Efficient Coupled PHY and MAC Use of Physical Bursts in WiMAX/IEEE 802.16e Networks

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Abstract: We address several issues related to the efficient use of Bursts in WiMAX/IEEE 802.16e systems. We look on the relation between the PHY layer budding blocks (FEC blocks) and the allocation of MAC level frames (PDUs) over these FEC blocks. In particular, we show how to transmit a given amount of MAC level data bits over a given Burst in order to maximize the number of successfully transmitted data bits in the Burst. We also compute, given an amount of data bits to transmit, what is the Burst size that maximizes each of the following three performance criterion: the number of successfully transmitted data bits in the Burst, the maximum ratio between the number of successfully transmitted data bits to the Burst size, and the number of successfully transmitted data bits per PHY slot. For the first problem the paper shows how to optimally divide the Burst into PDUs and shows that sometimes it is more efficient to use less reliable Modulation/Coding schemes. For the second problem the paper shows that using the PHY slots efficiently is the best criterion to consider.

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/WiMAX 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 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 a MS for its transmission on the Uplink, or to the BS for a transmission on the Downlink. 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. All the data bits in a FEC block have some probability p to arrive successfully at the receiver.

The BS and the MSs transmit *Protocol Data Units* (PDU) within Bursts. Within PDUs the BS and the MSs transmit their application packets that are denoted *Service Data Units* (SDU). Each PDU has a fixed header, denoted Generic MAC Header (GMH). Optionally, a PDU also has a CRC field. The GMH, CRC and other (sub)headers, not mentioned here, within a PDU, are considered to be *PDU overhead*.

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. Thus, if a PDU is transmitted within X FEC blocks, and every FEC block has a success probability p, then $Q = p^X$.

In this paper we assume the transmission of a bit stream in the PDUs, and not SDUs. The first problem

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that we investigate is as follows: Given a Signal-to-Noise-Ratio (SNR), a Burst and an amount of N data bits to transmit in the Burst, what is the most efficient way to allocate PDUs in the Burst so that the number of data bits that are transmitted successfully in the Burst is maximized. In the second problem we are given an SNR and N data bits to transmit. We look for the optimal Burst size in relation to three performance criterion. In the first one we look for the Burst size that maximizes the number of successfully transmitted data bits. In the second criterion we look for the Burst size that is most efficiently used, i.e. the relation between the number of successfully transmitted data bits in the Burst, to the Burst size, is maximized. In the third criterion we look for the Burst size that maximizes the number of successfully transmitted data bits per transmission slot. The above problems can arise, for example, when a MS is allocated a Burst and wants to use it in the most efficient way, and when the BS needs to allocate Bursts to MSs after receiving their traffic needs. Notice that a solution to the above problems is important in relation to a PHY layer that is based on CTC because the Burst length determines the FEC blocks that it contains. Next, PDUs are defined over these FEC blocks. Therefore, there is a direct correlation between the Burst size, the PHY layer and the MAC layer, which influences the efficiency of the transmissions.

The performance of IEEE 802.16e/WiMAX systems has been extensively investigated. Due to a space limit we do not give examples for relevant studies. 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., 2012b), (Alpert et al., 2010) and (Alpert et al., 2012a). These papers however, handle different problems than those in this paper.

The rest of the paper is organized as follows: In Section 2 we answer the question of which is the most efficient way to transmit a given amount of data bits in a given Burst. In Section 3, given an amount of data bits to transmit, we look for the optimal Burst sizes according to the criterion mentioned above.

2 THE OPTIMAL TRANSMISSION OF DATA IN A GIVEN BURST

2.1 Problem Description

We are given an SNR, a Burst of S slots, an amount of N data bits to transmit and the number of the PDU overhead bits. We want to decide on the best MCS to use in the Burst, and how to allocate PDUs in the Burst, such that an efficiency criterion, denoted *D-Goodput*, that we define next, is maximized. In Sections 2.2-2.4 we assume all the above parameters, and also a MCS. These parameters, all together, determine the number L of FEC blocks in the Burst, their size F in bits and a FEC success probability p. Then, in Sections 2.5 and 2.6 we show how to choose the best MCS.

2.2 Definition of the D-Goodput

We are given: A Burst of L FEC blocks, every FEC block contains F bits, every FEC block has probability p to arrive successfully at the receiver, N data bits to transmit in the Burst and every PDU has O overhead bits. We assume that $O < F$ since according to the IEEE 802.16e/WiMAX standard (IEEE, 2005), the total length of the overhead fields in a PDU is most likely to be smaller than one FEC block.

We want to transmit the N data bits in the Burst such that the *Data Goodput* (*D-Goodput*) is maximized. The *D-Goodput* is defined as follows. Let S be the number of data bits in the Burst, out of the N bits, that arrive successfully at the receiver. Then: *D-Goodput* $=\frac{S}{N}$. Notice that the D-Goodput it computed using N in the denominator, because the Burst is *given* and we want to use it to transmit to the receiver as many data bits as possible.

Data bits are transmitted within PDUs and so we need to decide on how many PDUs shall be allocated in the Burst, their length and their location. We call these decisions the *division* of the Burst into PDUs.

2.3 Optimal Division into PDUs

In order to find the optimal division of the Burst into PDUs, we prove the following 5 Theorems. We omit their proofs due to a space limit.

Theorem 1. *There is an optimal division of the Burst into PDUs such that every PDU begins and ends at exact boundaries of FEC blocks.*

Theorem 2. *Assume that for a given* $N > L(F-O)$ *an optimal division of the Burst contains I PDUs. Let*

l be the size of the longest PDU such that $l \geq 2$. Then, it is possible to locate all the free bits in the Burst, if such exist, in one PDU of length l.

Theorem 3. *In an optimal division of the Burst into PDUs where $N > L(F-O)$ there are at most $O-1$ free bits.*

Theorem 4. *In an optimal division of a Burst into PDUs, either all the PDUs are of the same length or the difference in length between the longest and the shortest PDUs is one FEC block.*

Theorem 5. *Assume an optimal division of a Burst into PDUs such that there are I PDUs in the division. Then, there is only one possibility to optimally divide the Burst into I PDUs such that the difference in length between the longest and the shortest PDUs is at most one FEC block.*

2.4 The Optimal D-Goodput

Following Theorems 1- 5 we now show how to find the unique division of the Burst into I PDUs such that the difference in length between the longest and the shortest PDUs is at most one FEC block. If I divides L and $L = I \cdot Z$ then the I PDUs are all of the same length of $Z = \frac{L}{I}$ FEC blocks. If I does not divide L then $L = I \cdot Z + r = (I-r) \cdot Z + r \cdot (Z+1)$ such that $Z = \left\lfloor \frac{L}{I} \right\rfloor$ and $r = L \ mod \ I,\ 1 \leq r \leq I-1$. Therefore, the I PDUs are divided into $(I-r)$ PDUs of Z FEC blocks each, and r PDUs of $Z+1$ FEC blocks each. For example, for $L = 13$ and $I = 3$ we get that $13 = 3 \cdot 4 + 1 = 2 \cdot 4 + 1 \cdot 5$, i.e. $Z = 4$ and $r = 1$. We get 2 PDUs of 4 FEC blocks and 1 PDU of 5 FEC blocks.

Following Theorems 1-5 *Algorithm D-Goodput* to find the maximum D-Goodput is as follows:
Algorithm D-Goodput(L, F, O, p, N):

- Compute:
  $X_{max} = \left\lfloor \frac{ln(0.8)}{ln(p)} \right\rfloor$, $I_{min} = \left\lceil \frac{L}{X_{max}} \right\rceil$, $N' = L \cdot F - I_{min} \cdot O$, if $(N > N')$ $N \leftarrow N'$, $I_{max} = \left\lfloor \frac{L \cdot F - N}{O} \right\rfloor$, $I = min\{I_{max}, L\}$
- Compute:
  $L = I \cdot Z + r,\ \ 0 \leq r < I.$
- *D-Goodput(L,F,O,p,N) =*

$$
\begin{cases}
p^{\frac{L}{I}} & r = 0 \\
\frac{(I-r)\cdot(F\cdot Z-O)p^{Z}}{N} + \frac{[N-(I-r)\cdot(F\cdot Z-O)]p^{Z+1}}{N} & otherwise
\end{cases}
$$

In the expression above for the D-Goodput, the term $(I-r) \cdot (F \cdot Z - O)p^Z$ denotes the contribution of the data bits in the short PDUs to the D-Goodput. The term $[N-(I-r) \cdot (F \cdot Z - O)]p^{Z+1}$ denotes the contribution of the data bits in the long PDUs to the D-Goodput.

2.5 Determining the Modulation/Coding Scheme in the Burst

IEEE 802.16e/WiMAX enables the use of the following Modulation/Coding schemes (MCSs) (IEEE, 2005): QPSK-1/2, QPSK-3/4, 16QAM-1/2, 16QAM-3/4, 64QAM-1/2, 64QAM-2/3, 64QAM-3/4 and 64QAM-5/6.

Recall that when a Burst is defined, actually it uses *slots* in the Physical layer. In any MCS the set of slots in a Burst is divided into groups such that any group is a FEC block. In every MCS it is possible to define groups of slots of different sizes, resulting in FEC blocks of different sizes. In general, the number of FEC blocks in a given Burst, and the number of data bits that can be transmitted in a Burst, becomes smaller as the reliability of the MCSs increases.

It turns out that there is a trade-off in using the set of slots of a Burst. On one hand it is possible to decide on a reliable MCS to be used in the Burst. However, the number of FEC blocks, and so the number of bits in the Burst, is low. On the other hand, a less reliable MCS results in more FEC blocks and bits in the Burst, but with a smaller success probability of the FEC blocks. A question arises now: Given a number N of data bits and a Burst of S slots, what is the best MCS to use in the Burst such that the D-Goodput is maximized. Due to space limits we omit numeric results for the question. In general however, it turns out that sometimes it is more efficient to use less reliable MCSs. There are two reasons for this outcome: First, less reliable MCSs sometimes enable the transmission of all the N data bits while more reliable MCSs do not enable this transmission. Second, the larger number of bits in the less reliable MCSs enables to define smaller PDUs, with a larger success probability than the PDUs in more reliable MCSs. This compensates for the smaller success probability of a single FEC block in the former MCSs.

2.6 Summary of Results

Combining the discussion in Section 2.5 together with *Algorithm D-Goodput* from section 2.4 and given an SNR, a Burst of S slots and an amount of N data bits to transmit, the following procedure should be used in order to maximize the D-Goodput:

1. For every MCS applicable in the given SNR:

1.1. Compute the number of FEC blocks in the Burst L, their size F and their success probability p.

1.2. If $(L \cdot F - I_{min} \cdot O - N < 0)$ then it is not possible to transmit the given N data bits in the Burst. Otherwise, compute the D-Goodput by *Algorithm D-Goodput* (I_{min} is taken from *Algorithm D-Goodput*).

2. Choose the MCS that yields the largest D-Goodput, if such exists.

Remark: if there is no MCS in which it is possible to transmit all the data bits, then one can reduce this number as it is shown in *Algorithm D-Goodput*.

3 THE OPTIMAL BURST SIZE FOR DATA TRANSMISSION

In this section we are given an SNR, an amount of N data bits to transmit and the number of the PDU overhead bits. We are looking for the optimal Burst size to transmit these data bits. We suggest 3 possible performance criterion, and for each criterion we decide on the best MCS to use in the given SNR and on the optimal Burst size.

The first performance criterion is *Max-Bits* which maximizes the number of successfully transmitted data bits in the Burst. The second criterion is *Burst-Goodput* that maximizes the ratio between the number of successfully transmitted data bits in the Burst, to the Burst size. The third criterion, *Slot-Goodput*, maximizes the number of successfully transmitted data bits per transmission slot.

When we consider a MCS in the given SNR, we are actually being given a FEC block size F and a FEC block success probability p. This probability is determined by the given SNR. Thus, for every MCS the input we have is: N data bits to transmit in a Burst, FEC blocks that contain F bits each, every FEC block has probability p to arrive successfully at the receiver, and every PDU has O overhead bits. $O < F$ from the same reasons as in Section 2.

For each of the performance criterion we look for the Burst size that maximizes the criterion in the considered MCS. Then, the MCS in which the best result is achieved, is the one to use in the given SNR. Finally, we compare between the three criterion. The outcome is that using the *Slot-Goodput* criterion is the best since on one hand it enables the transmission of data bits almost as *Max-Bits*, but on the other hand it uses much less resources.

3.1 The Max-bits Criterion

In this section we look for the Burst size that maximizes the number of successfully transmitted data bits in a Burst. Consider a Burst of L_{max} FEC blocks such that $L_{max} = \lceil \frac{N}{F-O} \rceil$. With this number of FEC blocks in a Burst, every FEC block is a separate PDU, and the number of successfully transmitted data bits in the Burst is $N \cdot p$. Clearly, this is the maximum possible.

Given an SNR, the MCS with the highest FEC block success probability p is the best to use.

3.2 The Burst-Goodput Criterion

3.2.1 Finding the Shortest and Longest Burst Sizes

In this section we look for the Burst size that is most efficiently used. In other words, we want to maximize the *Burst Goodput* (*B-Goodput*) that is defined as follows. Let S be the number of data bits, out of the N bits, that are successfully transmitted in a Burst. Let B be the length of the Burst in bits. Then, the *B-Goodput* is defined as *B-Goodput*$= \frac{S}{B}$. In this section we are looking for the optimal number of FEC blocks, L, such that $\frac{S}{B} = \frac{S}{L \cdot F}$ is maximal.

Notice that the Burst size in this case is not an input to the problem, and we look for the Burst that is most efficiently used. Therefore, the denominator of the B-Goodput is the Burst size.

First recall the value L_{max} such that $L_{max} = \lceil \frac{N}{F-O} \rceil$. With this number of FEC blocks in a Burst, one can define every FEC block to be a separate PDU. In this case the B-Goodput is $\frac{N \cdot p}{B}$. Using more FEC blocks only enlarges the denominator but the numerator remains the same. Therefore, there is no merit to consider Bursts with more than L_{max} FEC blocks.

We now compute L_{min}, the minimum number of FEC blocks that are needed to transmit the N bits. We want the success probability of a PDU to be at least 0.8 and so the maximal number of FEC blocks in a PDU is $X_{max} = \left\lfloor \frac{ln(0.8)}{ln(p)} \right\rfloor$. We now compute L_{min} by defining X_1 and X_2 as follows:

1. $X_1 = \left\lfloor \frac{N}{X_{max} \cdot F - O} \right\rfloor$. X_1 is the number of PDUs of length X_{max} FEC blocks that is needed for the transmission of the N data bits.
2. $X_2 = \left\lceil \frac{N - X_1 \cdot (X_{max} \cdot F - O) + O}{F} \right\rceil \cdot \left\lceil \frac{N - X_1 \cdot (X_{max} \cdot F - O)}{N - X_1 \cdot (X_{max} \cdot F - O) + O} \right\rceil$. $X_2 < X_{max}$ and it is the number of FEC blocks in a PDU that contains the remaining data bits that are not transmitted in a PDU of length X_{max}.

Also notice that if all the N bits can be transmitted in one PDU of length smaller than X_{max} then $X_1 = 0$.

Then, L_{min} is given by :

$$L_{min} = X_1 \cdot X_{max} + X_2$$

3.2.2 Finding the Optimal Burst Size

From Section 3.2.1 we can conclude that the optimal L is between L_{min} and L_{max}. For a given L the B-Goodput can be computed by *Algorithm D-Goodput* in Section 2.4, except that the denominator N in the expression for the D-Goodput is replaced by $L \cdot F$.

The following algorithm, *Compute L-Goodput*, computes the maximum B-Goodput for a given $L,\ L_{min} \leq L \leq L_{max} - 1$:
Compute L-Goodput(L, F, O, p, N):

- Compute:
  $I = \lfloor \frac{L \cdot F - N}{O} \rfloor, L = I \cdot Z + r,\ \ 0 \leq r < I.$
- *B-Goodput(L,F,O,p,N)* =

$$\begin{cases} \frac{N \cdot p^{\frac{L}{I}}}{L \cdot F} & r = 0 \\ \frac{(I-r)\cdot(F \cdot Z - O)p^{Z}}{L \cdot F} + \frac{[N-(I-r)\cdot(F \cdot Z - O)]p^{Z+1}}{L \cdot F} & otherwise \end{cases}$$

The B-Goodput for $L = L_{max}$ is always $\frac{N \cdot p}{L_{max} \cdot F}$. Therefore, we now define *Algorithm B-Goodput* that computes the optimal Burst size given F, O, p, N.

Algorithm B-Goodput(F,O,p,N):

1. Compute:
   $L_{max} = \lceil \frac{N}{F-O} \rceil$, $X_{max} = \left\lfloor \frac{ln(0.8)}{ln(p)} \right\rfloor$, $X_1 = \left\lfloor \frac{N}{X_{max} \cdot F - O} \right\rfloor$, $X_2 = \left\lceil \frac{N - X_1(X_{max} \cdot F - O) + O}{F} \right\rceil \cdot \left\lceil \frac{N - X_1 \cdot (X_{max} \cdot F - O)}{N - X_1 \cdot (X_{max} \cdot F - O) + O} \right\rceil$, $L_{min} = X_{max} \cdot X_1 + X_2$, $MaxGoodput = 0, OptimalL = NIL$
2. For every $L_{min} \leq L \leq L_{max} - 1$ if $Compute\ L - Goodput(L, F, O, p, N) > MaxGoodput$ then $\{\ MaxGoodput = Compute\ L - Goodput(L, F, O, p, N); OptimalL = L\ \}$.
3. If $\frac{N \cdot p}{L_{max} \cdot F} > MaxGoodput$ then $\{\ MaxGoodput = \frac{N \cdot p}{L_{max} \cdot F}; OptimalL = L_{max}\ \}$.
4. return$(OptimalL, MaxGoodput)$

3.2.3 Determining the Modulation/Coding Scheme in the Burst

The question of which is the best MCS to use, given an SNR, in order to receive the maximum B-Goodput depends on F,O,p and N. We do not have a closed term for the B-Goodput and so one needs to check all the applicable MCSs.

3.3 The Slot-Goodput Criterion

3.3.1 The Criterion Definition

In this section we define another performance criterion, denoted *Slot-Goodput*. This criterion counts, given a Burst and a MCS, the number of successfully transmitted data bits per *slot*. Or, in other words, we measure the contribution of the physical resource directly.

Given an SNR and a MCS, i.e. F and p, the number N of data bits to transmit and the number of PDU overhead bits O, the sizes of the possible Bursts are limited, as before, by L_{min} and L_{max}. The optimal L is computed by *Algorithm B-Goodput* since the difference between the *B-Goodput* and the *Slot-Goodput* is by a constant factor, $\frac{F}{j}$, where j is the number of slots in a FEC block.

3.3.2 Determining the Modulation/Coding Scheme in the Burst

Same as in the *Burst-Goodput* criterion.

3.4 Comparison between the Performance Criterion

The *Max-Bits* performance criterion maximizes the number of successfully transmitted data bits in a Burst. Therefore, from a single user perspective, it is the best one. However, this criterion consumes many resources because it uses many FEC blocks. This can lead to un-fairness among users if the system resources are limited. Therefore, if the system is not overloaded, the *Max-Bits* criterion is applicable. However, if the system is overloaded, the *Slot-Goodput* criterion shall be used because it uses the transmission slots in the most efficient way, as we show next.

In Figures 1 and 2 we check the following for two SNR values and different values of N: Given an SNR and N, we compute the optimal Burst size according to each of the three performance criterion. Then, for each such Block size we compute the number of successfully transmitted data bits, and the number of transmission slots that such a Burst occupies. Notice that in order to find the optimal Burst size for the *Burst-Goodput* and for the *Slot-Goodput* criterion, given an SNR and N, we check all the applicable MCSs, and choose the best among them.

From Figure 1 it turns out that using the optimal Burst sizes according to the *Burst-Goodput* and the *Slot-Goodput* criterion does not reduce significantly

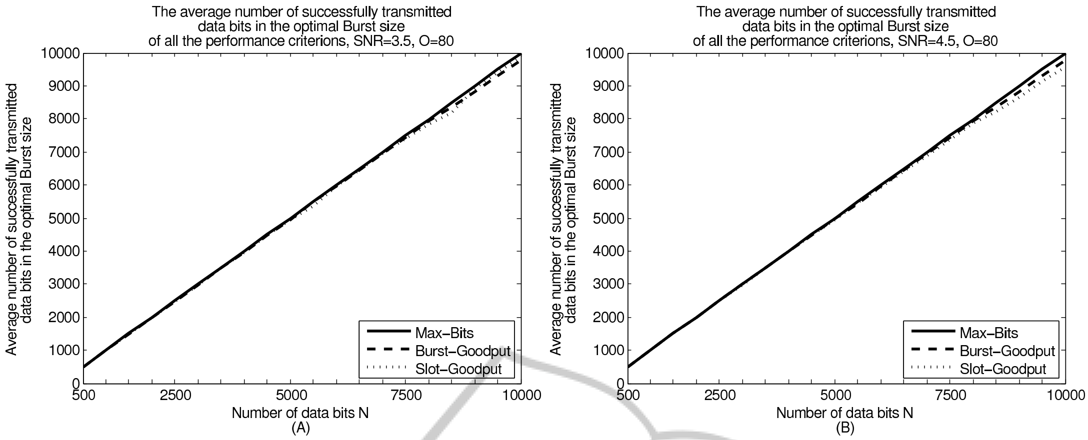

Figure 1: The number of successfully transmitted data bits in the optimal Burst size of the various performance criterion, for various SNRs(dB) and for a various number of data bits, $O = 80$ bits.

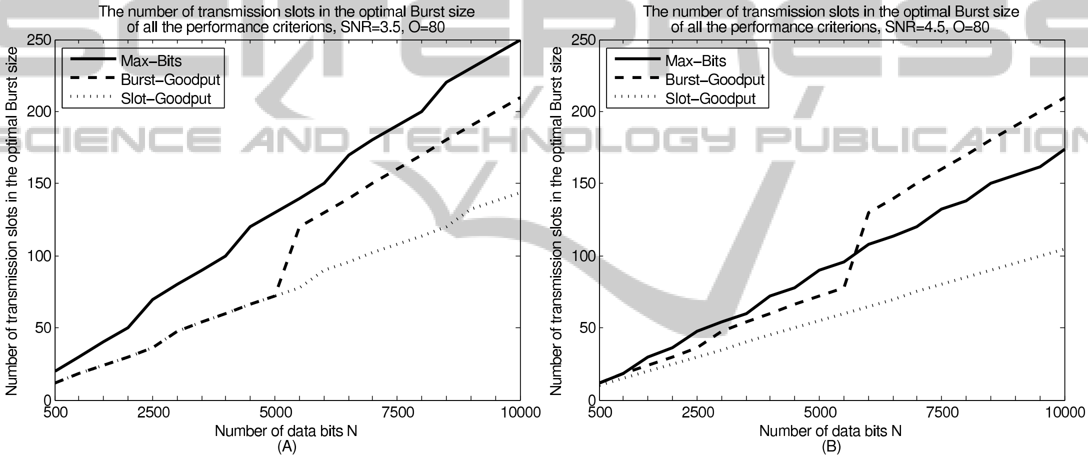

Figure 2: The number of slots in the optimal Burst size of the various performance criterion, for various SNRs(dB) and for a various number of data bits, $O = 80$ bits.

the number of successfully transmitted data bits, compared to the optimal Burst size of the *Max-Bits* criterion. On the other hand, from Figure 2 one can see that the saving in the number of the transmission slots is very significant. Therefore, the *Slot-Goodput* is the most attractive performance criterion to use.

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