Recycling of Bandwidth in Metropolitan Area Networks(MAN)

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1. Abstract

In case of variable bite rate application, the subscriber station requires bandwidth for downlink and uplink of data transmission. As subscriber station cant estimate how much data it wants and to ensure the QOS guaranteed services, It may reserve more bandwidth than its demand. As a result, the reserved bandwidth may not be fully utilized all the time. Hence there is a wastage of bandwidth. This paper consists of a scheme named as 'Bandwidth Recycling', to recycle the unused bandwidth without changing the existing bandwidth reservation. In this scheme the subscriber station will used the available unused bandwidth. By this system throughput can also increase while maintain the same quality of services. In this scheme we use mathematical analysis and simulation. And this results in the scheme can recycle 35% of unused bandwidth on average. The extension for this project can also be showed by the three scheduling algorithms. Thus the simulation results to improve overall throughput by 40% in a steady network.

Index terms**:- **IEEE 802.16 standards, QOS

1. Introduction

The worldwide interoperability for microwave Access (Wimax) which is based on IEEE 802.16 standard, is designed to facilitate services with high transmission rate for data and multimedia application in metropolitan areas. The physical (PHY) and Medium Access Control (MAC) layers of WIMAX have been specified in the IEEE 802.16 standards. Many advanced communication technologies such as Orthogonal Frequency Division Multiple Access(OFDMA) and Multiple-input & Multiple-output(MIMO) are also present in the standard. Supported by these modern technologies, WIMAX is able to provide a large services coverage, high data rates & QOS guaranteed services. Because of these features WIMAX is considered as a promising alternative for last mile broadband wireless access (BWA).

In order to provide QOS guaranteed services, the subscriber statics (ss) has to reserve necessary bandwidth from the base station(ss) has to reserve necessary bandwidth from the base station(BS) before any data transmission. In order to serve variable bit rate(VBR) applications, the SS tends to keep the reserve bandwidth to maintain the QOS guaranteed

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services. AS a result, the reserved bandwidth transmission data may be more than the amount of transmission data and the reserved bandwidth may not be fully utilized all the times. Although the amount of reserved bandwidth is adjustable via. Making bandwidth request(BR), the adjusted bandwidth is applicable to the next coming frame because of this the unused bandwidth in the current frame has no change to be utilize.

It is very difficult to adjust the amount of reserved bandwidth. Thus the SS may be exposed to the risk of degrading the QOS. To improve the bandwidth utilization while maintaining the same QOS guaranteed services, our research objective is two fold:

1. The existing bandwidth reservation is not changed to maintain the same QOS guaranteed services.2. Our research work focuses on increasing the bandwidth utilization by utilizing the unused bandwidth.

The concept in our scheme, "Recycling the bandwidth in the current frame" is that the remaining SSs other than the transmitting station will get a chance to utilize the bandwidth which remained unused. The unused bandwidth is not supposed to occur regularly, our scheme allow SSs with non-real time applications, which have more flexibility of delay requirements to recycle the unused bandwidth. Thus, our objective is clear that the maximum throughput with the unchanged QoS.

IEEE 802.16 standard says that each SS in order to transmit data in the current frame, has to be scheduled on the Uplink map. We called SSs as the TSS(Transmission SSs) in this paper. Later it is the work of the BS to schedule a SS to each TS, so that the unused bandwidth of the TS is utilized by the backup SS. So, we call the backup SS as the complementary station (ss).

In the IEEE 802.16 standard, BR's are made in pre-connection basis. The BS allocates bandwidth in per SS basic. It gives the SS flexibility to allocate the granted bandwidth to each connection locally. Therefore, the unused bandwidth is defined as the granted bandwidth which is still available after serving all connections running on the SS. The TS informs the CS about the unutilized bandwidth through a special message called Releasing message(RM). However, because of the variety of the geographical distance between TS and CS and the transmission power of the TS, the CS may not receive the RM. Our theoretical analysis shows that this probability is least 42% which is confirmed by our simulation. But still there are some factors that may effect this scheme:

1. The CS cannot receive the RM
2. The CS does not have non-real time data to transmit while receiving a RM.

To mitigate those factors, additional scheduling algorithms are proposed algorithm further improve the average throughput by 4% in a steady N/W.

3. Background Information

IEEE 802.16 is written by a working group established by IEEE Standards Board in 1999 to develop standards for the global deployment of broadband 'Wireless Metropolitan Area Networks'. Then although the 802.16 family of standards is officially called wireless MAN in IEEE, it has been commercialized under the name "WIMAX".

In the IEEE 802.16 standard the physical (PHY) and Medium Access Control (MAC) layers of wimax have been specified. AND in this three types of transmission mediums supported as the physical layer (PHY). They are single channel (SC) i.e., Using single signal at a given frequency and bandwidth, Orthogonal Frequency-Division Multiplexing (OFDM) i.e., it is essentially identical to coded OFDM (COFDM) and it is a frequency division multiplexing (FDM) scheme utilized as a digital multi –carrier modulation method orthogonal frequency-division multiple access (OFDMA) is a multi user version of the popular orthogonal frequency-division multiplexing (OFDM) digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users. Hence OFDMA assume as the PHY in our analytical model since it is employed to support mobility in IEEE 802.16e standard (the true mobile wimax standard of 802.16e is divergent from fixed wimax) and the scheme working in this should also work in others. Various types of modulations supported by OFDMA is BSPK (binary phase shift keying modulation) QPSK (quadrature phase shift keying modulation), 16-QAM (quadrature amplitude modulation) 64-QAM.

Here focused on point to multi point(PMP) made in which the ss will not allow to communicate with another ss but the bs directly. Depending on the transmission direction, bs and ss communication classified into downlink(DL) and uplink(UL) transmissions. Hence the former transmission is BS TO SS. Conversely SS to BS.

As IEEE 802.16 supports two types of transmission modes. Both UL and DL transmissions can not be operated simultaneously in time division duplex(TDD) but it can in frequency division duplex (FDD) mode. In this paper we focused on the TDD mode. BS is responsible for scheduling both UL and DL transmissions in wimax. All these behavior is expreddes in a MAC frame.

In IEEE 802.16 standard the structure of a MAC frame contains two parts, UL and DL subframe for UL transmissions and DL transmissions respectively. In this IEEE 802.16 networks is coordinated by the BS. All the required details including burst profiles and offsets is in the DL and UL maps, which are broadcasted at the beginning of a MAC frame. This is a connection-oriented. It gives the advantage of having better control over network resource to provide QOS guaranteed services. It support wide variety of applications, the IEEE 802.16 standard classifies traffic into five scheduling classes : Unsolicited Grant Service(UGS) i.e., is a service flow in which the transmission system automatically and periodically provides a defines number of timeslots and fixed packet size that is used by a particular receiver., Real Time Polling Service(rtPS) i.e., It is designed to support real-time service flows that generate variable size data packets on a periodic basis, such as MPEG video,, Non-Real Time Polling service(ntrPS) i.e., It is designed to support non –real time service flows that require variable size Data Grant Burst Types on a regular basis, such ashigh bandwidth FTP(File Transfer Protocol), Best Effort(BE), Extended Real Time Polling Service(ertPS) i.e., it is a scheduling mechanism that builds on the efficiency of both UGS and rtps. It is designed for realtime traffic with variable data rate over the WIMAX. Each application is classified inti one of the scheduling classes and establish a connection with the BS based on its scheduling class. The BS assigns a connection ID(CID) to each connection. The bandwidth reservation is made based on the CID via sending a BR when receiving a BR, the BS can either grant or reject the BR depending on its available resourse and scheduling polices.

SS may request bandwidth using two different types of BRs: incremental BR and Aggregate BR. The former allow the SS to indicate the extra bandwidth required for a connection. SS uses aggregate BR to specify about its connection. The BS resets its perception of that service's needs upon receiving the request. Consequently, the reserved bandwidth may be decreased.

4. Motivation And Related Work

In order to provide QOS guaranteed services, the subscriber statics (ss) has to reserve necessary bandwidth from the base station(ss) before any data transmission. Sometimes the SS may reserve more bandwidth after all the SS cannot predict the correct bandwidth all the time. As a result, the reserved bandwidth transmission data may be more than the amount of transmission data and the reserved bandwidth may not be fully utilized all the times. Ofcourse the Bandwidth Request (BR) can be used to adjust the bandwidth. But it is applicable to the next coming frame. Because of this the unused bandwidth in the current frame cannot be utilized properly.

5. Proposed Scheme

The objectives of our research are twofold:

1) The same QoS guaranteed services are provided by maintaining the existing bandwidth reservation.

2) the bandwidth utilization is improved by recycling the unused bandwidth.

To reach these objectives, our scheme named Bandwidth Recycling is proposed. The main idea is to allow the BS to pre-assign a CS for each TS at the beginning of a frame. The CS waits for its time(the possible opportunities) to recycle the unused bandwidth of its corresponding TS in this frame. The CS information scheduled by the BS is resided in a list, called complementary list (CL). The CL includes the mapping relation between each pair of pre-assigned CS and TS. Each CS is mapped to at least one TS. The CL is broadcasted followed by the UL map. To reach the backward compatibility, a broadcast CID (B-CID) is attached in front of the CL. Moreover, a stuff byte value (SBV) is transmitted followed by the B-CID to distinguish the CL from other broadcast DL transmission intervals.

The UL map including burst profiles and offsets of each TS is received by all SSs within the network. Thus, if a SS is on both UL map and CL, the necessary UL MAP and CL, the necessary information (e.g., burst profile) residing in the CL may be reduced to the mapping information between the CS and its corresponding TS. The BS only specifies the burst profiles for the SSs which are only scheduled on the CL. For example, CSj is scheduled as the corresponding CS of TSj , where $1 \leq j \leq k$. When TSj has unused bandwidth, it performs our protocol introduced in Section protocol. If CSj receives the message sent from TSj , it starts to transmit data by using the agreed burst profile. The burst profile of a CS is resided on either the UL map if the CS is also scheduled on the UL map or the CL if the CS is only scheduled on CL. Our proposed scheme is presented into two parts: the protocol and the scheduling algorithm. The protocol describes how the TS identifies the unused bandwidth and informs recycling opportunities to its corresponding CS.

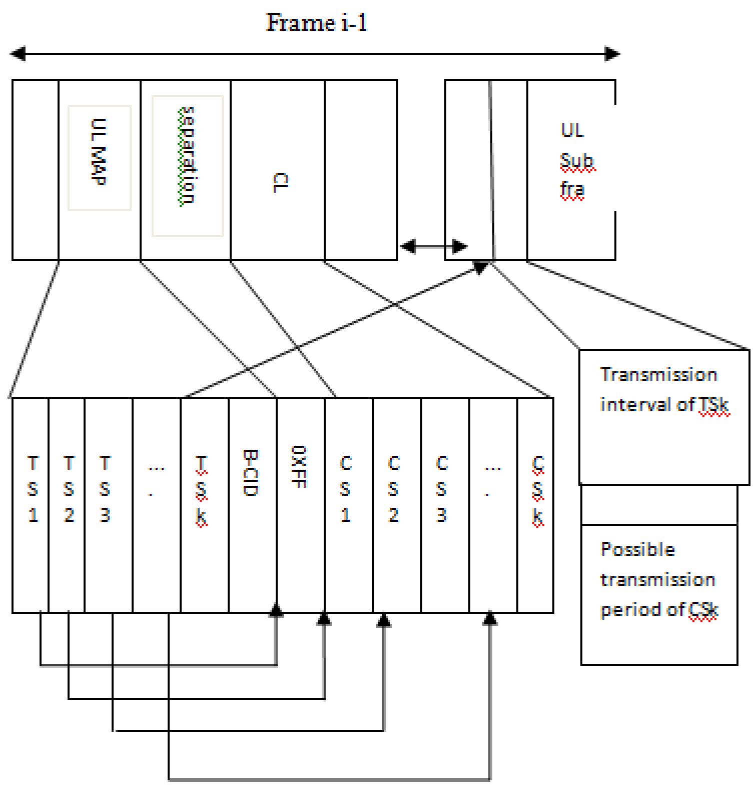

Figure 1. The Mapping relation between CSs and TSs in aMAC Frame

5.1 Protocol

IEEE 802.16 standard specifies that the unused reserved bandwidth has to be recognized with some value. For this we use a padding value called stuff byte value(SBV) i.e., 0xFF. If the size of the unused region is at least the size of a MAC header, the entire unused region is initialized as a MAC PDU. The padding CID is used in the CID field of the MAC PDU header. In this research, we intend to recycle the unused space for data transmissions. Instead of padding all portion of the unused bandwidth in our scheme, a TS with unused bandwidth transmits only a SBV and a RM. The SBV is used to inform the BS that no more data are coming from the TS. On the other hand, the RM comprises a generic MAC PDU with no payload. The mapping information between CL and UL map is based on the basic CID of each SS. The CID field in RM should be filled by the basic CID of the TS. The transmission range of the TS should be large enough so that the corresponding CS will receive the RM. To maximize the transmission coverage of the RM, one possible solution is to increase the transmission power of the TS while transmitting the RM. However,

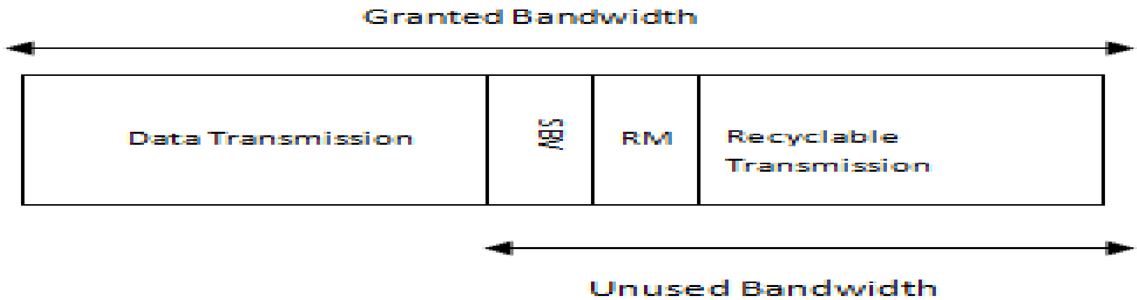

Figure 2. Messages to release the unused bandwidth within a UL transmission interval.

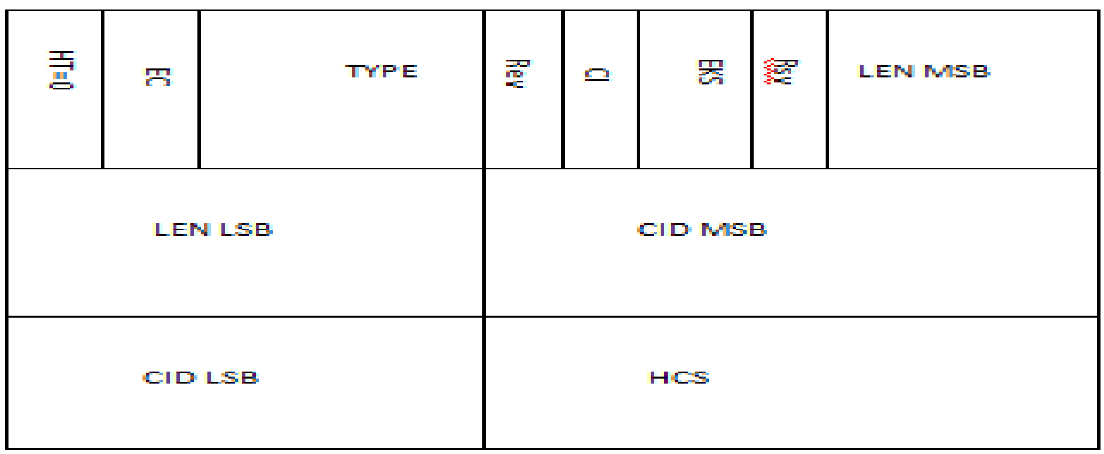

Figure 4. The format of RM.

the power may be a critical resource for the TS and should not be increased dramatically. Therefore, under the circumstance of without increasing the transmission power of the TS, the RM should be transmitted via BPSK which has the largest coverage among all modulations supported in the IEEE 802.16 standard. For example, illustrates the physical location of the BS, TS and CS, respectively. The solid circle represents the coverage of QPSK which is the modulation for data transmissions between BS and TS. The TS informs the BS that it has no more data to be sent by transmitting the SBV using the QPSK modulation. It is easy to observe that the corresponding CS is out of QPSK coverage. In order to maximize the coverage of the RM under the circumstance of without increasing the transmission power of the TS, the TS transmits the RM via BPSK which coverage is represented by the dished circle. The radius of the dished circle is *KL*, where *L* is the distance between TS and BS and *K* is the ratio of transmission range of BPSK to the transmission range of QPSK depending on the transmission power. Assume all channels are in good condition. As long as the CS is within the coverage of BPSK, it can receive the RM successfully and start to recycle the unused bandwidth. Since both UL map and CL can be received by the CS, the CS knows the UL transmission period of its corresponding TS. This period is called the UL transmission interval. The CS monitors this interval to see if a RM. An example of corresponding locations of

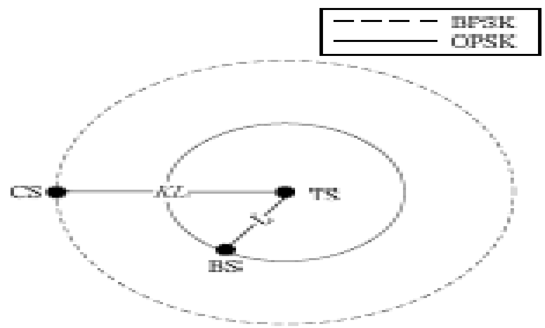

Fig.4.An example of corresponding locations of TS,BS and CS.

TS, BSand CS is received from its corresponding TS. Once received, the CS starts to recycle the unused bandwidth by using the burst profile residing in either UL map or CL , until using up the rest of the TS's transmission interval. If the CS does not have any data to transmit, it simply pads the rest of the transmission interval.

5.2. Scheduling Alogithm

Let us consider *Q* represents the set of SSs serving non-real time connections like nrtPS or BE connections and *T* is the set of TSs. As this scheme follows TDD , the UL and DL operations cannot be performed simultaneously, we cannot schedule the SS which UL transmission interval is overlapped with the target TS. For any TS, *St*, let *Ot* be the set of SSs which UL transmission interval overlaps with that of *St* in *Q*. Thus, the possible corresponding CS of *St* must be in $Q-Ot$. All SSs in $Q-Ot$ are considered as candidates of the CS for *St*. This scheduling algorithm, called *Priority-based Scheduling Algorithm* (PSA), is used to schedule a SS with the highest priority as the CS. The priority of each candidate is decided based on the scheduling factor (SF) defined as the ratio of the current requested bandwidth (CR) to the current granted bandwidth (CG). The SS with higher SF has more demand on the bandwidth. Hence, we give the higher priority to those SSs. The highest priority is given to the SSs with zero CG. Non-real time connections include nrtPS and BE connections. The nrtPS connections should have higher priority than the BE connections because of the QoS requirements. The priority of candidates of CSs is concluded from high to low as: nrtPS with zero CG, BE with zero CG, nrtPS with non-zero CG and BE with non-zero CG. If there are more than one SS with the highest priority, we select one with the largest CR as the CS in order to decrease the probability of overflow.

Algorithm 1 Priority-based Scheduling Algorithm

Input: T is the set of TSs scheduling on the ULmap
Q is the set of SSs running non-real time
Applications.

Output: Schedule CSs for all TSs in T.

For i=1 to ||T|| do

a. $S_t \leftarrow TSi$.
b. $Q_t \leftarrow Q\text{-}O_t$.
c. Calculate the SF for each SS In Q_t.
d. **If** Any SS $\in Q_t$ has zero granted bandwidth,
   If Any SSs have nrtPS traffics and zero granted bandwidth,
   Choose one running nrtPS traffics with the largest CR.
   Else
   Choose one with the largest CR.
   Else
   Choose one with largest SF and CR.
e. Schedule the SS as the corresponding CS of S_t.

End For

6. Analysis

The presence of percentage of potentially unused bandwidth occupied in the reserved bandwidth is critical for the potential performance gain of our scheme. we investigate this percentage on VBR traffics which is popularly used today. In order to that, in our scheme, each TS should transmit a RM to inform its corresponding CS when it has unused bandwidth. However, the transmission range of the TS may not be able to cover the corresponding CS. It depends on the location and the transmission power of the TS. There is chance that CS does not receive the RM, thus results in failure of utilizing unused unused bandwidth. So, the benefit of our scheme is reduced. In this section, we analyze mathematically the probability of a CS to receive a RM successfully. As a result probability affects the bandwidth recycling rate (BBR).BBR stands for the percentage of the unused bandwidth which is recycled. Moreover, the performance analysis is presented in terms of throughput gain (TG). At the end, we evaluate the performance of our scheme under different traffic load. All analytical results are validated by the simulation.

6.1 The Probability of RMs received by the corresponding CSs Successfully:

Let us assume a BS resides at the center of a geographical area. There are n SSs uniformly distributed in the coverage area of the BS. Since PMP mode is considered, the transmissions only exits between BS and SSs. Moreover, each SS may be in different locations. The transmission rate of each SS may be variant depending on the PHY transmission technology and transmission power. For a given SS, S_t ,let $R_t^{(B)}$,$R_t^{(Q)}$,$R_t^{(16)}$ and $R_t^{(16)}$ denote as the transmission range of BPSK,QPSK,16-QAM and 64-QAM,respectively. In our scheme, the RM should be transmitted via the most robust modulation. Since it has the largest coverage of RMs among all modulations supported by the IEEE 802.16 standard without adjusting the transmission power. Based on the fixed transmission power, the relation of transmission range between modulations is expressed as:

$$\mathbf{R_t^{(B)} = K_t^{(Q)} R_t^{(Q)} = K_t^{(16)} R_t^{(16)} = K_t^{(64)} R_t^{(64)}}$$

Where $K_t^{(Q)}$, $K_t^{(16)}$ and $K_t^{(64)}$ are constants depending on the transmission power of S_t and $K_t^{(64)} \geq K_t^{(16)} \geq K_t^{(Q)} \geq 1$. Then again the RM should be transmitted via BPSK. In the rest of the paper, we use R_t to represent the BPSK transmission range of S_t. Moreover, S_B and R are denoted the BS and its transmission range of BPSK, respectively.

Depending on the distance between them and the modulation used for communications. In our scheme, we do not intend to change the transmission power. Therefore, the RM should be transmitted via BPSK to maximize the transmission coverage of the RM may not be able to cover the whole servies area of S_B. Consequently, the CS may not able to receive the RM. And the location therefore, we must analyze the probability that a CS receives a RM from its corresponding TS successfully. We can analyze the probability that a CS receives a RM from its corresponding TS successfully. We can analyze the average value of this probability.

Transmission Station S_t, suppose S_j is denoted as the CS of S_t. The relation between S_t and S_B can be classified into two categories based on the location of S_t.

The Coverage of $S_t$is within the coverage of S_B:-

In this category, the coverage of S_t, denoted as A_{in}, can be derived as:

$$A_{in} = \pi R_t^2$$

The probability of S_j receiving a RM denoted as $P_c^{(t)}$ is the same as the ratio of coverage of S_t to S_B.

$$P_c(t) = R_t^2 / R^2$$

Moreover, the coverage of the two stations must intersect on no more than one point.

Suppose L represents the distance b/w S_t & S_B.

The condition here is

$$L \leq R - R_t$$

Because R_t represents the basic transmission range of S_t, we can have:

$$R_t = K L$$

Where K is a constant depending on the transmission power and modulation that S_t uses to communicate with S_B.

Thus

$$L \leq R / (K+1)$$

The probability of S_t within this category is

$$P_{oe}(t) = K^2 / (1+K^2)$$

The probability is S_j to receive a RM from S_t is concluded as:

Mean $\mathbf{P_t(t)=P_c(t).P_{oc}(t)}$

Consequently, in average, the probability of a CS to receive the RM from its corresponding TS is derived as

$$P_t = \frac{\sum_{t=1}^{\|T\|} P_t(t)}{\|T\|}$$

Where ,T is the set of all TSs.

6.2. Performance Analysis:

Assume Qn represents a set of SSs running non-real time connections and Q_{cl} is a set of SSs in Q_n scheduling as CSs. Q_{cl} is atmost T, where T is the set of all TSs.

For any SS, Sn Є Q_n, the probability of S_n Scheduling on the CL,$P_{cl}(n)$ is derived as

$$P_{CL}(n) = \begin{cases} \frac{\|Q_{CL}\|}{\|Q_n\|} & ||Q_n|| \geq ||Q_{CL}|| \\ 1 & \text{Otherwise} \end{cases}$$

It is possible that the CS fails to recycle the unused bandwidth due to the lack of no-real time data to be transmitted.

Suppose $Y_{i-1}$is amount of data in frames i-1.The probalility of CS, denoted as S_u, which has data to recycle the unused Bandwidth can be obtained as:

$$P_u(u) = \int_{Y_{i-1}}^{\lambda_{\max}^{nrt}} P(X)\,dX$$

Where λ^{nrt}_{max} is the maximal amount of non-real time data arriving in a frame.
we calculate the probability as

$$Pr = \frac{\sum_{j=1}^{\|Q_n\|} P_u(j) P_{CL}(j)}{\|Q_n\|}$$

We find the probability that unused bandwidth is recycled is

$$\mathbf{P_{recycle} = P_r\, P_t}$$

We find the throughput rain as

$$\mathbf{T_G = \frac{P_{recycle}\, B_W}{B_g - B_W}}$$

B_W -> *unused bandwidth*
B_G -> *Total bandwidth of the system.*

7. SIMULATION RESULTS

In this section, we first present our simulation model followed by introducing the definition of performance metrics used for measuring the network performance. The simulation results are shown as the third part of this section. At the end, we provide the validation of theoretical analysis and simulation results.

7.1 Simulation Model

In our model we comprises one BS residing at the center of geographical area and 50 SSs uniformly distributed in the service coverage of BS. The parameters of PHY and MAC layers used in the simulation are summarized in Table 1. PMP mode is employed in our model. Since our proposed scheme is used to recycle the unused bandwidth in UL subframe, the simulation only focuses on the performance of UL transmissions.

Parameters	Value
Node number	51(including BS)
Frame duration	20MS
UL/DL subframe duration	10MS
Modulation scheme	BPSK,QPSK,16QAM,64QAM
DCD/UCD broadcast interval	5s
TTG/RTG	10US
SS transition gap(SSTG)	4US

Table 1:The system parameters used in our simulation

CBR is a typical traffic type used to measure the performance of networks in WiMAX research. However, it may not be able to represent the network traffic existing in real life. Moreover, the IEEE 802.16 network aims to serve both data and multi-media applications. Most of these modern streaming videos are encoded by industrial standards (e.g., H.264 or MPEG 4) which generate data in variant rates. In this research, we include VBR traffics to illustrate H.264 and MPEG 4-encoded videos. In our simulation, the traffic models for these streaming videos are based on related research [12] [13] [14]. Additionally, other commonly used VBR traffics such as HTTP and FTP applications are also included in our simulation. The characteristics of traffic types are summarized in Table2.

In our simulation, each SS serves at least one and up to 5 connections. Each connection serves one type of traffic which is mapped to the scheduling classes supported in the IEEE 802.16 standards (i.e., UGS, rtPS, ertPS, nrtPS and BE). Table 2 enumerates all types of traffic and their corresponding scheduling classes used in our simulation. In particular, all VBR traffic in our simulation is considered as ON/OFF traffic. We fix the mean data rate of each application but make the mean packet size randomly selected from 512 to 1024 bytes. Thus, the mean packet arrive rate can be determined based on the corresponding mean packet size. As mentioned earlier, the size of each packet is modeled as Poisson distribution and the packet arrival rate is modeled as exponential distribution. For example, in order to simulate the network traffics more realistically, the start time of each connection is randomly selected from

0 to 15th second. Moreover, the real time connection stops to generate data from 75th to 100th second. It is for investigating the performance of our scheme when the large amount of unused bandwidth is available. Therefore, the number of active connections (the connections which are transmitting data) may be different during the simulation.

Application	VoIP	Multimedia	HTTP	FTP
Traffic type	CBR	VBR	VBR	VBR
Scheduling class	UGS	rtPS	BE	nrtPS
Start Time(sec.)	m*	m*	m*	m*
End Time(sec.)	n*	n*	100	100
Mean Packet Size	512	Z*	Z*	Z*
Mean Bit Rate	122kbps	2Mbps	2Mbps	50Mbps
Max burst Size(Bytes)	31	7.5k	10	1500k
Packet Size	Fixed	P*	P*	P*
Packet Arrival Rate	Fixed	E*	E*	E*
Note: m * is a random number between 0 and 15. n * is a random number between 75 and 100. Z* is a random number between 512 and 1024 bytes. P* stands for Poisson distribution E* stands for Exponential distribution.				

TABLE 2
The traffic model used in the simulation

7.2 The Performance Metrics

The simulation for evaluating the performance of the proposed scheme is based on the three metrics:

1) *Throughput gain (TG):*

It represents the percentage of throughput which is improved by implementing our scheme. The formal definition can be expressed as*:*

$$TG = \frac{T_{recycle} - T_{No\_recycle}}{T_{No\_recycle}}$$

where $T_{recycle}$ and $T_{no\text{-}recycle}$ represent the throughput with and without implementing our scheme, respectively. The higher TG achieved shows the higher performance that our scheme can make.

2) *Unused bandwidth rate (UBR):*

It is defined as the percentage of the unused bandwidth occupied in the total granted bandwidth in the system without using bandwidth recycling. It
can be defined formally as:

$$UBR = \frac{B_{unused\_bw}}{B_{total\_bw}}$$

where B_{unused_bw} and B_{total_bw} are the unused bandwidth and total allocated bandwidth, respectively. The UBR shows the room which can be improved by our scheme. The higher UBR means the more recycling opportunities.

3) *Bandwidth recycling rate (BRR):*

It illustrates the percentage of bandwidth which is recycled from the unused bandwidth. The percentage can be demonstrated formally as:

$$BRR = \frac{B_{recycled}}{B_{unused\_bw}}$$

where $B_{recycled}$ is the bandwidth recycled from B_{unused_bw}. BRR is considered as the most critical metric since it directly reveals the effectiveness of our scheme.

7.3 Simulation Results

Figure 4 presents the percentage of the unused bandwidth in our simulation traffic model (i.e., UBR). It shows the room of improvement by implementing our scheme. From the simulation results, we conclude that the average UBR is around 38%. In the beginning, the UBR goes down. It is because each connection still requests bandwidth from the BS. As time goes on, the UBR starts to increase when the connection has received the requested bandwidth. After 75th second of simulation time, UBR increases dramatically due to the inactivity of real time connections. The purpose to have inactive real time connections is to simulate a network with large amount of unused bandwidth and evaluate the improvement of the proposed scheme in such network status. The evaluation is presented in the later of this section.

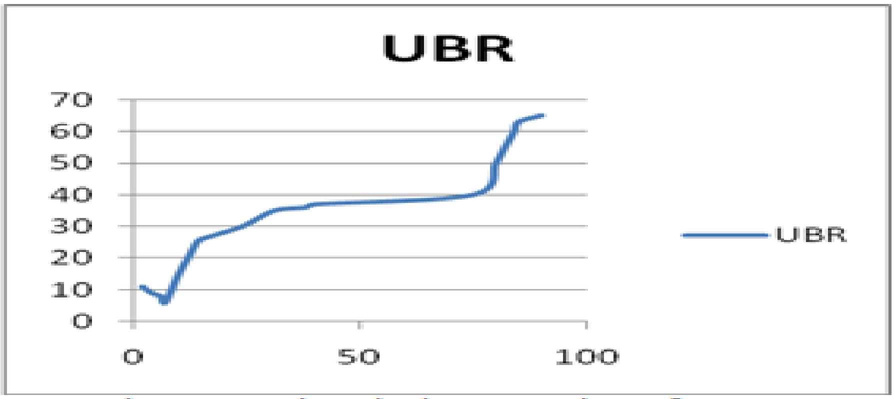

Figure 4. Simulation results of UBR

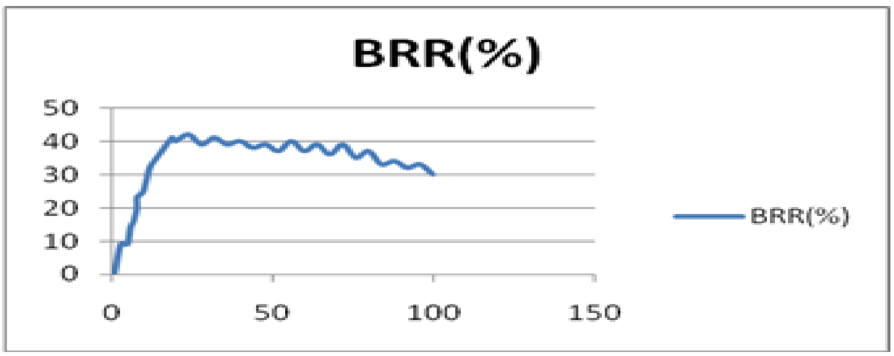

Figure 5. Simulation results of BRR

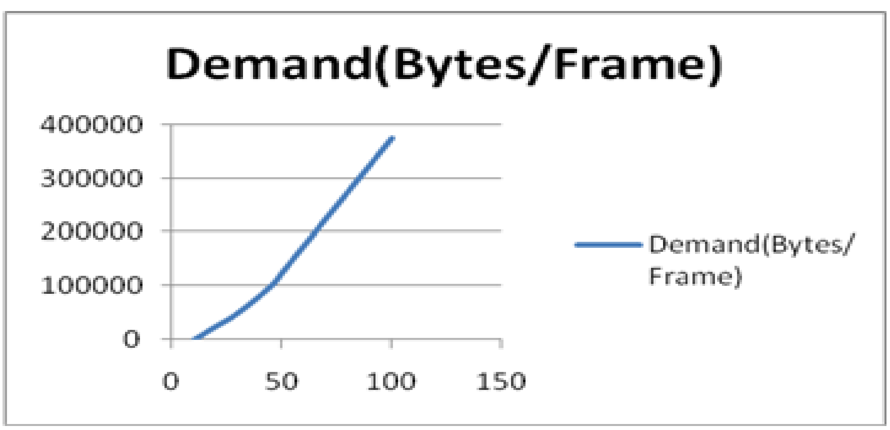

Figure 6. Total Bandwidth Demand

The simulation results of recycling rate are presented in Figure 6. From the figure, we observe that the recycling rate is very close to zero at the beginning of the simulation. It is because that only a few connections transmit data during that time and the network has a light load.

Therefore, only few connections need to recycle the unused bandwidth from others. As time goes on, many active connections join in the network. The available bandwidth may not be able to satisfy the needs of connections. Therefore, there is a high probability that the CS recycles the unused bandwidth. It leads a higher BRR. Fig. 10 shows the total bandwidth demand requestedby SSs during the simulation. In the figure, the dashed line indicates the system bandwidth capacity. During the simulation, the BS always allocates the bandwidth to satisfy the demand of real time connections due to the QoS requirement. Therefore, the amount of bandwidth allocated to non-real time connections may be shrunk. At the same time, the new non-real time data are generated. Therefore, the non-real time data are accumulated in the queue. It is the reason that the demand of bandwidth keeps increasing.

8. Further Enhancement

As our investigation, one of the factors causing recycling failures is that the CS does not have data to transmit while receiving a RM. To alleviate this factor, we propose to schedule SSs which have rejected BRs in the last frame because it can ensure that the SS scheduled as CS has data to recycle the unused bandwidth. This scheduling algorithm is called Rejected Bandwidth Requests First Algorithm (RBRFA). It is worth to notice that the RBRFA is only suitable to heavily loaded networks with rejected BRs sent from non-real time connections (i.e., nrtPS or BE). Notice that only rejected BRs sent in the last frame are considered in the RBRFA for scheduling the current frame. The RBRFA is summarized in Algorithm

The BS grants or rejects BRs based on its available resource and scheduling policy. In RBRFA, if the BS grants partially amount of bandwidth requested by a BR, then this BR is also considered as a rejected BR. Similar to Algorithm 1, Ot represents the set of SSs which transmission period overlaps with the TS, St, in QR. All SSs in Qt are considered as possible CSs of St. A rejected BR shows that the SS must have extra data to be transmitted in the next

Algorithm 2 Rejected Bandwidth Request Algorithm.

Input: T is the set of TSs scheduled on the UL map.
Q_R is the set of SSs which have rejected BRs
sent from non-real time connections in the last frame.
Output: Schedule a CS for each TS in T.
For i=1 to ||T|| do
a. $S_t \leftarrow$ TSi.
b. $Q_t \leftarrow Q\text{-}O_t$.
c. Randomly pick a SS $\in Q_t$ as the
Corresponding CS of S_t
End for

frame and no bandwidth is allocated for these data. The RBRFA schedules those SSs as CSs on the CL, so the probability to recycle the unused bandwidth while the CS receives the RM is increased. The other factor that may affect the performance of bandwidth recycling is the probability of the RM to be received by the CS successfully. To increase this probability, a scheduling algorithm, named history-Based Scheduling Algorithm (HBA), is proposed. The HBA is summarized in Algorithm 3. For each TS, the BS maintains a list,

Algorithm 2 History-Based Scheduling Algorithm.

Input: T is the set of TSs scheduled on the UL map.
Q_R is the set of SSs which have rejected BRs sent from non-real time applications.
Output: Schedule a CS for each TS in T.
For i=1 to ||T|| do
- **a.** $S_t \leftarrow TSi$.
- **b.** $Q_t \leftarrow Q\text{-}O_t$.
- **c.** Randomly pick a SS $\in Q_t$ as the Corresponding CS of S_t.
- **d.** **IF** the scheduled CS did not transmit data or SBV **Then** put this CS in the B L_i.

End For

called Black List (BL). The basic CID of a CS is recorded in the BL of the TS if this CS cannot receive RMs sent from the TS. According to our protocol, the CS transmits data or pad the rest of transmission interval if a RM is received. The BS considers that a CS cannot receive the RM from its corresponding TS if the BS does not receive either data or padding information from the CS. When the BS schedules the CS of each TS in future frames, the BS only schedules a SS which is not on the BL of the TS as the CS. After collecting enough history, the BL of each TS should contains the basic CID of all SSs which cannot receive the RM sent from the TS. By eliminating those SS, the BS should have high probability to schedule a CS which can receive the RM successfully. Therefore, HBA can increase the probability of scheduling a SS which is able to receive the RM as the CS. To support the mobility, the BL of each TS should be updated periodically. Moreover, the BS changes the UL burst profile of the SS when it cannot listen to the SS clearly. There are two possible reasons which may make the BS receive signals unclearly: 1) the SS has moved to another location. 2) the background noise is strong enough to interfere the data transmissions. Since those two factors may also affect the recipient of RMs, therefore, the BL containing this SS should be updated as well.

The two algorithms described above focus on mitigating each factor that may cause the failure of recycling. The RBRFA increases the probability that the CS has data to transmit while receiving the RM. The HBA increases the probability that the CS receives the RM. However, none of them can alleviate both factors at the same time.By taking the advantages of both RBRFA and HBA, an algorithm called Hybrid Scheduling Algorithm (HSA) is proposed. HSA can increase not only the probability of CSs to transmit data while receiving the RM but also the probability of CSs to receive the RM. The detail of HSA is summarized in Algorithm 4

Algorithm 2 Hybrid Scheduling Algorithm.

Input: T is the set of TSs scheduled on the UL map.
Q_R is the set of SSs which have rejected BRs sent from non-real time applications.
BL is the set of black lists of TSs.
Output: Schedule a CS for each TS in T.
For i=1 to ||T|| do
- **a.** $S_t \leftarrow TSi$.
- **b.** $Q_t \leftarrow Q\text{-}O_t$.

c. Randomly pick a SS Є Q_t as the
Corresponding CS of S_t.
d. **IF** the scheduled CS did not transmit data or SBV
Then put this CS in the B L_i.
End For

When the BS schedules the CS for each TS, only the SS with rejected BRs is considered. As mentioned before, it increases the probability of CSs to transmit data while receiving the RM. Moreover, the BS maintains a BL for each TS. It can screen out the SSs which can not receive the RM so that those SS cannot be scheduled as the CSs. The probability of receiving RMs can be increased. Again, the BL of each TS should be updated periodically or when the UL burst profile of the SS has been changed. By considering those two advantages, HSA is expected to achieve higher TG and BBR comparing to RBRFA and HBA.

9. CONCLUSIONS

Variable bit rate applications generate data in variant rates. It is very challenging for SSs to predict the amount of arriving data precisely. Although the existing method allows the SS to adjust the reserved bandwidth via bandwidth requests in each frame, it cannot avoid the risk of failing to satisfy the QoS requirements. Moreover, the unused bandwidth occurs in the current frame cannot be utilized by the existing bandwidth adjustment since the adjusted amount of bandwidth can be applied as early as in the next coming frame. Our research does not change the existing bandwidth reservation to ensure that the same QoS guaranteed services are provided. The proposed scheme has provided a way for utilizing the unused bandwidth in the current frame itself. In addition to the priority-based scheduling algorithm, other three additional algorithms have been proposed to improve the recycling effectiveness by considering various factors that effect our scheme. Further, the mathematical analysis and simulation model has shown that the proposed scheme is worth enough to provide good throughput and also ensure the QoS guaranteed services.

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