Smart Grid Last-Mile Communications Model and Its Application to the Study of Leased Broadband Wired-Access

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***Abstract*—This paper addresses the modeling of specific Smart Grid (SG) communication requirements from a data networking research perspective, as a general approach to the study of different access technologies suitable for the last mile (LM). SGLM networks serve customers' Energy Services Interfaces. From functional descriptions of SG, a traffic model is developed. It is then applied to the study of an access architecture based on leased lines from local broadband access providers. This permits consideration of the potential starvation of domestic traffic, which is avoided by applying well-known traffic management techniques. From previous results obtained for a purpose-built WiMAX SGLM network, the intuition that a leased broadband access yields lower latencies is verified. In general, the proposed traffic model simplifies the design of benchmarks for the comparison of candidate access technologies.**

***Index Terms*—Communication systems traffic control, diffserv networks, quality of service, smart grids, subscriber loops, WiMAX.**

I. Introduction

THE SMART GRID (SG) has raised many expectations as a result of the upcoming renovation of the electric grid, which will require state-of-the-art communications, computing, management, and control technologies. Utilities expect improvements in automation, integration of future energy sources and rapid-response automation mechanisms, while customers demand rich domestic applications for home management, satisfaction of their ecological concerns, and energy cost savings [1], [2].

Regarding the Smart Grid Last-Mile (SGLM), there is an open discussion on the most suitable communication technologies [3], [4]. This paper proposes a generalized SGLM traffic model designed to simplify the comparison of competing solutions, from a data networking research perspective.

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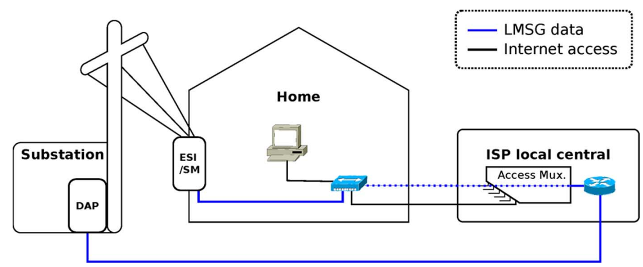

Fig. 1. A wired ISP access network carries SGLM data.

Even though communications architectures connecting households to the SG are usually called Advanced Metering Interfaces (AMI), we prefer to refer to them as Last-Mile networks to emphasize that meter reading is simply one possible application. For instance, AMIs and Distribution Automation Systems (DAS) may coexist in these architectures [5].

In a recent work [6] we assessed the viability of WiMAX for ad-hoc infrastructures for SGLM communications, showing that traffic priorities play a key role in performance. In this paper we generalize our traffic model to any access technology and perform a deeper analysis of the traffic-management plane of SGLM communications. We also discuss some relevant candidate access technologies for SGLM communications.

We validate our model by analyzing a *leased broadband* scenario, where domestic users possess some form of broadband wired Internet access, the Internet provider is willing to reach a data carrying agreement with the electric company, and the required bandwidth of SGLM traffic is comparably small (meaning that the existing network can handle the increase without extending its capacity) (Fig. 1).

The rest of this paper is organized as follows: Section II describes SGLM architectural constraints and provides a list of access technologies to be considered. In Section III we review functional characteristics of SG communications and develop an SGLM traffic model that allows the comparison of access technologies. In Section IV we discuss our earlier results for a WiMAX SGLM network. Based on the proposed model, Section V describes the setup and simulation results in a new scenario: a leased broadband SGLM network. Finally, Section VI concludes the paper.

II. Access Technologies for Smart Grid Last-Mile Communications

In this section we will briefly describe the variety of access technologies that are available for SGLM communications. More detailed comparisons can be found in the literature [3],

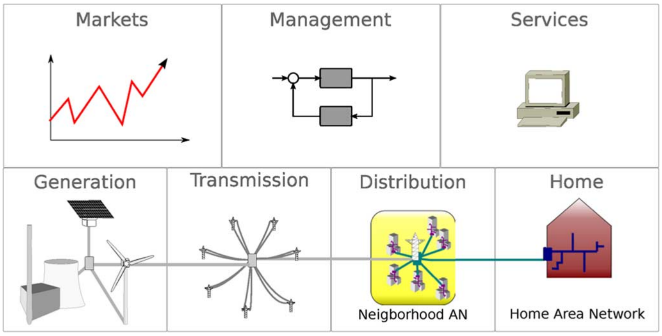

Fig. 2. The main entities of the SG according to IEEE Std. 2030-2011.

[4]. For SG communications, the following considerations must be taken into account:

- 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.
- To ensure that SG is viable in areas where broadband access is not fully available and to prevent monopolies, transport over user Internet connections should not be the only alternative. However, since broadband access is available in most cases, non-intrusive carrying agreements with Internet providers are of great interest.
- An Energy Services Interface (ESI), possibly the Smart Meter (SM) itself, acts as a gateway between utility and user domains, relaying, filtering or generating cross-domain messages according to a control model.
- Control is hierarchical, with messages being sent up or down the grid by the control devices in each section.

According to the IEEE Std 2030-2011 guide for SG interoperability [7], the power network is divided into seven domains: bulk generation, transmission, distribution, user segment, markets, management and service provider (Fig. 2). The aforementioned 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 controlled by the utility. Communications with markets are expected to take place between utilities and producers and will affect customers indirectly through the ESI, through demand-reduction programs and the like [8].

A customer HAN may be composed of appliances from different vendors. Consumer electronics markets are already producing standards and agreements for interoperability such as the ZigBee Smart Energy Profile [9] or the HomePlug technology for Power Line Communications (PLC) [10].

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. It aggregates traffic from different households, which can theoretically number up to tens of thousands [2]. The underlying network is called the *Neighborhood Area Network* (NAN) [7].

The communications network for the SGLM may be purpose-built or based on connections leased from an Internet Service Provider (ISP), and it may rely on wireless or wired technologies. The former allow faster set-ups and incremental system deployments, whereas the latter are more robust and scale better if the installation serves many users. It is also a matter of discussion whether the NAN will be subdivided in clusters or not; for example, the proposal in [11] has two tiers, with WiFi concentrators connecting several houses (a *Cluster Area Network*, CAN) to the DAP, as a single WiMAX NAN.

In principle, diverse standards may be used for a purpose-built wireless last-mile (LM) network [12]: WiMAX, IEEE 802.22, WiFi, ZigBee, etc.

For a purpose-built wired LM network, there are two possible types of deployment:

- A PLC LM exploiting the last power distribution stage; this would be cheap, but have a very limited capacity [13].
- With independent purpose-built wiring; in this case, installation costs could be prohibitive, but performance would be optimal, specially with optical fiber [14].

A leased wireless access could rely on specific mobile-IP devices (GSM, UMTS, LTE, etc.) installed in the ESIs [15].

Finally, in the case of a leased wired access, (over xDSL, HFC, FTTx, etc.), the operators must provide interfaces to connect the ESI [5].

Table I ranks alternative technologies according to the aspects of interest for SGLM deployment [16]:

- Capacity: The amount of traffic that the link will support. Lowest capacity systems are suitable for plain remote metering but not for advanced information services.
- QoS support: Traffic must be differentiated. In particular, alarm packets should never be dropped and the network must treat real-time traffic adequately.
- Footprint: The physical impact of the installation for the customers and the grid.
- Complexity: The engineering effort of system deployment.
- Coverage: Typical network coverage. Infrastructure costs are higher for technologies with smaller cells.
- Trust: Well-established and trustworthy technologies are preferable to newer and lesser known ones.
- Reliability: Probability that communication will be successful.
- Scalability: Capacity to accommodate more users and services in the future without major changes.
- Cost: Estimated expenditure.

Next we briefly describe the main technologies in Table I:

- IEEE 802.16-WiMAX: This standard [17] aims at wireless Metropolitan Access Networks (MAN). In principle, the maximum range (5 km) covers a neighborhood, and several QoS classes are supported natively.
- IEEE 802.22-White Spaces: This standard [18] supports cognitive exploitation of white spaces in the UHF band. It is designed for Rural Access Networks (RAN), a low population-density equivalent of MAN. It is technologically similar to IEEE 802.16, but several features are omitted for the sake of simplicity.
- The IEEE 802.11-WiFi standard [19] is well known for Wireless Local Area Networks (WLAN). Its low range im-

TABLE I
CANDIDATE TECHNOLOGIES FOR THE SG-LM

Tech.	Capacity	QoS support	Footprint	Complexity	Coverage	Trust	Reliability	Scalability	Cost
WiMAX	medium	high	medium	high	NAN	low	medium	high	medium
White Spaces	medium	high	low	high	NAN	low	low	high	low
WiFi	medium	low	medium	medium	CAN	high	low	low	medium
ZigBee	low	low	low	high	CAN - NAN	low	low	high	low
PLC	low	high	low	high	CAN	low	low	low	low
Wiring	high	high	high	medium	NAN	high	high	high	high
ISP ADSL	medium	negotiated	low	low	-	high	high	high	low
ISP HFC	high	negotiated	low	low	-	high	high	high	low
ISP FTTx	high	negotiated	low	low	-	low	high	high	medium
ISP Cellular	low	negotiated	medium	medium	-	high	low	low	medium

poses the need for complex frequency planning and lots of cells to cover a neighborhood (only three of its frequency bands do not overlap). Medium access by contention introduces uncertainty, inefficiency, and latency jitter in large installations. For these reasons, WiFi networks do not scale well. Moreover, many domestic users use WiFi as a WLAN solution in their home networks, contributing to interference in the surroundings.

- IEEE 802.15.4-ZigBee is an adequate wireless mesh solution for applications without highly demanding requirements. Its main advantages are ad-hoc deployment, mesh routing, theoretical good scalability, and a specific profile for smart energy applications [8]. Its disadvantages are low transmission rates ($\leq$250 kbps), difficult support of IP traffic, and low range (per hop). It operates at WiFi frequencies or in the lower 868/915 MHz ISM bands, which allow the trading of rate for low interference.
- Broadband Power Line (BPL) refers to the use of PLC over the electric distribution network to create an access network (e.g., IEEE 1901–2010 [20]). This approach is appealing, since it does not require specific independent wiring. Its main drawback is the intrinsic difficulties in using power wires for communications, such as high attenuation and weakness against interference (due to the lack of wiring shielding).
- Purpose built wiring for SGLM has higher capacities than, for instance, PLC. Optical fiber is preferable, in line with the future expectations for this technology. Unfortunately, the costs will remain prohibitive in the short term. Future research should improve cost-efficiency [14] by sacrificing performance, for instance, by using plastic optical fiber. Side benefits should also be considered, for example the leasing of part of the fiber capacity to ISPs.
- ISP-Cellular: Plugging a cellular module to equipment with moderate communication needs, such as meteorological stations or theft alarms, is quite common. However, applying this solution to SMs raises scalability problems. Ongoing research in the *Internet of Things* [15] and the advent of LTE-Advanced in the fourth generation of mobile telephony (4G) may provide solutions. Specific QoS agreements with the ISP are necessary.
- ISP-xDSL: Due to the star topology of the telephone network, in order to connect the SM to the DAP using legacy twisted pairs, utilities should place ad-hoc equipment at the telephone substation. Providers might be reticent to lease part of their resources as they would lose competitiveness.
- ISP-HFC: Hybrid providers have fiber backbones and coaxial wire access networks with intrinsic broadcast support. Individual customer communications and services are multiplexed in frequency in each coaxial wire segment.
- ISP - FTTx: Fiber To The Home/Curb/Neighborhood (FTTx) refers to novel approaches to broadband access using fiber to a point close to the user. Passive Optical Networks (PON) represent the next stage of wired networks. As capacities increase, operators might be more willing to share resources. However, they may be reluctant to install a new technology due to uncertainty regarding performance with respect to other alternatives.

As previously mentioned, our SGLM traffic model is independent of the underlying technologies. However, it can be used to compare and study the different candidates. In this paper we consider a wired access network relying on leased Internet connections (Fig. 1), which we can compare with our previous results using WiMAX [6].

III. MODEL FOR SMART GRID LAST-MILE TRAFFIC

The SG is expected to provide new ways of energy generation, distribution, storage and consumption. Expected functions that are relevant to SGLM traffic include [1]:

- *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 dynamically planned for a better load conforming. 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.

Energy providers still have to read meters manually, generally on a monthly basis. They are thus 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 empowering the user domain with enhanced capabilities fosters the development of new added-value applications. Hence, SG communications should be designed not only to strictly serve current SM reading needs, but also to anticipate the needs of future SG applications.

In SGLM, applications perform a series of tasks related to the functions above. We have classified communications into three categories according to their traffic profiles. Fig. 3 shows an abstract scenario of 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) [7].
- 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. For this traffic, we borrow assumptions from previous work: measurements are sporadic (with periods in the order of 1–15 min [11], [2], [9], [13]) 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, we consider a non-real-time traffic type for planning services to exchange information (dotted yellow lines). It includes firmware updates and similar file-transfer tasks. It may require higher information rates than the previous types, 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 [8]. 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.

It could be argued that the third type of traffic will terminate in the concentrator (the DAP), as utilities will possibly wish to control all their customers and structures from the same place. In this case, non-RT traffic may be transported to a different location after reaching the DAP. However, our model is still valid, as it focuses on the QoS of the first and second time-constrained types of traffic.

The previous traffic categories are descriptive of SGLM needs, but would not suffice for testing a network setup. Thus, we have reviewed and improved the traffic model we employed for WiMAX [6], in order to elaborate a model with nine SGLM applications that should enable the study of any access technology. The application components of the model $(a_0 \ldots a_8)$ and their traffic parameters are based on a review of SGLM literature, and they are the following:

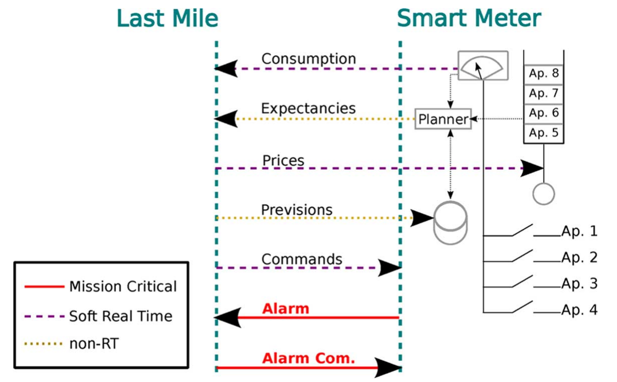

Fig. 3. Types of SG traffic. The blocks inside the SM are abstractions of its functions and do not represent a real implementation.

a_0) Alarm signals, from the ESI to the DAP (mission-critical traffic, solid red line in Fig. 3). Their arrival is modeled with a Poisson traffic generator. Each time an alarm arrives, a single packet of 1000 octets is sent to the DAP without response. The rate parameter for the generator is inferred approximately from the assumption in [5] that alarm traffic is expected to be 10–20% of metering traffic. We consider the worst case:

$$\lambda_a = \lambda_m \frac{0.2}{0.8} \frac{1}{60} = \frac{1}{240} \mathrm{s}^{-1}, \tag{1}$$

a_1) Alarm commands, from the DAP to the ESI (mission-critical traffic). Same traffic generation system as for alarm signals, but in the opposite direction.

a_2) Network joining: Session initiation messages that the ESIs send when they want to join the grid. We consider a small amount of traffic of this type in a normal day, with few ESIs going up and down. A blackout-recovery scenario with thousands of devices going up at the same time is not considered. This traffic is mission-critical because delaying it implies delaying other smart grid tasks. It has the same random exponential characteristics as alarm signals, but with a lower rate, representing an average of one network joining per hour: $\lambda_j = (1/3600)\ \mathrm{s}^{-1}$.

a_3) Metering data, from the ESI to the DAP, reporting energy usage. Soft real-time traffic (dashed purple lines in Fig. 3). The generation of this traffic must represent a deterministic periodic transmission of one packet of 1000 B from the ESI to the DAP, using reliable TCP transport. We followed the worst case in the literature, of one measurement per minute [11]: $\lambda_m = (1/60)\ \mathrm{s}^{-1}$.

a_4) Pricing signals, from the DAP to the ESI, reporting variable energy prices (soft real-time traffic). Same traffic generation as for metering data, but in the opposite direction.

a_5) Telemetry signals: Maintenance measurements originated within the household that the ESI relays to the DAP (soft real-time traffic). Same traffic generation behavior as for metering data. We consider these two flows separately because grid sensing and meter reading might originate at different sources.

a_6) ESI information reports: Non-real-time information (dotted yellow lines in Fig. 3) sent by the ESI to the DAP. On-off traffic with exponentially distributed duration, using TCP for reliability, with average times of

$$\overline{T}_{\text{on}} = 0.2\ \text{s}, \quad \overline{T}_{\text{off}} = 10\ \text{s} \tag{2}$$

a_7) DAP information broadcast: Non-real-time information sent by the DAP to the ESI (non-real-time traffic). Same traffic generation as for reports, but in the opposite direction.

a_8) Firmware updates: FTP file transfers from the DAP to the ESI (non-real-time traffic). A file transfer application configured to exploit all available bandwidth (as TCP congestion window management does).

In addition, for modeling leased technologies (wired or wireless) an additional application a_9 is required to take domestic Internet traffic (not considered SGLM traffic) into account. This application permits the analysis of the coexistence of both types of traffic, SGLM and Internet.

The Internet Engineering Task Force (IETF) published an extended overview of different IP-related protocols suitable for SGs in Request for Comments 6272 (RFC 6272) [21]. The interesting, well-known Differentiated Services (DiffServ) [22] feature allows the network to handle different flows. Traffic prioritizing ensures the lowest possible latency for mission-critical traffic. Our classification of traffic in three types requires a minimum of three priority levels in the system, but it is possible to set more.

In addition to explicit traffic management, some additional advantages can be obtained by choosing appropriate transport protocols for each type of traffic. There are two classical yet rather different protocols at the Internet transport layer [21], TCP and UDP. Unlike UDP, TCP has a congestion control mechanism. This means that UDP does not coexist well with TCP user services such as web browsing. Congestion control may impose undesired delays on alarm traffic.

Therefore, in order to avoid unnecessary disruptions, UDP, a connectionless protocol, is more suitable for carrying sporadic relevant traffic with negligible bandwidth, such as alarms, provided that the corresponding applications cope with packet losses. 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 prices, meter readings, and other non-critical reliable notifications, as well as for SM maintenance operations such as remote terminal, firmware updates, etc.

With this choice of protocols, complementary prioritizing will be inherently present in the network, thus enhancing the benefits of traffic management. Alarm traffic with the same priority level as user data will tend to use all the resources, because it will not lower its rates for congestion control. Other types of SGLM traffic with the same congestion control as user data will tend to share link capacity fairly.

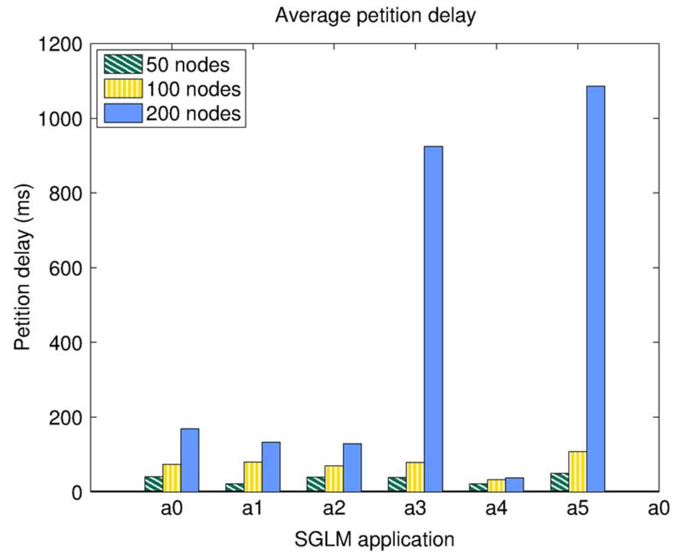

Fig. 4. Average delay experienced by SGLM applications $a_0 \ldots a_5$ in the WiMAX scenario.

IV. Previous Results: SGLM Traffic on a Purpose-Built WiMAX Network

In our previous work [6], the scenario consisted of a large number of households connected to the same WiMAX base station (BS).

The WiMAX MAC air interface employs Orthogonal Frequency Division Medium Access [17], dividing radio resources into both time and frequency slots [23]. WiMAX offers five Types of Service that use resources differently depending on the target type of traffic and QoS for each Service Flow (SF).

In our simulations, a possible issue was identified in the lack of persistence of real-time SFs at very low bit rates. Alarm traffic is not a session-oriented low-latency type of traffic like VoIP, and cannot exploit the real-time features of WiMAX because inter-alarm times tend to be long, causing SF session timers to expire, and thus long new-SF-setup delays for alarm packets. Simulations demonstrated that the architecture only satisfied requirements partially because of the way in which SF establishment is usually implemented in IEEE 802.16 networks.

We proposed extending the SF timeout parameter as a simple method to correct this deviation. After SF timeout correction, all alarm packets were treated as a single SF, regardless of the interval between packets. In a second simulation, we confirmed that the delay dropped dramatically. In addition, the simulation helped to explain the effect of wireless medium saturation on packet delivery ratio and throughput.

Fig. 4 shows traffic delay results of the second (corrected) simulation. Alarm traffic delays would be acceptable for the `MEDIUM` latency class of IEEE Std 2030 (160 ms) [7]. Metering traffic experiences longer delays, yet these delays are tolerable considering the real-time requirements of this type of traffic (in the range of minutes).

V. SGLM Traffic on Leased Broadband Wired-Access Networks

In this section, we applied our model to study a leased broadband access technology, simplified as a "pipe" with fixed

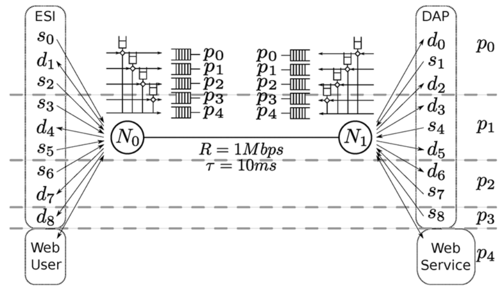

Fig. 5. Traffic model of the leased broadband wired-access scenario.

capacity and propagation delay between the household and the ISP access node. Fig. 1 illustrates the network topology, in which SGLM traffic is carried over the broadband access infrastructure. Examples of practical implementations would be connecting the SM to the Internet, or using technologies such as MPLS or L2TP to create a Virtual Private Network (VPN) for the SGLM.

SGLM traffic has different needs to those of user traffic and, due to the importance of the grid, we assume that the former should be prioritized. In addition, the different classes of SGLM traffic also require different priorities as previously described. However, a mere ordering of the applications according to priority would result in severe hampering of user-perceived web browsing quality during peaks in SGLM traffic, for example during firmware updates. In order to minimize this problem, we propose applying classic *token-bucket packet classification* [22], an algorithm in which a sustainable bit rate (SBR) and a maximum burst size (MBS) are defined for each category of traffic. Applications are able to transfer an MBS burst at the maximum network rate or to transfer information at an SBR rate for an unlimited time. These rules ensure that both urgent alarm traffic and periodic operation traffic leave room for the original Internet user service.

We performed a simulation using the $\mathtt{ns}-2$ simulator [24]. Specifically, the `DiffServ` packet differentiation module and the `TokenBucket` packet monitoring modules with Random Early Drop (RED) [22] queuing were employed in the core. Fig. 5 illustrates the traffic model of the leased broadband wired-access scenario as simulated. It has a point-to-point link with fixed capacity (1 Mbps) and delay (10 ms) connecting the network entities at the two endpoints of the access line[1]

The nodes in Fig. 5 have the aforementioned ten applications of our model attached. They transfer data through the domestic Internet access towards the ISP access node. From there, nine SGLM flows would be connected to the DAP. User web browsing, in contrast, would be directed to the public Internet. In the traffic model the ten application sources and destinations are denoted as s_i and $d_j, i, j \in [0, 9]$, respectively. Priority levels are denoted as $p_i, i \in [0, 4]$. Communication nodes may implement traffic differentiation (represented by different queues for each priority) and token-bucket traffic classification (represented by the token buckets that redirect excess packets of non-compliant traffic towards the lowest priority queue, p_4). Applications 0 to 8 are unidirectional and belong to the ESI-DAP system. Application 9 has bidirectional traffic and corresponds to web browsing.

Three simulation scenarios were considered:

1) No traffic management: All applications were simulated without traffic management. In this case, firmware updates and web traffic increased latency of critical traffic.
2) Five levels of traffic priorities: The three critical applications were assigned maximum priority, followed in second place by metering, price broadcast, and telemetry. The third priority class was for reports and maintenance. The fourth was assigned to firmware updates (these must take place eventually, even if the user is occupying the connection intensively). The fifth class was assigned to user non-SGLM traffic. It was expected that latencies would improve for high-priority classes and worsen as priorities decreased. User traffic was eventually blocked because the FTP application for firmware updates had a higher priority and took all available resources.
3) Priorities and Token-Bucket: Each traffic class was monitored with a token-bucket mechanism. An SBR of 1 Kbps was granted to all priority classes, even though metering and alarm traffic did not reach this rate. Packet size was 1000 B and MBS was 10000 B, or 10 packets.

It is important to remark that no advanced traffic management techniques are needed apart from the well-know algorithms in the literature [22]. In the simulation, five priority levels were considered, with independent RED queuing for forwarding. Packet classification was application-driven. For example, as indicated in Fig. 5, applications 0 to 2 were assigned the highest priority (p_0). The token-bucket packet classifier granted the applications 1 Kbps (SBR) on average, with full-rate bursts of ten packets at most ($\mathrm{MBS} = 10$ KB). Extra packets were downgraded to user-class traffic (p_5) regardless of their original class.

It is guaranteed that this mechanism does not interfere with alarm handling because the probability of over ten simultaneous alarm packets is very low: with the alarm packet rate of Section III, $\lambda_a = (1/240)\ \mathrm{s}^{-1}$, and a service time per packet of $\tau = 1000\ B/1\ \mathrm{Kbps} = 8$ s, the alarm downgrade probability during **a service time** is

$$1 - \sum_{i=0}^{10} P\left[Poisson(8\lambda_a) = i\right] < 6.77 \times 10^{-18}, \quad (3)$$

where multiplication by 8 converts λ_a from packets per second (s^{-1}) to packets per service time (τ^{-1}). Thus, for **a whole year**, the probability of an alarm packet being downgraded can be approximated by

$$\sim 1 - P(Bi(365 \times 24 \times 3600/8, 10^{-18}) = 0) \sim 10^{-10}, \quad (4)$$

and even if this happened, extra alarm packets would still be processed as standard user traffic, and would therefore still have

[1]Ns-2 only supports node-address-based packet classification. For the applications to be distinguishable, they had to be attached to different auxiliary nodes. Thus, those nodes were connected to the actual packet-classifier nodes used in the simulation. The applications shown in Fig. 5, attached to N_0, are actually auxiliary nodes to facilitate packet classification, corresponding to the simulated applications.

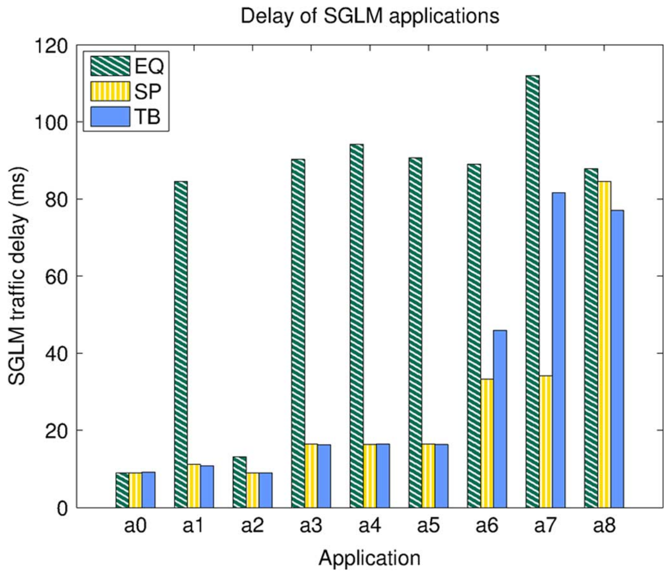

Fig. 6. Average delay of SGLM applications in the three leased broadband wired access simulation scenarios.

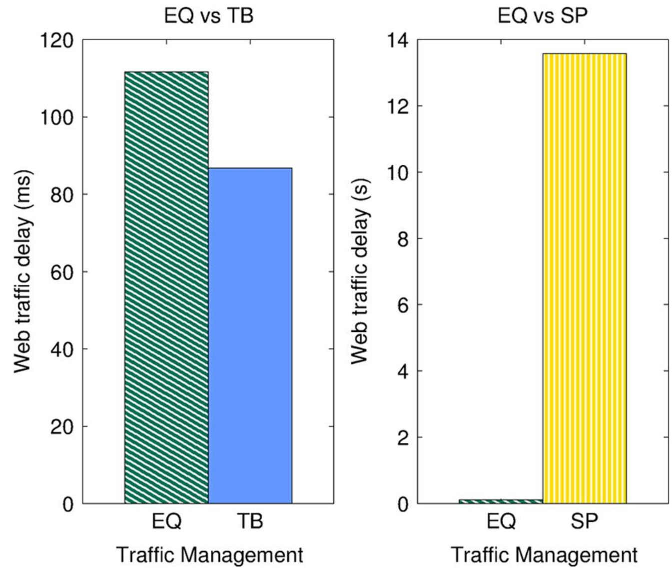

Fig. 7. Average delay of the user Internet application in the three scenarios of leased broadband wired access.

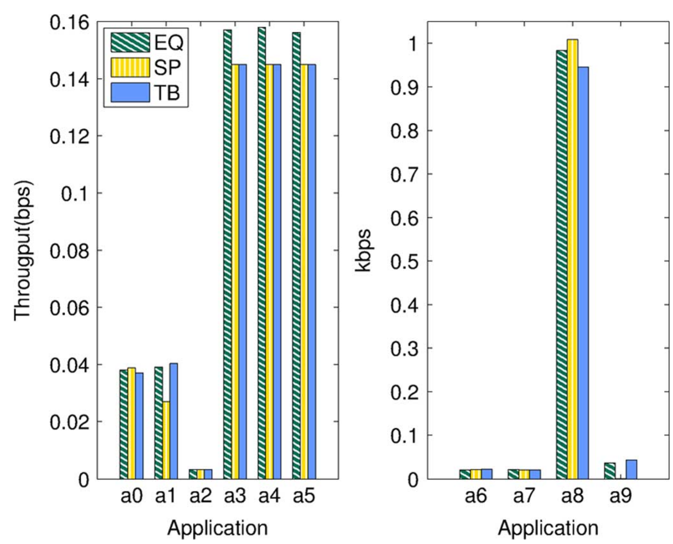

Fig. 8. Average throughput of all applications in the three leased broadband wired access simulation scenarios.

a good chance of delivery. Consequently, latencies are similar to those for strict priorities without token buckets, yet broadband users are less disturbed (in any case, developers should avoid alarm applications that tend to saturation, even without network constraints).

Soft real-time traffic (purple), which is periodic and deterministic, is never downgraded. Non-real-time traffic (yellow) applications are granted 1 Kbps for transfer when they are active, and the rest of the capacity is shared with user web applications. The capacity is partially or completely available depending on whether or not the contending applications are active at the same time.

Figs. 6–8 show the results of the simulation. Note that in Fig. 8 flows 0 to 5 carry few packets due to the extremely low bitrate of the corresponding applications: 33 bps for alarms and 133 bps for metering. Fig. 6 shows the average latency of SGLM traffic. The EQ columns correspond to the scenario without priorities, the SP columns to that with strict priorities, and the TB columns to the combination of token bucket and priorities. Without priorities, as the FTP application was responsible for most of the link usage, the traffic in applications 0 and 2 experienced lower latencies because they only had to coexist with FTP acknowledgements, which are smaller. The other applications (1, 4, and 7 and acknowledgments of 3, 5, and 6) had to coexist with the FTP flow in some manner. As a result, all applications except 0 and 2 experienced the same delay of $\sim$100 ms. Both prioritizing modes corrected this behavior with similar results.

Delay was reduced for the most important applications using DiffServ, as shown in the SP columns in Fig. 6. Prioritizing caused a sharp decrease in alarm latencies (let us remark that the link had a 10 ms delay, whereas the applications perceived a $\sim$11 ms delay). For the second and third classes, p_1 and p_2, latencies also improved significantly, although they did not reach the minimum. Unfortunately, the SP column in Fig. 7 indicates that user traffic experienced excessive delay. This is because the FTP updating application had more priority than the user application for Internet traffic. Thus, the latter was allowed to take as many resources as it wanted. At the same time, user traffic throughput and packet delivery dropped dramatically (a_9 SP columns in Fig. 8). The eight SGLM applications with the lowest traffic generation delivered approximately the same amount of information. FTP firmware updates took many resources with strict prioritizing, whereas the user traffic application received considerably fewer.

However, with token-bucket classification and priorities, resource sharing between FTP updates and user Internet traffic guaranteed user satisfaction for the latter. To summarize, the effect on user traffic of strictly assigning high priority to ESI traffic would be unacceptable for the ISP business model, but the token bucket mechanism mitigates the problem.

The TB bars show the results for the case of token-bucket traffic classification. In the TB a_8 column in Fig. 8 we can see that FTP updating throughput was limited to $\sim$1 Kbps and that user traffic throughput was quite similar to that in the original situation (without priorities). In addition, the user traffic delay in Fig. 7 is tolerable (TB column). Note that introducing the token-bucket mechanism does not significantly alter the benefits of traffic prioritizing, as confirmed by the fact that the TB and SP bars in Fig. 6 indicate the same alarm and metering delays.

VI. Conclusion

SG communications are challenging because of their particular requisites, which differ from those in traditional data networks. In the LM, diverse modern technologies may handle the connection of large populations of SMs to ESIs.

In this paper we propose a conceptual model for SGLM traffic and network design characteristics that is valid to compare communication technologies. It allows the comparison of different design perspectives, such as the purpose-built SGLM wireless network in our earlier work and the general-purpose leased broadband wired access network in this paper.

The traffic model is the composition of traffic generators for nine SGLM applications taken from the literature. These applications are classified into three traffic types for management and prioritization. Jointly, they yield an accurate representation of realistic SGLM traffic exchange.

In our previous work on traffic transport over WiMAX, we discussed SF Types Of Service, and identified a possible problem in the lack of persistence of real-time flows with very low bit rates. We also checked the resulting traffic delays.

In the leased broadband wired access scenario, the traffic model has allowed to discuss priority levels for SGLM traffic transport and to identify the problem of user traffic starvation, which was solved with token-bucket packet classification. Simulations demonstrate that this approach works correctly.

Comparatively, the alarm traffic delays are much lower in the leased broadband wired access scenario that in the WiMAX scenario. According to IEEE Std 2030–2011 [7] the latter would be able to support the `HIGH` and `MEDIUM` latency profiles, whereas the former would also be able to support the `LOW` latency profile. The $\texttt{LOW} - \texttt{LOW}$ profile ($\leq$ 3 ms) would be unfeasible in both scenarios. Apparently, the strong dependency of WiMAX on the physical medium scheduler and its asymmetric behavior affect its performance.

As many other access technologies compete to serve SGLM communications, our model is helpful for their study as an SGLM representation. It allows to design benchmarks easily to study and compare access technologies.

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