Quality of Service Differentiation in WiMAX Networks

Pedro Neves[1], Susana Sargento[2], Francisco Fontes[1], Thomas M. Bohnert[3] and João Monteiro[2]
[1] Portugal Telecom Inovação
Portugal
[2] University of Aveiro / Institute of Telecommunications
Portugal
[3] SAP Research CEC Zurich
Switzerland

1. Introduction

Broadband Wireless Access (BWA) based on the IEEE 802.16 standards [IEEE 802.16, 2004] [IEEE 802.16, 2005], also known as Worldwide Interoperability for Microwave Access (WiMAX), is gaining momentum as more and more field trials are transformed in commercial roll-outs. Very much likely, this is certainly a merit of the combined effort of the IEEE 802.16 standardization community, the WiMAX Forum [WiMAX Forum a, 2008] [WiMAX Forum b, 2008] and the research community. As of today, standards have matured, the WiMAX Forum has setup its certification program in order to foster interoperability, and the research community went through technological details up to an extent, such that many operators consider the risks associated with commercial deployment predictable.

Yet, WiMAX is still not deemed as globally established. This technology is very new and a competing system, namely Long-Term Evolution (LTE) [3GPP, 2009], is progressing in a similar pace. Which technology will finally make it through in the market, or will we have even several co-existing ones, is, among others, influenced by the research community. The better a technology is understood, the more likely it will be adopted by manufacturers, vendors and operators.

Key to scientific consideration is the availability of reliable simulation tools. This applies equally to WiMAX and any other technology and is embodied by an emerging business of commercial simulators like OPNET [OPNET] and Qualcomm [Qualcomm]. Unfortunately, these simulators are fairly expensive and/or their use is strictly licensed. As monetary considerations and openness frequently prevail, in particular in academia, NS-2 [NS-2], as open-source alternative, still retains its position.

Naturally, open-source software rarely approaches commercial standards, especially in terms of completeness and documentation. This is, for example, the case for the public available WiMAX module for NS-2. This module supports several WiMAX features but lacks a very essential one, Quality of Service (QoS) support. The lack of this feature motivates the work presented in this chapter. This chapter describes a novel QoS framework for WiMAX with efficient service differentiation. The QoS framework is composed by a packet classification mechanism, as well as by a novel cross-layer scheduling algorithm based on user's prioritization and radio resources optimization [Monteiro, 2009].

Furthermore, in order to validate and evaluate the designed solution, a set of QoS oriented scenarios have been simulated in Network Simulator (NS-2) [NS2-NIST], demonstrating that the designed model is able to efficiently differentiate users in a competitive environment, differentiating between the traffic classes defined for WiMAX, mainly in throughput and delay metrics.

The reminder of this chapter is organized as follows. Section 2 briefly overviews WiMAX, focusing on the Medium Access Control (MAC) layer functionalities. Section 3 provides an overview about the WiMAX NS-2 module, focusing on its main features and limitations. Section 4 describes the proposed QoS model, including the packet classification mechanism and the scheduler, whereas Section 5 discusses the obtained simulation results for several scenarios. Finally, Section 6 concludes the chapter.

2. WiMAX High Level Description

Ubiquitous broadband Internet access is an important requirement to satisfy user demands and support a new set of real time services and applications. WiMAX, a Broadband Wireless Access (BWA) solution for Wireless Metropolitan Area Networks (WMAN), covering large distances with high throughputs, is a promising technology for Next Generation Networks. WiMAX supports both fixed and mobile users, based on IEEE 802.16-2004 [802.16, 2004] and IEEE 802.16e-2005 [802.16, 2005] standards, respectively. IEEE 802.16 system is connection oriented and provides Quality of Service (QoS) assurances through service flows and scheduling services. Therefore, all tasks are based on a connection, uniquely identified by a 16-bit Connection Identifier (CID), and no packets are allowed to traverse the wireless link without a specific connection allocated. A connection is, by definition, a unidirectional mapping between the WiMAX Base Station (BS) and the WiMAX Subscriber/Mobile Station (SS/MS) for transporting a service flow's traffic. Succinctly, scheduling services specify the policy used by the WiMAX BS and SS/MSs to manage the poll and grant procedures. Five scheduling services are defined to meet the QoS needs of the data flows carried over the air link:

- *Unsolicited Grant Service (UGS)*: designed for real-time service flows that generate fixed size data packets on a periodic basis, such as VoIP. The service offers fixed size unsolicited data grants (transmission opportunities) on a periodic basis. This eliminates the latency and overhead of requiring the SS/MS to send requests for transmission opportunities, and assures that grants are available to meet the flow's real-time needs;
- *real-time Polling Service (rtPS)*: designed for real-time service flows that generate variable size data packets on a periodic basis, such as video streaming. The service offers real-time, periodic, unicast request opportunities, which meet the flows real-time needs and allow the SS/MS to specify the size of the desired grant. In this case, the SS/MS is not allowed to use any contention request opportunities;

- *extended real-time Polling Service (ertPS)*: designed for real-time services that generate variable size data packets on a periodic basis, such as VoIP with silence suppression. This scheduling mechanism is based on UGS and rtPS. Unicast grants are provided to the MSs in an unsolicited manner, like in UGS, and therefore the latency of a bandwidth request message is saved. Instead of providing fixed allocations such as UGS, ertPS provides dynamics allocations;
- *non real-time Polling Service (nrtPS)*: designed for non-real-time service flows that require variable size data grants on a regular (but not strictly periodic) basis, such as high bandwidth File Transfer Protocol (FTP). The service offers unicast polls on a periodic basis but uses more space intervals then rtPS. This ensures that the flow receives request opportunities even during network congestion;
- *Best Effort (BE)*: designed for traffic where no throughput or delay guarantees are provided. The SS/MS sends requests for bandwidth in either random access slots or dedicated transmission opportunities. The occurrence of dedicated opportunities is subject to network load, and in contrast to the nrtPS, the SS/MS cannot rely on their presence.

A set of convergence sublayers are defined to map the upper layer packets into the 802.16-2004 system. The convergence sublayers support packet based protocols, such as Internet Protocol version 4 (IPv4) and Internet Protocol version 6 (IPv6), as well as cell based protocols, such as Asynchronous Transfer Mode (ATM). Both point-to-multipoint (PMP) and mesh modes of operation are supported by the standard, despite the mesh mode of operation is optional. During the WiMAX SS/MS network entry process, three pairs of management connections, with distinct QoS levels and hence reflecting three different QoS requirements, are established:

- Basic connection to transfer short, time-critical MAC management messages;
- Primary management connection to transfer longer, more delay tolerant management messages;
- Secondary management connection to transfer delay tolerant, standard-based management messages such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP) and Simple Network Management Protocol (SNMP).

Besides the aforementioned three pairs of management connections, a broadcast connection is configured by default and is used to transmit MAC management messages to all the SSs/MSs. Moreover, a multicast polling connection is used by the SSs/MSs to join multicast polling groups, allowing them to request bandwidth via polling. Finally, to satisfy the contracted services, transport connections are allocated for data packets.

With respect to the IEEE 802.16 protocol stack, it defines the Physical (PHY) and the Medium Access Control (MAC) layers. Internally, the MAC layer is divided in three sublayers: Service Specific Convergence Sublayer (CS), Common Part Sublayer (CPS) and Privacy Sublayer (PS). Figure 1 illustrates the IEEE 802.16 protocol stack, focusing on the MAC CS classification mechanism.

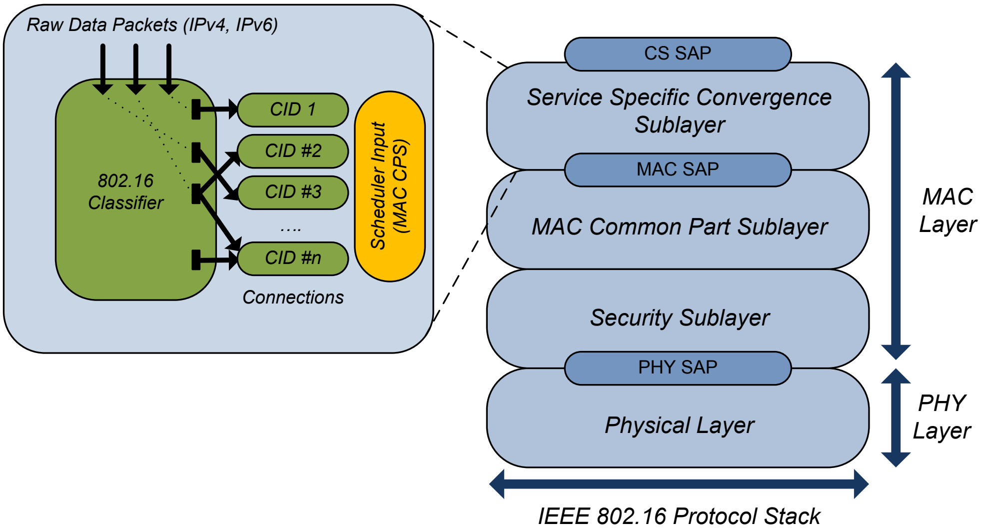

Fig. 1. IEEE 802.16 Protocol Stack

The interface between the 802.16 system and the upper layers from the protocol stack is provided by the CS, receiving the higher layer MAC Service Data Units (SDU) coming through the CS Service Access Point (SAP) and classifying them to the appropriate connection. The 802.16 classifier is a set of packet matching criteria applied to each packet. It consists of some protocol-specific fields, such as IP and MAC addresses, a classifier priority and a reference to a particular CID. Each connection has a specific service flow associated providing the necessary QoS requirements for that packet. If no classifier is found for a specific packet, a specific action must be taken. Since the classifier implementation is vendor dependent, the chosen decision depends on the algorithm implemented by the vendor – the packet can be discarded, sent on a default connection, or a new connection can be established for it, if enough resources are available. Downlink classifiers are applied by the WiMAX BS and uplink classifiers are applied by the WiMAX SS/MS. Two main types of CSs are defined within the standard for mapping services to and from the 802.16 system connections: the Packet Service Specific Convergence Sublayer (Packet CS) and the Assynchronous Transfer Mode Service Specific Convergence Sublayer (ATM CS). The Packet CS sublayer is defined for packet-based protocols, whereas the ATM CS is defined to support cell-based protocols.

The CPS is the second sublayer from the MAC layer. It receives classified packets arriving from the CS and is responsible for a set of functions, such as addressing, construction and transmission of the MAC PDUs, scheduling, bandwidth allocation, request mechanisms, contention resolution, among others. Finally, the PS is the third and last sublayer from the MAC layer and provides authentication, data encryption and security mechanisms.

Since the IEEE 802.16 standards are focused on defining the PHY and MAC layers for the air interface, the WiMAX Forum, in particular the Network Working Group (NWG), is specifying an “All-IP” end-to-end network architecture for IEEE 802.16 [WiMAX Forum a, 2008] [WiMAX Forum b, 2008]. The WiMAX Forum extends the IEEE 802.16 architecture by defining the Network Reference Model (NRM), which is a logical representation of the WiMAX network architecture, based on a set of functional entities and standardized interfaces, known as Reference Points (RPs) – R1 to R8. Using this model, multiple implementation options for a given functional entity are allowed, maintaining interoperability across them through the RPs. Three functional entities are defined: Connectivity Service Network (CSN), Access Service Network (ASN) and the Subscriber Station (SS)/Mobile Station (SS/MS). The WiMAX NRM is presented in Figure 2.

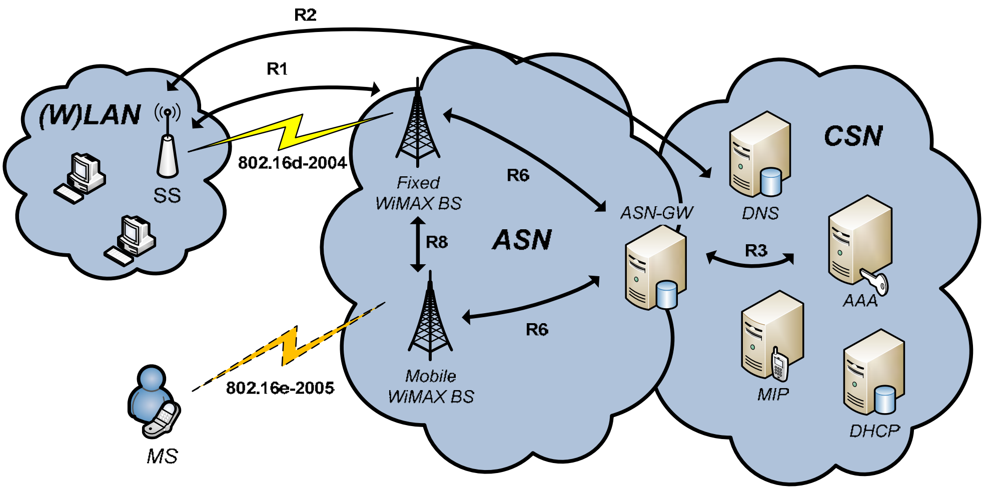

Fig. 2. WiMAX Network Reference Model

The SS and the MS are responsible for establishing radio connectivity with the WiMAX BS, for the fixed and mobile standards, respectively. The ASN is generally composed by several WiMAX BSs connected to one or more ASN-Gateways (ASN-GW); it establishes connectivity with the CSN. The ASN includes a set of functionalities in order to provide radio connectivity to WiMAX subscribers. Additionally, it also performs relay functions to the CSN in order to establish IP connectivity and authentication mechanisms. Finally, the CSN contains the DHCP, DNS, AAA (Authentication, Authorization, and Accounting) and MIP servers. Moreover, the CSN is responsible for establishing connectivity with the IP backbone.

After briefly describing WiMAX, the next section aims to depict the functionalities provided by default by the WiMAX QoS model implemented by the National Institute of Standards and Technology (NIST) [NS2-NIST] for the Network Simulator (NS2) [NS2].

3. NIST WiMAX QoS Model

The NS2 IEEE 802.16/WiMAX module [NS2-NIST] was developed by the NIST *Seamless and Secure Mobility Group* and henceforth the principal focus is on IEEE 802.16e/Mobile WiMAX.

Nevertheless, the overall architecture is set on top of a basic subset of IEEE 802.16-2004 [IEEE 802.16, 2004] and IEEE 802.16e-2005 [IEEE 802.16, 2005] common functionalities.

Out of the four specified physical (PHY) layers in the combined standard documents, a multi-carrier air interface using Orthogonal Frequency Division Multiplexing (OFDM) with 256 carriers was adopted, also known as WirelessMAN-OFDM, and Time Division Duplexing (TDD) was chosen as the duplexing technique. The 2 – 11 GHz licensed band provides lower transmission rates (75 Mbit/s) compared to the 10 – 66 GHz band, but it supports both Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) environments. Different modulations can be configured statically, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-state Quadrature Amplitude Modulation (QAM) and 64-QAM, allowing the formation of varying robustness and efficient burst profiles. However, information coding is yet missing and hence the module does not support any Adaptive Modulation and Coding (AMC) scheme.

The TDD duplexing technique is illustrated in Figure 3, presenting both downlink and uplink subframes decomposition. The downlink subframe is composed by a Preamble used for synchronization, followed by the Frame Control Header (FCH). The FCH contains the Downlink MAP (DL-MAP) and Uplink MAP (UL-MAP) MAC management messages, indicating the location and burst profile of each downlink and uplink burst, respectively. Moreover, it contains the downlink and uplink channel descriptors (UCD and DCD management messages). Following the FCH, starts the downlink data bursts section. Downlink bursts are transmitted in order of decreasing robustness – QPSK followed by 16-QAM and finally 64-QAM. The WiMAX SSs/MSs listen to all the bursts that they are capable to decode, specifically bursts with profiles of equal or greater robustness compared with the one negotiated with the WiMAX BS during the connection setup phase. Thereafer the SS analyses the MAC header of each MAC Protocol Data Unit (PDU) inside each burst to check if the Connection Identifier (CID) belongs to it. At the end of the frame, the Transmit Transition Gap (TTG) is used to separate the downlink and the following uplink bursts. The TTG allows the WiMAX SS to switch from receive to transmit mode.

In the beginning of the uplink subframe there are two contention slots. The first contention slot is used by the WiMAX SSs/MSs for initial ranging (Initial Ranging), whereas the second contention slot is used by the WiMAX SSs/MSs to send bandwidth request PDUs to the BS (Request Contention). The remaining transmission slots are grouped by SSs/MSs. Each SS/MS has a specific slot allocated for uplink data transmission. The Subscriber Station Time Gap (SSTG) is a time interval used to separate the transmissions of the various SSs/MSs during the uplink subframe. Finally, the Receive Transition Gap (RTG) is used to separate the uplink and downlink bursts. The RTG allows the WiMAX SS/MS to switch from transmit to receive mode.

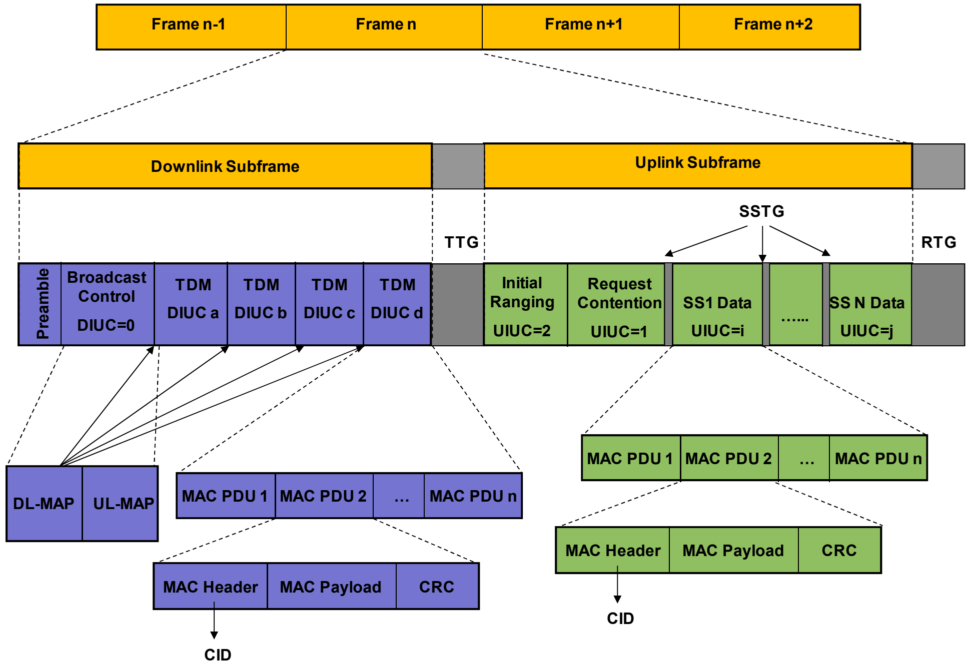

Fig. 3. WiMAX Frame Structure (Downlink and Uplink subframes)

The OFDM specific countermeasure to Inter Symbol Interference (ISI), the cyclic prefix, can also be configured, i.e. its length. Given these parameters, the module is able to compute the OFDM symbol duration, packet transmission time per modulation, maximum packet size per modulation and the number of OFDM symbols. As the implemented architecture is an extension of the NS-2 wireless networking sub-module, the standard NS-2 channel models and transmission power levels can be set accordingly to the NS-2 standard tools [NS2]. As for the PHY layer, the MAC layer supports only a subset of the IEEE 802.16 standard. For example, currently only the Packet Convergence Sublayer (Packet CS), as detailed in Section 2, is implemented. Although the module can be easily extended, the Packet CS is essentially a classifier, supporting the IP destination address as the classifier parameter. The connection oriented nature of IEEE 802.16 between MAC instances has also been implemented in the NIST model. As the IEEE 802.16 standard defines, each pair of WiMAX BS and SS establishes three management connections, Basic, Primary and Secondary. One of the drawbacks of the NIST implementation is that each MAC instance only supports one data transport connection. Additionally, out of Fragmentation, Packing and Automatic Repeat Request (ARQ), only the first, Fragmentation, is currently supported. With respect to mobility, channel scanning, communication parameters negotiation, initial ranging and registration, the provided implementation adheres largely to IEEE 802.16-2004 and IEEE 802.16e-2005 standards. Periodic ranging used to adjust coding and modulation is left out for now. Finally, the most crucial missing feature, which motivates this work, is the lack of a complete 802.16 compliant QoS model. The software has been prepared for future QoS integration but it was not implemented. Despite scheduling services, service flows and a basic bandwidth request mechanism for BE (Best Effort) traffic is available, the current scheduler implements a simple Round-Robin discipline for the scheduler.

4. Proposed QoS Model

4.1 Packet Classification Mechanism

As defined in the 802.16 standard, packets received at the MAC layer, specifically at the Convergence Sublayer (CS), must be mapped to the correspondent Connection Identifier (CID), based on a set of packet matching criteria. In order to handle the incoming packets and the new QoS classes, we have modified the NIST CS module. Besides the existing connections (Basic, Primary, Secondary and Data connections), additional connections for UGS (Unsolicited Grant Service), rtPS (real time Polling Service), ertPS (extended real time Polling Service), nrtPS (non real time Polling Service) and BE (Best Effort) service classes have been established. The creation of these new connections required the addition of new CID ranges, providing each peer node a unique CID for these types of traffic.

To allow the creation of new connections between the WiMAX BS and the SSs/MSs, the *PeerNode* class in NIST was changed to have new members of type *Connection*, for receiving and sending packets of different traffic classes. These modifications were performed in the existing *DestClassifier* class. This new classifier is a subclass of the Service Data Unit Classifier (*SDUClassifier*) class, as shown in Figure 4. To improve the packet classification mechanism, the *QoSClassifier* class was implemented, also as a subclass of the *SDUClassifier* class.

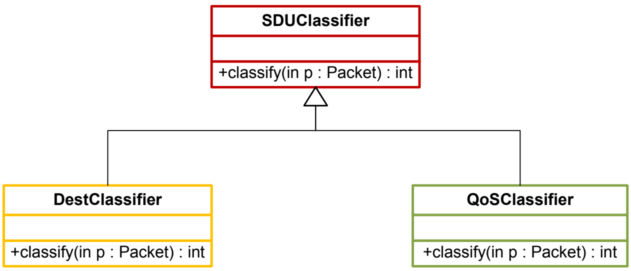

Fig. 4. Classifier Class Diagram

The most important method to implement the classification is the *classify()* method, called for all packets, which finds the appropriate *PeerNode* based on the destination address and QoS requirements. Thereafter, based on the packet type, the packet is sent to the appropriate connection queue on the scheduler, as illustrated in Figure 5. For example, if a broadcast packet is received on the BS classifier, a Broadcast CID is given; if the same packet is received on the SS/MS classifier, it will be classified with the Secondary Management CID. On the other hand, if a data packet arrives at the BS/SS classifier, it will be given a new transport CID and queue allocation correspondent to its traffic type.

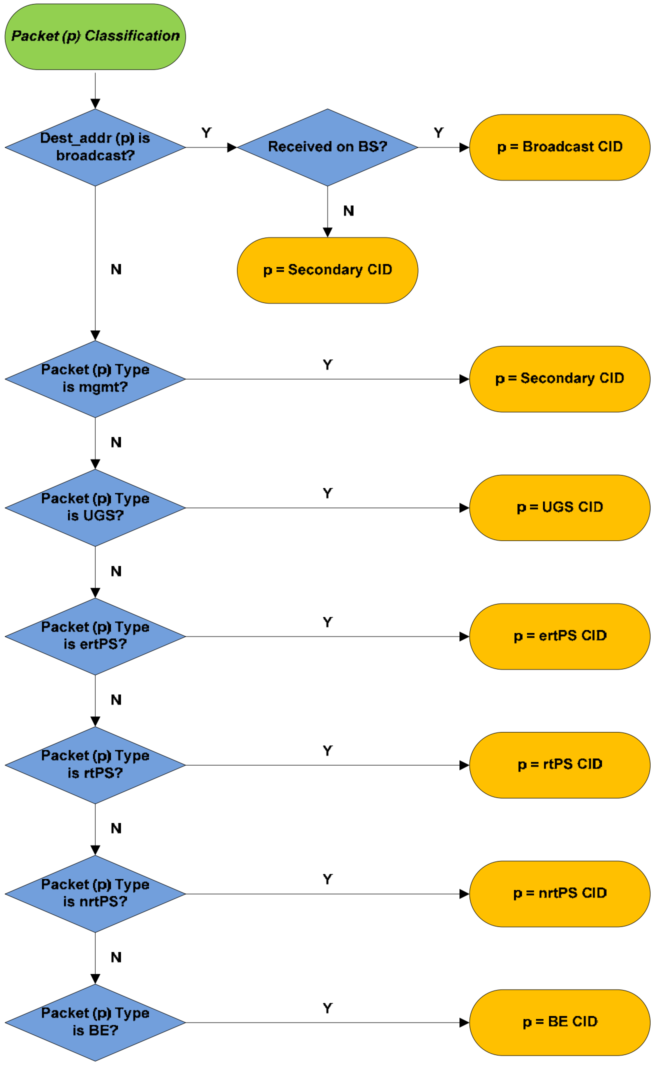

Fig. 5. Packet Classifier Diagram

Furthermore, new service classes were introduced in the model, as previously referred – UGS, ertPS, rtPS, nrtPS and BE. For each one of these service classes, a range of transport CIDs for the data connections was given. Apart from this association, modifications throughout the different functions that make use of the service classes were made. For instance, in the *Connection* function used by the WiMAX BS to initialize a new connection and assign the correspondent CID, the support for new connection types was added. In this case, a new type of connection is distinguished according to its type and respective CID.

4.2 Enhanced Scheduling Algorithm

The implemented BS scheduler enhances the simple Round Robin (RR) algorithm used in NS2-NIST/WiMAX module by adding a priority scheme – **priority Round Robin (PRR)**. Instead of equally distributing the available bandwidth between the registered SSs/MSs, the PRR scheduler prioritizes the most important service classes. Likewise, the SS/MS scheduler also uses a priority RR algorithm, distributing the available slots in the uplink direction. The proposed procedure is executed using a priority scheme to distinguish and transmit data packets in the following order of existing traffic type connections: UGS, ertPS, rtPS, nrtPS and BE. The new scheduler class – *QoSBSScheduler* – is also used as a subclass of the existing *BSScheduler*, as shown in Figure 6.

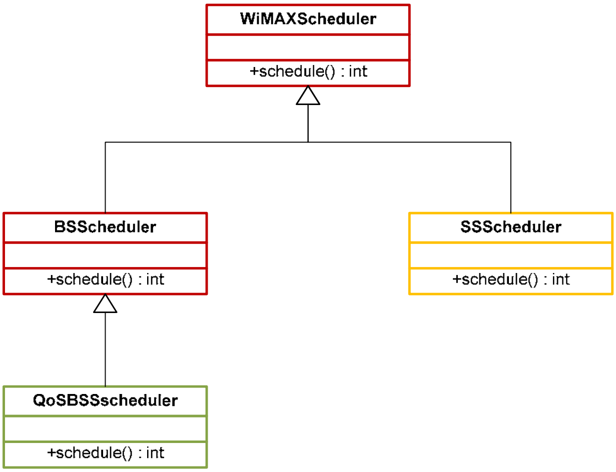

Fig. 6. Scheduler Class Diagram

5. Performance Evaluation

This section is devoted to the results and performance evaluation of the implemented QoS model. In order to evaluate the modifications to the existing NIST model, several simulation scenarios were implemented to test QoS using distinct network topologies. The obtained results use performance metrics, such as packet loss, latency, jitter and bandwidth usage, and also make use of differentiated traffic sources for each service class.

5.1 Simulation Scenario

The tested network topologies consider differentiated traffic going in the uplink direction from different hosts. Point-to-Point (PTP) and Point-to-Multipoint (PMP) scenarios, as illustrated in Figure 7, were considered. In the PTP case, four hosts directly connected to one WiMAX SS establish communication with the WiMAX BS, whereas in the PMP scenario, four WiMAX SSs communicate simultaneously with the WiMAX BS. Each host's traffic represents one connection flow in the uplink direction.

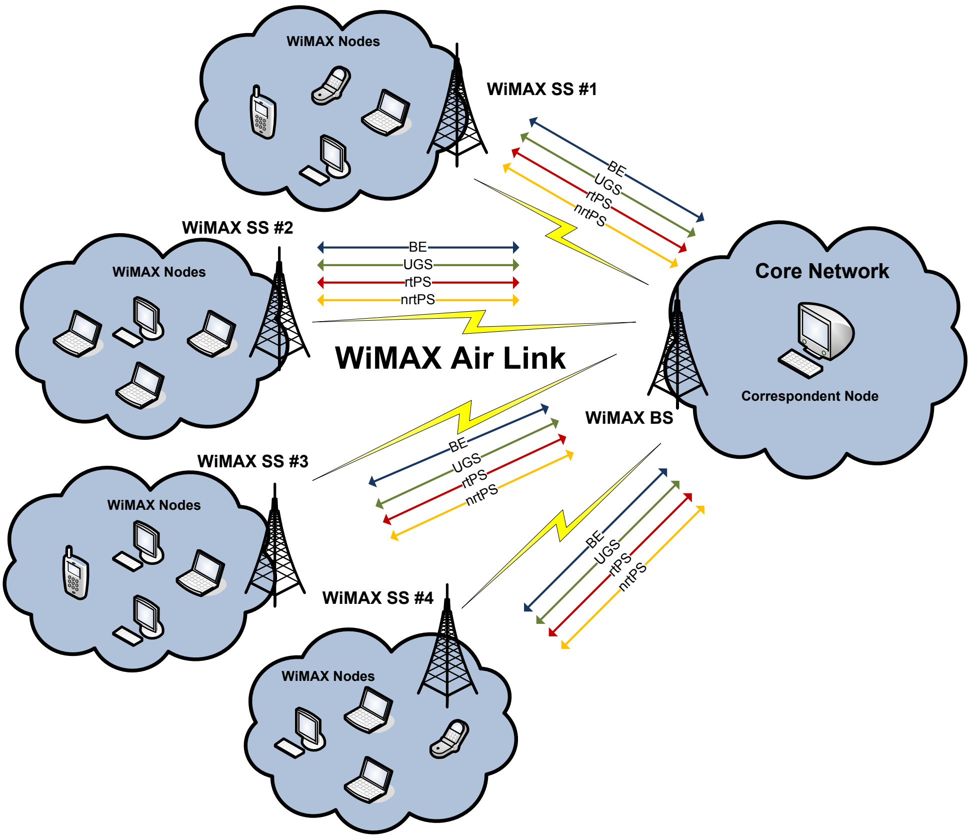

Fig. 7. Evaluation Scenario

In order to test the different network topologies, assuring differentiation between the different service classes, we defined and implemented new traffic sources. As an example, BE traffic generator contains a variable packet size and interval to emulate FTP/web traffic, and an UGS traffic generator contains a constant transmission rate. The different values adopted for these traffic generators are briefly presented in Table 1.

Service Class	Bitrate (Mbps)	Packet Size (Bytes)
BE	1	512 to 1024
UGS	1	300
rtPS	1	200 to 980
nrtPS	1	256 to 1024

Table 1. Service Classes Parameters

5.2 Simulation Results

Initial simulations made use of the PTP topology between the WiMAX BS and the WiMAX SS#1, presented in Figure 8, with four hosts connected to SS#1 and conveying differentiated traffic in the uplink direction. From this scenario we have also defined the WiMAX radio link parameters that would optimize the traffic transmission and subsequent simulation scenarios. The most important parameters are summarized in Table 2.

Modulation	Queue length	Bandwidth
64 QAM ¾	50 Packets	5 Mhz

Table 2. WiMAX Air Link Simulation Parameters

Initially, we tested a scenario in which four nodes, connected to each one of the WiMAX SSs, generate traffic competing for resources in the uplink direction. Each node has a traffic source dedicated to a specific WiMAX service class, specifically, UGS, rtPS, nrtPS and BE. The obtained throughput results are presented in Figure 8.

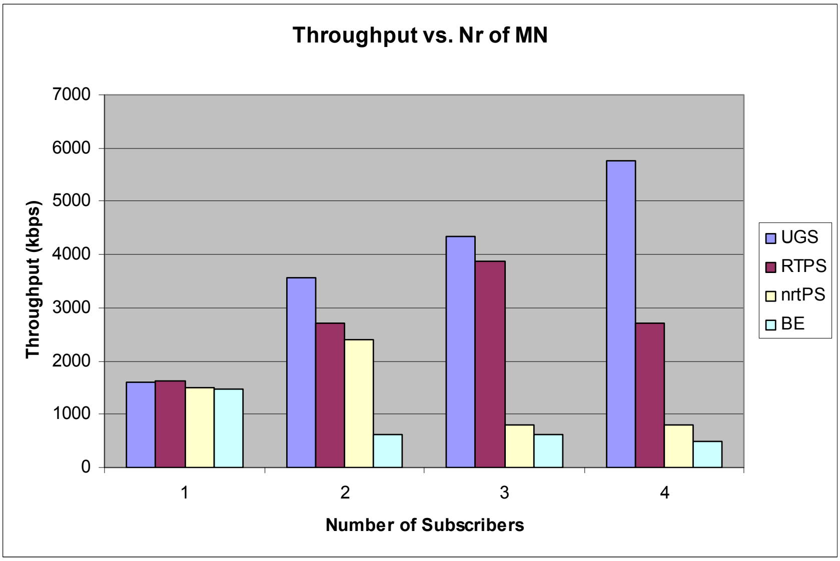

Fig. 8. Throughput vs. Number of WiMAX Subscribers Results

As depicted in Figure 8, the throughput values obtained for UGS services are quite satisfactory, with a reduced latency (Figure 9), jitter (Figure 10) and packet loss (Figure 11), when compared with the BE service. Therefore, packet differentiation is obtained, prioritizing the UGS related packets over the BE packets. Furthermore, one can see that with the increasing number of SSs, the obtained throughput is variable for each service class. Since the bandwidth is distributed into a higher number of WiMAX SSs, less bandwidth will be available for each one of them and, consequently, the less prioritized classes will be more degraded in terms of QoS.

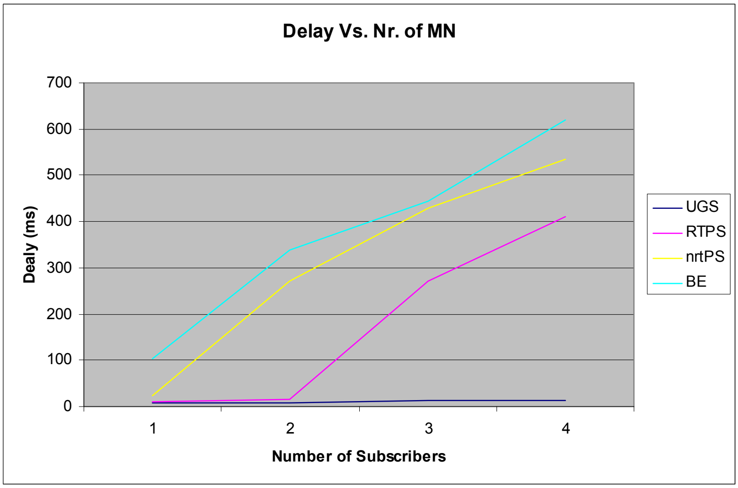

Fig. 9. Delay vs. Number of WiMAX Subscribers Results

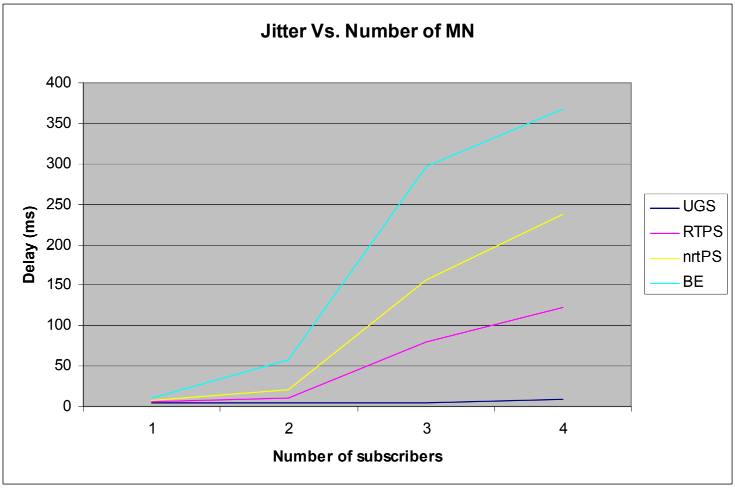

Fig. 10. Jitter vs. Number of WiMAX Subscribers Results

Analyzing the obtained results for the delay and jitter, presented in Figure 9 and Fig 10, respectively, it is visible that for the UGS traffic class these values always maintain reasonable and significantly very low values. Concerning the remaining traffic classes, with the increasing of subscribers, the delay and jitter values are, as expected, significantly affected.

With respect to the packet loss results, illustrated in Figure 11, the UGS service class remains almost unaffected, whereas the remaining service classes progressively drop more packets, due to the prioritization algorithm.

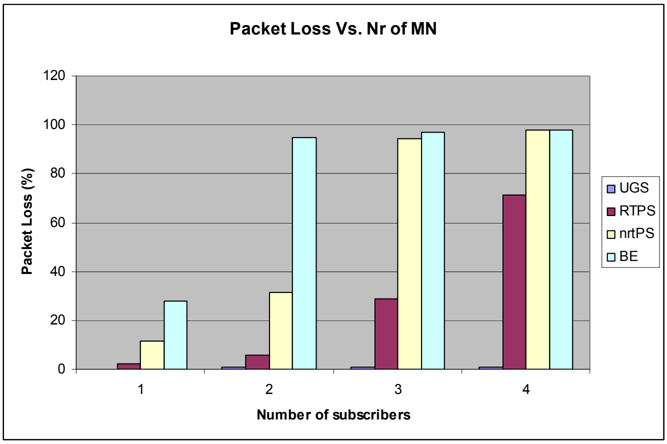

Fig. 11. Packet Loss vs. Number of WiMAX Subscribers Results

Finally, Figure 12 presents the bandwidth usage for each service class.

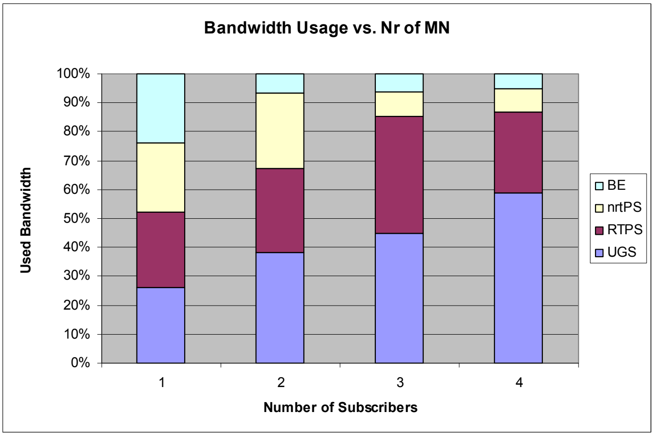

Fig. 12. Bandwidth Usage vs. Number of WiMAX Subscribers Results

It is visible a fair allocation of the available resources within each one of the service classes. When the number of WiMAX SSs increases, more bandwidth is allocated to the higher prioritized classes (e.g. UGS), avoiding starvation of the less prioritized classes (e.g. BE).

Summarizing, from the obtained results, one can see that the highest QoS demanding services achieve higher transmission throughput, penalizing the BE service. This differentiation is less visible for a single WiMAX SS, but increasing the number of WiMAX SSs, it is more clear the different treatment given to the packets that belong to different WiMAX scheduling services. This is explained by the fact that the BS has to distribute the available bandwidth between four SSs separately, leaving less available bandwidth for each one.

6. Conclusions

In this chapter we presented an enhancement for the NS2-NIST/WiMAX model in order to efficiently support QoS. Specifically, a packet classification mechanism and the associated scheduler, based on priority RR (PRR), have been designed, implemented and tested. Through the performance evaluation measurements with different topologies, point-to-point (PTP) and point-to-multipoint (PMP), it was possible to verify the differentiated behavior of the implemented WiMAX QoS classes. Based on the obtained results, we can conclude that there is a traffic differentiation visible by the different values obtained for the QoS parameters (latency, delay, bandwidth usage) in the test scenarios. Moreover, it was always assured a minimum transmission for all the service classes, although with different performances due to prioritization. The observed parameters degradation when using more subscribers is related to the priority RR implemented scheduler, in which less priority queues may not be served in the case of network overload or congestion.

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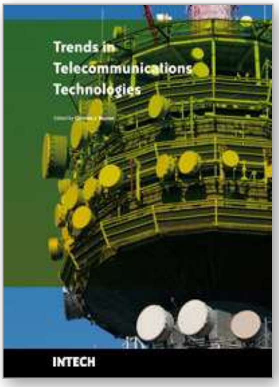

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The main focus of the book is the advances in telecommunications modeling, policy, and technology. In particular, several chapters of the book deal with low-level network layers and present issues in optical communication technology and optical networks, including the deployment of optical hardware devices and the design of optical network architecture. Wireless networking is also covered, with a focus on WiFi and WiMAX technologies. The book also contains chapters that deal with transport issues, and namely protocols and policies for efficient and guaranteed transmission characteristics while transferring demanding data applications such as video. Finally, the book includes chapters that focus on the delivery of applications through common telecommunication channels such as the earth atmosphere. This book is useful for researchers working in the telecommunications field, in order to read a compact gathering of some of the latest efforts in related areas. It is also useful for educators that wish to get an up-to-date glimpse of telecommunications research and present it in an easily understandable and concise way. It is finally suitable for the engineers and other interested people that would benefit from an overview of ideas, experiments, algorithms and techniques that are presented throughout the book.