Optimization of Frame Structure for WiMAX Multi-hop Networks

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Abstract. To enhance the system throughput and to extend coverage of IEEE 802.16 networks, relay stations can be implemented. If a user station is attached to the base station (BS) through several relays stations (RS), a multi-hop communication occurs. To enable multi-hop communication, the IEEE 802.16j standard proposes two approaches how RSs can be implemented into the network. The first approach groups BSs and several RSs into a multi-frame with repetition of relay zones. In the second approach, the BS schedules several relay zones in one frame. While the first approach causes long packet delays, the second approach has high requirements on RS's processing capabilities. This paper proposes an optimized frame structure that allows using second approach whilst the requirements on RS's processing time are still kept in reasonable range. The obtained simulation results indicate that packet delays in downlink and uplink direction can be significantly reduced.

Keywords: Relay Station, frame structure, IEEE 802.16j, packet delay.

1 Introduction

Over the last years, broadband wireless systems established themselves as one of the fastest growing and developing area in the field of telecommunications. One of the most promising technologies represents WiMAX widely known as wireless networking standard that addresses interoperability across IEEE 802.16 standard-based products. So far, IEEE Std. 802.16-2004 [1] intended for fixed terminals was approved. In addition, amendment to the former standard labeled as IEEE 802.16e [2] was adopt as well. Its purpose is to enrich WiMAX by further features such as handover and power management modes to enable user's mobility.

To facilitate QoS management of individual users, the standard specifies five QoS scheduling services; i) Unsolicited Grant Service (UGS), ii) real time Polling Service (rtPS), iii) extended real time Polling Service (ertPS), iv) non real time Polling Service (nrtPS) and the last one v) Best Effort (BE).

In order to enhance the system throughput and extend Base Station's (BS) coverage, a Relay Station (RS) that enable multi-hop communication can be introduced into the network. The multi-hop communication occurs when data are transferred from the source to the destination node via one or more RSs. The implementation of relay stations into the WiMAX system is within the scope of IEEE 802.16j working group [3] that was established in 2006.

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According to [3], three types of RSs are specified; fixed, nomadic and mobile RSs. This paper considers only the fixed RSs, i.e. RSs that are permanently installed at the same location. The RSs are in most cases build in, owned and controlled by service provider. An RS is not directly connected to the wire infrastructure and has minimum functionalities to support the multi-hop communication. In addition, two types of RSs can be distinguished: transparent and non-transparent one. The transparent RS (T-RS) transmits neither long preamble at the beginning of frame nor broadcast MAC management messages such as DL/UL maps or DCD/UCD. Therefore, a Mobile Station (MS) has to be in the BS coverage area. The only aim of the T-RS is to enhance the throughput within the BS cell; a T-RS is used in cooperation scenarios when data are sent via several independent radio channels. The second category of RSs is known as non-transparent RS (NT-RS). In comparison with T-RS, NT-RSs transmit long preamble and broadcast MAC management messages. Thus, the NT-RSs are more suitable for a scenario where a MS is out of BS range, e.g. due to the shadowing effect or when the MS is actually to far-away to receive BS's signal with satisfactory quality. Nonetheless, a NT-RS can be also used to enhance the cell throughput.

Basically two types of NT-RSs can be considered: i) centrally controlled RS (CC-RS) and ii) de-centrally or distributed controlled RS (DC-RS). The former type of RS is completely controlled by the BS. This means that the BS handles and schedules all data and control transmissions between the RS and its own users. In case of DC-RS, the RS itself (without BS help) schedules all control and data transmissions of its users. As we consider exclusively multi-hop scenarios where a MS may be out of the BS range, only the NT-RSs will be taken into account.

The rest of the paper is organized as follows. In subsequent section several approaches of MAC frames for WiMAX system with relays are contemplated. The next section describes in more details the frame concepts based on IEEE 802.16 and proposal based on [4]. Section four investigates possible frame modifications in order to reduce packet delays in multi-hop scenarios. In section five, simulation scenario is depicted together with presentation of simulation results. The last section concludes our paper.

2 Related Work

If a RS is implemented into the WiMAX network, the original MAC frame needs to be updated in order to support multi-hop communication. So far, several research works had been done during the last few years. The main goal is to effectively integrate RSs to IEEE 802.16 standard while still keeping backward compatibility with the legacy MSs. In [5], authors proposed a simple and flexible frame structure based on IEEE 802.16e. Within the IEEE 802.16j working group, proposals for T-RS and NT-RS were introduced ([3], [6]). However, the NT-RS proposal supposes that a BS and its subordinate RSs simultaneously transmit during the broadcast part of frame and DL/UL access zones. In order to avoid mutual interference of BS and NT-RS transmissions, a multi-frame structure is proposed in [7]. Other interesting concept how to integrate NT-RSs into the existing WiMAX network and to avoid unwanted interferences is presented in [4]. The frame concept for more than two hops is defined in [8] where out-frame and in-frame multi-hop relaying is considered. By out-frame relaying is meant the situation when data from the BS to MS are forwarded subsequently in following frames. The second case reflects to the situation when data are sent between the BS and MS within one frame. The similar concept for multi-hop communication is also introduced in [3]. While the first method excessively prolong the packet delays, the second method interpose high requirement on RS's CPU processing capabilities. To that end we propose a modification to frame structure based on the second method which lower requirements on RS's CPU processing. Although the proposal is applied to CC-RS frame structure specified in [4], the whole idea can be extend to other frames concepts.

3 Frame Structure

The frame concept of NT-RS based on IEEE 802.16 is shown in Fig. 1. Both, BS and RS frames, begin with broadcasting part composed of long preamble, FCH (Frame Control Header) field and DL/UL MAPs. Subsequently, one or more DL access zones follow. The access zone is an interval in which the BS and RS send DL/UL data bursts to its subordinate stations. The rest of DL subframe is reserved to BS-RS transmissions specified by DL relay zone(s). Since the DL access zone precedes the DL relay zone, data are delivered to the MS in the second frame at best (for 2 hop scenario). In the first frame, the BS transmits within the DL relay zone data to the RS. The RS retransmits the data burst in a subsequent frame.

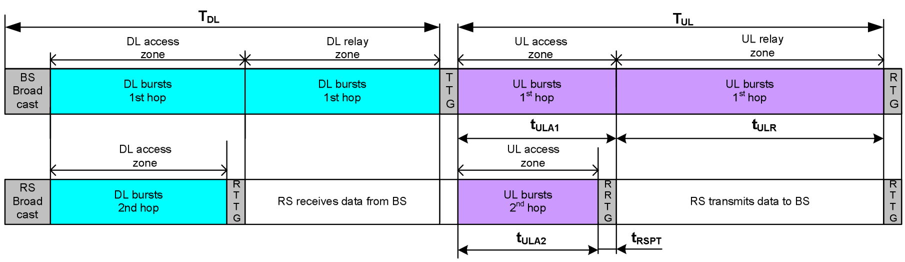

Fig. 1. Frame concept for NT-RS according IEEE 802.16j [3]

The UL subframe begins similarly as the DL subframe with the access zone during which MSs transmit data bursts to their super-ordinate stations. The MAC frame ends up by UL relay zone(s). Between the DL/UL subframes are included gaps to enable the BS antenna switch from the transmission to reception mode and vice versa. Furthermore, the RTTG (RS transmit/receive transition gap) and RRTG (RS receive/transmit transition gap) gaps are necessary to facilitate RS's antenna switching. The data can be sent from the MS to the BS in one frame if the RS has enough time for processing data received within UL access zone. In other words, the time which has the RS to process all received data (in Fig.1 specified as t_{RSPT}) must be greater or equal to t_{RSPC} as indicated in the following expression,

$$t_{RSPT} \geq t_{RSPC} \quad . \tag{1}$$

where t_{RSPC} is exactly the time needed for processing of received data during t_{ULA2} which is directly proportional to that amount of data. The t_{RSPT} can be expressed as,

$$t_{RSPT} = T_{UL} - \left(t_{ULA2} + t_{ULR}\right) . \tag{2}$$

where T_{UL} represents the duration of UL subframe, t_{ULA2} is the interval when MSs attached to the RS are transmitting and t_{ULR} corresponds to the length of UL relay zone when the RS is in transmitting mode. The length of T_{UL} depends on the current requirements and demands of individual users since the BS is able to dynamically change the DL and UL subframes duration. On the other hand, the length of t_{ULA2} and t_{ULR} generally depend on actual traffic load and could be computed as,

$$t_{ULA2} = \sum_{i=0}^{l}\left(\frac{D_{ULi}}{D_{bps_i}} * t_S\right), t_{ULR} = \sum_{j=0}^{m}\left(\frac{D_{ULj}}{D_{bps_j}} * t_s\right) . \tag{3}$$

where D_{ULi} expresses the number of bits sent in the current frame by *i-th* MS, D_{bpsi} is the number of bits that could be transmitted per one OFDM(A) symbol by *i-th* MS, t_s represents the length of one symbol and l indicates the number of MSs active in the current frame and attached to the RS. The D_{bpsi} is derived from modulation and coding scheme applied for that particular transmission and dependents on received SNR (see [2]). Similarly, the D_{ULj} is the number of bits send by *j-th* RS, D_{bpsj} is the amount of bits transmitted per one OFDM(A) symbol by *j-th* RS and m is the number of active RS. Only at low traffic load, as frame is not fully occupied, the RS is able to retransmit data within one frame. This is due to the fact that the BS is able to schedule individual transmission in such a way that the gap between the UL access zone on the 2nd hop and UL relay zone are far greater than t_{RSPC} (or at least of equal length as t_{RSPC}). With increasing traffic load, the condition indicated in expression (1) can not be satisfied and certain amounts of data have to be sent in consecutive frames.

The concept based on [4] assumes that RSs and BS share radio resources within every BS cell and utilize the same frequency channel. Consequently, dynamic sharing of radio resources according to current stations requirements may be used. The frame structure of CC-RS is illustrated in Fig 2. At the beginning of frame, the BS sends its control information to all subordinate stations. Note that BS transmits alone while other stations (both RS and MS) are in receiving modes; hence no intra-cell interference arises. Since the BS schedules all transmissions on any other subsequent hops, DL

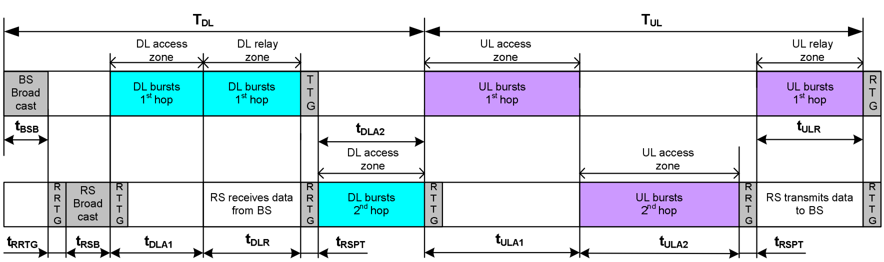

Fig. 2. Frame concept with CC-RSs [4]

and UL MAPs are considerably larger comparing to standard MAP messages in legacy WiMAX systems. After the BS's broadcast interval follows a RRTG gap which provides sufficient time to switch RS antenna from receiving to transmitting mode.

From the received BS broadcast information the RS extracts relevant parts and re-broadcast it to its subordinate stations (MSs or/and RSs). When the RS(s) broadcast transmission is over, its RS antenna needs to be switched to the receiving mode and waits for the DL access zone which ideally occurs at the end of DL subframe. At the same time, the BS starts to distribute data to the MSs on the first hop within the first DL access zone. While the beginning and end of DL subframe is dedicated to the DL access zones, the middle part is assigned to one or several DL relay zones. In order to enable the RS's antenna transition from receiving to transmitting mode, a RRTG gap is inserted. After the BS transmission, the RS itself sends data on the 2nd hop within the scheduled second DL access zone. Similarly as in case of DL subframe, the uplink subframe is composed of at least one UL access zone at the side of BS and one UL access zone at the RS's side. The end of UL subframes is assigned to the UL relay zone.

In comparison with the frame concept based on [3] data transmissions in both directions can be ideally accomplished in one frame. However, the same condition as in previous case must be fulfilled, i.e. the t_{RSPT} has to be greater or equal to t_{RSPC}. Note that the t_{RSPC} for the DL direction is proportional to the amount of data received during t_{DLR} (not to t_{ULA2} as in UL direction). In DL case, t_{RSPT} is computed as,

$$t_{RSPT} = T_{DL} - \left(t_{BSB} + t_{RRTG} + t_{RSB} + t_{DLA1} + t_{DLA2} + t_{DLR}\right) \quad (4)$$

where t_{BSB} (t_{RSB}) is the length of BS (RS) broadcast interval, t_{RRTG} corresponds to the time dedicated for RS's antenna switch, $t_{DLA1,2}$ marks the duration of DL access zones and finally t_{DLR} represents the duration of DL relay zone. The time necessary for broadcasting part of the frame is further derived from the following expression,

$$t_{BSB,RSB} = t_{LP} + t_{FCH} + t_{BM} \quad (5)$$

where t_{LP} is the length of long preamble (commonly 2 symbols), t_{FCH} corresponds to the duration of FCH field and t_{BM} is the time required for broadcasting of MAC management messages (e.g. DL and UL maps). The length of t_{DLA1}, t_{DLA2} and t_{DLR} can be evaluated by adopting the expression (3) as,

$$t_{DLA1} = \sum_{x=0}^{n}\left(\frac{D_{DLx}}{D_{bpsx}} * t_S\right), t_{DLA2} = \sum_{i=0}^{l}\left(\frac{D_{DLi}}{D_{bpsi}} * t_S\right), t_{DLR} = \sum_{j=0}^{m}\left(\frac{D_{DLj}}{D_{bps_j}} * t_s\right) \quad (6)$$

where n is the number of active MSs attached directly to the BS. The rest of the parameters have the same meaning as already described in expression (3) but are related to the DL direction. In UL direction, the t_{RSPT} may be expressed as,

$$t_{RSPT} = T_{UL} - \left(t_{ULA1} + t_{ULA2} + t_{ULR}\right) \quad (7)$$

where t_{ULA1} corresponds to the time dedicated for data transmission between the MS and BS. The expressions (4) and (7) imply that requirements on RS' CPU are higher at heavy traffic load similarly as in the frame concept based on [3].

Up to now, only two hops between the BS and MS have been considered. According to [3] [5], two approaches are specified to support more than two hop communication. The first approach groups BS and several RSs into multi-frame with repetition of relay zones. For example, if the multi-frame is composed of two frames, the relay zone in the first frame is assigned to the RS on the first hop whereas in the second frame the relay zone is assigned to the RS on the second hop. Thus, data are sent in consecutive order between the BS and MS. The disadvantage of such principle is a significant increase of packet delay which is crucial for delay sensitive services such as VoIP. The solution is offered by the second approach as several relay zones are scheduled in one frame. Consequently, data are transferred within one frame which minimizes the packet delays. The drawback of this method is higher requirements on RSs processing capabilities. Nevertheless, to fully utilize the potential of second approach, the frame scheduling and planning of frame structure needs to be properly done. Our suggestion, how to schedule the frame is described in the next section.

4 Optimization of Frame Scheduling

In order to minimize the packet delay, individual parts of frame have to be scheduled in such manner that data in the UL and DL direction has to be sent as soon as possible. Generally, the packet delay depends on two parameters; i) the number of frames between packet arrival at the originator station and reception at the destination station and ii) the position of data burst in the frame. Especially the first parameter influences the overall packet delay. Concerning the position of data burst in the frame, the DL subframe always precedes subframe in the UL direction. Thus, in the DL direction are foreseen shorter packet delays. Decreasing of packet delay is achieved by successive filling of data burst from the left to the right side of frame. However, this method has only effect as long as the system load is low.

The optimized frame structure is presented in Fig. 3. In the same manner as described in Fig. 2, the individual DL/UL access and relay zones are allocated in such way that data can be ideally transmitted in one frame. In the DL direction, data are sent on the first hop between the BS-MS/RS prior to the transmission on the second or any other hop. On the other hand, in the UL direction is possible to change transmitting order as UL bursts on the higher hops are primarily scheduled.

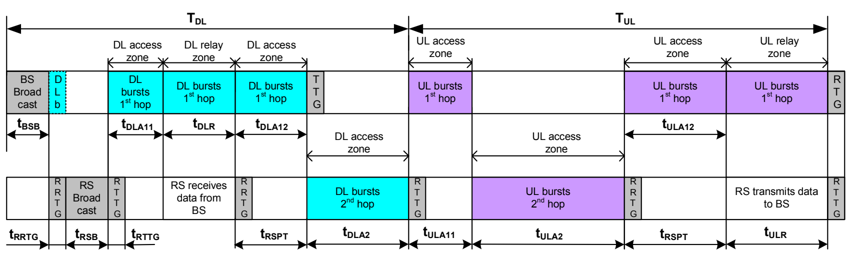

Fig. 3. Optimized CC-RS's frame structure based on [4]

In comparison with the original concept, two advantages are foreseen. Firstly, the radio resources are exploited in more efficient manner as all RRTG gaps are filled out with data transmissions. To be more specific, the RRTG gaps scheduled in the DL subframe can be used for DL transmissions between the BS and MS. The RRTG gap following the second UL access zone is utilized for transmission from the MS to BS. The second advantage is that the packet delays, both in DL and UL directions, are cut down to minimum.

While the beginning and end of BS's DL bursts are dedicated to DL access zones (in Fig. 3 the time intervals corresponds to the t_{DLA11} and t_{DLA12}), the middle part is assigned to DL relay zones. This way is ensured that a RS has time to switch to receiving mode during the first DL access zone and come over to transmitting mode within the second access zone. Additionally, the RSs have more time to process data which increase the probability that data are relayed in the same frame. In other words, the RS's processing time is prolonged exactly by the t_{DLA12}. Consequently, it is possible to schedule the DL relay zone is scheduled right after the RTTG gap in order to provide RS with sufficient processing time at heavy load. Note that in such case the t_{DLA11} is equal to t_{RTTG}. If this condition is satisfied, the t_{RSPT} in the DL direction could be formulated as,

$$t_{RSPT} = T_{DL} - \left(t_{BSB} + t_{RRTG} + t_{RSB} + t_{RTTG} + t_{DLR} + t_{DLA2}\right) \tag{8}$$

In the UL direction, the UL access zone on the 1st hop is similarly split into two parts as in DL direction. The most significant gain is foreseen if the BS schedules UL bursts on the 2nd hop immediately after RTTG gap, i.e. duration of RTTG gap equals to t_{DLA11}. This will grant sufficient time (t_{RSPT}) to the RS to process all received data which could be expressed as,

$$t_{RSPT} = T_{UL} - \left(t_{RTTG} + t_{ULA2} + t_{ULR}\right) \tag{9}$$

In the UL direction, the delay is further increased by requesting mechanism specified in WiMAX networks. If a MS needs to send data to a BS, a request has to be issued in the predefined time slot scheduled by the BS. When the MS is attached to the BS via one or more RSs, a RS retransmits this request on behalf of the MS. To deliver the request to the BS in the fast fashion, time slots allocated for that purpose need to be efficiently assigned. As an example, MS's request is sent at the beginning of UL bursts field on the second hop (which corresponds to the second UL access zone in Fig. 3) whilst the RS relay this request during the UL relay zone.

5 Simulations

5.1 Simulation Scenario

To determine packet delays for different scenarios, MATLAB system level simulator has been developed. The used parameters during simulation are summarized in Table 1. The simulation model is composed of one BS and eight fixed RSs. The maximum distance between the RS and BS is restricted to two hops. The RSs positions are chosen in such way that all MSs are always in a transmission range of at the least one station (BS or RS). The simulator works in the following way. In every simulation step (the length of one MAC frame) is generated certain traffic load. According to that traffic load, the BS is able to compute the duration of individual MAC frame's parts (i.e. duration of access and relay zones, etc.). Consequently, the BS can decide if the t_{RSPT} is greater than t_{RSPC} or not. If the former is true, all data are transmitted within one frame. Otherwise, some data must be sent in the consecutive frame.

There is implemented a mobility model for every MS. At the beginning of simulation, an initial position of each MS is randomly determined in such manner, that the MS is located within a defined range, i.e. between 0 to 800 m from the BS. Additionally, a velocity and random movement direction are determined for all individual MSs in the system. The MSs are moving along straight line until the distance from the BS is equal or larger than the defined BS cell area. In such circumstance, a new MS direction is established. This mechanism guarantees, that no MS moves out of the BS range during the simulation process.

The path between the BS and MS is determined according to the minimum Radio Resource Cost (RRC) metric (more details may be found in [9]). The RRC is measured in a number of OFDM symbols needed for transmission of certain amount of data burst (e.g., 1000 bits). To decide which point of attachment is the best from the point of system performance, the RRC compares all available routes from (to) the BS and determines how much system resources have to be allocated.

The traffic model assumed in simulation is based on VoIP with suppression of silence intervals as defined in [10]. The size of packets generated during active/inactive state is denoted in simulation as *AS*/*IS* (see Table 1). The packet size includes user's payload and protocol headers (RTP, UDP, IPv4, 802.16 generic MAC header and CRC).

Table 1. Simulation parameters

Parameter	Value
Frequency band [GHz]	3.5
Channel bandwidth [MHz]	20
Number of MS [-]	1-100
MS's velocity [m/s]	10-50
Frame duration [ms]	20
BS transmit power P_t [dBm]/height [m]	30/30
RS transmit power P_t [dBm]/height [m]	30/30
MS transmit power P_t [dBm]/height [m]	30/2
BS cell area [m]	800
Max number of hops between the BS and MS [-]	3
Channel model between BS-RS, RS-RS	LOS [10]
Channel model between BS-MS, RS-MS	NLOS [10]
Length of simulation [min.]	30
Noise [dBm]	-100.97
Packet size during active (AS)/inactive state (IS) [b]	696/456

The packet delay considered in simulation corresponds to a time interval between a packet arrival and reception at the station's MAC layer. Thus, delays introduced by higher protocol layers and the rest of network are not considered. Furthermore, the packet delay is evaluated under assumption that MSs use rtPS scheduling services in the uplink directions. Another factor which influences the packet delay is offered traffic load, i.e. number of active MSs in the system. The maximal considered offered traffic (MOT) corresponds to state when all MSs in the system are active and generates traffic which corresponds to two VoIP connections. Note that packets eventually discarded by system due to congestion are not considered. Thus, only packets successfully arriving at the destination are taken into account.

Three simulation scenarios are compared depending on RS's processing capabilities (i.e. different t_{RSPC}); i) RS needs from 0 to 5ms to process received data (in the next section depicted as Scenario A), ii) RS needs from 0 to 3ms to process received data (in the next section depicted as Scenario B) and iii) RS needs from 0 to 1ms to process received data (in the next section depicted as Scenario A). The bottom boundary corresponds to the situation when the RS has not received any data (no data are processed at all). The upper boundary is statistically derived from the average t_{RSPC} for 100% of MOT.

There are considered two cases for the DL direction in every scenario. The first one corresponds to non-optimized frame (see Fig. 2). The second scenario considers the optimized frame structure described in Fig. 3. In case of UL direction, three cases are taken into account. The first case reflects the situation when the RS cannot transmit/receive data during one frame. In addition, MS's requests are relayed to the BS in the following frame. The second case optimizes the requesting mechanism but data are relayed in similar manner as in the first case. Finally, the last case considers the fully optimized method as described in the previous section.

5.2 Simulation Results

Fig. 4 depicts the mean packet delay in the DL direction depending on the system traffic load and different RS's processing capabilities. If the system traffic load is low, all investigated scenario perform equally. The RSs have enough time to process received data and forward them to the MS/RS in the same frame. The reason is twofold,

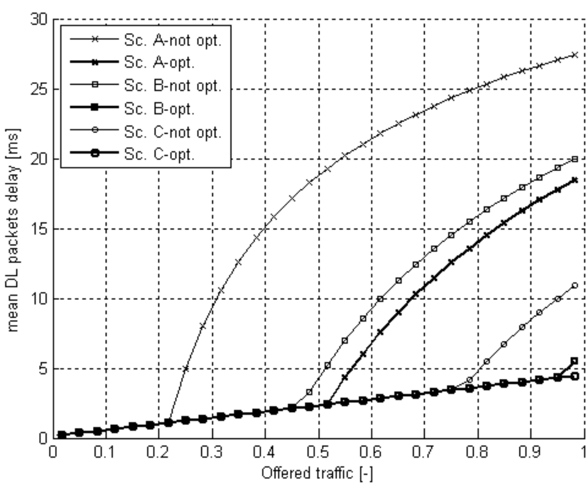

Fig. 4. Mean packet delay in DL direction

i) the whole frame is generally not occupied by data transmission and BS is able to include between DL relay and DL access zones sufficient time interval, ii) as small data burst are transmitted, the data are process faster. When increasing the traffic load, the packet delay roughly linearly increases. Nonetheless, from certain point the packet delay is significantly increased.

If we assume the frame structure according to Fig. 2, the system utilizing RSs equipped with long CPU's processing time (scenario A) shows sudden rise in packet DL approximately at 23% of MOT. From this point on, the RSs are not able to process all data burst in the same frame and have to wait for another frame to send the remaining data. With more powerful CPU's, the RSs are able to better cope with the heavy traffic load. To be more precise, RSs manage to relay data in one frame into the 49% of MOT for scenario B and into the 79% of MOT for scenario C. This situation is improved considerably if the proposed optimization of frame structure is applied. Even thought when the system is enhanced by RSs with low processing capability, the RSs are able to transfer all data within one frame up to 53% of MOT. For scenarios B and C, RSs actually manage to send all data bursts regardless the current system traffic load. The observed mean packet delays in the DL direction are up to 27ms depending on the current traffic load and processing capability of RS's CPU.

In the UL direction, the packet delays are generally longer (see Fig. 5). Firstly, this is due to the fact that the whole UL subframe follows the DL subframe. Secondly, the requested mechanism which allows MSs to ask for a transmission opportunity significantly increases packet delivery time. Note that the UL packet delay starts to substantially increase at the same value of MOT as in the DL case. The reason for it is that the BS's scheduler allocates the same guard intervals between the DL relay and DL access zones (respectively UL access and UL relay zone). If non-optimized frame is taken into account and RSs are not able to send MS's request in the same frame, the mean UL packet delay varies between 40 and 70ms. The mean packet delay can be considerably shortened by proper allocation of time slots for MSs (RSs) bandwidth requests. If the optimized frame is used, the packet delays further decrease, i.e. below 30ms.

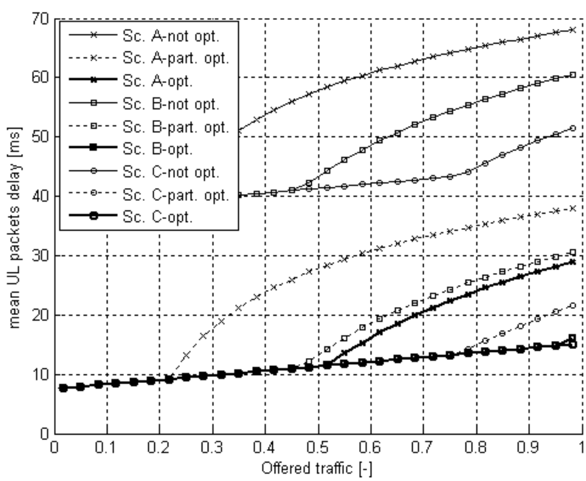

Fig. 5. Mean packet delay in UL direction

6 Conclusion

The paper focuses on frame structure of WiMAX networks and suggests an optimization for multi-hop communication in order to minimize the packet delay. A description of frame for CC-RS according to IEEE 802.16j and [4] has been introduced. To support the multi-hop communication, two approaches can be considered. The first one introduces multi frame and repetition of relay zones. However, the packet delay in multi-hop scenario is quite high. On the other hand, the second approach allows RS to receive (transmit) and transmit (receive) data bursts in one frame. The drawback of this method is high requirement on RSs processing capabilities. The simulation results show that if the proposed scheme of frame structure is applied, the RSs have more time to process data which decrease the overall packet delays as for DL as for UL directions.

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