This is the author's version of an article that will be published in Proc. LATINCOM 2015

Improving Performance of TCP-based Applications in Power Line Communications for Smart Grids

Claudio Estevez and Sandra Céspedes
Department of Electrical Engineering
Universidad de Chile
Santiago, Chile
{cestevez,scespedes}@ing.uchile.cl

***Abstract*—Information and communication technologies play a fundamental role in the development of Smart Grids. Smart Grids work in the optimization and efficient integration of the electric power lines networks with different types of elements in the generation, transmission and distribution of power. This work focuses on enhancing the throughput performance of data transmission, in scenarios where data integrity is a priority for TCP-based applications deployed in Smart Grid networks employing Power Line Communications (PLC) as the communications technology. More specifically, we propose the implementation of TCP proxy nodes in regeneration units deployed across the PLC network. The TCP proxy node acts as an intermediary for data transmission reducing latency by sending confirmations prematurely to the transmitter node when a data packet arrives at the regeneration unit. The regeneration unit will also forward any information that is queued more expeditiously in the event of a packet loss, which may be a common case considering the channel behaviour in PLC networks. The proposed scheme achieves an improvement of throughput in different PLC scenarios. The scheme is validated through analytical results and simulations.**

***Index Terms*—Broadband PLC; Narrowband PLC; Power Line Communication; Regenerator Unit; Smart Grids; TCP Proxy; Throughput**

I. INTRODUCTION

Non-renewable energy sources, such as carbon-based and organically-derived fuels, are estimated to deplete within a century, some predict this could happen even in the next 30 years [1]. Additionally, many renewable sources, arguably most, have to some extent a negative impact on the environment. These are two of the reasons that have elevated concerns, which propel the research for more energy efficient power grids. Smart Grids aim at taking on this challenge and designing with the future demands in mind. There is not a single unanimous definition for Smart Grid but all agree in that communications will play a huge role in managing energy generation, transmission, and distribution in the most efficient way.

A feasible and attractive candidate to carry the communication plane of smart grids are the power line communication (PLC) systems [2]. PLC employs the same conductor for both transmitting electric power and carrying data, with data rates that vary between tens Kbps up to hundred Mbps. The main reason and greatest advantage of employing PLC in Smart Grid communications is that the infrastructure is already built, which makes it a much more extensive and pervasive technology than other wired/wireless options [3].

Several standardization efforts have evolved to create different PLC specifications, from which two classes are of interest in this work: Narrowband PLC (NB-PLC) technologies: with data rates from tens Kbps (IEEE 1901.2 [4]) up to 1 Mbps (PRIME and G3-PLC [5]); and Broadband PLC (BB-PLC) technologies: with data rates from several Mbps up to hundred Mpbs (IEEE 1901 [6]). BB-PLC is originally defined for connectivity in local area networks and broadband Internet access, but some variations have been also adapted for Smart Grid communications with rates up to 3Mbps [7].

Although the aforementioned PLC advantages, it is expected that Smart Grid communications will not be supported by a single technology; instead, a group of heterogeneous networking technologies will support the different applications requirements. As a result, there is not a standardized stack of protocols for Smart Grid communications. Nevertheless, a strong tendency toward an IP-based stack of protocols seems to be a clear path to follow. Many researchers have suggested that, to be inherently compatible with the existing networks, a reasonable alternative is to implement the ubiquitous TCP/IP protocols [8][9][10].

There are many advantages of using TCP/IP, for example, its inherent compatibility would make it compatible with local area networks (LAN) and therefore greatly increasing the scalability of the grid network. Furthermore, this will allow inter-connectivity between the Smart Grid and the Internet. Accordingly, Smart Grid applications are being characterized in terms of the type of protocol to be employed (TCP or UDP), besides other requirements such as packet frequency and end-to-end delay. Table I presents a summary of smart grid applications and transmission requirements [10][11].

For a successful transmission of Smart Grid applications, the performance of the underlaying technology needs to meet certain requirements. In the case of PLC, recent advances in channel modeling have identified several aspects to consider: communication signals that are transmitted through PLC channels for medium and low voltage lines experience log-normally distributed attenuation. Moreover, BB-PLC suffers from frequency-selective fading over large distances [10]. Since channel conditions are far from perfect, IP-based ap-

TABLE I
SMART GRID APPLICATIONS REQUIREMENTS

Application	Protocol	Packet frequency	Other
AMR (meter reading, meter events and alarms, grid events and alarms, prepaid services)	TCP,HTTP	300s–3600s	Payload 200 bytes
Real-time metering	IP	0,012s-0,020s	delay$<$15s
Real time pricing	TCP,HTTP	900s,3600s	delay-tolerant
Wide area measurements (syncrophasors)	IP,TCP	0,04s–0,1s	delay$<$20s

plications may experience packet losses and retransmissions.

With the aim of protecting TCP-based applications deployed in Smart Grid environments that employ PLC, there are techniques that can be implemented to improve transmission performance. In this paper, TCP proxies are studied to improve performance mainly by reducing the round-trip time (RTT) and therefore increasing the overall transmission throughput. This technique can be utilized by smart grids running either NB-PLC or BB-PLC, or any other scheme that employs PLC for communications, such as broadband Internet access through PLC. The proposed scheme takes advantage of specific regenerator units required in PLC (BRUs). The principal task of these units is to amplify the signal with the lowest noise figure possible. Since BRUs are found dispersed through the grid (approximately equidistant from each other) these devices are in the ideal location for TCP proxies. An example of a BB-PLC network and BRUs deployment is illustrated in Fig. 1

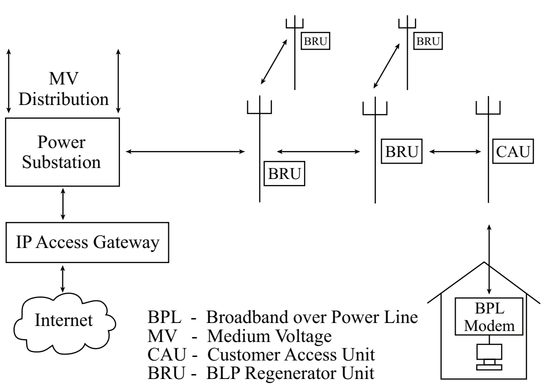

Fig. 1. Broadband over Power Line components

The remainder of this paper is organized as follows: Section II presents the main characteristics of PLC technologies and explains the principles of TCP proxies. Sections III describes the proposed scheme and mathematical analysis. Sections IV and V present the simulations and discussion of results. Finally, Section VI concludes this paper.

II. BACKGROUND

A. Narrowband PLC (NB-PLC)

Initial communications through power lines were employed to implement Automated Meter Reading through disturbances to the voltage and current waveforms. Such initial deployments, known as ultra narrowband PLC, were usually a one-way communication system. Later on, the NB-PLC with two-way communications and improved data rate appeared. NB-PLC technologies operate in frequency bands from VLF to MF (3-500KHz), and support single carrier and multi-carrier transmissions [3]. In the PHY layer, NB-PLC standard [4] specifies the use of orthogonal frequency division multiplexing (OFDM) and supports multiple modulation schemes: DBPSK, DQPSK, and D8PSK are mandatories, and QPSK and QAM are optional. In the MAC layer it specifies CSMA/CA for channel access.

B. Broadband PLC (BB-PLC)

This technology is defined originally for broadband Internet access and home/local area networks. It employs frequency bands from HF to VHF (1.8-250KHz). Deployments for Internet access were not very successful, but many commercial implementations have been demonstrated to be useful in more limited areas such as home networking, with data rates of 14Mbps, 85Mbps, and 200Mbps, but with interoperability issues among the different products [3]. Later on, the same technology was adapted to medium voltage and low voltage distribution networks for communications in the smart grid. In the PHY layer, BB-PLC standard [6] specifies the use of FFT-OFDM and wavelet-OFDM. In the MAC layer, the standard specifies support for both contention-free TDMA and contention-based CSMA/CA for channel access.

C. Power Line Regenerator Unit (BRU)

To transmit at high data rates PLC has to implement regeneration units. These units have to be equidistant to regenerate the incoming signal. In the past, amplifiers were used to transmit in lossy channels over long distances, where each iteration adds noise to the signal [12]. When using BRUs the signal is regenerated, so noise does not accumulate. Literature specifies that the optimal distance between BRUs is somewhere between 200 and 800 meters. Since power lines can cover tens to hundreds of kilometers a significant amount of RTT is added to the system. If the end systems implement any type of connection-oriented transmission protocol (e.g. standard IP/TCP), the amount of RTT in the line can have a detrimental effect on the performance. This is the motivation of proposing the implementation of TCP proxies in the BRUs.

D. Transmission Control Protocol Proxy

Transmission control protocol proxies aim at reducing the RTT effect caused on connection-oriented transport protocols [13][14]. There are various types of proxies, but the main three that aim at the reduction effects of RTT are discussed here: Split, Snoop and Spoof.

1) TCP Split Proxy: In split TCP [15] each TCP proxy would terminate the detected TCP connection through the receiving port and initialize a new TCP session through the output port. This process is completely transparent to the end nodes. One disadvantage of this method is that the TCP proxy could have unbalanced connections. By this it is meant that the input port could be faster than the output port or vice versa. Either case could generate problems particularly if the input port is faster, since the TCP proxy node could overload. Even if it reports the limited space to the sender on time, it would have to slow down the flow, and therefore defeat the purpose of using TCP proxy nodes. In the opposite scenario, where the output port is faster, the TCP proxy will not be able to sustain the congestion window size, nevertheless the node will continue to function so this scenario is not detrimental. In summary, the isolation of the connections could have a negative impact on the overall flow.

2) TCP Snoop Proxy: This proxy is located near the receiver node. It is used mostly when the last link has higher probability of error than the middle or core links. An example been a weak wireless connection. The TCP Snoop proxy node buffers the incoming packets that arrive through the transmitter-side port while monitoring the ACK packets from the receiver-side port. If it detects a triple duplicate ACK it immediately resends the lost packets, without notifying the transmitter of this loss. This will avoid the reduction of the congestion window size that would otherwise be done by the transmitter. One disadvantage is that the recovery process takes time and if the transmitter node does not receive any information from the virtual receiver it will timeout and switch to slow start mode with the minimum congestion window size.

3) TCP Spoof Proxy: A TCP Spoof Proxy [16][17][18] is in a way a combination of the above two. This type of proxy node can be located anywhere in between the two end nodes. The TCP Proxy will copy each packet that arrives from the transmitter-side port and buffers it, while forwarding the other copy. It differs from the Split type in the sense that it does not terminate the connection nor initiate another, it just forwards and buffers. Once it receives an ACK from the receiver-side port it deletes the buffered packet and reports to the transmitter-side port the minimum window between the one reported by the receiver-side or its own. This will have an overall effect that after one RTT all nodes will know which is the limiting node and will transmit at the bottleneck's rate. This will avoid overloading any nodes. If anything changes, and another node becomes the bottleneck, after another RTT all nodes will transmit at this rate. Hence the system will never collapse, there will be a decrease in the perceived RTT and a significant improvement of the throughput. This is the type of TCP Proxy to be incorporated in the proposed scheme.

III. Proposed Throughput Improvement through PLC Reflection and Regeneration Unit

In this work, we propose the use of a well-know technique, employed particularly in satellite communications, known as TCP spoofing. There is a clear benefit of implementing this technique in PLC networks, which is to increase the transmission speed by reducing the effects of the RTT. The architecture of the proposed network is the same as that of a PLC network with BRUs, but instead of having a regular BRU, a more advanced version would replace it. This updated version, called here a PLC reflection and regeneration unit (BR^2U), performs all the functions of a regular BRU, but additionally it reflects an ACK packet for every data packet received. The data packets are stored in the BR^2U, just as they would in a traditional TCP proxy node. To distinguish the reflected ACKs, from the regular ACKs, these are referred to as RACKs. The RACKs are identical in structure to the ACKs. The architecture described here is portrayed in Fig. 2.

To describe the proposed operation mode lets consider the downstream flow of data. After the data has traveled from an IP source (e.g., from the Internet) through the gateway (GW) it will reach the Power Substation (PS). The PS multiplexes the data into the power line where it flows toward the destination. When it reaches the BR^2U, this device stores the data packets forwarding a copy to the destination port, while acknowledging with a RACK. The purpose of storing a copy of the packet is because when the data is RACKed the source will shift its TCP sliding window; hence, the source will no longer keep a copy of the buffered packet (without buffering the whole file again). So the only copy of the packet now remains in the BR^2U. As soon as the BR^2U receives an ACK, which could also be a RACK, it will erase the copy of the packet it was holding. If this release of resources was due to a RACK, it means that another BR^2U now holds the backup copy of the data packet. If a packet is lost, it only has to reach to the previous BR^2U that was holding the data packet, reducing the RTT significantly.

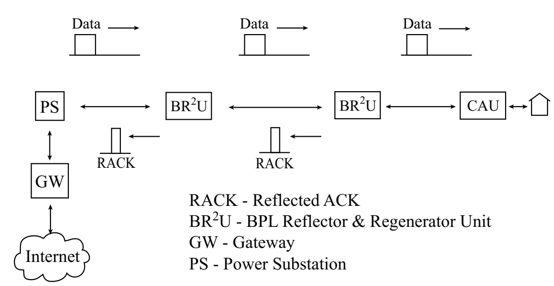

Fig. 2. Proposed architecture and operation mode

To derive the theoretical expression of the throughput observed by implementing BR^2Us, first lets consider the case where there is no TCP proxies. The throughput depends on the connection-oriented transport protocol implemented, so TCP Reno is assumed. The derivation for any other transport protocol can be easily deduced from this methodology. The TCP Reno analytic steady-state throughput, without TO events, is given by:

$$T = min\left(\frac{rbuf}{RTT}, \frac{MSS}{RTT\sqrt{\frac{2p}{3}}}\right), \tag{1}$$

where RTT corresponds to the delay, p to the packet loss rate, MSS is the maximum segment size for effective throughput (or full packet size that can be used for total throughput), and $rbuf$ is the receiver buffer size. The minimum is calculated, because in case of little or no loss the second term will yield infinity. If that is the case, the throughput will be limited by the receiver buffer size. Since each BR^2U has a buffer (or queue) size, the transmission would be limited by the BR^2U with the smallest buffer size or the link with the highest packet loss.

To simplify the expression, it is assumed that the receive buffer is not a limitation (i.e., it is infinite), in which case the expression is reduced to:

$$T = \frac{MSS}{RTT\sqrt{\frac{2p}{3}}}, \tag{2}$$

this is the end-to-end throughput expression, where the RTT is the time that is takes the data to travel from the source to the destination plus the time it takes the ACK from the destination to reach back the source. The throughput is inversely proportional to the RTT. Because there are multiple BR^2Us in the path, then the final expression takes into consideration that the bottleneck is the throughput between the longest path:

$$T = \frac{MSS}{max(RTT_i)\sqrt{\frac{2p}{3}}}, \tag{3}$$

where RTT_i represents all the RTTs between BR^2Us and between the PS and the first BR^2U and the last BR^2U and the CAU.

IV. Simulation Scenarios

To test the performance of the proposed system, six simulation scenarios are devised. The scenarios can be organized in three types of PLC systems and for each system the presence and lack of proxies is tested. For the scenarios with proxies, three proxies are used. The three PLC systems are: narrowband PLC, broadband PLC, and a hypothetical future broadband PLC. For all scenarios the packet loss rate p is varied logarithmically from 0.001 to 0.01 and the throughput is recorded. The actual loss rate is computed to plot the simulated data. The simulation parameters are described in table II. The delays are justified, in both cases, due to processing power by either the regenerator unit or the TCP proxy.

TABLE II
Simulation Parameters

NB-PLC link capacity	130 kb/s
BB-PLC link capacity	3 Mb/s
FBB-PLC link capacity	10 Mb/s
Number of TCP proxies	3
Packet loss rate	0.01-0.001
End-to-end delay	100 ms
proxy-to-proxy delay	25 ms
Packet size	1500 B
File size	10,000 packets (15 MB)
Receive buffer	Infinite

V. Results and Discussion

The results are organized by network type. The three types of network tested are: narrowband PLC (NB-PLC), broadband PLC (BB-PLC), and a hypothetical future-broadband PLC (FBB-PLC). In each type of network, two scenarios are compared: with no proxies and with three proxies in the path to destination (as shown in Fig. 3). Results from simulations are also compared with the analytic results. The analytic results are provided as a reference, nevertheless, the theoretical expression only considers the steady-state throughput and the simulation has the slow-start algorithm implemented, which explains in part the error between the simulated and analytic results.

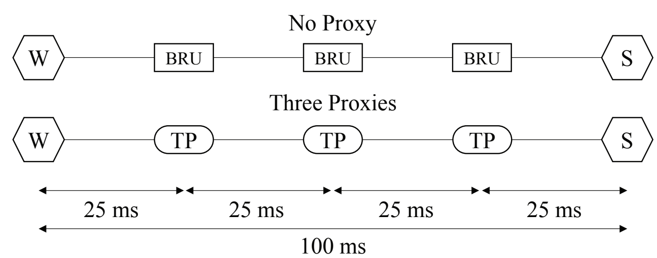

Fig. 3. Topology of the tested scenarios

In the narrowband case, it can be observed in Fig. 4 that the performance of the scenario with the absence of proxies performs similar to the scenario with proxies. This is reasonable because the link capacity, i.e. 130 kbps, is fairly low, hence to obtain a significant difference the packet loss rate or the RTT should be higher. For a reasonable set of network parameters for Smart Grid PLC, the throughput is limited by the link capacity. Therefore, in this test case there is no great advantage of implementing proxies at the BRU points.

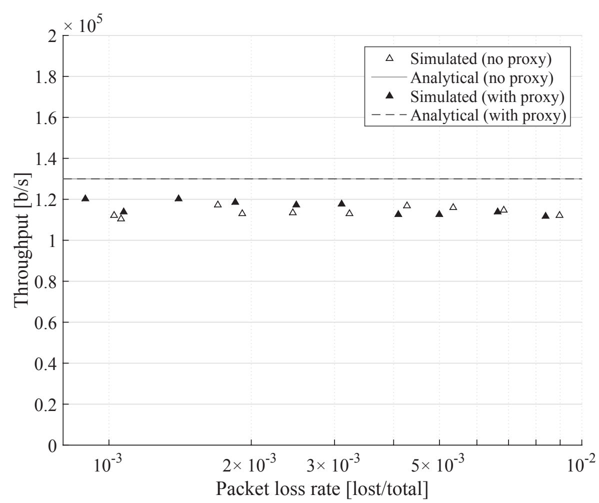

Fig. 4. Throughput results varying the packet loss rate for the narrowband PLC scenario

For the broadband case, it can be observed that the proxy scenario performs significantly better. In an ideal scenario, the performance of the 3-proxy case should be 4 times better than the no-proxy case, as long as the 3-proxy case does not reach the link capacity. Although such a gain is not observed in our broadband scenario, there is an improvement of approximately 50% to 150% in throughput gain, depending on the packet loss rate observed in the channel. This occurs because the 3-proxy case reaches the link capacity. In addition, from the simulations we have established that a similar performance gain could have been achieved with only one or two proxies, but only for cases in which the packet loss rate is lower than 3×10^{-3}.

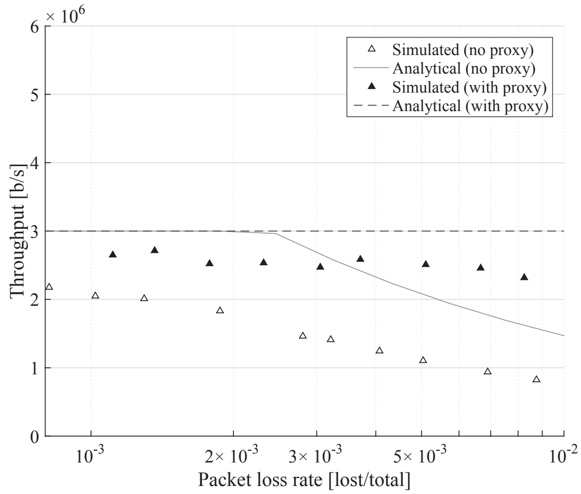

Fig. 5. Throughput results varying the packet loss rate for the broadband PLC scenario

Additional to the narrow and broadband PLC scenarios, a hypothetical case with a broadband performance of 10 Mbps was simulated for comparison reasons. Although, to the best of our knowledge, such a capacity has not been reached for PLC employed in Smart Grid environments, similar (or higher) capacities are already reached in home area networking PLC; hence, it is expected that better data rates will soon be achieved also in Smart Grid scenarios. According to the simulation results, PLC communications reaching link capacities of 10 Mbps obtain a performance improvement of approximately 300% for packet loss rates over 5×10^{-3}, and over 200% for the remaining observable range of packet loss rate. 300% is also the theoretical maximum performance improvement for a scenario with three proxies. For Smart Grid PLC exceeding 10 Mbps in link capacity, these results show that the 3-proxy configuration can improve the performance by a factor of four. If the distance covered is greater and the link capacity allows for even greater data rates, more TCP proxies are recommended to fully utilize the link capacity.

VI. Conclusion

In this work, it is proposed to improve the throughput of TCP-based applications deployed in Smart Grids that employ Power Line Communications as the communication technology. The proposed scheme uses TCP proxies co-located with the regular Power Line Regeneration Units (BRUs). Through simulations and analytical results, it is shown that for typical PLC network parameters, the narrowband PLC case would not benefit from implementing TCP proxies at the BRUs, this due to the low link capacity that limits the performance of the proxy implementation. For the broadband PLC case, it is shown that there is a significant improvement, nevertheless, with possibility to reducing the number of proxies and still getting throughput improvement. For the case of Future Smart Grid PLC networks surpassing link capacities of 10 Mbps, the network will see a great improvement when implementing the proposed TCP proxies. The greatest impairment of TCP transmissions is the delay, and BRUs regenerate the data, so there is not a fluid transmission, but a delay due to buffering and regeneration. Having the proposed TCP proxies significantly compensates for this. It is demonstrated that future Smart Grid networks can benefit tremendously from having TCP proxy capabilities at the BRU stations.

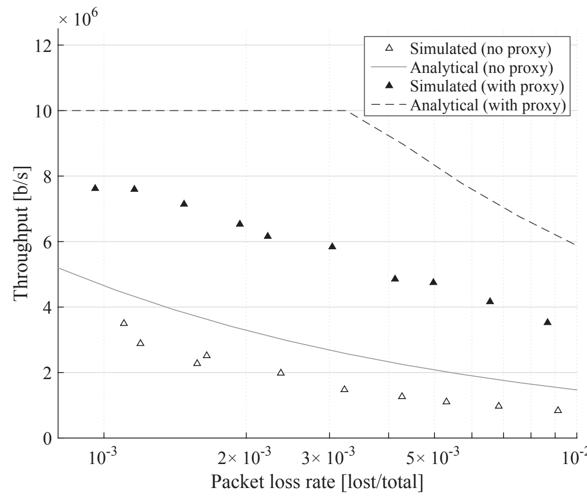

Fig. 6. Throughput results varying the packet loss rate for a hypothetical future broadband PLC scenario

Acknowledgment

This work is partially funded by Project FONDECYT No. 11121655 and Project FONDECYT No. 11140045.

References

[1] S. Shafiee and E. Topal, “When will fossil fuel reserves be diminished?” *Energy Policy*, vol. 37, no. 1, pp. 181–189, 2009.

[2] R. W. Rochelle, F. W. Symonds, and R. K. Adams, “Power line communication,” Nov. 15 1988, uS Patent 4,785,195.

[3] S. Galli, A. Scaglione, and Z. Wang, “For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid,” *Proceedings of the IEEE*, vol. 99, no. 6, pp. 998–1027, Jun. 2011.

[4] “IEEE Std 1901.2-2013 IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications,” New York, NY, USA, p. 269, 2013.

[5] Prime Project, “PRIME Technology Whitepaper PHY, MAC and Convergence layers,” Tech. Rep., 2008. [Online]. Available: http://www.prime-alliance.org/portals/0/specs/MAC_Spec_white_paper_1_0_080721.pdf

[6] “1901-2010 - IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications,” New York, NY, USA, p. 1586, 2010.

[7] N. Berezak-Lazarus, “Smart grid enabled and enhanced by broadband powerline,” in *ENERGY 2013, The Third International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies*, 2013, pp. 77–82.

[8] Y.-J. Lin, H. A. Latchman, M. Lee, and S. Katar, “A power line communication network infrastructure for the smart home,” *Wireless Communications, IEEE*, vol. 9, no. 6, pp. 104–111, 2002.

[9] H. Meng, Y. L. Guan, and S. Chen, “Modeling and analysis of noise effects on broadband power-line communications,” *Power Delivery, IEEE Transactions on*, vol. 20, no. 2, pp. 630–637, 2005.

[10] R. H. Khan and J. Y. Khan, “A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network,” *Computer Networks*, vol. 57, no. 3, pp. 825–845, Feb. 2013.

[11] D. F. Ramírez and S. Céspedes, “Performance Evaluation of Future AMI Applications in Smart Grid Neighborhood Area Networks,” in *IEEE COLCOM, to appear*, 2015, pp. 1–6.

[12] S. Zhao and K. Roy, “Estimation of switching noise on power supply lines in deep sub-micron cmos circuits,” in *VLSI Design, 2000. Thirteenth International Conference on*. IEEE, 2000, pp. 168–173.

[13] J. Border, M. Kojo, J. Griner, G. Montenegro, and Z. Shelby, “Performance enhancing proxies intended to mitigate link-related degradations,” RFC 3135, June, Tech. Rep., 2001.

[14] R. Cohen and S. Ramanathan, “Using proxies to enhance tcp performance over hybrid fiber coaxial networks,” *Computer Communications*, vol. 20, no. 16, pp. 1502–1518, 1998.

[15] V. Farkas, B. Héder, and S. Nováczki, “A split connection tcp proxy in lte networks,” in *Information and Communication Technologies*. Springer, 2012, pp. 263–274.

[16] J. Ishac and M. Allman, “On the performance of tcp spoofing in satellite networks,” in *IEEE Milcom*, 2001, pp. 700–704.

[17] N. Ehsan and M. Liu, “Modeling tcp performance with proxies,” *Computer Communications*, vol. 27, no. 10, pp. 961–975, 2004.

[18] D. Velenis, D. Kalogeras, and B. Maglaris, “Satpep: A tcp performance enhancing proxy for satellite links,” in *NETWORKING 2002: Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications*. Springer, 2006, pp. 1233–1238.