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Exploring the intra-frame energy conservation capabilities of the horizontal simple packing algorithm in IEEE 802.16e networks: an analytical approach

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Abstract The power saving capabilities of the mobile devices in broadband wireless networks constitute a challenging research topic that has attracted the attention of researchers recently, while it needs to be addressed at multiple layers. This work provides a novel analysis of the intra-frame energy conservation potentials of the IEEE 802.16e network. Specifically, the power saving capabilities of the worldwide interoperability for microwave access downlink sub-frame are thoroughly studied, employing the well-known simple packing algorithm as the mapping technique of the data requests. The accurate mathematical model, cross-validated via simulation, reveals the significant ability to conserve energy in this intra-frame fashion under different scenarios. To the best of our knowledge, this is the first work providing intra-frame power-saving potentials of IEEE 802.16 networks. Additionally, this is the first study following an analytic approach.

Keywords IEEE 802.16 · Downlink mapping · Intra-frame power saving · Sleep slots · WiMAX

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1 Introduction

Worldwide interoperability for microwave access (WiMAX) forms one of the most promising wireless access technologies for metropolitan area networks. Its standardization, realized by the original IEEE 802.16 [1], initially allowed for fixed subscribers' communication. In the sequel, its advancement, enhanced IEEE 802.16e [2], enabled both fixed and mobile subscribers' communication access to backbone networks and mesh inter-connectivity in an efficient way. Considering the fact that service quality and duration are highly dependent, besides the type and characteristics of the mobile device used (e.g., PDA, mobile phone, laptop etc.), on the battery longevity, power consumption issue is constituted of paramount importance. In this perspective, the current work focuses on power management, enabling the mobile station (MS) to conserve its battery resources, even during the occurrence of a single data frame.

Power management addressed by the standard at medium access control (MAC) layer provides a power saving mode (referred to as sleep mode) and an idle mode of operation [3, 4]. Under the sleep mode, the MS temporarily disrupts its connection over the air interface with the WiMAX base station (BS), reducing, thus, its power consumption, being, however, unable to send or receive data. The amount of time that an MS is set to sleep mode is called sleep window. Upon the completion of the sleep window the MS restores its connection with BS. This period is called listen window.

According to the specification, three different power-saving classes have been defined in the context of the power saving mode (PSM) in order to address various types of applications and services [4]. In the first power-saving class, each listen window of fixed length is followed by a sleep window whose length is twice the length of the previous sleep window, without however exceeding a final sleep window size. Before entering the first power-saving class, the BS indicates to the MS the initial sleep window size and the final sleep window size. Once the final sleep window size is reached, all the subsequent sleep windows are of the same length [4]. The sleep windows of power-saving class two have a fixed length and are followed by a listen window of fixed length. Again, the BS indicates to the MS the sleep and listen window sizes. Lastly, the third power-saving class operation, on the contrary to the other classes, involves a single sleep window. In a similar manner to the first and second power saving class, the BS informs the MSs about the start time and the length of the sleep window. At the end of the sleep window, the power-saving operation becomes inactive.

Various studies have investigated power management issues based on these three classes; indicatively see [5–7]. However, all past research efforts limit their attention to power saving techniques in terms of frame time basis, disregarding intra-frame power saving potentials. Aiming to cover this absence of known relevant research attempts in the literature, the contribution of our paper lies in intra-frame power saving investigation, studying the potential power savings of intra-frame sleep periods. Recent studies [8–11] show that modern WiMAX transceivers [12] exhibit sufficiently low power demands that justify the intra-frame energy conservation perspectives analyzed in this paper. Hence, bearing in mind that the in-frame requests' mapping process is quite important in WiMAX systems, since it affects the whole network performance (e.g., the unmapped requests are returned to the scheduler and they should be reallocated, leading to performance degradation) and green broadband access networks form a very hot and concurrently critical research field, this paper constitutes an effort to contribute novel power saving related aspects to the IEEE 802.16 wireless networks. In the light of the aforementioned, this work examines the downlink sub-frame, adopting the simplest requests' allocation technique, which is widely considered as one of the default WiMAX requests' mapping schemes, and provides analytical results concerning the average time that an MS could be set to sleep mode, considering the number of connected MSs, the downlink load, and the given sub-frame dimensions, while the power consumption when transiting to receive/sleep states is also taken into account.

For comparison reasons, it could be taken into consideration that the PSM defined by the WiMAX standard [3, 4] in regards to inter-frame energy conservation implies message transmission related to sleep mode switching, which constitutes a major factor when estimating overall power consumption. On the other hand, the intra-frame power saving perspectives analyzed in this work involve no message exchange when transiting to or from sleep mode.

The remaining paper is organized as follows. The adopted multi-access technique and the intra-frame bandwidth allocation are described in Sect. 2. Section 3 presents the environment and the analytical approach of the proposed energy conservative mapping. Section 4 validates our analysis via simulation and provides extensive performance results in terms of potential sleep time. Finally, Sect. 5 concludes this paper and highlights our future plans.

2 OFDMA background and intra-frame allocation

Orthogonal frequency division medium access (OFDMA) constitutes the main multi-access technique adopted by WiMAX, allowing multiple subscribers to share the time and the frequency domain in a flexible way. The BS allocates distinct bandwidth regions to the connected MSs for sending and receiving data, realizing two-way communication via two distinct sub-frames: the uplink sub-frame, responsible for carrying data streams from MSs to BS, and the downlink sub-frame, transmitting data streams originated in the backbone from BS to MSs. Adoption of the frequency division duplexing (FDD) technique leads to the transmission of the downlink and uplink data streams in parallel in different frequencies, while in case of the time division duplexing (TDD) technique, the uplink and the downlink sub-frame are repeated one after the other in time in the same frequency. Here, the flexible TDD technique is adopted.

In essence, OFDMA operation takes place between the physical (PHY) and the MAC layer. The PHY layer is responsible for the MAC framing, defining the term of slot, which is the minimum framing structure unit. The bandwidth distribution is associated with slot assignment in an intra-frame allocation fashion. The process of allocating available slots to the subscribers' requests is defined as mapping. The mapping operation includes (a) request gathering from the scheduler and (b) creation of a complete transmission program, defining the exact time and frequency of transmitting (uplink stream) and receiving (downlink stream) data for each connected MS. The IEEE 802.16e frame structure is shown in Fig. 1. Each frame begins with a preamble, a short control period used for synchronization and channel estimation. The downlink sub-frame includes two control messages, the downlink map (DL-MAP) and the uplink map (UL-MAP), which define the time duration of each burst, the modulation, and the forward error control (FEC) coding scheme for each MS. The frame control header (FCH) field proceeds DL- and UL-MAP, as it provides frame configuration information, such as the MAPs' length and their corresponding PHY properties (e.g., modulation, coding scheme, and usable subcarriers). Two guard gaps, named

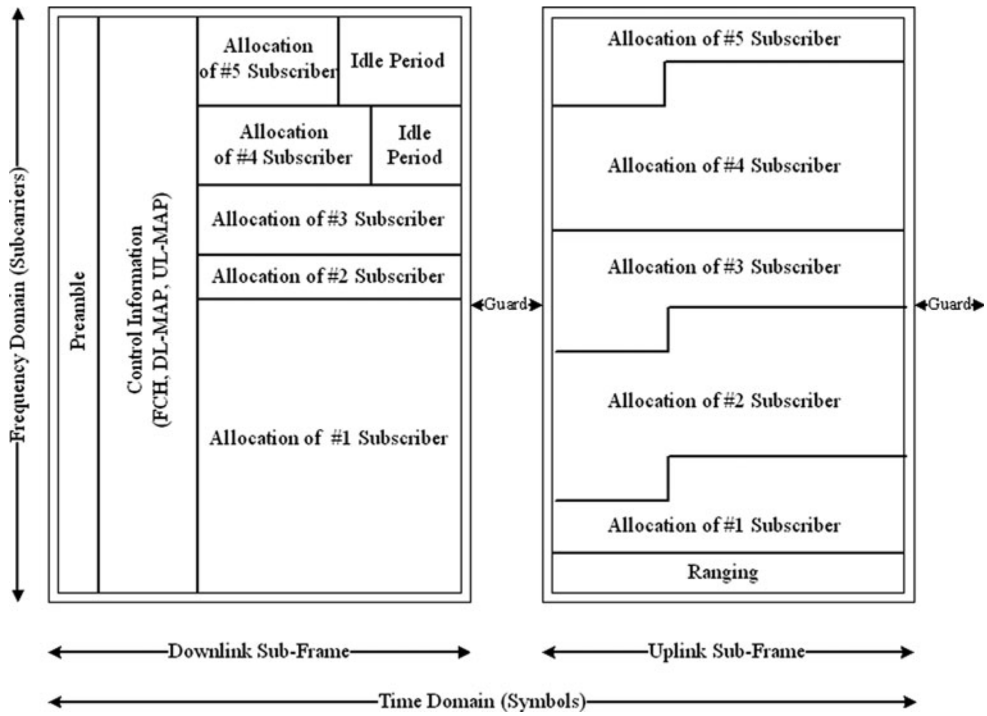

Fig. 1 The IEEE 802.16 TDD frame structure

transmit-receive transition gap (TTG) and receive-transmit transition gap (RTG) protect the BS from interference during switching from transmit mode to receive mode and vice versa.

Due to the fact that each frame, based on TDD technique, has fixed length and each sub-frame's duration is predetermined, periods of inactivity is possible to occur. As time passes, an MS could be inactive if its data transmission or reception finishes before the sub-frame completion. In this case, intra-frame sleep periods could be set in order to reduce power consumption within the sub-frame. In this letter, the potential sleep periods in intra-frame fashion are examined.

The intra-frame power conservation potentials strongly depend on the applied downlink mapping method. The mapping process provides an assignment of the MSs requests to the OFDMA allocation space, conforming to the shaping restriction imposed by the standard, according to which each downlink request should form a two-dimensional rectangular. The mapping process may result to inefficient solutions, leaving a large portion of the allocation space idle (i.e., not utilized), while it may constitute a complex procedure. Even though many interesting mapping schemes have been proposed in related research literature [13–15], the simplest dynamic mapping algorithm called simple packing algorithm (SPA) [16] has been adopted in the context of this study due to its simplicity, effectiveness, and broad acceptance. Our approach contributes towards an accurate analytical approach regarding the intra-frame sleep time considering SPA, verified by comparison against simulation outcome. Our approach inherits the advantages of simplicity and ease-of-use from the SPA logic, fact that could easily lead to a feasible application of a low complexity intra-frame power management component.

3 Presentation and analysis of energy conservative mapping

3.1 Horizontal SPA and power saving

One of the less demanding with respect to processing time straightforward technique for mapping user reception requests to slots provided by the 2-dimensional (time vs frequency) 802.16 downlink sub-frame is based on horizontal or vertical SPA [16]. Here we focus on the horizontal variant of the known SPA, allocating slots on a row by row intra-frame fashion. According to its operation each MS is assigned slots along the time axis according to the requested resources and the adopted modulation scheme. If the number of slots that correspond to a single sub-channel is not adequate to satisfy the MS downlink requirements, then slots of the next sub-channel are also utilized. It should be noted that, due to PHY layer restrictions, the WiMAX standard constrains downlink data requests' allocation in the form of rectangular shapes, called data regions [3], as shown in Fig. 1. Hence, the examined mapping technique allocates to each MS rows of slots beginning with the time axis (i.e., downlink sub-frame width) and then proceeding to the frequency axis (i.e., downlink sub-frame height). This process continues until all requests are mapped or no adequate sub-channels are left in the specific downlink sub-frame to serve the remaining requests. The steps of the examined algorithm are described below.

- Set the number of MSs in the network equal to N
- Initiate the set of MS requests $\mathbf{S} = \{R_i | i \in [1, N]\}$, measured in number of slots
- Set the downlink sub-frame width (i.e., the maximum number of slots available on the time axis) equal to W
- Set the downlink sub-frame height (i.e., the maximum number of slots available on the frequency axis) equal to H
- Initiate $Res\_W = W$
- Initiate $Res\_H = H$
- For each $R_i \in \mathbf{S}$
  - If $R_i \leq Res\_W$
    - Set $Res\_W = Res\_W - R_i$
    - Set $\mathbf{S} = \mathbf{S} - \{R_i\}$
  - Else If $R_i \leq Res\_H \times W$
    - Set $Res\_H = Res\_H - [R_i/W]$
    - Set $Res\_W = W$
    - Set $\mathbf{S} = \mathbf{S} - \{R_i\}$
  - End when $\mathbf{S} = \varnothing$ or ($R_i > Res\_W$ and $R_i > Res\_H \times W, \forall R_i \in \mathbf{S}$)

This mapping technique is characterized by energy conservation capabilities. To be more specific, considering the typical scenario of data reception during the downlink sub-frame, an MS that is allocated downlink slots on a single sub-channel may not utilize the whole sub-frame duration for data reception. Thus, in case the MS is allocated slots on a single row of the OFDMA allocation bin and the number of allocated slots is less than W (downlink sub-frame's width in slots), it is able to transit to sleep mode during the slots that involve no data exchange, constituting, thus, idle slots for the MS under consideration (i.e., *W-allocated slots*). When in sleep mode within a single frame (the respective slots are referred to as sleep slots), the MS is unavailable, not able to send or receive data, but notably low energy consumption is achieved. In sleep mode, it is shown that an MS consumes as low as one twelfth of the energy consumed when being in idle mode [8–12]. The fact that an MS in sleep mode cannot transmit or receive data does not degrade network performance at all, since the examined mapping scheme involves no data transfers that concern the specific MS during the sleep slots. At this point it should be noted that an MS which is allocated slots in more than one sub-channel is not capable of power saving by transiting to sleep mode, because it remains in receive mode during the whole downlink sub-frame tuned at least at one sub-channel. Additionally, the MS can remain in the same operation mode (sleep/idle mode) for the whole duration of a single frame, in case it is not involved in any data exchange.

An example of the slots allocation and the power saving capabilities of the horizontal SPA mapping technique is depicted in Fig. 2. The downlink sub-frame is represented by a grid of OFDMA slots that constitutes the available resource space. According to this example, MS1 utilizes four slots for reception and may transit to sleep mode for two slots, since the each row, which corresponds to a sub-channel, is here assumed to be six slots long. MS2 occupies two rows, because its request is 11 slots long. Given that MS2 must be active for the whole duration of the downlink frame, it is not able to transit to sleep mode at all. In the example, the last slot in the middle row remains unexploited, since it belongs to the rectangular data region occupied by MS2. On the other hand, MS3's request in mapped to two slots, leaving the residual four slots of the respective sub-channel available for sleeping. Finally, MS4 starts reception right after the end of the slots used by MS3 and it lasts for three slots. Thus, it has at its disposal for transiting to sleep mode the first two slots as well as the last slot of the specific row.

3.2 Mathematical analysis

In this subsection we introduce a mathematical analysis for the presented horizontal SPA aiming to estimate the power saving capabilities of the respective mapping technique. The notations of all variables used in this paper can be found in order of appearance in Table 1. It is assumed that generated user requests with respect to each MS are independent identically distributed following Poisson distribution with rate λ (a typical assumption for this type of analytical approaches). In fact, an MS request could never be lower than 1 slot or exceed the total downlink frame space; hence, it is not possible a simple MS request to be larger than the total available downlink allocation bin.

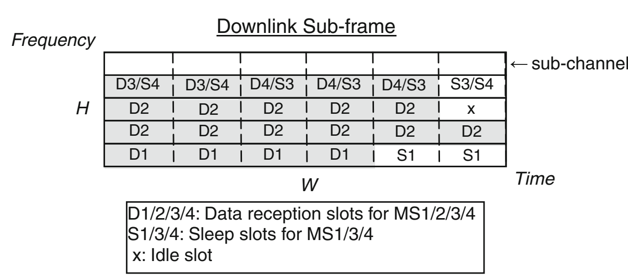

Fig. 2 Allocating downlink slots to four MSs

Table 1 Notations of variables

Notation	Explanation
N	Number of MSs in the network
S	Set of MS requests
R_i	MS request i
W	Downlink sub-frame width
H	Downlink sub-frame height
Res_W	Residual downlink sub-frame width
Res_H	Residual downlink sub-frame height
λ	Poisson parameter
$p[k]$	Probability of a request occupying k rows
M	Mean number of rows occupied by request
$U[c]$	Probability to have c sleep slots for the examined MS
s	Mean number of sleep slots per MS
R	Mean number of MSs that are served in a downlink sub-frame, assuming that no more than one request is mapped per row
$Q[l]$	Probability that l successive requests are mapped in a single row
$P_y[x]$	Probability that the total number of slots requested by y MSs equals x
$P_y[>x]$	Probability that the number of requested slots is higher than x
A	Mean number of requests that occupy slots in a row already used by another MS
E	Mean number of MS requests that occupy rows already used by other MSs
$V[c]$	Probability that one MS, which utilizes a row already occupied by other MSs, uses c sleep slots
z	Mean number of sleep slots used by each one of the E MSs
SS	Mean number of all sleep slots present in a downlink sub-frame
SS_N	Mean number of all sleep slots present in a downlink sub-frame for a finite number of N MSs

Subsequently, the number of requested slots is actually distributed according to a variant form of the Poisson distribution, which disallows values lower than zero or higher than the downlink sub-frame capacity. Thus, in the context of the provided analysis, the employed equations involve the respective normalization.

Before proceeding with the analysis, Fig. 3 that depicts some key notions of the presented work is provided in order to assist the reader better comprehend the points raised by the authors. Specifically, on the same resource grid that was shown in Fig. 2, we highlight with thick borders the data regions used by the four considered MSs requesting for downlink bandwidth and explain basic magnitudes considered in the following analysis. As a first step, we consider the mapping of the request of a single MS. The MS can sleep before and after the slots it occupies in the current sub-frame. A request occupies k rows with the probability p of involving more than $(k-1) \times W$ slots and less or equal to $k \times W$ slots, as shown by the following expression:

$$p[k] = \frac{\sum_{i=(k-1)\times W+1}^{k\times W} e^{-\lambda}\frac{\lambda^i}{i!}}{\sum_{i=1}^{W\times H} e^{-\lambda}\frac{\lambda^i}{i!}}, \quad \lambda > 0, \quad 1 \le k \le H, \quad k, W, H \in \mathbb{Z}^+ \tag{1}$$

It is clarified that the probability p refers to the case that there are sufficient available slots to allocate to the specific request. In fact, it concerns MSs that are eventually served and are the first to occupy rows. The resource space limitations are considered subsequently in this analysis, in order to estimate the total number of mapped requests. Based on (1), the mean number of rows occupied by a mapped request is given by the weighted average:

$$M = \sum_{k=1}^{H} p[k] \times k, \quad H \in \mathbb{Z}^+ \tag{2}$$

Then, we calculate the probability U to have c sleep slots for the examined MS in the current downlink sub-frame. It is derived by the probability to have $W-c$ requested slots. Hence, it holds:

$$U[c] = \frac{e^{-\lambda}\frac{\lambda^{W-c}}{(W-c)!}}{\sum_{k=1}^{W\times H} e^{-\lambda}\frac{\lambda^k}{k!}}, \quad \lambda > 0, \quad 1 \le c \le W-1, \quad c, W, H \in \mathbb{Z}^+ \tag{3}$$

The mean number of sleep slots per MS is then resulted by the following weighted average:

$$s = \sum_{c=1}^{W-1} U[c] \times c, W \in \mathbb{Z}^+ \tag{4}$$

In order to determine the total number of sleep slots, we first estimate the mean number of MSs that are served in a

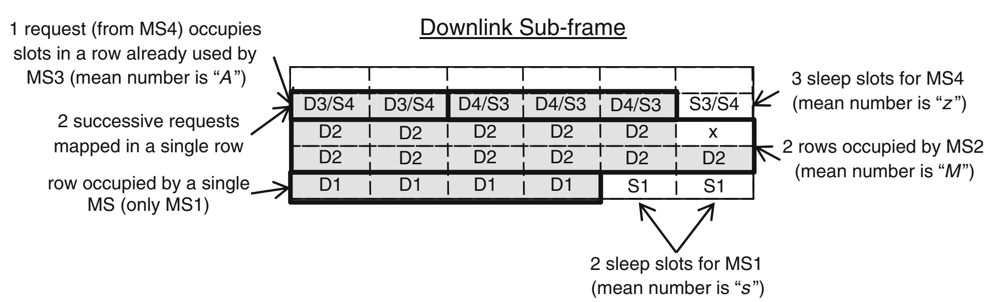

Fig. 3 Example of notions adopted in the analysis

downlink sub-frame, assuming that no more than one request is mapped per row. Referring to the example provided in Fig. 3, MS1, 2, and 3 belong to this type of MSs, but not MS4. Thus, we have:

$$R = \frac{H}{M}, \quad M \le H, \quad H \in \mathbb{Z}^+ \tag{5}$$

Next, we need to compute the mean number of requests that are mapped to rows already occupied by another MS. This calculation is based on the probability $Q[l]$ that l successive requests are mapped in a single row of width W:

$$Q[l] = \sum_{i=0}^{W-l} P_l[W-i] \times P_1[>i], \quad 1 \le l \le W, \quad l, W \in \mathbb{Z}^+ \tag{6}$$

At this point, it is noted that $P_y[x]$ represents the probability that the total number of slots requested by y MSs equals x, while the probability that the number of requested slots is higher than x is given by $P_y[>x]$. In this analysis, the computation of $P_y[x]$ cannot be based on the theorem that the sum of Poisson variables follows the Poisson distribution, given that our random variables do not really follow the Poisson distribution, as already mentioned. Taking into consideration that the respective calculation can be recursively expressed, we end up with the equation:

$$P_y[x] = \sum_{i=1}^{x-(y-1)} P_{y-1}[x-i] \times P_1[i], \quad x \ge y, \quad x, y \in \mathbb{Z}^+ \tag{7}$$

According to the problem definition, $P_y[x] = 0$, when $x < y$, since there are no null bandwidth requests, and when $x > y \times W \times H$, because the scheduler never provides requests larger than the downlink mapping area. The recursive formula in (7) is initialized by the following quantity:

$$P_1[x] = \frac{e^{-\lambda} \frac{\lambda^x}{x!}}{\sum_{i=1}^{W \times H} e^{-\lambda} \frac{\lambda^i}{i!}}, \quad \lambda > 0, \quad x \in \mathbb{Z}^+ \tag{8}$$

The expression $P_y[>x]$ employed in Eq. (6) is calculated as follows:

$$P_y[>x] = \sum_{i=x+1}^{\infty} P_y[i] = 1 - \sum_{i=y}^{x} P_y[i], x \ge y, x, y \in \mathbb{Z}^+ \tag{9}$$

Finally, the mean number of requests that occupy slots in a row of width W already used by another MS is estimated as shown below:

$$A = \sum_{i=2}^{W} Q[i] \times (i-1), \quad W \in \mathbb{Z}^+ \tag{10}$$

Taking into account that multiple MSs per row can be served only in case that the initial request does not demand more than a single row for mapping, the mean number of MS requests that occupy rows already used by other MSs equals:

$$E = p[1] \times A \times \frac{H}{M} \xrightarrow{(5)} E = p[1] \times A \times R, \quad H \in Z^+ \tag{11}$$

In Fig. 3, only the request generated by MS4 is mapped in such a manner. On the grounds that each one of the E MSs utilizes no more than $W - 1$ slots, since the latter belong to rows already occupied by another MS, the probability that one such MS uses c sleep slots is given by:

$$V[c] = \frac{e^{-\lambda} \frac{\lambda^{W-c}}{(W-c)!}}{\sum_{k=1}^{W-1} e^{-\lambda} \frac{\lambda^k}{k!}}, \quad \lambda > 0, \quad 1 \le c \le W-1, \quad c, W, H \in \mathbb{Z}^+ \tag{12}$$

Therefore, each one of the E MSs uses on average z sleep slots, as shown below:

$$z = \sum_{c=1}^{W-1} V[c] \times c, \quad W \in \mathbb{Z}^+ \tag{13}$$

We can now calculate SS, which represents the mean number of all sleep slots present in a downlink sub-frame. Considering that each one of the R MSs exploits on average s sleep slots, whereas each one of the E MSs exploits z sleep slots, it is resulted that:

$$SS = R \times s + E \times z \tag{14}$$

Equation (14) provides the average number of sleep slots per downlink sub-frame when there are enough requests to occupy the resource space. At this point, we adapt this analytical expression to suit the case of finite number of MSs that generate downlink bandwidth requests. Specifically, when there are more than $R + E$ requests, Eq. (14) holds as is. However, if there are N MS requests, with N lower than $R + E$, then $R/(R + E)$ of the MSs utilize on average s sleep slots each, while the remaining MSs can exploit z sleep slots each. The final expression is formed as follows:

$$SS_N = \begin{cases} R \times s + E \times z & N \ge R + E \\ \frac{N}{R+E} \times (R \times s + E \times z) & N < R + E \end{cases}, \quad N \in \mathbb{Z}^+ \tag{15}$$

4 Analytical and simulation results

4.1 Numerical outcomes

In order to cross-validate our analytical model, we developed a simulator of the described horizontal SPA in MATLAB.[1] Then, we conducted simulations and mathematical calculations to estimate the mean number of sleep

[1] The simulator source code is readily available and provided upon request.

Table 2 IEEE 802.16 frame modeling parameters

OFDMA PHY mode	PUSC ($H = 30$ sub-channels)
Frame duration	5 ms (default)
	10 ms
DL to UL sub-frame ratio	1:1
	$W = 9$ timeslots (5 ms frame)
	$W = 21$ timeslots (10 ms frame)
	2:1
	$W = 12$ timeslots (5 ms frame)
	$W = 27$ timeslots (10 ms frame)
	3:1
	$W = 15$ timeslots (5 ms frame)
	$W = 33$ timeslots (10 ms frame)
Requests' mapping technique	Horizontal SPA
Scheduled requests' distribution	Poisson (mean value: λ)

slots per downlink sub-frame. The partially used sub-channelization (PUSC) mode was adopted, which is the most common frequency diversity mode. PUSC defines 30 sub-channels (represented by variable *H*). The downlink-to-uplink sub-frame ratio can be adjusted to 1:1, 2:1, and 3:1. The frame duration is also defined as a parameter that varies from 2 ms to 20 ms. In this work, the considered frame duration values are 5 ms (default value) and 10 ms. Excluding the preamble, MAP, and FCH fields, a 5 ms long frame includes a downlink sub-frame that is 9, 12, and 15 timeslots (represented by variable *W*) long for downlink-to-uplink sub-frame ratios of 1:1, 2:1, and 3:1, respectively. Likewise, the downlink sub-frame of a 10 ms long frame is 21, 27, and 33 timeslots long for downlink-to-uplink sub-frame ratios of 1:1, 2:1, and 3:1, respectively. The aforementioned frame modeling parameters are summarized in Table 2.

In what follows, the analytical results are presented along with the simulations' output. A comparison with similar mathematical analyses of the SPA or any other mapping technique is not possible, since there are not any known in the existing related research literature.

First of all, it should be noticed that all the respective graphs (Figs. 4, 5, 6, 7) reveal an almost exact match between the analytical and simulation results, which confirms that our model is valid. Initially, the mean number of sleep slots per downlink sub-frame was estimated, varying the mean number of requested slots (represented by the Poisson parameter λ). In Fig. 4, the results for 5 ms long frame are depicted. As expected, low values of λ and high downlink-to-uplink ratio increase the sleep slots. It can be also seen that for high λ the slope of the three curves decreases and eventually the number of sleep slots reaches zero. This may be attributed to the fact that when large size (i.e., slot demanding) requests are mapped to a "narrow" downlink sub-frame, they occupy more than one sub-channel, thus, constituting impossible the transition to sleep mode. In Fig. 5, we depict the mean number of sleep slots for 10 ms long frame. It is evident that the higher the duration of the sub-frame, the more power saving capabilities are provided.

The results provided in Figs. 4 and 5 were calculated with the assumption that there are always enough MS requests to occupy all the sub-channels of the downlink sub-frame when mapped. Following, we present results considering variable number of MSs and a fixed mean number of requested slots $\lambda = 10$. Note that each request corresponds to one MS, thus, the number of requests equals to the number of MSs. Figure 6 shows the mean number of sleep slots per downlink sub-frame for varying number of MSs, when the frame duration is 5 ms. It is obvious that in total more MSs can conserve more energy, since the power saving capabilities of each MS depends only on the number of slots it occupies considering a single channel. Furthermore, it can be seen that the higher the downlink-to-uplink ratio the later the respective curve converges to a specific value. The reason is that each downlink sub-frame size can support a limited number of MSs. When this threshold is reached, the residual MSs are simply not served, so the number of sleep slots remains constant. Notice that this value of convergence is equal to the respective mean number of sleep slots that we previously estimated and depicted in Fig. 4 for $\lambda = 10$ and unlimited number of MSs. The results for frame duration equal to 10 ms are plotted in Fig. 7. In this case, the increased energy conservation capabilities are obvious. The downlink sub-frame is long enough to enable the MSs transition to sleep mode, since most requests do not exceed one sub-channel.

The results presented concerning the number of sleep slots for different downlink-to-uplink ratios and frame durations are based on the different number of slots provided for allocation in the time and frequency domains for each considered scenario. The provided analytical approach has already shown that the time intervals during which MSs can transit to low power sleep mode depend on the dimensions of the resource space. Thus, for identical rectangular slot areas, the number of sleep slots is expected to remain constant. However, the examined schemes correspond by definition to different downlink sub-frame dimensions, hence, they cannot be considered on exactly the same resource space without violating their characteristics. In such a case, the differences in downlink-to-uplink ratio and frame duration would be eliminated, the schemes would lose their unique features, and the study would not be able to provide usable information on realistic WiMAX implementations, following the standard's specifications. Nevertheless, a normalization of the given results for the same operation interval could lead to useful conclusions on

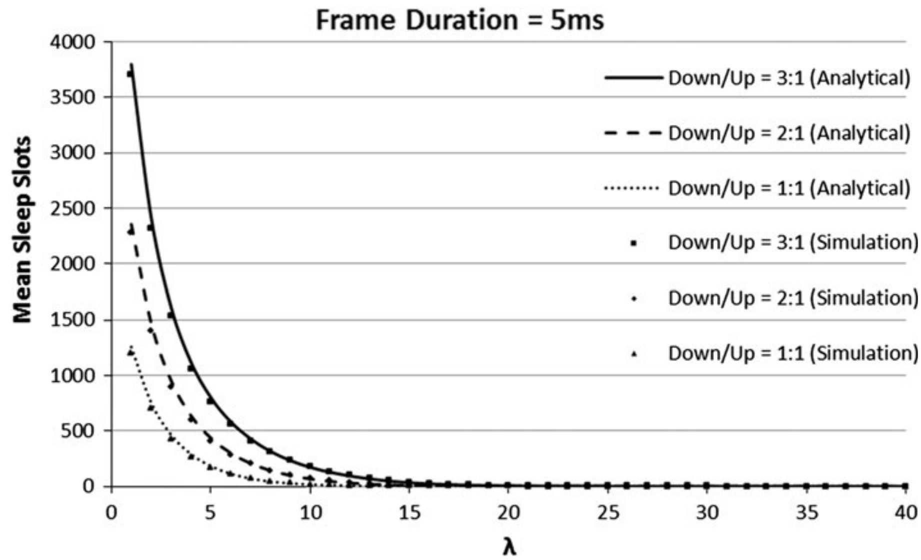

Fig. 4 Mean number of sleep slots per downlink sub-frame as a function of the mean number of requested slots λ, for 5 ms long frame

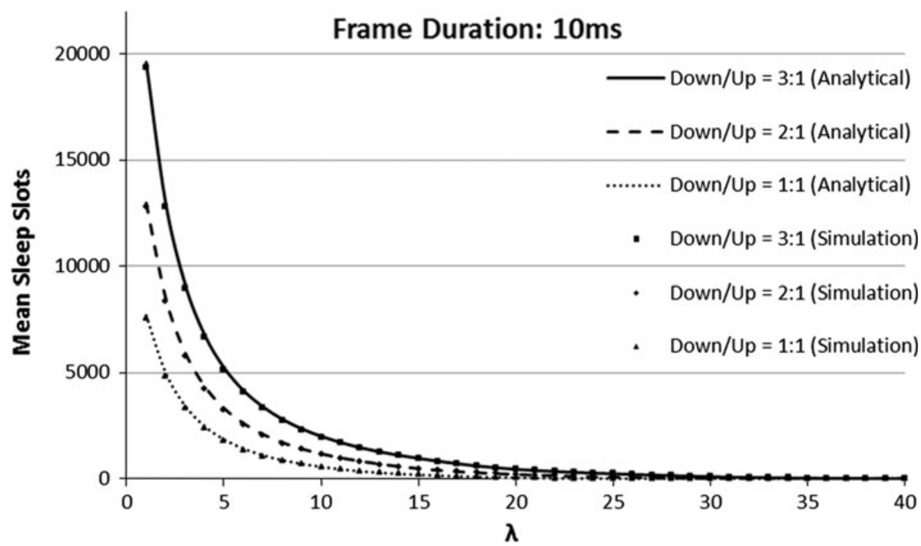

Fig. 5 Mean number of sleep slots per downlink sub-frame as a function of the mean number of requested slots λ, for 10 ms long frame

the power saving capabilities of the examined scenarios, considering that the involved transmissions last for the same time duration. For instance, a downlink sub-frame which is part of a 10 ms long frame with downlink-to-uplink ratio equal to 1:1 corresponds to two downlink sub-frames which are part of two 5 ms long frames considering the same downlink-to-uplink ratio. Table 3 presents the number of acquired sleep slots considering different scenarios normalized to the duration of a 10 ms long frame with downlink-to-uplink ratio equal to 1:1. The considered value for λ is 10, whereas the available MSs are unlimited. The respective results confirm that even when assuming the same operation interval, the larger the width of the resource space, the higher the number of available sleep slots. This behavior is attributed to the fact that wide slot areas allows for the arrangement of user requests to single sub-channels according to horizontal SPA, which makes transition to sleep mode possible.

4.2 Feasibility study

For reasons of accuracy and completeness, we perform at this point a feasibility study regarding the presented intra-frame energy conservation procedure. More specifically, we examine in detail the effect of switching from reception mode to sleep mode and vice versa. This transition between different energy statuses is considered as overhead that may degrade power saving efficiency. The considered power requirements when receiving, being idle, and sleeping are taken equal to 280, 120, and 10 mW respectively, whereas switching is considered to consume additional 1 mW. These are commonly adopted energy

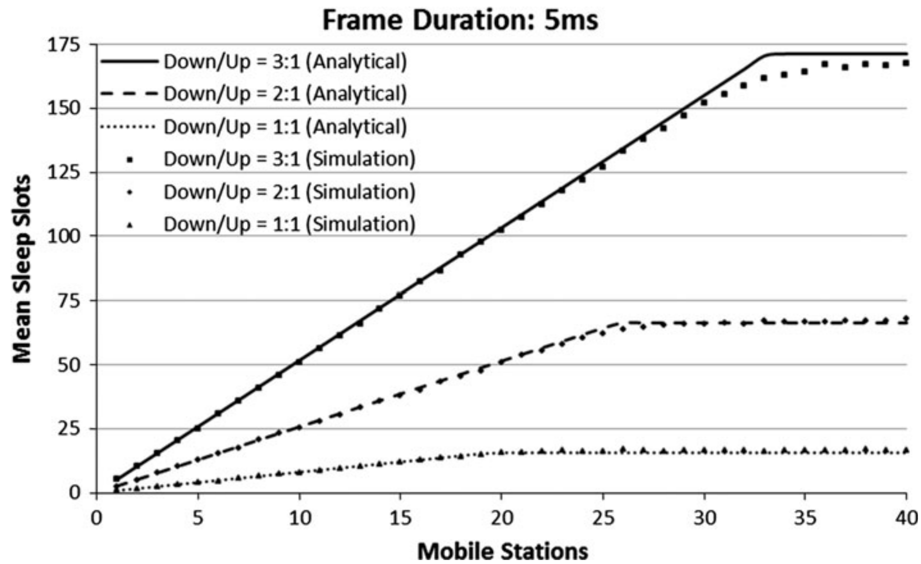

Fig. 6 Mean number of sleep slots per downlink sub-frame as a function of the number of subscriber stations, for 5 ms long frame

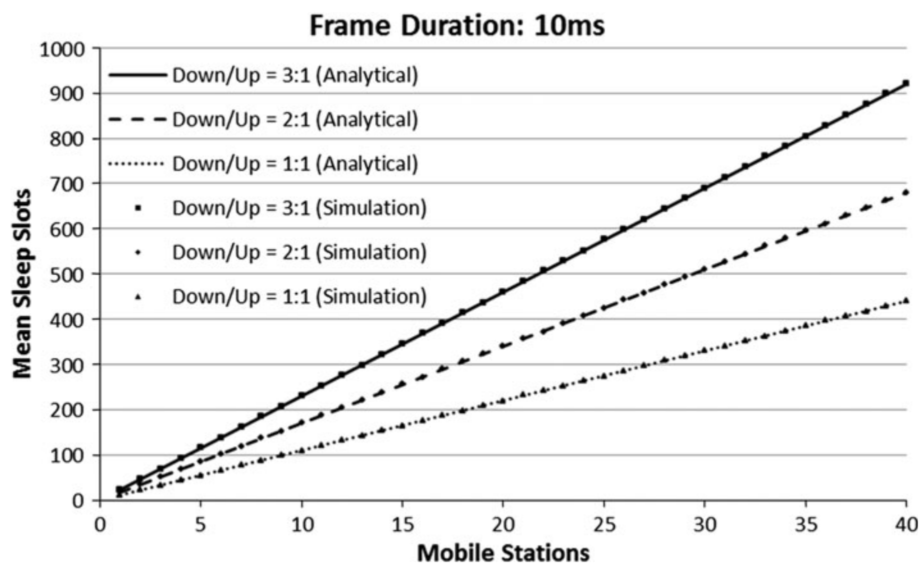

Fig. 7 Mean number of sleep slots per downlink sub-frame as a function of the number of subscriber stations, for 10 ms long frame

Table 3 Number of sleep slots normalized to the duration of 1:1 DL sub-frame (part of 10 ms frame), for $\lambda = 10$ and unlimited MSs

DL/UL ratio	5 ms frame	10 ms frame
1:1	31	561
2:1	100	880
3:1	228	1,334

consumption values that come from related WiMAX studies [8–11], which are based on the WiMAX chipset specification described in [12]. The exact duration of switching between reception and sleep mode constitutes a highly specialized chipset characteristic and as such it is difficult to be estimated based on existing implementations. An approximation could come from other wireless technologies, like wireless sensors [17, 18] and wireless local area network [19], however, the considered values vary from a few microseconds up to a millisecond.

A complete study is performed here for a large range of switching intervals, considering as closest approximation for the examined WiMAX case the switching duration assumed for a wireless local area network scenario. On this ground, we estimate the maximum achievable power reduction in order to draw conclusions on the feasibility of intra-frame energy conservation. Carefully taking into account the exact specifications of the adopted WiMAX standard, one time slot is considered to consist of two OFDMA symbols, each symbol lasting for 102.9 μs [2]. The maximum reduction of consumed energy for low λ ($\lambda = 1$) is graphically presented in Figs. 8 and 9. It becomes evident that intra-frame power saving capabilities are notable for multiple values of switching duration (measured in slots), especially for large frames. As

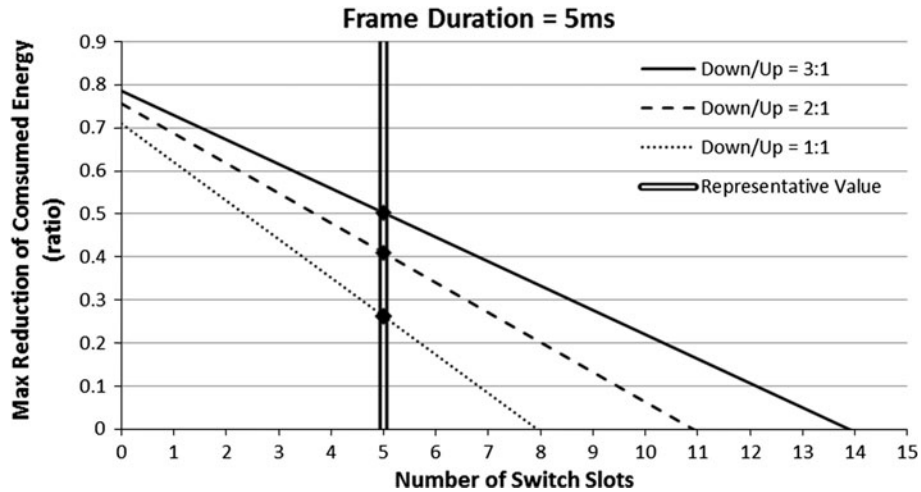

Fig. 8 Maximum reduction of consumed energy (expressed as ratio) as a function of the number of switch slots, for 5 ms long frame

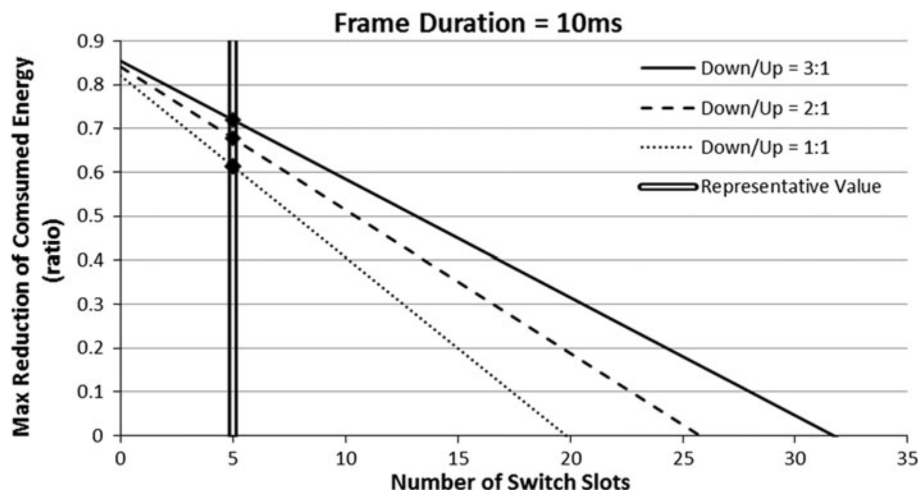

Fig. 9 Maximum reduction of consumed energy (expressed as ratio) as a function of the number of switch slots, for 10 ms long frame

the number of switch slots reaches the downlink sub-frame length, the ability to conserve energy fades and eventually for extreme switching duration values it disappears. The respective graphs highlight with a vertical line the maximum reduction of consumed energy achieved for five slots switching (corresponding to 1 ms interval considered in [19]). In more specific, for this particular switching duration, which is considered as the most representative value, the consumed power can be reduced up to 72 %, in case of large sub-frame width ($W = 33$), and up to 27 %, in case of small sub-frame width ($W = 9$).

To generalize this study on the feasibility of intra-frame power saving, it is noted that the switching overhead can eliminate energy conservation, when the power saved during sleep is less than the extra power consumed during switching compared to the typical no-sleep scenario. Thus, an inequality formula can be derived to show when transiting to sleep mode is energy beneficial:

$$\begin{aligned} SlotsI \times PowerI > {} & SlotsSW \times PowerSW \\ & + (SlotsI - SlotsSW) \times PowerSL \end{aligned} \tag{16}$$

where *SlotsI* and *SlotsSW* denote the number of idle slots available for sleep and the number of switch slots, respectively, whereas *PowerI*, *PowerSW*, and *PowerSL* denote the power consumption when being idle, switching, and sleeping, respectively. Hence, based on the aforementioned energy consumption values and considering as switching duration the representative value of 1 ms (16) leads to the conclusion that a MS can exploit intra-frame power saving when it has more than 1.038 ms long interval available for sleeping in a single downlink sub-frame. This finding confirms the intra-frame power saving perspectives analyzed in this paper.

5 Conclusions

This work provided a novel analysis of the power saving capabilities of the IEEE 802.16e downlink sub-frame, when the well-known horizontal SPA mapping technique is implemented. The respective algorithm allows transition to a low power sleep mode during the idle slots, when an MS does not exploit more than one sub-channel. The number of sleep slots that can be supported per frame was mathematically calculated for multiple frame sizes, varying number of MSs, and different request sizes. The introduced analytical model was validated via simulation, whereas the results revealed higher energy conservation potentials for larger downlink sub-frames and the ability of saving up to a maximum of 72 % of the consumed power (considering the energy consumption parameters discussed in [8–12, 17–19]). In the future, we plan to provide models for analyzing the power saving capabilities of other WiMAX mapping schemes.

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