WiMAX Multiple Hops Architecturein Smart Grid Communications

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Abstract —This paper proposes a multiple hops WiMAX topology to serve as a wireless communication for the smart grid. A simulation model is developed to evaluate the network performance based on the quality of service requirements of the smart grid applications in order to explore the possible solutions for the grid. The simulation results demonstrated that different service flow types affect the latency of the network. For class 1) applications, no more than 450 smart grid devices should be used to satisfy the latencyrequirement. For class 2) applications, a maximum of 250 smart grid devices can be placed in one cell in order to satisfy the latency requirement. For both classes and under the recommended number of smart grid devices, it was found that the CB-SPQ scheduling algorithm is the best for the satisfactory performance. For class 3) and class 4) applications, a cell can accommodate a maximum of 150 smart grid devices and the CB-WFQ scheduling algorithm is the best. For class 5) applications, no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

Index Terms—Smart grids, multihop, diffServ, scheduling, WiMax

I. Introduction

The smart grid communication layer is evolving in a way that enables the grid to expand to a wider geographical area enabling the grid users to communicate in two directions. The IEEE introduced a framework of features, the IEEE P2030 that classifies the applications according to certain distance ranges and qualitative measures. These features depend on the area of coverage, latency, data type, reliability and security, which in part help to determine the best communication network technology [1]. Table I and Table II present the smart grid data characteristics and classification for the IEEE P 2030 reference model [1]. The coverage area is divided into four ranges. The distance or range depends on the transmission power, the substation locations, and the consumption premises distance.

The second data characteristic is the latency which can be defined as the delay of the data transmitted between the smart grid devices and the operation center. The IEEE P2030 reference model categorizes the smart grid applications latency into real time and non-real time categories. The real time category requires from few milliseconds response time while the non-real time category requires a medium (< sec) to high (> sec) response time.

Latency is mainly impacted by the transfer rate and the number of hops between the smart grid devices. The most stringent requirement for latency comes from the mission-critical control applications where the data may have to be transferred to the control center and an automatic command is issued within a specific time [2]-[4]. An example of such applications is the substation automation which requires 15 to 200 milliseconds latency. Some other applications, such as advanced metering infrastructure latency is not critical [5], [6].

The IEEE model divides the smart gird applications into two synchronization groups. Some applications require to be synchronized with others within the entire network and some do not require any synchronization. The generated data is characterized based on the data burst size, the occurrence interval, the broadcast mode and the priority.

The next characteristic of the smart grid applications comprises qualitative measures that are defined by the quality of information, availability and impact on the grid operations. Last but not least, data security is measured by its confidentiality, integrity and availability, all of which classifies itself into none, low, medium and high.

Multiple hops networking extends the reach of a utilities energy network [7]-[10]. It also provides easy installation on existing assets and a high flexibility in the deployment options. This may improve the transmission rate and helps in avoiding the congestion at the utility center [11].

The IEEE P2030 also introduced a mapping between the smart grid communication layer and the different network protocols standards. A mixture of wired and wireless standards has been defined to connect the smart grid devices in different domains.

The capabilities of the IEEE 802.16 WiMAX standard will potentially allow the implementation of different communication scenarios for the smart grid. WiMAX standard can serve as a backhaul or a point-to-multipoint access network. In addition, WiMAX can provide full end-to-end Quality of Service (QoS) that makes it a good alternative for smart grid communication networks. So far, few researches have been carried out to investigate the performance of WiMAX multiple hops networks.

WiMAX supports wide coverage areas with a coverage radius for the WiMAX cell up to 50km. Moreover,

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WiMAX standard is designed to operate in Non-Line of Sight (NLOS) mode at operating frequencies equal to 11GHz or below, and in Line-of-Sight (LOS) mode at operating frequencies between 10 to 66GHz. In addition, WiMAX data rates may go up to 70Mbps depending on the radio channel condition and the type of adaptive modulation and coding (AMC) used.

TABLE I: DATA CLASSIFICATION TABLE FOR IEEE2030 REFERENCE MODEL [1]

Data Characteristics		Classification /Value Range			
Area of Coverage		<10 m	<100 m	< 1 km	>1 km
Latency		Real Time		Non-Real Time	
Synchronicity		Yes		No	
Data Type	Burst size	Bytes	Kilobytes	Megabytes	Gigabytes
	Occurrence Interval	Milliseconds	Seconds	Minutes	Hours
	Broadcast Method	Unicast	Multicast	Broadcast	All
	Priority	None	Low	Medium	High
Information Reliability	Quality	Informative	Important		Critical
	Availability	Low	Medium		High
	Impact	Limited	Serious	Severe	Catastrophic
Security	Confidentiality	None	Low	Medium	High
	Integrity	None	Low	Medium	High
	Availability	None	Low	Medium	High

TABLE II: SMART GRID APPLICATIONS QOS REQUIREMENTS [3]

Smart Grid Application	Reliability	Bandwidth (kbps)	Latency Traffic	Type
Substation Automation	99.0 -99.99%	9.6 -56	15-200 ms	Periodic 15-60 minutes
WASA	99.0 -99.99%	600 - 1500	15-200 ms	Periodic/Random
Outage Management	99.0 -99.99%	56	2000 ms	Random
Distribution Automation	99.0 -99.99%	9.6 -100	100 ms -2 sec	Periodic
DER	99.0 -99.99%	9.6 -56	100 ms -2 sec	Random
Smart Meter	99.0 -99.99%	10-100 /meter 500 /concentrator	2000 ms	Random
Demand Response	99.0 %	14 - 100	500 ms-min	Continuous
DSM	99.0 %	14 – 100	500 ms-min	Occasional
Assets Management	99.0 -99.99%	56	2000 ms	Random

WiMAX supports QoS using service flows. Service flows such as the unsolicited grant service (UGS), real time polling service (rtPS), extended real time polling service (ertPS), non-real time polling service (nrtPS) and best effort (BE) are excellent features that make WiMAX a healthy network technology to serve in the smart grid.

As mentioned above, some of the smart grid applications require real-time response, others may require non-real-time or best effort. Such features were not explored or fully utilized in the smart grid communications.

II. NETWORK MODEL AND ASSUMPTIONS

A. *Traffic Classification*

The smart grid can be divided into applications that are based on the generation, transmission, distribution and consumption domains of the smart grid. Each application has many parameters and requirements that have to be satisfied in order to better manage operate the grid. These parameters depend on the application nature. Table II shows the smart grid applications reliability, bandwidth, latency, and security requirements [3]. Based on the smart grid QoS requirements and the IEEE2030 reference model, the smart grid applications are classified and assigned to three WiMAX service classes, i.e. rtPS, nrtPS and BE. Based on this classification and the mapping between the Diffserv and WiMAX service classes, a new tailored DSCP implementation has been proposed for supporting smart grid applications. A detailed discussion on the applications' classification is provided in reference [3]. Table III shows the result of this classification.

TABLE III: PROPOSED CLASSIFICATION

Smart Grid Application	Class	DSCP
Substation Automation	rtPS	67,64
Wide Area Situational Awareness Systems		55
Outage management		43
Distribution Automation		33
Distributed Energy Resources and Storage	nrtPS	
Meter Readings (periodic)		15
Meter Readings (critical)		31
Demand Side Management		11
Asset Management	BE	

B. *Network Topology*

This paper proposes a multiple hops WiMAX network architecture. The selection of single hop and multiple hops architecture is based on the geographical distribution as well as the quality of service requirements. In the multiple hops network, the smart grid data and commands are transmitted from multiple applications to the control center using multiple WiMAX hops. Having multiple hops may expand the area of coverage over a wider geographical area compared to the single hop topology. It may also reduce the number of dedicated communication links from the smart grid devices to the command and dispatch center optimizing the communications bandwidth [12]. Fig. 1 shows the proposed multiple hops network topology.

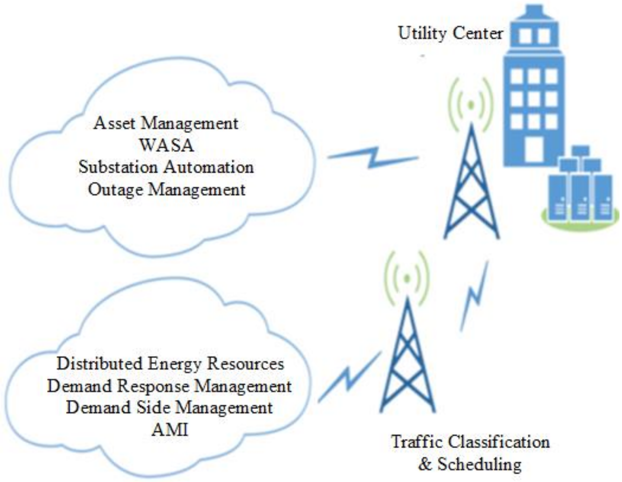

Fig. 1. An illustrative framework of the smart grid multiple hops topology. The traffic generated from the smart grid applications is forwarded

Data traffic from the distribution automation, distributed energy resources, demand response management, demand side management and outage management applications is aggregated and forwarded to the utility command center through multiple network hops [13], [14].

Data traffic from substation automation, asset management and wide area situational awareness applications are transmitted directly to the command and dispatch center. This topology may be suitable for dense urban areas that have a large number of smart meters, i.e. 2000/km^2.

Although it is expected that more services can be handled, signaling overhead and accumulated latency between multiple hops may not satisfy the latency requirements of some of the smart grid applications.

C. Scheduling Techniques

Each device has local scheduling mechanism where the generated traffic is locally queued based on the traffic service flows. Then, the local queues contents are forwarded to the base station uplink scheduler for further processing.

Based on the QoS parameters, the base station uplink scheduler determines the transmission period and the burst profile for every connection [15].

This paper proposes three different uplink scheduling algorithms namely; CB-WFQ, CB-DWRR and CB-SPQ. Detailed implementation of the scheduling techniques is presented in reference [16].

III. Delay Analysis

To calculate the end-to-end delay for processing a complete smart grid application request, let$D_{(i,n)}$ denotes the delay of the packet i at the nth hop of the network, and k is the total number of hops [8]-[10].

$$D_{(i:n)} = kD_{(n)} + \sum_{n=1}^{k}\left[D_{Q(i,n)} + D_{S(i,n)} + D_{R(i,n)}\right] \quad (1)$$

$$D_{(n)} = d_p + d_g + d_t + \mu \quad (2)$$

$D_{Q(i,n)}$ is the queuing delay and can be calculated by the following equation:

$$D_{Q(i,n)} = T_{(a,n)} - T_{(d,n)} \quad (3)$$

where $T_{(a,n)}$ and $T_{(d,n)}$ respectively are the arrival and departure time of the ith packet at the nth hop of the network.

$D_{S(i,n)}$ is the scheduling delay, which is defined as the time interval from the end of sending a corresponding bandwidth request message to the time when the corresponding base station grant becomes the first one in the BS grants shared buffer. $D_{R(i,n)}$ is the reservation delay, which is defined as the time interval from the packet arrival at the smart grid device to the start of sending a corresponding bandwidth request message to the BS. In equation (2), d_p is the processing time, which is the time a BS or smart grid device spends processing a packet; this includes error checking time, reading the packet header time and time for finding the link to the next hop. Here, d_t is the transmission time which is defined as the time interval from the time when a BS bandwidth grant becomes the first one in the BS grants buffer to the start of the successful transmission of the corresponding packet in the UL sub-frame [12].

The parameter μ is the transmission time of a data packet, and the prameter$d_g$is the propagation delay which is the time that it takes a signal to propagate through the communication media from a hop to the next hop. It can be calculated using the following equation:

$$d_g = \frac{L}{s_g} \quad (4)$$

where L is the distance between hop and the next hop and s_g is the propagation speed.

IV. Result and Analysis

A. Simulation Parameters

The simulation algorithm is developed to measure the round trip time delay for each smart grid application. Smart grid applications classification and their requirements are summarized Table II. In order to find the network architecture that satisfies the applications requirements, a software program was developed. The program inputs are the data and commands, hereafter information, from the smart grid applications that spread throughout the power network. While the information is propagating within the smart grid communication networks, the proposed algorithm performs several processes to calculate the round trip time latency. Simulation models for the architecture were implemented using OPNET.

The simulation parameters, traffic models, and performance metrics are specified in reference [16].

B. Physical Layer Parameters

The WiMAX network configuration that are specified to satisfy the proposed smart grid applications data and commends transfer and exchange are shown in Table IV.

TABLE IV: PHYSICAL PARAMETERS

Parameters	Configuration
Network	2 Celled WiMAX Network
Cell Radius	5-15 Km
No. Of workstations per BS	50-450
Frequency	2.5 GHz
Physical Layer	OFDM
Frame Structure	TDD
Frame duration	5 ms
Symbol duration (us)	102.86
Number of Subcarriers	2048
TTG/ RTG (microseconds)	106/60
Uplink / Downlink Modulation	QPSK
Code Rate	1/2
Scheduling Algorithms	CB-WFQ, CB-DWRR, CB-SPQ
Total Capacity (Mbps)	11.6544 Mbps
Total Uplink/ Downlink Capacity	5.3184/ 6.3360 Mbps

C. Results Analysis and Discusion

Five different simulations run were conducted. It is worth mentioning that, in the multiple hops topology, the network geographical distance is extended and the network coverage became larger. Fig. 2 shows the simulation result the multiple hops topology network for class (1) traffic. The figure shows that the scheduling algorithms CB-WFQ, CB-DWRR and CB-SPQ are able to meet the maximum delay requirement of 200 milliseconds; keeping in mind that Class (1) traffic is aggregated only at the command and dispatch center.

Therefore, delay values in the multiple hops topology will be close to the ones in the single hop topology [16]. Claim 1: In multiple hops topology, for class (1) applications, it is recommended that no more than 450 smart griddevices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best and the other two can best used, as well. Fig. 3 shows the simulation result for the average delay of class (2) traffic in the multiple hops topology. The average delay has increased in this topology compared to the single hop topology [16]. This is because one of class (2) applications, i.e. the distribution automation is aggregated and scheduled at the distribution level and then once more at the command and dispatch center. Accordingly, the bandwidth request, the queuing as well as the scheduling areperformed twice. It was found that the three scheduling algorithms have met the maximum delay boundary at a small number of smart grid devices, 250, 150 and 50 under CB-SPQ, CB-WFQ and CB-DWRR respectively. In spite of that class (2) has real-time polling service (rtPS) connections; it suffers large delays because of the signaling overhead in the bandwidth request process and the accumulated queuing as well as scheduling delays. Claim 2: In multiple hops topology, for class (2) applications, it is recommended that no more than 250 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best.

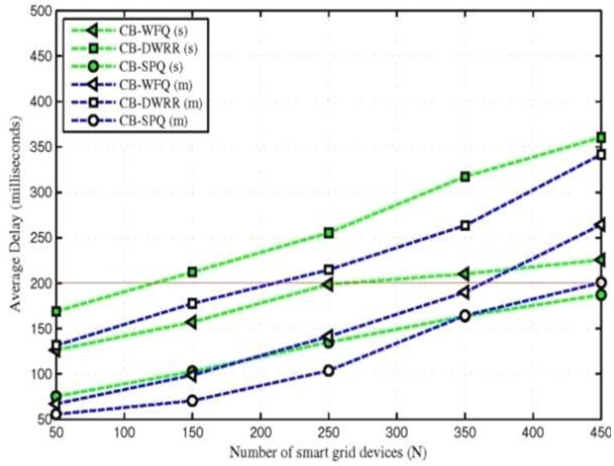

Fig. 2. Class (1) Average End-to-End delay under different queuing discipline

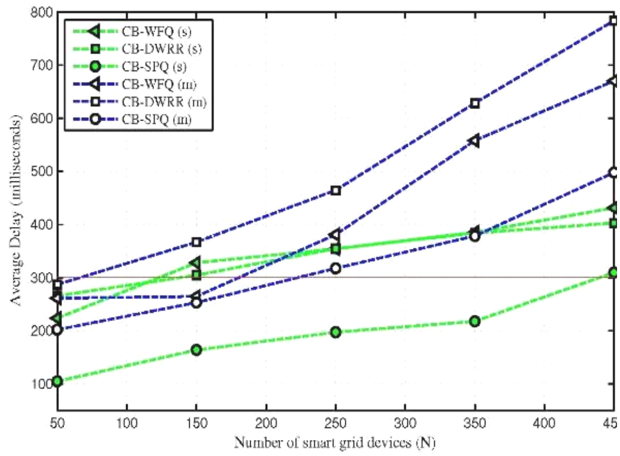

Fig. 3. Class (2) End-to-End delay under different queuing disciplines

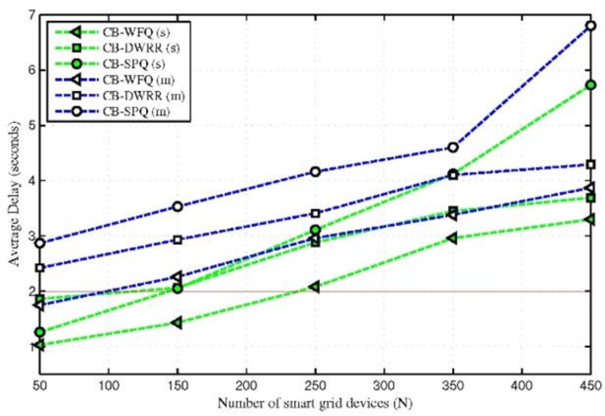

Fig. 4. Class (3) Average End-to-End delay under different queuing disciplines using the multiple hops topology.

Fig. 4 and Fig. 5 show the average delays of class (3) and class (4) traffic respectively in the multiple hops topology network. CB-WFQ is still showing a fair resource distribution, so a reasonable delay can be offered to non real-time polling service (nrtPS) connections assigned to class (3) and class (4) traffic. Each connection has its own First In First-Out queue and the weight is assigned for each queue according to the requested bandwidth. Claim 3: In multiple hops topology, for class

(3) applications, itis recommended that no more than150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best. Therefore, nrtPS connections are unlikely starved even under the high load of rtPS connections generated from class (1) and class (2) applications. Class (3) and class (4) are aggregated and scheduled at concentrators first, and then forwarded again from concentrators to the command and dispatch center for further scheduling. Polling for bandwidth at two hops results in high delay values compared to the single hop topology. Claim 4: In multiple hops topology, for class (4) applications, it is recommended that no more than 150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

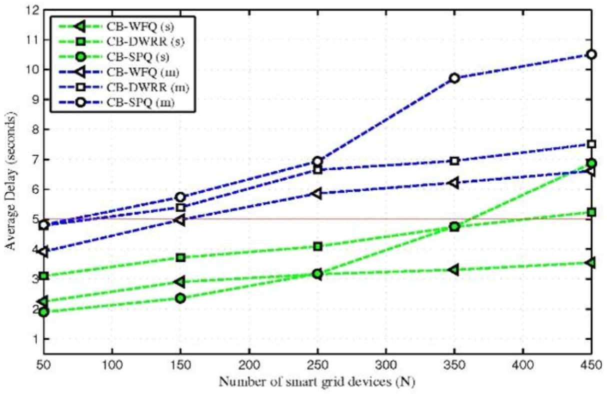

Fig. 5. Class (4) Average End-to-End delay under different queuing disciplines using the multiple hops topology.

In Fig. 6, class (5) traffic is aggregated and scheduled only at the command and dispatch center. Claim 5: In multiple hops topology, for class (5) applications, it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best and the other two can best used, as well.Given the above delay analysis, resource allocations and scarce bandwidth tolerance for all priority classes, it can be seen that CB-WFQ algorithms assign a weight parameter to each traffic class and distribute the available bandwidth to the classes based on the weights. On the contrary, CB-SPQ algorithms distribute the bandwidth in the order of priority; thus the traffics with higher priority are transferred earlier than the low priority traffic [12]. CB-WFQ ensures the fairness of resource allocation and avoids the starvation problem that arises by the absolute priority process of CB-SPQ. On the other hand, CB-SPQ maximizes the usage of resources of high priority classes by allocating its resources and avoiding the added delay of weight calculations and assignments. So, active rtPS connections can reach the maximum throughput in a lower available bandwidth than those under CB-DWRR and CB-WFQ. However, under high priority traffic loads, CB-SPQ can create a network environment where a reduction in the QoS delivered to the rtPS is delayed until the entire network is devoted to the rtPS packets processing only.

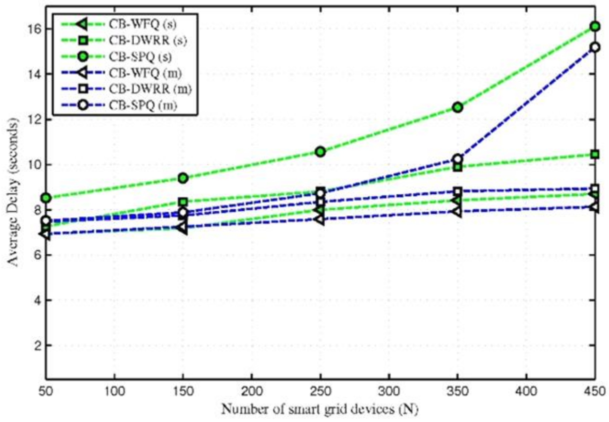

Fig. 6. Class (5) End-to-End delay under different queuing disciplines using the multiple hops topology.

Despite the good performance results, scalability could be an issue for the CB-WFQ. This is because CB-WFQ is originally designed to support fair allocation for variable sized packets which resulted in a high computational complexity of the algorithm. Expanding the network range for more than two hops may significantly degrade the performance of the CB-WFQ. In addition to that, for low priority traffic such as smart metering, minimizing delay to the granularity of a single packet transmission may not be worth the computational expense [14].

Even though CB-DWRR failed to achieve the best delay performance for any traffic class, it should be noted that CB-DWRR is usually used in a variable-sized packets networks. The assumption that all the generated packets have the same size; i.e., 1024 Kbyte may have obstructed the CB-DWRR algorithm to gain over the performance of the other algorithms. Furthermore, the implementation of CB-DWRR has lower computational complexity compared to the CB-WFQ, which makes it a good candidate for the multiple hops topology as well as bursty networks; i.e., distribution domain networks.

Claim 6: Under the given assumptions, for rtPS high priority applications, it is recommended that no more than 250 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best. For nrtPS and BE applications, it is recommended that no more than 150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

D. The Impact of WiMAX Service Flows on the Delay Performance

As mentioned in before, smart grid applications are mapped to rtPS, nrtPS and BE service flows. Fig. 7, Fig. 8 and Fig. 9 show the delay performance for the different service flow types under the three queuing disciplines. The CB-WFQ and CB-DWRR schedulers have a better performance for low QoS classes on the expense of the high QoS classes. Both CB-WFQ and CB-DWRR can control the performance of each class by assigning a different weight to each queue to prevent a bandwidth starvation of low QoS classes.

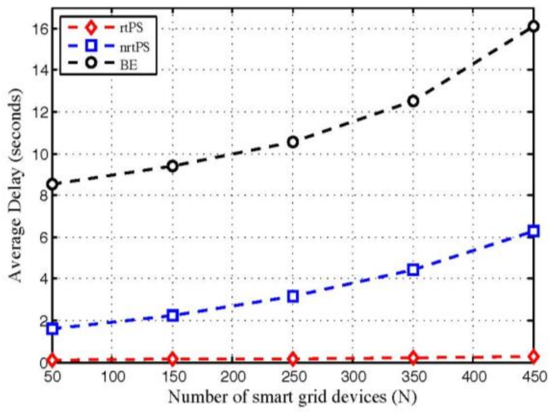

Fig. 7. End-to-End delay of different traffic types under CB-WFQ.

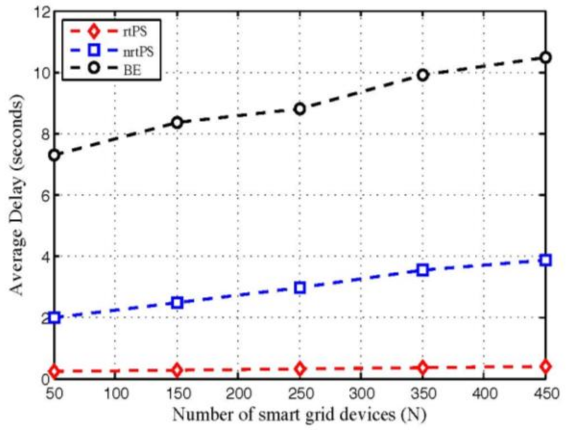

Fig. 8. End-to-End delay of different traffic types under CB-DWRRQ.

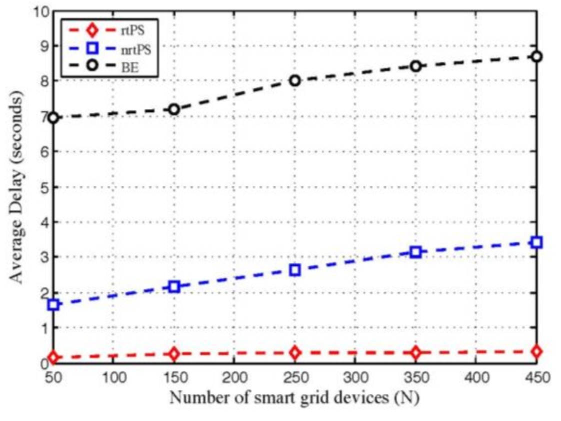

Fig. 9. Average End-to-End delay of different traffic types under CB-SPQ.

None of the packets experienced a delay around zero because the CB-WFQ and CB-DWRR schedulers monitor the delay boundaries of packets, as well as the MSTR and MRTR configured in the service flows parameters.

If packets can tolerate the delay until the next frame arrival, the scheduler reserves the corresponding time slot to be assigned to the BE traffic to avoid its starvation; otherwise, the packets are scheduled in the current frame to provide delay bound guarantees for the connections.

CB-SPQ scheduling has the minimum delay level for rtPS traffic, as the algorithm always grants a bandwidth for rtPS first. If there is no packet in the rtPS queue and there is available bandwidth left for the smart grid device, then the bandwidth is allocated for the nrtPS service flows. If there are no packets in rtPS and nrtPS queues and there is available bandwidth left for the smart grid device, then the bandwidth is allocated to the BE service flows. In CB-SPQ, when rtPS traffic increases significantly by the increase in the load submission, there will be no resource left for nrtPS and BE flows. Therefore, no packets from the nrtPS or BE will be served, and their throughputs will be dropped to zero. As a result, nrtPS and BE flows may starve under high rtPS traffic.

E. The Impact of DSCP on the Delay Performance

The DSCP is one of the major QoS measures. It is used to reserve the network resources based on priority traffic classes rather than individual service flows [15]. This section shows the impact of the DSCP on the delay performance of the smart grid application. Fig. 10 and Fig. 11 display the effect of having another level of QoS, i.e. differentiated service code point, on the delay performance of the smart grid applications.

Fig. 10 demonstrates the variation in the average delay of the substation automation, distribution automation, outage management and distributed energy resources and storage applications. Substation automation and distribution automation are mapped to the same service flow i.e. rtPS and have an equal inter-arrival time (1 second). However, the substation automation traffic accomplished with lower average delay value. This is due to the fact thatthe DSCP for the substation automation is equal to 67 while the DSCP for the distribution automation is equal to 33. The DSCP code provided an inter-class QoS assurance for the same service flow class. Outage management and distributed energy resources and storage applications are mapped to the same service flow i.e. rtPS have an equal inter-arrival time (5 minutes). However, the outage management application has a higher DSCP value (DSCP =43) than the distributed energy resources and storage (DSCP =44). Therefore, outage management traffic has lower delays values.

Fig. 11 exposes the variation in the average delay of the demand response and demand side management applications. The two applications are mapped to the same service flow i.e. nrtPS and have an equal inter-arrival time (30 minutes). The two applications also have the same DSCP value (DSCP =11). The figure indicates a minor variation in the delay of the two applications.

In both multiple hops architecture, presented here, and single-hop architecture presented in [16], the results clearly show that CB-SPQ achieved the best performance for high priority classes and worst performance for the low priority classes. CB-WFQ achieved relatively medium performance for high priority classes and the best performance for the rest of priority classes. CB-DWRR failed to achieve the best performance under any priority class.

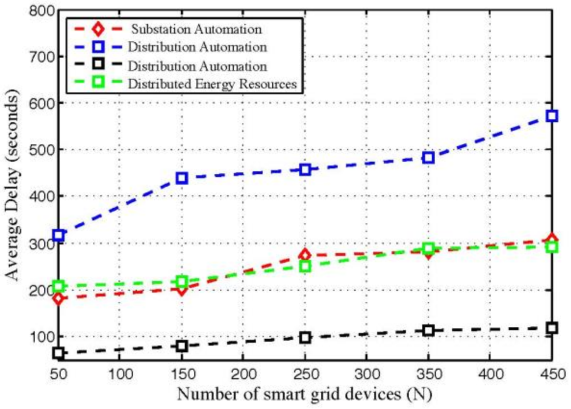

Fig. 10. End-to-End delay of rtPS connections with different DSCP under CB-WFQ

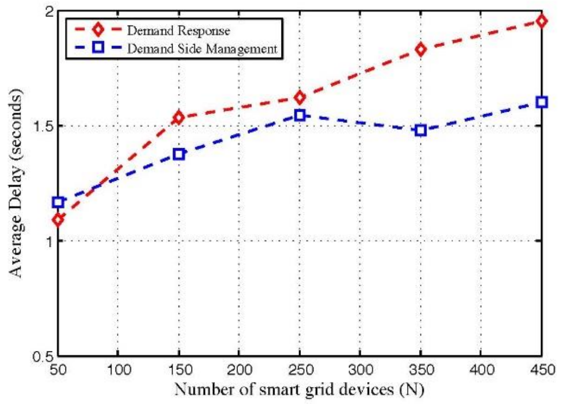

Fig. 11. End-to-End delay of nrtPS connections with the same DSCP under CB-WFQ

For different priority classes and under varying the number of smart grid devices, CB-WFQ, CB-SPQ and CB-DWRR achieved the best performance with the respective percentages of 52%, 48% and 0% in the case of the single-hop architecture, and 40%, 60% and 0% in the case of the multiple-hops architecture. CB-WFQ, CB-SPQ and CB-DWRR achieved the worst performance with the respective percentages of 12%, 40% and 48% for the single-hop architecture, and 60%, 0% and 40% for the multiple-hops architecture.

Depending on the network range, the single hop architecture can be an efficient solution for short-range smart grid network. Multiple hops architecture increases the capacity and coverage, however, scheduling become a challenging problem. It introduces aggregate latency, increased complexity of protocols (routing, management, security), and the overhead involved to compute the route and to find the return path to send the response back is extremely huge.

V. Conclusion

This research has been carried out to design and simulate the IEEE802.16 WiMAX multiple hops deployment model to serve as a wireless communication infrastructure for the smart grid. Based on the bandwidth, latency and service flow of the AMR and AMI+ smart grid applications and communication requirements, the traffic was classified into five priority classes. Three priority queuing algorithms namely; weighted fair, deficit weighted roundrobin, and strict priority queuing. The scheduling algorithms were used to simulate the proposed single and multiple hops network architectures to find the a deployment solution that satisfies the QoS requirements of the smart grid applications.

Each proposed model maps the smart grid applications with the WiMAX MAC service flow types and the differentiated service code point. The simulation results demonstrated that different DSCP values and service flow types affect the delay of the network. It was found that for class (1) applications, no more than 450 smart grid devices should be used to satisfy the latency requirement. For class (2) applications, a maximum of 250 smart grid devices could be placed in one cell in order to satisfy the latency requirement. For both classes and under the recommended number of smart grid devices, it was found that the CB-SPQ scheduling algorithm is the best for the satisfactory performance. For class (3) and class (4) applications, a cell can accommodate a maximum of 150 smart grid devices and the CB-WFQ scheduling algorithm is the best. For class (5) applications, no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best [3].

Possible future research directions include: Investigating the performance of other scheduling algorithms such as the earliest deadline first (EDF), or other hybrid implementations such as the earliest deadline first round robin (EDFRR), other smart grid applications can be included such as video surveillance, and voice data, virtual Private Network (VPN) implementations between the customers premises and the utility control and dispatch center can be investigated, investigating the performance of hybrid wireless and power line network architecture for the smart grid applications, investigating other performance metrics such as the loss rate, the utilization and the throughput, expanding the range of the network for more than two hops and investigating the performance of centralized vs. distributed scheduling of traffic.

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