

# On Effectively Determining the Downlink-to-uplink Sub-frame Width Ratio for Mobile WiMAX Networks Using Spline Extrapolation

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**Abstract**—One of the most valuable design issues of the Worldwide Interoperability for Microwave Access (WiMAX) standard is its flexibility. It allows multiple downlink-to-uplink duration definitions concerning the width of the corresponding sub-frames, thus, the telecommunication companies and businesses are able to define the downlink-to-uplink width from 3:1 to 1:1 respectively to meet the traffic demands of the connected subscribers. However, the decision on defining the most appropriate ratio is not yet solved, since current efforts on developing scheduling and mapping schemes consider it as fixed. In this work, a novel adaptive mapping approach – based on cubic spline extrapolation – is proposed in order to dynamically determine the most appropriate downlink-to-uplink width ratio in accordance to the downlink and uplink traffic demands. The method proposed is evaluated through realistic simulation scenarios, whereas its performance is compared with static approaches maintaining a fixed ratio. The results indicate that the approach suggested succeeds noticeable improvements in terms of network service capabilities and bandwidth utilization.

**Keywords**-Extrapolation, IEEE 802.16, mapping, OFDMA, splines, WiMAX

## I. INTRODUCTION

Wireless broadband communications have attracted the attention of industry and academic community in the recent years. The Worldwide Interoperability for Microwave Access (WiMAX) solution defined by the IEEE 802.16 group in 2001 has been a promising technology for point to multipoint broadband wireless access. The current 802.16e standard known as mobile WiMAX supports subscribers' mobility exploiting the Orthogonal Frequency Division Medium Access (OFDMA) multi-carrier modulation scheme for communication.

Communication in an 802.16e access network is carried out between a Base Station (BS) and a number of connected Mobile Stations (MS). The BS establishes a full-duplex communication link with each MS. Information is transmitted in frames incorporating data exchanged from the BS to MSs (downlink direction) and from MSs to BS (uplink direction). Respectively, each frame consists of an uplink and a downlink sub-frame, the width of which varies from 3:1 to 1:1. WiMAX supports both Time Division Duplexing

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(TDD) and Frequency Division Duplexing (FDD) to provide bidirectional communication. In TDD the downlink sub-frame precedes the uplink sub frame in the time domain with a small guard interval in between whereas in the FDD both sub frames are transmitted in parallel over different carriers. The majority of WIMAX implementations use TDD due to its simple design and flexible frame partitioning [1]. TDD technique is also adopted in this work. The BS allocates MS requests in the uplink and downlink sub-frames. Bandwidth requests are structured in a rectangular shape of two dimensions. The vertical dimension associates with frequency whereas the horizontal associates with time. OFDMA allows subscribers to use different bandwidth regions in both time and frequency domains consisting of contiguous series of slots. A slot is the minimum time-frequency resource allocated to a single subscriber. Moreover, each downlink request (or a set of requests that share common PHY characteristics referred to as a burst) must follow the rectangular shape. This rule does not apply for uplink requests, simplifying, thus, the uplink allocations.

Recent scheduling and mapping approaches presented by the research community try to allocate bursts of various sizes to downlink and uplink sub frames. However, they consider a fixed bandwidth size in each sub frame without taking advantage of the dynamic adaptation scheme proposed by the standard. In this work, a novel approach is proposed that adjusts the capacity of the downlink and uplink sub frames of the OFDMA framework to accommodate demanding traffic load and new incoming requests.

The determination of the most suitable downlink-to-uplink width ratio is addressed by applying an extrapolation method. In this way the well-known cubic spline interpolation technique is applied in a set of scattered data, obtained by previous transmissions. More specifically, the applied extrapolation method, called Extrapolated Ratio Determination (ERD), attempts to estimate the most appropriate ratio based on the most recent previous observations. The estimated ratio is given as an input for the next transmission, hence defining the width of the downlink and the uplink sub-frames.

The rest of the paper is structured as follows. Section II describes briefly the OFDMA technique while Section III outlines recent allocation proposals from the related research literature. In section IV the proposed mapping approach is

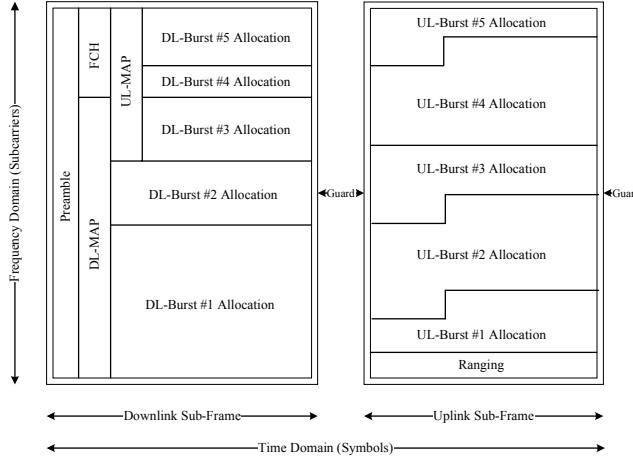


Figure 1. A Mobile WiMAX TDD frame.

presented. Section V provides a set of indicative results of the efficiency of the proposed model. Finally, conclusions are given in Section VI.

## II. BACKGROUND

The IEEE 802.16 OFDMA technique provides a multiple access mechanism to subscribers. Its TDD frame is depicted in Fig. 1. The TDD frame is structured in time and frequency domains composed by a downlink sub frame and an uplink sub frame with a small guard interval between them. Sub-frames' width duration could be configured varying from 3:1 to 1:1. This functionality renders the standard adjustable to dynamic traffic profiles allowing the modification of the downlink-to-uplink ratio even on a frame-by-frame basis.

The downlink sub-frame begins with a preamble that is used to achieve time and frequency synchronization, followed by a frame control header (FCH) and two MAP messages. The FCH includes information concerning the MAP fields such as message length, coding and modulation information. Downlink and uplink MAP fields define transmission instructions for each MS, including burst allocations in each sub frame.

## III. RECENT MAPPING SCHEMES

In this section, we briefly present the most recent mapping schemes for Mobile WiMAX. Most research efforts [2-6] concentrate on downlink mapping due to the restriction for rectangular allocation in the downlink sub frames. The authors in [2] formalize the two dimensional mapping problem and propose heuristic algorithms which could also support QoS constraints. In [3] a binary-tree full search approach is used for optimal placement of rectangular bursts in a time-frequency frame. Accordingly, the authors limit the user requests to eight per frame due to the high search complexity. Efforts in [4-6] include an initial sorting of the incoming requests in descending order followed by the mapping procedure. The authors in [4, 5] follow an approach where the requests with common transmission characteristics are grouped into buckets. In the sequel, buckets are mapped in a column by column basis of the rectangular bin. The

mapping procedure in [6] involves allocation of resources from right to left and from bottom to top.

In our previous work, the AHBM algorithm was proposed for accommodating downlink requests [7]. The idea introduced applies an initial creation of horizons, which constitutes the basis of the forthcoming requests. Hence, initial requests define horizons and then the forthcoming requests are mapped according to horizons. Large requests are accommodated first, leaving minimum remaining idle space, while horizons are formed in a right to left and bottom to top manner. In the sequel, the remaining requests are mapped based on the horizons. According to the performance evaluation results, the AHBM scheme seems to present considerable improvements compared to other leading schemes [2, 6]. Therefore, we employ the AHBM scheme as the main downlink mapping tool for our study.

The uplink mapping is straightforward since there is no restriction on the allocation of bursts in the uplink sub-frame. The simplest scheme used for resource allocation in the uplink sub-frame is the horizontal mapping of sub-channels in the frequency domain. Each request occupies horizontal strips of the allocation bin one after the other without leaving idle slots in between. This method allows contiguous slots to be accommodated on a row-by-row basis until all requests are mapped or the allocation is fully filled. We also adopt this technique as the main uplink mapping scheme for our study due to its simplicity.

Several scheduling and mapping approaches on resource allocation in Mobile WiMAX employ sub-frames of fixed size, ignoring that downlink-to-uplink ratio could be dynamically modified as specified by the standard. It is worth mentioned that our previous work [7] limits its focus on the downlink sub-frame, since it examines only the feedback provided from the downlink mapping process in contrary to this study that considers both the performance of downlink and uplink mapping processes in order to dynamically adjust the downlink-to-uplink ratio.

## IV. DOWNLINK-TO-UPLINK RATIO DETERMINATION

### A. Scope and Motivation

Static scheduling and mapping schemes may limit network performance by keeping the sub-frames' length fixed, particularly in a dynamically environment of a WiMAX access network. A fixed downlink-to-uplink ratio of the OFDMA framework could result in failure to map a portion of subscribers' requests, even though there are available resources in the whole frame. This weakness is addressed in the current study by proposing a novel mechanism that dynamically adjusts the capacity of downlink and uplink sub-frames' width in order to accommodate existing traffic requests. The adaptation scheme used employs an effective technique, stemming from the numerical analysis field, called extrapolation spline.

### B. Cubic Splines

The interpolation and extrapolation techniques are widely used to fit smooth continuous function through discrete data. Among other interesting interpolation techniques, spline

method seems to be one of the most attractive one, since it infers piecewise cubic polynomials to interpolate the data points. One of the most interesting advantages of low-order polynomials is the low complexity, since they keep the computational requirements low compared to other interpolation techniques that include complex numerical calculations involving higher degree curves [8].

### C. ERD Algorithm

The downlink-to-uplink width ratio adjustment is the main objective of the ERD algorithm proposed. In order to efficiently operate, the algorithm needs recent scattered data. This set of collected data will be the basis of the extrapolation, applied by the ERD scheme so as to estimate the next - most suitable - ratio. The set of collected scattered data is obtained by the execution of the downlink and uplink mapping processes. The ERD algorithm receives the feedback obtained by each mapping process and estimates the most appropriate ratio with respect to the bandwidth needs of both sub-frames. In other words, the ERD scheme determines the granted symbols per direction, which means it is able to offer more symbols to the direction that needs more bandwidth. Furthermore, the mapping approach proposed should be capable of balancing the bandwidth sharing between the two sub-frames.

The current status of each mapping process is advertised by the feedback info. The feedback is formed with respect to two basic performance metrics. The first one is called *unserved\_slots* and denotes the cumulative number of requests that fail to find accommodation space, measured in slots. The second one is called *idle\_slots* and refers to the total number of wasted slots within the examined sub-frame (downlink or uplink sub-frame):

$$\text{downlink\_feedback} = \left\lceil \frac{\text{unserved\_slots}^d - \text{idle\_slots}^d}{H} \right\rceil$$

$$\text{uplink\_feedback} = \left\lceil \frac{\text{unserved\_slots}^u - \text{idle\_slots}^u}{H} \right\rceil$$

where  $\text{unserved\_slots}^d$  ( $\text{unserved\_slots}^u$ ) stands for the *unserved\_slots*, produced from the downlink (uplink) mapping process. In the same manner,  $\text{idle\_slots}^d$  ( $\text{idle\_slots}^u$ ) denotes the number of *idle\_slots*, defined by the downlink (uplink) mapping process. The parameter  $H$  symbolizes the allocation bin's height. Positive feedback implies that there is no sufficient allocation space ( $\text{unserved\_slots} > \text{idle\_slots}$ ), while a negative one affirm bandwidth wastage, since one or more columns are in excess. Lastly, zero feedback stands for a consummated mapping.

The ERD scheme is described in *Algorithm1*. Two states, the *current* and the *ideal*, obliquely show the downlink-to-uplink ratio. The set of all possible states shows all possible width values that the downlink (or the uplink) may receive in relation to the uplink (or the downlink) sub-frame. For example, if the frame width is set to 42 slots and the initial downlink-to-uplink ratio is 1:1 then the width of the downlink sub-frame is 21, the same as the uplink sub-frame. The couple of values (21, 21) denotes the first possible state of the pool, so in this case *current* = 1. The next possible

state, giving *current* = 2, gives the set (22, 20), while the final possible state of the set is given by *current* = 13, denoting the set (33, 9). Beyond the *current* state, the *ideal* state points out the state that could return the most efficient feedback if was applied and of course it is known only after the completion of both mapping processes. In the light of the aforementioned remarks, the algorithm consists of a *IF-ELSE IF* central loop, in which the *ideal* state is determined based on the feedback obtained by the mapping procedures. The latest  $V$  ideal states are recorded into an array, called *history*, which is used in order to provide the y-axis scattered data for the extrapolation technique. Specifically, the history vector continuously updates its values and upon the completion of the mapping processes provides its values to the applied extrapolation technique in order to estimate the  $\text{history}[V+1]$  ideal state for the next frame. Hence, the algorithm provides an estimated downlink-to-uplink width ratio based on the previous most appropriate  $V$  ratios and the forthcoming frame begins with this value ( $\text{current} = \text{history}[V+1]$ ). It should be noted that the estimated state is not allowed to surpass the upper and lower limits in accordance with the standard ratio limits, i.e., from 1:1 to 3:1. Finally, it is worth mentioning that the extrapolation process may be erroneous, returning state values out of the bounds. For this purpose, it is considered that if the extrapolation technique estimates a value out of the bounds (e.g., denoting a ratio 4:1) then the *ideal* state is adopted ( $\text{current} = \text{ideal}$ ).

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#### Algorithm1: ERD mapping algorithm

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- Set the initial downlink-to-uplink width ratio 1:1, i.e., current = 1
- FOR each frame
  - Apply the downlink mapping algorithm adopted by [7].
  - Apply the fixed uplink mapping algorithm.
  - Calculate downlink_feedback and uplink_feedback.
  - IF downlink_feedback > 0 uplink_feedback < 0 THEN
    ideal = current
    - + min(|downlink_feedback|,|uplink_feedback|)
  - ELSE_IF downlink_feedback < 0 uplink_feedback > 0 THEN
    ideal = current
    - - min(|downlink_feedback|,|uplink_feedback|)
  - ELSE_IF downlink_feedback > uplink_feedback THEN
    ideal = current
    - + 
$$\left\lceil \frac{\text{downlink\_feedback} - \text{uplink\_feedback}}{2} \right\rceil$$

  - ELSE_IF downlink_feedback < uplink_feedback THEN
    ideal = current
    - - 
$$\left\lceil \frac{\text{uplink\_feedback} - \text{downlink\_feedback}}{2} \right\rceil$$

  - END_IF
- FOR counter = 1: $V-1$ 
  - history[ $V-\text{counter}+1$ ] = history[ $V-\text{counter}$ ]
- END_FOR
- history[1] = ideal

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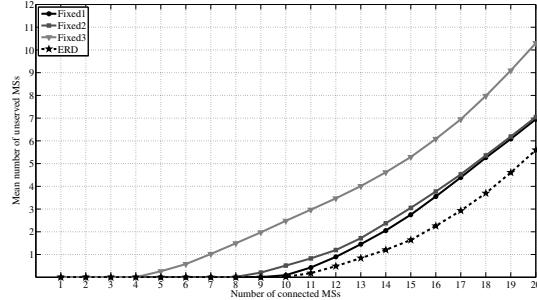


Figure 2. Scenario1: Mean number of unserved MSs.

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- Apply Cubic Spline Extrapolation with  $x = 1, 2, \dots, V$  and
 $y = history[1], history[2], \dots, history[V]$  and calculate
 $history[V + 1]$ 
- Set  $current = history[V + 1]$ 
- END FOR

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## V. PERFORMANCE EVALUATION

The performance of the ERD is evaluated in this section in a custom Matlab environment. Apart from ERD, three static mapping schemes, maintaining static and predefined downlink-to-uplink ratio, are developed also in order to be compared with the ERD approach. All schemes adopt the AHBM algorithm [7] as the main mapping process regarding the downlink mapping and the fixed uplink mapping scheme as the algorithm for the uplink sub-frame. It is assumed that for each frame MSs may request only a single burst for each direction. For each simulation conducted, a single BS is considered along with multiple MSs that have been established communication to the BS. Both downlink and uplink directions are considered.

Regarding the simulation parameters, the partially used sub-channelization (PUSC) mode is adopted due to its common frequency diversity for mobile communication environments defining 30 distinct channels. The frame length is fixed and it is considered as 10 ms. In addition, three symbols are dedicated to control information (one symbol for Preamble, and two symbols for MAP and FCH fields). As previously mentioned, the ERD scheme is able to define the downlink-to-uplink ratio on a frame-by-frame basis. The three fixed schemes maintain a fixed ratio in the context of all simulation scenarios conducted in this work. Therefore, the so-called *Fixed1* mapping scheme defines the downlink-to-uplink ratio stable and equal to 1:1, allowing 21 symbols for each sub-frame. Similarly, the *Fixed2* scheme maintains the ratio to 2:1 offering 27 available symbols to

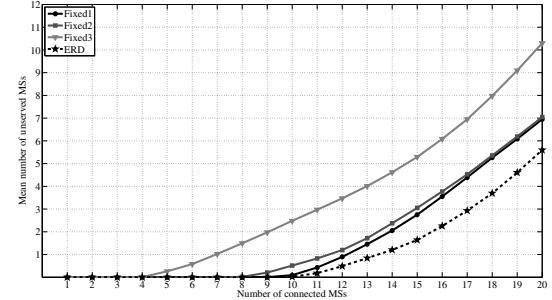


Figure 3. Scenario1: Mean number of unserved slots.

downlink sub-frame and 15 to the uplink one. Lastly, the third standard mapping scheme, called *Fixed3* keeps the ratio equal to 3:1, allowing 33 symbols for downlink and 9 for uplink. The ERD scheme adjusts the ratio from 1:1 to 3:1, allowing 21 to 33 available symbols to be exploited in the context of the downlink sub-frame and 9 to 21 available symbols dedicated to uplink sub-frame, respectively.

Three performance metrics are considered. First, the mean number of unserved MSs is considered, which expresses the portion of MSs that fail to be accommodated in both downlink and uplink sub-frame due to lack of resources, second the mean number of unserved slots is measured, which denotes the total number of slots that fail to find allocation space in both sub-frames due to lack of resources, and three the mean number of idle slots, which indicates the utilization of the available allocation bin.

The performance evaluation is subdivided in two scenarios. In the former one, the performance of the four mapping approaches is evaluated as the number of the connected MSs to the BS increases. In the latter one, the mapping performance is evaluated as the downlink traffic load increases – keeping the uplink traffic load stable. Each simulation experiment elapses after 3000 contiguous transmission frames. The generated traffic follows a Poisson process, considering different  $\lambda$  for each direction. In the first evaluation scenario the number of the connected MSs varies from 1 to 20, while the Poisson mean values vary as time passes, indicating an unpredictable, realistic, and alterable behavior. In the second scenario the number of the connected MSs is considered stable and equal to 20 for each direction, altering, however, the Poisson mean value of the downlink requests, denoted by  $\lambda_d$ .

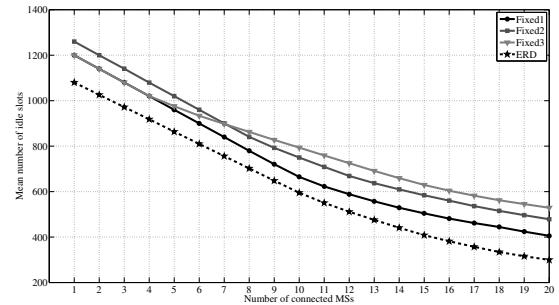


Figure 4. Scenario1: Mean number of idle slots.

TABLE I. POISSON REQUEST VALUES

# of Frame iteration	$\leq 500$	$\leq 1000$	$\leq 1500$	$\leq 2000$	$\leq 2500$	$\leq 3000$
$\lambda_d$ (slots)	20	40	55	15	20	5
$\lambda_u$ (slots)	20	15	15	40	60	55

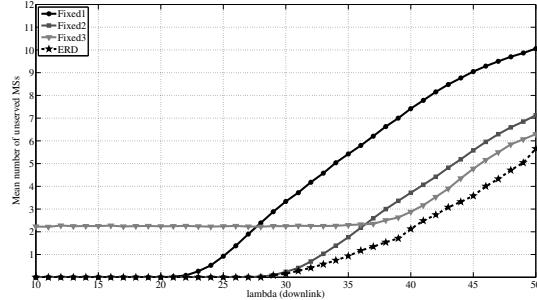


Figure 5. Scenario2: Mean number of unserved MSs.

Specifically, the Poisson mean value of the uplink requests remains fixed and equal to 20, while  $\lambda_d$  is increased from 10 to 50.

Table I summarizes the exact number of Poisson values for the first evaluation scenario. The evaluation results are expressed in Figs 2-4, where Fig. 2 shows the performance of the four schemes, in terms of the mean number of unserved MSs, Fig. 3 depicts the mean number of unserved slots, and Fig. 4 illustrates the mean number of idle slots, as the number of MSs increases. It is clear that the role of the approach proposed is beneficial, since it achieves a) to reduce the number of subscribers that fail to be mapped, b) to decrease the portion of wasted bandwidth, and c) to limit the number of slots that should be returned to the scheduler in order to be re-allocated in the following frames.

In essence, the ERD senses the bandwidth needs of both directions and assign the wasted portion of allocation space, if any, to the sub-frame that could really exploit it. This ability is caused by the appropriate downlink-to-uplink ratio estimation, which provides more allocation opportunities to the sub-frame that needs it mostly.

In the second set of experiments (Fig. 5-7), the obtained results with respect to the aforementioned performance metrics are acquired keeping the number of the connected MSs stable and equal to 20 for each direction, altering, however, the  $\lambda_d$ . Specifically, the Poisson mean value of the uplink requests remains fixed and equal to 20, while  $\lambda_d$  is increased from 10 to 40. Fig. 5 shows the mean number of unserved MSs, Fig. 6 presents the mean number of unserved slots, and Fig. 7 depicts the mean number of idle slots.

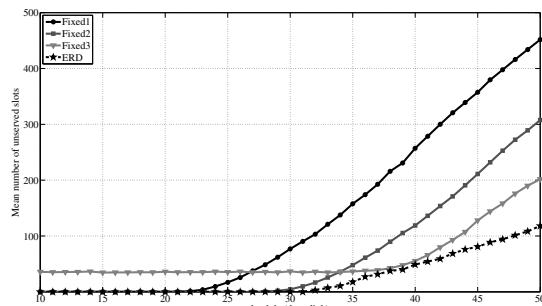


Figure 6. Scenario2: Mean number of unserved slots.

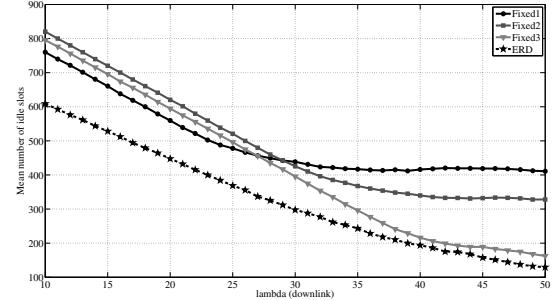


Figure 7. Scenario2: Mean number of idle slots.

Once again the ERD approach presents better network performance compared to the fixed schemes. Its ability to adequately adjust the downlink-to-uplink width ratio leads to considerable improvements, since the ERD effectively exploits the available bandwidth, re-defining the sub-frame's boundaries based on the traffic needs.

## VI. CONCLUSIONS

Recent scheduling and mapping approaches presented in the literature assume a fixed downlink-to-uplink width ratio, resulting in limited network performance. A novel approach was presented in this paper, by adjusting the capacity of the downlink and uplink sub frames of the OFDMA framework so as to accommodate demanding traffic load and new incoming requests. The idea beyond this approach lies in the cubic spline extrapolation technique, which is applied in order to estimate the most suitable ratio. The approach presented is evaluated in realistic scenarios, whereas the performance results indicate considerable performance improvements.

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