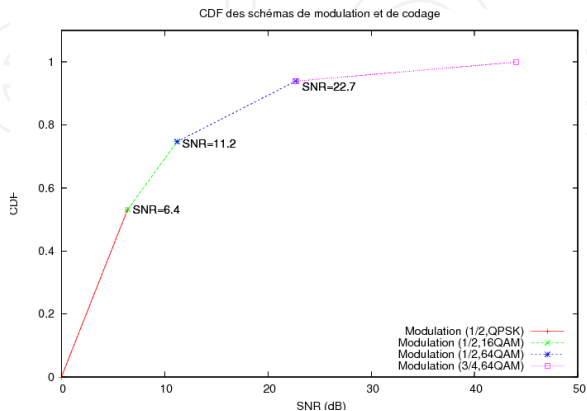
Fig. 13. Modulation scheme distribution (CDF) when the channel is varrying

the queue. We have combined these methods with the ITERATIV and MAXSNR mapping solutions explained above.

The simulation duration is 10s which is equivalent to 2000 frames sent and 5 hours time machine and we chose the following weights $\phi_i = 1$ for UGS class, $\phi_i = 2$ for rtPS class and $\phi_i = 3$ for nrtPS class. Simulation results are presented in the next section.

7.2 Performance parameters

In this evaluation we focused on several evaluation parameters such as the average data rate of each MSS, the average delay of each service class, the utilization ratio and packet loss. In what follows we give the results for the second scenario with 6 MSSs, the first scenario with 3 MSSs shows the same results. To facilitate understanding of our analysis and results we follow the following notations:

1. State F: all users channel SNR are set to 11dB.

2. State P: all users channel SNR are perturbed.

3. State UGS-P: only users receiving UGS traffic have a perturbed channel.

4. State rtPS-P: only users receiving rtPS traffic have a perturbed channel.

5. State nrtPS-P: only users receiving nrtPS traffic have a perturbed channel.

The first parameter that we evaluate is the utilization ratio which corresponds to the ratio between the average number of slots used and the total number of slots ($90 * 6 = 540$). This ratio is expressed with the following equation:

$$U = \frac{E[\sum_{n=1}^{N} \sum_{s=1}^{S} \sum_{t=1}^{T_s} a_{s,t}^n]}{540} \tag{31}$$

We are also interested in the average delay per class i per user expressed as follows:

$$D_i = E[T_{s,i} - T_{g,i}] \tag{32}$$

Where $T_{s,i}$ is the service time and $T_{g,i}$ is the MPDUs generation time for class i. Finally, it is also important to estimate the MPDUs loss which corresponds to those that they could not be served on time, this loss is expressed as the mean number of lost packets per user per frame, denoted $Loss_i(t)$. We assume that a UGS or rtPS packet is lost only if it waits longer than 40 ms in the queue before to be served.

$$Loss_i(t) = \frac{\sum\limits_{d_i >= 40} n_{MPDUS,d_i}(t)}{2000} \tag{33}$$

$n_{MPDUS,d_i}(t)$ is the number of MPDUs of class i that should b served at time t and the waiting time is $d_i = T_{s,i} - T_{g,i}$.

7.3 Analysis

As we have several combinations of channel perturbations and mapping and user selection strategies in 5 blocks we obtain about sixty curves. Here are results that we obtained for the performance parameters that we described before: For the utilization ratio in figure 14 we have a heavy traffic load, between 96% and 100%. The required average rate of all classes are
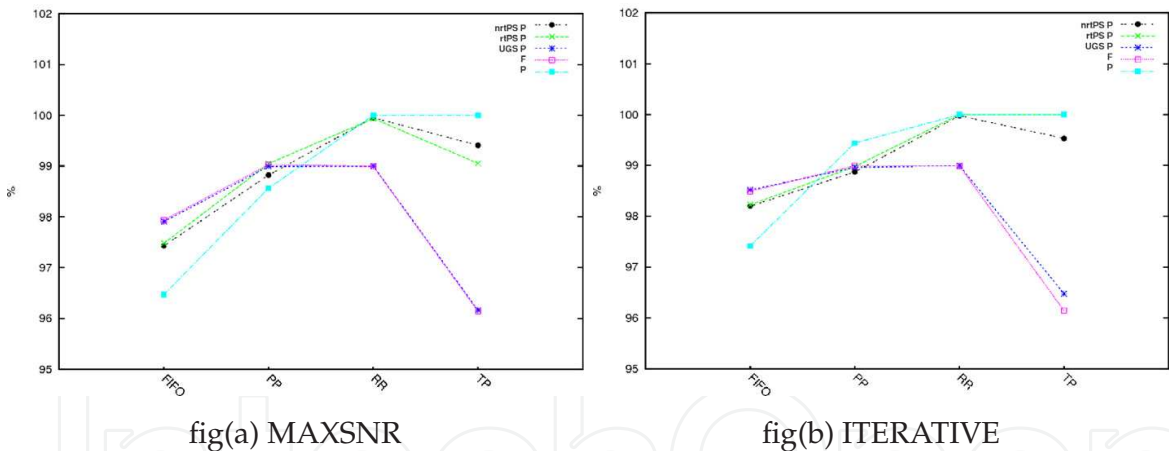

fig(a) MAXSNR   fig(b) ITERATIVE

Fig. 14. Frame average utilization ratio

satisfied with all strategies, TP ensures exactly the requested rate without bandwidth waste and therefore it optimizes the use of the system capacity, an example for rtPS is given in figure 15.

As we see in figure 16 TP strategy shows also a best performance regarding delays since there is no delay for rtPS which is a real time constringent application. We observed loss for the rtPS traffic for FIFO, RR and PP strategies and we can deduce that MAXSNR mapping solution is better than the ITERATIVE one. The block user selection is efficient since in its absence (ie when we use FIFO method), rtPS delay is greater than 40 ms which is equivalent to rtPS packet loss. As a conclusion the combination that it is recommended is to use TP as a selection traffic granularity method with MAXSNR as a mapping slot strategy after processing traffic by our proposed hybrid scheduling block.
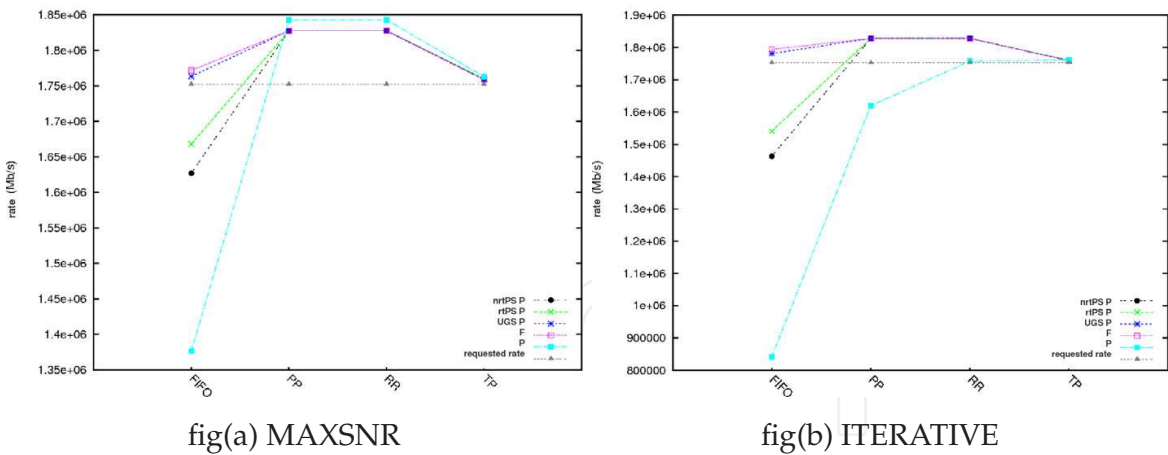
fig(a) MAXSNR   fig(b) ITERATIVE

Fig. 15. rtPS average rate

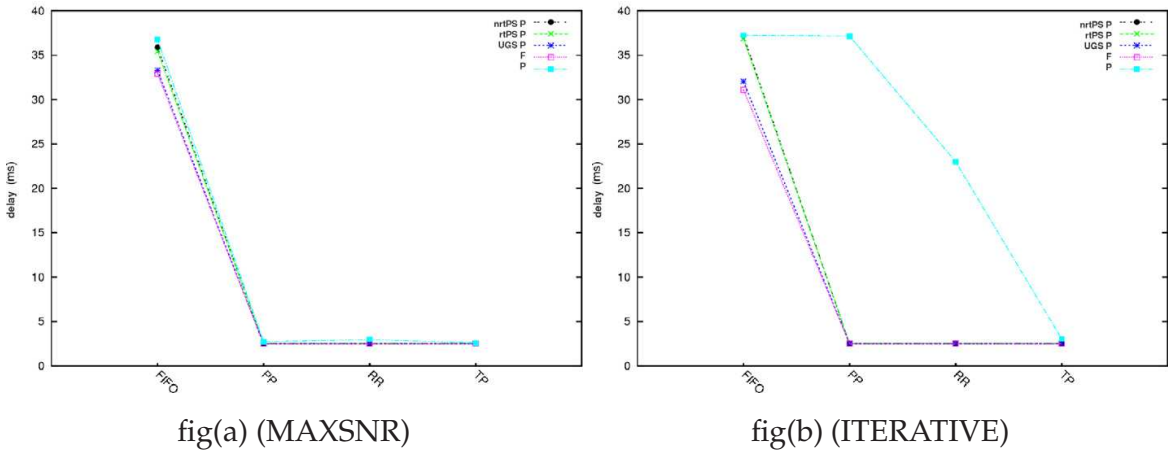fig(a) (MAXSNR)   fig(b) (ITERATIVE)

Fig. 16. rtPS average delay

8. Conclusion

This chapter presents one of the fundamental requirements of next generation OFDMA based wireless mobile communication systems which consist on the cross-layer scheduling and resource allocation mechanism.

The purpose of the first part of the chapter was to give an overview of QoS mechanisms in WiMAX systems and to explain the optimization problems related with these features. The rest of this chapter presents case study in order to analyse and discuss several solution developed to guarantee QoS management of a mobile WiMAX system.

Nevertheless, the growth of network access technologies in the mobile environment has raised several new issues due to the interference between the available accesses. This is why the novel resource allocation solution must integer a new concepts like SON (Self-Organizing network) features in a framework of general policy management. The next generation wireless communications standard (i.e., IEEE 802.16e/m, 3GPP-LTE and LTE-Advanced ...) has to include smart QoS management systems in order to obtain an optimal ubiquitous operating system any time and any where.

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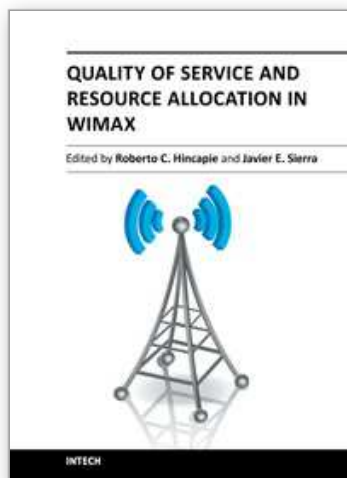
Quality of Service and Resource Allocation in WiMAX

Edited by Dr. Roberto Hincapie

This book has been prepared to present state of the art on WiMAX Technology. It has been constructed with the support of many researchers around the world, working on resource allocation, quality of service and WiMAX applications. Such many different works on WiMAX, show the great worldwide importance of WiMAX as a wireless broadband access technology. This book is intended for readers interested in resource allocation and quality of service in wireless environments, which is known to be a complex problem. All chapters include both theoretical and technical information, which provides an in depth review of the most recent advances in the field for engineers and researchers, and other readers interested in WiMAX.

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