IEEE 802.16 Capacity Enhancement Using an Adaptive TDD Split

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***Abstract*— In urban areas, users have become more and more accustomed to the availability of broadband access. However, in rural and suburban areas, it is often too expensive for network providers to serve every user with traditional wired broadband access such as DSL or cable modem. In such areas, WiMAX (worldwide interoperability for microwave access) networks based on the IEEE 802.16 standard are the most promising solution.**

In this paper, we focus on the performance of the IEEE 802.16 time division duplex (TDD) mode in rural areas with only one cell. When using TDD, the duration of the downlink and uplink subframe can be set individually, which is called adaptive time division duplex (ATDD). However, the ratio between downlink and uplink is normally set to a fixed value. We will show the performance of different fixed downlink/uplink ratios for several traffic models. Furthermore, we propose an algorithm for an adaptive downlink/uplink boundary in dependence on the current traffic load in the cell. The results show an enormous performance gain compared to the fixed settings.

***Index Terms*— 802.16, WiMAX, ATDD, TDD, framing**

I. Introduction

In 1999, the IEEE 802 committee has set up a new working group for outdoor broadband wireless access applications, namely IEEE 802.16. Similar to the IEEE 802.11 Wi-Fi alliance, the WiMAX forum, responsible for defining interoperability specification, was set up. Thus, the IEEE 802.16 networks are often referred to as WiMAX networks.

Currently, there are two different standards, which are certified by the WiMAX forum, the IEEE 802.16-2004 [1] for fixed broadband wireless access and the IEEE 802.16e-2005 [2] for mobile users. Typical deployment scenarios for a WiMAX system are connecting home networks, apartment houses, small companies, or WLAN hotspots to the Internet. In this case, a WiMAX base station (BS) serves a number of subscriber stations (SSs) that each may serve a number of users again.

WiMAX networks can be configured for two types of duplexing methods to separate uplink (UL) and downlink (DL) communication. Either TDD or FDD can be used, where both provide clear advantages in dependence of their field of application. In this paper, we focus on the WiMAX TDD mode, where uplink and downlink share the same frequency band. To separate downlink and uplink, time division multiple access (TDMA) is used. According to the IEEE 802.16-2004 standard, this segmentation can be set dynamically, even during runtime. Unfortunately, this is neither implemented in any base station nor addressed in any paper. Several papers have been published analyzing the best bandwidth request strategy [3], [4], [5] and proposing scheduling and admission control mechanisms [6], [7], [8] for IEEE 802.16 networks. However, none of these papers analyzes the performance of an adaptive subframing.

In this paper, we compare different settings for the TDD split and evaluate their strengths and weaknesses for several traffic profiles. Furthermore, we propose an algorithm for a dynamic setting of this ratio in a single cell scenario, depending on the current load conditions. In multi cell environments, the base stations have to coordinate the downlink and uplink ratio due to interference problems. However, as most WiMAX networks are set up in rural areas, with only one base station, the single cell consideration is sufficient.

The rest of the paper is organized as follows: In Section II an overview of the WiMAX MAC layer is given. Section III presents our adaptive subframing algorithm. This is followed by Section IV where the simulation setup and the results are shown. Finally, Section V concludes this paper.

II. Overview of the IEEE 802.16 MAC Layer

The IEEE 802.16-2004 [1] standard separates the time into frames with a length between 2 ms and 20 ms. When using TDD, each frame is split into a downlink and an uplink subframe which is shown in Fig. 1. Between the two subframes, a transmission time gap is introduced for half duplex stations to switch from the reception of packets to transmission.

Each downlink frame starts with a preamble followed by a frame control header (FCH). Afterwards, the first data burst is transmitted which contains information about the complete frame. First, the downlink map (DL-Map) defines the remaining part of the downlink frame and assigns the data

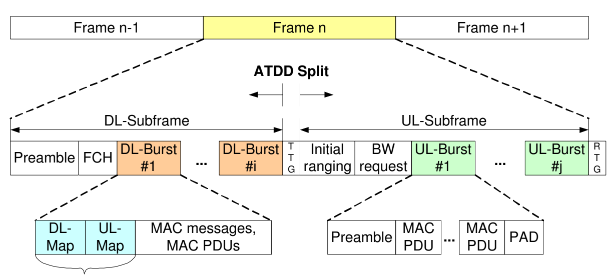

Fig. 1. WiMAX TDD frame structure

bursts to the different subscriber stations. The uplink map (UL-Map) on the other hand comprises the bandwidth allocations in uplink direction. These management messages are followed by normal data bursts.

The uplink subframe starts with a number of slots for initial ranging and bandwidth requests. The initial ranging phase is needed for network entry and the bandwidth request phase is one possibility to request uplink bandwidth. In this paper, bandwidth is always requested using broadcast transmission opportunities during the bandwidth request phase where one opportunity is the time needed to transmit one bandwidth request. A more detailed description of WiMAX can be found in [9], [10].

III. Adaptive Time Division Duplex (ATDD) Splitting Algorithm

As already mentioned in the introduction, the TDD downlink/uplink ratio is not fixed in order to reach maximum flexibility according to the scenarios. Normally, this boundary is set to a fixed value when the WiMAX network is planned or already set by the WiMAX hardware vendor. Typical ratios are 70/30, 60/40, and 50/50, where the first number denotes the downlink length and the second number the uplink length in percent. In our simulations, we evaluate the performance of these three settings for different traffic models like VoIP, FTP, and web traffic. Furthermore, we have developed an algorithm for an adaptive setting of the boundary depending on the load in the network which will be described in this section.

Due to the fact that it is rather complicated to estimate the bandwidth demand when planning a WiMAX network, an adaptive downlink/uplink ratio seems a good solution. If capacity in one direction is not used over several frames, for example on the uplink, the capacity can be assigned for the downlink as shown in Fig. 2.

Our adaptation mechanism is based on measurements, whereby we do not consider just the last frame, but base the algorithm on history data over the last n frames:

$$n = \frac{ri}{fd} \cdot 10, \quad \text{with } ri = x \cdot fd \text{ and } x \in \mathbb{N}^{+}, \tag{1}$$

with fd as the frame duration and ri as the refresh interval, which denotes the time interval between two possible frame duration changes. If the average usage over all frames during the last n frames, $u_{all}(i)$, is larger than 50 percent, see Equation 2, we have to decide whether to enlarge the downlink or the uplink subframe.

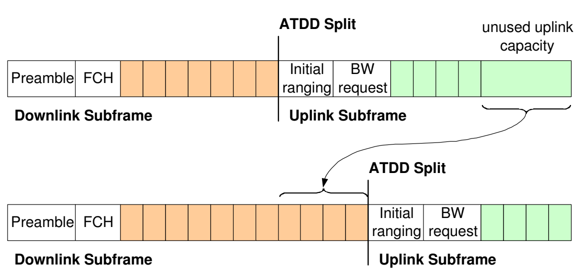

Fig. 2. Adaptive TDD splitting

$$u_{all}(i) = \frac{\sum_{j=i-n}^{i-1} \frac{u_{dl}(j)+u_{ul}(j)}{2}}{n} > 0.5, \quad \text{with } i > n+1 \tag{2}$$

$u_{dl}(j)$ is the downlink and $u_{ul}(j)$ is the uplink usage in percent of frame j. The decision of whether to enlarge the downlink, the uplink subframe, or if the boundary is left unchanged depends on the average usage of the single subframes, u_{dl} and u_{ul}. If u_{dl} is larger than u_{ul} and the usage is higher than 65 percent, the downlink subframe sf_{dl} will be 5 percent increased. Otherwise, the uplink subframe sf_{ul} will be 5 percent enlarged. If both loads are similar, the algorithm will not change the TDD split, see Equations 3, 4, and 5.

$$p = \begin{cases} 0.05 & \text{if } \; u_{dl}(i) > 0.65, u_{dl}(i) > u_{ul}(i) \\ -0.05 & \text{if } \; u_{ul}(i) > 0.65, u_{dl}(i) < u_{ul}(i) \\ 0 & \text{else} \end{cases} \tag{3}$$

$$sf_{dl}(i) = sf_{dl}(i - \frac{ri}{fd}) + p \cdot fd \tag{4}$$

$$sf_{ul}(i) = sf_{ul}(i - \frac{ri}{fd}) - p \cdot fd \tag{5}$$

IV. Performance Evaluation

In order to evaluate the performance of different downlink/uplink ratios, we conducted a comprehensive simulation study using the OPNET Modeler [11] simulation environment. The simulation model accounts for both, the MAC and the PHY layer. A WiMAX cell is configured with a frame size of 5 ms and only the best effort service class with a round robin scheduling unit is used. Further simulation settings are shown in Table I.

The downlink/uplink ratios and the adaptive algorithm is tested for several traffic models which are shown in Table II. For the web traffic model, a standard http model from the 3GPP2 [12] is used which is recommended by the WiMAX forum.

In order to compare the performance for the different ratios, the mean delay over 30 simulation runs is determined, where

TABLE I
IEEE 802.16 simulation settings

parameter	value
frame size	5 ms
duplexing	TDD
duration of an OFDM symbol	50 μs
bits per OFDM symbol	200
overall bandwidth	3.84 Mbps
OFDM symbols per transmission opportunity	2
Initial Ranging transmission opportunity	1
Bandwidth Request transmission opportunity	4
QoS class	best effort
scheduling	round robin
request mechanisms	broadcast
starting DL/UL ratio for ATDD split	50/50
SS starting interval	uniform (3 s,5 s)

TABLE II

TRAFFIC MODEL PARAMETERS

traffic class	Reading time	packet size	number of packets
VoIP	constant (10 ms)	constant 640 bytes	constant(1)
UL FTP	exponential (mean 5 s)	constant 100000 bytes	constant(1)
DL FTP I	exponential (mean 4 s)	constant 24000 bytes	constant(1)
DL FTP II	exponential (mean 180 s)	truncated lognormal mean = $2{\cdot}10^6$ bytes Std. = 0.722 Mbytes max. = 5 Mbytes	constant(1)
HTTP main object	exponential (mean 30 s)	truncated lognormal mean = 10710 bytes Std. = 25032 bytes min. = 100 bytes max. = 2 Mbytes	constant(1)
HTTP embedded objects		truncated lognormal mean = 7758 bytes Std. = 126168 bytes min. = 50 bytes max. = 2 Mbytes	truncated pareto mean = 5.64 max. = 53

the delay is the time it takes to completely transmit a packet inside the WiMAX network. The performance is evaluated for 70/30, 60/40, and 50/50 fixed boundaries and the adaptive algorithm. The number of SSs is chosen according to the maximum number of supported stations for settings specified in Table I and the used traffic profiles.

A. Performance for VoIP traffic

For the first scenario, the number of SSs is steadily increased from 1 to 10 and a closer look is taken at the uplink packet delay. We assume that the delay increases in dependence on the number of VoIP users because the stations have to compete on the one hand for bandwidth request slots and on the other hand for available bandwidth. The ITU-T G.711 [13] voice codec with a data rate of 64 kbps is used and the frame size is set to 10 ms. Due to the fact that the traffic volume is similar in both directions, the 50/50 ratio should provide the best performance. The results are shown in Fig. 3.

The figure reveals that the 70/30 partition soon leads to inconsistency if more than six SSs are present. This is expected because of the short uplink subframe. A similar behavior can be seen for the 60/40 ratio, but up to eight SSs can be supported without any problems. The best results in terms of delay are given by the 50/50 ratio. The increasing delay is here only caused by collisions in the bandwidth request phase. Our adaptive algorithm shows similar low mean delays with only a slight difference for a large number of SSs. The difference is caused by uplink channel descriptor (UCD) and downlink channel descriptor (DCD) messages, containing information about the backoff parameter and the burst profiles, which are transmitted in regular intervals. The higher load on the downlink provokes our algorithm to enlarge the downlink subframe for a short time. Thus, the uplink bandwidth is at its limit resulting in higher mean delays.

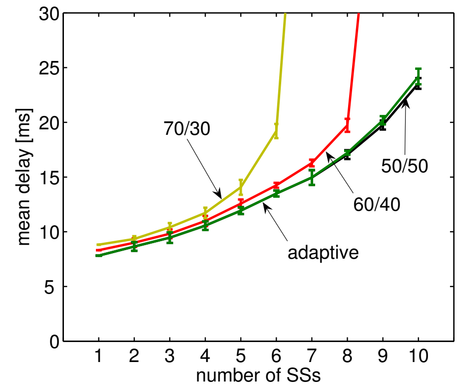

Fig. 3. Different configurations for VoIP traffic

B. Performance for FTP traffic

In contrast to the previous scenario with bidirectional VoIP traffic, the 70/30 ratio should be best suited for downlink FTP traffic because only the file requests and the TCP Acknowledgments have to be transmitted on the uplink. The WiMAX settings are similar to the previous scenario and the simulation is again started with one subscriber station and increased to 15. All stations are configured with the DL FTP I traffic profile, shown in Table II. This setting was chosen in order to guarantee that the traffic volume can be handled by all ratio settings. In contrast to the VoIP scenario, the packet delay is now measured on the downlink. The resulting graphs are shown in Fig. 4.

As expected, the 50/50 ratio shows the worst performance. It has to be mentioned that the larger 90% confidence intervals are caused by the current downlink utilization. In contrast to the previous scenario, the number of actively transmitting SSs is not constant but varies due to the exponentially distributed FTP off periods. This effect decreases for the 60/40 and 70/30 curves due to the larger downlink capacities and are also

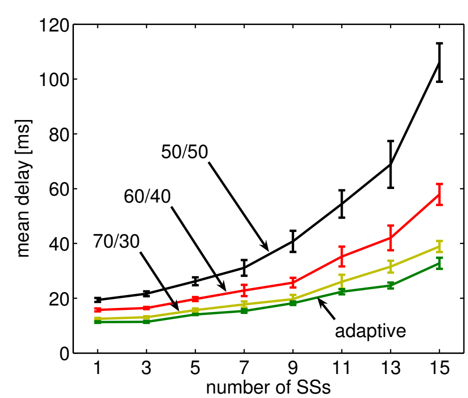

Fig. 4. Different configurations for DL FTP traffic

reflected in the smaller delays. The lowest delay is obtained by the adaptive algorithm.

In Fig. 5 the cumulative distribution function is plotted for the same scenario with 15 clients. The plot again clarifies these statements. Furthermore, it reveals that the variance for the adaptive algorithm and the 70/30 ratio is rather low. 90 percent of the packets are transmitted within 70 ms for the adaptive algorithm and within 80 ms for the 70/30 ratio. However, the variance of the 50/50 ratio is really high. It takes up to 260 ms to transmit 90 percent of the packets, whereas the first 20 percent of the packets are received within 20 ms.

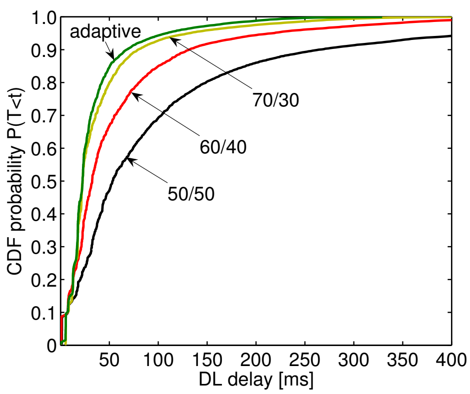

Fig. 5. CDF for 15 FTP DL clients

C. Web traffic performance

After having seen that the adaptive algorithm works well for FTP and VoIP traffic, we take a look at the performance for an HTTP 1.1 web traffic scenario. The stations are configured according to the 3GPP2 web traffic model which is shown in Table II. In contrast to the FTP scenario, the variance of the traffic amount on the downlink is higher due to the heavy-tailed distribution for the number of embedded objects. Furthermore, the number of requests and TCP Acknowledgments on the uplink is higher. The number of subscriber stations is this time increased from 1 to 19. Similar to the FTP scenario, the mean delay is measured on the downlink. The resulting graphs can be found in Fig. 6.

As shown by the confidence intervals, the delay variance is very high for all subframe settings. Furthermore, the graph shows that the delay increases comparably for all configurations with a rising number of stations. The mean delays for 70/30, 60/40, and the adaptive algorithm are very similar and low. Only the 50/50 scenario has a larger delay due to missing capacity on the downlink. The adaptive algorithm shows again the best simulation results which are more obvious in this web traffic scenario compared to the VoIP and especially the FTP download scenario.

Concluding the last three scenarios with VoIP, FTP, and web traffic, it is obvious that a fixed downlink/uplink ratio can result in long end to end delays. However, the adaptive

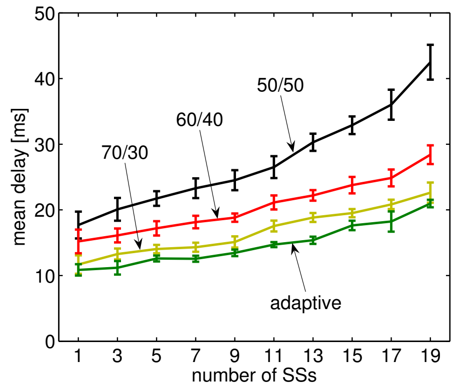

Fig. 6. Different configurations for web traffic

algorithm has shown the best performance in all scenarios. Finally, we want to evaluate our algorithm for a VoIP/FTP traffic mix.

D. Traffic mix

An interesting question is how the different ratios and our algorithm work in a scenario with a mix of traffic profiles. Therefore, a scenario with a changing environment is configured. Three different traffic phases, illustrated in Fig. 7, are used. During the entire simulation process, three VoIP clients are active using the G.711 traffic profile without silence detection. Between seven and twelve seconds, three SSs start their FTP Uplink profile, UL FTP from Table II, uploading FTP files to the backbone network behind the base station. This phase ends after about 30 seconds simulation time. Meanwhile, three DL clients begin the download of files with a size between 100 byte and 2 Megabyte using the DL FTP II traffic profile which is taken from the 3GPP2 specification [12].

The intention of the mixed scenario is to validate the adaptive algorithm and show if it reacts before performance loss occurs. Fig. 8 illustrates the behavior of the adaptive algorithm in this scenario. The algorithm starts with a 50/50 downlink/uplink ratio. The start of the VoIP clients does not have an effect on the boundary due to an equally distributed

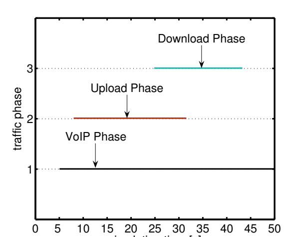

Fig. 7. Traffic phases

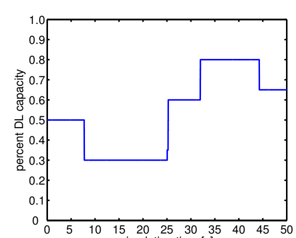

Fig. 8. Percentage of the whole frame used for the downlink subframe

traffic load. However, when the first SS starts with the FTP upload process, the partition is shifted in order to guarantee low delays on the uplink. Now, 70 percent of the frame is used for the uplink but the remaining 30 percent downlink capacity is sufficient to support the VoIP traffic. At about 25 seconds, the downlink phase starts, meaning that FTP traffic is transmitted on the downlink. The border between downlink and uplink is again shifted, but this time 60 percent is used for the downlink. When the uplink FTP traffic profile finishes, 80 percent of the frame is reserved for the downlink. Finally, after around 45 seconds, the downlink FTP traffic profile ends and the downlink is decreased to 65 percent of the frame duration. The only reason why the boundary is not shifted back to a 50/50 partition is the low traffic load of the three VoIP clients which makes a further repartitioning unnecessary.

Finally, the mean delay for the downlink and uplink FTP subscriber stations in the traffic mix scenario is measured. The start times and the VoIP users remain the same. However, for the downlink delay measurements, three simulation settings are performed, with one to three FTP download stations using the same 3GPP2 traffic profile. The results are plotted in Fig. 9 and reveal that the adaptive algorithm outperforms all other three configuration settings. Further, it can be noticed that the fixed partition of 50/50 rises relatively fast with a delay of about 150 ms for three downloading SSs. This is due to the high bandwidth demands of the traffic profile and also the reason why only up to three SSs are considered.

For the completeness of the measurements, a simulation for a changing number of FTP upload traffic is performed. Fig. 10 shows the mean delay of the UL FTP scenario. The higher delays for all settings are caused by collision in the bandwidth request phase. Up to nine stations have to compete for the four transmission opportunities in this phase. Especially for the 70/30 configuration, the high mean delays are also caused by packet congestion due to the small uplink subframe. Furthermore, it is shown that the order for the fixed ratio is now contrariwise.

Concluding the traffic mix scenarios we can say that the adaptive algorithm is the best solution because it adapts the framing according to the changing traffic conditions. Thereby, it makes no difference which application is running. A fixed setting is only suited if the provider knows the traffic demands while planning the WiMAX network.

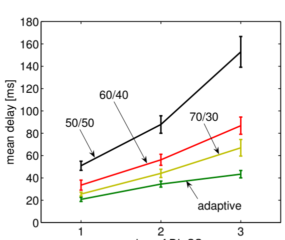

Fig. 9. DL FTP traffic with varying background traffic

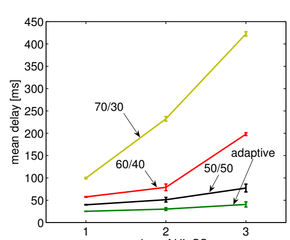

Fig. 10. UL FTP traffic with varying background traffic

V. Conclusion

In this paper, the performance of different downlink/uplink ratios was evaluated for several services. It has been shown that a fixed boundary is only suited for specific application demands and leads to congestion if the demand changes. Therefore, we have proposed an adaptive framing algorithm which adjusts the downlink/uplink frame length according to the actual traffic load. If capacity in one communication direction is left unused, the capacity is assigned to the opposite direction. It has been shown that this adaptive solution provides the best results in terms of delay in every simulation scenario.

In future work, we will try to extend our adaptive subframing algorithm in order to work in a multi-cell environment where the base stations will have to coordinate the subframing.

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