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WiMAX for Smart Grid Last-Mile Communications: TOS Traffic Mapping and Performance Assessment.

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***Abstract*—This paper addresses specific smart grid communication requirements. It considers a last-mile network based on an IEEE 802.16 cell deployed to cover a group of customers and serve their Energy Services Interfaces. Based on the communication requirements of smart grid last-mile applications and entities, we propose a traffic priority model and setup for the WiMAX air interface. Finally, we evaluate the proposal using a discrete-event simulator.**

***Index Terms*—Smart grids, Metropolitan area networks, WiMAX**

I. Nomenclature

3GPP:	Third Generation Partnership Project
AMI:	Advanced Metering Interfaces
BE:	Best Effort
BR:	Bandwidth Request
BS:	Base Station
CBR:	Constant Bit Rate
DAS:	Distribution Automation System
DSA:	Dynamic Service Addition
DSA-REQ:	Dynamic Service Addition Request
ert-PS:	Extended real-time Polling Service
ESI:	Energy Services Interface
EV:	Electric Vehicle
HAN:	Home Area Network
IEEE:	Institute of Electrical and Electronics Engineers
IP:	Internet Protocol
ISP	Internet Service Provider
LM:	Last Mile
LTE:	Long Term Evolution
NAN:	Neighborhood Area Network
nrt-PS:	Non-real-time Polling Service
OSI:	Open Systems Interconnection
PLC:	Power Line Communications
QoS:	Quality of Service
rt-PS:	Real-time Polling Service
SF:	Service Flow
SG:	Smart Grid
SGLM:	Smart Grid Last Mile
SM:	Smart Meter
SS:	Subscriber Station
TCP:	Transmission Control Protocol
TOS:	Type of Service
UGS:	Unsolicited Grant Service

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II. Introduction

This article proposes a communications solution for the Smart Grid Last Mile (SGLM) using a WiMAX network infrastructure as in Fig. 1. Although communication architectures connecting households to the smart grid (SG) are usually referred to as Advanced Metering Interfaces (AMI), we prefer the term Last Mile (LM), to emphasize the fact that AMI represents only one possible use of the LM network. For instance, the same network might serve AMI and Distribution Automation Systems (DAS) as in [1]. In our target scenario, a large number of domestic users with low bandwidth requirements for SGLM traffic are connected to a WiMAX station, forming an IEEE 802.16 network.

WiMAX is an appealing candidate for SG communications due to its built-in capabilities for real-time traffic and its maturity as a standard. The trend towards 3GPP's LTE for mobile broadband communications suggests that IEEE 802.16 may evolve as a supporting technology for specialized applications[2].

The SG has raised many expectations regarding the upcoming renovation of the electric grid, which will involve state-of-the-art communications, computing, management and control technologies [3]. Utilities expect improvements in automation, integration of future energy sources and rapid-response automation mechanisms. On the other hand, customers are increasingly demanding rich domestic applications for home management, technological solutions to ecological concerns, and energy cost reductions [3], [4].

The SG is expected to provide energy generation, distribution, storage and consumption. Expected functions that are relevant for SGLM traffic include [3]:

- *Demand-Side Management:* Customers will adapt their usage to changes in power availability.
- *Integration of Distributed Generation:* Renewable and/or small generation facilities will be connected to the SG and remotely managed.
- *Energy Storage:* Temporary storage of electricity will allow production surplus to be stored for later use.
- *Accommodation of Electric Vehicles (EVs):* Power demand will increase significantly, yet recharging will be

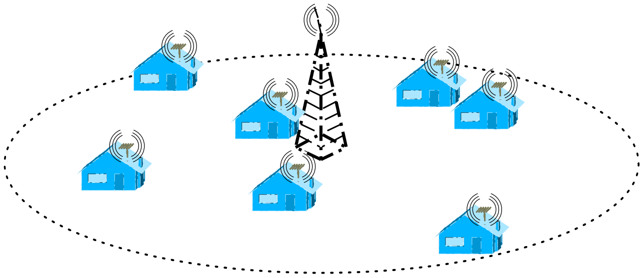

Fig. 1. WiMAX network, serving a population of several households.

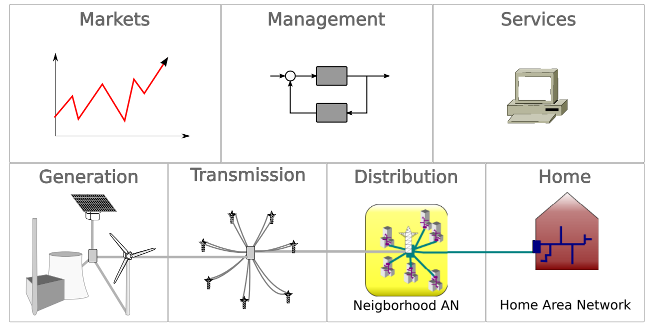

Fig. 2. The main entities of the SG according to IEEE 2030.

dynamically planned for a better conforming of loads. Moreover, batteries of parked EVs will be exploited as additional storage.
- *Automated Fault Detection:* Sensor networks will provide real-time information on the transport network.
- *Self-Healing:* The system will handle common failures automatically.
- *Isolated Operation:* Microgrids, i.e. groups of consumers and producers connected together and capable of self-sustainment, will join or leave the main grid according to their instantaneous needs.
- *Advanced Home Energy Management:* Third parties will provide consumers with rich applications related to domestic energy management.

This paper is organized as follows: Section I shows the list of abbreviations used in the paper. Section III describes our SGLM communications architecture. In section IV the SGLM traffic model is defined. Section V presents the WiMAX setup solution. Section VI discusses the results of the simulations. Finally, section VII concludes the paper.

III. System Model

For simplicity, only the general features of a WiMAX SGLM model are outlined. For this purpose, we make the following considerations:

- The SG is not a network of light intermediaries and heavy edges like the Internet. Unlike the IP protocol, which covers OSI layer 3, the nodes in the middle of the SG network perform OSI layer 7 (application) duties.
- There is a provision for an *Energy Services Interface* (ESI), possibly the *Smart Meter* (SM) itself. This acts as a gateway between utility and user domains, relaying, filtering or generating cross-domain messages according to an established control model.

In the *IEEE Std. 2030 Interoperability Guide for Smart Grid* [5], the power network is divided in seven domains: bulk generation, transport, distribution, user segment, markets, management and service provider (Fig. 2). The standard characterizes entities and interfaces within those domains at three different levels: electrical, communications and information. The entities described in this paper (ESI, SM, etc...) are based on this recommendation.

The ESI acts as a gateway for customers, separating the *Home Area Network* (HAN) from the part of the grid that is controlled by the utility. Communications with markets are expected to take place between utilities and producers and they will affect customers indirectly through the ESI, through demand-reduction programs and the like [6]. Moreover, rich user applications will be optional, which means that, the communications of the Services domain would have to be supported by the customers' Internet connections.

By SGLM communications we refer to the flow of data originating at the ESI or relayed from the HAN towards the Distribution Access Point (DAP). The DAP is the first control entity in the distribution network and it aggregates traffic from several households (theoretically, up to tens of thousands [4]). The underlying network is called the *Neighborhood Area Network* (NAN) [5]. Of all the subnetworks in the SG, the NAN is critical because the user population is large and many different technologies may be involved.

The communications network for the SGLM may be purpose-built or based on connections leased from an Internet Service Provider (ISP). In this work, a wireless network is considered, using WiMAX technology in which a large number of households are connected to the same base station (BS). WiMAX configuration is simplified as a standalone wireless network, focusing on the air interface and not considering the backhaul that would probably be present in a real implementation. Moreover, no distinctions are made regarding network device ownership. Devices could belong to a third party, the energy provider, civil authorities, etc.

The WiMAX air interface employs Orthogonal Frequency Division Medium Access (OFDMA) [7], dividing radio resources into both time and frequency slots [8]. Radio access is typically performed in a coordinated centralized way, with a small phase of contention-based access in which stations request additional resources from the scheduler. Periodically, the BS starts a new frame by transmitting a management header for user coordination. This header is followed by a segment of resources dedicated to subscriber station (SS) downlink. Finally, the last segment of resources is dedicated to the SS uplink, of which a small part is assigned to contention access, for users to attempt to transmit resource assignment requests. Requests may also take place in contention-free opportunity windows, or be piggybacked within data transfer assignments.

WiMAX can employ five different Types of Service (TOS) that employ resources differently depending on the type of traffic and the Quality of Service (QoS)[1].

- Unsolicited Grant Service (UGS), to minimize resource assignment overhead for constant bit rate (CBR) applications. The BS is aware of the rate and periodically assigns resources without control messages.
- Real-Time Polling Service (rt-PS), to reduce variable bit rate (VBR) traffic overhead. When the BS discovers that a source needs to send information periodically, but with varying information size, it reserves resources to allow the station to transmit Bandwidth Requests (BRs).
- Extended Real-Time Polling Service (ert-PS): This TOS adds *silence suppression* to VBR sources. The resources assigned to the SS may be used for BRs or data indistinctly. Assigning resources for a single BR is equivalent to polling a silent source until it has data to transmit.
- Non-Real-Time-Polling Service (nrt-PS), designed for data transmissions without QoS requirements. It is similar to rt-PS but its polling intervals are more variable to take advantage of the flexibility of non-real-time traffic.
- Best Effort (BE): The BS does not allocate resources to the SS in any prearranged way. The SS has to transmit its BR headers by contention or piggybacking.

IV. Smart Grid Last-Mile Traffic Model

Energy providers still have to read meters manually once a month. For this reason, they are interested in minimal communications infrastructures that will allow the same task to be performed in a cost-effective way. However, consumer communications have demonstrated that providing users with enhanced capabilities boosts the development of new added-value applications. Hence, SG communications should not only be designed to strictly serve the current needs for meter reading, but also to support extended functionalities.

The application layer is the top entity in the OSI and Internet communication architecture. In the SGLM, applications perform a series of tasks related to SGLM functions. These include SM reading, maintenance, firmware updates, load management, distributed generation support, EV support, etc. We have classified communications into three categories according to their traffic profiles. Fig. 3 represents a scenario of intense SM traffic exchange.

- Mission-critical traffic (solid red lines) is the most constraining type of traffic, and represents alarms raised by users and alarm-response commands sent by providers. The network must be prepared to support the highest QoS for this type of traffic when present. Related messages are expected to demand the immediate transmission of information. The tightest latency class envisioned by IEEE Std. 2030 is `LOW-LOW` (3 ms), followed by `LOW` (16 ms), `MEDIUM` (160 ms) and, finally, an unbounded `HIGH` latency class ($>$ 160 ms) [5].
- The second type of traffic (dashed purple lines) corresponds to soft real-time interactive maintenance commands, periodic meter readings and other measurements, and the dissemination of energy pricing and other policies. Modeling of this traffic borrows assumptions from previous works: measurements are sporadic (with periods in the order of 1-15 min [9], [4], [10], [11]) and latency requirements are soft ($\sim$ 1 min). Real-time pricing (broadcast or multicast) has the same moderate requirements as measurements.
- In addition to the previous two delay-constrained types of traffic, the scenario considers a non-real-time type used by planning services to exchange information (dotted yellow lines). It may require higher information rates, but it is delay-tolerant. This category has been included to cater for the upcoming generation of consumer electronics devices with planning features, which will be aware of electricity costs and will participate in load control programs [6]. These devices will need to exchange information with the grid before power consumption takes place, using reliable non-real-time transport protocols such as TCP. Firmware updates and similar file-transfer tasks are delay-tolerant traffic.

[1]This term varies in the different disciplines where it is used. In the context of network communications, it refers to prioritizing certain traffic types over the rest to improve their performance, e.g. response time.

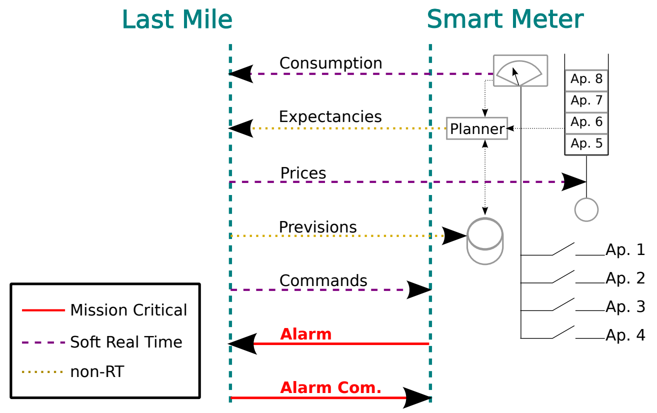

Fig. 3. Types of traffic in SG. The entities inside the SM are abstractions of its functions and do not represent a real implementation.

It could be argued that the third type of traffic will terminate in the DAP, as utilities will possibly wish to control all their customers and structures from the same location. However, our model is still valid, as it focuses on the QoS of the two time-constrained types of traffic.

V. WiMAX SGLM Network

The SGLM WiMAX model is shown in Fig. 4, with k domestic ESIs, which are WiMAX SSs (nodes $N_1 \ldots N_k$), and the DAP connected to the BS (node N_0). Each ESI handles seven application flows with the DAP through its WiMAX interface.

By prioritizing traffic, the lowest possible latency is ensured for mission-critical traffic. Three priority levels are considered and packet classification is application-based. In addition, WiMAX TOS options need to be considered. Due to the irregular nature of alarm traffic, which may have long silences followed by periods of activity, and the fact that this traffic needs to be processed in real-time, ert-PS is selected as the TOS. Metering and other deterministic soft real-time traffic use UGS. Finally, non-real-time traffic uses BE.

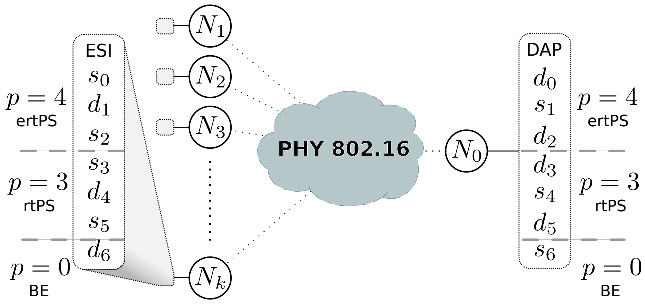

Fig. 4. Architecture of the proposed WiMAX network. Application sources and destinations are denoted as s_i and d_i for $i \in [0,6]$; p denotes the value of the *precedence* field of IP packets for each type of application.

Unfortunately, typical high-level WiMAX management layers do not allow a particular TOS to be specified for each level of priority. For instance, in the simulator employed for the tests in section VI, the WiMAX system inferred the TOS parameter from the Precedence field of IP packets according to table I. Thus, it is necessary to follow a suboptimal TOS strategy for metering traffic (rt-PS) to ensure that applications remain ordered by priority. As shown in Fig. 4, SG applications are configured as follows:

Table I
MAPPING BETWEEN TOS AND IP PRECEDENCE IN QUALNET

TOS	UGS	ert-PS	rt-PS	nrt-PS	BE
Precedence	7,5	4	3	6,2,1	0

- a_0) Alarm signals: Originated from the ESI towards the DAP. Mission-critical traffic. Precedence $p=4$.
- a_1) Alarm commands: DAP towards the ESI. Mission-critical traffic. Precedence $p=4$.
- a_2) Network joining: Session initiation messages sent by ESIs when they want to join the grid. Precedence $p=4$. We assume that on a regular day there will be little traffic of this type, with few ESIs going up and down. A blackout-recovery scenario where thousands of devices go up at the same time is not considered in this paper. This traffic is of the mission-critical type because if it is delayed, it will also delay the operation of other grid tasks.
- a_3) Metering data: ESI towards the DAP, reporting energy usage. Soft real-time traffic. Precedence $p=3$.
- a_4) Price signals: DAP towards the ESI, reporting variable energy prices. Soft real-time traffic. Precedence $p=3$.
- a_5) Telemetry signals: Maintenance measurements originated within the household, relayed by the ESI to the DAP. Soft real-time traffic. Precedence $p=3$.
- a_6) Information exchange and firmware updates: Files transferred from the DAP to the ESI. Non-real-time traffic. Precedence $p=0$.

Theoretically, if alarm traffic is treated as ert-PS and there are enough resources to attend the petitions at each polling instant, the maximum delay of this traffic would be

$$\tau = (N_{poll}+1)T_{frame}, \quad (1)$$

where T_{frame} is the WiMAX frame duration and N_{poll} is the number of IEEE 802.16 frames between two successive polls to the node. One extra frame bounds the delay between the polling event and the actual resource slot assignment to the request (note that the assumption of sufficient resources implies that the request can always be allocated in the next frame). Even though this theoretical bound could achieve latencies as low as 10 ms (using WiMAX forum recommended $T_{frame} = 5\ ms$), this would require considerable polling overhead in every node.

This overhead can be analyzed as the resources needed to transmit one BR header (48 b according to [7]) every N_{poll} WiMAX frames:

$$R_{poll} = \frac{48b}{N_{poll}T_{frame}} bps. \quad (2)$$

Thus, if the goal is to achieve the minimum latency possible ($N_{poll}=1, T_{frame}=5\ ms$), with alarm traffic at $R_{alarm} = 4.3\ bps$ (see section VI for the justification of this value), the required ratio between overhead and useful information would be:

$$\frac{R_{poll}}{R_{poll}+R_{alarm}} = 99.95\%, \quad (3)$$

which is unacceptable for a practical solution.

Moreover, these theoretical bounds would probably never be achieved because they would require the BS to store flow information for traffic handling between packets, so once a flow was established it would always be available. Because of the large user population and low alarm rates, this would require several *KB* of status data to be stored permanently, only for infrequent usage. Any practical WiMAX implementation is unlikely to behave like this. Thus, if the packet flow scheduler fails to identify the alarm flows, the theoretical bounds are unfeasible. Instead, every single alarm packet would have to perform a Dynamic Service Acquisition (DSA) process, by sending a DSA Request (DSA-REQ) control packet and waiting for a response. This delay would be the most constraining factor on alarm message delay.

In addition to explicit traffic management, some additional advantages may be obtained by choosing appropriate transport protocols for each type of traffic. There are two classical, rather different transport protocols: TCP and UDP. It is important to remark that UDP, unlike TCP, does not have a congestion control mechanism. This means that it does not coexist well with TCP user services such as web browsing. However, congestion control may also be a drawback because it can impose unwanted delays on alarm traffic.

Therefore, in order to avoid unnecessary disruptions, UDP is more suitable for carrying only sporadic relevant traffic with negligible bandwidth, such as alarms and metering data, provided that the application copes with packet losses, because UDP is an unreliable connectionless protocol. UDP is also adequate for carrying zero-knowledge petitions that devices may launch when joining the grid. On the other hand, TCP seems better for reliable transmission of non-real-time reliable notifications, SM maintenance operations such as remote terminal, firmware updates, etc...

In our model, alarm signals and commands always imply a response, and so does the network joining function. Therefore, two flows of information are studied for each of the three mission-critical applications $a_0 \dots a_2$. In these flows, delivery success probability and delay are the main parameters of interest. Soft real-time notifications do not trigger a response, so a single flow of packets per application ($a_3 \dots a_5$) is studied. In this case, delivery success, delay, and throughput are studied. Finally, the analysis of the non-real-time component of the application set (a_6), which corresponds to file transmission, focuses on throughput, since latency and delivery are irrelevant for a non-real-time reliable application.

VI. Simulations and Results

A simulation was performed using Qualnet 4.5.1 [12]. Specifically, the *Advanced Wireless* module was employed to simulate a WiMAX network. Fig. 4 illustrates the configuration of cell nodes.

The simulation scenario consisted of a terrain measuring $1500 \times 1500\, m^2$ and nodes employing the `PHY802.16` model with 20 *MHz* bandwidth, 20 *dBm* transmission power and an Fast Fourier Transform size of 2048 samples. Antenna and propagation parameters were borrowed from Qualnet *Advanced Wireless* examples[2]. SGLM traffic was generated using `SUPERAPLICATION` applications for $a_0 \dots a_5$ and `FTP/GENERIC` for a_6.

In order to emulate the traffic of the applications, the following seven traffic generation profiles were employed:

- a_0) Alarm signals: These are simulated using a Poisson traffic generator. Each time an alarm occurs, a single packet of 1024 *B* is sent to the DAP, which responds with a packet of the same size. The rate parameter is calculated using the table in [1] and the rate of metering. Alarm traffic is expected to be 20% of metering traffic $\lambda_a = 0.2\lambda_m = 0.2\frac{1}{60} = \frac{1}{300}s^{-1}$.
- a_1) Alarm commands: Same traffic generation profile as for alarm signals, but originated in the DAP and sent to the ESI.
- a_2) Network joining: Random exponential traffic with the same characteristics as alarm signals but with a lower rate, representing an average of ten session-related messages per hour, $\lambda_j = \frac{1}{360}s^{-1}$.
- a_3) Metering data: Deterministic periodic transmission of one packet of 1024 *B* from the ESI to the DAP, using reliable TCP transport. For test purposes, the most stressful case in the literature was used: one measurement per minute [9] $\lambda_m = \frac{1}{60}s^{-1}$.
- a_4) Price signals: Same traffic generation behavior as for metering data, but in the opposite direction of transmission.
- a_5) Telemetry signals: Same traffic generation behavior as for metering data. Two separate flows were considered because grid sensing and meter reading might originate at different sources.
- a_6) Firmware update: A file transfer application configured to exploit all available bandwidth (as occurs with TCP congestion window management), transferring a file from the DAP towards the ESIs.

Two different simulations were executed. The first used the default value for the Qualnet parameter `MAC802.16-SERVICE-FLOW-TIMEOUT`, 15 *s*, which is the time of inactivity after which a Service Flow (SF) is eliminated. This simulation confirmed the observation in section V that flow timeouts that occur between successive packet transmissions delay SGLM traffic considerably, and that this delay is not related to the choice of TOS parameter. In the second simulation, this was solved by setting `MAC802.16-SERVICE-FLOW-TIMEOUT=10000` *s*.

Each simulation was run for a different number of nodes to evaluate how node density affects the ability of WiMAX technology to meet SGLM requirements. Simulations were run for $k = 50$, $k = 100$ and $k = 200$ SS. Note that the simulator always considers $k + 1$ nodes, including the BS.

A. Simulation with default timeout parameter

Figs. 5 and 6 show the results of the simulation with `MAC802.16-SERVICE-FLOW-TIMEOUT=15` *s*. Note the long delays (in excess of $1s$) experienced by uplink traffic in applications $a_0 \dots a_3$, and a_5. These delays are surprisingly high, specially because the TOS employed (ert-PS) is meant for silence-suppressing voice over IP (VoIP), a feature that requires very low latencies. As discussed in section V, these delays are due to the fact that packet transmissions are so far apart in time that previously established SFs expire and DAS processes need to be initiated for each packet transmitted, as proven by the following calculations.

Simulation statistics files reported a total of 83809 DSA-REQ packets received by the BS, for $k = 200$ SS. This is equivalent to an average of about 421 DSA-REQ per node, while each node only had 7 QoS uplink flows running (a_4 transmits from DAP to ESI without triggering responses, thus it does not have any uplink component). If flows persisted, there should be an average of seven packets per node at most, even for some session losses. This validates the assumption that flows expired again after every packet transmission, due to the separation between transmissions.

Moreover, the theoretical number of DSA-REQ packets can be computed with the assumption that there is a timeout after 15 *s* of inactivity. For metering, this corresponds to all the traffic because it has a deterministic inter-arrival time higher than 15 *s*. For exponentially distributed mission-critical traffic the corresponding DSA-REQ traffic can be computed using Erlang's formula:

$$\lambda_{a_i,timeout} = \begin{cases} \lambda_{a_i} & a_i \in \{a_3, a_5\} \\ \lambda_{a_i} \left(1 - B(\lambda_{a_i} h, 1)\right) & a_i \in \{a_0 \dots a_2\} \end{cases} \quad (4)$$

This formula represents the existence of an SF as an "occupied resource" and the traffic arriving during this "occupation" as "blocked" (this is, while the SF still exists). Thus, "non blocked" traffic arrives when the SF is closed and is identical to the DSA-REQ generation process. Finally, after multiplying

[2] Available with the simulator distribution, located in `$Qualnet/advanced_wireless/WiMAXHomeToOffice/*`

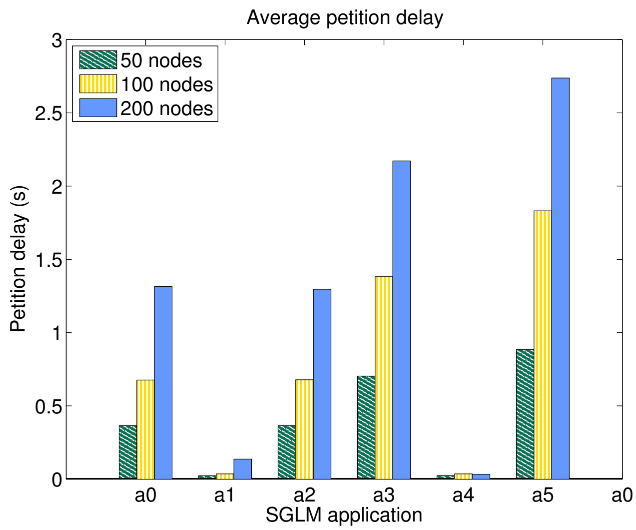

Fig. 5. Average delay experienced by SGLM applications $a_0 \dots a_5$ with MAC802.16-SERVICE-FLOW-TIMEOUT=15s

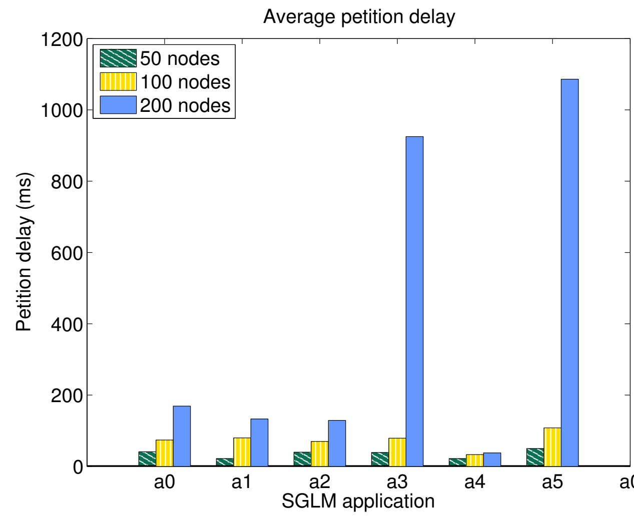

Fig. 7. Average delay experienced by SGLM applications $a_0 \dots a_5$ with MAC802.16-SERVICE-FLOW-TIMEOUT=10000s

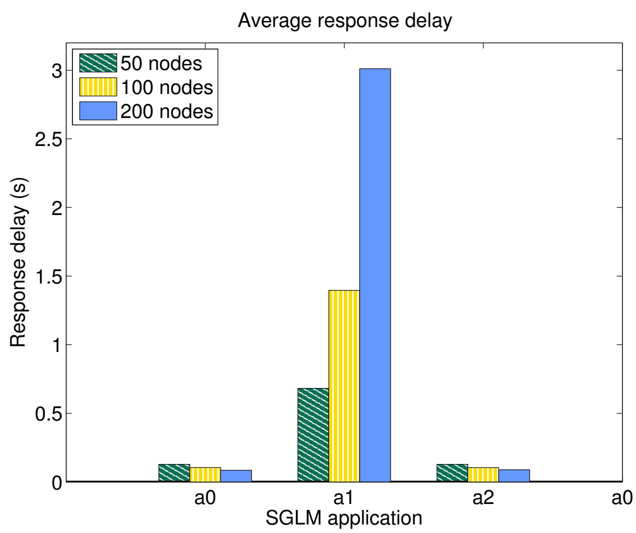

Fig. 6. Average delay experienced by SGLM responses of alarm applications $a_0 \dots a_2$ with MAC802.16-SERVICE-FLOW-TIMEOUT=15s

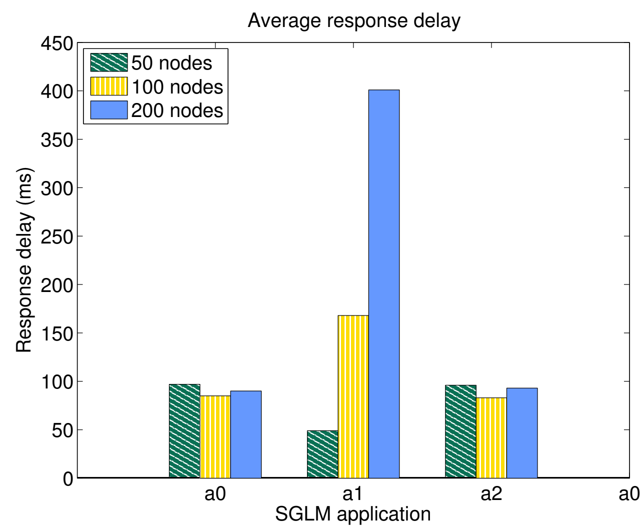

Fig. 8. Average delay experienced by SGLM responses of alarm applications $a_0 \dots a_2$ with MAC802.16-SERVICE-FLOW-TIMEOUT=10000s

the aforementioned rates by the simulation duration and adding one packet for the file transfer, the very same number of packets as that observed in the experiment is obtained.

$$1 + 10^4 \times \sum_{a_i \in (a_0 \dots a_3, a_5)} \lambda_{a_i,timeout} = 420.95 \text{ packets} \quad (5)$$

Therefore, the assumption is confirmed. Consequently, in the SGLM context, a typical implementation of WiMAX cannot achieve low delays in practice.

B. Simulation with extended timeout parameter

Figs. 7 to 13 show the results of the simulation with MAC802.16-SERVICE-FLOW-TIMEOUT=10000 s. Fig. 7 shows a decrease in alarm traffic delays by an order of magnitude, allowing latencies that could be acceptable even for the MEDIUM latency class of IEEE Std 2030 [5] (160 ms). Due to prioritizing, only metering traffic experienced long delays. However, this is tolerable because this traffic has delay requirements in the order of minutes. In addition, the number of DSA-REQ MAC headers received by the BS dropped to an average of 7.1 per node. These results prove the opposite of the prediction in section V: that for a long SF timeout parameter, SFs do not expire between consecutive SGLM packets and the delay is closer to that of the theoretical prediction. This is a relevant find for SGLM deployments using WiMAX: traditional implementations of the protocol will never attain low alarm latencies, and custom MAC layer modifications will be necessary. Note that polling overhead will still need to be resolved to reach the theoretically predicted low latencies.

The second most relevant result is shown in Figs. 9 to 11, which indicate that changes in throughput for different numbers of nodes (the “shape” of each group of bars) are strongly related to the direction of information flow. This is not surprising as in the downlink direction, firmware update flows

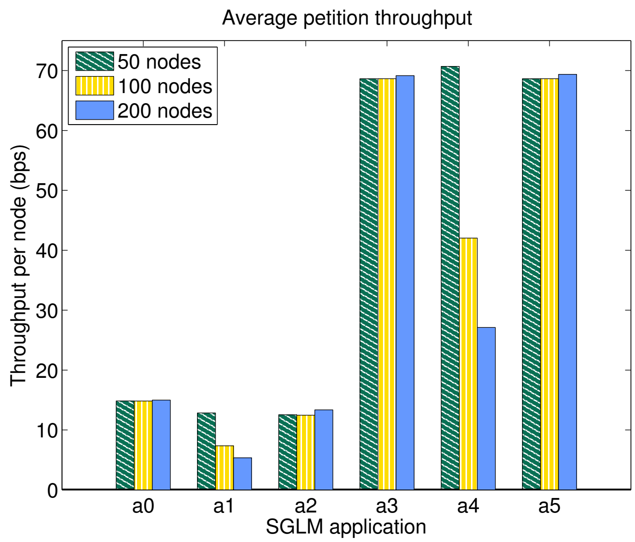

Fig. 9. Throughput of SGLM applications $a_0 \ldots a_5$ with `MAC802.16-SERVICE-FLOW-TIMEOUT`=10000s

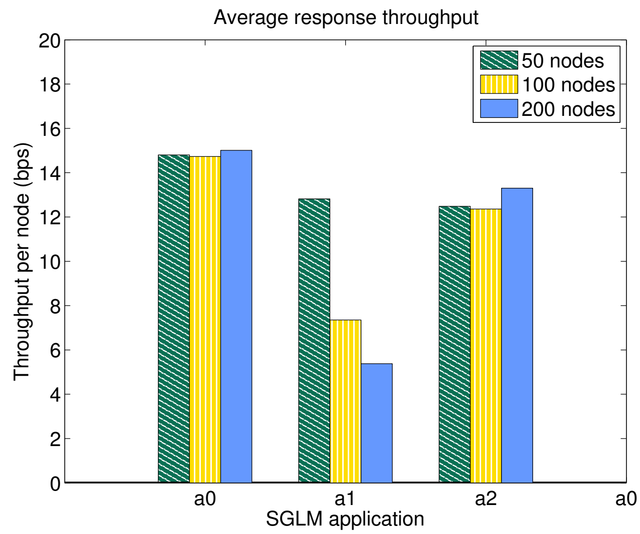

Fig. 11. Throughput of SGLM responses of alarm applications $a_0 \ldots a_2$ with `MAC802.16-SERVICE-FLOW-TIMEOUT`=10000s

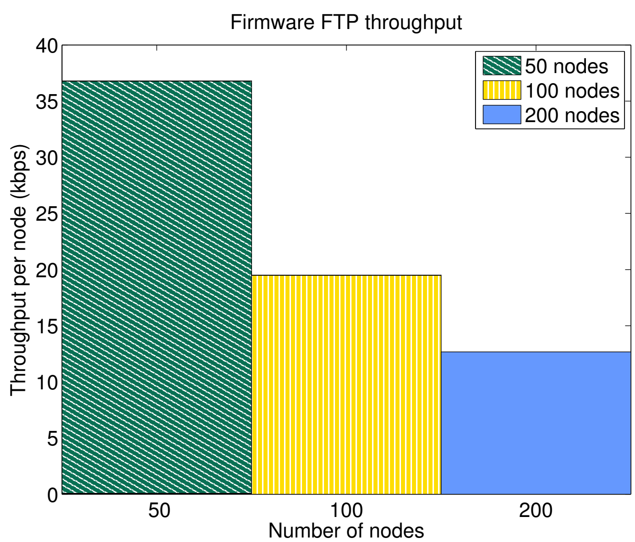

Fig. 10. Throughput of SGLM firmware application a_6 with `MAC802.16-SERVICE-FLOW-TIMEOUT`=10000s

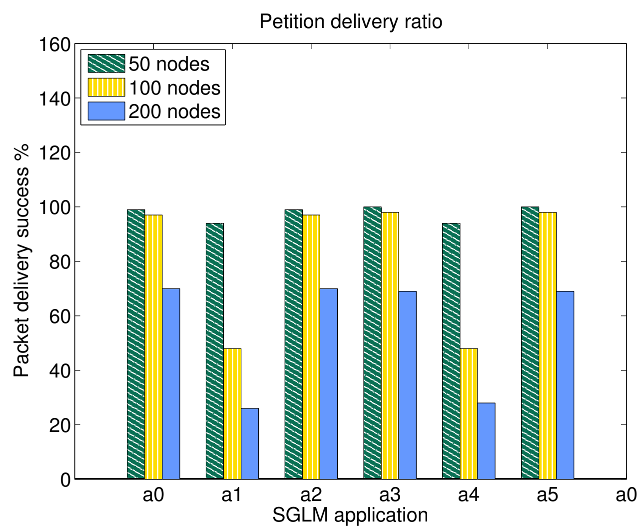

Fig. 12. Delivery success of packets from SGLM applications $a_0 \ldots a_5$ with `MAC802.16-SERVICE-FLOW-TIMEOUT`=10000s

typically consume all available resources. Even though critical and soft-real-time flows are prioritized, they are degraded by the higher occupation of the physical medium in the downlink direction.

Finally, Figs. 12 and 13 show how user density growth affects the probability of SGLM message delivery. In Fig. 12 there are few differences with the asymmetric behavior seen in the previous throughput figures. However, in Fig. 13 the response delivery ratio does not decrease significantly with the number of nodes, even for a_1, which exhibits a very sharp decrease in petition delivery. We interpret this as a consequence of the increased likelihood of response packets gaining resources (petitions discarded by the scheduling process will not originate a response), so there will be more resources available for response messages. As the latter are less affected by scheduling and their delivery success is higher, it can be concluded that delivery depends fundamentally on scheduling, whose improvement demands further research efforts.

VII. Conclusions

The SG is very challenging for communications researchers because its requirements differ greatly from those of traditional data networks. In particular, it is necessary to solve the last-mile connection of large populations of SMs to each ESI with a combination of technologies. Deploying purpose-built networks to serve SGLM communications offers the possibility of high customization and absolute control of the network. Particularly, WiMAX technology has been proposed as a good option [2] for SGLM due to its native capabilities for real-time traffic and the fact that equipment costs are expected to come down. However, SGLM traffic differs from that of mobile services, and the IEEE 802.16 standard must

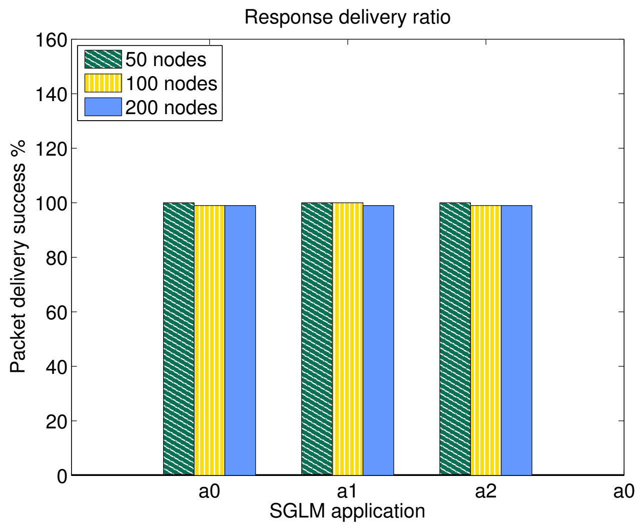

Fig. 13. Delivery success of response packets from SGLM applications $a_0 \dots a_2$ with MAC802.16-SERVICE-FLOW-TIMEOUT=10000s

be carefully examined in order to validate its capabilities for the SG.

In this paper, we have identified architectural and functional characteristics of SGLM traffic transport over WiMAX, and formulated a model featuring seven different SGLM application types. Discussion on traffic priority levels and TOS, and their relationship in a typical implementation, is provided. Also, the resulting performance was tested. Moreover, a problematic issue was identified in the lack of persistence of real-time flows at very low bit rates. Specifically, alarm traffic, unlike Vo-IP, is not session-oriented low-latency traffic and cannot exploit the real-time features of WiMAX because setup times, which affect each alarm separately, tend to be long. Qualnet simulations demonstrate that the architecture only partially satisfies requirements, not because of the IEEE 802.16 standard itself, but because of the way in which it is usually implemented. To correct this deviation it is sufficient to extend the MAC802.16-SERVICE-FLOW-TIMEOUT parameter. With this modification, all alarm packets are treated as a single service flow, no matter how separated in time they are. In a second simulation, the correction was tested and it was confirmed that delays drop dramatically with this approach. We were also able to extract other knowledge from the simulation, such as the effect of wireless medium saturation on packet delivery ratio and throughputs.

To sum up, we have verified that WiMAX networks can successfully carry a rich variety of SGLM traffic, with different constraints and priorities. However, the deployment of such networks requires several protocol modifications to achieve good results. Thus, SGLM WiMAX deployments may work but they will require engineering efforts.

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VIII. Biographies

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