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6LoPLC FOR SMART GRID APPLICATIONS

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Abstract- Reliable monitoring, intelligence and control achieved through Information and Communication Technology (ICT) will determine the success of next generation power grid. This paper proposes a Low Power transmission of Internet Protocol version 6 in PLC (6LoPLC) to provide network reliability with acceptable latency in Advanced Metering Infrastructure (AMI). The analysis presented here are preliminary results from an ongoing research that attempts to leverage existing wireless techniques to achieve energy efficiency in PLC. A model was developed using NS-3 to measure and analyze the performance of low-power Narrow Band PLC (NBPLC) in AMI services. Simulation results obtained so far are quite promising.

Keywords— Low-Power Power Line Commnication, 6LoPLC, ZigBee, Narrow Band PLC, Smart Grid, LLN, AMI, Smart Metering, 6LoWPAN, NAN, HAN, Packet Fragmentation.

I. INTRODUCTION

The energy landscape is changing; legacy power grid was installed mainly for electricity delivery to customers and is devoid of intelligence, limited in communication and lacking in control. Furthermore, it only allows flow of electricity from point of generation to consumer's premises. Arguably, one of the most critical infrastructure relied on for daily living, demand for electrical power has not only soared over the years, consumers also expect power to be available at all times, hence it is sometimes taken for granted. However, over the last few decades, demand growth and expectations have not been matched with significant infrastructure upgrade or redesign; the results have been blackout, unavoidable brownouts and unmet consumer expectations. Advent of Plug-in Electric Vehicles (PEV) is revolutionary and will further help to uncover new possibilities by operating as energy island to provide power to homes and valley-filling energy supply during peak demands. Next generation power grid is therefore envisioned to incorporate silos of renewable energy sources for the sake of sustainability and environmental stewardship. These revelations have caused internal resonance within the research community resulting in fresh drive and renewed commitment to push next generation power grid from laboratory to reality. Motivated by these, governments and research organizations in different parts of the world have considered and are still considering increased usage of energy from non-fossil sources and the need to seamlessly integrate them into the grid. The last few decades have recorded a phenomenal growth in resource constrained smart devices. The aggressive development witnessed in machine-to-machine (M2M) communication and recent developments in Internet of Things (IoT) community are particularly encouraging. Industry players are already evaluating their potential opportunities in various applications markets especially Advanced Metering Infrastructure (AMI). In practice, the decision to use a communication channel must be matched with operational and economic realities. For example in North America, PLC-based AMI systems are less attractive because there are 1 to 6 customers per transformer [1-2], hence PLC technologies for in-grid communication are considered expensive compared with Europe where 100-300 customers [3-4] share a transformer. Therefore, the eventual communication platform may be heterogeneous in nature. With adoption of IPv6 by most industry players, scalability and coverage are expected to even be better. Field trial results in DLC+VIT4IP project [5] are particularly encouraging; a further attestation that performance of IPv6 in PLC is not in doubt. The successful use and preference of PLC in smart metering projects in some parts of Europe [6] has further favoured PLC as an access medium for smart grid. In state-of-the-art analysis of Distribution Line Carrier systems reported in [7], some companies (including ERDF, Maxim etc.) adapted features of 6LoWPAN in PLC. However, those implementations were based on RFC 4944 [8], which involves fragmentation of packets. Since PLC natively supports full IPv6 packet (1280 bytes), our approach is to transmit IPv6 without fragmentation in power line channel. This is expected to improve the channel performance. Taking a cue from 6LoWPAN, our contribution is presentation of power line as an alternative channel for AMI based on IPv6 low power communication. Remaining part of this paper is organized as follows: Sections II discusses the need for low-power communication in smart grid, it also introduces the concept of 6LoPLC; an adaptation of 6LoWPAN-equivalent in power line channel. In section III, our simulation results are presented and discussed while section IV concludes the paper with direction of future research in this area.

II. SMART GRID COMMUNICATION

A. *IPv6-based Low Power PLC (6LoPLC) for AMI*

Monitoring of future power grid will rely heavily on low-cost devices enabled with low-power communication capabilities. The cohesive power of such subsystems will be harnessed via large-scale integration over the entire electrical power value chain; spanning generation to smart meters. A major beneficiary of such integration are the smart meters deployed to monitor the consumer end of electricity distribution environments and send measured observations to a target of interest; usually a server, these features summarily describe them as sensors [9]. In addition to automatic reading, smart meters will act as sensors, sending estimates of power quality, alarms, and other information useful for price setting, thereby providing better visibility. However, domestic loads do not contribute to the energy powering smart meters or spent during bi-directional communication with utility servers, hence such energy is not billable. It is therefore compelling for utilities and hardware manufacturers to ensure that energy budget with respect to communication activities is very low. While efficient electronic design is one way of achieving that goal, ultra-low power Digital Signal Processing (DSP) and energy-efficient communication protocols are also of immense values. The foundation has been laid in LoWPAN devices (IEEE 802.15.4), considering the scale envisaged in terms of number of hardware and processes that would make a functional smart grid, every unit of energy saved is a tangible achievement that would eventually have far-reaching effects. Therefore, a sustained campaign for low-power smart grid communication is an absolute necessity. Different authors [10-12] have written in favour of 802.11 (WLAN), 802.15.4 (ZigBee), 802.16 (WIMAX) etc, for various segments of smart grid but we argue here that bearing in mind the several scores or hundreds of indoor meters required to connect to each other in a mesh topology, there are many odds against low-power wireless connectivity. In power distribution network, electricity meters are installed per household many of which may be separated by concrete building walls and fences. The implication is that wireless signal will experience building penetration losses (due to attenuation and absorption) as it propagates the walls and that can only be compounded by the very low antenna gain and low transmit power typically found in low-power wireless devices. Secondary losses like signal reflection, refraction and diffraction can also occur, these forms of losses combined can result in network black holes, which are unfavourable for applications. This may even be worse in smart grid applications with strict QoS requirements. Spectrum licensing is another concern; we therefore propose 6LoPLC as an alternative using NBPLC.

B. Advanced Metering Infrastructure (AMI)

Unlike Automated Meter Reading (AMR), which simply uploads consumption information from meter to a few remote servers, AMI facilitates the measurement and control of energy distribution and consumption via a 2-way communication between smart meters, Smart Meter Data Management (SMDM) and other servers in utility's network. Such communication can be periodic or on-demand depending on configuration and situation. AMI also allows remote configuration and querying of smart meters, for instance, energy supply to a consumer's facility can be remotely shut down. As the ubiquitous part of the smart grid, meters in close proximity communicate with each other directly using low-power links and can also act as transit node for packet routing in a mesh-like topology. The number of meter per routing cluster varies from about 1,000 meters in rural areas to around 10,000 in urban centres [13]. In the end, each AMI will contain millions of smart meters clustered in smaller service areas. In theory, the smart meters could interconnect in a mesh topology using low-power links (eg IEEE802.15.4, 802.11, 1901.2), a common feature of these links is their lossy nature. As the last mile of AMI, NAN can use wireless, PLC or a mix; we chose PLC in this paper. Smart meter can also act as gateway for other meters (gas, water), Home Area Network (HAN) devices and PEV; all of which are resource-constrained; hence, AMI is crucial to success of the smart grid program. Across the Wide Area Network (WAN), each cluster of smart meters connects to the larger IP network through Data Concentration Units called Low-power and Lossy Network Border Routers (LBRs). LBRs provide WAN connectivity from IP network to smart meters within the NAN according to IETF RFC 5548 [8]. Requirements of smart grid applications are summarised in table 1 below.

Table 1: Communication Requirements of Smart Grid [12-14]

Application	**Bandwidth (kbps)**	**Reliability (%)**	**Latency**
Substation Automation	9.6-56	99.0-99.99	15-200ms
Overhead Transmission Line Monitoring	9.6-56	99.0-99.99	15-200ms
Home Energy Management	9.6-56	99.0-99.99	300-2000ms
AMI	10-1000/ node, 500 for backhaul	99.0-99.99	2000ms
Wide Area Situation Awareness (WASA)	600-1500	99.0-99.99	15-200ms
Demand Response (DR)	14-100/ node	99.0	500ms- several mins
Outage Management	56	99.0	2000ms
Distribution Automation	9.6-56	99.0-99.99	20-200ms
Distribution Management	9.6-100	99.0-99.99	100ms-2sec
Asset Management	56	99.0	2000ms
Meter Data Management	56	99.0	2000ms
Distributed Energy Resources & Storage	9.6-56	99.0-99.99	300ms-2sec
Vehicle-to-Grid	9.6-56	99.0-99.99	2sec-5min
EV charging	9.6-56	99.0-99.99	2sec-5min

Typically, in web applications, small data is sent in form of Hypertext Transfer Protocol (http) or Hypertext Transfer Protocol Secure (https) request to a server from which larger amount of data is downloaded, hence it not unusual to use connections with low uplink bandwidth and high downlink bandwidth. However, in AMI with many tens, hundreds or thousands of meters in a locality, it is expected that the NAN segment of the smart grid will require a relatively high bandwidth to upload data from smart meters to utility server.

Table 2: QoS Requirements of AMI [13-15]

Traffic Class	**Services**	**Requirements/characteristics**
High Priority and Critical	Power outage, pricing notification, event and emergency messages	≥ 98% packet delivery within 5s Payload ≤ 100bytes
Critical	Power quality, meter service, connection and disconnection	≥ 98% packet delivery within 10s Payload ≤ 150bytes
Normal Priority	System events: Faults, security, configuration	≥ 98% packet delivery within 30s Payload ≤ 200bytes
Low Priority	Periodic meter reading	≥ 98% packet delivery within 2 hrs, 6 times/day Payload ≤ 400bytes
Background	Firmware/software download	98% of devices processed within 7 days. Update file ≤ 1MB

In the case of AMI, traffic QoS is defined in table 2. Using NS-3 simulator and based on Fig. 1, we simulated AMI in section III of this paper.

C. Simulation Model

Using the NS-3 (NS-3.21), we simulated 2 important traffic classes in AMI involving 200-1000 smart.

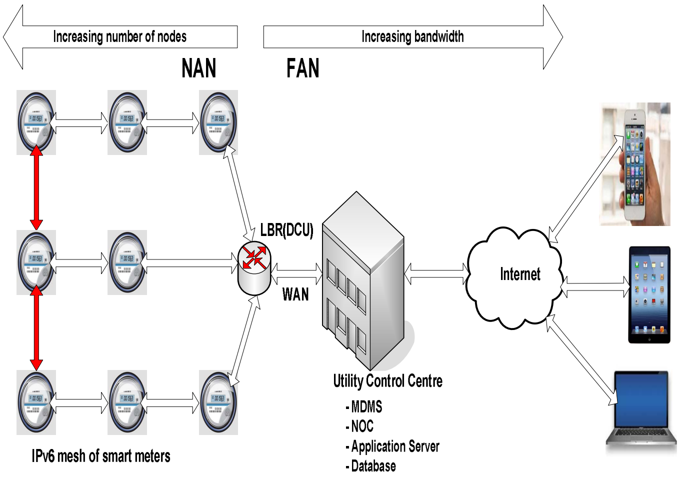

Fig. 1. PLC 2-way communication among smart meters in AMI

Development of low-power devices began at a time IP was considered by many vendors as too intensive in terms of memory, processor and bandwidth. That led to development of many proprietary Logical Link Control (LLC) protocols as a sub-layer of the Data Link layer, examples are Bluetooth, USB and ZigBee. Following the widespread adoption of IP, 6LoWPAN was introduced as an adaptation layer between the Data Link and Network layers to enable transmission of IPv6 packets over 802.15.4 networks. 6LoWPAN support fragmentation/ reassembly to meet IPv6 minimum MTU requirement. Here we investigate an adaptation layer for IPv6 traffic over low-power NBPLC in smart grid environment where smart meters are represented as IPv6 nodes. NBPLC (below 500 kHz) supports indoor and outdoor uses and can deliver maximum of about 500kbps. The physical layer and MAC sub-layer are based on IEEE1901.2 PHY and MAC specification.

D. Adaptation Layer: 6LoPLC

Although the 6LoWPAN was originally developed by IETF for resource-constrained wireless networks, some authors [13] have shown that PLC shares some MAC sub-layer features of 802.15.4. However, unlike 802.15.4 with MTU size of 127 bytes, 190.1.2 MAC standards support MTU size of 1280 bytes; hence, it can transport full IPv6 packets without fragmentation. This is a major advantage over 6LoWPAN, which uses fragmentation and reassembly. Similar to 6LoWPAN, header compression is relevant in 6LoPLC. A representation of IPv6 header is given in table 3.

Table 3: IPv6 header

Version (4 bits)	Traffic Class (8 bits)	Flow Label (20 bits)	Payload Length (16 bits)	Next Header (8 bits)	Hop Limit (8 bits)
Source Address (128 bits)					
Destination Address (128 bits)					

According to IETF RFC 2460 [8], the standard IPv6 header is 40 bytes as summarized in table 3 above. Given that entire 802.15.4 MTU is 127 bytes; such a huge transmission overhead will naturally result in low data payload. We therefore expect 1901.2 to perform better in this regard, following its MTU of 1280 bytes. TCP and UDP add extra overhead of 20 bytes and 8 bytes respectively.

E. Header Compression

In 6LoWPAN, IPv6 headers compression is achieved using common or predictable values as identifiers. For instance, in a cluster of 100 smart meters, all meters register with the LBR. Given that the network part of the IPv6 address is common to them, LBR can exclude that network portion of the host address from the IPv6 headers, thereby compressing the packets sent across to low-power nodes. Specifically, 6LoWPAN reduces the overhead as follows:
Source Address: Derived from link address (using EUI-64)
Destination Address: Derived from link address (EUI-64)
Traffic Class and Flow Label: Can be zero.
Next Header: UDP, TCP or ICMP (predictable). This feature is expected to yield performance gain in low power PLC.

III. SIMULATION AND RESULTS

The narrow band power line channel used in this paper was modelled using LoWPAN PHY and MAC standards in 9 -500 kHz spectrum, combined with random delay and propagation loss to obtain a semblance of power line channel from previous work. As there is no native power line module in NS3, these added impairments account for unpredictable or abrupt variations in network impedance, which accordingly affects attenuation. To that extent, the channel is not assumed perfect but gives an acceptable power line scenario.

A. 6LoWPAN vs 6LoPLC

We begin by comparing performance of the PLC system with 6LoWPAN, based on simulation of a simple meter reading with 200 smart meters. The smart meters connected to the LBR (gateway) form NAN segment of the AMI. All smart meters upload readings to the remote UDP server via the LBR.

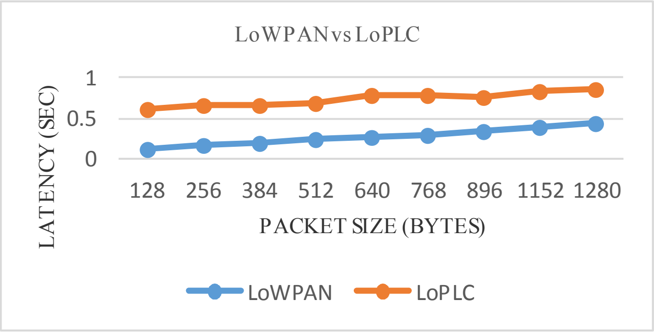

Fig. 2. WPAN vs PLC

Power line is used in the NAN only, while WAN link is modelled as a high-speed link with latency of 1ms typical of fiber optic links since that would support multiple NANs in reality. The comparison is presented in Fig. 2 above. To further understand peculiar communication characteristics in low power PLC, we simulated two AMI application scenarios namely: smart metering and alarm transmission. Given that latency (delay) and throughput are key channel attributes upon which many AMI application performances can be measured, we investigated time taken to deliver data packet of a UDP application and system throughput. The system is also being investigated over a more realistic narrow band PLC channel with the additive impulsive noise.

B. *Fragmentation*

Given that 802.12.5 frames support maximum size of 127 bytes, the payload in it can be as low as 81 bytes (63.8%) or less. However, the minimum MTU of IPv6 is 1280 bytes; hence, part of the functions 6LoWPAN is to provide fragmentation/reassembly mechanisms. During transmission, if one fragment is lost, all of them must be retransmitted thereby contributing to inefficient use of resources in a network that is constrained ab-initio. We infer from table2 that data of some smart grid application can be low enough to fit into a single LoWPAN frame. For such, fragmentation can actually be avoided. Additionally, services like firmware upgrade, extraction of historical data and logs from smart meters would involve transfer of bulk data. Again, since these are not priority services, there is no merit in applying fragmentation in their delivery.

C. *Smart Metering*

As documented in [1-4], meter density per transformer varies among regions. For the purpose of comparative analysis, we simulated smart metering with 100, 200 and 400 meters. We assumed the LBR is situated in same shelter as the transformer and provides WAN connectivity to the smart meters. To enable us observe performance under typical meter reading scenario, NS-3 simulation environment was setup as indicated in table 4. We measured latency of the traffic and throughput offered by the system. The smart meters were configured as UDP echo clients and Smart Meter Data Management (SMDM) server as UDP echo server. An upload window (time allocated to upload readings from meters to server) of 2 minutes, subdivided into120 timeslots of 0.5 second each was applied. Our results are presented in Fig. 3

Table 4: Smart metering simulation parameters

LoWPAN parameters		
Point-to-Point Link	Data Rate	2Mbps (E1)
	Delay	1ms
CSMA channel	MTU	130 Bytes
	Delay	25ms
	Data Rate	140kbps
	Force Ethertype	True (48MACAddress)
No of smart meters	100 - 1000	
PLC parameters		
OFDM		
Frequency	5 – 500KHz	
FFT size	128	
Code Rate	BPSK 1/2	
Upload window	120 seconds (duration of readings upload)	
Application type	Client/Server UDP application	

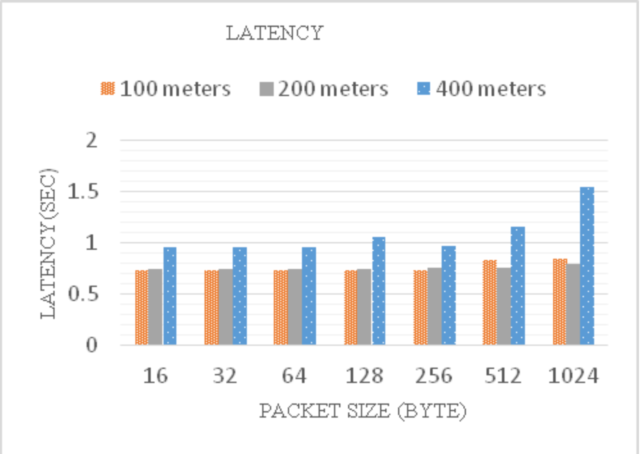

Fig. 3 Delay as a function of packet size and load.

From Fig. 3 above, it is evident that application packet size has a direct bearing on end-to-end delay between smart meters and SMDM server. Though it could be argued that large packets tend to occupy slow link for longer period, this can easily be countered by the delay caused by fragment buffering as the number of fragments increases. Additionally, large packet sizes provide more throughput given constant transmission overhead. The results presented in Fig. 3 were obtained from transmission of full IPv6 packet without fragmentation. Although the PLC channel did not show a better performance in terms of latency, the results obtained fall within acceptable limit of smart grid traffic requirements per table 2. Fragmentation happens when an IPv6 packet is larger than the path MTU toward the receiver. The received fragments are reassembled at the receiver. Apart from the delay introduced, extra processor power is expended when fragments are awaiting reassembly. This also creates opportunity to send a large number of uncompleted packet fragments thereby forcing the receiving node to expend most of its resources buffering and waiting for reassembly operation. This could potentially lead to denial of service even within the fragmentation timeout. Therefore, fragmentation should be avoided as much as possible.

D. *Alarm Transmission Delay*

From table 2, unlike meter reading data with maximum payload size of about 400 bytes, alarm transmission only requires a maximum of 100 bytes because of the precision of information they carry. However, timely delivery of alarm messages is essential. A cluster of smart meters could asynchronously send alarm message to a server notifying it of a general outage or unusual power condition. This is a typical example of high priority/critical traffic earlier summarised in table 2. From Fig. 3, we can see the effect of cluster size on latency. The steady rise in latency as number of smart meters increases is an indication that though individual alarm messages are small, when aggregated in hundreds or thousands in a NAN, there could significant impact on network performance. It is therefore instructive for application developers to consider that small packet size is needed to ensure timely delivery of critical application traffic within acceptable QoS boundaries.

E. System Throughput

We also investigated the actual throughput (per node) of the system using different numbers of meters as presented in Fig 4

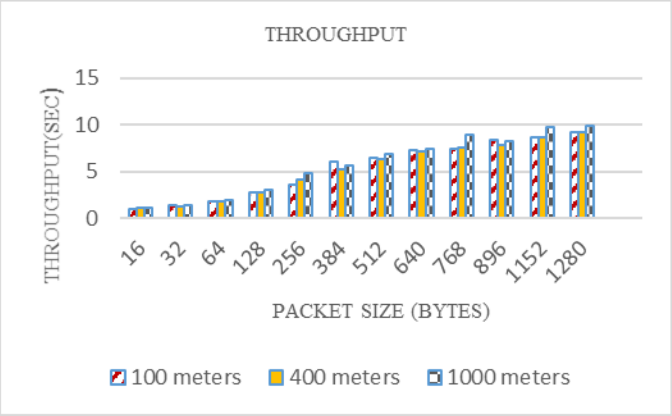

Fig. 4. System Throughput

According to field measurements presented in [3], meter reading comprising of 300 meters will require a raw throughput of 2kbps per node in certain cases. To have a broader view of the system behaviour, we simulated with 100 – 1000 meters and measured the throughput. From Fig. 4, throughput of the network varies linearly with packet size. This does not only conform with normal system behaviour but also means that even without fragmentation, low-power PLC can potentially support smart grid applications. Therefore, applications for this environment need to be customised to reduce or avoid fragmentation

IV. CONCLUSION AND FUTURE WORK

From the simulations conducted, packet size is a major determinant of AMI application performance. Smart grid application developers must therefore consider this regardless of the channel to be used. In Figs. 3 and 4, we demonstrated that even without packet fragmentation, PLC is promising for low-power communication in smart grid. The results discussed are based on preliminary observation from a bigger ongoing project that sets out to reduce the overall energy consumption of PLC system and make it more adaptable for low power, lossy networks. We have through this paper drawn attention to this potential approach and hope it will encourage other researchers in this burgeoning area of smart grid communication not only expand the scope of what has been presented here but also uncover more possibilities. Future work in this area will be to refine the channel to a more realistic one, conduct a comparative analysis of energy consumption and transmit power between 6LoWPAN and 6LoPLC based on empirical investigation. That will involve investigation of a range of techniques like co-operative multi-hopping, pre-transmission channel estimation, parasitic energy reduction among others.

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