Optimized WiMAX Profile Configuration for Smart Grid Communications

Fariba Aalamifar and Lutz Lampe, *Senior Member, IEEE*

***Abstract*—Worldwide interoperability for microwave access (WiMAX) is one of the wireless communication technologies adopted for communication in smart grids. Due to the inherent differences between smart grid and mobile broadband applications, it is important to adjust planning and deployment of wireless technologies, including WiMAX. To this end, WiMAX is being amended to feature a smart grid system profile known as WiGrid. In this paper, we investigate the optimized configuration of this WiGrid profile, i.e., the choice of frame duration, type-of-service to traffic mapping, scheduling strategies, as well as the system architecture, such that smart grid communication requirements are met. The simulation-based evaluation of WiGrid networks with optimized configurations is facilitated through a newly developed WiGrid module for the network simulator-3 environment. Our results indicate that a priority-based scheduler is an appropriate solution for scheduling time-critical smart grid applications. Furthermore, schedulers should be implemented in such a way that grant sizes smaller than the packet size are avoided, and adjusting the uplink/downlink bandwidth ratio to favor uplink traffic is important to achieve the required latency defined for smart grid applications.**

***Index Terms*—Worldwide interoperability for microwave access (WiMAX), WiGrid, smart grid communication networks (SGCNs), quality of service (QoS), profile configuration, scheduling strategies, type of service to traffic mapping, network simulator-3 (NS-3).**

I. INTRODUCTION

THE CONCEPT of smart power grids is tightly coupled to the availability of an underlying communication infrastructure that supports the multitude of monitoring, data collection and control tasks foreseen in future smart grids. The U.S. National Institute of Standards and Technology (NIST) [2] and the IEEE Project 2030 [3] have developed reference architecture models for such smart grid communication networks (SGCNs). The IEEE 2030 reference architecture defines three domains, namely Home Area Networks (HANs) at the customer-side, Field Area Networks (FANs) in the distribution section, which can also include Neighbourhood Area Networks (NANs) responsible for collecting the traffic from smart meters, and Wide Area Networks (WANs) in the transmission domain see [4, Ch. 1], [5]. These architectural considerations are technology agnostic, and different wired and wireless technologies including powerline communication, WiMAX and Long-Term Evolution (LTE) compete for use in different SGCN domains, see [4, Ch. 5].

The selection of an appropriate communication technology depends on a number of criteria among which the required network coverage and the types of data traffic with their quality-of-service (QoS) requirements are among the most important. These requirements are specific to the smart grid domain. For instance, HANs cover shorter links compared to FANs and WANs, and scheduling automated devices at home is not as critical as the monitoring, control and protection traffic that occurs in FANs, where incorrect or delayed information can cause major disruptions. Also, environmental characteristics such as user density, which can impact the required network capacity, and network accessibility, considering that some technologies might be unavailable in certain areas, affect the choice of technology.

WiMAX is a 4th generation broadband wireless technology and based on the IEEE 802.16 series of standards. Its features are consistent with the communication and QoS requirements occurring in FAN and WAN implementations. In particular, WiMAX offers long-range coverage, high data rate, and helps to meet the diverse service requirements from smart grid applications through its available set of service types.

The viability of WiMAX technology for NANs and FANs has been investigated in the literature, several field trials [6], [7], and recent surveys [8], [9]. Under the umbrella of the NIST Priority Action Plan (PAP) 2 guideline [10], range and capacity analyses have been conducted for different usage models to give some insights of the capability of WiMAX technology for backhauling smart metering traffic. References [11] and [12] consider a heterogeneous Wireless Local Area Network (WLAN)-WiMAX technology for collecting and backhauling smart metering traffic. This allows for extending the network coverage and improving the link quality. Aguirre *et al.* [13] formulate the capacity provided by WiMAX in order to estimate the number of smart meters that can be served using this technology. References [1] and [14] investigate the performance of WiMAX technology considering different sets of FAN applications and network architectures.

The aforementioned works and others such as [15]–[17] generally confirm that WiMAX is a viable choice for FAN and NAN applications. Furthermore, it is implied that when

Manuscript received September 30, 2015; revised January 2, 2016; accepted February 22, 2016. This work was supported in part by the Powertech Labs Inc., in part by the Mathematics of Information Technology and Complex Systems Internship Program, and in part by the Natural Sciences and Engineering Research Council of Canada. A part of this paper has been presented in [1]. Paper no. TSG-01239-2015.

The authors are with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC V6T1Z4, Canada (e-mail: faribaa@ece.ubc.ca; lampe@ece.ubc.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2016.2536145

wireless technologies are designed for smart grid implementation, they should be configured differently than when used for mobile broadband (MBB) applications for which they were originally designed. For example, MBB applications are downlink (DL) centric, while uplink (UL) traffic dominates in many smart grid applications. Automated devices in smart grids generate relatively small per-device traffic, which results in large aggregate data rates though. Furthermore, the coverage provision is mandatory, while it is only highly desirable in cellular networks [18]. Pertinent discussions in the literature include [12], [16], and [19], which propose a type-of-service to traffic mapping for smart metering via WiMAX, and optimizes the base station (BS) transmission power, respectively.

In light of this, the WiMAX Forum has defined a new system profile based on the IEEE 802.16 series of standards considering smart grid requirements [20]. This so-called WiGrid profile is developed in a two-phase approach known as WiGrid-1 and WiGrid-2. In the first phase, the advantages of the current features that already exist in the IEEE 802.16e and IEEE 802.16m standards are taken into account. The typical configuration of these features is modified considering smart grid network characteristics and requirements. In the second phase, the advantages of the existing amendments developed in the IEEE 802.16p and IEEE 802.16n standards, respectively, designed for enabling machine-to-machine (M2M) communication and increasing the network reliability for WiMAX networks, are taken into account. An overview of these two standard amendments has been presented in [21], where smart grid is recognized as one of the use cases which requires both greater network reliability and M2M communication. In the second phase, these two standards will further be amended with features specifically designed for SGCNs. So far, the WiMAX Forum has mostly focused on the first phase of the WiGrid development and suggested several modifications to the current WiMAX configuration. These modifications are summarized in the "WiMAX Forum System Profile Requirements for Smart Grid Applications" [18]. They include a dynamic Time Division Duplexing (TDD) UL/DL ratio from 1 to 1.75 and the support of 64QAM transmission.

In this paper, we also focus on the first phase of the WiGrid development and optimize the configuration and/or implementation method for several other existing WiMAX features namely, frame duration, type-of-service to traffic mapping, and scheduling solution. This optimization is conducted such that the key QoS requirements namely, latency and reliability,[1] for SGCNs are best met. In particular, our main contributions are summarized as follows.

1) We identify the characteristics and requirements associated with each smart grid traffic class and devise a scheduling solution such that on-time and reliable arrival of mission-critical traffic can better be assured. The devised scheduler also ensures that the traffic is fairly collected from automated devices within the same traffic class.
2) We investigate an optimized configuration of the abovementioned WiMAX features under what we call "profile configuration". Different such profile configurations are compared considering both smart metering and distribution automation traffic. The latter is different from most of the literature, which only focuses on smart metering traffic, e.g., [9]–[12], [19], and [23].
3) We present a WiGrid NS-3 module [24] to facilitate the simulation of SGCNs for both the academic research and industry case studies around the world. Using this module, we evaluate the performance of the developed WiMAX profile configurations for smart grid communication scenarios with realistic parameters for the number of automated devices and their associated data traffic patterns based on [18] and [25].

The rest of this paper is organized as follows. In Section II, the paradigm for optimized profile configuration for WiGrid is developed. In Section III, the amendments that have been applied to the NS-3 environment in order to develop the WiGrid module are explained. In Section IV, WiGrid simulation results are presented and discussed. Finally, conclusions are provided in Section V.

II. OPTIMIZED WIMAX PROFILE CONFIGURATION

Considering the first phase of the WiGrid development, in this section we discuss the effects and selection of WiMAX frame duration (Section II-A), types-of-service to traffic mapping (Section II-B), scheduling (Section II-C), unsolicited grant allocation scheme (Section II-D) and system architectures (Section II-E) for communication in smart grid FANs.

A. Frame Duration and Latency

In WiMAX, the physical layer frame is divided into a DL subframe and an UL subframe. Possible values for the total frame duration depend on the type of physical layer. In the orthogonal frequency-division multiplexing (OFDM) physical layer, the frame duration can be either 2.5, 4, 5, 8, 10, 12.5, or 20 ms. For orthogonal frequency-division multiple access (OFDMA), 2 ms is also possible [26]. Although seven or eight different values can be considered for frame duration, 5, 10 and 20 ms are most commonly used in network configurations. This is because larger frame durations cause less fragmentation and consequently, less resources are wasted. The 20 ms frame duration is however not recommended for smart grid communication as the resources are not given fast enough for several latency-critical applications. On the other hand, scheduling resources in a relatively short frame duration of 5 ms is challenging specially when the network is almost fully loaded. Therefore, depending on the network load and the required latency for the defined applications we suggest using either a 5 ms or a 10 ms frame duration.

B. Mapping WiMAX Scheduling Types to Smart Grid Traffic Classes

WiMAX offers five types of services namely unsolicited grant service (UGS), real-time polling service (rtPS), extended rtPS (ertPS), non-real-time polling service (nrtPS) and best

---

[1] Reliability is defined as the probability that a packet is successfully received by the destination within a certain deadline [22].

TABLE I
TRAFFIC CLASSES AND THEIR PROPERTIES AND QoS REQUIREMENTS [18]

Flow ID	Use case	Direction	Packet Size (Bytes)	Data rate (kbps)	Active/idle (s)	Latency (ms)	Traffic Type	**Proposed Scheduling Type**
0	Situational awareness	UL	256	5.0	1/5	1000	Deterministic	**nrtPS**
1	Monitoring	UL	384	300	Continuous	100	Deterministic	**UGS**
2	Control	UL	128	5.0	1/5	100	Random	**rtPS**
3	Protection	UL	192	150	Continuous	20	Random	**ertPS**
4	Smart metering	UL	256	1.0	0.1/4.0	5000	Deterministic	**BE**
5	Situational awareness	DL	256	1.0	1/5	1000	Deterministic	**nrtPS**
6	Monitoring	DL	128	10.0	Continuous	100	Deterministic	**UGS**
7	Control	DL	128	1.0	1/5	100	Random	**rtPS**
8	Protection	DL	192	150	Continuous	20	Random	**ertPS**

effort (BE) to support multiple levels of QoS that are needed for serving traffic classes with different characteristics and requirements [27]. In this part, we discuss how the offered WiMAX scheduling types should be used in order to address the requirements associated with FAN applications. The characteristics of FAN traffic classes are adopted from [18] and presented in Table I. The last column of this table will be explained in the following.

The UGS scheduling type is inherently suitable for serving constant-bit-rate (CBR) applications as it provides fixed-sized grants periodically. Furthermore, since UGS guarantees the bandwidth, it is a suitable choice for traffic that requires low latency and high reliability. Therefore, we choose the UGS scheduling type for serving the monitoring traffic which is a CBR application and requires low latency.

Whenever we have a real-time variable-bit-rate (VBR) traffic that requires low latency and high reliability, rtPS scheduling type can be used for serving such an application where the required bandwidth is requested through the available unicast request opportunities. For example, rtPS can be used for serving control application which is a real-time VBR traffic that requires 100 ms latency.

However, rtPS can hardly satisfy the much lower latency and higher reliability requirements associated with, e.g., protection applications compared to control traffic. This is because when rtPS scheduling type is used, many data requests should be transmitted, which adds to the latency and bandwidth overhead. In this case, we suggest using ertPS by reserving bandwidth according to the current maximum data rate associated with the traffic flow. When needed, a change of the size of UL allocations can be requested through available unicast opportunities provided by the BS, which can be used for both data transmission and bandwidth requests [27].

As the nrtPS scheduling type offers unicast request opportunities rarely, it is suitable for serving the traffic that requires partial bandwidth guarantee. Therefore, we use the nrtPS scheduling type for serving situational awareness traffic that is relaxed in its latency requirement while still requiring a latency lower than that for smart metering traffic. Since the BE scheduling type mainly offers contention-based request opportunities, it is suitable for serving the traffic with non-sensitive delay requirement such as firmware upgrades or smart metering traffic. We have also provided a general guideline in Table II which shows when to use each scheduling type for serving different types of applications.

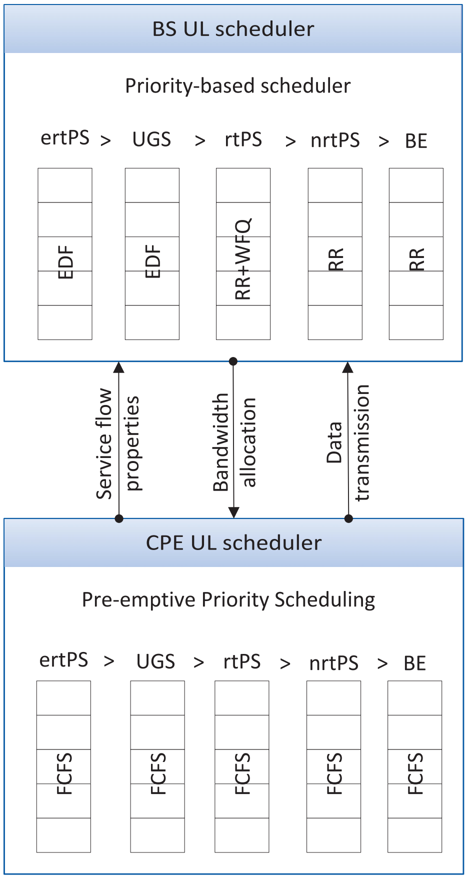


Fig. 1. Proposed WiGrid scheduling framework.

C. Scheduler

The IEEE 802.16 standard allows vendors to implement their own schedulers in the BS and CPE devices. The BS allocates bandwidth to the CPE devices according to their connection properties. However, the user itself decides how to distribute this bandwidth among its service flows [28]. Generally, the schedulers at both the BS and CPE devices are composed of two steps: 1) inter-class scheduling and 2) intra-class scheduling methods [29]. Figure 1

TABLE II
APPROPRIATE TYPE OF SERVICE FOR DIFFERENT APPLICATIONS

Application Type (CBR/VBR)	Latency Requirement	Reliability	Appropriate Scheduling Type
CBR	low	high	UGS
VBR	low	high	rtPS
VBR	very low	high	ertPS
CBR/VBR	intermediate	intermediate	nrtPS
CBR/VBR	relaxed	intermediate	BE

illustrates the scheduling framework we have developed for WiGrid.

1) Inter-Class Scheduling Policy: As the arrival of certain traffic classes, specifically protection and monitoring, are essential for the survivability of the power grid, we employ a priority-based scheduling strategy as the inter-class scheduling methods in both BS and CPE devices. The priority-based scheduler considers the scheduling type priorities across all the nodes with the following order: ertPS > UGS > rtPS > nrtPS > BE, where A > B means scheduling type A is served before type B. In addition, a pre-emptive policy is employed by the CPEs so that by the arrival of a higher priority traffic, the transmission of a lower priority one stops immediately.

2) Intra-Class Scheduling Policy: Since protection and monitoring are both receiving unsolicited grants and they require low latency, we apply an earliest deadline first (EDF) scheduling policy to advance serving traffic flows with earlier deadline. Since rtPS control traffic follows a random distribution and it also requires low latency, we poll it in a round-robin (RR) manner and serve it according to a weighted fair queueing (WFQ) scheduling policy so that no service flows are starved and at the same time, we give a higher weight to the service flows with earlier deadline and currently higher rate. For more details on the implementation of WFQ, please refer to Section III (item number 3). As the situational awareness and smart metering are deterministic traffic with low priorities, we give them a fixed bandwidth in an RR manner only if bandwidth is still available after serving the higher priority flows.

D. Unsolicited Grant Allocation Strategies

Two different algorithms namely average (AVG) and Grant/Interval have been proposed in the literature for allocating unsolicited grants to the service flows. Here, we compare the advantages and disadvantages of each method for SGCN and then, we propose the appropriate grant size that should be given to the service flows when Grant/Interval allocation algorithm is used.

1) Average (AVG) Allocation Algorithm: In this method, in every uplink subframe a fixed amount of resource is assigned to the connection [30]. The grant size is computed according to the minimum reserved traffic rate configured for the flow as

$$\begin{aligned} \mathit{GrantSize}(\mathit{Byte}) &\doteq \mathit{BytesPerFrame} \\ &\doteq \mathit{MinReservedTrafficRate}(\mathit{bps}) \\ &\quad \times \mathit{FrameDuration}(s)/8. \end{aligned} \tag{1}$$

As the AVG algorithm distributes the grants over all frames, fitting the whole packet would not be possible in the small grant size of each frame. Therefore, many packet fragmentations may occur, especially for low data rate traffic. This would in turn cause a large latency and low throughput. The AVG algorithm may also cause resource wastage since it allocates grants every frame ignoring the fact that there might be no data available for transmission.

2) Grant/Interval Allocation Algorithm: To overcome the fragmentation problem in the AVG algorithm, we suggest using the Grant/Interval algorithm which allocates larger grants based on the packet size and the traffic generation interval. This means that in every interval, a grant equal to the packet size is given to the service flow [27]. However, if the interval is less than one frame duration, the amount of generated data per frame would be more than one packet size and therefore, every frame a grant equal to the generated data size should be allocated for the service flow. In summary, we propose to allocate the grant size as

$$\mathit{GrantSize} = \begin{cases} \mathit{BytesPerFrame}, & \text{if } \mathit{Interval} < \\ & \mathit{FrameDuration}, \\ \mathit{PacketSize}, & \text{otherwise.} \end{cases} \tag{2}$$

The Grant/Interval algorithm is more complex to implement compared to the AVG algorithm, since a timer is required for tracking the interval. Despite its complexity, there are several advantages associated with this algorithm. Firstly, it maximizes the bandwidth utilization through allocating the grants whenever needed. Furthermore, in order to avoid undesired latency, the BS can be provided with the synchronization information of the application in CPE so that the grants can be scheduled at appropriate frames [27]. According to the above discussion, we conclude that the Grant/Interval allocation algorithm is suitable for SGCNs that have several critical low data rate traffic classes.

E. Architecture

There are two possible modes through which automated devices can transmit their information to the utility control center in a FAN: direct access and aggregation mode [1, Fig. 2]. In the direct access mode, all automated devices transmit their information directly to the WiMAX BS, which is connected to the utility control center. On the other hand, in the aggregation mode, a data aggregator is responsible for collecting the traffic from several automated devices and forwarding it to the WiMAX BS.

Although the aggregator architecture is more costly and harder to deploy, it has the following merits concluded from our previous study [1] compared to the direct access mode for smart grid implementation.

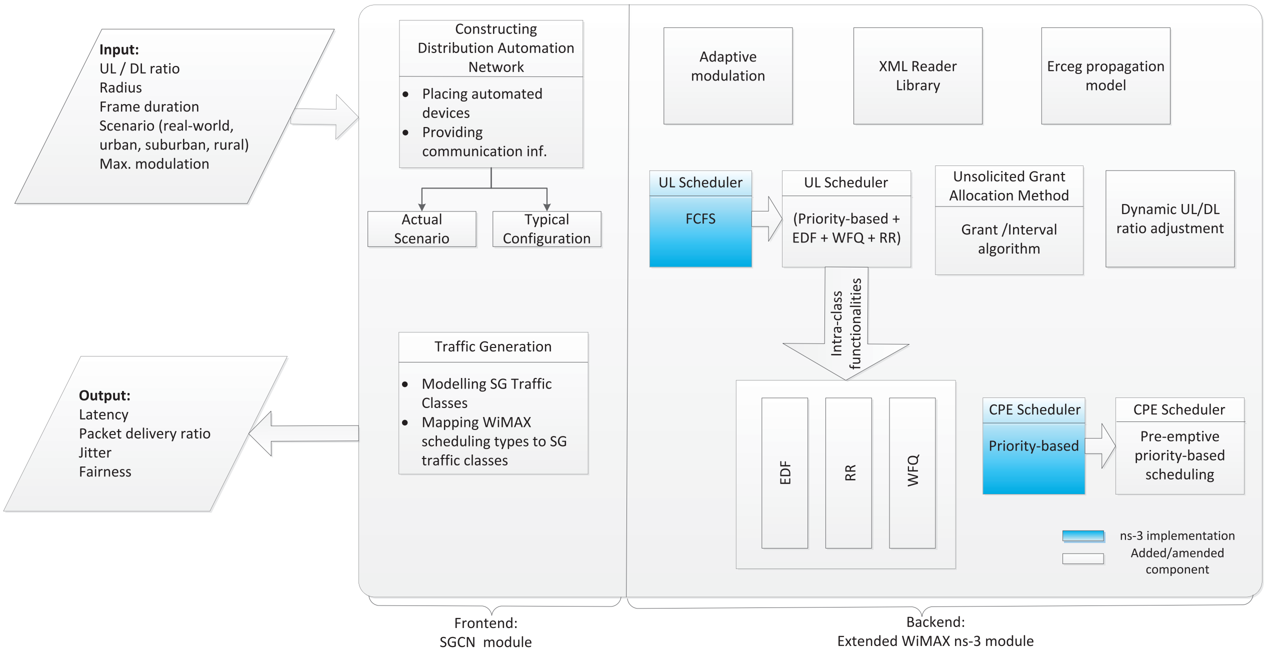


Fig. 2. The WiGrid NS-3 module.

1) The obtained throughput is often higher, since there are fewer active connections to the BS and therefore the collision and packet loss probabilities decrease.

2) The case that collisions among active connections to the BS happen can be dealt with better [31]. The solution for collision avoidance is to back-off and decrease link data rates. In direct access mode, the data rate associated to each device is already low and lowering it further does not make much difference. However, since the aggregate data rate is higher, decreasing it can resolve congestion faster.

3) A larger number of nodes can be supported. This is because of the data compression that is usually conducted at the data aggregators as well as the better link qualities experienced by data aggregators mounted for example, on top of transmission-line poles, and also automated devices as their link distances are decreased.

The above advantages make the aggregation mode a preferable choice for SGCNs with plenty of low data rate automated devices.

III. AMENDMENTS FOR A WiGRID MODULE

We have developed a software module based on the WiMAX module of the NS-3 [32], [33] which can be used for performance studies and capacity planning of WiGrid systems. The features of this module are illustrated in Figure 2. The WiGrid simulator consists of a front-end SGCN module and the back-end extensions made into the WiMAX module of the NS-3.

The front-end interface constructs an SGCN topology and communication infrastructure based on the user's input. The user can either ask for a typical rural, suburban or urban scenario, or pass an XML file containing the network information of a certain actual scenario. In the typical case, the numbers of automated nodes and smart meters located in each area type are set according to the BC Hydro distribution automation implementation plan [25]. Similarly, all related configurations for the base station and automated devices such as transmission power and antenna height are taken from smart grid projects conducted by BC Hydro and Powertech Labs Inc. The traffic within distribution automation networks is modelled according to the traffic patterns given by [18] and as shown in Table I. Further details on this are given in Section IV.

The specific enhancements made into the backend module are as follows.

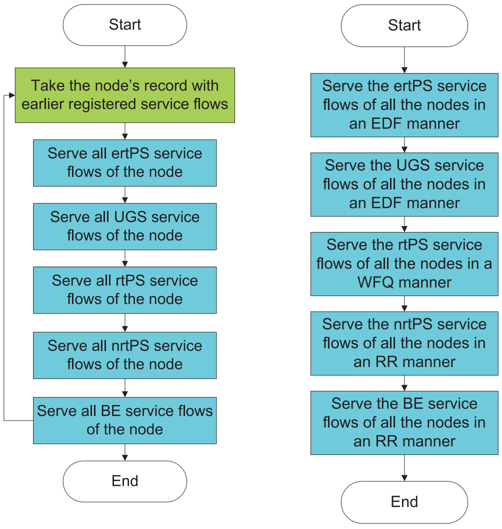
1) We have defined a new setSubFrameRatio function which accepts an arbitrary UL/DL ratio as an argument. This function can be called at the start of each frame for dynamic UL/DL ratio adjustments.

2) We have implemented the priority-based scheduler together with the intra-class scheduling policies at the uplink scheduler of the BS as discussed in Section II. Figures 3(a) and 3(b) respectively show the flowcharts of the existing FCFS and the new priority-based uplink schedulers in NS-3. As can be seen in the figure, at each step of the FCFS algorithm, the record of the node[2] that has registered its service flows earlier is chosen and then all its service flows are scheduled according to ertPS $>$ UGS $>$ rtPS $>$ nrtPS $>$ BE. In the priority-based scheduler, the service flows with the same scheduling type (starting from ertPS) from all nodes are stored in a priority queue and served according to its related intra-scheduling policy. Then, the algorithm conducts the same procedure for the service flows of other scheduling types across all the nodes with the order mentioned above.

3) In order to implement WFQ among rtPS service flows, we apply the following procedure. First, we allocate the bandwidth to the users whose latencies are going to expire in

---

[2] The node's record contains the information about all the node's service flows that have already been registered at the BS.



(a) (b)

Fig. 3. The flowcharts of the (a) FCFS and (b) priority-based UL schedulers.

TABLE III
MAJOR USE-CASE CATEGORIES AND ASSOCIATED DEVICE CLASSES AND NUMBER OF DEVICES IN A CIRCULAR AREA OF 2 km RADIUS ACCORDING TO [10] AND [25]

Use-Case and Devices	Number of devices	
	Rural	Suburban
Monitoring	**≈ 16**	**≈ 32**
Recloser	6	9
Capacitor fixed	2	3
Regulator	1	1.5
Fault Circuit Indicator	5	15
Feeder meter	1	3
Feeder sensor	0.6	0.6
Situational Awareness	**≈ 8**	**≈ 18**
Powerline/Transformer sensor	3/2	5/4
Capacitor Switched	3	9
Control	**≈ 10**	**≈ 18**
Recloser	6	9
Capacitor switched	2	6
Regulator	1	1.5
Feeder sensor	0.6	1.6
Protection	**≈ 3**	**≈ 11**
Recloser	3	4.5
Automated switch	0	6
Smart Metering	**≈ 120**	**≈ 3350**

the next frame duration. For the remainder, we employ the same scheme as proposed in [33]. In particular, the bandwidth requests from all CPE devices are added together. In case the size of the total bandwidth requests is greater than the remaining bandwidth for allocation, the difference is divided by the number of users and deducted equally from all the requesters. Hence, it is ensured that no service flow is starved and also more bandwidth is allocated to the service flow with higher current rate.

4) For allocating unsolicited grants to the traffic, we implement the Grant/Interval algorithm instead of the original NS-3 AVG algorithm. The size of the grants are determined according to Equation (2).

5) Adaptive modulation is not supported in the current NS-3 version. As smart grid devices are usually fixed, we assume that the channel quality stays constant and therefore, we assign each device with a constant reliable modulation at the start of the program based on its signal to noise ratio characteristic. Modulation and coding rate can be selected according to the required reliability, see [22].

6) Network specifications are usually given in XML files. To this end, we have created an automatic XML reader library which reads the XML tags from the file and passes the extracted network characteristic data such as modulation, antenna height, transmission power and coordinates into the simulator.

7) The NIST PAP2 guideline [10] recommends the Erceg SUI propagation model to emulate the signal attenuation for the rural and suburban scenarios. Therefore, the implementation for this propagation model has been added to the NS-3 WiMAX module.

In addition to the modifications described here, several errors including incorrect configuration of node properties in the COST231 propagation model, incorrect mapping of signal-to-noise ratio (SNR) to block-error rate (BLER) and incorrect frame length computation have been corrected. The modified NS-3 module and the detailed list of fixed bugs and extensions has been made available at [24].

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we apply the considerations and methods from Section II and use our developed simulator from Section III to quantify the effects of different system parameters to characterize an optimized WiGrid profile configuration for FAN scenarios in SGCNs.

As mentioned in Section I, latency and reliability are key QoS requirements for SGCNs [7], [34], [35]. Therefore, we first compare the performance of different profile configurations in terms of average latency and the percentage of packets that are reliably received by the destination for different traffic classes. We also study the capability of each WiGrid-1 feature in terms of the reliability improvement that can be obtained considering different numbers of automated devices. Finally, we evaluate the fairness index for each traffic class using our proposed scheduling algorithm. Note that simulation results for comparing the direct and aggregator architectures are provided in [1].

A. *Simulation Settings*

We consider rural and suburban distribution networks within a circular area of 2 km radius for simulations. Typical numbers of automated nodes and smart meters located in this area obtained from the BC Hydro distribution automation implementation plan [25] and the NIST PAP2 document [10], respectively, are summarized in Table III with a categorization according to the use cases from Table I. Table IV summarizes the default signal propagation and system settings considered for the following results. In this table, RS+CC/CC refers to Reed Solomon with convolutional coding/inner-checksum coding [27].

TABLE IV
DEFAULT SETTINGS FOR WiGRID SIMULATIONS

Scenario	Suburban
Path Loss	Erceg Type-B [10]
Fading	Rayleigh
Scheduler	FCFS
Unsolicited Grant Allocation	Grant/Interval
UL/DL Ratio	1.75
Bandwidth	10MHz
Phy Layer	OFDM
Modulation	64QAM
Number of Sectors	3
MAC Protocol	TDMA
Duplexing	TDD
FEC Code Rate/Type	3/4 / RS+CC/CC
Frame Duration	10 ms
Architecture Type	Aggregation

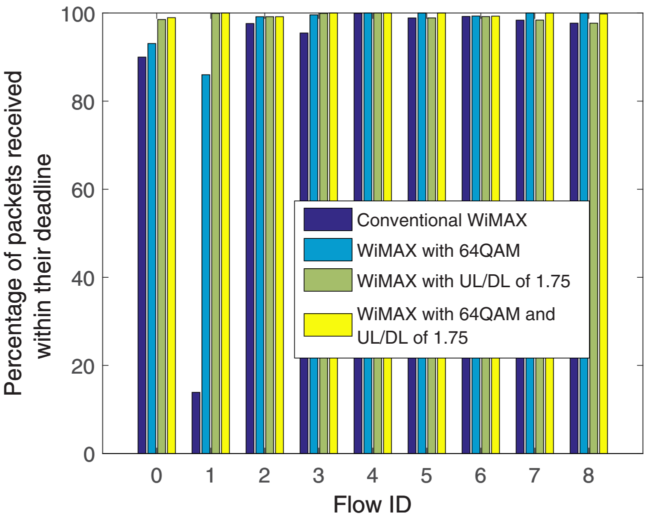


Fig. 4. The effect of WiGrid amendments on the percentage of packets correctly received within the deadline.

The traffic classes listed in Table I are modelled according to the following assumptions. The NS-3 on/off applications are used for all traffic classes. For deterministic traffic, constant values for the on-time and off-time periods are considered. In order to model the random traffic, the packet inter-arrival time (off-time) follows an exponential distribution where the mean is equal to either the idle period (e.g., for flow IDs 2, 7) or the *PacketSize/DataRate* (e.g., for flow IDs 3, 8). It should also be noted that for the random traffic there is a small probability that the packet arrival rate exceeds the available resources. In that case, the scheduling of packets is delayed beyond the latency requirement.

B. UL/DL Ratio and Modulation Type

In conventional WiMAX, support of modulation types higher than 16QAM is optional and the UL/DL ratio is typically configured to be close to 1. As discussed in Section I, because of the larger UL traffic in SGCNs, a UL/DL ratio of 1.75 and the support of 64QAM has been proposed by the WiMAX forum. In order to investigate the effect of these amendments on WiGrid performance, we consider the following four scenarios: i) a conventional WiMAX configuration (maximum supported modulation of 16QAM and UL/DL ratio of 1), ii) WiMAX with support of 64QAM, iii) WiMAX with UL/DL ratio of 1.75, and iv) WiMAX with both amendments. Figure 4 shows the results in terms of the percentage of packets that are correctly received within their deadline. As can be seen, the support of 64QAM modulation increases the percentage of packets that are reliably received for both UL and DL. The increase is more significant for flow ID 1 (monitoring) which has a high data rate traffic and is associated with a higher number of automated devices. Increasing the UL/DL ratio to 1.75 also increases the percentage of packets received in the UL without compromising the DL traffic. The UL improvement due to increasing the UL/DL ratio is somewhat more pronounced compared to that when supporting a higher modulation, since it also benefits the nodes that are farther from the BS. An increase in the packet reception is also noted for flow ID 0 when both amendments are applied. For the other flows, only slight improvements are achieved with a UL/DL ratio of 1.75 and WiMAX supporting 64 QAM.

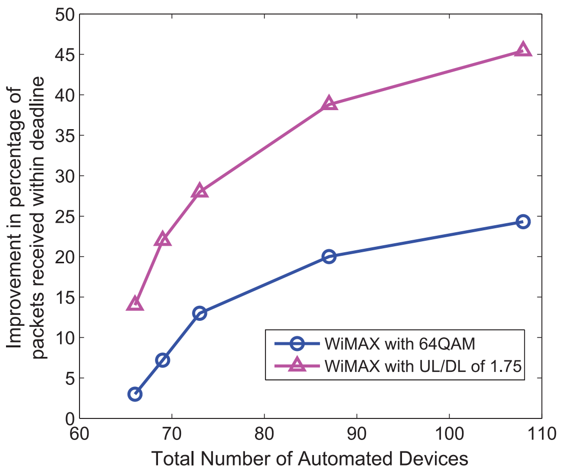


Fig. 5. Comparing the effect of 1) supporting 64 QAM and 2) increasing UL/DL bandwidth ratio to 1.75 for the improvement of the packet delivery ratio for different numbers of automated devices.

C. Scalability and Supporting Higher UL/DL Ratio and Modulation Type

Figure 5 illustrates the improvement of timely packet delivery that can be obtained when either resource efficiency is increased or more resources are allocated for the uplink transmission. We observe that the improvement is more significant when a higher UL/DL bandwidth ratio is applied. This is due to the uplink dominated traffic in SGCNs and the fact that the required bandwidth for remote nodes can only be provided when a higher UL/DL bandwidth ratio is employed. We also note that as the number of nodes increases, the rate of improvement decreases which indicates the bandwidth saturation for a certain number of nodes.

D. Frame Duration

We now turn to the effect of different frame durations on the performance in terms of the experienced latency, latency variation and the percentage of reliably received packets.

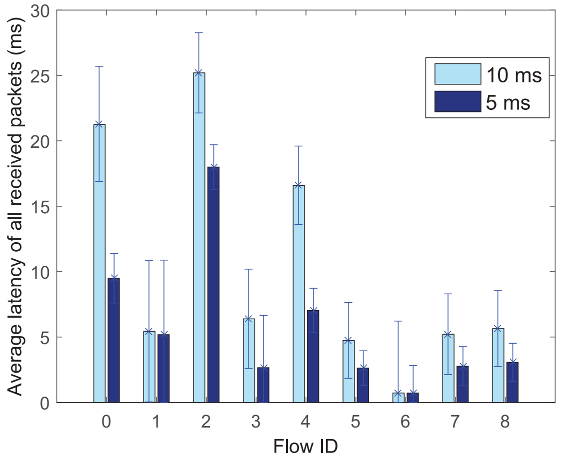


Fig. 6. The effect of different frame durations on average latency for the rural scenario. The error bars indicate delay variations.

TABLE V
FAIRNESS INDICES FOR FCFS AND PRIORITY-BASED SCHEDULERS

Scheduler / Flow ID	0	1	2	3	4
FCFS	1.0	0.78	0.86	0.98	1.0
Priority-based	0.99	1.0	0.97	1.0	1.0

The results for the rural scenario are shown in Figure 6, and for the suburban scenario in Figures 7 and 8. Error bars in Figures 6 and 7 indicate the latency variations.

Focusing on the rural scenario, we first note that almost all packets are received successfully (more than 99% for all service flows) under both frame durations.[3] However, as can be seen in Figure 6, latencies decreased notably when a 5 ms frame duration is employed. This is because of the faster allocation of resources in the case of shorter frame duration, which causes service flows to experience less waiting time when they request bandwidth. Turning now to the suburban scenario with higher device density and thus traffic demands, it can be seen from Figures 7 and 8 that the network can easily become overloaded and suffer from high latency and delay variation (e.g., flow ID 1)[4] and packet loss (e.g., flow IDs 1 and 3) if the relatively short frame duration of 5 ms is used. This is due to the fact that fewer number of grants are available in each frame, leading to frequent packet fragmentation. We conclude that the 10 ms frame duration is preferred for heavily loaded FANs as considered in the suburban scenario. We also note that the delay variations for all flows in stable scenarios (suburban with 10 ms and rural with both frame durations) are small.

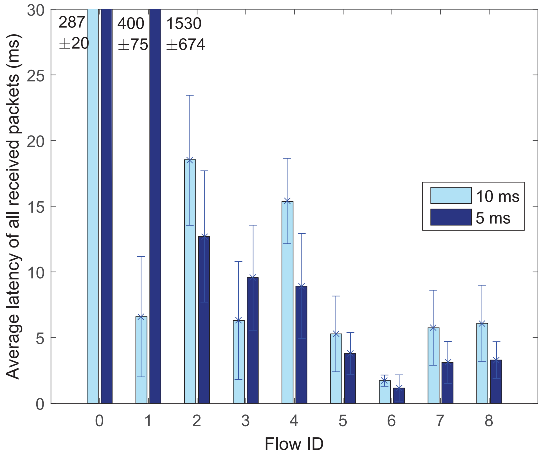


Fig. 7. The effect of different frame durations on average latency and delay variations for the suburban scenario.

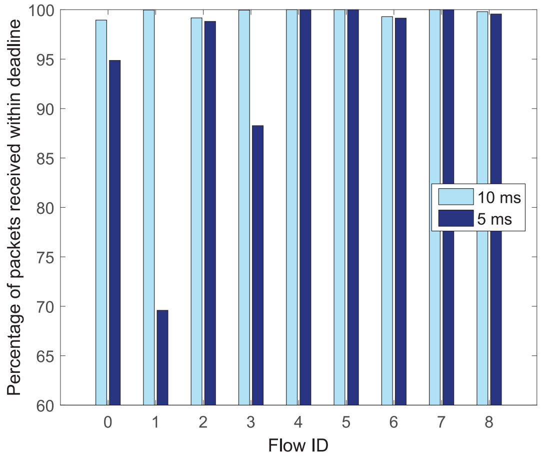


Fig. 8. The effect of different frame durations on the percentage of packets correctly received within their deadline for the suburban scenario.

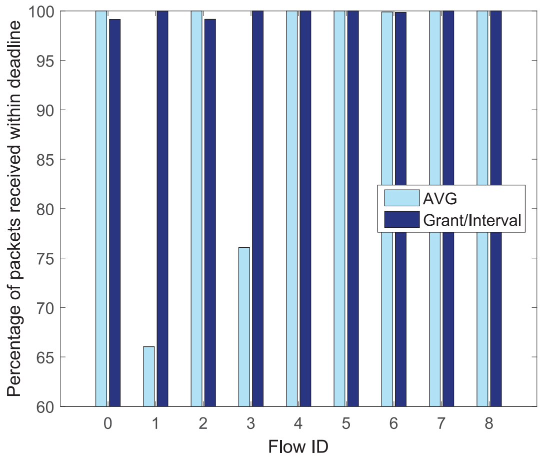


Fig. 9. Comparing AVG and Grant/Interval unsolicited grant allocation strategies.

E. Unsolicited Grant Allocation Strategies

The different allocation methods for scheduling unsolicited grants, presented in Section II-C, are now compared considering the rural FAN scenario. Figure 9 shows the percentage of reliably received packets for the AVG and Grant/Interval allocation algorithms for the rural scenario. We observe that the AVG algorithm causes packet loss for the traffic in flow IDs 1 and 3. The AVG algorithm wastes resources through allocation when there is no traffic. Furthermore, the required grants are distributed over all the UL subframes, so that only a few symbols are granted at each UL subframe. This causes extra

---

[3] As the received percentages for all service flows for this case are almost the same and more than 99%, the result figure is omitted.

[4] Flow ID 0 experiences 400 ms latency which is still within the deadline.

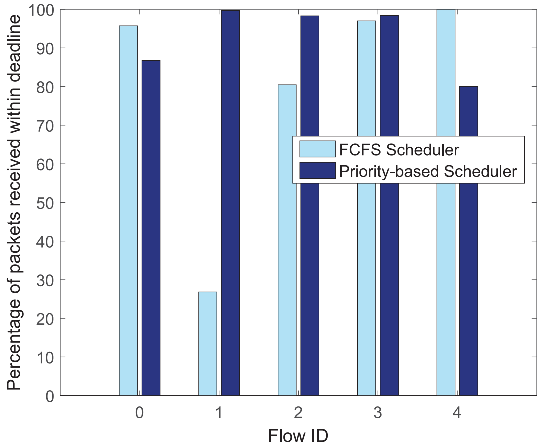


Fig. 10. Comparing FCFS and priority-based uplink schedulers for the suburban scenario with radius of 2.2 km.

TABLE VI
OPTIMIZED PROFILE CONFIGURATION FOR THE FAN TRAFFIC

Scheduler	Priority-based
Unsolicited Grant Allocation Strategy	Grant/Interval
Maximum Supported Modulation Type	64QAM
UL/DL Ratio	1.75
Frame Duration	5 ms (normal load, rural), 10 ms (high load, suburban)
Traffic Class	**Scheduling Type**
Situational awareness	nrtPS
Monitoring	UGS
Control	rtPS
Protection	ertPS
Smart metering	BE

overhead due to packet fragmentation. This is prevented by the application of the Grant/Interval algorithm in the scheduler implementation, which thus appears to be preferable.

F. Comparing Two Schedulers

Finally, in order to show the importance of scheduling smart grid traffic classes based on their priorities, we consider a higher load circular suburban area of 2.2 km radius where the number of monitoring nodes is increased to 39. As can be seen in Figure 10, the priority-based scheduler at both the BS and CPE devices improves the percentage of the packets that are reliably received for higher-priority flow IDs, namely flow IDs 1 (UGS), 3 (ertPS) and 2 (rtPS) by de-prioritizing lower-priority ones, namely flow IDs 0 (nrtPS), and 4 (BE).

We have also computed the fairness indices that can be obtained from both schedulers according to Jain's fairness index [36] and compared them in Table V. Fairness here is defined as the percentage of packets that have successfully delivered to the destination from each automated device. We observe that the intra-scheduling methods we have employed in the priority-based scheduler notably improve the fairness among different automated devices. For example, the EDF scheduling method we have applied for scheduling monitoring traffic, flow ID 1, ensures the latency satisfaction of the packets originated from different devices. The marginal difference seen for flow ID 0 is due to the logic of the priority-based scheduler, which de-prioritizes lower priority traffic and therefore, a few nrtPS nodes did not receive the same bandwidth as others.

We conclude from the above scenarios that the combination of all the optimized features as summarized in Table VI leads to an optimized profile configuration that better meets the latency and throughput requirements of FAN traffic.

V. CONCLUSION

In this paper, an optimized WiMAX profile configuration that consists of the selection of scheduling strategies, type-of-service to traffic mapping, and frame duration was investigated. Our conceptual considerations were complemented through simulations enabled by modifications to the WiMAX NS-3 module that includes WiGrid amendments. Our numerical results for two SGCN scenarios suggest that a 5 ms frame duration is advisable for rural areas while, for higher density areas a 10 ms frame duration is suggested as it can still satisfy network requirements but avoids many packet fragmentations that would occur with a shorter frame duration. We have also shown that priority-based scheduler is consistent with smart grid objectives where the reliable reception of mission-critical traffic must be assured. Finally, the advantages associated with an aggregator architecture make it often a preferable choice for SGCN implementations.

ACKNOWLEDGMENT

The authors would like to thank Mr. Eugene Crozier (Powertech Labs Inc.) for his valuable insights about WiGrid developments and SGCNs.

REFERENCES

[1] F. Aalamifar, L. Lampe, S. Bavarian, and E. Crozier, "WiMAX technology in smart distribution networks: Architecture, modeling, and applications," in *Proc. IEEE PES T&D Conf. Expo.*, Chicago, IL, USA, Apr. 2014, pp. 1–5.

[2] G. Locke and P. D. Gallagher, "NIST framework and roadmap for smart grid interoperability standards, Release 1.0," Office Nat. Coordinator Smart Grid Interoperability, U.S. Dept. Commerce, Nat. Inst. Standards Technol., Gaithersburg, MD, USA, Tech. Rep. 1108, Jan. 2010.

[3] *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation With the Electric Power System (EPS), End-Use Applications, and Loads*, IEEE Standard 2030-2011, pp. 1–126, Sep. 2011.

[4] E. Hossain, Z. Han, and H. V. Poor, Eds., *Smart Grid Communications and Networking*. New York, NY, USA: Cambridge Univ. Press, 2012.

[5] W. Wang, Y. Xu, and M. Khanna, "A survey on the communication architectures in smart grid," *Comput. Netw.*, vol. 55, no. 15, pp. 3604–3629, 2011.

[6] R. Ma, H.-H. Chen, Y.-R. Huang, and W. Meng, "Smart grid communication: Its challenges and opportunities," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 36–46, Mar. 2013.

[7] V. C. Güngör *et al.*, "Smart grid and smart homes: Key players and pilot projects," *IEEE Ind. Electron. Mag.*, vol. 6, no. 4, pp. 18–34, Dec. 2012.

[8] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Communication network requirements for major smart grid applications in HAN, NAN and WAN," *Comput. Netw.*, vol. 67, pp. 74–88, Jul. 2014.

[9] E. Bou-Harb, C. Fachkha, M. Pourzandi, M. Debbabi, and C. Assi, "Communication security for smart grid distribution networks," *IEEE Commun. Mag.*, vol. 51, no. 1, pp. 42–49, Jan. 2013.

[10] (2012). *NIST PAP2 Guidelines for Assessing Wireless Standards for Smart Grid Application*. [Online]. Available: http://tinyurl.com/NIST-PAP2-Guidelines.

[11] R. H. Khan and J. K. Khan, "A heterogeneous WiMAX-WLAN network for AMI communications in the smart grid," in *Proc. IEEE 3rd Int. Conf. Smart Grid Commun. (SmartGridComm)*, Tainan City, Taiwan, Nov. 2012, pp. 710–715.

[12] B. Sivaneasan, P. L. So, H. B. Gooi, and L. K. Siow, "Performance measurement and analysis of WiMAX-LAN communication operating at 5.8 GHz," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1497–1506, Aug. 2013.

[13] J. F. Aguirre and F. Magnago, "Viability of WiMAX for smart grid distribution network," *Eur. Int. J. Sci. Technol.*, vol. 2, no. 3, pp. 181–196, 2013.

[14] P. Rengaraju, C.-H. Lung, and A. Srinivasan, "Communication requirements and analysis of distribution networks using WiMAX technology for smart grids," in *Proc. IEEE Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Limassol, Cyprus, Aug. 2012, pp. 666–670.

[15] D. Bian, M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Analysis of communication schemes for advanced metering infrastructure (AMI)," in *Proc. IEEE PES Gen. Meeting Conf. Expo.*, 2014, pp. 1–5.

[16] P. P. S. Priya and V. Saminadan, "Performance analysis of WiMAX based smart grid communication traffic priority model," in *Proc. IEEE Int. Conf. Commun. Signal Process. (ICCSP)*, Melmaruvathur, India, 2014, pp. 778–782.

[17] V. C. Güngör *et al.*, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.

[18] (2013). *WiMAX Forum System Profile Requirements for Smart Grid Applications: Requirements for WiGRID*. [Online]. Available: http://tinyurl.com/Smart-Grid-Utility-Requirement.

[19] F. Gómez-Cuba, R. Asorey-Cacheda, and F. J. González-Castaño, "WiMAX for smart grid last-mile communications: TOS traffic mapping and performance assessment," in *Proc. IEEE PES Int. Conf. Exhibit. Innov. Smart Grid Technol. (ISGT Europe)*, Berlin, Germany, 2012, pp. 1–8.

[20] (2015). *Wimax Forum*. [Online]. Available: http://www.wimaxforum.org.

[21] M.-T. Zhou *et al.*, "Greater reliability in disrupted metropolitan area networks: Use cases, standards, and practices," *IEEE Commun. Mag.*, vol. 53, no. 8, pp. 198–207, Aug. 2015.

[22] Open Smart Grid-Users Group. (2012). *Smart Grid Networks System Requirements Specification-Release V5.1*. [Online]. Available: http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/Latest_Release_Deliverables/SG%20Network%20SRS%20Version%20V5%20Final.doc, accessed Mar. 7, 2016.

[23] R. R. Mohassel, A. Fung, F. Mohammadi, and K. Raahemifar, "A survey on advanced metering infrastructure," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 473–484, Dec. 2014.

[24] F. Aalamifar. (2015). *An Extension to the WiMAX-NS3 Module*. [Online]. Available: https://bitbucket.org/Saba_Al/wimax/.

[25] "Distribution automation implementation plan," BC Hydro, Vancouver, BC, Canada, Internal Rep., 2012.

[26] L. Nuaymi, *WiMAX: Technology for Broadband Wireless Access*. Hoboken, NJ, USA: Wiley, 2007.

[27] *IEEE Standard for Air Interface for Broadband Wireless Access Systems*, IEEE Standard 802.16-2012, pp. 1–2442, Aug. 2012.

[28] C. Eklund, R. B. Marks, and S. Ponnuswamy, *WirelessMAN: Inside the IEEE 802.16 Standard for Wireless Metropolitan Area Networks*. Piscataway, NJ, USA: IEEE Press, 2006.

[29] C. So-In, R. Jain, and A.-K. Tamimi, "Scheduling in IEEE 802.16e mobile WiMAX networks: Key issues and a survey," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 2, pp. 156–171, Feb. 2009.

[30] C. So-In, R. Jain, and A.-K. Al Tamimi, "SWIM: A scheduler for unsolicited grant service (UGS) in IEEE 802.16e mobile WiMAX networks," in *Access Networks*. Heidelberg, Germany: Springer, 2010, pp. 40–51.

[31] T. Khalifa *et al.*, "Split-and aggregated-transmission control protocol (SA-TCP) for smart power grid," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 381–391, Jan. 2014.

[32] J. Farooq and T. Turletti, "An IEEE 802.16 WiMAX module for the NS-3 simulator," in *Proc. 2nd Int. Conf. Simulat. Tools Tech. (SIMUtools)*, Rome, Italy, 2009, Art. no. 8.

[33] M. A. Ismail, G. Piro, L. A. Grieco, and T. Turletti, "An improved IEEE 802.16 WiMAX module for the NS-3 simulator," in *Proc. 3rd Int. Conf. Simulat. Tools Tech. (SIMUTools)*, Málaga, Spain, 2010, Art. no. 63.

[34] Open Smart Grid-Users Group. (2015). *Home-Open Smart Grid—OpenSG*. [Online]. Available: http://osgug.ucaiug.org/default.aspx, accessed Mar. 7, 2016.

[35] M. Daoud and X. Fernando, "On the communication requirements for the smart grid," *Energy Power Eng.*, vol. 3, no. 1, pp. 53–60, 2011.

[36] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer system," vol. 38, Eastern Res. Lab., Digit. Equipment Corporation, Hudson, MA, USA, 1984.

Fariba Aalamifar received the Master's degree from Queen's University, ON, Canada, in 2012, where she investigated the viability of power line communications (PLCs) for smart grid communication networks, which has received notable academic and industries interest. She is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, University of British Columbia (UBC). Since 2013, she has been collaborating with the Smart Utilities Laboratory, Powertech Labs Inc., Surrey, BC, Canada. She joined the Data Communication Laboratory, UBC, and (co-)developed power line communication and WiGrid modules based on the network simulator-3. Her research interests include scheduling, design, and optimization of wireless and PLC technologies toward smart grid realization.

Lutz Lampe (M'02–SM'08) received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the University of Erlangen, Erlangen, Germany, in 1998 and 2002, respectively. Since 2003, he has been with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada, where he is a Full Professor. His research interests are broadly in theory and application of wireless, optical wireless, and power line communications. He was a (co-)recipient of a number of best paper awards, including awards at the 2006 IEEE International Conference on Ultra-Wideband, the 2010 IEEE International Communications Conference, and the 2011 IEEE International Conference on Power Line Communications. He was the General (Co-)Chair for the 2005 ISPLC, the 2009 IEEE ICUWB, and the 2013 IEEE SmartGridComm. He is currently an Associate Editor of the IEEE WIRELESS COMMUNICATIONS LETTERS, and IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, and has served as an Associate Editor and a Guest Editor for several IEEE TRANSACTIONS and journals.