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FINAL PROJECT
TRAFFIC ANALYSIS OF A SIMULATED BPL OVER PLC NETWORK

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1 ABSTRACT

The use of Broadband over Power Lines (BPL) using Power Line Communication (PLC) can be used in medium/low-voltage supply networks for the delivery of various communication services, such as Internet access, voice over IP (VoIP), automatic meter reading (AMR), and home and building automation. BPL uses PLC by sending and receiving radio signals over power lines to provide access to the Internet. The BPL modems are capable of handling power line noise on a wide spectrum and are mandated to be designed to notch out frequencies on which radio interference with short-wave and ham radios occurs. Successful implementation of BPL enables distributing electricity via a digital network. This decentralized “smart grid” approach would overlay the ordinary electrical grid with an information and net metering system that could be used to manage and provision power distribution. For this project, we used OPNET to simulate a basic BPL over PLC network to investigate the burstiness (variation in data throughput) of three different types of traffic: constant-sized self-similar traffic, exponential-interarrival time traffic, and traffic following a Poisson-distribution pattern.

2 INTRODUCTION

The development of new devices which are able to communicate through PLC networks has changed its goal. Nowadays, these networks are used not only for power distribution, but to add new applications such as Internet access and IP (Internet protocol) based services. AMR and power transmission control using BPL over PLC can allow for closed-loop control using an observer-based controller design which is an ideal control method for the multiple-input multiple-output (MIMO) nature of the power distribution grid. This approach may result in lower electric power costs, less pollution and greater reliability, and home automation could be achieved by allowing home appliances to communicate with each other.

2.1 BPL Technology Overview

BPL technology provides an internet connection over electric distribution lines by installing power line adaptors at centralized locations to carry broadband Internet traffic over medium voltage power lines. These adaptors receive internet data and translate it using orthogonal frequency-division multiplexing (OFDM), which is the ideal modulation scheme for the noisy power line environment due to its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long wire and narrowband interference) without complex filters. The endpoint BPL modems separate the data from the electricity, sending the data to an Ethernet port. BPL can be
used for providing up to 200Mbps (total, upstream plus downstream) by means of the power grid. The coverage is often the last half mile (typical distance from the medium-to-low voltage transformer to the customer premise meter) and as an in-home network.

Access BPL is a new technology to carry broadband Internet traffic over medium voltage (MV) power lines. Commonly there are three electric phases each carrying 1kV-30kV volts. One phase is usually enough to power the houses on a residential street, and two or three phases can be joined together to power the big electric motors in an industrial or commercial area. BPL modems are connected to the medium voltage power lines using inductive couplers which transfer the communications signal onto the power line without physical contact. A potential challenge is the delivery of the signal from the MV line to the low voltage (LV) line that enters the home or office, because the transformer that lowers the electric power from several thousand volts down to 110V/120V could act as a bottleneck to the broadband signal.

### 2.2 Traffic Models

Good traffic modeling is a basic requirement for accurate network planning. This report attempts to provide an overview of throughput variation for 3 network traffic models over the PLC link.

Analysis of the traffic provides information like the average load, the throughput, and numerous other details. Traffic models enable network designers to make assumptions about the networks being designed based on past experience and also enable prediction of performance for future requirements. Traffic models are used either as part of an analytical model or to drive a Discrete Event Simulation (DES), which is the case in this project.

The three traffic models used in the simulation are: (1) self-similar, (2) constant-sized exponential-interarrival, and (3) following a Poisson distribution.

Internet traffic can be modeled as a sequence of arrivals of discrete packets. A counting process \( \{ P(t) \}_{t=0}^{\infty} \) is a continuous-time, integer-valued process, where \( P(t) \) represents the number of packet arrivals in the time interval \( (0,t] \). An interarrival time process is a non-negative random sequence \( \{ I_p \} \), where \( I_p = T_p - T_{p-1} \) indicates the length of the interval separating packets \( p-1 \) and \( p \). Counting processes and interarrival time are related by

\[
\{ P(t) = p \} = \{ T_p \leq t < T_{p+1} \} = \left\{ \sum_{k=1}^{p} I_k \leq t < \sum_{k=1}^{p+1} I_k \right\}.
\]
One important issue is the ability to describe traffic burstiness. A sequence of arrival times will be bursty if the $T_p$ tend to form clusters and if the corresponding $\{l_p\}$ sees a mix of relatively long and short interarrival times. Traffic experiencing high burstiness will vary fluctuate more in throughput than non-bursty traffic. The Hurst parameter $H$ can be used as a measure of burstiness in case of self-similar traffic, and OPNET allows for configuration of this parameter.

### 2.2.1 Self-Similarity in Traffic

Self-similarity describes the phenomenon where a certain property of an object is preserved with respect to scaling in space or in time. The fact that much of network traffic is self-similar in nature is a reminder that new discoveries do not necessarily require new mathematical concepts, statistical techniques, or in this case, new networking technologies. Instead, the discovery often lies in applying a well-known mathematical concept such a self-similarity in a newer context such as networking. Network traffic that is bursty on many or all timescales can be described statistically using the notion of self-similarity, where the traffic structure remains unchanged at varying timescales.

The definition of self-similarity involves a packet sequence

$$X = X(i), i \geq 1.$$  

Let

$$X^m(k) = \frac{1}{m} \sum_{i=(k-1)m+1}^{km} X(i), k = 1,2,3 \ldots$$

be the corresponding aggregated sequence with level of aggregation $m$, obtained by dividing the original series $X$ into non-overlapping blocks of size $m$ and averaging over each block. The index $k$ labels the block. If $X$ is the increment process of a self-similar process, then if for all integers $m$,

$$X = m^{1-H}X^m,$$

where $H$ is the Hurst Parameter and the sequence is said to be exactly self-similar.

### 2.2.2 Exponential Interarrival ON-OFF Traffic
In the exponential interarrival on-off model, the packet stream from a single source is modeled as a sequence of alternating burst periods and silence periods. The duration of each burst is exponentially distributed with mean $1/a$. During such a period, packets are generated with constant interarrival time $T$. After that, an exponentially distributed silence period with mean value $1/b$ follows. Three parameters that can be configured in OPNET for exponentially-arriving traffic are:

- Peak bit rate ($p$): peak bit rate of packets when the source is in the active state, or the maximum amount of network bandwidth needed by the source.
- Mean bit rate ($m$): the mean bit rate, or the average amount of network bandwidth requested by the source.
- Mean active time ($T_{on}$): the mean active/holding duration.

Burstiness ($\beta$), can be defined as the ratio of the peak packet rate and the average packet rate ($b = p/m$). The corresponding values for $a^{-1}, b^{-1}, T$ can therefore be calculated as

$$T = 1/p,$$
$$a^{-1} = T_{on},$$
and
$$b^{-1} = a^{-1} \cdot (\beta - 1).$$

### 2.2.3 The Poisson Distribution and Network Traffic

Assuming pure-chance packet arrivals and pure-chance terminations means that the number of packet arrivals in a given time has a Poisson distribution:

$$P(a) = \left(\frac{\mu^a}{a!}\right) e^{-\mu},$$

where $a$ is the number of call arrivals and $\mu$ is the mean number of call arrivals in time $T$. For this reason, pure-chance traffic is also known as Poisson traffic. The number of call departures in a given time also has a Poisson distribution:

$$P(d) = \left(\frac{\lambda^d}{d!}\right) e^{-\lambda},$$

where $d$ is the number of call departures and $\lambda$ is the mean number of call departures in time $T$. The intervals, $T$, between call arrivals and departures are intervals between independent, identically distributed random events. It can be shown that these intervals have a negative exponential distribution:
\[ P[T \geq t] = e^{-t/d}, \]

where \( d \) is the mean holding time.

3 NETWORK MODELING

3.1 General Network Topology

In the BPL over PLC network, there is a central device which distributes the power to all endpoint units within homes. The power line link utilized by BPL will be modelled in OPNET at medium voltage (1000 – 35,000 V) over standard aluminum power lines. The internet signal is transmitted from the BiPAC 2300 BPL Access head-end unit over this transmission medium and received at the destination building by a BiPAC 2103 BPL Access end-point unit (modem), which is connected by Ethernet to the computer or device. The general network topology is illustrated in Figure 1.

![Figure 1: BPL Network Topology](image)

For the purposes of this project, the simulated network model consists of the BiPAC 2300 Access Head-end unit, two BiPAC 2103 Access End-point units, and a workstation connected to each end-point unit. The head-end unit is connected to internet source traffic nodes, which generate one of the three traffic types discussed in the section above. The simplified model diagram is shown in Figure 2.
3.2 OPNET Modelling

OPNET is a discrete event simulator that allows simulating and analyzing protocols. In the case of this project, since the power-line physical layer is not natively supported by OPNET, the improvised solution is the modification of the centralized head-end node’s processor model in order for it to act as a medium for communication between the other network nodes. The central process model encapsulates the physical layer emulator and emulates the duplex 100Mbit/second link connecting the head-end and end-point units as MV power line.

Each OPNET processor model is defined by a finite state machine which represents the module’s logic and contains the module’s behaviour described in OPNET Proto C code.

For this project, two scenarios were created and simulated. The first deals with self-similar and exponential traffic being generated and carried through PLC MV link to a head-end unit, where it is bridged to the end-point units, where it is demodulated and converted into Ethernet data and delivered to the PC workstation. The second scenario is identical except for the fact that exponentially-distributed traffic is replaced with Poisson-distributed traffic.

3.2.1 Node and Process Modelling of BPL End-point and Head-end Units

The BiPAC 2103 BPL Access End-point Unit was modeled in OPNET as a modem and demodulator utilizing OFDM to transmit signal over power line into Ethernet data. **Figure 3** shows the node model of the end-point unit.
Figure 4 shows the associated process model of the BPL_Demod_Hub process. The state variables for the above shown process model are displayed in Figure 5.
The BiPAC 2300 BPL Access Head-end Unit was modeled in OPNET as a BPL bridge and a medium which encapsulates the physical layer emulator in order to allow approximate modelling of the PLC link. **Figure 6** shows the node model of the head-end unit.

![Figure 6: BPL Head-end Unit Node Model](image)

**Figure 5: BPL End-point Unit Process State Variables**

![Table of BPL End-point Unit Process State Variables](image)
Figure 7 shows the associated process model of the BPL_Bridge process, which ended up consisting of five states, with physical layer emulation being performed in the idle state’s exit block.

![Diagram showing BPL Head-end Unit Process Model]

The state variables for the above shown process model are displayed in Figure 8.

![Table showing BPL Head-end Unit Process State Variables]

3.2.2 PLC Link Modelling

Because a power-line link is not natively supported in OPNET, two problems needed to be solved. First, the speed in access BPL is not equal to that of Ethernet, and the speed also fluctuates over different environments. Second, the distribution of the users in a power grid is much more random than that of the bus model generated by OPNET.
Bus topology versus Star topology

The feasibility of replacing a bus topology by a star topology is tested using a contributed model downloaded from the OPNET online model library [4]. The same parameters are set for these two topologies as shown in Figures 9 and 10. The distance distribution from users to the sensor is identical in both topologies.

In order to eliminate the influence of the random number generator in the software, 100 different simulation seeds are defined. The end-to-end delay is chosen as the measurement criterion. The results are shown in Figure 11. From the results of the simulation, it can be found that for a large number of experiments with different random seeds, the delay difference between star topology and bus topology becomes smaller. This justifies that the bus topology can be replaced by a star topology in the lab environment.
The PLC link model parameters and attributes are shown in Figure 12.

![Figure 12: PLC Link Model and Attributes](image)

### 3.2.3 Network Construction of Scenario 1 – Self-similar vs. Exponential

The OPNET network model for Scenario 1 is shown below in Figure 13. The scenario consists of a star topology with one BPL head-end unit, two BPL end-point units, two PC workstations and two traffic sources – one generating constant-sized packet traffic using a self-similar, or fractal, distribution pattern and one generating constant-sized packet traffic using an exponential packet interarrival rate. The self-similar traffic was configured with Hurst parameter = 0.8 and a fractal onset time scale of 0.001.
As evident from **Figure 13**, the head-end unit is connected to the end-point units and the traffic sources via PLC link (thick line), which has been approximately modelled as a 100Mbit/second data link with high susceptibility to background noise. The configured attributes for the PLC link are shown later on in this report. The PC workstations, each receiving their own type of traffic, are connected to the end-point units with 100BaseT duplex Ethernet link. **Figures 14 and 15** illustrates the node and process model for the self-similar traffic generator subnet, as well as configuration parameters and process-model state variables, respectively.
As seen in the figure, the Hurst parameter for the self-similar traffic generator was set at 0.8. This was done to ensure that the increments of packet traffic were positively correlated.

The enter executives of the initialization state in the self-similar packet generator is shown in the code snippet below.

```c
/* Initialize the state variables used by this model. */
rgp_dispatcher_sv_init();

/* Register IP0 as a higher layer protocol over IP layer and retrieve */
/* an auto-assigned protocol id. */
higher_layer_proto_id = Ip0.Protocol_UNSPEC;
Ip_Higher_Layer_Protocol_Register ("rgp", higher_layer_proto_id);

/* Register this process in the network wide process registry so that */
/* lower layers can detect our existence. */
rgp_dispatcher_register_self();

/* Read RPG related simulation attribute values into global variables */
/* unless another rgp_dispatcher process already did this task. */
if (rgp_sim_attr_read == 0) {
    /* We are the first. Read the attributes if they exist (otherwise */
    /* the default value is 100.0 secs) */
    if (op_lma_sim_attr_exists("IP0 Start Time") == OPC_TRUE)
        op_lma_sim_attr_get (OP_LMA_DOUBLE, "IP0 Start Time", &rgp_start_time);

    /* Switch the flag */
    rgp_sim_attr_read = OPC_TRUE;
}

/* Schedule a self interrupt to wait for lower layer process to */
/* initialize and register itself in the model-wide process registry */
/* This is necessary since global RPG start time may have been set as */
/* low as zero seconds, which is acceptable when operating over MAC */
/* layer. */
op_intcpt_schedule_self (op_sim_time (), RPGC_INIT);
```
This code was commented in order to be explanatory.

**Figures 16 and 17** illustrates the node and process model for the exponential traffic generator, and the configuration parameters and process-model state variables, respectively.

![Figure 16: Exponential Traffic Generator Node and Process Model](image1)

![Figure 17: Exponential Traffic Generator Attributes and State Variables](image2)
3.2.4 Network Construction of Scenario 2 – Self-similar vs. Poisson

The OPNET network model for Scenario 2 is shown below in Figure 18. This scenario consists of a star topology with one BPL head-end unit, two BPL end-point units, two PC workstations and two traffic sources – one generating constant-sized packet traffic using a self-similar, or fractal, distribution pattern and one generating packet traffic using a Poisson distribution packet size and interarrival time. The self-similar traffic was configured with Hurst parameter = 0.8 and a fractal onset time scale of 0.001 and the Poisson traffic with a mean of 5.

As in Scenario 1, the head-end unit is connected to the end-point units and the traffic sources via PLC link (thick line), which has been approximately modelled as a 100Mbit/second data link with high susceptibility to background noise. The configured attributes for the PLC link are shown later on in this report. The PC workstations, each receiving their own type of traffic, are connected to the end-point units with 100BaseT duplex Ethernet link. The node and process model for the self-similar traffic generator subnet, as well as configuration parameters and process-model state variables are identical to those as in Scenario 1 and are shown in Figures 14 and 15.

Figure 19 illustrates the configuration parameters and process-model state variables for the Poisson-distribution traffic generator subnet.
Once the two scenarios were created, individual DES results were selected in order to enable collection of data throughput and queuing delay for the PLC links connecting the network nodes. These results are discussed in the next section of the report.

4 DISCUSSION AND CONCLUSIONS

The modelled scenarios were simulated in OPNET for a simulation duration of 25 minutes. The results are displayed below.

![Simulation Results – Throughput](image-url)
Figure 20 shows the data throughput simulation results for both scenarios. The graphs display the average data throughput in bits/second throughout the course of 25 minutes of simulated time. The graph labelled (1) shows the bandwidth in the PLC link connecting the BPL head-end unit to a BPL end-point unit. This link is transmitting self-similar traffic. This graph shows significant variation in throughput (burstiness) present in this traffic model.

The graph labelled (2) also shows the bandwidth in the PLC link connecting the BPL head-end unit to a BPL end-point unit, however this link is transmitting Poisson traffic. This graph shows moderate variation in throughput (burstiness) present in this traffic model.

The graph labelled (3) also shows the bandwidth in the PLC link connecting the BPL head-end unit to a BPL end-point unit, but this link is transmitting exponential traffic. This graph shows virtually no variation in throughput (burstiness) present in this traffic model.

Figure 21 shows point-to-point queuing delay simulation results for both scenarios. The graphs display the average point-to-point queuing delay throughput in seconds throughout the course of 25 minutes of simulated time. The graph labelled (4) shows the queuing delay for packets travelling from the BPL head-end unit to a BPL end-point unit.
This link is transmitting self-similar traffic and experiences an average point-to-point delay of 0.000058 seconds.

The graph labelled (5) shows the queuing delay for packets travelling from the BPL head-end unit to a BPL end-point unit, but this link is transmitting Poisson traffic and also experiences an average point-to-point delay of 0.000058 seconds.

The graph labelled (6) shows the queuing delay for packets travelling from the BPL head-end unit to a BPL end-point unit. This link is transmitting exponential traffic and experiences an average point-to-point delay of 0.000082 seconds.

From the results obtained from simulation, it is apparent that traffic modelled following an exponential interarrival time experiences the least amount of burstiness in the PLC medium. Self-similar traffic and Poisson traffic undergo much more burstiness through the PLC link, with Poisson traffic showing slightly less burstiness than self-similar traffic.

Although exponential traffic shows the most promise regarding burstiness in the PLC link, the point-to-point delay is over an order of magnitude greater than the self-similar or Poisson modelled traffic. Whether this difference in delays is significant in a larger PLC network remains to be seen and could be investigated in future work using more robust BPL over PLC network simulations.
5 REFERENCES


APPENDIX A: OPNET 14.0 CONFIGURATION FILE

#number of logical channels
log_channels: 1

#tells what type of protocol exists in each logical channel
log_channel_0 : BPL_PLC

log_channel_1 : BPL_alt

log_channel_2 : BPL_alt

#tells the number of slave nodes
slave_nodes : 2

#initial repeater level
repeat_downlink : 1
repeat_uplink : 1

#number of retries
number_retries : 2

#timeslot for start of collecting statistics
start_timeslot : 0