Analysis and Enhancement of Bandwidth Request Strategies in IEEE 802.16 Networks

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***Abstract*— IEEE 802.16 based broadband wireless access network is considered as one of the most promising wireless access technologies. It employs a request/grant scheme in bandwidth allocation where each subscriber station (SS) can send bandwidth requests (BRs) to the base station (BS) before bandwidth can be granted to SSs. The 802.16 standard defines two types of BR strategies, namely incremental requests and aggregate requests. In this paper, we first present an analytic model to analyze their performance and show that both types of BRs have rooms for improvement when facing two common types of traffic patterns, called the uphill traffic pattern and the periodic/bursty traffic pattern, in terms of overhead and data waiting time in the queue. Then, we propose two enhancement strategies, called the aggressive strategy and the conservative strategy, that exploit the property of the two traffic patterns to improve the performance. The simulation results show that the two enhancement strategies can effectively reduce the overhead and data waiting time, at the price of somewhat less bandwidth utilization in the case of conservative strategy.**

***Index Terms*—IEEE 802.16, WiMAX, Bandwidth Request, Bandwidth Allocation, Traffic Pattern.**

I. Introduction

IEEE 802.16 Worldwide Interpretability for Microwave Access system (WiMAX) is a promising broadband wireless access technology aimed to support the high transmission rate and large service range. IEEE 802.16 standard [1, 2] defines both the Medium Access Control (MAC) and Physical (PHY) layers of a broadband wireless network. A bandwidth reservation scheme is used in the MAC layer to allow the SS to reserve any required bandwidth from the BS in order to support quality of service (QoS) guaranteeing services. The BS coordinates bandwidth reservations for all data transmissions and receptions.

The IEEE 802.16 standard defines an abstract concept of connection and uses it to uniquely identify a service flow from an SS. The BS assigns a connection ID (CID) to each connection for management purpose. The standard also specifies bandwidth request/grant mechanisms, which are used to address the dynamic traffic pattern and bandwidth need of a service flow over the time. According to the standard, SSs can request bandwidth for their connections to ensure their QoS based on the CIDs. The BS can either grant or reject the requests based on its available resources and scheduling policies. Two types of bandwidth requests (BRs), incremental requests and aggregate requests, are defined in the IEEE 802.16 standard. The incremental request allows an SS to specify the extra amount of bandwidth needed for a specific connection. Therefore, the amount of reserved bandwidth for this connection can only be increased by making an incremental request. On the other hand, the aggregate request allows an SS to specify the current state of queue for a particular connection. After receiving it, BS resets its perception of the corresponding connection's bandwidth needs. Consequently, the amount of reserved bandwidth for the connection may be increased or decreased according to the state of the queue. However, although the standard specifies the functionalities of these two types of BRs, it does not mention their implementations and effects. Potentially, there are three possible implementations of using BRs: (a) incremental BRs only, (b) aggregate BRs only, and (c) both incremental BRs (to request more BW) and aggregate BRs (to release unused BW). In this paper, we will focus on cases (a) and (c), since (b) is less efficient than (c) in sending BR messages.

Our contribution in this paper is twofold. First, we evaluate both case (a) and case (c) in terms of bandwidth request overhead and bandwidth utilization. To the best of our knowledge, this is the first attempt to analyze those two cases of BR implementation. Second, we propose two enhancement strategies to improve the performance of the two types of BRs when facing two given types of traffic patterns, namely the uphill traffic pattern and the periodic/bursty traffic pattern.

The rest of the paper is organized as follows. In Section II, we give a brief overview of related works. In Section III, we introduce our system model and assumptions. In Section IV and V, we give analysis of the above two cases (a) and (c), respectively. In Section VI, we propose schemes for improving the performance of bandwidth request according to two specific types of traffic patterns. In Section VII, we discuss our simulation setup and show the simulation results. Finally, we conclude and discuss future work in Section VIII.

II. Related Works

In the literature, there are few related works about bandwidth requests in WiMAX networks. In [3] and [8], analytical models for BR contention period size are presented in order to get optimal system performance. In [4], the authors model a contention-based bandwidth request scheme called truncated binary exponential backoff (TBEB) and analyze its performance on bandwidth efficiency and channel access delay. In [5], the authors propose an adaptive scheme for an SS to send the BS requests for extra bandwidth beforehand by speculating the real time polling service (rtPS) traffic patterns. However, none of the above works discuss and analyze the two types of BRs (i.e., the incremental BR and the aggregate BR), their implementation, and their effects, which are the focus of this paper.

III. System Model and Assumptions

In this section, we first present the traffic generation model [6]. We assume that the real-time traffic is used with variable bit rate (VBR) and the time interval between consecutive packet arrivals is considered as exponential distribution. Let λ and λ_{max} be the mean data arrival rate and the maximum data arrival rate, respectively. The steady state probability of the traffic model can be characterized by Poisson distribution.

We assume there are n SSs served by one BS and, for simplicity, there is only one real time polling service (rtPS) running in each SS. According to the standard, the SS which wants to set up rtPS connections will need to negotiate with the BS the minimum reserved traffic rate (R_{min}) and maximum sustained traffic rate (R_{max}) during connection establishments. In our model, we assume that the BS initially assigns bandwidth B_0 to each connection and supports incremental request for each connection until the amount of assigned bandwidth reaches R_{max}.

Suppose D_f represents the frame duration and W_0 is the initial capacity per frame (in terms of byte), we can derive:

$$W_0 = B_0 D_f \tag{1}$$

Additionally, we assume that the queue capacity of each connection is infinite but a threshold, T, is set for ensuring the satisfaction the maximum delay requirement, i.e. the SS tries to send BRs if the amount of accumulated data in queue is greater than T. Assume D_{max} is the maximum tolerable delay of the connection, then we can get the initial threshold T_0 and the threshold at frame i as:

$$T_0 = W_0 \frac{D_{\max}}{D_f}, \quad T_i = W_i \frac{D_{\max}}{D_f} \tag{2}$$

In our model, we assume that SSs can always use their received bandwidth to send BRs via piggybacking in a frame without polling opportunities. As mentioned before, this paper attempts to analyze two cases of bandwidth request implementation: 1) the case of using only incremental BRs; 2) the case of using both types of BRs. We assume that SSs use incremental requests to request more bandwidth and use aggregate requests to release unused bandwidth. In this paper, we do not consider the issue of self-correcting nature of the request/grant protocol for aggregate requests. Moreover, we assume that the arrived data are first stored in the queue and will be transmitted after the previous data in the queue has been transmitted in the following frames.

IV. Analysis of Using Incremental Bandwidth Request Only

This section presents the case in which only incremental BRs are involved. As described before, if the amount of data accumulated in queue is more than T, an incremental BR will be sent.

Suppose X_{i-1} represents the amount of data arrived at frame i-1 (in terms of byte), where $1 \le i \le N$ and N is the total number of frames we analyzed. The condition for sending an incremental BR in frame i is:

$$Q_{i-1} + X_{i-1} - W_{i-1} > T_{i-1} \tag{3}$$

where Q_{i-1} is the data stored in queue before transmitting frame i-1, ($X_{i-1} - W_{i-1}$) represents the amount of data in frame i-1 that will be added to the queue, and T_{i-1} represents the threshold at frame i-1. From (2) and (3), we can derive:

$$X_{i-1} > \frac{D_{\max}}{D_f} W_{i-1} + W_{i-1} - Q_{i-1} = Y \tag{4}$$

So, we can derive the probability, P_I, of sending an incremental BR at frame i:

$$P_I(i) = \int_Y^{\lambda_{\max}} p(X) dX \tag{5}$$

where $p(X)$ is the probability of data arrival rate being X.

Suppose S is the set of frames with unicast polling opportunities. The expected value of the amount of requested bandwidth, W_{extra}, in frame i is:

$$W_{extra}(i) = \begin{cases} \int_Y^{\lambda_{\max}} f(X) dX + M_I & i \in S \\ \int_Y^{\lambda_{\max}} f(X) dX + M_p & i \notin S \end{cases} \tag{6}$$

where M_I and M_P are the size of stand-alone incremental BR messages and the size of piggyback subheaders, respectively, and $f(X)$ represents $(X\text{-}Y)p(X)$. Since the BS can support the bandwidth need of each connection until reaching R_{max}, the expected granted bandwidth in frame i+1, W_{i+1}, is $min\{W_i + W_{extra}(i), R_{max}\}$.

Moreover, the overhead, O_i, caused in frame i can be derived as follows:

$$O_i = \begin{cases} M_I P_I(i) & i \in S \\ M_P P_I(i) & i \notin S \end{cases} \tag{7}$$

Consequently, the total overhead, O_{total}, in N frames is

$$O_{total} = \sum_{i=1}^{N} O_i \tag{8}$$

The bandwidth utilization is an essential metric in measuring the performance of networks. Only when the data in queue is less than the granted bandwidth, will the bandwidth not be fully utilized. Consequently, we can get the following condition:

$$Q_{i-1} + X_{i-1} - W_{i-1} < W_i \tag{9}$$

We can rewrite (9) as:

$$X_{i-1} < W_i + W_{i-1} - Q_{i-1} = Z_i \tag{10}$$

The expected value of unused bandwidth in frame i, E_i, is equal to:

$$E_i = \int_0^{Z_i} (Z_i - X) p(X) dX \tag{11}$$

Thus, the bandwidth utilization in frame i, U_i, is

$$U_i = \frac{W_i - E_i}{W_i} \tag{12}$$

and the overall bandwidth utilization in N frames, denoted by U_I, is

$$U_I = \sum_{i=1}^{N} (W_i - E_i) \Big/ \sum_{i=1}^{N} W_i \tag{13}$$

V. ANALYSIS OF USING BOTH TYPES OF BANDWIDTH REQUEST

Next, we evaluate the case of using both incremental BRs and aggregate BRs. Note that according to the IEEE 802.16 standard, aggregate requests can only be transmitted via stand-alone messages. It can be done by using either (A) unicast polling opportunities or (B) *bandwidth stealing* (a term used in IEEE 802.16 standard) when there is enough unused bandwidth, but no polling opportunities.

A. In the Frames with Unicast Polling Opportunities

We first discuss the case of the frames with polling opportunities (i.e. frame i, $i \in$ S), which can be used to send aggregate BRs to release unused bandwidth. The unused bandwidth exists when the allocated bandwidth is greater than the actual required bandwidth:

$$Q_{i-1} + X_{i-1} - W_{i-1} < W_i \tag{14}$$

We can rewrite (14) as

$$X_{i-1} < W_i + W_{i-1} - Q_{i-1} = H_1 \tag{15}$$

The probability of sending an aggregate request in frame i is

$$\mathrm{P}_A(i) = \int_0^{H_1} p(X)dX \tag{16}$$

Therefore, the expected amount of bandwidth to be released is

$$W_{release}(i) = \int_0^{H_1} (H_1 - X)p(X)dX \tag{17}$$

B. In the Frames with Enough Unused Bandwidth

Next, we discuss the case of the frames without polling opportunities, i.e. frame $i \notin S$. The condition of sending aggregate requests is very similar to the one described in the previous case. However, since there is no extra bandwidth received from the BS, SSs will send an aggregate request via bandwidth stealing only if there is enough unused bandwidth left. We can conclude the condition as the following:

$$Q_{i-1} + X_{i-1} - W_{i-1} < W_i - M_A \tag{18}$$

where M_A indicates the message size of an aggregate request. Similarly, we can rewrite (18) to get

$$X_{i-1} < W_i + W_{i-1} - Q_{i-1} - M_A = H_2 \tag{19}$$

The probability of sending an aggregate request in frame i is

$$\mathrm{P}_A(i) = \int_0^{H_2} p(X)dX \tag{20}$$

The expected amount of bandwidth to be released by the aggregate request in frame i is:

$$W_{release}(i) = \int_0^{H_2} (H_2 - X)p(X)dX \tag{21}$$

By combining (5), (6), (16), (17), (20), and (21), we can derive the overall requested change of the reserved bandwidth, W_{change}, in frame i as:

$$W_{change}(i) = W_{extra}(i)\mathrm{P}_I(i) - W_{release}(i)\mathrm{P}_A(i) \tag{22}$$

Therefore, the reserved bandwidth in frame i+1 should be $min\{W_i + W_{change}(i), R_{max}\}$. The overall overhead for frame i, denoted as O_i, is:

$$O_i = \begin{cases} M_I \mathrm{P}_I(i) + M_A \mathrm{P}_A(i) & i \in S \\ M_P \mathrm{P}_I(i) + M_A \mathrm{P}_A(i) & i \notin S \end{cases} \tag{23}$$

The total overhead can be calculated using equation (8).

Finally, the bandwidth utilization in frame i can be calculated as equation (12), and the overall bandwidth utilization in N frames can be calculated as equation (13).

VI. ENHANCEMENT STRATEGIES FOR GIVEN TYPES OF TRAFFIC PATTERN

Although these two basic implementations of BRs support the general bandwidth needs of the SSs, they may not be efficient for two given types of traffic patterns, namely the uphill traffic pattern and the periodic/bursty traffic pattern.

The uphill traffic pattern is defined as a sequence of frames with monotonically increasing amount of data arriving at the SS, until a peak rate is reached. Common examples of the uphill traffic pattern include TCP's slow start mechanism, and P2P applications such as BitTorrent [9] in which the downloader becomes the seed for more peers as the downloading continues. The bandwidth needs of the uphill traffic pattern can be supported by using only incremental BRs because the bandwidth needs of the connection keep growing. However, according to the 802.16 standard, an SS only requests bandwidth for the data that has already arrived at the SS from users. That is, an SS will request bandwidth in the next frame for the data arriving in the current frame, and the BS will grant the requested bandwidth after the next frame. Obviously, there is latency between the frame during which the data arrived at the SS and the frame during which the data is actually transmitted. For the uphill traffic pattern in which the amount of data arriving in each frame keeps increasing, the SS will have to continuously send incremental BRs in every frame before the peak is reached, and all the data will suffer from the above latency.

The periodic/bursty traffic pattern is defined as a sequence of *on* frames during which new data arrives at the SS, followed by a sequence of *off* frames with no new data arriving, and the same cycle is repeated over and over again. If the number of consecutive *on* frames and the number of consecutive *off* frames are constant, we regard the pattern as *periodic*; examples include the network maintenance tasks and periodic reporting messages in sensor networks [7]. If the number of consecutive *on* frames and the number of consecutive *off* frames are dynamic, we regard the pattern as *bursty*; examples include VoIP and instant messaging applications. The bandwidth needs of the periodic/bursty traffic pattern can be supported by using both incremental BRs and aggregate BRs because the SS can release the unused bandwidth back to the BS during an *off* period, and request more bandwidth when the next *on* period comes. However, if the *off* period is not very long, for example only a few frames, then the SS will have to send another incremental BR to request bandwidth shortly after an aggregate BR was sent. In this case, the SS will keep sending the incremental BR and the aggregate BR in turn, and the data will suffer from the aforementioned latency.

A. Aggressive Strategy for Uphill Traffic Pattern

To address the uphill traffic pattern, we propose to use the aggressive strategy. If the SS knows that the amount of data arriving in the subsequent frames will increase monotonically, it can first calculate the normal amount of bandwidth to request using formulas (2) and (3), and apply the aggressive strategy to "aggressively" request α percent more bandwidth in advance than what it should request. Thus, if the amount of data arriving in the next frame is within α percent more than the amount of data arriving in the last frame, then the extra new data can be transmitted using the extra bandwidth requested in advance, without the need for the SS to issue another incremental BR and wait for the BS to grant the requested bandwidth. If the amount of data arriving in the next frame is more than α percent more than the amount of data arriving in the last frame, the SS can dynamically adapt α to handle the excessive data.

B. Conservative Strategy for Periodic/Bursty Traffic Pattern

To address the periodic/bursty traffic pattern, we propose to use the conservative strategy. If the SS knows that a specific connection is associated with an application which generates periodic/bursty traffic pattern, then when there is unused bandwidth in the connection, the SS will not send an aggregate BR right away, but instead the SS will "conservatively" hold the sending of aggregate BR for *k* frames, where *k* is a positive integer. If new data from the user arrives at the SS during these *k* frames, then there is no need to request for bandwidth because the previously granted bandwidth is still available, and the new data can be transmitted immediately in the next frame. If no new data arrives during the *k* frames, then the SS will send an aggregate BR to release the unused bandwidth to the BS.

There is a tradeoff about the selection of an appropriate *k*. On one hand, if *k* is defined too large, then the average bandwidth utilization will be lower. In fact, if *k* is larger than the length of any *off* period, then it is equivalent to the case of using incremental BRs only. On the other hand, if *k* is defined smaller than the length of any *off* period, then the unused bandwidth will still be released before the next data arrives, making the benefit of the conservative strategy limited.

VII. Simulation and Evaluation

To verify our analysis of the two basic implementations of BRs and evaluate our two enhancement strategies, we conduct various simulations using the Qualnet 4.5 network simulator.

A. Performance of Two Basic Implementations of BR

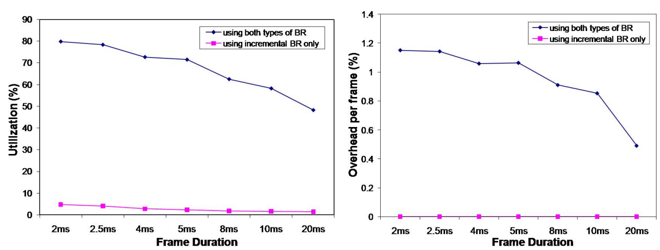
We first simulate the two basic implementations of BRs. The parameters used in our simulation environment are shown in Table I. Initially, the amount of bandwidth assigned to the connection is 0. Then, when data arrives at the SS, the SS starts to send the incremental BR to the BS. Following to the 802.16 standard, we set the size of one stand-alone incremental BR message (M_I) to be 19 bytes and the size of piggyback subheader (M_P) to be 6 bytes.

Figure 1(a) and 1(b) show the bandwidth utilization of two cases described before and the average percentage of overhead occupied in the received bandwidth per frame, respectively. From Figure 1(a), we can observe that the utilization in the case of using only incremental BRs is much lower than the case of using both types of BR, and the same situation happens in the overhead shown as Figure 1(b). We believe that the case of using only incremental BRs results in low bandwidth utilization because the amount of received bandwidth is never decreased even when SSs have no data to transmit. This also explains why the incremental BRs are rarely sent, because the SS retains all the granted bandwidth.

In the case of using both types of BRs, an aggregate BR is sent once the received bandwidth is more than the data in queue. Therefore, the overall utilization and overhead are much higher than the case of using incremental BRs only. Additionally, we can also get that both utilization and overhead in the case of using both types of BRs are related with the frame duration. We believe the reason is that SSs have more opportunities to adjust the received bandwidth in our simulation time.

TABLE I: PARAMETERS USED IN SIMULATION OF THE TWO BASIC IMPLEMENTATIONS OF BRS

Parameters	Values
Simulation time	30 sec
Channel frequency	2.4GHz
Traffic type	Variable bit rate
Mean packet arrival interval	500 ms
Interval distribution	Exponential distribution
Maximum tolerable delay	100 msec
Maximum packet size	1024 bytes
Packet size distribution	Poisson distribution
Modulation	OFDMA
Frame duration	2, 2.5, 4, 5, 6, 10, 20ms



(a) bandwidth utilization (b) overhead per frame

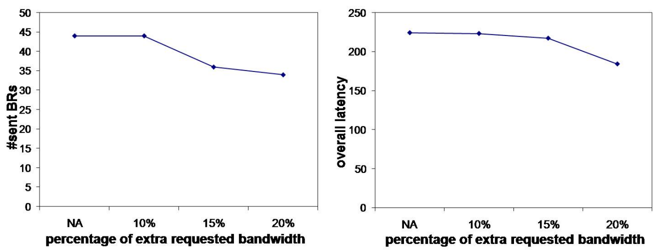
Figure 1: Simulation results of the two types of BR implementation.

B. Performance of the Aggressive Strategy

Next, we use simulations to show the inadequacy of the two basic implementations of BRs when facing the uphill traffic pattern and the periodic/bursty pattern, and evaluate the performance of the two enhancement strategies.

The simulation for the aggressive strategy goes as follows. The simulated traffic pattern starts with 512 bytes of data arriving in the first frame. For every subsequent frame, the amount of arriving data increases by 10% until reaching the maximum of 4096 bytes. This traffic pattern lasts for a total of 50 frames. We test the aggressive strategy by requesting extra 10%, 15%, and 20% more bandwidth, respectively, than what should normally be requested according to formulas (2) and (3). For contrast purpose, we also run one simulation which uses the original method in the 802.16 standard, i.e. normal incremental BRs without requesting for extra bandwidth.

Figure 2 shows the results of our simulation on the aggressive strategy. In this simulation, we consider the overhead as the total number of sent incremental BRs. The overall latency is computed as follows: first, the latency of each frame of data is calculated as the difference between the index of the frame when the data is actually transmitted and the index of the frame when the data arrived at the SS. Then, the overall latency is computed as the sum of the latency of each frame of data. From Figure 2(a), we can see that when the original method in the 802.16 standard is used (denoted as NA), the total number of sent incremental BRs is 44. When



(a) overhead (b) latency

Figure 2: Simulation results of the aggressive strategy.

10% extra bandwidth is requested in the incremental BRs, the total number of sent BRs is still the same. However, when 15% or more extra bandwidth is requested in the incremental BRs, the total number of sent BRs starts to drop. When 20% extra bandwidth is requested in the incremental BRs, the total number of sent BRs drops by about 25%. The result of overall latency, as shown in Figure 2(b), is consistent with Figure 2(a), which drops by about 25% when 20% extra bandwidth is requested in the incremental BRs. This is because when extra bandwidth is requested in advance, it can be readily used to transmit the excessive data arriving in the next frame, thus reducing the number of incremental BRs and the latency of transmitting the newly arrived data.

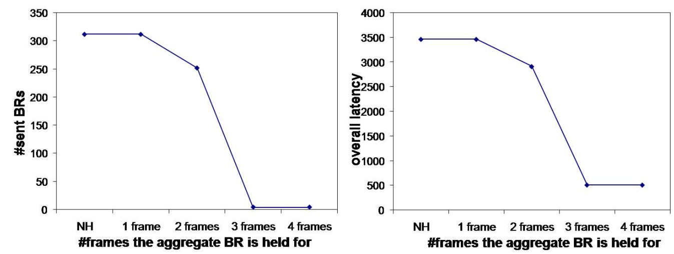
One point worth noting is that in this set of simulation, all the granted bandwidth that was aggressively requested is used, because the amount of arriving data in each subsequent frame keeps increasing. Therefore, when the aggressive strategy is applied, the bandwidth utilization remains 100%.

C. Performance of the Conservative Strategy

The simulation for the conservative strategy goes as follows. The simulated traffic pattern is 4 consecutive *on* frames, with 512 bytes of data arriving in each *on* frame, followed by 4 consecutive *off* frames, in which no data arrives. This traffic pattern is repeated for a total of 1248 frames. We test the conservative strategy by holding a to-be-sent aggregate BR for 1 frame, 2 frames, 3 frames, and 4 frames, respectively. For contrast purpose, we also run the simulation for the case of sending the aggregate BRs without holding.

Figure 3 shows the results of the conservative strategy. The overhead and overall latency are computed the same way as in Figure 2. From Figure 3(a), we can see that when the original method in the 802.16 standard is used (denoted as NH), the total number of sent BRs (including both incremental BRs and aggregate BRs) is 312. When the aggregate BR is held for 1 frame, the total number of sent BRs is still 312, because the *off* period is 4 frames and holding the aggregate BR for only 1 frame cannot catch the next *on* period. When the aggregate BR is held for 2 frames, the total number of sent BRs starts to drop. When the aggregate BR is held for 3 frames or more, we can see that the total number of sent BRs drops sharply to 4. Indeed, the 4 sent BRs are all incremental BRs sent in the beginning, and no aggregate BR is sent afterward because the conservative strategy bridges the *off* period gap between two *on* periods. The result of overall latency, as shown in Figure 3(b), is consistent with Figure 3(a), which drops sharply when the aggregate BR is held for more than 2 frames.

We also measure the bandwidth utilization when the conservative strategy is used. When the aggregate BR is not held, the bandwidth utilization is around 92%. When the aggregate BR is held for 1, 2, 3, and 4 frames, the bandwidth



(a) overhead (b) latency

Figure 3: Simulation results of the conservative strategy.

utilization drops a little to 87%, 83%, 73%, and 73%, respectively. Compared to the sharp drop in the overhead and overall latency, the benefit of the conservative strategy is apparent if the BS has some spare bandwidth to use.

VIII. Concluding Remarks

In this paper, we addressed the bandwidth request strategies for IEEE 802.16 networks. We first presented a model that analyzes the overhead, bandwidth utilization, and data waiting time in the queue, and showed that the two basic implementations of bandwidth requests in the IEEE 802.16 standard have room for improvement when facing an uphill traffic pattern and a bursty periodic traffic pattern, in terms of the overhead and the data waiting time. Then, we proposed two enhancement strategies that are designed according to the nature of these two traffic patterns to improve the performance. The simulation results show that these two strategies can effectively reduce the overhead and data waiting time at the price of somewhat less bandwidth utilization in the case of conservative strategy. Therefore, when the BS has spare capacity, the two strategies are beneficial to the performance of the network.

In our future work, we will explore further how to design adaptive bandwidth request strategy for other common traffic patterns, and investigate the relationship and interaction between the SS's bandwidth request strategies and the BS's bandwidth allocation strategies.

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