Optimal MAC PDU Size in ARQ-enabled Connections in IEEE 802.16e/WiMAX Systems

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Abstract: In this paper we address an aspect of the mutual influence between the PHY layer budding blocks (FEC blocks) and the MAC level allocations in the Uplink and Downlink of IEEE 802.16e/WiMAX systems, In these systems it is possible to transmit MAC level frames, denoted MAC PDUs, such that a PDU contains an integral number of fixed size Data Blocks. We compute the optimal size of a PDU that maximizes the Goodput of the PDU. The Goodput depends on the success probability of the PDU, which in turn depends on the FEC blocks over which the PDU is allocated. We then compare among the maximum PDU Goodputs in different sizes of the FEC blocks and the Data Blocks. The main outcome is that the PDU Goodput is sensitive only in the case where Data Blocks are very large. We also give guidelines on how to choose the best Modulation/Coding Scheme (MCS) to use in a scenario where the Signal-to-Noise Ratio (SNR) can change significantly during transmissions, in order to maximize the PDU Goodput.

1 INTRODUCTION

Broadband Wireless Access (BWA) networks constitute one of the greatest challenges for the telecommunication industry in the near future. These networks fulfill the need for range, capacity, mobility and QoS support from wireless networks. IEEE 802.16e (IEEE, 2005), also known as WiMAX (Worldwide Interoperability for Microwave Access) is the industry name for the standards being developed for broadband access.

IEEE 802.16e is a cell based, Point-to-MultiPoint (PMP) technology, providing high throughput in Wireless Metropolitan Area networks (WMANs) . The IEEE 802.16e standard reference model includes the Physical and Medium Access Control (MAC) layers of the OSI protocol stack. Multiple physical layers are supported, operating in the 2-66 GHz frequency spectrum and supporting single and multi-carrier air interfaces, each suited to a particular environment. For IEEE 802.16e to be able to fulfill the promise for high speed service, it must efficiently support advanced Modulation and Coding schemes (MCSs) and progressive scheduling and allocation techniques.

In this study we focus on the influence between the PHY layer budding blocks (FEC blocks) and the length of the MAC layer frames denoted *MAC PDUs*, in the Uplink and Downlink of IEEE 802.16e systems, assuming that Data Blocks are transmitted in the PDUs, as will be explained later.

1.1 The IEEE 802.16e/WiMAX Network Structure

IEEE 802.16e/WiMAX is a standard for a Broadband Wireless Access (BWA) network (IEEE, 2005) which enables home and business subscribers high speed wireless access to the Internet and to Public Switched Telephone Networks (PSTNs). The system is composed of a Base Station (BS) and subscribers, denoted Mobile Stations (MSs), in a cellular architecture. The transmissions in a cell are usually Point-to-Multipoint, where the BS transmits to the subscribers on a Downlink channel and the subscribers transmit to the BS on an Uplink channel.

A common PHY layer used in IEEE 802.16e is Orthogonal Frequency Division Multiple Access (OFDMA) in which transmissions are carried in *transmission frames* (IEEE, 2005). Every frame is a matrix in which one dimension is a sub-channel (band of frequencies) and the other dimension is time. A cell in the matrix is denoted as a *slot*. The number of data bits that can be transmitted in a slot is a function

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of the Modulation and Coding scheme (MCS) that is used in the slot.

A Burst in a frame is a subset of consecutive slots sharing the same MCS, which is designated to the MSs and to the BS for their transmissions. In this paper we assume that the Convolutional Turbo Code (CTC) is used as the coding scheme, and in this case a Burst also maps *Forward Error Correction (FEC) blocks* to the slots. In this paper knowing the details behind the FEC technology is unnecessary so we will not elaborate on this subject. The only property needed is that all the data bits in a FEC block have some probability p to arrive successfully at the receiver.

1.2 Transmissions in IEEE 802.16e Systems

The BS and the MSs transmit *Protocol Data Units* (PDU) within Bursts. The MAC layer of IEEE 802.16e is connection oriented and PDUs, which are the MAC level frames, thus belong to MAC connections (IEEE, 2005). Within PDUs the BS and the MSs transmit their application packets that are denoted *Service Data Units* (SDU). An SDU can be an IP packet, ATM cells, etc. The PDUs are used to map SDUs into the MAC connections, to protect the SDUs from transmission errors, to enable encryption of the SDUs, etc. Each PDU has a fixed header, denoted Generic MAC Header (GMH). This header is mainly used to associate a PDU to a MAC connection. Optionally, a PDU also has a CRC field. Any of the other aforementioned functions performed on the PDU payload requires an additional subheader. All the (sub)headers within a PDU are considered to be *PDU overhead*.

Let p be the probability that all the bits of a FEC block, after decoding, arrive correctly at the receiver. This probability is a function of several parameters such as the Coding rate, the number of decoding iterations in the case of Turbo codes (Huang, 1997), the Signal-to-Noise Ratio (SNR) of the channel and the length, in bits, of the FEC block (Huang, 1997). p is bigger for longer FEC blocks. In this paper, based on (Alpert et al., b), we assume that all the FEC blocks are of the same size and that p is similar for all the FEC blocks of a transmission frame, i.e. there is no correlation dependency between the success probabilities of FEC blocks of the same size in a transmission frame.

The probability Q that a PDU arrives correctly at the receiver is the probability that all its bits arrive correctly. This is also the probability that all the FEC blocks that contain a part of the PDU arrive correctly [1]. Thus, in view of the above assumption on p, if a PDU is transmitted within X FEC blocks, holds $Q = p^X$.

In this paper we concentrate on one type of MAC connections, *ARQ-enabled* connections. In such connections the SDUs are divided into Blocks, denoted *Data Blocks*, of the same size. This size is defined at the time when a connection is established. In the case where the length of an SDU is not an integral number of the Data Block size, the last Data Block of the SDU is shorter, but it is not padded.

The purpose of the division into Data Blocks is to enable the transmitter to know whether the SDUs it transmits arrive successfully at the receiver. This is accomplished by ARQ Feed-backs that are transmitted back from the receiver to the transmitter. The receiver notifies the transmitter about every Data Block whether it arrived successfully or not. In the case where a Data Block is not received successfully, it is retransmitted by the transmitter. The only correctness check that a receiver is performing is in the PDU level. Thus, the receiver considers all the Data Blocks in a PDU as either arriving correctly or not.

1.3 Problem Definition

In view of the influence that FEC blocks have on the success probability of PDUs, in this paper we consider one aspect of this influence and we compute the optimal length of PDUs in ARQ-enabled connections. The optimal length is defined as the PDU length that maximizes the *PDU Goodput*. The PDU Goodput is defined as the ratio between the number of data bits in a PDU that arrive correctly at the receiver, to the total number of bits of the PDU. The PDU Goodput is computed as follows.

We assume that every PDU contains the Generic MAC Header (GMH), the CRC field and one additional subheader which is used to number the Data Blocks in the connection. In addition there might be bits that are a *remainder*, as will become clear later. All the overhead and remainder bits are not counted in the Goodput computation.

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[1] This is actually an approximation. It can happen that the bits of a FEC block that are contained in a PDU arrive correctly, and thus also the PDU, while other bits of the FEC block arrive damaged. However, we use this approximation following the WiMAX radio performance testing (WiMAX, 2008). In this testing it was found that the bursty nature of errors in the air IF, and the operation of the interleaver in CTC codes, tend to disperse the bit errors (after decoding) over the FEC block, so that there is usually more than a single error, and the errors would be distant from one another. The result is that all the PDUs, with bits in a FEC block, would most likely suffer.

Assume that every PDU contains X equal sized FEC blocks. Every FEC block contains F data bits and has a probability p to arrive correctly at the receiver. Thus, as mentioned, the probability that the PDU arrives correctly at the receiver is p^X. If a PDU does not arrive correctly at the receiver all the Data Blocks in the PDU are considered to be lost and are all retransmitted.

Thus, a PDU is transmitted/retransmitted until success (Actually, there is a limit on the number of retransmissions. When this limit is reached without a positive ack, the PDU is dropped). If the success probability is p^X, and successive transmissions are independent, then the average number of transmissions is $\frac{1}{p^X}$.

Let H be the total number of overhead bits in the PDU, and R the number of bits in the remainder. Then, the PDU Goodput is $\frac{(F\cdot X-H-R)p^X}{F\cdot X}$. In this paper we find the optimal X such that the PDU Goodput is maximized, for different values of F and different Data Blocks' sizes, which have a direct relation on the amount of remainder bits in the PDU.

1.4 Related Work

The performance of IEEE 802.16e/WiMAX systems has been extensively investigated. The interested reader can find in (So-In et al., 2009) and (Sekercioglu et al., 2009) a very good survey on WiMAX performance. Most of the papers deal with scheduling methods and the efficiency of transport layer protocols in IEEE 802.16e systems. These papers assume the assignment of Bursts to MSs. However, they do not consider the issue of efficient transmissions in the Bursts. The only works that we are aware of, and that deal with the mutual influence between the PHY layer budding blocks (FEC blocks) and the MAC layer PDUs in IEEE 802.16e/WiMAX systems are (Martikainen et al., 2008), (Alpert et al., b), (Alpert et al., 2010) and (Alpert et al., a). In (Martikainen et al., 2008) the optimal size of PDUs is computed, given fixed length FEC blocks and the transmission of a Bit stream. However, the PDU size in (Martikainen et al., 2008) is not accurate because it should have been rounded off to an integral number of FEC blocks, as was shown later in (Alpert et al., b). (Alpert et al., 2010) and (Alpert et al., a) consider the division of Bursts into PDUs in a way that maximizes the utilization of the Burst. However, they do not deal with the issue of MAC connections carrying fixed length Data Blocks.

In this paper we find the optimal length of PDUs, given that only fixed size Data Blocks are transmitted in the PDUs. We are not aware of works that deal with this optimality scenario.

1.5 Our Results

We suggest an algorithm to compute the optimal length of PDUs, given that only fixed size Data Blocks are transmitted in the PDUs. We generalize the results from (Martikainen et al., 2008) and (Alpert et al., b) which deal with the optimal size of PDUs assuming the transmission of a Bit stream.

We then compare among the maximum PDU Goodputs in all the FEC blocks' sizes and Data Blocks' sizes that are allowed in the IEEE 802.16e/WiMAX standard, and find that unless the Data Blocks are not very large, the optimal PDU Goodput is not sensitive to the above sizes.

We also assume various FEC blocks' success probabilities p, $p = 0.999$, $p = 0.99$ and $p = 0.9$, and give guidelines on how to choose the proper MCS, which determines the FEC block size, in cases where the estimation of p is not accurate.

The rest of the paper is organized as follows: In Section 2 we compute the optimal PDU length for a data stream, i.e. every Data Block is one bit. We omit the algorithm that computes the optimal PDU length for the case of Data Blocks of length larger than one bit. In Section 3 we compare between the PDU Goodputs in various FEC Blocks' and Data Blocks' sizes, and give guidelines on how to determine the proper MCS.

2 THE OPTIMAL LENGTH OF PDUs WITH A BIT STREAM

We compute the maximum PDU Goodput assuming a Bit stream, i.e. we assume that the length of the Data Blocks is one bit. Let $G(X)$ be the Goodput of a PDU with X FEC Blocks. Thus, $G(X) = \frac{FX-H}{\frac{1}{p^X}\cdot FX} = p^X(1-\frac{H}{FX})$, where H is the total number of overhead bits in the PDU. In order to maximize the Goodput we derive the expression of the Goodput according to X and find that the optimal X, denoted X^*, equals

$$X^* = \frac{H}{2F}(1+\sqrt{1-\frac{4F}{Hln(p)}}) \qquad (1)$$

Notice that X^* must be an integer. Therefore, we need to check which of the two values, $\lfloor X^* \rfloor$ or $\lceil X^* \rceil$ yields a better Goodput.

3 GOODPUT RESULTS AND DISCUSSION

In IEEE 802.16e/WiMAX there are 8 possible Modulation/Coding Schemes (MCS) (IEEE, 2005). See Table 1. We only consider 7 of them since 64QAM-1/2 is practically not used (Alpert et al., 2010). In every MCS there can be various size FEC blocks. In the following discussion we only consider the longest ones. We denote the number of bits in the longest FEC block in every MCS by F. In QPSK-1/2, 16QAM-1/2 and 64QAM5/6 holds F=480. In QPSK-3/4, 16QAM-3/4, 64QAM-1/2 and 64QAM-3/4 holds F=432. In 64QAM-2/3 holds F=384. See Table 1 under column F.

The IEEE 802.16e/WiMAX also allows the following Data Blocks' sizes only : 128, 256, 512, 1024, 2048, 4096 and 8192 bits. Recall that we denote by B the size of a Data Block.

In Figure 1 we assume three FEC block success probabilities p: 0.999, 0.99 and 0.9 . In the figure we show, for the three success probabilities and for all the possible values of B and F, the maximum PDU Goodputs. We assume that the PDU contains the GMH and CRC fields of 6 and 4 bytes respectively, and one subheader of 3 bytes which contains the serial numbers of the Data Blocks. Thus, the total number of the PDU overhead bits is 104. Notice that every PDU size can also have remainder bits, which are not used for the transmission of data. This happens when the PDU size, minus the overhead bits, is not divided by the Data Block size. There is a trade-off in determining the optimal PDU length: on one hand adding another FEC block to a PDU reduces its success probability. However, on the other hand, it adds data bits to the PDU, which contribute to the Goodput. Recall that the use of fixed size *Data Blocks* only, results with remainders which reduce the Goodput. Also, especially for long Data Blocks, their size mandates a minimum number of FEC blocks in a PDU, in order to accommodate at least one Data Block.

We see for $p = 0.999$ that the Goodputs for all the possible values of B and F are almost the same, and very high, due to the high value of p. There is some reduction in the Goodput for B=8192 because many FEC blocks are needed to accommodate one such Data Block, with somewhat low PDU success probability.

For $p = 0.99$ and $512 \leq B \leq 2048$, F=432 is slightly better than the other two values of F. For $512 \leq B \leq 2048$ and F=432, the optimal PDU sizes are all 5 FEC blocks. For F=480 the optimal sizes are 11,11 and 9 FEC blocks respectively, and for F=384 they are 7,11 and 11 respectively. For all the considered values of B, F=432 has a remainder of 8 bits after 5 FEC blocks, and thus it uses the first 5 FEC blocks very efficiently. In F=480 the remainders in the short PDUs are quite large, over 200 bits, and therefore the optimal PDU size is relatively large compared to F=432, and the Goodput, therefore, is slightly lower. For F=384 the addition of one Data Block to the PDU sometimes requires the addition of two FEC blocks. On one hand this addition contributes to the Goodput because there are more data bits. On the other hand it causes the optimal PDU length to be slightly larger than for F=432, with a smaller success probability, and therefore with a small reduction in the Goodput. In summary, compared to F=480 the case of F=432 is better because of smaller remainders in the short PDUs. Compared to F=384 it is better because in the later the PDU size sometimes has "jumps" in order to accommodate an additional Data Block.

Notice that for B=4096 and B=8192 the large number of FEC blocks that is needed to accommodate at least one Data Block causes a low PDU success probability. This is the dominant parameter and the FEC blocks' sizes F and the remainders are less important. Therefore, the Goodputs are almost the same for all the values of F.

For $p = 0.9$ every additional FEC block reduces the Goodput significantly and therefore, for B=128, 256, 512, 1024 the best F is the one where a low remainder is received first. For B=128 and F=384 a remainder of 24 bits happens after 2 FEC blocks, resulting with F=384 having the best Goodput. For B=256 both F=384 and F=480 have low remainders after 3 FEC blocks while in F=432 there is a small remainder only after 4 FEC blocks. For B=512, B=1024 and F=384, a low remainder is received after 3 FEC blocks while for F=432 and F=480 the first three FEC blocks have a large remainder. Therefore, F=384 has the highest Goodput. For B=2048, 4096 and 8192 the large number of FEC blocks that is needed to accommodate at least one Data Block makes all the Goodputs low, with a lower impact to the remainders.

In Figure 2 we compare the Goodput in the case of a PDU with a Bit stream (Eq.1) to the Goodput of PDUs with Data Blocks. Figures 2(A),(B) and (C) show the results for F=480, 432 and 384 respectively. Since the results are similar in all the cases of F, we only concentrate in the case of F=480.

We again consider $p = 0.999, p = 0.99$ and $p = 0.9$. For $p = 0.999$ the high FEC success probability makes the number of FEC blocks in the optimal size PDUs less dominant. The Goodput in Bit stream is slightly better than in the case of Data Blocks only due to the remainders in the later. For B=8192 the optimal size of a PDU is 35 FEC blocks and it con-

Table 1: The number of slots j, the number of data bits F and the success probability p in various SNR values of the largest FEC block in various MCSs.

MCS	j	F	$\frac{F}{j}$	SNR(dB)								
				2	2.5	3	3.5	4	4.5	5	5.5	6
QPSK 1/2	10	480	48	0.998	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
QPSK 3/4	6	432	72	0.38	0.85	0.96	0.998	0.999	0.999	0.999	0.999	0.999
16QAM-1/2	5	480	96	*	*	0.43	0.82	0.976	0.998	0.999	0.999	0.999
16QAM-3/4	3	432	144	*	*	*	*	*	*	0.42	0.79	0.957
64QAM-2/3	2	384	192	*	*	*	*	*	*	*	*	*
64QAM-3/4	2	432	216	*	*	*	*	*	*	*	*	*
64QAM-5/6	2	480	240	*	*	*	*	*	*	*	*	*

MCS	SNR(dB)											
	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
QPSK 1/2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
QPSK 3/4	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
16QAM-1/2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
16QAM-3/4	0.995	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
64QAM-2/3	*	*	*	0.56	0.79	0.941	0.991	0.999	0.999	0.999	0.999	0.999
64QAM-3/4	*	*	*	0.33	0.46	0.73	0.92	0.990	0.999	0.999	0.999	0.999
64QAM-5/6	*	*	*	*	*	0.3	0.41	0.45	0.8	0.959	0.994	0.999

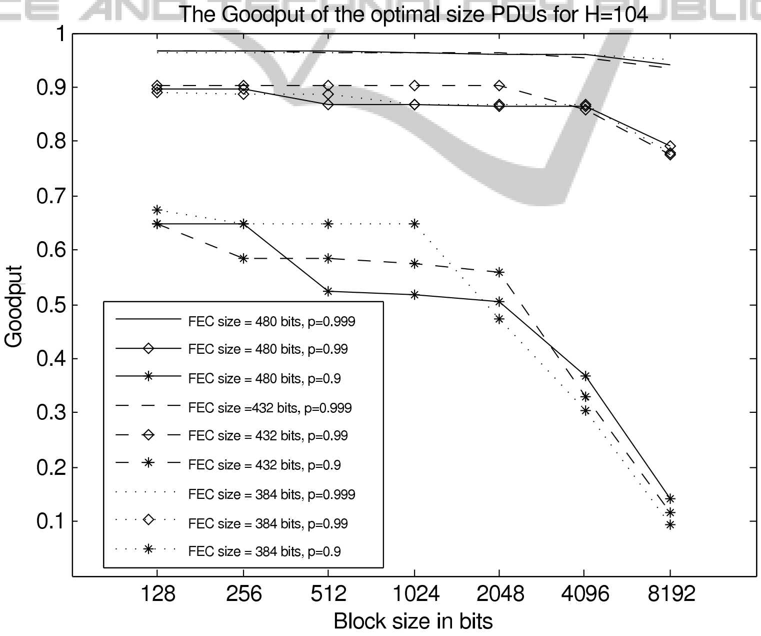

Figure 1: The Goodput of the optimal size PDUs in various FEC Block sizes and success probabilities, H=104 bits.

tains two Data Blocks. This large number of FEC blocks reduces the PDU success probability, and together with the remainder, makes the difference between the Goodputs of the Bit stream and the Data Blocks the biggest in this case.

For $p = 0.99$ and B=128 or B=256 the optimal PDU sizes for Data Blocks are 4 FEC blocks, compared to 5 FEC blocks in the case of a Bit stream. However, the remainders in the case of Data Blocks make their Goodputs slightly lower than that of a Bit stream.

For $512 \leq B \leq 4096$ the optimal size PDUs are between 9 to 11 FEC blocks. Since there are large remainders in the short PDUs, the optimal size PDUs are relatively long. The relatively big size of the optimal PDUs results with a low success probability of the PDUs and therefore, compared to $p = 0.999$, the Goodput of the Bit stream is relatively much better

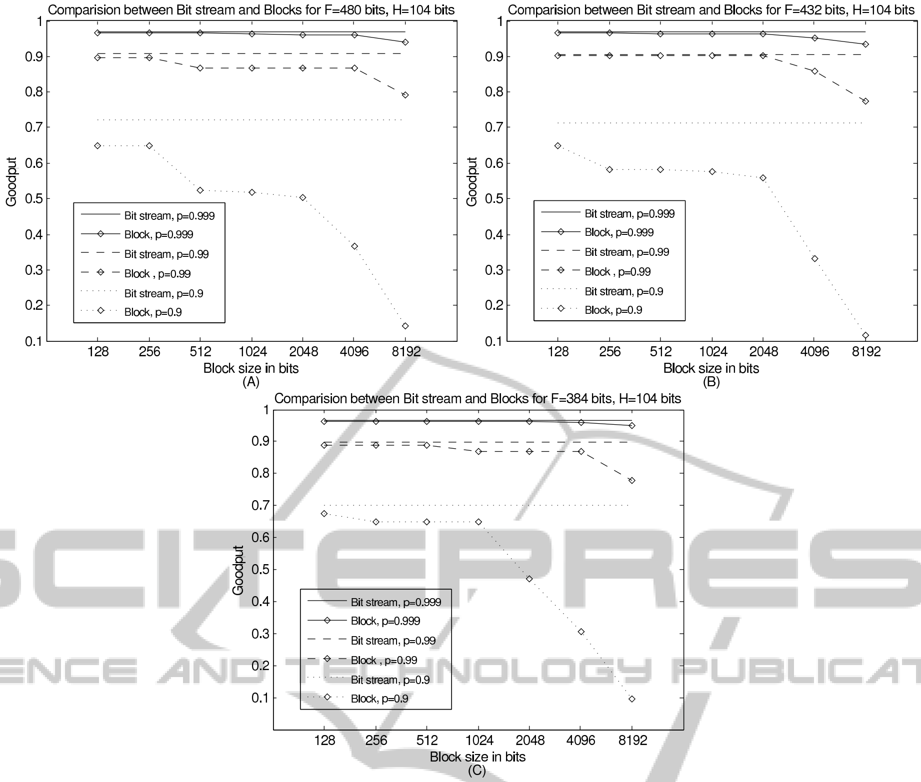

Figure 2: Comparison between the Goodput of a Bit stream and PDUs with Data blocks for various FEC blocks' sizes and success probabilities, *H*=104 bits.

than those of the Data Blocks. This effect becomes much more dominant for $p = 0.9$ where the Goodput of the Bit stream is now much better than those of Data Blocks.

In Figure 3 we show the same results as in Figure 2, but from a different view point. In Figure 3 we show, for every optimal size PDU, how many data bits are transmitted successfully, on average, in a single FEC block. E.g., for F=480, $p = 0.999$ and B=8192, the optimal PDU size is 35 FEC blocks and the Goodput is 0.9416 . Thus, the number of data bits that are transmitted successfully in the PDU is 15427, or 440 bits/FEC block.

For every possible FEC blocks' and Data Blocks' sizes, and for $p = 0.999, p = 0.99$ and $p = 0.9$, we show the average number of data bits that are transmitted in a FEC block. Above each marker we also show the number of FEC blocks in the optimal PDU size. Thus, e.g. for F=480, B=8192 and $p = 0.999$, 440 data bits are transmitted, on average, in a FEC block, and the optimal size PDU contains 35 FEC blocks. The results follow those in Figure 2. For $p = 0.999$ and $p = 0.99$ the data bits that are transmitted successfully per a FEC block are about the same for all the Data Blocks' sizes. For $p = 0.9$ and for the large Data Blocks this number is smaller dramatically, following the significant drop in the Goodputs, as it is shown in Figure 2.

We also checked the results for $H = 184$. This amount of overhead assumes two additional fields in the PDU which are used for encryption. The results are about the same as for the case $H = 104$.

The following outcomes can be derived from Figures 1- 3:

1. For $p = 0.999$ and $p = 0.99$ the Goodput results are not sensitive to the FEC block size F. For $p = 0.9$ this is not the case. This outcome is important due to the following aspect. In IEEE 802.16e/WiMAX the BS decides, for every Burst, on the MCS to be used. This decision is based, among other parameters, on the Signal-to-Noise-Ratio (SNR) of the channel, which can change during the connection life time. The change in the MCS can result with a different F. However, the Data Block size is determined once, when a connection is established, and it is not changed later. Consider Table 1 again. In this table we show, for every MCS, the number j of slots that the largest FEC block occupies in the transmission frame, the number F of bits in every such FEC block, and the success probability p of the FEC blocks in var-

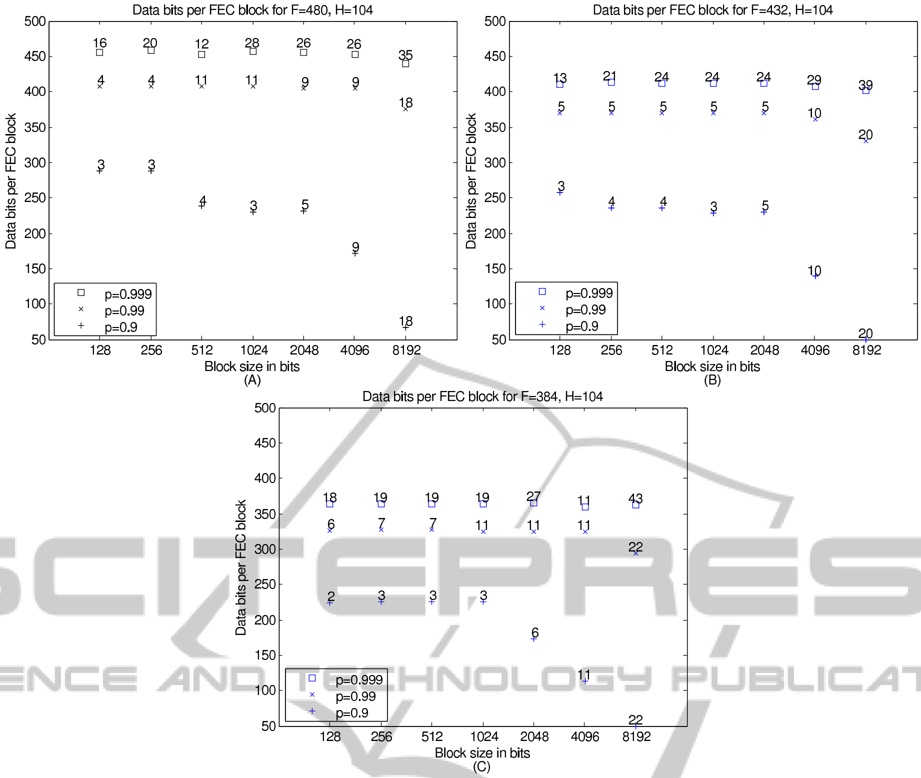

Figure 3: The average number of Data bits that a FEC block transfers successfully for various FEC blocks' sizes and success probabilities. H=104 bits.

ious SNR values. The success probabilities are received from (Jum, 2010). The input from (Jum, 2010) contains graphs that show, for every MCS, the success probabilities for all possible size FEC blocks in the considered MCS, in different SNR values.

Consider SNR=12dB. In this SNR the largest FEC blocks in all the MCSs have $p = 0.999$. In this SNR it is most efficient to use either 64QAM-2/3, 64QAM-3/4 or 64QAM-5/6. These MCSs have the same PDU Goodputs as all the other MCSs, and in all the possible values of B (Figure 1). Also, the FEC blocks in all the MCSs transfer the same average number of data bits (Figure 3). However, the above 3 MCSs use the lowest number of transmission slots, j =2. Therefore, in these MCSs the *transmission slots* are used most efficiently, i.e. transfer the largest number of data bits. But what happens if the measure of the SNR is not accurate, and the actual success probability of the FEC blocks is little lower than 0.999 ? Assume that B=512. Then, it is better to use 64QAM-3/4 with F=432 because, on one hand, for $p = 0.999$, this F has a PDU Goodput equal to that of the other values of F, but, on the other hand, for $p = 0.99$, it is better than the others. Therefore, if according to the measured SNR holds $p = 0.999$, but actually it is 0.99, F=432 is the best in both cases. If the measured SNR is far from the actual one, and instead of p =0.999 holds p =0.9, then it is better to choose 64QAM-2/3 with F=384 because this is the best F for both p =0.999 and $p = 0.9$.

2. For $p = 0.999$ and $p = 0.99$ there is no significant difference between the Goodputs received for a Bit stream and for Data Blocks, except for B=8192. This conclusion is important because it shows that the division into Data Blocks, in order to increase the reliability of the transmissions, does not effect the efficiency in using the transmission channel.
3. For $p = 0.999$ and $p = 0.99$ all the Data Blocks' sizes between 128 and 4096 have about the same Goodput results. For B=8192 the Goodput results are lower.
4. For $p = 0.9$ it is significantly more efficient to use Data Blocks of sizes between 128 to 1024 bits.

4 CONCLUSIONS

In this paper we compute the size of a PDU that maximizes its Goodput where only Data blocks are transmitted. We then compare among the maximum PDU Goodputs in different sizes of the FEC blocks and the Data Blocks. The main outcome is that the PDU Goodput is sensitive only in the case where Data Blocks are very large. We also show that it is possible to give guidelines on how to choose the best Modulation/Coding Scheme (MCS) to use in a scenario where the Signal-to-Noise Ratio (SNR) can change significantly during transmissions, in order to maximize the PDU Goodput.

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