WiMAX capacity estimations and simulation results

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***Abstract*—In this paper, we propose some considerations for the WiMAX capacity. The developments realized for a WiMAX NS-2 module are presented. This module allows the evaluation of the WiMAX. We present the spectrum efficiency and mean sojourn time of WiMAX determined through simulations for different scheduling algorithms. It is then possible to compare theoretical values and simulation results of WiMAX spectral efficiency and highlight some interesting comments. This is done for two proposed scenarios.**

I. Introduction

WiMAX is a new and powerful Broadband Wireless Access (BWA) Technology. It is based on the IEEE 802.16-2004 standard [1] and its amendment 802.16e [2]. It offers different tools for different environments. Many procedures and algorithms of WiMAX are not mandatory in the IEEE 802.16 standard and then represent open problems. Then, vendors and providers must choose or propose their own procedures and algorithms. The network simulation presents a solution to test the performance before applying these algorithms to the reality. Network Simulator 2 (NS-2) [3] is a widely-used tool to simulate wireless networks. Until today, this simulator does not contain a WiMAX module. Yet, there are some contributions such as the modules that are implemented by National Institute of Standards and Technology (NIST) [4] and Network and Distributed Systems Laboratory (NDSL) [5].

The available features of the NIST module are Wireless-OFDM physical layer, Time Division Duplexing (TDD), management messages, Round Robin (RR) uplink scheduler, IEEE 802.16e extensions to support scanning and handovers, and fragmentation and reassembly of frames [6]. In the other hand, the available features of the NDSL module are Wireless-OFDMA physical layer, TDD, management messages, RR uplink scheduler, and Control Admission Control (CAC) mechanism [7].

Since we work on the Wireless-OFDM physical layer, our NS-2 developments are based on the NIST implementation. Our contribution in this existing implementation consists of the addition and management of Quality of Service (QoS)

parameters and the implementation of some scheduling algorithms. Then, we assess the scheduling methods by determining the spectrum efficiency and mean sojourn time performance measures. The mean sojourn time represents the average time a data packet spends from its generation to its delivery at the destination. Simulation results are given for two different scenarios: rural and urban scenarios. These scenarios assess scheduling methods at low and high signal-to-noise ratio (SNR) conditions, respectively.

This paper is organized as follows. In Section II, we present the system model. In Section III, we introduce the WiMAX capacity as well as some considerations about the throughput and spectrum efficiency. In Section IV, we describe our proposed NS-2 module. In Section V, we present some simulation results of scheduling methods. We conclude in Section VI.

II. System Model

The IEEE 802.16 standard defines the PHY and MAC layers. The PHY layer defines five physical interfaces. We consider the Orthogonal Frequency Division Multiplexing (OFDM) PHY layer in our system model. The MAC layer defines five QoS classes: Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), extended real-time Polling Service (ertPS), non real-time Polling Service (nrtPS), and Best Effort (BE) QoS classes. We consider the UGS, rtPS, and BE QoS classes in our system model. Each QoS class has its mandatory QoS parameters. The main parameters of a QoS class service flow in IEEE 802.16 are summarized in Table I.

The SFID, CID, and traffic priority are mandatory for all the QoS classes. The other mandatory service flow parameters depend on the kind of the class used. For example, Maximum Sustained Traffic Rate, Maximum Latency, and Tolerate Jitter are mandatory for the UGS QoS. Maximum Sustained Traffic Rate, Maximum Sustained Traffic Rate, and Maximum Latency are mandatory for rtPS.

The BS provides radio resources for the different SS with taking into account the QoS parameters of the different service flows. Evidently, the link adaptation is useful for the BS to deliver QoS. The SNR value of a subscriber station (SS) is used to determine the MCS. The determination of the MCS depends on two values:

- The minimum entry threshold: represents the minimum SNR required to start using a more efficient MCS.
- The mandatory exit threshold: represents the SNR below which the current MCS can no longer be used. It is required to start using a more robust MCS.

Values of the receiver SNR assumptions are proposed in Table 266 of the IEEE 802.16e amendment of the standard (see Table II).

TABLE I
MAIN PARAMETERS OF A SERVICE FLOW

Parameter	Description
Service Flow Identifier (SFID)	Primary reference of a service flow.
Connection Identifier (CID)	Identifier of the connection.
QoS Class Name	Refers to a predefined BS service configuration.
Traffic Priority	Priority assigned to the service flow.
Maximum Sustained Traffic Rate	Peak information rate of the service flow.
Minimum Reserved Traffic Rate	Minimum reserved rate of the service flow.
Service Flow Scheduling Type	Scheduling type of the service flow (one of the five defined QoS classes).
Tolerated Jitter	Maximum delay variation of the connection.
Maximum Latency	Maximum latency between the reception of a packet and the forwarding of this packet.

TABLE II
RECEIVER SNR ASSUMPTIONS (VALUES OF THE IEEE 802.16E STANDARD)

Modulation	Coding	Receiver SNR (dB)
BPSK	1/2	3.0
QPSK	1/2	6.0
	3/4	8.5
16-QAM	1/2	11.5
	3/4	15.0
64-QAM	2/3	19.0
	3/4	21.0

III. WIMAX CAPACITY

In this paper, we consider the OFDM PHY layer. The system capacity determines the maximum throughput that the WiMAX system can support without excessively decreasing the quality of service of the different connections. The system capacity strongly depends on the number of OFDM symbols in the frame. In the rest of this paper, a symbol is an OFDM symbol unless where mentioned. The IEEE 802.16 standard specifies that two symbols are taken for the preamble, used for synchronization, and one symbol for the Frame Control Header (FCH). The main broadcast messages are the downlink map (DL-MAP) and uplink map (UL-MAP) broadcast MAC management messages. When the BS makes the scheduling decision, it informs all the SSs, at the beginning of each frame, about his OFDM symbols allocation. This information is transmitted through the DL-MAP and UL-MAP messages, for the downlink and uplink directions, respectively. If the Modulation and Coding Scheme (MCS) used for the DL-MAP and UL-MAP is BPSK 1/2 (the most robust MCS), the size of the DL-MAP is (64 + 32 * n) / 96, and the size of UL-MAP is (56 + 48 * n) / 96, where:

- n: represents the total number of SSs that are served in the current frame (active SSs).
- 96: represents the number of useful bits carried by an OFDM symbol.
- 32 and 48: represent the number of bits carried by a DL-MAP Information Element (DL-MAP_IE) and UL-MAP Information Element (UL-MAP_IE), respectively.

Then, the total number of symbols per frame is computed. If we subtract from it the number of symbols used for the preamble, FCH, and broadcast messages, we obtain the number of symbols used for data transmission.

For the OFDM PHY, the total number of subcarriers is equal to 256 (N_{FTT} = 256) where only 192 subcarriers are used for useful data transmission. The sampling factor, denoted fs, is equal to the nominal channel bandwidth BW multiplied by the sampling factor n.

The time duration of an OFDM symbol (TD_{OFDM}) can be computed as follows:

TD_{OFDM} = useful symbol time + guard time
TD_{OFDM} = useful symbol time + *G* * useful symbol time
TD_{OFDM} = 1 / (one subcarrier spacing) * (1 + *G*)
TD_{OFDM} = [1 / (f_s / N_{FTT})] * (1 + *G*)
TD_{OFDM} = [1 / (*n* * *BW* / N_{FTT})] * (1 + *G*)

Given the values of *BW*, *n*, and *G*, the OFDM symbol duration can be computed. With frame duration of 20 ms, channel bandwidth of 5 MHz, sampling factor of 144/125, and Cyclic Prefix (CP) ratio, denoted *G*, of 1/4, the OFDM symbol duration is equal to 55.5 μs and the total number of symbols is equal to 360 symbols. Those symbols are used for the preamble, FCH, broadcast messages and downlink bursts. We recall that the number of symbols used for the broadcast messages depends on the number of SSs ((64 + 32 * *n*) / 96 + (56 + 48 * *n*) / 96). Given the MCS used, *G*, and the number of SSs, we can compute the spectrum efficiency (see Table III).

IV. SIMULATION MODEL

Our developed module is based on the NITS implementation [4] of the WiMAX module. The simulator used is Network Simulator (NS-2) version 2.29 and the programming language is the C++. The existing implementation contains two main modules: the PHY and MAC modules. The PHY module consists of the OFDM PHY layer with some configurable parameters such as the transmitter power, the cyclic prefix, and the frequency bandwidth. The MAC module supports the TDD mode. It also contains some configurable parameters such as the frame duration, burst modulation and contention size. In addition to the PHY and MAC modules, the existing implementation contains management messages such as the Downlink Channel Descriptor (DCD), Uplink Channel Descriptor (UCD), DL-MAP, UL-MAP, ranging request, ranging response, registration request, and registration response messages.

Our contribution consists of the addition of some QoS parameters to the service flow, the link adaptation, and some scheduling methods for the UGS, rtPS, and BE QoS classes. We also implemented unicast and contention request opportunities as defined in the standard. The main parameters of the simulation model are represented in Table IV.

A. Service Flow

The parameters of the service flows allow the BS to identify the service requirement for the associated connection. The

TABLE III
SPECTRUM EFFICIENCY VALUES EXPRESSED IN BIT/S/HZ

n	G	BPSK 1/2	QPSK 1/2	QPSK 3/4	16QAM 1/2	16QAM 3/4	64QAM 2/3	64QAM 3/4
1	1/32	0.41	0.82	1.23	1.64	2.46	3.28	3.69
1	1/16	0.4	0.8	1.2	1.6	2.4	3.2	3.6
1	1/8	0.38	0.76	1.14	1.52	2.28	3.04	3.42
1	1/4	0.34	0.68	1.02	1.36	2.04	2.72	3.06
10	1/32	0.41	0.82	1.23	1.64	2.46	3.28	3.69
10	1/16	0.39	0.78	1.17	1.56	2.34	3.12	3.51
10	1/8	0.37	0.74	1.11	1.48	2.22	2.96	3.33
10	1/4	0.33	0.66	0.99	1.32	1.98	2.64	2.97

TABLE IV
MAIN PARAMETERS OF THE SIMULATION MODEL

Parameters	Values
Frequency band	5 MHz
Sampling factor	144/125
Propagation model	Two Ray Ground
Antenna model	Omni antenna
Antenna height	1.5 m
Transmit antenna gain	1
Receive antenna gain	1
System loss factor	1
Transmit power	0.025
Receive power threshold	205e-12
Carrier sense power threshold	0.9 * Receive power threshold
Link adaptation	Enabled
Frame duration	20 ms
Cyclic prefix (CP)	0.25
Mean packet length	1024 bytes
Simulation duration	100 s

existing module contains only the SFID and Service Flow Scheduling Type parameters. The added parameters are CID, Traffic Priority, Maximum sustained Traffic Rate, Minimum Reserved Traffic Rate, Tolerated Jitter, and Maximum Latency.

Once the service flow parameters are initialized, the addition of a new service flow can be performed. This needs an exchange of Dynamic Service Addition (DSA) packets. These packets are defined in IEEE 802.16 and already implemented in the existing NS-2 module. There are three types of DSA packets: Dynamic Service Addition Request (DSA-REQ), Dynamic Service Addition Response (DSA-RSP), and Dynamic Service Addition Acknowledgment (DSA-ACK). These packets are used in order to create a new service flow between an SS and a BS.

Since the existing implementation of the DSA-REQ and DSA-RSP packets does not contain the service flow parameter, we add this parameter to the packets and therefore the sizes of these packets are modified. The added service flow parameter contains the following parameters: the SFID, Service Flow Scheduling Type, CID, Traffic Priority, Maximum Sustained Traffic Rate, Minimum Reserved Traffic Rate, Tolerated Jitter, and Maximum Latency parameters. In addition to the modification of the service flow parameter of the DSA-REQ and DSA-RSP packets, we need to add some instructions:

- When a DSA-REQ packet is sent, the flow service parameter is added to this packet as defined in the IEEE 802.16 standard.
- When a DSA-REQ packet is received, the service flow and QoS parameters of the created data connection are filled up from the service flow parameter of the received DSA-REQ packet. Then, a value of the CID parameter of the service flow is generated and assigned.
- When a DSA-RSP packet is sent, the service flow parameter is added to this packet.

When a DSA-RSP packet is received, the service flow and QoS parameters of the created data connection are filled up from the service flow parameter of the received DSA-RSP packet.

B. Link Adaptation

The existing implementation does not take into account the SNR values and all the subscribers use a same MCS. The default value of the used MCS is BPSK . To provide the possibility of using different modulation and coding schemes, the BS must know the SNR values of the different subscribers. The SNR value can change during the simulation and therefore the subscribers can use different MCS. The used MCS is determined from the values of SNR which are defined by the IEEE 802.16e standard.

C. Base Station Uplink Scheduling

The existing implementation does not differentiate between the different QoS classes. The scheduling algorithm of the existing implementation is described as follows. After taking sufficient number of symbols to send its packets, the BS reserves the rest of symbols for a single station, during the whole frame, using the RR scheduler. Thus, at each frame, at most one subscriber can send its packets independently of the QoS classes. The implemented scheduling algorithm has to be changed in order to differentiate between the QoS classes and take into account the QoS parameters. In this paper, we consider only three of them: UGS, rtPS and BE QoS classes.

1) Scheduling for UGS QoS Class: The proposed UGS scheduler is described as follows. The BS determines all the subscriber stations that have UGS connections. For each UGS connection, the BS determines the transmission time using the Maximum Sustained Traffic Rate parameter. Then, the BS determines the number of symbols to be reserved using the determined transmission time and MCS used values. The available symbols must be sufficient to serve all the UGS connections. Once the number of symbols to allocate is determined, the BS updates the UL-MAP message and adds a new uplink burst.

2) Scheduling for rtPS QoS Class: The rtPS scheduling consists of two parts. The BS periodically provides unicast request opportunities. When the SS receives an unicast request polling, it sends a bandwidth request. The bandwidth request contains the length of its uplink data connection queue. We assume that subscribers are disciplined and they use these grants to only send bandwidth requests.

On the other hand, the BS provides resources to the rtPS subscribers using the received bandwidth requests. The BS performs a scheduling algorithm to determine the rtPS connections to serve. Then, it determines the number of symbols to be reserved. The BS allocates the remaining symbols if there are not enough radio resources. After each allocation, the BS updates the bandwidth to reserve in the following frames.

In this paper, we focus on the rtPS schedulers and implement some of them in our NS-2 module. The implemented schedulers are the RR, maximum Signal-to-Interference (mSIR), Weighted Round Robin (WRR), and Temporary Removal Scheduler (TRS) schedulers. We briefly describe these schedulers. The RR scheduler equitably distributes channel resources to all the SSs. The mSIR scheduler allocates radio resources to SSs that have the highest SNR. The WRR scheduler is an extension of the RR scheduler and based on static weights. The TRS scheduler [8] temporarily blocks SSs having SNR smaller than a defined threshold. We combine the TRS scheduler with the RR and mSIR schedulers (called TRS+RR and TRS+mSIR, respectively). The TRS+RR scheduler reserves 1/k of the whole radio resources if there are k SSs to schedule. While the TRS+mSIR reserves the whole radio resources for SSs that have the highest SNR.

3) Scheduling for BE QoS Class: The BE scheduling consists of two parts. The BS provides contention request opportunities at the beginning of each uplink subframe. Periodically, an SS uses the contention request opportunities to send, with contention, a bandwidth request that contains the length of its uplink data connection queue.

On the other hand, the BS provides resources to the BE subscribers using the received bandwidth requests. The BS performs the RR scheduler to determine the BE connections to serve. Then, it verifies if the SS has a bandwidth request. If it has not, the BS checks the next SS. Otherwise, the BS determines the transmission time and the number of symbols to be reserved. If there are not enough radio resources, the BS only allocates the remaining symbols and updates the bandwidth to reserve during the following frames.

V. Simulation Results

A. Rural Scenario

In the rural scenario, we assume that the subscribers use the QPSK 1/2, QPSK 3/4, or 16QAM 1/2 MCSs. There are nine UGS connections, nine rtPS connections, and two BE connections. In this section, we study the behavior of some rtPS schedulers in such SNR conditions.

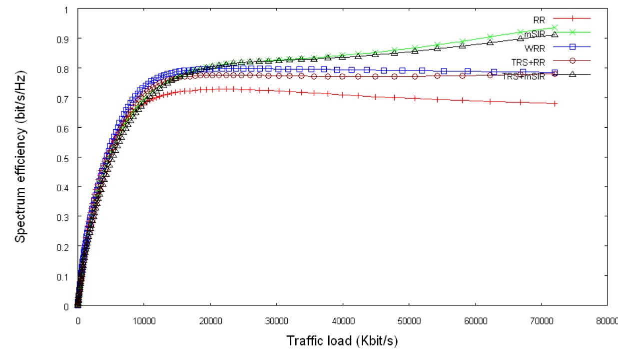

Fig. 1. Spectrum efficiency versus traffic load

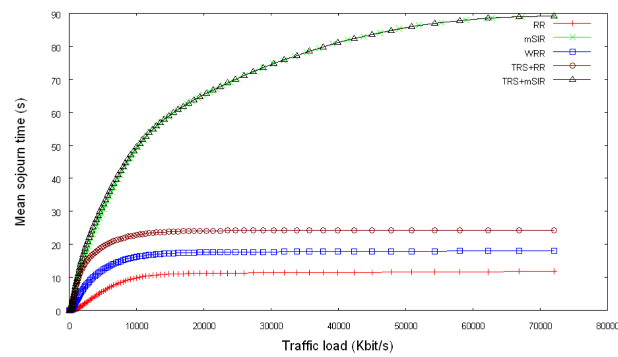

Fig. 2. Mean sojourn time versus traffic load

Fig. 1 shows the spectrum efficiency as a function of the traffic load submitted to the network. This figure shows that the spectrum efficiency is between 0.7 bit/s/Hz (for the RR scheduler) and 0.93 bit/s/Hz (for the mSIR scheduler). We observe that the TRS+mSIR scheduler is less efficient than the mSIR scheduler. This is because the TRS+mSIR scheduler may temporarily block the traffic of the SSs having small SNR even if there are remaining symbols for data frame transmissions.

We also note that the WRR and TRS+RR schedulers outperform the RR scheduler. This is due to the taking into account the SNR of the different subscribers. Indeed, the WRR scheduler assigns high weights to the SSs having higher SNR. On the other hand, the TRS+RR scheduler temporary blocks the SSs having small SNR.

The mean sojourn time is shown on Fig. 2. We point out that the mean sojourn time represents a vital parameter for real applications. We interestingly note that the mSIR and TRS+mSIR schedulers require a large average delay to deliver data frames. This is due to the traffic freeze of the SSs having small SNR. We observe that the three others schedulers exhibit a mean sojourn time less than 20 s even if the networks is overloaded. This is because these schedulers do not block any connection independently of its SNR.

B. Urban Scenario

In the urban scenario, we assume that the subscribers use the 16QAM 3/4, 64QAM 2/3, or 64QAM 3/4 MCSs. There

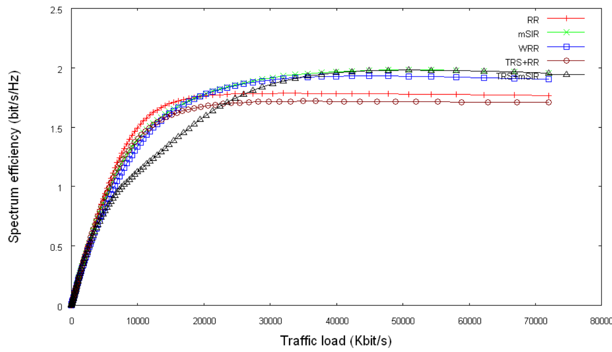

Fig. 3. Spectrum efficiency versus traffic load

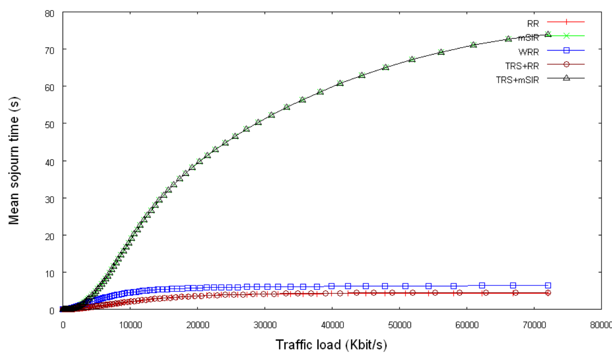

Fig. 4. Mean sojourn time versus traffic load

are nine UGS connections, nine rtPS connections, and two BE connections. In this section, we study the behaviour of some schedulers in such SNR conditions.

Fig. 3 depicts the spectrum efficiency as a function of the traffic load. This figure shows that the spectrum efficiency of the five schedulers is between 1.71 bit/s/Hz (for the TRS+RR scheduler) and 2.03 bit/s/Hz (for the mSIR and TRS+mSIR schedulers). We note that the RR scheduler, with spectrum efficiency equal to 1.79 bit/s/Hz, outperforms the TRS+RR scheduler. Indeed, the TRS+RR scheduler does not block any SS because of the high SNR values of all the subscribers. Moreover, since a preamble is added to each uplink burst, the BS schedules less useful symbols when it serves more SSs per frame.

We also observe that the WRR scheduler, with spectrum efficiency equal to 1.95 bit/s/Hz, outperforms the RR and TRS+RR schedulers. This is due to the taking into account the MCSs used by the different SSs.

The mean sojourn time of the five schedulers is shown in Fig. 4. As the mSIR and TRS+mSIR schedulers block the traffic of the SSs having small SNR, we observe that the mean sojourn of these schedulers is very high.

We also note that the three other schedulers exhibit a mean sojourn time less than 6.5 s. The RR and TRS+RR schedulers slightly outperforms the WRR scheduler. This is because the complete cycle of the WRR scheduler is longer than that of the RR and TRS+RR schedulers.

VI. Conclusion

In this paper, we considered the capacity and spectrum efficiency of WiMAX. We consider both simple analytical computations and NS-2 simulations. Evidently, WiMAX capacity is completely dependent of the scenario (the environment) and the scheduling algorithm. The mSIR and TRS+mSIR schedulers provide the highest spectrum efficiency at low and high SNR conditions (0.93 bit/s/Hz and 2.03 bit/s/Hz, respectively). The RR, WRR, and TRS+RR schedulers provide mean sojourn time smaller than 6.5 s and 20 s at high and low SNR conditions, respectively. The WRR scheduler outperforms the RR and TRS+RR schedulers with spectrum efficiency equal to 0.8 bit/s/Hz and 1.95 bit/s/Hz at low and high SNR conditions, respectively. At high SNR conditions, the mSIR and TRS+mSIR schedulers slightly outperform the WRR scheduler with a difference between spectrum efficiency values equal to 0.08 bit/s/Hz while this difference is almost the double at low SNR conditions.

Our results are obtained for an environment where all the available bandwidth is used in every cell of the network. Yet, it is now well-known that a reuse factor of the order of 3 is needed (see, e.g., [9]) if intelligent antennas techniques such as MIMO (Multiple-Input, Multiple-Output) and smart antennas are not used. Then, our figures represent rather optimistic values if intelligent antennas techniques are not applied. As future research, we intend to study WiMAX capacity for other scheduling algorithms and other environments.

Acknowledgment

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