Enabling “Quality of Service” in IEEE802.16 Networks for Distributed Mesh Topologies

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Abstract—Almost all deployed implementations of the IEEE802.16 standard (also known as WiMAX) employ the Point to Multipoint (PMP) topology. With such a topology Quality of Service (QoS) can be easily achieved, but the coverage area is limited. The other architectural topology is the Mesh Mode which is able to provide a larger coverage area, but cannot support the QoS required. This paper addresses the issue of supporting QoS for WiMAX when used in a Mesh Mode configuration. Doing so will motivate WiMAX vendors to support the Mesh Mode configuration for their WiMAX systems more cost-effectively. Our proposed approach makes use of an efficient Bandwidth Manager, a Packet Scheduler and an Admission Control mechanism. The Bandwidth Manager utilizes the ‘Deficit Round Robin’ algorithm, and the Packet Scheduler uses a ‘Self-Clocked Fair Queuing’ scheduling algorithm. The performance results obtained with the proposed scheme demonstrate that QoS support is achievable in this mode.

Index Terms— DRR, IEEE802.16, QoS, Packet Scheduling, SCFQ, WiMAX

I. INTRODUCTION

It is commonly known that the success of Broadband Wireless Access systems is strongly related to the performance, QoS, and deployment cost of the system. In WiMAX, the deployment cost is heavily affected by the network topology adopted. The topology of the system also affects the QoS. Therefore, in this paper we propose a scheme that ensures QoS while keeping the overall deployment cost as low as possible.

A WiMAX communication system consists of two main parts: Base Stations (BS) and Subscriber Stations (SS). The BS provides broadband wireless access for the SSs, in which multiple services can be supported. In this work, all we use the Fixed WiMAX system, IEEE Standard 802.16-2004 version [1]. The WiMAX architectural topologies are Point to Multipoint (PMP) and Mesh. In the PMP mode, SSs are only permitted to communicate to the Base Station (BS) to gain access to the network. The BS manages all scheduling of the PMP network. Managing the Quality of Service (QoS) in PMP system is simple, as all the control is BS centralized. However, using the PMP topology requires all the Service Stations (SSs) to be within the transmission range of the BS. Deployment of the PMP topology requires the presence of an adequate number of BSs, which can be cost inefficient.

On the other hand, the mesh mode allows the SSs to communicate with each other in order to gain access to the BSs. In the mesh mode, the WiMAX standard defines two scheduling approaches: Centralized Scheduling and Distributed Scheduling. In the centralized scheduling, all SSs in the mesh network inform the BS of their resources and requirements. The BS notifies the SSs of the schedule it generates.

In the case of distributed scheduling, each SS is responsible for determining the appropriate neighboring SS node that will provide the most efficient connectivity to the BS. Mesh networks increase the coverage of the WiMAX system and reduce the deployment cost because a smaller number of BSs are required to be installed. Nevertheless, managing the QoS in mesh networks is a tedious task. The 802.14-2004 standard states that links among mesh nodes has no QoS parameters and the QoS must be provisioned on a message-by-message basis. By supporting QoS in the mesh mode, we hope that this will encourage vendors to adopt the mesh topology in WiMAX systems and makes the technology more cost effective.

The rest of the paper is organized as follows. Section II presents the related work efforts. In section III we describe our proposed scheme. Section IV presents the simulation results and performance analysis of our scheme. Section V makes some concluding remarks, and finally, section VI presents our future work.

II. RELATED WORKS

The main purpose of this research is to achieve an acceptable QoS level in Mesh Networks using the Distributed Scheduling scheme of WiMAX systems. To do so, certain requirements must be met:

- Provide maximum bandwidth for real time traffic
  - High throughput
  - Low Packet Delay rate
  - Low Packet Error/Drop rate
- Ensure fairness for non-real-time traffic
  - Adequate minimum throughput threshold
  - Packet Delay tolerant
  - Packet Error/Drop tolerant

The requirements described above can be met if the following schemes are supported as efficiently as possible:

- Routing Scheme
- Transmission Coordinator
- Bandwidth Manager
- Packet Scheduler

A. Routing Scheme

The authors of [2] introduce a routing metric called Short-Widest Efficient Bandwidth (SWEB). It takes into account three factors; Link Packet Error Rate ($P_e$), Link Capacity ($C_l$) and hop count ($h$) from the source node to the destination. The SWEB routing metric provides a balanced performance in terms of throughput, packet delay, and packet error/drop. However, SWEB only takes into account the traffic activity of nodes within its two-hop neighborhood, and does not consider the activity of other nodes along the path. Such information is not available locally in the source node. The next section explains the protocol process that addresses this issue.

The authors of [3] propose a routing protocol process which allows a node to select a path that meets its QoS requirements. The protocol has the advantage of guaranteeing a connection that meets the QoS requirements. However, the overhead might be expensive. Furthermore, in congested networks, connection rejections might occur frequently which will affect the performance of the network.

B. Transmission Coordinator

In the distributed mesh networks, issues and limitations exist on the Three-way handshake process (THP) of the coordinator. The authors of [3] put forward three proposals that are capable to resolve the issues addressed earlier: Multi-Grant (MG), Multi-Request (MR) and Multi-Request-Multi-Grant (MRMG). Those schemes maximize the data subframe utilization. The schemes also take into consideration the QoS requirements and ensure high throughput and low packet delay for real-time traffic.

On the other hand, the authors of [4] address the inefficiencies of the Election Based Transmission Timing (EBTT) mechanism of the coordinator and propose a two-phase hold-off time setting scheme. Using this proposed scheme, the THP time is almost halved.

C. Bandwidth Manager

The author of [7] proposes a bandwidth manager that consists of two main parts: Weight Calculator and ‘Deficit Round Robin’ scheduler. The main goal of the scheme is to ensure that each node is allocated an appropriate number of minislots in a round robin fashion, based on node weights. Minislots scheduling is a very complex task. The process requires nodes to be aware of the availability of other nodes within its two-hop neighborhood. Hence, any minislots scheduler must be able to compensate nodes that were not able to transmit due to their neighborhood status. The Deficit Round-Robin (DRR) is very efficient in doing such a task since the scheme keeps track of nodes that missed their turn in a cycle and compensates them in the next cycle. Furthermore, the DRR algorithm is simple and does not require any extensive computation power or memory.

D. Packet Scheduler

In [7], the author uses the DRR scheduling scheme in the packet scheduler. The algorithm is similar to the one used by the same author for the bandwidth manager. In the packet scheduler, the bandwidth is shared among different flows based on the priority value of each flow, which can be found on the packets MAC Connection IDentifer (CID) priority parameter. As explained earlier, the DRR algorithm is simple and does not require any extensive computation power or memory. Nevertheless, when used as a packet scheduler, it will result in packets being scheduled in spurts and the packet delay is expected to increase. Furthermore, it takes a whole cycle of the DRR in order to see the fairness of the scheduling. Hence flows that are active for a short period of time are at a disadvantage.

III. PROPOSED APPROACH

After reviewing the related works on WiMAX mesh networks, we found that that not many of the current scheduling algorithms allow fast and versatile bandwidth and packets scheduling. Furthermore, many failed to acknowledge the importance of admission control for guaranteed QoS.

Our proposed scheme consists of three main parts: Bandwidth Manager, Packet Scheduler and Admission Control. The bandwidth manager uses the DDR scheduling algorithm to distribute bandwidth among the nodes. The Packet scheduler uses a Self-Clocked Fair Queuing scheduling algorithm which is explained in [8].

We make the following assumptions:

1. Every flow has an end-to-end source ID of its source node and a destination ID of the base station of the mesh network.
2. The routing scheme used is a static tree based and can only be changed by network administrators when the network is down.
3. All the nodes must use the same burst profile scheme (the service provider (BS – for Base Station?) can dictate the burst profile used).
4. The maximum number of nodes in a mesh network is set in a way that when the network is congested, each node is supposed to be able to have an adequate bandwidth to support normal network operations.

In a congested mesh network, the minimum-maximum end-to-end bandwidth for every active node can be expressed as:

$$B_w = \begin{cases} \frac{E}{N} & \text{when } \sum S_n < N \\ \max\left(\frac{E}{N}, \frac{B_{SN}}{N}\right) & \text{when } \sum S_n \approx N \end{cases}$$

(1)

where $B$ is the maximum bandwidth of the mesh network can support, $N$ is the number of active nodes in the mesh network, $S_n$ is the maximum bandwidth satisfaction index of the n-th node, and $B^{SN}$ is the required bandwidth by the n-th node.

The proposed scheme is independent of the number of priority levels used. The network administrator must specify: the number of priority levels of different traffic, and the preferred bandwidth for each priority level. The IEEE802.16 standard can support up to eight priority levels.
A. Bandwidth Manager

The bandwidth manager is responsible for allocating the transmission time for each node based on its priority weight. The weight of a certain node is dependent on how many other nodes are using that node to communicate to the base station and vice versa.

The most important factors in a scheduling algorithm are performance and fairness. In an ideal world, a Generalized Process Sharing (GPS), or one of its equivalence, is the appropriate algorithm to insure total fairness of bandwidth distribution. However, GPS is unrealistic and cannot be applied for bandwidth distribution in WiMAX mesh networks for many reasons. For example, due to the complexity of mesh topologies, nodes are not able to transmit or receive data at any given time. A specific scheduling algorithm is required, which is not time-dependent on the time availability, but is rather dependent on deficit counters. The required algorithm should be able to keep track of the amount of data sent by each node, and compensate less privileged nodes that have not been able to transmit/receive due to their neighborhood status.

The algorithm proposed is the Deficit Round Robin (DRR) and was also used in [7]. However with our proposed scheme the Node Weights are calculated based on bandwidth values set by the network administrator. The DRR scheme is suitable for allocating bandwidth in complex mesh networks. DRR is a weighted round robin algorithm that provides priority to certain nodes.

B. Packet Scheduler

Packet scheduling occurs after the bandwidth manager has allocated minislots for a node. A node is able to schedule any packet from any flow in its buffer. However, the process must be done in an efficient and fair way. As mentioned earlier, Generalized Process Sharing (GPS) scheduling is ideal, but unrealistic, choice for this purpose. Nevertheless, there exists a scheduling algorithm that has a close behavior to the GPS scheme. The algorithm proposed is the Self-Clocked Fair Queuing (SCFQ) which is explained in [8]. The SCFQ is a very responsive scheme that allows assigning a specific bandwidth rate for each flow based on its priority. Fairness of this scheme converges in a very short period of time, unlike the DDR where the fairness can only be noticed after a complete round robin cycle. Equation 2 shows the fairness convergence time of the SCFQ algorithm.

\[ T = \frac{P^{\text{max}}}{B} \]  

where \( P^{\text{max}} \) is the maximum size of a packet and \( B \) is the link bandwidth.

The SCFQ algorithm used is as follows:

- **Parameters**
  - Current Virtual Time (T)
  - Packet Size in a certain flow \( (P) \)
  - Flow Required Bandwidth \( (B) \)
  - Packet Virtual Finish Time \( (\text{PFT}) \)

- **Algorithm**
  1) Initially \( T = 0 \)

2) When a packet for a certain flow is received by the SCFQ scheduler its Packet Virtual Finish Time is calculated

\[ \text{PFT}_j = \text{Max}(T, \text{PFT}_{j-1}) + \left( \frac{P_j}{B} \right) \]

3) When the scheduler is given a certain amount of bandwidth by the bandwidth manager, it schedules the packets that have the lowest PFT values first.

4) Whenever a packet is scheduled, \( T \) is updated to the PFT of the currently scheduled packet

\[ T = \text{PFT}_j \]

The \( B \) of each flow is assigned based on the flow’s priority value found in the MAC CID. This algorithm ensures that each flow will get its assigned \( B \) value as long as a node’s collective bandwidth rate supplied by the bandwidth manager can support \( \sum B_i \). The Admission Control mechanism makes sure that \( \sum B_i \) does not exceed a node’s collective bandwidth rate supplied by the bandwidth manager.

C. Admission Control

Admission control is important in mesh networks in order to achieve the required QoS levels. The admission control is performed in hop-by-hop basis. This means a flow might be accepted by certain nodes along the path, but might be rejected by a node closer to the destination. The previous nodes on the path are informed of the rejection. The requesting node cannot immediately request to establish another flow and it needs to wait for a certain period of time.

The transmission time must be shared equally among all the active nodes in the mesh network. A node is considered active when it has data to transmit. Inactive nodes are not considered in the scheduling process until they become active. The extra unused bandwidth of nodes with low activity must be shared equally among other nodes. Inactive nodes that become active have to wait for a specific period of time in order to be able to be integrated within the bandwidth distribution structure. This might involve capping the bandwidth of other privileged nodes or dropping certain flows that belong to privileged nodes. A node is considered privileged if it is allocated more bandwidth than its minimum-maximum end-to-end bandwidth.

The admission control main tasks are:

1) In the case of a congested network, a node should only be given its fair share of the bandwidth. In the case that the node is already assigned its fair share of the transmission time and requests to establish a new flow, which the network cannot support, the flow must be rejected.

2) In the case that an inactive node becomes active in a congested network, the admission control must claim back the extra bandwidth that was distributed among the other nodes. This is done by reducing the bandwidth of those nodes’ ‘greedy’ flows (e.g. FTP/HTTP). Low priority flows might be dropped in order to claim the required bandwidth.

IV. EXPERIMENTS AND RESULTS

The proposed algorithm is simulated using ‘Network Simulator 2’ (NS2) [9], version 2.31. The official NS2 release does not have an implementation of the IEEE 802.16 standard; however a WiMAX patch exists for the NS2
which is created by [10]. Changes are made to the patch in order to incorporate the proposed scheme into it.

The NS2 simulation is conducted using the configurations described in Table 1. The configuration parameters are similar to those used in [7] to compare the results of our proposed approach with those of SCFQ with DRR. Three types of flows are used in the simulation which are: Constant bit-rate flow (CBR) (a function that generates a one Kilobyte packet at a rate of 2 Mbps), Variable bit-rate flow (VBR), and best effort flow (BE). A ‘Video on Demand’ (VoD) connection is used as a VBR flow. An FTP connection is used as a BE flow. CBR and VBR flows are considered non-greedy flows, whereas the BE flows are considered greedy flows. A flow is considered greedy when it has no constant data rate demand.

CBR and VBR have high QoS expectations. Bandwidth satisfaction indexes (BSI) of such flows must be kept as high as possible (~100%). Packet delay for those flows must always be kept as low as possible. On other hand, BE flows are considered ‘greedy flows’, and has no strict QoS requirements. In this simulation, BE flows are allowed a minimum of 40 Kb data rate. Refer to Table 2 for the flows’ configurations.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>CONFIGURATION OF SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>10 s</td>
</tr>
<tr>
<td>Number of Channels</td>
<td>1</td>
</tr>
<tr>
<td>OFDM Symbol Duration</td>
<td>20 us</td>
</tr>
<tr>
<td>OFDM Symbols in a frame</td>
<td>500</td>
</tr>
<tr>
<td>Physical prorogation</td>
<td>20 us</td>
</tr>
<tr>
<td>Frequency</td>
<td>10 MHz</td>
</tr>
<tr>
<td>MSH-DSCH control slots in a frame</td>
<td>4</td>
</tr>
<tr>
<td>Number of MSH-DSCH messages between two consecutive MSH-NCFG messages</td>
<td>16</td>
</tr>
<tr>
<td>Number of priority levels</td>
<td>3</td>
</tr>
<tr>
<td>Priority levels values</td>
<td>0 (BE) = 40000 Bits</td>
</tr>
<tr>
<td>1 (VBR) = 125000 Bits</td>
<td></td>
</tr>
<tr>
<td>2 (CBR)= 250000 Bits</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>CONFIGURATION OF FLOWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR</td>
<td>Packet Size</td>
</tr>
<tr>
<td></td>
<td>1 Kb</td>
</tr>
<tr>
<td>VBR (Vod)</td>
<td>Rate</td>
</tr>
<tr>
<td></td>
<td>2 Mb</td>
</tr>
<tr>
<td>BE (FTP)</td>
<td>TCP Max Congestion window size</td>
</tr>
<tr>
<td></td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>TCP Max Segment Size</td>
</tr>
<tr>
<td></td>
<td>1024</td>
</tr>
</tbody>
</table>

A few scenarios were simulated in order to determine the efficiency and correctness of our Proposed Scheme (P). The results are also compared with the results of the scheme proposed by [7].

Test scenarios 1 and 2 are used to evaluate the proposed scheme in a congested network that has more than one subscriber node. As expected, the P value is lower as shown in tables 3 and 4. P provides higher throughput than that of [7], except for the greedy flows (BE). However greedy flows do not require QoS assurance.

In congested networks, the bandwidth satisfaction indices in P are always higher than the algorithm presented in [7]. The reason for that is because P uses as SCFQ packet scheduler which is more accurate in delivering the exact recommended data rate of CBR and VBR flows.

Furthermore, the packet delay of flows in the P scheduler is usually lower due to the smooth scheduling nature of the SCFQ algorithm. Hence it can be concluded that the SCFQ packet scheduler when used in conjunction with a DRR bandwidth manager is much more suitable in ensuring the QoS for different types of flows.

Further simulations were conducted to determine the performance impact when the number of flows is increased linearly. The topology used in those scenarios is illustrated in 3. Figure 4 and 5 show that the throughput and packet delay changes when the number of CBR flows increases. The throughput of the CBR flows increases until it reaches a certain point where it remains constant. The throughput of the VBR flow stays almost constant. The throughput of the BE flow decreases and after a certain point it stays almost constant. As for the packet delay, the CBR flows delay increases linearly, the VBR flow packet delay is constant, and the BE flow packet delay increases slightly, and then stays constant.

Figures 5 and 6 show similar results where the number of VBR flows increases. The VBR throughput increases to a certain point and the delay also increases, while the BE flow throughput decreases until it stays constant. The CBR flow throughput and delay stay constant. It can be concluded from the previous results that when the number of non-greedy flows of priority i (NGFi) increases, the following changes occur:

- NGFi throughput increases and then stays constant
- NGFi packet delay starts increasing when the link cannot support the increase in bandwidth demand. This occurs when the admission control reject any more flows from being established.

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>SCENARIO 1 RESULTS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>CBR</td>
</tr>
<tr>
<td>P</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1665.17</td>
</tr>
<tr>
<td>T</td>
<td>165.250</td>
</tr>
<tr>
<td>B</td>
<td>66.1%</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>TABLE 4</th>
<th>SCENARIO 2 RESULTS</th>
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<tbody>
<tr>
<td></td>
<td>CBR</td>
</tr>
<tr>
<td>P</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2671.85</td>
</tr>
<tr>
<td>T</td>
<td>243.875</td>
</tr>
<tr>
<td>B</td>
<td>97.55%</td>
</tr>
</tbody>
</table>

D = Delay (ms), T = Throughput (Kb), B = Bandwidth Satisfaction Index
- Greedy flows throughput decreases until the throughput reaches the minimum allocated bandwidth for greedy flows.
- NGF\textsubscript{p} throughput and packet delay stay constant.

In contrast, Figures 7 and 8 show that an increase on the BE flows has no effect on the other flows throughput or packet delay. The BE flows collective throughput also stays constant, but the packet delay increases linearly. Once again, the admission control is responsible for ensuring that no new flows can be established after the delay has increased to a certain threshold.

The proposed SCFQ packet scheduler in conjunction with the DRR bandwidth manager results in a more stable performance that can support QoS requirements. We note that an increase in non-greedy flows can be supported as long as the network can support the increase in bandwidth demand. We also note that greedy flows are able to receive a minimum amount of bandwidth, and also receive any extra non-used bandwidth. An increase in the number of greedy flows has no effect whatsoever on non-greedy flows, which is a very important aspect for guaranteed QoS. Our results also showed that fairness is retained at all times.

V. SUMMARY AND CONCLUSION

This work examines the process of achieving “Quality of Service” in WiMAX Network running in a distributed mesh mode configuration. The IEEE 802.16-2004 standard and various previous works were discussed related to our proposed scheme were reviewed. Our proposed approach consists of three main parts: admission control, bandwidth manager, and packet scheduler. The bandwidth manager exploits the deficit round robin scheduling algorithm. The packet scheduler uses the self-clocked fair queuing scheduling scheme.

We conducted simulation scenarios using Network Simulator 2 in order to investigate the efficiency and correctness of our proposed approach. The simulation results demonstrate that the proposed scheme performs better than the scheme proposed by [7]. The results also showed that proposed scheme is capable of ensuring Quality of Service as long as the network can satisfy the bandwidth demand. The admission control is responsible for ensuring that no new flows can be established after a certain threshold. Our scheme can be significantly improved. But due to time limitations we focused on and simulated only the core of the scheme. The next section presents some future proposed improvements to our proposed algorithm.
VI. FUTURE WORK

Ensuring QoS in WiMAX mesh networks is achieved using a combination of schemes and algorithms that regulate the flow of traffic. Nodes must be able to determine the most suitable path for its packets to the BS. Nodes must be able to compete for transmission opportunities effectively and use them efficiently. Furthermore, a proper admission control is required.

Future work should cover two important areas: routing, transmission operation and admission control. Routing Scheme

The SWEB routing metric introduced by [2] is adopted. When one BS only exists in the mesh network, each SS node periodically calculates its best path to the BS. When more than one BS exists in the mesh network, each node will periodically calculate two paths that lead into two different BS: the Main Path and the Fallback Path. The main path has the largest SWEB value, whereas the fallback path has the next largest SWEB value that leads to a BS different from the main paths of the BS. The Main and Fallback paths are calculated every time a node receives the MSH-NCFG message. Each BS station calculates its best path to every other node using the same SWEB algorithm.

When a bandwidth satisfaction index of a node is above a certain threshold, all its traffic is routed using the main path. When a node’s bandwidth satisfaction index is below a certain threshold, all delay-tolerant traffic is routed using the fallback path. This approach helps to increase the throughput and to reduce the packet delay time experienced by the delay-tolerant traffic. This method exploits the spiral reuse feature of the distributed mesh networks.

The SWEB algorithm is used because it is capable of selecting the most efficient path for the source to the destination, without incurring expensive overheads. Its SWEB metrics only requires local information available in every node. The routing protocol process proposed by [3] might provide more accurate results; however it will incur expensive overheads, especially when the network is congested and connection rejections occur frequently.

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