A Novel Adaptive Mapping Scheme for IEEE 802.16 Mobile Downlink Framing

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***Abstract*—IEEE 802.16 (WiMAX) constitutes one of the most promising broadband access technology for high-capacity and high-distance wireless access networks, supporting user mobility. The allocation operation in downlink sub-frame identifies interesting research issues, since the standard requires all downlink allocations to be mapped in a two-dimensions rectangular shaping. The target of the mapping operation is to accommodate as many as possible subscribers' requests, since the restrictions regarding the capacity of the downlink frame may violate QoS guarantees, resulting high delays and high packet loss. The contribution of this paper is twofold. Firstly, a novel mapping scheme is introduced, applying horizon mapping. Secondly, an efficient adaptive prediction-based scheme is presented, which is able to adjust the downlink sub-frame capacity, accordingly to the traffic load, since the standard allows the downlink-to-uplink subframe ratio to be changeable from 3:1 to 1:1. The novel adaptive horizon burst mapping (AHBM) scheme is evaluated by simulation experiments, which indicate that the proposed scheme operates effectively and efficiently, by reducing the number of unserved users, the number of traffic requests, and the portion of wasted bandwidth.**

***Index Terms*—IEEE 802.16, Downlink mapping, Prediction, OFDMA**

I. Introduction

Wireless communications and networks have gained the interest of the academic community and industry in recent years. Many industry partners and observers along with the majority of the academia believe that broadband wireless can deliver applications and services to the subscribers adequately. Since 1998 when the IEEE formed a group called 802.16 to develop a standard for what was called a wireless metropolitan area network the WiMAX standard presented a tremendous progress [1]. Today, the IEEE 802.16e standard constitutes the basis for the WiMAX solution for nomadic and mobile applications.

One of the most interesting technical design challenges of the current IEEE 802.16e standard is the efficient multiplexing services supporting. This standard, known as mobile WiMAX, makes use of the orthogonal frequency division multiple access (OFDMA), which identifies a multicarrier modulation technique in order to meet the multi-user communication problem [2]. The OFDMA technique innovates by applying a different multi-access approach, whereby subscribers exploits the available bandwidth, by sharing both subcarriers and timeslots.

The communication process, based on the WiMAX standard, consists of a base station (BS) and a number of mobile stations (MSs), where the participants exchange data within specific time periods. Time is organized into fixed frame periods, while the frame is divided into uplink and downlink sub-frames. The bi-directional communication can be realized by applying either frequency division duplexing (FDD) or time division duplexing (TDD). In the FDD technique uplink and downlink periods use different frequency bands, allowing the simultaneous transmission of both downlink and uplink sub-frames. The TDD technique offers a flexible bandwidth allocation, by allowing a downlink frame followed by an uplink frame after a small guard interval. TDD is favored by a majority of applications [2] and it is adopted in this work.

Concerning the multiple access issue the BS is fully responsible for accommodating all MSs, in both uplink and downlink sub-frames. One of the most noticeable limitation on the downlink allocation procedure is the rectangular restriction. According to this the MSs' requests have to be formed in a 2D-rectangular fashion, which is called a burst, with one dimension associated with the time domain and the other associated with the frequency domain. Hence, a considering open research area is identified in the accommodation of the traffic requests on the downlink sub-frame, since this procedure is not standardized and it is based on the WiMAX implementation.

So far recent allocation schemes and mapping algorithms have presented various burst construction techniques, trying to accommodate 2D-rectangular requests into the downlink sub-frame. The common drawback of recent efforts lies in the consideration of the fixed downlink sub-frame, which results in degrading the allocation scheme's performance, since the capacity of the available bandwidth space remains fixed, independent of the MSs' requests amount. In this work, the flexibility of the WiMAX standard in choosing uplink-to-downlink data rate ratios is exploited. Various research efforts

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[3, 4] suggest that adaptation could offer significant benefits. More specifically, a prediction mechanism is introduced, which is able to adjust the capacity of the downlink sub-frame based on the MSs' traffic load in order to efficient accommodate the incoming requests. Since the downlink-to-uplink-subframe ratio may be varied from 3:1 to 1:1 to support different traffic profiles [5], the available downlink bandwidth capacity could be changed to adapt to the subscribers' requests. In this manner the applied prediction mechanism reduces the width (in the time domain) of the downlink sub-frame if the subscribers' traffic load is low and increases it if the load turns high. Concurrently, a low-complexity allocation burst scheme is introduced, applying horizon scheduling, which divides the sub-frame capacity into simple horizons, permitting bursts to be scheduled efficient and in a simple way, following the horizons as pilots. The novel adaptive horizon burst mapping (AHBM) scheme achieves the adaptive allocation of the incoming requests, as the simulation results indicate, under various traffic load scenarios.

The paper is organized as follows. Section II describes the OFDMA multi access background and Section III presents related work and past efforts on the current research area. Section IV presents and explains in detail the proposed accommodation scheme and Section V shows simulation results of the presented scheme evaluation and comparison results, in terms of performance metrics between the proposed scheme and recent mapping algorithms. Finally, Section VI concludes this paper.

II. OFDMA Multi-Access Background

The OFDMA technique is responsible to provide multiple access to multiple subscribers by dividing the available bandwidth in the domains of frequency and time. The minimum allocation entity that can be defined by the WiMAX implementation is called a slot. Each slot consists of one subchannel over one, two, or three OFDM symbols, depending on the particular subchannelization scheme used [2]. Multiple adjacent slots state a subscriber's region, in which the incoming requests are accommodated.

The WiMAX frame structure is depicted in Figure 1, operating in a TDD mode. The frame size is fixed and may vary from 2 to 20 ms. Two subframes, a downlink and an uplink, composes the whole frame, while two small guard intervals are interpolated between the sub-frames. The downlink sub-frame begins with a synchronization preamble. Next, the frame control header (FCH) and the downlink MAP messages follow. The FCH field provides frame configuration information, such as the MAP message length, the modulation and coding scheme, and the usable subcarriers. The transmission instructions for the MSs are specified in the uplink and downlink MPA control information (DL-MAP and UL-MAP). MAP instructions include the burst profile for each subscriber, which defines the modulation and coding scheme

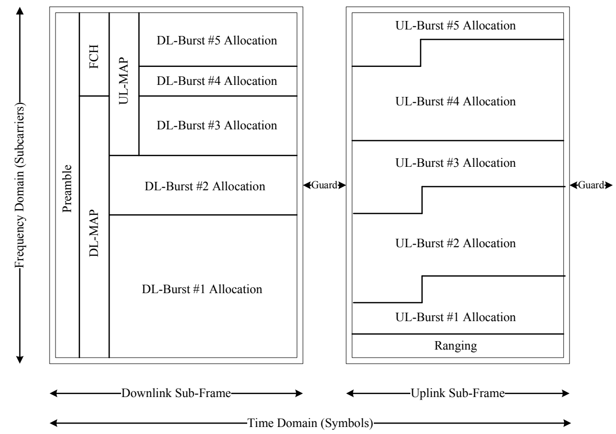

Fig. 1. A TDD frame instance of IEEE 802.16 standard.

used in that registration.

The burst profile collects multiple connection sessions either from different subscribers or from one subscriber only. As the frame structure indicates the WiMAX implementation comprises a flexible and elastic multi access technique, based on which each subscriber may easily accommodated in a single subscriber region or in a subscriber's burst. However, an efficient mapping scheme is needed to accommodate the incoming subscribers' requests into the available downlink sub-frame space, given that both requests' and sub-frame's structure follow a rectangular shaping.

III. Related Downlink Mapping Schemes

The simplest mapping approach is the static predefined burst mapping, which assign request in an a priori predefined way, accommodating *S* fixed rectangles, where *S* denotes the number of the connected MSs. Beyond the simplicity of this approach, the static mapping scheme presents inefficient performance, since the predefined allocations are static and may notably vary compared to the subscribers' requests. In this manner, valuable bandwidth portion is wasted and an extra control mechanism is needed to provide the a priori knowledge of the incoming requests before the mapping procedure.

In [6] a different mapping scheme has been introduced for the downlink sub-frame mapping issue. In this scheme the downlink sub-frame is thoroughly scanned in a slot-by-slot basis and the incoming requests are accommodated in line one after the other. This approach seems simple and low-complex but suffers in terms of flexibility, since each incoming request is handled as individual burst, fact that leads to increasing control information that has to be maintained in the DL-MAP field. Apparently, given that the number of incoming requests per frame is not known, each request is accommodated as single burst and the size of control information increases, reducing the available space for data allocation.

The scheme presented in [7] introduced full-search mapping tries, until the optimized one can found. A binary-tree full search operation is applied to exhaustively calculate the total possibilities. In is clear that such an effort demands crucial operational time to be executed, hence the authors limit the number of accommodated subscribers to eight per frame.

Efforts in [8] and [9] present similar techniques, which include the construction of buckets, where multiple requests are gathered in allocation columns. Each bucket collects requests in the frequency domain with common transmission characteristics. Even though these schemes present better performance compared to the static mapping scheme, their accommodation logic leaves significant number of unused slots, when the bucket fails to cover the entire column in the frequency domain.

Finally, in [10, 11] two simple heuristic mapping schemes have been proposed, aiming to keep the mapping operational complexity low. According to eOCSA [11], which constitutes the latest well-performed mapping scheme, the accommodation strategy lies in the fact that each subscriber's request is scheduled into the downlink sub-frame as an individual downlink burst, resulting in reduced DL-MAP overhead. In the first step, the algorithm includes an initial sorting in a descending order of the incoming bursts and a mapping procedure, which suggests mapping strategy from bottom to top and from left to right. During the second step, known as vertical mapping, and given that H denotes the downlink sub-frame height, W_i denotes the burst allocation width, H_i denotes the burst allocation height, and A_i denotes the number of requests slots of the i_{th} incoming request, the requests are mapped as follows:

$$W_i = \lceil A_i / H \rceil, H_i = \lceil A_i / W_i \rceil$$

The remaining unallocated space is handled by in the third step, in which the horizontal mapping takes place, where the eOCSA tries to assign the unallocated space to the next largest request that can be accommodated in.

It is worth mentioning that all previous schemes consider the downlink-to-uplink ratio stable. Obviously, given that the frame has unchangeable size, if the requested downlink traffic is low a considerable portion of the available bandwidth is wasted. Similarly, if the incoming downlink traffic exceeds the downlink sub-frame capacity traffic requests will remain unallocated, leading to performance degrading and high levels of service delay. In order to address this issue a novel mapping approach is introduced, including prediction-based frame size adjustment based on the downlink traffic amount.

IV. Proposed Adaptive Mapping Scheme

A. Proposed Horizon Mapping

The proposed mapping technique defines Horizon allocations in its first phase, creating pilots for the forthcoming requests. The logic beyond this design aims at reducing the complexity of the mapping operation, since requests that are scheduled during the first phase are accommodated in an efficient way, leaving the less possible wasted space.

Initially, the suggested mapping technique applies a descending order sorting, giving the opportunity to large requests to be accommodated firstly. Then the first phase begins, where each accommodated request creates a scheduling Horizon pilot. AHBM selects the appropriate dimensions of the rectangle, before starting the accommodation procedure. The main criterion of the dimension choosing assessment is the idle (wasted) space that each request leaves behind. The scheme calculates this quantity, using one pointer called W_rest, indicating the available width of the downlink bin. Since the bin has initial dimensions $H \times W$ the pointer W_rest receives the initial value W. Apparently, the first request for each frame can be accommodated in an available space equal to $H \times W\_rest$. Supposing that the number of slots of the i_{th} (first scheduled) request equals to A_i then the next step is the determination of request dimensions (rectangle's width and height), having as upper limit the value H and W_rest for height and width respectively. The burst mapping begins from the below right corner of the bin and moves towards the right corner. The Algorithm1 shows the mapping procedure during phase one:

Algorithm 1 Defining Horizons and right-to-left Mapping

1: Define the collection set of incoming downlink requests $S = \{A_1, A_2 ... A_i ...\}$

2: Set the available bin height equal to H

3: Set the available bin width equal to $W\_rest = W$

4: **Do**

5: Select the largest request and set it as A_i

6: Find the $\underset{x \in [1, W\_rest]}{\arg\min} (x \times \lceil A_i / x \rceil - A_i)$

7: Schedule A_i in the rectangle specified as:
Upper left point coordinates in the bin:
$(W\_rest - x, H - \lceil A_i / x \rceil)$
Burst rectangle dimensions:
$height = \lceil A_i / x \rceil, width = x$

8: Set the i_{th} Horizon specifications as:
Upper left point coordinates in the bin:
$(W\_rest - x, H)$

9: Horizon_i rectangle dimensions:
$Horizon_i(height) = H - \lceil A_i / x \rceil, Horizon_i(width) = x$

10: Update the available width: $W\_rest = W\_rest - x$

11: Remove the scheduled burst from the S set $S = S - \{A_i\}$

12: Select the next largest burst from the S as A_i

13: **While** $(H \times W\_rest < A_i \ OR \ S \in \varnothing)$

At the end of the first phase a set of Horizons has been defined and at least one burst has been mapped. Defining width and height, each Horizon indicates an unallocated 2D-rectangular region. In the third phase, the AHBM scheme tries to accommodate the remaining requests into the Horizon regions according to the following algorithm:

Algorithm 2 Right-to-left mapping of the remaining bursts

1: Define the collection set of remaining unmapped requests $S' = \{A_1, A_2 ... A_i ...\}$

2: **For** {each remaining unmapped request}

3: **Do**

4: Select the largest request and set it A_i

5: Find the x:

$\arg\min_x (Horizon_x(width) \times \lceil A_i / Horizon_x(width) \rceil MOD A_i)$

6: **If** ($Horizon_i(height) \times Horizon(width) \leq A_i$) **Then**

7: Schedule A_i in the rectangle specified as:

Upper left point coordinates in the bin:

$(W - Horizon_x(width), H - Horizon_x(height))$

Burst rectangle dimensions:

$height = \lceil A_i / Horizon_x(width) \rceil,$

$width = Horizon_x(width)$

8: Update the x_{th} Horizon specifications as:

Upper left point coordinates in the bin:

$(W\_rest - x, H)$

Horizon rectangle dimensions:

$height = Horizon_x(height) - \lceil A_i / Horizon_x(width) \rceil,$

$width = x$

9: Remove the scheduled burst from the *S'* set

$S' = S' - \{A_i\}$

10: Select the next largest burst from the *S'* set and set it as A_i

11: **Else** Select the next minimum Horizon_x

12: **End_if**

13: **While**(there are still unchecked Horizons *OR* $S' \in \varnothing$)

14: **End_for**

B. *Proposed Prediction Module*

The introduced prediction module aims at estimating the width of the downlink sub-frame bin. Based on the estimating width value, the prediction module adjusts the width of the next downlink sub-frame. This adjustment is limited by a minimum and a maximum threshold, named *min_width* and *max_width* respectively, configured by the WiMAX implementation. The prediction module is implemented via a hidden markov chain (HMC) model. This model is described by a set of $(\max\_width - \min\_width) + 1$ distinct states:

$S_{(\max\_width - \min\_width + 1)} =$

$\{S_0, S_1, ..., S_{(\max\_width - \min\_width) + 1}\}$

Each distinct state denotes an individual downlink sub-frame width value. The frame instants are denoted as: $t = 1, 2, ...$ Also, the actual state at frame *t* is denoted as q_t. The notations along with the specifications of the observation notations are more clearly defined below:

$$P(O_t = k_z \mid q_t = S_z),$$

where $\min\_width \leq z \leq \max\_width,$ while

$k_0 = \min\_width,\ k_1 = \min\_width + 1$

...

$k_{(\max\_width - \min\_width) + 1} = \max\_width$

The state transition probability distribution is considered as follows:

$$a_{i,j} = P[q_{t'} = S_j \mid q_t = S_i],$$

where $0 \leq i, j \leq (\max\_width - \min\_width) + 1$

In the above equation *t* denotes the number of frame, in which the downlink sub-frame width is equal to *i*. Subsequently, *t'* denotes the number of frame, where the downlink sub-frame width is equal to *j*. The state transition coefficients have the properties:

$a_{i,j} \geq 0$ and $\sum_{i=0}^{(\max\_width - \min\_width) + 1} a_{i,j} = 1$

For example, transition probability $A_{27,29}$ corresponds to the transition from state S_{27} to state S_{29}. This transition means that the size of the downlink sub-frame width changes from 27 to 29 symbols. Regarding the initial state probabilities is worth to mention that are identical for all possible width values as the following equation indicates:

$\pi_i = P[q_1 = S_{\min\_width}],$ while $0 \leq i \leq (\max\_width - \min\_width) + 1$

The prediction module tries to estimate the appropriate width size in order to accommodate the incoming downlink requests efficiently, reducing concurrently the wasted portion of bandwidth. In essence, the predictor is responsible to increase the width size if the amount of requested slots demands more capacity, in terms of columns, compared to the width size of the previous frame. Apparently, the predictor reduces the width size if it senses that the downlink traffic load is decreased. In order to be adaptive the predictor needs a feedback from the mapping procedure. This feedback shows the number of columns that the previous downlink sub-frame wasted or extra needed. More specifically, the feedback is given as follows:

$feedback = \lceil unserved\_slots - unused\_slots \rceil / height$

TABLE I
SIMULATION ASSUMPTIONS

Channel Mode	PUSC
Frame Size	10 ms
Preamble Size	1 Symbol
MAP, FCH Sizes	2 Symbols
Downlink sub-frame Symbols	21 to 33 (1:1 to 3:1 downlink-to-uplink ratio)
Total sub-frame capacity	630 to 990 slots
Frame Iterations (Trials)	2000
History Vector Size (V)	10

The number of *unserved_slots* refers to the cumulative number of requests that fail to find accommodation space, measured in slots, while the term *unused_slots* refers to the total number of wasted slots into the downlink sub-frame bin. The parameter *height* stands for the bin's height, which in the most cases is stable and equal to 30 symbols [2].

The output of the predictor is the state that is indicated by the most probable transition. The introduced model needs a data structure to be able to support operations with memory demands. For this purpose, a set of history vectors are applied to store and handle the feedback obtained by the end of each frame. The number of entries of each history vector is a system parameter, denoted by *V*:

$$H_z(h) = \{H_z(1), H_z(2), ..., H_z(V)\},$$
$$\text{where } 1 \le h \le V, \text{for each } z,$$
$$\text{where } 0 \le z \le \max\_\ width + 1$$

For instance, the entry $H_{27}(5) = 31$ indicates that the transition from S_{27} to S_{31} state has stored 5 entries before into the history vector. After filling the history vectors, the model predicts the most probable state, indicating the most appropriate width size for the next frame. Assuming that after frame *t* the feedback indicates ph_t state and after frame *t'* the feedback related to ph_t state. Then it holds that the active current state after frame *t* is $ph_{t'}$. Afterwards, the history vector update takes place as follows:

$$H_{ph_t}(h) = H_{ph_t}(h-1), \text{ for each } h, \text{ where } 2 \le h \le V$$
$$\text{and } H_{ph_t}(1) = ph_{t'}$$

Then the corresponding transition probabilities are updated, according to history vectors:

$$a_{ph_t, j} = \frac{\text{frequency of } j \text{ in } H_{ph_t}}{V}$$
$$\text{for each } j, \text{ where } 0 \le j \le (\max\_\ width - \min\_\ width) + 1$$

Finally, the predictor modules chooses the most probable transition state and stores it to vector F_t, which determines the size of the next downlink sub-frame, where *t* is the current frame, as follows:

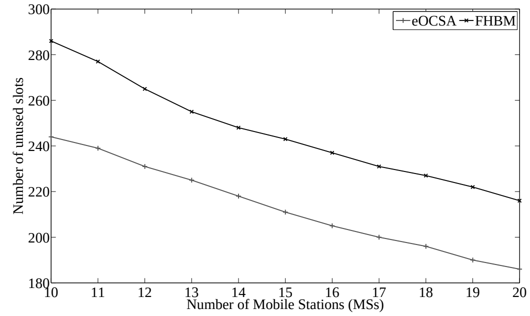

Fig. 2. Number of unused slots vs. number of MSs.

$$F_t = O_t(\arg\max_{\zeta}[a_{ph_t, \zeta}]),$$
$$\text{where } 0 \le \zeta \le (\max\_\ width - \min\_\ width) + 1$$

V. PERFORMANCE EVALUATION AND SIMULATION RESULTS

In order to evaluate the performance of the proposed AHBM scheme a set of simulation experiments have been conducted. The experiments evaluate the performance of the AHBM scheme compared to the eOCSA mapping scheme [9], which has been chosen due to its low complexity, its common burst construction technique, and its efficient performance compared to older mapping schemes. The adopted simulation assumptions are shown in Table I.

Considering the partially used sub-channelization (PUSC) mode, which constitutes the most common frequency diversity mode for mobile communication environments, the downlink sub-frame defines 30 channels. The downlink-to-uplink sub-frame ratio is adjustable and may be varied from 1:1 to 3:1. The frame size is also a system parameter, varying from 2 to 20 ms. Here, this parameter is set to 10 ms, allowing 95 symbols to attach the downlink and the uplink sub-frames. Three symbols are destined to control information (Preamble, MAP and FCH fileds) and are excluded from the available slots for allocation needs. The available symbols which are destined to downlink sub-frame may be varied from 21 to 33 for 1:1 and 3:1 ratio respectively for the AHBM scheme, contrary to eOCSA scheme which uses a stable 2:1 ratio allowing 27 available symbols. Hence, a set of 630 (30 × 21) to 990 (30 × 33) total slots is available for allocation in the simulated WiMAX implementation. Regarding the downlink traffic load the size of incoming requests follows a Poisson process. The traffic load of each MS is identical. Furthermore, the parameter λ of the Poisson process is changed periodically, adopting a realistic scenario with continuous load changes. Each experiment has been conducted for 2000 frames. The exact values of the parameter λ are shown in the Table II. The prediction operation of the AHBM scheme is triggered after a short learning period. This learning period, in which the downlink sub-frame width is stable and equal to 27 symbols, lasts for 100 frame iterations.

TABLE II
POISSON TRAFFIC VALUES

# of Frame Iteration	≤ 250	≤ 500	≤ 750	≤ 1000
λ (slots)	70	120	170	20
# of Frame Iteration	≤ 1250	≤ 1250	≤ 1750	≤ 2000
λ (slots)	10	10	80	120

In the first set of experiments the amount of wasted bandwidth is examined in terms of the number of unused slots. The number of unused slots is measured by calculating the number of slots being idle in the downlink sub-frame allocation space. Figure 2 depicts the performance of eOCSA and AHBM, in terms of unused slots. The number of connected MSs varies from 10 to 20. It is clear that AHBM reduces the number of unused slots compared to eOCSA scheme. The main reason of the notably improvement lies on the applied prediction-based mapping scheme. Keeping the downlink-to-uplink ratio changeable the FHBM achieves better performance, by reducing the sub-frame capacity when the downlink traffic is low, while the eOCSA keeps static the downlink sub-frame capacity, causing bandwidth deficit.

The mean number of unserved MSs per frame is shown in Figure 3. Again, the number of connected MSs varies from 10 to 20. Once more, the superiority of the proposed scheme is confirmed, since the proposed adaptive scheme permits the accommodation of more MSs than the eOCSA. This happens because the AHBM adjusts the downlink sub-frame capacity based on the incoming traffic load. In this manner, the downlink capacity may be increased, adding more columns, if the prediction module of AHBM estimates that the incoming traffic load pushes for more allocation space.

Finally, the average number of unserved slots is presented in Figure 4. The unserved slots metric results from the unallocated slots measurement of the unserved MSs. Substantially, the unserved slots are directly associated with the amount of MSs that failed to find free allocation space. The results of Fig. 4 indicate that the proposed scheme succeeds to accommodate more traffic requests than the eOCSA one, in terms of average number of slots. In other words, the suggested adaptive scheme presents higher throughput than the compared scheme, allowing more downlink traffic to be scheduled per frame.

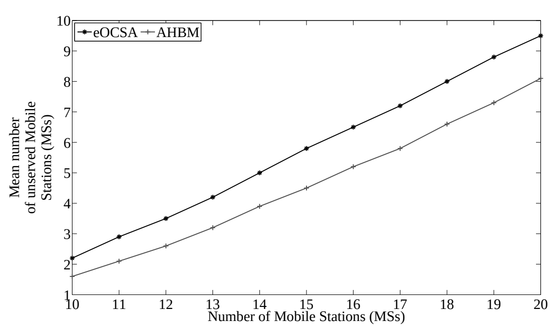

Fig. 3. Mean number of unserved MSs vs. number of MSs.

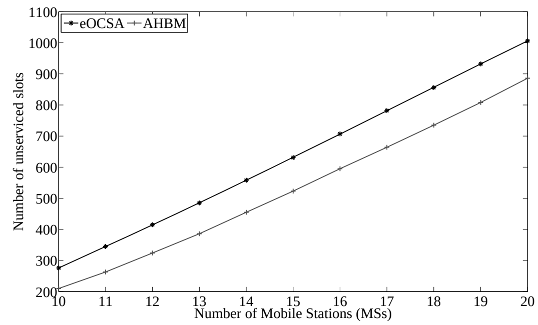

Fig. 4. Number of unserved slots vs. number of MSs.

VI. CONCLUSION

A novel adaptive burst mapping scheme have been presented in this paper. The novelty of the suggested scheme lies on the ability to adjust the downlink sub-frame capacity in accordance to the incoming downlink traffic. Given that the downlink-to-uplink ratio is changeable, the enhanced prediction-based scheme is able to take decisions about the amount of the forthcoming traffic, adding or reducing columns regarding the 2D-rectangular downlink sub-frame shape. Concurrently a novel efficient burst accommodation technique has been introduced. Simulation results confirm that the novel scheme attains high bandwidth efficiency, allowing more subscribers to be scheduled than other mapping schemes.

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