On the Performance Bounds of OFDM-based 802.16 Broadband Wireless Networks

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***Abstract*—In this paper, we evaluate the performance bounds of 802.16 technology under different physical and MAC parameters settings. The saturation throughput that can be reached in 802.16 networks is investigated through several scenarios in which we vary for instance the frame duration, the channel bandwidth, and the modulation and coding scheme in use. An original analytical framework was developed based on technical properties and system profiles specified by the IEEE 802.16 standard for systems using the WirelessMAN-OFDM (Orthogonal Frequency Division Multiplexing) air interface. The obtained results outline the importance of considering the MAC and physical overhead when evaluating the performance of 802.16 networks. They also highlight the impact of packing and fragmentation techniques, proposed by IEEE 802.16 standard, on the MAC performance and show the trade-off between decreasing the channel bandwidth and increasing the resulting saturation throughput.**

***Keywords:* IEEE 802.16, OFDM, analytical framework, performance bounds, saturation throughput**

I. INTRODUCTION

The development of 802.16 standards for Broadband wireless access technologies was motivated by the rapidly growing need for high-speed, ubiquitous and cost-effective access. To achieve this ambitious goal, IEEE 802.16 technology addresses multiple service classes and offers the possibility of adapting the modulation and coding schemes based on the channel conditions. It also proposes a set of mechanisms such as packing and fragmentation to allow efficient use of the available bandwidth. The standard, however leaves open the resource management and scheduling issues.

Unlike in [3], our main focus here is not to propose a scheduling mechanism for 802.16 QoS classes, rather we are interested in evaluating the performance of 802.16 systems regardless of the scheduling mechanism in use. The main parameter investigated in this paper is the saturation throughput that may be reached in 802.16 networks depending on the packet size, the frame duration, the channel bandwidth, and the modulation and coding scheme in use. Our study is based on an analytical framework in which we detail the main features related to systems operating with the WirelessMAN-OFDM air interface. To the best of our knowledge, this is the first study that focuses on the performance bounds of the OFDM-based IEEE 802.16 systems considering all the overhead induced by the MAC and PHY layers. Indeed usually the performance of IEEE 802.16 networks is evaluated based on the QoS architecture proposal [4], [5], [6] and only a very few works take into account the resulting overhead (management and control messages, MAC headers, gap and contention intervals, etc.) when proposing a new scheduling or CAC algorithm [7].

Therefore our analysis is aimed at outlining the impact of a number of key concerns that have not been sufficiently addressed in previous research works. We highlight for instance the importance of MAC and physical overhead that is usually ignored or roughly estimated causing an over-estimation of the channel capacity. Also we show the benefits and limits of packing and fragmentation techniques along with their impact on MAC efficiency. In other words, for which kind of traffic they may be cost-effective and when they may yield negligible improvement of the throughput. A similar work has been done by Xhafa *et al.* [8] for the IEEE 802.16e networks based on an analysis of the OFDMA frame structure [1]. The authors have studied the impact of the MAC frame size, the MAC SDU (Service Data Unit) sizes, and the number of connections on the overall MAC performance of the IEEE 802.16e networks considering both sectorized and non-sectorized cell scenarios.

The remainder of this paper is structured as follows. Section II gives an overview of 802.16 standard. An analytical framework considering technical properties of WirelessMAN-OFDM PHY variant is developed in Section III. The performance evaluation study is detailed in Section IV. Section V concludes the paper by outlining the main obtained results.

II. OVERVIEW OF 802.16

The IEEE 802.16 Standard [2] specifies the air interface for fixed BWA systems in the frequency ranges 10-66 GHz and sub 11 GHz. The standard covers both the Media Access Control (MAC) and the physical (PHY) layers. The 802.16 MAC layer was designed to accommodate different PHYs and services, which address the needs of different environments. In this paper, systems of interest are those operating at frequencies below 11 GHz—where line-of-sight (LOS) is not required—and using OFDM modulation known as "WirelessMAN-OFDM" air interface.

The basic topology of an IEEE 802.16-based network consists of one Base Station (BS) and one or more Subscriber Stations (SSs). In point-to-multipoint (PMP), which is the only mode for sharing media considered in this paper, the SSs within a given antenna sector receive the same transmission broadcast by the BS—corresponding in general to the ISP—on the downlink channel (DL). Each SS is required to capture and process only the traffic addressed to itself . On the uplink channel (UL) however, the Time Division Multiple Access (TDMA) scheme is applied. Downlink and uplink channels are duplexed using one of the two following techniques: Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). In this paper, we focus on 802.16 systems operating in TDD mode. Figure 1 shows an example of the OFDM frame structure in TDD mode. It is worth mentioning that the description of this structure is relevant for the remaining of the paper since the whole analytical framework, presented in Section III, is based on.

In the IEEE 802.16, the channel consists of a fixed-length frames, as shown in Figure 1. Each frame is divided into a DL and an UL subframes. [2] specifies that, when using TDD, the UL subframe and DL subframe durations shall vary within the same shared frame. The downlink subframe consists of one single PHY PDU (Protocol Data Unit) while the uplink subframe consists of two contention intervals followed by multiple PHY PDUs, each transmitted by a different SS. The first contention interval is used for ranging which is the process of adjusting the Radio Frequency (RF). The second interval may be used by the SSs to request bandwidth since bandwidth is granted to SSs on demand. Two gaps separate the downlink and uplink subframes: transmit/receive transition gap (TTG) and receive/transmit transition gap (RTG). These gaps allow the BS to switch from the transmit to receive mode and vice versa.

The downlink PHY PDU consists of one or more bursts, each transmitted with a specific burst profile; a burst profile is a set of parameters describing the transmission properties (modulation type, forward error correction (FEC) type, etc.) corresponding to an interval usage code (IUC). The length of each burst is set by the BS. Indeed, at the beginning of each frame, the BS schedules the uplink and downlink grants (by mechanisms that are outside the scope of the Standard) and then broadcasts the DLFP (DL Frame Prefix), the DL-MAP and the UL-MAP informing the SSs of its scheduling decisions. The DLFP describes the location and profile of the first downlink bursts (at most four). The DL-MAP, when sent, describes the location and profile of the other downlink bursts—if any. The UL-MAP should be transmitted in each frame. It contains information elements (IE) that indicate the types and the boundaries of the uplink allocations directed to the SSs. As can be seen from Figure 1, the UL-MAP, the DL-MAP as well as the other broadcast MAC control messages are transmitted in the first DL burst. The profile of each downlink and uplink burst are specified in the Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD), respectively. The BS broadcast the DCD and the UCD messages periodically—every DCD/UCD Interval—in order to define the characteristics of the downlink and uplink physical channels. Referring to Figure 1, we note that each burst consists of one or more MAC PDUs. The burst may also contain padding bytes since each burst should consist of an integer number of OFDM symbols. UL bursts begin with a preamble used for PHY synchronization.

III. ANALYTICAL FRAMEWORK

In this section, we first need to detail some technical features related to WirelessMAN-OFDM PHY. Secondly we carry out an analytical study of the OFDM PHY frame structure described in Section II. This study is aimed at giving analytical expressions of the saturation throughput that may be reached in 802.16 networks while taking into account the MAC and PHY overhead. As mentioned in Section II, WirelessMAN-OFDM PHY is designed for frequencies below 11 GHz where LOS is not necessary and where multipath may be significant. To collect multipath, a cyclic prefix (CP) is used. This prefix corresponds to a copy of the last T_g of the useful symbol time T_b of an OFDM symbol T_{sym}. The OFDM symbol transmission time is then expressed as follows: $T_{sym} = T_g + T_b$; where the guard time T_g is given by: $T_g = g * T_b$. g corresponds to the ratio of CP time to useful time.

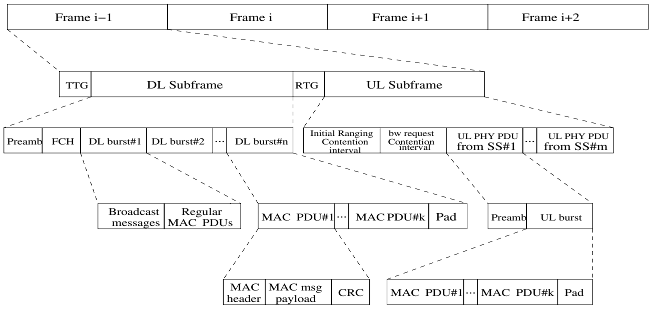

Fig. 1. OFDM Frame Structure with TDD

System Profile ID	BW (MHz)	Sampling factor n
profP3_1.75	1.75	8/7
profP3_3	3	86/75
profP3_3.5	3.5	8/7
profP3_5.5	5.5	316/275
profP3_7	7	8/7

TABLE I
WIRELESSMAN-OFDM SYSTEM PROFILES

As for the frequency domain structure, an OFDM symbol is composed of data subcarriers (for data transmission), pilot subcarriers (for estimation purposes) and null subcarriers such as guard subcarriers. The total number of subcarriers corresponds to the fast fourier transform (FFT) size N_{fft}. According to [2], $N_{fft} = 256$. Let BW, n and F_s denote the nominal channel bandwidth, the sampling factor and the sampling frequency, respectively. The sampling frequency corresponds to: $F_s = n * BW$. The value of the sampling factor n depends on the channel bandwidth BW as it is illustrated by Table I. The values of BW to be considered in this paper correspond to those specified in the system profiles proposed by the IEEE 802.16 standard [2] for systems operating with the WirelessMAN-OFDM air interface. As shown in Table I, five PHY profiles are specified for these systems, each corresponding to a channel bandwidth. Suppose that $\triangle f$ stands for the subcarrier spacing, then: $\triangle f = F_s / N_{fft}$ and the useful time is given by: $T_b = 1/\triangle f$.

Let's consider the OFDM PHY structure illustrated by Figure 1. First we focus on fixed-size fields/intervals. Therefore let us consider the following parameters:

- T_{frame}: duration of a time frame (in seconds).
- T_{av}: time duration (in seconds), still available in the frame. Initially, we have: $T_{av} = T_{frame}$.
- T_{sym}: duration of an OFDM symbol (in seconds).
- $T_{pream}^{(short)}$: duration of a short preamble (in seconds). According to [2], $T_{pream}^{(short)} = T_{sym}$.

- $T_{pream}^{(long)}$: duration of a long preamble. According to [2], $T_{pream}^{(long)} = 2 * T_{sym}$.
- T_{ttg}: duration of a transmit/receive transmission gap (in seconds).
- T_{rtg}: duration of a receive/transmit transmission gap (in seconds).
- T_{dlfp}: duration of the DLFP (in seconds). [2] specifies that $T_{dlfp} = T_{sym}$.
- $T_{opp}^{(rng)}$ and $T_{opp}^{(bw)}$: duration (in seconds) of a contention ranging and bandwidth request interval, respectively.

Note that all the above-cited parameters are multiples of T_{sym}, so we can deduct their respective durations from T_{av} since T_{av} should always be kept as an integer number of OFDM symbol duration.

$$\begin{aligned} T_{av} &= T_{frame} - \Big(T_{pream}^{(long)} + T_{dlfp} + T_{ttg} \\ &\quad + T_{opp}^{(rng)} + T_{opp}^{(bw)} + T_{rtg}\Big) \end{aligned} \tag{1}$$

Recall that the first DL burst contains the broadcast MAC control messages: DCD, UCD, DL-MAP, and UL-MAP. The sizes of these messages depend on the number of DL/UL burst profiles described in the DCD/UCD messages, and on the number of DL/UL IEs specified in the DL-MAP/UL-MAP messages, respectively. However since we are interested in the performance bounds of 802.16 systems, we will consider only one SS and one BS[1]. We also assume that the SS sends continuously to the BS and does not receive any data from it. It is important to mention that a descriptor should be included into DCD message for each DIUC used in the DL-MAP except those associated with Gap, End of Map and Extended IEs. Thus since we assume that no data is transmitted on the downlink, only one DL burst profile is needed to describe the transmission properties of the first DL burst carrying MAC management messages. As for the UL, a burst descriptor shall be included into the UCD message for each UIUC that is to be used in the UL-MAP. Yet, in addition to the end of map IE and to the data grant IE that will specify the amount of bandwidth granted to the SS, an initial ranging IE, and a request IE should be specified in the UL-MAP message to draw the limits of the initial ranging and bandwidth request contention intervals. Obviously, in our case, these two intervals will be reserved to the single SS belonging to the network. Each of these four IEs will be associated to an UIUC.

Based on the above considerations, let us define the following parameters:

- S_{dcd}: size (in bytes) of a DCD message specifying one DL burst profile.
- S_{ucd}: size (in bytes) of a UCD message specifying four UL burst profiles.
- S_{dlmap}: size (in bytes) of a DL-MAP message that does not specify any burst: it corresponds to the minimum size of a DL-MAP—containing only an end of map IE. Since we have only one DL burst, its limits are specified in the DLFP.
- S_{ulmap}: size (in bytes) of an UL-MAP message containing four IEs—data grant, initial ranging, request, and end of map IE.

These sizes are computed with respect to the TLV encoding form specified by the standard [2]. They include the MAC overhead (generic header and CRC field). Since DCD, UCD and DL-MAP messages are sent periodically, let $DcdToSend$, $UcdToSend$, and $DlmapToSend$ denote three boolean variables indicating whether a DCD, an UCD or a DL-MAP message will be sent in the current i^{th} frame, respectively. These parameters are set to 1 each time the timers associated to the following intervals expire: DCD Interval, UCD Interval, and Lost DL-MAP Interval, respectively. As for UL-MAP message, it must necessarily exist in each frame.

To compute the length of the first DL burst, we should take into account the possibility of padding since every burst should consist of an integer number of OFDM symbols. This rule is to be respected each time a burst size is updated. Given a burst k and its modulation and coding scheme, the number of padding bits is computed such that:

$$\frac{L_{bst}[k] + L_{pad}[k]}{L_{sym}[k]} = n; \quad n \in \mathbb{N} \quad and \quad L_{pad}[k] < L_{sym}[k] \tag{2}$$

where:

- $L_{bst}[k]$ is the number of bits transmitted in burst k (payload, MAC, and Physical overhead) except the padding bits.
- $L_{pad}[k]$ is the number of padding bits sent in burst k.
- $L_{sym}[k]$ is the number of bits per OFDM symbol for the burst k.

Applying (2) to the first burst characterized by $L_{bst}[1]$, $L_{pad}[1]$, and $L_{sym}[1]$, we obtain:

$$\begin{aligned} L_{bst}[1] &= \Big(DcdToSend * S_{dcd} + UcdToSend * S_{ucd} \\ &\quad + DlmapToSend * S_{dlmap} + S_{ulmap}\Big) * 8 \end{aligned} \tag{3}$$

and $L_{pad}[1] = compute\_pad\,(L_{sym}[1], L_{bst}[1])$; where $compute\_pad()$ is a function that returns the number of padding bits necessary for a burst k given its length and its number of bits per OFDM symbol:

$$compute\_pad\,(L_{sym}[k], L_{bst}[k]) = L_{sym}[k] - (L_{bst}[k] \% L_{sym}[k]) \tag{4}$$

Once $L_{bst}[1]$ and $L_{pad}[1]$ are computed, the available time is updated as follows:

$$T_{av} = T_{av} - \frac{L_{bst}[1] + L_{pad}[1]}{L_{sym}[1]} * T_{sym} \tag{5}$$

Referring to Figure 1, we notice that all the durations corresponding to MAC management messages, contention intervals, gaps and preambles were considered in the above study. A short preamble duration $T_{pream}^{(short)}$—necessary for SS PHY synchronization—should nevertheless be subtracted from the remaining frame duration to get the whole duration available for data transmission: $T_{av} = T_{av} - T_{pream}^{(short)}$.

Recall that our main objective is to determine the performance bounds of IEEE 802.16 systems. Therefore it is interesting to compute the maximum number of PDUs N_{pdu}^{max}

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[1] Just a few modifications are needed to adapt the analytical study to a more general case involving many SSs with different DIUC/UIUC.

that may be transmitted by the SS during the available time. Obviously, this parameter depends on the considered size of the MAC SDU (S_{pkt}), on the modulation and coding scheme used for the UIUC in addition to other PHY parameters like the channel bandwidth BW and the frame duration T_{frame}.

$$N_{pdu}^{max}(S_{pkt}) = \frac{(T_{av}/T_{sym}) * L_{sym}[k]}{(S_{gmh} + S_{pkt} + S_{crc}) * 8} \tag{6}$$

As can be seen in (6), the MAC overhead corresponding to the CRC field and to the MAC generic header and resulting from the transmission of each MAC PDU, are taken into account. Based on (6), the maximum MAC goodput—corresponding to the maximum IP throughput (in bps)—that can be reached in such a configuration of 802.16 networks, can be derived as follows:

$$Thput^{max}(S_{pkt}) = \frac{N_{pdu}^{max}(S_{pkt}) * S_{pkt} * 8}{T_{frame}} \tag{7}$$

IV. PERFORMANCE EVALUATION

As mentioned in Section I, the main parameter investigated in our study is the saturation throughput. The saturation throughput is defined as the highest data rate that could be achieved in the medium. This metric is very important in wireless networks and provides an absolute limit of the amount of data packets that could be successfully sent in the channel. The value of the saturation throughput depends on the overhead induced by the medium access control mechanism. In this section, g is set to 1/4, the value of both T_{ttg} and T_{rtg} is $2 * T_{sym}$, $T_{opp}^{(rng)}$ and $T_{opp}^{(bw)}$ are set to 1 and 4 OFDM symbols, respectively. N_{dl_bp}, N_{ul_bp}, N_{dlmap_ie}, and N_{ulmap_ie} stand for the number of DL burst profiles, UL burst profiles, DL-MAP IEs, and UL-MAP IEs, respectively. These parameters are set to 1, 4, 1, and 4, respectively. Other parameters such as the channel bandwidth, the frame duration, and the modulation and coding scheme will be fixed according to the objective of each scenario. The effect of these parameters on MAC efficiency is investigated in several scenarios.

A. *Effect of frame duration and modulation and coding scheme*

To show the impact of the frame duration and the modulation and coding scheme on the MAC goodput we consider two scenarios. In the first one, we set the frame duration to 20 ms and compute the resulting IP throughput for different modulation and coding schemes. In the second one, we fix the modulation and coding scheme to 64-QAM 3/4 and compute the resulting IP throughput for different frame durations. In both scenarios, the channel bandwidth BW is set to 7 MHz. Figures 2(a) and 2(b) depict the IP throughput variation, as a function of MAC SDU size, for scenario 1 and scenario 2, respectively.

As expected, the IP throughput increases with frame duration as shown in Figure 2(b) and, as depicted in Figure 2(a), the less robust is the burst profile, the higher is the obtained IP throughput. It is interesting to see that for all the modulation and coding schemes considered in the first scenario, the maximum throughput is reached for nearly the same packet size (more than 100 bytes) and it remains almost the same. However, as can be seen in Figure 2(b), a higher fluctuation on MAC goodput can be observed when the frame duration gets shorter. Indeed for a frame duration of 5 ms, the IP throughput fluctuates from almost 9 Mbps to more than 12 Mbps, depending on the packet size; and the bigger is the MAC SDU size, the higher is the fluctuation. This may be explained by the fact that since the fragmentation capability is disabled, in these first scenarios, the possibility that a big packet cannot be transmitted is more likely to happen when the frame duration is short which increases the resulting throughput. Note that the maximum IP throughput (19.275 Mbps) obtained for a frame duration of 20 ms and 64-QAM 3/4 as modulation and coding scheme, corresponds to the saturation throughput of the considered systems since it uses the biggest channel bandwidth (7 MHz) specified by the system profiles of IEEE 802.16 standard, the longest possible value of frame duration (20 ms) and the less robust modulation and coding scheme (64-QAM 3/4).

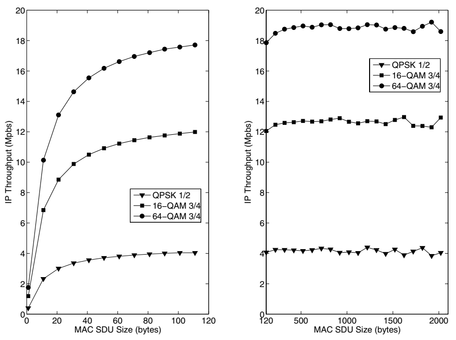
We are still investigating the effect of the frame duration and the modulation and coding scheme on MAC performances. However, in this case, we are more interested on how the whole frame is used: what are the respective proportions—in terms of time—of payload and overhead and what would be the amount of wasted bandwidth in absence of fragmentation. Therefore we introduce two parameters which are the overhead and the wasted time. The overhead (in terms of time) is computed as follows:

$$\begin{array}{rcc} Ovhd^{max}(S_{pkt}) = & & T_{frame} - T_{av} \\ & + & \Big(N_{pdu}^{max}(S_{pkt}) * (S_{gmh} + S_{crc}) * 8 \\ & + & compute\_pad\,(L_{sym}[k], L_{bst}[k])\,\Big) \\ & / & L_{sym}[k] * T_{sym} \end{array} \tag{8}$$

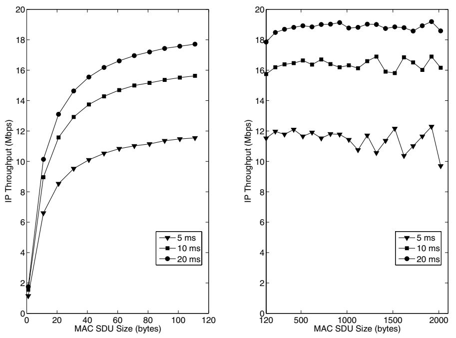
where T_{av} corresponds to the last value of available time. The overhead corresponds then to the ratio of time—of the frame duration—used for gaps, preambles, contention intervals, and management messages transmission. It also includes the MAC overhead resulting from the transmission of the maximum number of PDUs and the necessary padding. The wasted time corresponds then to the remaining of the frame duration, after omitting the overhead (8) and the time needed for the transmission of the maximum number of PDUs (6). These three proportions of the time frame are illustrated in Figures 3(a) and 3(b) for three values of T_{frame}: 5 ms, 10 ms, and 20 ms. What makes the difference between these two figures is that in Figure 3(a), we suppose that the SS uses QPSK 1/2 modulation and coding scheme while in 3(b), 64-QAM 3/4 is used.

Figure 3(a) shows that the longer is the frame, the bigger is the proportion of time reserved for payload transmission and the smaller are the proportions of overhead and wasted time. It is worth mentioning that the overhead may constitutes more than 90% of the frame duration for packets of less than 400 bytes; and this is more likely to happen since, according to [9], almost 75% of the packets of the Internet traffic are smaller than 522 bytes and nearly half of the packets are 40 to 44 bytes in length. In the case of 5 ms frame duration, even for bigger MAC SDUs, the overhead may reach more than 40% of the total frame size.

Now let us compare two frame compositions corresponding to the same frame duration but using two different modulations. If we consider for instance a frame duration of 5 ms in both cases (Figure 3(a) and 3(b)), we observe that the ratio of overhead increases when using 64-QAM 3/4. This may be



(a) 20 ms



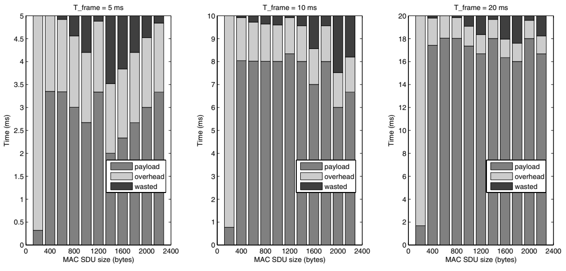
(b) 16-QAM 3/4

Fig. 2. Effect of frame duration and modulation and coding scheme on IP throughput

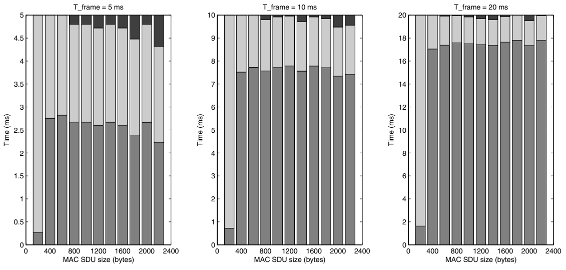
explained as follows. Using a less robust modulation (64-QAM 3/4) implies a bigger number of bits per OFDM symbol which offers the possibility of sending more MAC PDUs but also more MAC headers and CRC fields. It also implies the possibility of more padding bits when necessary, in other words more overhead. However having bigger proportion of overhead—in terms of time—does not mean necessarily a decrease of resulting IP throughput since for the same duration, more data can be sent when using 64-QAM 3/4 than when using QPSK 1/2, as we have seen in Figure 2(b). Also when comparing Figure 3(a) and 3(b), we notice that the ratio of wasted time decreases in the case of 64-QAM 3/4, which decreases the effect of absence of fragmentation. Indeed having the possibility of sending more data within the same duration increases the chance of sending even big MAC PDUs and then saving bandwidth.

B. *Effect of channel bandwidth*

Recall that in previous scenarios, the channel bandwidth was fixed to 7 MHz. The scenarios considered here are aimed at showing the effect of the channel bandwidth on MAC goodput, therefore we will consider different values of channel bandwidth which implies different values of sampling factor (see Table I) and consequently different durations of OFDM symbol as we have seen in Section III. However, we are more interested here in evaluating the MAC efficiency than in knowing the corresponding value of IP throughput. The MAC efficiency is defined as the percentage ratio between the MAC goodput and the physical rate.



(a) QPSK 1/2



(b) 64-QAM 3/4

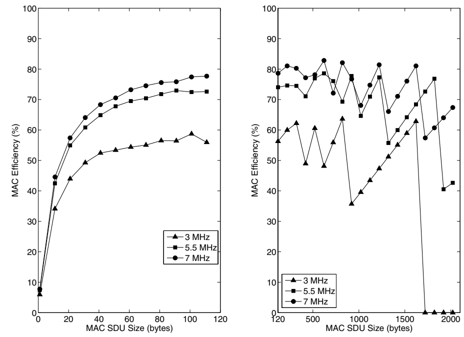
Fig. 3. Effect of frame duration and modulation and coding scheme on bandwidth utilization

Figure 4(a) and 4(b) depict the MAC efficiency as a function of the MAC SDU size for three values of channel bandwidth: 3, 5.5, and 7 MHz. Note that each value corresponds to one of the PHY systems profiles specified by the IEEE 802.16 standard and reported in Table I. The results presented in both figures are obtained for a frame duration of 10 ms. However in Figure 4(a), QPSK 1/2 is used while in 4(b) the modulation and coding scheme is set to 64-QAM 3/4.

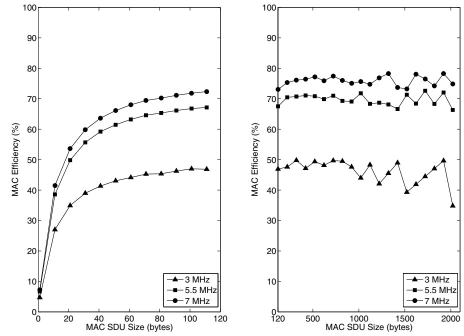
Comparing the two figures, we observe that the obtained curves fluctuate a lot when using QPSK 1/2, and the larger is the bandwidth channel, the less visible is the fluctuation. This effect is similar to the one observed when varying the frame duration in 2(b) but here it is more noticeable. In Figure 4(a), we see that for a channel bandwidth of 3 MHz, reaching a certain value of MAC SDU size (almost 1600 bytes), packet transmission is no longer possible with a frame duration of 10 ms. This is due not only to the shortness of channel bandwidth and frame duration but also to the absence of fragmentation. The two other curves corresponding to a channel size of 5.5 and 7 MHz, respectively exhibit almost the same behavior. Indeed, with MAC SDUs of more than 100 bytes, the MAC efficiency for 5.5 MHz fluctuates between 43.05 % and 80.84 % while for 7 MHz it varies between 56.5 % and 84.7 %. With a modulation and coding scheme of 64-QAM 3/4, the same behavior is noticed since MAC efficiency fluctuates between 64.16 % and 73.29 % for a channel bandwidth of 5.5 MHz while it is between 71.66 % and 76.79 % for a channel bandwidth of 7MHz. The conclusion that may be derived from this is that the use of more than 20 % of extra bandwidth in the case of a channel size of 7 MHz does not imply a considerable improvement on MAC efficiency.

C. *Impact of fragmentation and packing*

Till now, the observed MAC performances were obtained when fragmentation and packing were disabled. However, we



(a) 10 ms and QPSK 1/2



(b) 10ms and 64-QAM 3/4

Fig. 4. Effect of channel bandwidth on MAC efficiency

are interested in seeing how we could take advantage of these techniques, offered by the IEEE 802.16 standard [2], to improve the MAC efficiency. For this purpose, we consider the same plot shown in Figure 3(a) for a frame duration of 10 ms. Recall that this plot was obtained when both fragmentation and packing were deactivated. In the proposed scenario, we keep the same frame duration and modulation and coding scheme i.e. 10 ms and QPSK 1/2, respectively.

As fragmentation and packing are mutually exclusive [2], we first activate packing and prohibit fragmentation (see Figure 5). Note that we consider the fixed-length MAC SDUs variant of packing since the MAC SDUs have the same size. Comparing the proportions of overhead obtained when packing is activated and when not (Figure 5), we notice that packing has almost no impact on wasted ratio however it considerably increases the throughput when the MAC SDUs are small. This may be explained by the fact that when packing fixed-length MAC SDUs, only one packing subheader is needed for the whole MAC PDU (see Section II) what decreases considerably the resulting overhead particularly for small MAC SDUs (less than 400 bytes). Indeed instead of having a MAC header and a CRC field for each MAC SDU, we need only one generic MAC header, one CRC field, and a single packing subheader for all the MAC SDUs transmitted during a time frame. Still referring to Figure 5, we are interested in seeing the impact of fragmentation on the frame composition. Comparing the case where packing and fragmentation are disabled to when the latter is enabled, we notice that the unused proportion of bandwidth is used to send more data and of course the resulting overhead. However the improvement of IP throughput is hardly visible even though we are considering the optimal fragmentation case i.e. where the fragment size is adapted to the unused bandwidth.

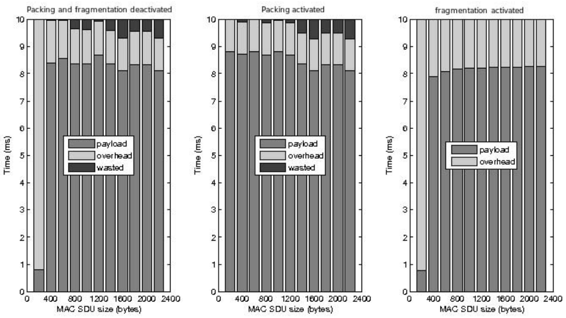


Fig. 5. Effect of packing and fragmentation

V. CONCLUSION

In this paper, an original analytical framework was developed to investigate the performance bounds of OFDM-based 802.16 systems. This analytical framework was carried out with respect to what have been specified in the IEEE 802.16 standard [2]. It outlines a number of key features proposed by the standard and that have been hardly addressed in previous research works. Based on this framework, several scenarios were considered to evaluate the performance bounds of 802.16 systems under different MAC and PHY settings. The obtained results highlight the importance of considering the MAC and PHY overhead when evaluating the performance of IEEE 802.16 systems. Indeed this overhead, that is usually ignored or roughly estimated in most research works, may constitute 80 % of the whole frame. Also we have shown that using a larger bandwidth channel may yield minimal improvements on MAC performances. Also when investigating fragmentation and packing impact on MAC performance, we have shown that packing may considerably improve the resulting throughput especially for Unsolicited Grant Service (UGS) traffic carrying fixed-size packets. The fragmentation technique however provided insignificant improvements.

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