A Measurement Based Study to Assess Power Line Communication Network Throughput Performance

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Abstract— **Power line communications (PLC) is a known low cost technology which is easily installed and extended to the various connections especially to areas with poor wireless coverage. Unfortunately, designers and users experience technical problems that arise from the difficulty of operating on a complex time varying medium and that limits the expected high throughput. Therefore, testing and understanding network dynamics of PLC systems before usage is a necessity. This paper presents the findings obtained from the experiments carried out in order to verify the throughput performance of PLC systems. Experimental measurements are realized in different testbeds, under different times and conditions, in order to achieve an idea of the practical PLC performance. Data obtained from the measurements have been stored and the throughput is analyzed by the help of software. Following, using distribution fitting methods, it is shown that the PLC throughput may be modeled by the extreme value distribution. Furthermore, adding a basic noise to the network, simply by lamps, results with a degraded performance. The noise changes the parameters of the derived distributions; a decrease in expected value and an increase in standard deviation are observed.**

Index Terms— **Experimental measurements, extreme value distribution, distribution fitting, power line communications, throughput performance.**

I. INTRODUCTION

THE NEED of network for broadband applications in local areas is growing rapidly. Although performance of the wireless systems within a room is satisfactory, in room to room connectivity, data throughput decreases dramatically due to high signal attenuation caused by walls or ceilings. On the other hand, wired networks like Ethernet need additional installation effort for cabling. In a home or office network, broadband throughput for room to room without any extra installation is desirable. Power Line Communication (PLC) fulfills these requirements and is an alternative solution. PLC uses the preexisting electrical grid as a communication channel and owing to modern modulation techniques the power network is able to ensure high data rate services [1-5].

The main advantage of PLC technology is that it uses the installed electric power networks. Nevertheless, it is difficult to operate on such a medium, since it is not designed for communication but for power transmission, and is characterized by complex time varying channel. Besides, the cable infrastructure is a potential source of interference for radio communication services since it works as a radiating system. These points give rise to practical problems for designers and testers when network quality of service (QoS) performance parameters such as throughput, latency, jitter, and reliability are under investigation [6, 7].

Theoretical QoS performance of PLC is quite satisfactory. But a critical degradation may be faced because of ambiguity caused by variable corruptive factors. i.e. grid size and topology, channel attenuation and impedance, number and positions of sockets, distance and path between the transmitter and the receiver, number and type of disturbing loads connected, positions of interfering sources in relation to the transmitter and the receiver. Therefore, paying attention to these factors and testing before the installation and usage of a PLC system is a critical task. The available researches are mainly focus on the methods and measurement procedures for channel characterization of PLC systems. The studies related to QoS performance measurement are not sufficient yet, so that no reference tests, set-ups and measurement methodologies [7, 8]. Indeed, standardization is a difficult task because the scenarios in which PLC modems can work and the set of parameters related to the performance are wide.

There are some research papers in the literature interested in the performance of PLC systems: [8] works on standardization of the measurements and proposes reference test setups and measurement methodologies for reliable assessment of PLC network performance. A power line testbed is developed in [9], which provides a platform to simulate the power line environment in a controlled and reproducible manner. The combination of different technologies has motivated authors of [10] and [11]. In [10], authors look for the coverage and

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capacity of a hybrid network compared to standalone Wi-Fi and PLC networks and in [11] a comparative study of the performance of PLC, wireless and their combination is given. Authors of [12] give a set of measurements conducted on a laboratory testbed for analyzing the PLC usage in the last mile broadband access. Reference [13] develops a PLC network testbed for understanding the network dynamics of PLC systems. A comparison regarding performance is seen in [14], between different architectures and between testbed and commercial installation. In [15], a set of measurements is carried out over the low voltage networks, in order to characterize the performance of the TCP/UDP/IP (Transmission Control Protocol / User Datagram Protocol / Internet Protocol) protocol stack. Reference [16] proposes a new analytic model to evaluate throughput and delay of HomePlug 1.0 under saturation and under normal traffic conditions. The goal of [17] is to investigate flow-level performance problem of TCP over PLC, and to propose methods for coping with these problems. The authors of [18] explore how simple household devices significantly impact the performance of the PLC networks and show that the performance in the home environment is good, but it is far worse than the best-case promised by the manufacturers. Reference [19] brings into focus the need for a systematic approach to qualify in-house power line equipment and networks for audio and video streaming applications.

We are limited to studying the PLC behavior using end-to-end measurements. Characterized by a large number of variables, it is difficult to forecast the actual network performance that can be achieved under real operating conditions. Thus, it is not easy to realize well-controlled measurement setups for reliable and reproducible results if we use a real PLC system in analyzing where the throughput is time varying because of uncontrollable different noise supplies. Therefore in this study, a measurement based evaluation of throughput for a PLC system has been carried out in a laboratory instead of a real house or office. An efficient measurement procedure was developed to reliably assess the performance of PLC modems. It is based on both creating a reconfigurable grid to which real disturbing loads may be connected. Methods have also been provided to analyze the measurement results and the distribution of throughput. We also aimed to explore the effect of a basic disturbance factor, the lamp, on the performance of PLC, by observing the degradation in throughput performance. Our main findings are that PLC provides a quite satisfactory throughput when there is no load in the network but there is a critical degradation in performance when lamps are added.

II. MEASUREMENT SETUP

We performed experiments with NetMaster PWE-500C power line adapters (Ethernet bridge and power line extender), which are compliant to HomePlugAV 1.0 standard. They are advertised to support PHY data rates of 500 Mbps and information rates up to 150 Mbps. The devices operate in the 2-68 MHz frequency band and are able to communicate over maximum 300 m ac cabling. We evaluated a power line network in a laboratory setup consists of nine nodes. The network design is limited by the designers' imagination and the research's general goals and frame, since the possibilities of network architecture are virtually endless. The realized PLC throughput measurement setup is shown in Fig. 1. It emulates a standard grid with a star topology. Usually with more connections, the star topology is considered as the optimum architecture with regard to bandwidth usage and throughput [14]. It allows expansions in all directions, thus the given topology can be extended for a typical house size. Another topology would be a straight line of nodes. But it is not a realistic model for houses especially and it is shown that in such a topology although the ping time is increasing as the node get further, the PLC throughput performance is not changing significantly [14].

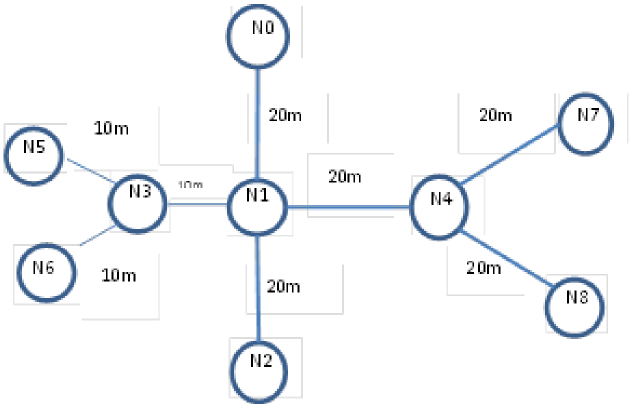

Fig. 1. The power line network topology used in measurement.

The PLC network under test has been separated from the main ac grid with a cabling in order to decrease the effect of noise that may come from the main. In the setup, the wire size of primary lines (segments of 20 m length) is 2.5 mm2 and the size of secondary lines (segments of 10 m length) is 1.5 mm2, and grid designs are compliant with the general rules for the electric installation design. The adapters under test have been controlled by means of two laptop PCs powered by an ac line different from the testbed. The PCs have Ethernet card 100 Mbps and are connected to the network where one acted as a server and the other as a client. As for the measurement setup, all the possible combinations that can be achieved result with huge possible measurement configurations. For the sake of brevity, in order to reduce the number of experiments, a few well rounded scenarios have been selected. In all scenarios PLC transmitter was connected in node 0 (N0) and PLC receiver was moved such as it was connected in each node during the measurements. Measurements have been repeated with a basic load, the lamp, with different placement in the network to understand the relation between the performance and the load, and the locality of transmitter and receiver.

We treated the power line adapters as black boxes and use end-to-end network measurements to reason about the performance of the devices. As suggested by ETSI [7], figures of merit for the assessment of the QoS performance of a PLC network can be selected by considering the throughput, the latency, the jitter and the reliability. In this study, the throughput has been selected to be the parameter for observing the performance, which is defined as the quantity of data that can be transmitted in a time interval and is typically expressed in Mbps. The PLC network throughput measurements have been performed using a combination of typical software tools, jperf 2.0.2 and ping. Jperf has been used in establishing a link between the transmitter and the receiver, generating the desired traffic conditions and estimating the throughput. The measurements were done during a period of half an hour and were repeated in different time of the day and on various days. The motivation behind this was eliminating the dependence on all possible disturbances. The time delay was estimated using the "ping" application. This application allows to measure the delay time of every packet and, moreover, the average time delay of all packets transmitted since the beginning of the application. Finally, we have obtained the statistics of the throughput.

III. PERFORMANCE EVALUATIONS

The amount of data collected from the measurements was too large to be all presented in details; therefore a well-chosen summary of the findings is presented in this paper. In the first scenario the PLC transmitter was connected to node N0 and the PLC receiver was connected to all nodes, each in turn, during the measurements. Available throughput was monitored using jperf software that generated and measured data traffic transmitted through TCP protocol. For each configuration, the transmission time interval has been fixed to 30 min and the throughput is recorded with a report time interval fixed at 1 s (1800 reported data per interval). The throughput may vary considerably during the tests and therefore its estimation depends on the time interval in which the measurement is performed as well as its length. It is clear that smaller measurement windows reduce the time needed for testing but considerably increase the measurement uncertainty. A total measurement time of about 8 hour per day (between 8:30-16:30) has been considered, with the aim of analyzing the performance of PLC network throughout the day. In addition, the measurements have also been repeated on different days to take into account the uncertainty component due to the arrangement of test setup and the characteristics of test site. For all the results presented, it is guaranteed that every measurement has been repeated in different periods of the day and on different days at least ten times, until we concluded that the real performance was obtained and we have eliminated the nonstandard measurements that may be caused by uncontrollable effects. Finally, the measurement results have been suitably stored.

Fig. 2 shows a sample of the time evolution of throughput when client is connected to node N0 and the server is at node N2 in the absence of external disturbing loads, thus no load is connected to the network. (Note that throughput performance is independent of transmission direction. Measurements were done when client was connected to N2 and server was connected to N0, and it has been proved that the performance is independent of direction.) In the figure, the combination of 4 time intervals, each 30 min, which makes a total time period of 2 hours (7200 s) is presented. As seen, although it varies slightly, finally the throughput fits to 94.91 Mbps line. Rarely critical drops in the throughput performance are observed with the minimum is 66.6 Mbps.

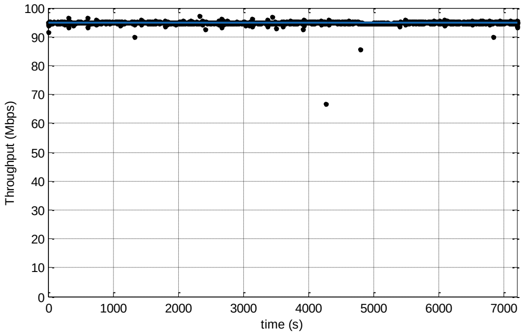

Fig. 2. Throughput versus time, N0 – N2 connection, no load connected.

Fig. 3 and Fig. 4 give the throughput between nodes N0 – N6 and N0 - N8, respectively. The throughput fits to 94.87 Mbps line with minimum 47.8 Mbps in Fig. 3 and to 94.81 Mbps line with minimum 40.0 Mbps in Fig. 4. As seen from the figures, although very close results are obtained, as we get further from the transmitter, slightly lower performance with increased drops is observed. The worse is N0 – N8 throughput performance.

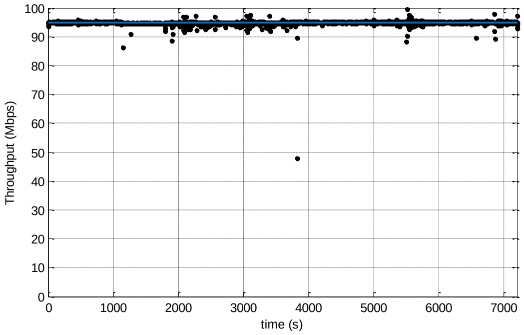

Fig. 3. Throughput versus time, N0 – N6 connection, no load connected.

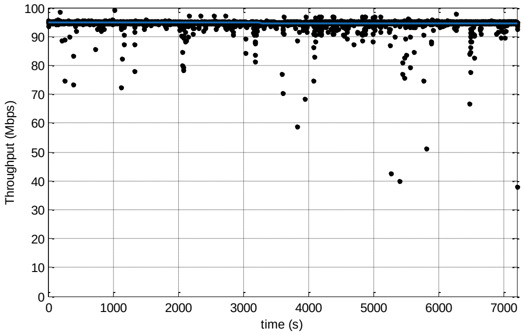

Fig. 4. Throughput versus time, N0 – N8 connection, no load connected.

As disturbing load, compact fluorescent lamps with integrated control gear (energy saver, 24 W) have been selected to be added to the network. The motivation about this selection is that lamps are the basic elements of power networks in our homes and offices, every time and everywhere present. Some tests have been performed to investigate the performance degradation of the given PLC network under different load configurations and the results are presented in tables and graphs. In the first configuration, lamps have been added to all nodes except node N0. This is expected to be the worst scenario, since the disturbing loads are placed all over the network. Fig. 5, Fig. 6 and Fig. 7 give the throughput of N0 – N2, N0 – N6 and N0 - N8 connections, respectively. The degradation and the activity in the throughput caused by lamps can easily be seen when we compare the figures with the previous ones.

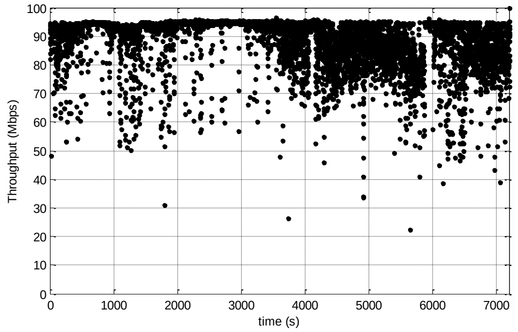

Fig. 5. Noisy throughput versus time, N0 – N2 connection.

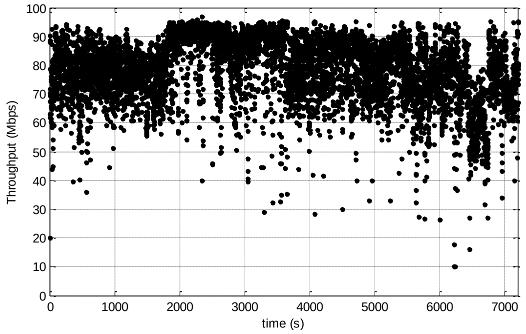

Fig. 6. Noisy throughput versus time, N0 – N6 connection.

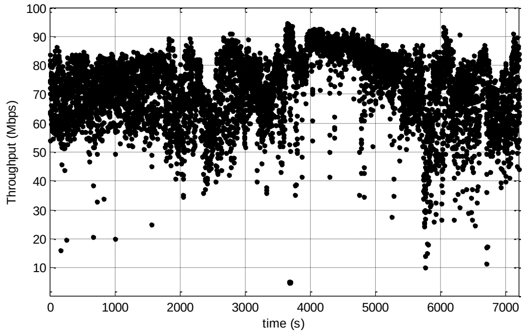

Fig. 7. Noisy throughput versus time, N0 – N8 connection

Table 1 presents the mean value and standard deviation of throughput between node N0 and the other nodes when no load connected to the network and when all nodes have connected lamps. For the configuration with no load, it is clearly seen that the performance of the PLC network is very close in all nodes in terms of mean (only a slight decrease in the furthest nodes performance is observed) but an increase in the standard deviation is realized as we get further from the transmitter. When we connected the lamps to the network, we can easily see the drop in the throughput performance, which we have already noticed in Figure 5, Figure 6 and Figure 7. There is degradation in all connections' performances but the most noticeable one is in the performance of the connection between N0 and N8 (or N7), the furthest nodes. Beside the drop in the throughput mean, the increase in standard deviations is significant. It is also interesting to observe that the performance of N0 – N1 connection is better than that of N0 – N0 connection. This result proves the existence of compensation and amplification effects among the interference generated by the multipath structure of the channel that can significantly affect the throughput. This evidence stresses the significance of testing modems before usage by developing a real grid and by using real disturbing loads.

TABLE I
MEANS AND STANDARD DEVIATIONS OF THROUGHPUTS BETWEEN N0 AND OTHER NODES.

Connection	No load connected to the network		All nodes have connected lamps	
	mean	Std. dev.	mean	Std. dev
N0 - N0	94.9352	0.4111	94.8512	1.2157
N0 - N1	94.9328	0.2506	94.9286	0.3571
N0 - N2	94.8800	0.4668	88.7530	8.5857
N0 - N3	94.9331	0.2980	89.3220	9.3323
N0 - N4	94.9379	0.4572	86.3286	10.3999
N0 - N5	94.9299	0.6012	78.7611	11.4268
N0 - N6	94.8556	0.6870	78.2866	11.3561
N0 - N7	94.8397	1.5931	71.0347	11.5691
N0 - N8	94.7086	1.6950	72.0789	12.1890

A common method to test the delay characteristics of networks is to send ping packets and measure the round trip return time (RTT) for each transmission. We have measured the RTT by sending ping command with 128 byte for 10 times before and after the throughput measurements and it has been seen that the results are so far close to min 3 ms, max 10 ms and the average 3 ms for all measurements. We have concluded that RTT does not give us informative data; therefore we have analyzed the throughput performance only in the rest of the study.

Table 2 gives the results related to the measurements between N0 and the others (transmitter is at node N0) when lamps are connected to nodes N1, N3 and N4 (lamps are on the center) or N3, N5 and N6 (lamps are placed on one side of the network). As expected, adding lamps to the network decreases the throughput performance. When the lamps are on N1, N3 and N4, the degradation is observed everywhere and it gets more significant as the node gets further from the transmitter. When lamps are locally placed, the significant degradation is observed in the performance of nodes with lamps, but a slight degradation is also observed in nodes N7 and N8 because of the multipath effects.

TABLE II
MEANS AND STANDARD DEVIATIONS OF THROUGHPUTS BETWEEN N0 AND OTHER NODES.

Connection	N1, N3 and N4 have connected lamps		N3, N5 and N6 have connected lamps	
	mean	Std. dev.	mean	Std. dev
N0 - N0	94.8497	1.6807	94.9272	0.2614
N0 - N1	94.8577	0.3277	94.9266	0.4504
N0 - N2	94.4149	3.5877	94.8235	1.5409
N0 - N3	93.0962	5.3390	94.5119	2.7328
N0 - N4	92.4736	5.0989	93.8660	3.6022
N0 - N5	90.4185	6.5017	85.9407	9.5047
N0 - N6	91.0793	6.3420	84.8404	9.2614
N0 - N7	81.3266	8.8003	92.0392	4.7405
N0 - N8	82.7344	8.8166	92.1321	4.6845

As a result, regardless the distance of the PLC transmitter and receiver the ping time is not changing (since the topology is star it is the expected) whereas the physical speeds (throughputs) slightly decrease when no load is connected to the network. But this degradation becomes significant when loads (noise factors) are connected to the network. The effect of the noise depends on the number and placement of disturbing factors. The performance degradation is more significant close to noise.

IV. THROUGHPUT STATISTICS

Probability distributions can be viewed as tools for dealing with uncertainty. Calling the uncertainty as a random process, distribution fitting allows you to develop valid models of random processes you deal with, and enables you to make better decisions. Distribution fitting forecast the frequency of occurrence of the magnitude of the data in a certain interval and select a statistical distribution that fits to the data set.

There are many potential probability distributions that can be fitted, but depending on the characteristics of the data, some may be fitted more closely than others. For selecting the best fitted one, the histograms of the data were plotted first. Fig. 8, Fig. 9 and Fig. 10 give the throughput histograms while no load is connected to the network, between nodes N0 – N2, N0 – N6 and N0 – N8, respectively. As seen from the figures, all distributions have a shape with skew to the left. The distribution fittings of various left skewed distributions were compared related to the goodness of fit. We have decided whether the probability distribution is a good fit by looking at the plots and by comparing the log likelihood value, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) [20]. Attempts have shown that the extreme value distribution [21] is best fitting to the data. The distribution fitting results are also given on the same figures with the histograms.

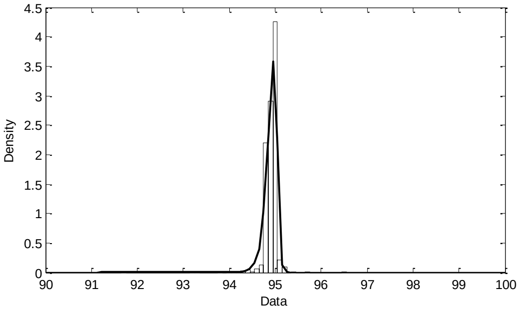

Fig. 8. Throughput distribution between N0 – N2, no lamp is connected.

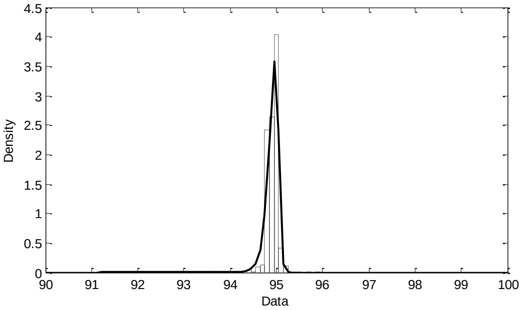

Fig. 9. Throughput distribution between N0 – N6, no lamp is connected.

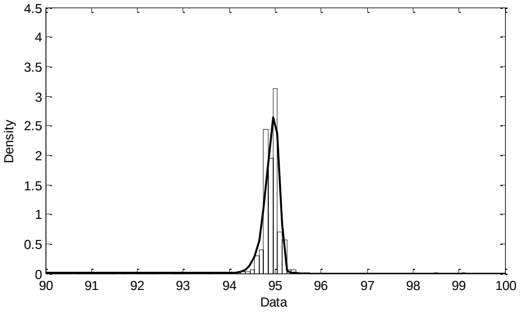

Fig. 10. Throughput distribution between N0 – N8, no lamp is connected.

Extreme value distributions [21] are popular to model the smallest or the largest value among a large set of independent, identically distributed random values representing measurements or observations, as in our case. The probability density function of the standard extreme value distribution is given by [19]

$$g(v)=\exp\left(-(e^{-v}+v)\right), \quad v\in\Re . \qquad (1)$$

The expected value (mean) is equal to Eular constant, i.e. $E\{V\}=\gamma\approx 0.5772$ and the variance is $\operatorname{var}\{V\}=\pi^2/6\approx 1.6449\approx 1.2825^2$.

The standard extreme value distribution is generalized by applying a linear transformation. i.e., $X=\mu+\sigma.V$ has the extreme value distribution for maximums with location parameter $\mu \in \Re$ and scale parameter $\sigma \in (0,\infty)$ and the probability density function

$$f(x)=\frac{1}{\sigma}.\exp\left(-\frac{x-\mu}{\sigma}\right).\exp\left(-e^{-\frac{x-\mu}{\sigma}}\right),\quad x\in\Re\,. \tag{2}$$

The extreme value distribution is a flexible model that covers Gumbel, Fréchet, and Weibull distributions by adjusting the parameter values. The reversed Weibull distribution is a quite rarely used model and also well fitted to our data. But since it is a subset of the extreme value distribution, it is not given here. We have found that the distribution parameters are $\mu = 94.96,\ \sigma = 0.10$, and $\mu = 94.97,\ \sigma = 0.10$, and $\mu = 94.98,\ \sigma = 0.13$ in Fig. 8, Fig. 9 and Fig. 10, respectively. The parameter values are close as expected from the results seen in Table 1.

The histograms of throughput while a lamp is connected to each node of the network under test are also investigated. Analyzing these histograms, we have noticed that the histograms of various measurements differ. Fig. 11, Fig. 12 and Fig. 13 give a set of throughput histograms and their distribution fittings of the connections N0 – N2, N0 – N6 and N0 – N8, respectively. Again all distributions are left skewed and extreme value distribution is best fitting to the data, with $\mu = 87.64,\ \sigma = 5.14$, and $\mu = 79.78,\ \sigma = 6.27$, and $\mu = 73.84,\ \sigma = 8.95$ in Fig. 11, Fig. 12 and Fig. 13, respectively. As expected, the location parameter is decreasing whereas the scale parameter is increasing as we get further from the transmitter. Again these results are well matched with Table 1.

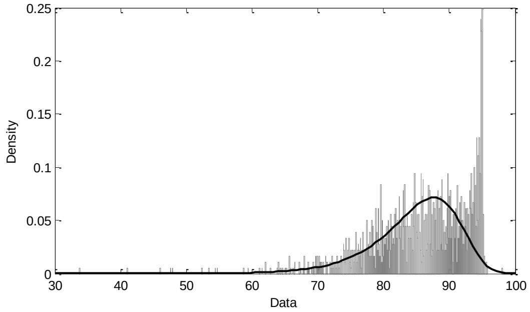

Fig. 11. Throughput distribution between N0 – N2, all nodes have lamps.

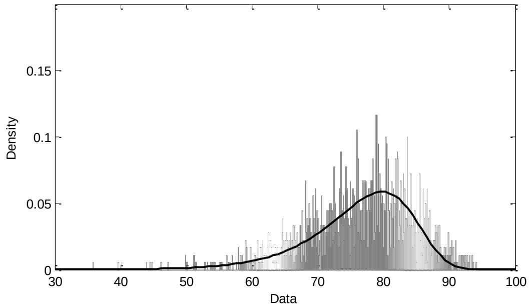

Fig. 12. Throughput distribution between N0 – N6, all nodes have lamps.

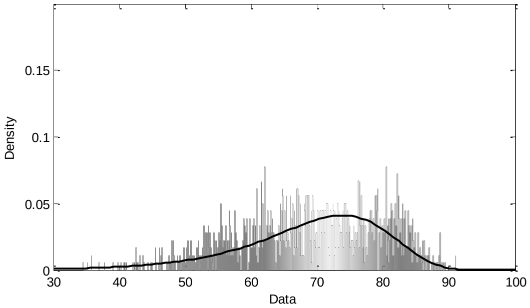

Fig. 13. Throughput distribution between N0 – N8, all nodes have lamps.

V. CONCLUSIONS

The PLC technology has technical challenges that arise from the difficulty of operating on a complex time varying medium. Frequently degradation is observed in practical PLC performance compared to the manufacturers' expectations. This paper presents the findings obtained from the experiments carried out in order to understand network dynamics of PLC systems and verify the throughput performance. The measurements are realized under different times and conditions and an idea of the practical PLC performance is achieved. Using jperf software the throughput is analyzed and by the help of distribution fitting, it is shown that the PLC throughput may be modeled by the extreme value distributions. Furthermore, the basic noise sources, the lamps, are added to the network and throughput performance is analyzed again. It is seen that this attempt is resulted with a degraded performance even in a small network, as expected. Although the histograms still best fitted to extreme value distributions, the parameters of the derived distributions have been changed: a decrease in expected value and an increase in standard deviation are observed.

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