Satellite-based Data Collection Architecture for Virtual Power Plant Management in Rural Areas

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ABSTRACT

Smart grid is envisaged to be the next-generation electrical power grids and this is founded based on successfully building up smart grid communication networks that can support all identified smart grid functionalities. Despite a range of communication choices available, utilities still struggle with how to affordably and reliably extend their networks to 100% of their service territories, especially to remote locations. In all smart grid models, it is often emphasized that consumers play a vital role in electricity management of supply and demand, and are expected to be co-producers of electricity, so-called *prosumers*. As such, virtual power plants (VPPs) by interconnecting hundreds of prosumers are expected to be a new paradigm shift in smart grid systems to better utilize the distributed energy sources. However, efficient VPP management is of great challenge in rural areas that are beyond the reach of primary networks while requiring enormous data exchange. To provide connectivity in rural areas, this paper proposes a satellite-based smart grid communication architecture for the efficient VPP management that requires collecting data from prosumers forming the VPP. Also, a priority-based scheduling algorithm for different smart grid data types is proposed to improve the performance of delay-sensitive applications. Simulation results demonstrate that the satellite-based communications can be a viable solution as a mean of smart grid communications for VPPs.

KEYWORDS
Smart grid communications, virtual power plant, smart meter, satellites.

1. Introduction

The smart grid - a paradigm shift to electrical grid systems, brings the Internet, data communication and intelligent control ideas to ensure its reliability, improve security, increase efficiency and provide more flexibility for integrating new energy sources. This transformation requires intelligent and bi-directional flow of data alongside the energy throughout the entire grid to connect thousands of sensors, small-scale renewable energy generators, smart meters and so on [1]. Thus, it is imperative to make the current electricity network connected with reliable, efficient, and secure communication technologies.

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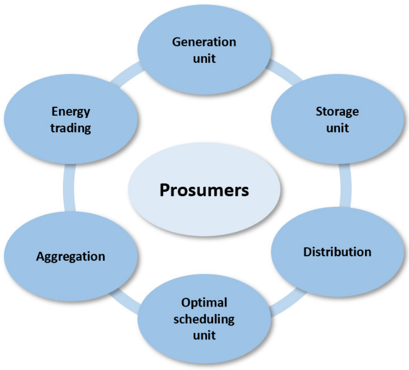
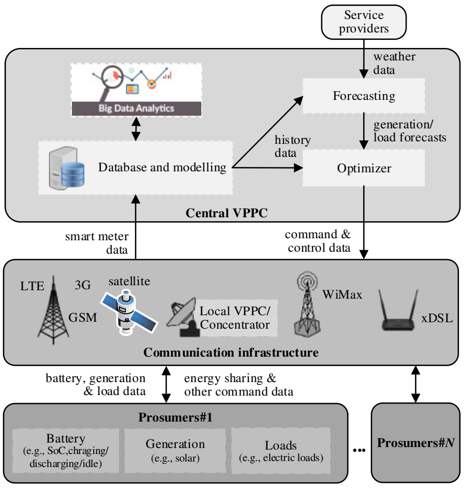


Figure 1.: Taxonomy of new market roles of prosumers



VPPC: Virtual Power Plant Controller, SoC: State of Charge of a battery

Figure 2.: A generic VPP system architecture incorporating different communication infrastructures

In traditional grid systems, the end users are seen as pure energy consumers and the electricity is essentially generated in large power plants while users are not expected to make any contribution to power generation [2]. However, the users in the future smart grid will no longer be pure energy consumers [3]. In fact, consumers are expected to have some residential storage and power generation capabilities using renewable energy sources [4, 5]. As such, users in the future smart grid will gradually transform from pure consumers into small generation (*i.e.*, production) and consumption units, so-called *prosumers*. A virtual power plant (VPP) can then be formed by aggregating hundreds of small-scale prosumers. Fig. 1 shows a taxonomy of prosumers that offers generation, distribution, storage, aggregation, trading and balancing of energy within smart grids. Moreover, most of the isolated rural areas are living either without electricity or may have little grid reach [6]. The concept of VPP can be implemented on those rural areas offering the reduction of traditional costly energy generation and the overall energy costs. However, the most important requirement for the VPP energy management is to efficiently collect an enormous amount of fine-grained data (e.g., energy consumption, generation, storage measurements, etc.) collected from prosumers' smart meters, and be available to the utility centre.

Although there are many communication technology options available for smart grids [7, 8, 9, 10], most of the isolated rural areas are cut-off from the conventional broadband technologies due to the lack of reach of cable as well as poor cellular coverage. For rural areas, satellite can provide the connectivity coverage for interconnecting prosumers within a VPP. As such, this paper proposes a satellite-based architecture that can provide the connectivity coverage for interconnecting prosumers within a VPP in rural areas. Since there are different types of data to be exchanged between smart meters and the utility centre while some are delay-sensitive, a priority-based packet scheduling is also proposed to meet the requirement of delay-sensitive services.

The structure of the paper is: In Section II, an overview of the concept of VPP technology is discussed. A satellite-based architecture and the priority-based scheduling algorithm are presented in Section III. Section IV provides the performance of the proposed solution while Section V concludes the paper.

2. Virtual Power Plant Technology

A VPP is a set of geographically sparse smart grid entities including distributed energy resources such as small-scale distributed power generators (*e.g.*, home solar, wind firms, etc.), controllable loads and storage that are aggregated in a way that it performs as a single power facility [3, 11, 12, 13]. While multiple VPPs can be connected to the main, a single VPP can also work on its own. The VPP then optimizes these entities with its standard portfolio to reduce peak periods [14, 15], to balance the grid, to avoid outages, to extend asset life, and so on.

The VPP is usually operated by a central controller (often utilities or VPP operators), where owner can receive the forecasted information and has a direct control on each unit. The objective of the controller is to minimize the system operating costs. The VPP units are of close geographically proximity, and can be connected to the main grid through a distribution line or operated independently [13]. The VPP not only provides reliable power at a reasonable price and a greater customer flexibility, but also to encourage carbon reduction, which is one of the global major concerns from governments and regulatory bodies.

Fig. 2 shows a generic VPP system architecture with different communication infrastructure for data exchange between the prosumers and utility centre. The core modules in the architecture includes: central utility centre (VPP controller (VPPC)), prosumers (smart meters) and communication infrastructure. The central VPPC performs efficient energy management based on information from prosumers, grids, and other external service providers, e.g., weather forecast for solar generation. Data are usually stored for future analysis through an intelligent algorithm (optimizer) that combines historical data along with real-time data gathered from various grid entities and computes optimal energy sharing decisions. It enables a smart grid to manage consumable demands by providing real-time pricing, peak shaving and energy conservation.

A residential prosumer may have three entities: (i) battery storage, (ii) an integrated renewable generator (wind/solar), and (iii) loads. In-home smart meter gathers information, e.g., the primary energy source, instantaneous energy generation from PV panels, battery status and loads, and provides real-time measurements to the VPPC via communication infrastructure in order to efficiently manage energy within the VPP to reduce the overall energy cost. Moreover, the VPP can receive pricing information utilized for internal resource optimization procedure in relation to energy trading, which is out of the scope of this paper.

For exchanging data between prosumers and the VPPC, different communication infrastructure such as 3G/4G(LTE)/5G cellular, satellite, xDSL, etc. can be used while availability of terrestrial networks is highly unlikely in many rural areas [10, 16]. Different smart grid services require specific levels of communication system performance for their reliable operation. For the VPP energy sharing operation among prosumers, the energy consumption reporting rate is usually 4-6 times per hour, *i.e.*, each consumption measurement is sent every 10-15 minutes. As for the VPP operation in rural areas where terrestrial communication infrastructure is very limited or unavailable, satellite-based VPP can be a feasible option to deploy the VPP in remote areas due to its ubiquitous coverage.

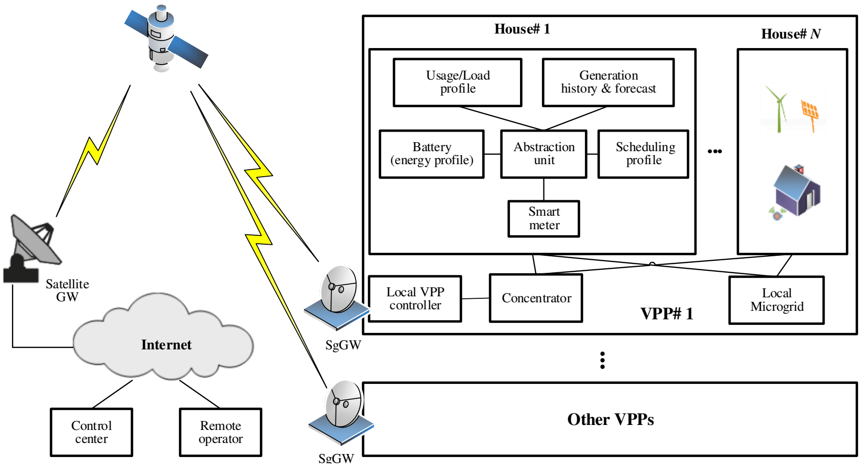


Figure 3.: A satellite-based communication architecture for VPP management

3. Satellite-based Communication Architecture for VPP

In rural areas, houses are usually spaced out and finding faults in the grid in case of outages becomes difficult [16] and the development of satellites is considered as a key factor in lowering the vulnerability degree of complex interactive networks, such as the electrical grids. In this paper, a satellite-based communication infrastructure is proposed for the collection of data from prosumers mainly because of its broad geographic coverage, flexible datarate performance, highly reliable connectivity, IP-enabled and seamless integration with terrestrial networking technologies, faster roll-out and ease of installation, robustness against disasters, etc. As smart grid networking become more deeply embedded within the critical grid infrastructure, the reliability and resiliency of communications becomes increasingly important. In the case of VPPs, the use of satellite for collecting the VPP network information provides last-mile connectivity to reach most remote locations as VPPs are

Fig. 3 illustrates the proposed satellite-based communication architecture for the VPP energy management, where a number of houses (or prosumers) within a VPP is connected to a local VPP controller. It is assumed that all smart meters installed in every house send their energy consumption and other monitoring data, e.g., battery state of charge (SOC), controllable load status, etc. to the local VPP controller by using either any available dedicated wired connections or any other wireless technologies such as Point-to-Point, wireless mesh, etc. The smart meter usually collects in-house data via home area network (HAN). The local VPP controller acts as a concentrator that collects the data from a number of smart meters under its coverage range. There can be multiple local VPP controllers within a VPP and they are connected to a node with satellite connectivity, *i.e.*, serving gateway (SgGW). Finally, the SgGW then sends all the data to the utility center (VPPC) via the satellite link.

In each house, the smart meter performs some basic processing on the raw data such as energy usage, generation profile, battery status, load scheduling profile sets by users before transmitting them to the concentrator. The abstraction unit is a part of the smart meter, which provides the level of abstraction set to interface the VPP concentrator. The rationale for the data abstraction is to ensure customer privacy by making certain customer information anonymous.

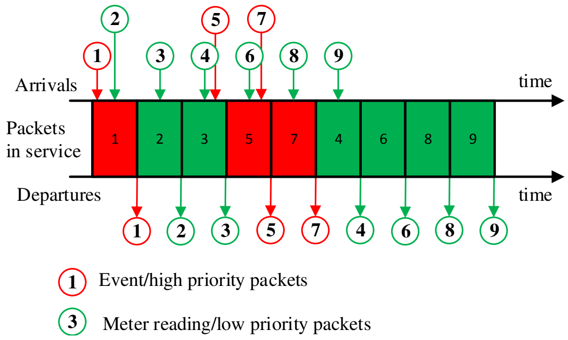


Figure 4.: Operation of the priority queue

3.1. *Traffic Modeling for Energy Management*

As mentioned before, one of the challenging issues in smart grid communications is the management of a vast amount of data generated by a large number of smart meters. The smart meter traffic can be classified as: (i) fixed-scheduling (FS), which is an operational traffic and occurs on a period basis, *e.g.*, smart meter reading or (ii) event-driven (ED), which occurs as a response to the electricity supply conditions, *e.g.*, demand response and fault detection. The FS and ED traffic have different communication requirements. For example, the ED traffic is more delay-sensitive than the FS traffic while the amount of generated FS traffic is large. The traffic pattern for the VPP energy management based on the FS and ED traffic can be defined as:

- **Periodic traffic pattern** - scans with all data returned continuously, which can be modelled as continuous bit rate source. For example, the load and generation profile data are required to be updated in every few minutes or an hourly basis.
- **Aperiodic traffic pattern** - data return for the detection of any changes (closest to a Poisson distribution). For example, when there is an abrupt changes in load or faulty in any high energy consuming smart appliance, it should be considered in the scheduling process.

This paper considers three data types: advanced meter reading (MR), fault and other event monitoring (EM) data and pricing (PR) updates. The MR and PR traffic are modelled as a deterministic distribution (FS periodic pattern) where the time between two consecutive arrivals is fixed and is given by T. On the other hand, the EM traffic is modelled as random Poisson process with mean inter-arrival rate of $1/\lambda_{EM}$. In general, the data rates in the range of few hundreds of kilobits per second can be considered adequate for target performance [17]. However, since different traffic have different requirements, it is therefore important to develop a priority-based packet scheduling. This paper proposes a priority-based packet scheduling algorithm to improve the performance of the high priority (HP) traffic described in Subsection III.B.

3.2. *Priority Queue-based Scheduling*

For implementing the priority-based packet scheduling, a priority queue model is proposed: high priority (HP) and low priority (LP) queues. The data packets from prosumers are prioritized based on the packet types such as the MR or EM type. The EM packets are delay-sensitive, and they are always given the highest priority than the

MR packets by using the type of service (ToS) field in the packet header. Based on the priority value in the packet header, a packet would be placed in an outgoing queue. If there are packets in the HP queue such as the EM packets, it is served before packets from low priority queue, *i.e.*, the MR packets. An illustration of the operation of the priority queue-based scheduling is shown in Fig. 4. For example, packets 1, 5 and 7 belong the HP class and other packets belong to the LP class. Moreover, packets 5 and 7 are served before packets 4 and 6 being served. The rationale for prioritizing packets is to ensure lower delay and higher throughput to be achieved for the delay-sensitive packets. The steps in the priority queue-based scheduling are as follows:

(1) Each data packet is assigned with a priority tag in the packet header by the abstraction unit of smart meter based on the traffic types (*e.g*, MR, EM and PR.
(2) The local VPP controller strips-off the packet header, en-queued the packet in the corresponding outgoing queue.
(3) Data packet with the HP tag is kept in the HP queue. Note that the local VPP controller maintains multiple transmission queues (e.g., HP and LP queues).
(4) The local VPP controller de-queues data packets as: (i) packets from the HP queue are preempted over other priority queues and always scheduled over other packets; and (ii) if two packets have the same priority, they are served according to their order in the queue.

On the other hand, the utility usually transmits the PR update to customers periodically and the PR update should be the same for all customer within a VPP. While the MR and EM are the unicast traffic types, the PR data traffic is multicast that allows a unidirectional information exchange between one source and one or many destinations [18]. The satellite IP multicast is a bandwidth-conserving technology that reduces traffic by simultaneously delivering a single stream of information (*e.g.*, PR updates) to potentially hundreds of homes. Multicast packets are replicated in the networks at the point where paths diverge by the concentrator enabled with Protocol Independent Multicast (PIM) and other multicast protocols.

4. Simulation and Results Evaluation

To evaluate the performance of the proposed satellite-based architecture for VPP energy management, a scenario where many houses (prosumers) are connected to a utility center via a concentrator using a satellite link. Each house represents a smart meter node and they communicate with a local VPP controller (via concentrator) with the capability to act as a satellite terminal (SgGW). The local VPP controller is responsible for relaying packets between the smart meter and the utility through the satellite-based wide area network. It is assumed that the SgGW collects meter readings data from all smart meters using dedicated wired connections. The size of each MR packet is in the range of 100-300 bytes according to a pre-configured sending interval set (periodic) by the utility [17] while the EM is modelled as Poisson process with 2 packets per unit of time [17]. The satellite link between the SgGW and the utility center uses GEO satellite (BGAN) with a link capacity of 492 kbps. All other simulation parameter settings is given in Table I. In practice, the locations of the smart meters are fixed and they are connected to the SgGW (acts as a fixed satellite terminal), which does not require any handovers. The aim of the performance evaluation is to improve the performance of the proposed packet scheduling of packets in terms of throughput and latency for different packet sizes, K and the number of prosumers, N.

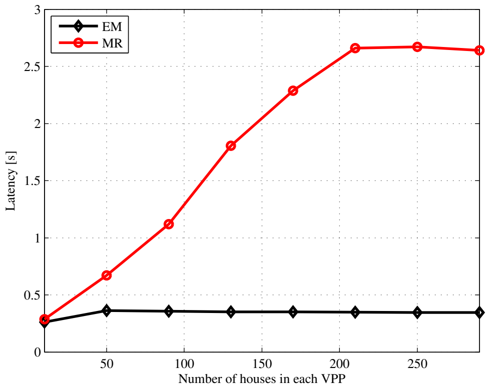


Figure 5.: Delay performance for MR and EM data collections

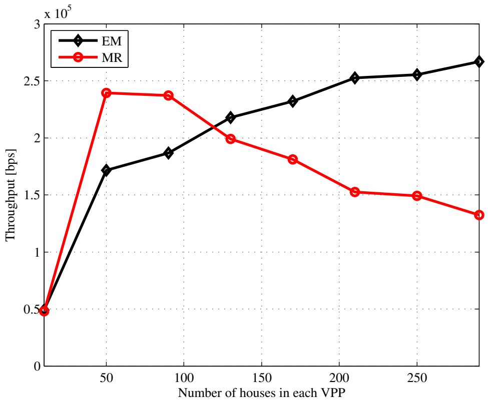


Figure 6.: Throughput performance for MR and EM data collections

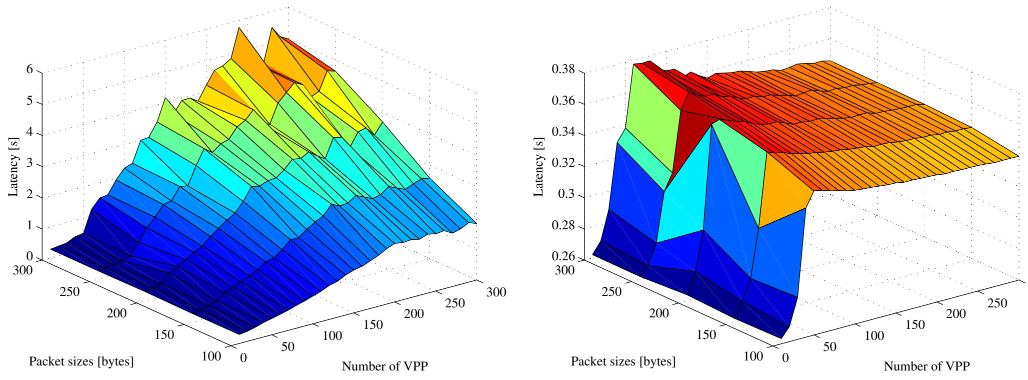
Fig. 5 illustrates the delay performance of the unicast link for the MR and EM traffic. It is seen that the latency of EM packets is much lower than that of the MR packets as the EM packets always have the higher priority over the MR packets. It can also be seen that as the number of houses, N in each VPP increases, the latency for the MR packets also increased, however still below 3s meeting the delivery requirements for the AMI applications. This is because the priority-queue based scheduling at the local VPP controller and the higher number of smart meters in each VPP causes to generate the higher number of the EM traffic, which has high priority, and hence, the MR traffic experience higher delay.

Fig. 6 shows the throughput performance of the MR and EM traffic when the packet size of each packet type is assumed to be 150 bytes. It is seen that the throughput of

Table 1.: Simulation parameters

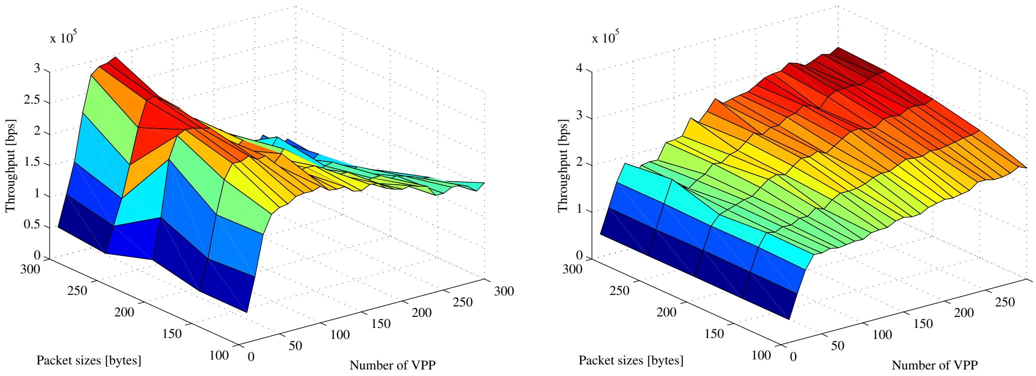
Parameters		**Values**
Satellite link capacity		492 kbps
Latency (satellite link)		250ms
Packet sizes	MR data	100-300 bytes
	EM data	100 bytes
	PR updates	100-300 bytes
Transport protocols	MR and EM type packets (unicast)	TCP
	PR packets (multicast)	UDP
Traffic type	MR and PR	CBR
	EM	Poisson distributed
Multicast routing strategy		PIM-DM*
Prune time out		0.5s
IP buffer size		1000 packets
#of customers/meters within each VPP, N		10-300

*Protocol Independent Multicast - Dense Mode



(a) MR (b) EM

Figure 7.: Latencies of MR and EM traffic for different meter reading packet sizes and the size of a VPP

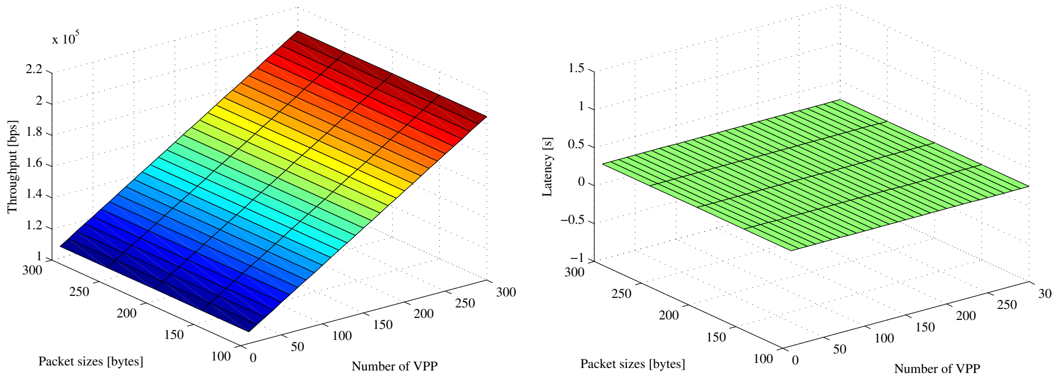


(a) MR (b) EM

Figure 8.: Throughput analysis of MR and EM traffic for different meter reading packet sizes and the size of a VPP

the MR traffic initially increased to a peak of about 240 kbps for $N = 50$ in each VPP, then it starts to decrease for the higher values of N. This is because of the higher latency of the MR packets. Contrarily, the throughput of the EM traffic exponentially increases with increasing N. In both cases, the throughput is always over 100 kbps for the higher values of N.

The impact of the MR packet sizes (K) ranging from 100 to 300 bytes on the latency is analyzed while the packet size of the EM packet is assumed to be 100 bytes, as shown in Fig. 7. It is observed that the latency of the MR traffic (Fig. 7(a)) is almost the same for all packet sizes for smaller N. However, the delay is significantly increased for larger packet sizes and higher N. For example, when the MR packet size is 300 bytes and $N = 300$, the latency is over 5 s. Fig. 7(b) shows that the overall latency of the EM traffic is below 380 ms for $N = 50$ and the MR packet size of 300 bytes while the latency is reduced for higher N and smaller MR packet size. Similarly, the throughput of the MR traffic increases with increasing its packet size (Fig. 8(a)) while little impact on the throughput of the EM traffic (Fig. 8(b)) for varying the MR packet sizes and smaller N. However, when N increases, the increase of MR packet size rather declines its throughput. Contrarily, the throughput of the EM traffic is improved for increasing



(a) Throughput

(b) Latency

Figure 9.: Performance analysis of multicasting of the pricing data (PR) for different settings

the MR packet size and N. Therefore, it can be concluded that the performance of the high priority traffic (EM) can be further improved by increasing the packet size of the MR traffic.

Fig. 9 illustrates the performance evaluation of the PR multicast traffic in terms of throughput and latency for different MR packet sizes. It is seen that the MR packet size does not have any impact on the multicast PR traffic while it linearly increases with increasing N as expected. It is also observed that the latency trend is also the same regardless of varying packet sizes and the number of prosumers in each VPP.

5. CONCLUSION

Advances in satellite technologies and cost-effectiveness are likely to increase the percentage of satellite use within the smart grid communications mix. This paper proposes a satellite-based communication architecture for virtual power plant (VPP) energy management in rural areas. Due to different requirements of data traffic, a priority-based packet scheduling is proposed to improve the performance of the more critical data such as faults/events monitoring. In this paper, three types of data such as meter reading, event monitoring and pricing data are considered and transmitted over satellites in either unicast or multicast transmission depending upon the traffic type. Extensive simulation experiments based on GEO satellites (BGAN) for different data traffic are carried out and the results indicate that the data delivery timeliness of different traffic types could meet the requirements to manage and operate VPPs. Future work will focus on the integration of terrestrial and satellite communication networks with the expectation that an integrated communication solution can provide a complete smart grid WAN solution.

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