Using Learning Automata for Adaptively Adjusting the Downlink-to-Uplink Ratio in IEEE 802.16e Wireless Networks

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***Abstract*—IEEE 802.16e allows for flexibly defining the relation of the downlink and uplink sub-frames' width from 3:1 to 1:1, respectively. However, the determination of the most suitable ratio is left open to the network designers and the research community. Existing scheduling and mapping schemes are inflexibly designed. In this paper, a novel adaptive mapping scheme is proposed aiming to dynamically adjust the downlink-to-uplink ratio, following adequately the modification of the load requests with respect to both downlink and uplink directions. A learning automaton is exploited in order to sense the performance of the downlink and uplink mapping processes and to determine the most appropriate length ratio of both sub-frames in order to maximize the network performance. The suggested ratio determination scheme is evaluated through realistic scenarios and it is compared with static schemes that maintain a fixed ratio. The results show that our proposed scheme introduces considerable improvement, increasing the network's service ratio and reducing the bandwidth waste.**

Keywords-IEEE 802.16, learning automata, mapping, OFDMA, WiMAX

I. INTRODUCTION

Recent advances on Worldwide Interoperability for Microwave Access (WiMAX) constitute it a promising technology for access and mesh wireless networking. The initial standard, called fixed WiMAX, was defined by IEEE 802.16 group in 2001 and has proven itself a pioneer providing an attractive air interface. Its main limitation, i.e., absence of mobility, has been addressed by its descendant, IEEE 802.16e, also known as Mobile WiMAX. Beyond its major asset, i.e., subscribers' mobility, the mobile WiMAX exploits a flexible multi-access technique based on the Orthogonal Frequency Division Medium Access (OFDMA).

OFDMA acts between the PHYsical (PHY) and the Media Access Control (MAC) layers, allowing multiple subscribers to make use of different bandwidth regions in both the time and frequency domains. In essence, OFDMA technique is responsible for allocating PHY resources to MAC requests, giving to them physical hypostasis. In this manner, it allocates time and frequency resources to various subscribers in units of slots, which are the smallest quanta of PHY layer resource that can be allocated to a single subscriber in the time and frequency domain [1].

Two-way communication in a typical IEEE 802.16e wireless access network involves two major partners: the Base Station (BS) and the connected Mobile Stations (MSs). The BS is responsible for establishing, preserving, and maintaining a viable full-duplex communication, delivering data to MSs (downlink direction) and receiving data from MSs (uplink direction) on a frame-by-frame basis. Each frame is composed of two distinct regions dedicated to the downlink and the uplink communication: the uplink sub-frame and the downlink sub-frame. A duplexing technique governs the transmission of the two sub-frames. Fixed and mobile WiMAX support both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) techniques. TDD is favored by the majority of implementations due to its strong aspects such as flexibility, ability to exploit channel reciprocity, and simple design [1]. In this study, TDD technique is adopted.

The standard does not include specific algorithms for utilizing the available bandwidth through the OFDMA technique. Hence a new challenging research area comes into play: efficient exploitation of the available bandwidth. Bandwidth usage is accompanied with a set of rules and restrictions. Due to OFDMA's nature the available bandwidth is formed as a two-dimensional allocation bin in a rectangular shape, having one dimension associated with frequency (height) and the other associated with time (width). 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.

The standard employs QoS scheduling and mapping processes as conjunctional functions between the MAC and the PHY layers. Regarding the downlink sub-frame, the QoS scheduler is aware of the QoS requirements of the MAC data units and forwards these requests to the mapper. The mapper collects the requests and constructs a downlink reception program, where each MS is aware of the time and the sub-frequency of its dedicated data. Concerning the uplink sub-frame, the mapper forms the uplink program, which informs all MSs about the exact time and frequency of their transmissions. The uplink requests are defined by the uplink QoS scheduler according to the call admission policy of the system. The operation of scheduling and mapping functions is critical. Their efficiency affects the whole network, since requests that fail to be mapped are returned to the respective scheduler and their transmission is postponed for at least one entire frame. Recognizing this issue, the standard supports flexible and dynamic adjustment of the downlink-to-uplink ratio, which may be varied from 3:1 to 1:1.This feature could be considerably beneficial considering different traffic profiles, variant multimedia traffic etc.

Existing scheduling and mapping techniques proposed in related research literature are inflexibly designed and define static allocations. Mapping schemes seem to ignore the downlink to uplink load balance ratio, proposing algorithms unaware of the relative efficiency of downlink and uplink allocations. This paper endeavors to address this weakness by proposing a novel adaptive scheme capable of efficiently adjusting the downlink to uplink ratio. A Learning Automaton (LA) is adopted in order to enhance the mobile WiMAX mapper with a learning tool. The introduced adaptive scheme called Dynamic Ratio Determination (DRD) monitors the mapping operation of both downlink and uplink sub-frames, receives feedback from both processes and proceeds to the appropriate selection of the forthcoming downlink-to-uplink ratio. The target is to improve the performance of both mapping operations, leading to improved allocation results, in terms of bandwidth utilization and system service ratio.

The rest of the paper is organized as follows. Section II briefly presents OFDMA basics and Section III describes related mapping techniques proposed in research literature. Section IV presents the proposed adaptive scheme and Section V evaluates its performance. Finally, Section V concludes this paper.

II. OFDMA Basics

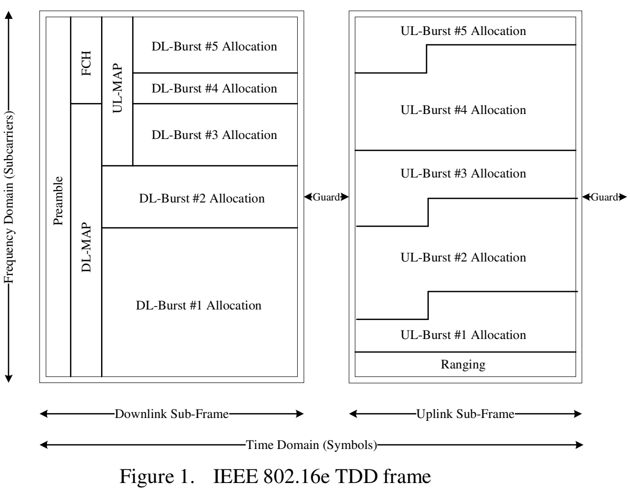

Figure 1. IEEE 802.16e TDD frame

Figure 1 illustrates the mobile WiMAX TDD frame structure. The frame has fixed time period and the downlink sub-frame is followed by the uplink sub-frame after a time gap, which aims at avoiding interference between the downlink and uplink signals. After preamble, used for synchronization, downlink control information is transmitted, consisting of a frame control header (FCH) and two MAP messages. The FCH message includes the physical information required to decode the following MAP messages (i.e., coding and modulation). The MAP messages carry user-specific control information, required for the next sub-frames, such as the subschannel and the symbol of users' transmission and reception. It is important to note that the length relation between the downlink and uplink sub-frames is variable and defined by the downlink-to-uplink ratio. This feature follows dynamic modifications of communication requirements in an efficient manner, altering the respective ratio on a frame-by-frame basis (if necessitated).

III. Related Mapping Techniques

Various mapping schemes have been proposed for both uplink and downlink streams in the related research literature. Due to the strict shaping rule that must be followed in the downlink sub-frame, research efforts on downlink mapping are more frequently met than in the uplink domain, where this restriction does not apply. Therefore, numerous schemes have been proposed in the literature [2-6], aiming to address the downlink mapping issue. Amongst them, simple packing algorithm (SPA) [2] was one initial attempt. The technique involves a top to bottom and left to right slot allocation, accommodating symbols (rows) and subschannels (columns) for each request in a first in first out (FIFO) way, until the requested number of slots is met. If this number is not an integer multiple of the frequency or the time dimension respectively, the remaining unallocated space remains idle. The scheme in [3], tries to apply a rigorous mapping technique using a persistent binary-tree full search tree, but the final result indicates complex operation, limited to eight users. Other attempts involve as a first step an initial request sorting in terms of the number of requested slots and as a second step either bucket definition and accommodation [4-6], where the combined bursts define buckets [4, 5] that are accommodated in a column by column basis into the allocation bin, or heuristic packing algorithms, accommodating the incoming requests in a two step procedure, first a horizontal mapping and then vertical accommodation [6].

In our previous work, a mapping algorithm for the downlink sub-frame has been presented [7]. The so-called AHBM algorithm applies horizon-based allocation, creating initial pilots for the forthcoming requests. Large requests are accommodated first, leaving minimum remaining idle space, while pilots are formed in a right to left and bottom to top manner. In the sequel, the remaining requests are mapped based on the pilots. Based on extensive evaluation experiments, the performance of the AHBM scheme seems to be improved with respect to other leading schemes [2, 6]. Thus, it is adopted as the main downlink mapping technique for the rest of our study.

The operation of the uplink mapping is much simpler than the downlink one, due to the absence of the rectangular restriction. The simplest and most effective way of accommodating the UL requests lies on a row-by-row basis. One after the other, UL requests are accommodated into the uplink sub-frame, without occurrence of row cuts. Upon the accommodation of a UL request, the following one is sided directly next to it, without leaving gaps (i.e., idle slots). In this manner, the set of UL requests fill uniformly the allocation bin, until either all requests are mapped or the bin comes full. This fixed and simple uplink mapping technique is also adopted in this study.

Most proposed scheduling and mapping schemes are inflexibly designed, defining static allocations. We aim to cover this gap by defining and dynamically modifying the downlink to uplink ratio in accordance with the requests' requirements, taking into account feedback provided from both the downlink and uplink process. At this point it should be noted that the AHBM [7] involves a prediction tool based on hidden markovian chains in order to redefine the length of the downlink sub-frame in accordance with downlink traffic profiles. However, it takes into account only 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. PROPOSED ADAPTIVE RATIO DETERMINATION

A. *Motivation*

The motivation of the current research lies in the fact that determination of a fixed downlink-to-uplink ratio may lead to network performance degradation. Considering that a BS may receive requests from fixed, mobile, nomadic, or randomly moving subscribers in conjunction with the fact that it is extremely difficult to have an a priori knowledge of the context of operation, a static definition of downlink-to-uplink ratio may result to wasting large portion of slots or leaving unserved a large number of requests for a long time. Thus, appropriate determination of the downlink-to-uplink ratio plays a key role in the network performance, especially when the bandwidth demand is unknown and/or unpredictable. This work aims to cover this pitfall by proposing a novel dynamic ratio determination scheme based on a well-known, effective, and simple tool: the learning automata.

B. *Learning Automaton*

A Learning Automaton (LA) is a finite state machine that interacts with a stochastic environment and tries to learn the optimal action offered by the environment via a learning process. The selection is based on a probability vector, which contains the probability of each possible action. The selection is given as input to the environment and the environment responds with a feedback. The feedback affects the probability vector exploiting a learning algorithm. The target of the automaton is to determine the optimal solution, expressed as an action from a pool of possible actions.

Learning automata have been thoroughly examined as a learning method with estimation features [8-10]. In this work, learning automata may be adopted to achieve the estimation of the appropriate downlink-to-uplink ratio. Here, the pool of actions contains 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 2:1 then the width of the downlink sub-frame is 27, while the uplink sub-frame lasts for 15 slots. The set of values (27, 15) is one action that the learning automaton may decide. The pool of possible actions vary from (21, 21), i.e.., 1:1 to (33, 9), i.e., 3:1. Thus, the possible pool consists of 13 possible actions. The learning automaton uses a vector $p(n) = \{p_1(n), p_2(n), ..., p_M(n)\}$, which represents the probability distribution for choosing one of the actions $a_1, a_2, ..., a_M$ (*M=13*) at frame *n*. Obviously, $\sum_{i=1}^{M} p_i(n) = 1$.

C. *Operation*

The aim of this paper is to dynamically configure the downlink-to-uplink ratio, taking into account feedback received from both downlink and uplink mapping processes. The DRD should balance the available symbols (columns into the allocation bin) in order to improve the mapping process with respect to both sub-frames. In this perspective, the learning module should be able to grant more symbols to the direction that needs them more. For example, if the downlink mapper receives only a few requests from the scheduler and produces a mapping program that comprises many idle slots, while at the same time the uplink mapper needs more symbols (more bandwidth) to accommodate uplink requests, then the LA should decide to grant more allocation space to the uplink sub-frame, altering the current downlink-to-uplink width ratio. Additionally, the LA should be capable of supporting load balancing to both sub-frames. For instance, if the available allocation space is not sufficient for both mappers due to high requesting loads and the downlink mapper needs larger portion of allocation space than the uplink one, then the automaton should balance the allocation, granting more width to the downlink sub-frame.

The LA should be enhanced with effective sensing criteria in order to take efficient decisions. The sensing criteria, function of the received feedback, inform the LA about the status of the environment. Feedback definition considers two main performance metrics: *unserved_slots* referring to the cumulative number of requests that fail to find accommodation space, measured in slots and *idle_slots* referring to the total number of wasted slots within the examined sub-frame (downlink or uplink sub-frame). In this context, the feedback of each mapping process is defined as follows:

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

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

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

As long the LA actions are concerned, possible actions are associated with specific downlink and uplink width values. More specifically, the *current_action* and the *ideal_action* are defined. *current_action* refers to the action that the LA has currently chosen. The *current_action* corresponds to the downlink and uplink width values that the automaton has currently selected. Having chosen the *current_action*, feedback is produced. Based on this, the LA calculates the *ideal_action*, which indicates the most appropriate action based on the past indications. The DRD combines feedback received from both uplink and downlink processes and the *current_action* to calculate the *ideal_action* as follows:

$$\text{if } (downlink\_feedback > 0 \; AND \; uplink\_feedback < 0)$$
$$ideal\_action = current\_action + \min(|downlink\_feedback|, |uplink\_feedback|)$$
$$\text{elseif } (downlink\_feedback < 0 \; AND \; uplink\_feedback > 0)$$
$$ideal\_action = current\_action - \min(|downlink\_feedback|, |uplink\_feedback|)$$
$$\text{elseif } (downlink\_feedback > uplink\_feedback)$$
$$ideal\_action = current\_action + \left\lfloor \frac{|downlink\_feedback - uplink\_feedback|}{2} \right\rfloor$$
$$\text{else}$$
$$ideal\_action = current\_action - \left\lceil \frac{|downlink\_feedback - uplink\_feedback|}{2} \right\rceil$$
$$\text{endif}$$

The above code tries to find out whether a downlink (uplink) sub-frame could provide the uplink (downlink) subframe with extra columns, without harming itself. The first two conditions check whether the downlink (first if) and the uplink then (second elseif) could offer extra allocation space to the uplink and the downlink sub-frame, respectively. This is possible in case one sub-frame returns negative feedback, meaning that it comprises at least one idle symbol. The two latter conditions balance the relation of both sub-frames in case there is not sufficient allocation space for satisfying all requests at both downlink and uplink directions.

The core of the LA's operation is the probability updating algorithm. To provide for adaptivity, the proposed approach suggests that the BS should use the probability updating scheme of an S-model linear reward minus inaction (SL_{R-I}) learning automaton [8]. Suppose that the frame *f* has just been transmitted and the automaton has received feedback from the downlink and uplink mapping processes. The probability updating scheme after the transmission of frame *f* is given in accordance with the following equation:

$$p_i(f+1) = p_i(f) - L(p_i(f) - a), \; \forall \; i \neq ideal\_action$$
$$p_{ideal\_action}(f+1) = p_{ideal\_action}(f) + L(p_{ideal\_action}(f) - a)$$

where L is a parameter that governs the speed of the automaton convergence and α is a parameter that prevents zero probabilities. The initial probability values are equal to:

$$p_i = \frac{1}{number\ of\ possible\ actions}$$

Hence, if the number of possible actions is 13 then $p_i(1) \simeq 0.076 \; \forall \; i \in \{1, 2, \ldots 13\}$.

Finally, the DRD selects the action with the largest probability in order to determine the downlink-to-uplink ratio for the next frame.

V. Performance Evaluation & Results

In this section we present indicative evidence of the performance of the proposed DRD scheme. A simulation environment has been built in Matlab, in order to study, evaluate, and compare the DRD behavior with fixed schemes having static and predefined downlink-to-uplink ratio. The DRD scheme adopts 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. MSs may concurrently request downlink and uplink slots, while it is assumed that each MS may request only one set of slots (a single burst) for downlink and uplink directions.

The IEEE 802.16e network parameters adopted in the simulation environment are described below: The well-known partially used sub-channelization (PUSC) mode is adopted, because it is considered as the most common frequency diversity mode for practical mobile communication environments. Under PUSC mode, 30 distinct channels are defined. The frame length has fixed length and for the following experiments it has been set equal to 10 ms. As long as the control information is concerned, three symbols are destined to control information (one symbol for Preamble, and two symbols for MAP and FCH fields) and are excluded from the available slots for allocation purposes, while the available symbols for forming the downlink and the uplink sub-frames depend on the downlink-to-uplink ratio. Besides the DRD scheme, which is capable of adjusting the downlink-to-uplink ratio on a frame-by-frame basis according to the bandwidth demand, three more mapping schemes have been designed and implemented. These three schemes adopt the same mapping algorithms as DRD, however, they keep the ratio fixed in the context of all experiments for comparison reasons. Therefore, the so-called *Standard1* mapping scheme maintains the downlink-to-uplink ratio stable and equal to 1:1, allowing 21 symbols for each sub-frame.

TABLE I. POISSON REQUEST VALUES

# of Frame iteration	$\leq$500	$\leq$1000	$\leq$1500	$\leq$2000	$\leq$2500	$\leq$3000
λ_d (slots)	20	40	60	10	10	5
λ_u (slots)	20	10	10	40	60	60

Similarly, the *Standard2* scheme preserves the ratio to 2:1, offering 27 available symbols to downlink sub-frame and 15 to the uplink one. Lastly, the third standard mapping scheme, called *Standard3* keeps the ratio equal to 3:1, allowing 33 symbols for downlink and 9 for uplink. The DRD 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. Since, each symbol constitutes a single column into the allocation bin, a set of 630 (30×21) to 990 (30×33) slots define the downlink sub-frame and 270 (30×9) to 630 (30×21) the uplink sub-frame, both in a rectangular shape. Regarding the automaton operation, parameter L is set to 0.15 and α is set to 10^{-4}. Furthermore, the automaton's probabilities are not allowed to raise more than 50% of their initial values or decrease more than 50% of their initial values for fast convergence.

The performance of each scheme is evaluated based on three metrics: a) the mean number of unserved MSs, which expresses the portion of MSs that fail to be accommodated in both downlink and uplink sub-frame due to lack of resources, b) the mean number of unserved slots, which denotes the total number of slots that fail to find allocation space in both sub-frames due to lack of resources, and c) the mean number of idle slots, which indicates the utilization of the available allocation bin.

The first group of figures (Fig. 2-4) presents comparison results of the considered mapping schemes as the number of the connected MSs to the BS increases. Both downlink and uplink requests are assumed to follow a Poisson process. In order to stimulate a realistic scenario, the Poisson mean values vary as time passes, indicating an unpredictable and alterable behavior.

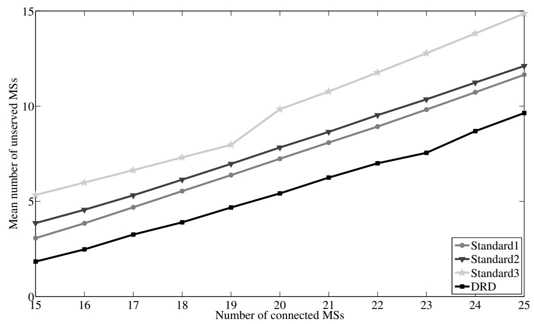

Figure 2. Mean number of unserved MSs as the number of connected MSs increases

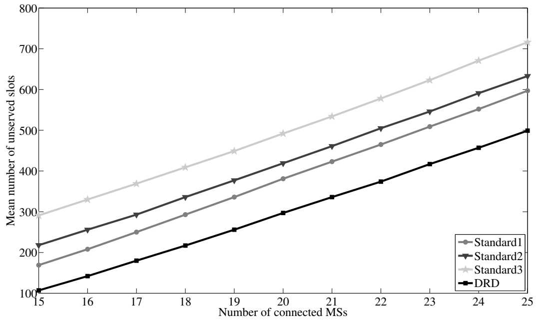

Figure 3. Mean number of unserved slots as the number of connected MSs increases

Each experiment has been conducted for 3000 contiguous frames. Table I summarizes the exact number of Poisson values. Fig. 2 depicts the performance of the four schemes, in terms of the mean number of unserved MSs. It becomes evident that DRD achieves to reduce the number of subscribers that fail to be mapped due to its adaptive nature. More specifically, the DRD allows the adjustment of downlink-to-uplink ratio according to the specific needs of downlink and uplink sub-frames.

Its ability to sense the individual needs of each mapping process allows for increasing the portion of MSs that succeed to be served, providing more allocation space to the sub-frame that needs it mostly. This is also justified by the results illustrated in Fig. 3, which shows the mean number of unserved slots, when the number of the connected MSs varies. By achieving better service ratio, the DRD scheme succeeds in reducing the number of slots that are returned to the scheduler for re-scheduling due to lack of resources, leading to more efficient mapping results. The beneficial role of DRD can be extracted from Fig. 4 too, whereby the mean number of idle slots is measured as the number of the connected MSs increases. DRD achieves to balance the length relation between the two sub-frames, resulting in decreasing the portion of wasted bandwidth. This may be attributed to the fact that the DRD algorithm manages to assign wasted portion of allocation space to the sub-frame that really needs it.

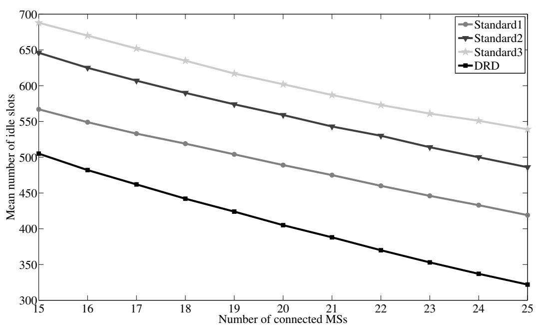

Figure 4. Mean number of idle slots as the number of connected MSs increases

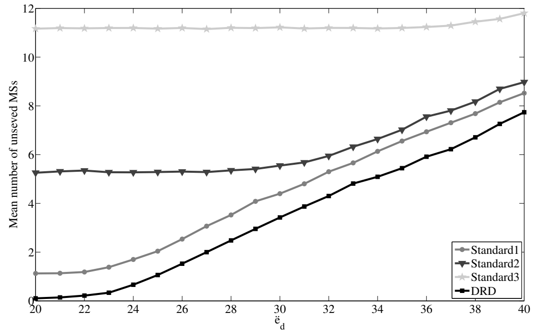

Figure 5. Mean number of unserved MSs as the λ_d increases

In the second set of experiments (Fig. 5-7), the 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 Poisson mean value of the downlink requests, denoted by λ_d . Specifically, the Poisson mean value of the uplink requests remains fixed and equal to 30, while λ_d is increased from 20 to 40. Fig. 5 presents the mean number of unserved MSs. Once more, the superiority of the proposed scheme is confirmed, since the proposed adaptive scheme enables the accommodation of more MSs than the other schemes. The same conclusions are obtained from Fig. 6 that shows the mean number of unserved slots. Again, the adaptive capabilities of DRD allow for better exploiting the available bandwidth, resulting in higher service ratio. Finally, the mean number of idle slots is presented in Figure 7. Independently of the λ_d rate, the DRD offers better OFDMA utilization, reducing considerably the wasted bandwidth. As a final note, it is worth to say that the proposed adaptive scheme manages to present notably improvements in network performance, without harming or overshadowing other metrics in a simple and effective way.

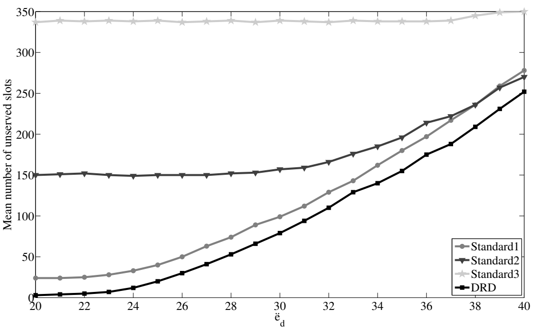

Figure 6. Mean number of unserved slots as the λ_d increases

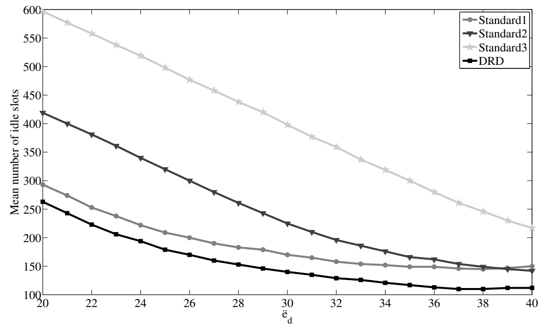

Figure 7. Mean number of idle slots as the λ_d increases

VI. CONCLUSIONS

A novel adaptive scheme has been presented in this paper aiming at efficiently adjusting the downlink-to-uplink ratio for OFDMA-based wireless systems. The scheme, which is based on a learning automaton operation, receives feedback from the mapping processes and calculates the most appropriate ratio for the next frame. The suggested approach is suitable for IEEE 802.16e wireless networks, where the core bandwidth distribution mechanism is based on OFDMA technique. Extensive evaluation results indicate the superiority of the proposed scheme.

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