Studies on Techniques for Improving End-to-End TCP Performance over PLC with Wired and Wireless Networks

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Preface

In recent years, the fast progess in the services provided to the users in a residence are demanding more and more of the home-networking technologies to meet their requirements. It is known that WLAN is the key technology used in indoor environment at present because it provides mobile connectivity to the end-users. However, with the approval of the IEEE 1901 standard (IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications), Power Line Communication (PLC) has become an emerging in-home network technology because it enables high speed data and voice transmission over existing electrical wiring. In addition, once PLC makes use of the infrastructue already installed in a house the cost, and time to deploy it can be substantially lower than wired or wireless technologies, nowadays PLC is a topic of growing interest as a potential infrastructure where LAN and/or WLAN are not economically or technically feasible.

The main objectives of this dissertation are to propose new schemes to increase the efficiency and reliability of end-to-end data transmission over PLC connected to both wired and wireless networks without modifying the Media Access Control (MAC) technology of HD-PLC standard, which is the technology we investigate in our study.

Chapter 2 describes the PHY and MAC layer specifications of PLC and WLAN technologies. Then, Chapter 3 makes a brief explanation of Transmission Control Protocol (TCP) regarding the flow and congestion control it employs in order to offer smooth communication to the end-user and avoid network congestion, respectively. That is, since most of the in-home network applications run over TCP it is indispensable to know how such protocol works to understand how our flow-level performance investigation of TCP over PLC, more specifically HD-PLC, was realized.

Chapter 4 focuses on the evaluation of IP over PLC network connected to the Internet because on-demand service such as AcTVila is delivered to the end-users through the Internet. Existing studies done so far have not considered PLC connected with multiple flows with different RTTs passing through the Internet. Thus, I investigate the communication performance from the end-user perspective through an unstable Internet environment, where both RTT difference and cross traffic over Internet were taken into consideration in order to simulate a realistic network scenario. To make a comparative study, I investigated an existing scheme which also covers the end-to-end flow-level performance of IP over PLC but under the scenario previously mentioned. The result of the thorough investigation of this scheme pointed out some issues in terms of throughput unfairness because the RTT of the TCP flows tends to be different and change in the Internet due to adverse factors such as cross-traffic. That is, the existing *awnd dynamic adaptation scheme* calculated the amount of information that must be sent from the sender to the receiver based on the RTT estimation made only during the connection establishment period and did not update the *awnd* value according to the RTT changes during the communication period. That is the reason why such scheme only worked when there was no large RTT difference between the TCP flows. Thus, I proposed a new dynamic adaptation scheme by using the RTT value of the coexisting flows during all the communication in order to obtain a more accurate and dynamic update of the amount of information that should be sent to the receiver according to the transmission condition on PLC as well. More specifically, the proposed scheme deals with the large RTT difference that can occur between coexisting flows. Second, it deals with the existence of heavy cross traffic that significantly influences the RTT values, and consequently causes a drastic performance imbalance. Last, when TCP/VoIP flows coexist in an unstable environment, the proposed scheme mitigates the degradation in network performance and fulfills the necessary one-way delay QoS requirement as well. Through the simulation results I show that the throughput fairness is obtained without degrading the maximum communication performance. That is due to the fact that TCP inherently has a robust characteristic against TCP-ACK loss.

Chapter 5 focuses on how to integrate multiple home network technologies based on the IEEE 1905.1 standard. As I previously mentioned the two technologies we studied here are WLAN and PLC. First, I evaluate power line networks in three different conditions according to the PHY data rate to see how it impacts the communication performance. That is, good, normal and poor environmental conditions. The simulation results show that a drastic throughput performance degradation occurs at a hostile physical environment, that can be explained by the data retransmission mechanism employed by HD-PLC. Then, I investigate how the distance can influence on the TCP throughput performance on WLAN. The findings confirm that the TCP throughput over WLAN significantly degrades as the distance increases. Last, considering that both PLC and WLAN suffer from different degradation factors and have scope for improvement I propose a dynamic cooperative transmission scheme between these two technologies. More specifically, the proposed scheme consists of using PLC to mainly send TCP-DATA and TCP-ACK is sent through WLAN, which does not require the packets to be concatenated before being transmitted as in PLC network, unless its communication media becomes unfeasible. In that case we use PLC link to be used to send TCP-ACK instead. After a thorough investigation under different and practical network conditions the findings have led to conclude that despite of CBR cross-traffic on the WLAN link and the coexistence of two bidirectional flows, the scheme showed to be very effective in terms of throughput performance. That is due to the fact that TCP inherently has a robust characteristic against TCP-ACK loss.

I hope that the presented dissertation will be helpful for further studies in this field.

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Chapter 1

Introduction

With the need for people to have access to any kind of information from anywhere and at anytime the growth of many daily activities involving some kind of wireless services and applications are steadily increasing. However, due to the limited available spectrum and the inefficiency in the spectrum usage in today's wireless networks the data communication performance through this technology most of the time is affected somehow. In addition, in a home environment where WLAN possibly suffers from interference caused by other home appliances the performance degradation gets even worse.

There are several technologies available deployed in a residence or under development at present to achieve full connectivity in order to facilitate communication and interoperability among digital devices inside a house and guarantee a satisfactory communication quality to the end-user. Considering that in a house there are so many factors that can influence on the communication performance according to the transmission media used, choosing a suitable network technology in such environment is a difficult task. However, since the mid-1900s a technology called Power Line Communication (PLC) [LRC03] [KKK03] has attracted the attention of researchers and engineers from universities and industry worldwide. Today, PLC has reached maturity and achieved performances that have surpassed LAN and WLAN technologies in some aspects but currently not superseded them as the mainly used in-home network technology.

For a better understanding of this promising technology it is crucial to be aware of some critical differences it has when compared to the wired and wireless networks in some areas. First, in case of installation, in contrast to wired and wireless, PLC networks require no new wiring to be installed. Second, analyzing the cost, since PLC uses a facility existing electrical wiring as the data transmission medium, the expenses with installing copper or fiber is not considered, consequently the cost will not be so high compared to the wired and wireless one. Third, with many of the reliability obstacles overcome in the latest evolution of PLC technology due to the implementation of OFDM, error detection and automatic repeat request (ARQ), power line communications is now a feasible alternative to wired and in many cases supersedes wireless networks in terms of its reliability. Finally, in terms of security, compared with wireless LANs, PLC networks provide greater physical security because access to AC wiring is required and encryption is used to further enhance security.

The indoor radio law deregulation process in Japan started in 2004 and was completed in 2006. In the same year the first PLC modem provided by Panasonic Systems Network Corporation was launched in the market with a maximum transmission rate of 190Mbps and later on in 2010 Broadband PLC was established as a global standard. However, Broadband PLC can be only used indoor in Japan because BB-PLC outdoor is still forbidden. Despite of the efforts done so far, the deregulation on outside the home is still under discussion. The acceleration of the worldwide expansion of the high-speed powerline communication (i.e. HD-PLC) technology I investigate in this dissertation came with the approval of IEEE 1901 and ITU-T G.9972 standards [STD10] [ITU10].

1.1 Background

The first power line communications (PLC) products came up in early 2000. However, the idea behind the PLC technology has not emerged from that time. The first time power lines were used to carry communication signals was through the technique called Ripple Control in 1950. This technique was designed and deployed over low and medium-voltage electrical power supply networks (i.e. The carrier frequency was between 100Hz and 1kHz) with the purpose of support applications like the remote control of switching on and off street lights and for load management.

Two-way communication through power grid networks started to be developed from the early 90s. With the pass of the years some communication companies have proposed PLC specifications which have become the facto standard in their scope of operation. X-10 [X10], CE BUS [Eva01] and LonWorks [Ech] are example of low data rate specifications that were proposed to make application management. Moreover, when compared to today's networks the main difference is that modern networks use higher frequencies and provide higher data rate.

The first higher data rate specification for in-home and in-building power line networking was HomePlug 1.0 [LNL+03], which was released in 2001 by Homeplug Powerline Alliance [HPA]. Then, other ones such as HomePlug Turbo, HomePlug AV [HP005], DS2/UPA [DS2] and HD-PLC [PLC] came up later on. A more in-depth view of HD-PLC PHY/MAC specification is provided in Sections 2.1.1 and 2.1.2 because as previously mentioned this is the PLC technology investigated throughout this dissertation.

1.2 Outline of Dissertation

Power Line Communication (PLC) enables high speed data and voice transmission over existing electrical wiring. Given that the cost, effort, and time to deploy and maintain a PLC network can be substantially lower than wired and wireless networks, PLC is a topic of growing interest as a potential infrastructure where wired and/or wireless are not economically or technically feasible. In the last few years Internet-enabled household appliances such as TV and HDD have made people's lives more convenient because once connected to the Internet such appliances provide services like AcTVila in Japan, which had already 2.5 million paying subscribers by mid-2011. Such service gives access either for free or as a premium service to movies and TV programmes on demand, as well as weather forecast information, games and other applications to the end-users. Thus, it is essential to keep stable in-home networking connection under any circumstances in order to meet the requirements of those applications. Moreover, with the approval and publication of the IEEE 1905.1 standard in 2013 [STD13], the future in-home networking technologies tend to interoperate among themselves. For that reason, I also investigate how to improve the TCP throughput performance in a home network based on two of those network technologies: Wireless LAN (WLAN), which is a widely used technology nowadays, and Power Line Communication (PLC), which is an emerging in-home network technology. However, despite of the numerous advantages of PLC it is important to note that communication performance over PLC is often degraded by several factors such as power level attenuation, source impedance and background noise caused by household appliances. Moreover, the Internet environment is subject to many adverse factors like cross-traffic, network congestion that can contribute to the communication performance degradation. Therefore, it is crucial to deal with the adverse factors like the ones previously mentioned that applications are subject to in both in-home and Internet networks in order to meet the requirements of the services provided to the end-user in a residence.

As far as I know, several dedicated layer-2 mechanisms for PLC have been employed to increase the efficiency and reliability of data transmission over PLC. On the other hand, few studies focus on the flow level-performance analysis. Thus, once I made experiments with real production-level PLC modem and then used the data (i.e. packet-level error rate and PHY rate) in our simulator to obtain a realistic simulation setting, in this study I survey new techniques on how to improve the flow-level performance of end-to-end data transmission over PLC connected to wired (i.e. IP over PLC network connected to the Internet) and wireless networks (i.e. Another widely used technology supported by IEEE 1905.1) under a practical network environment without modifying the Media Access Control (MAC) Technology of HD-PLC standard, which is the PLC technology covered in here. That is, the new techniques proposed in this study focus on the layer-4 of the OSI model.

Chapter 2 describes the PHY and MAC layer specifications of PLC and WLAN technologies. Then, Chapter 3 makes a brief explanation of Transmission Control Protocol (TCP) regarding the flow and congestion control it employs in order to offer smooth communication to the end-user and avoid network congestion, respectively. That is, since most of the in-home network applications run over TCP it is indispensable to know how such protocol works to understand how our flow-level performance investigation of TCP over PLC, more specifically HD-PLC, was realized.

Chapter 4 focuses on the evaluation of IP over PLC network connected to the Internet because on-demand service such as AcTVila is delivered to the end-users through the Internet. Existing studies done so far have not considered PLC connected with multiple flows with different RTTs passing through the Internet. Thus, I investigate the communication performance from the end-user perspective through an unstable Internet environment, where both RTT difference and cross traffic over Internet were taken into consideration in order to simulate a realistic network scenario. To make a comparative study, I investigated an existing scheme which also covers the end-to-end flow-level performance of IP over PLC but under the scenario previously mentioned. The result of the thorough investigation of this scheme pointed out some issues in terms of throughput unfairness because the RTT of the TCP flows tends to be different and change in the Internet due to adverse factors such as cross-traffic. That is, the existing *awnd dynamic adaptation scheme* calculated the amount of information that must be sent from the sender to the receiver based on the RTT estimation made only during the connection establishment period and did not update the *awnd* value according to the RTT changes during the communication period. That is the reason why such scheme only worked when there was no large RTT difference between the TCP flows. Thus, I proposed a new dynamic adaptation scheme by using the RTT value of the coexisting flows during all the communication in order to obtain a more accurate and dynamic update of the amount of information that should be sent to the receiver according to the transmission condition on

PLC as well. More specifically, the proposed scheme deals with the large RTT difference that can occur between coexisting flows. Second, it deals with the existence of heavy cross traffic that significantly influences the RTT values, and consequently causes a drastic performance imbalance. Last, when TCP/VoIP flows coexist in an unstable environment, the proposed scheme mitigates the degradation in network performance and fulfills the necessary one-way delay QoS requirement as well. Through the simulation results I show that the throughput fairness is obtained without degrading the maximum communication performance. That is, the proposed rate control scheme can efficiently cope with the coexistence of multiple and different types of flows on IP over PLC network connected to the Internet.

Chapter 5 focuses on how to integrate multiple home network technologies based on the IEEE 1905.1 standard. As I previously mentioned the two technologies studied here are WLAN and PLC. First, I evaluate power line networks in three different conditions according to the PHY data rate to see how it impacts the communication performance. That is, good, normal and poor environmental conditions. The simulation results show that a drastic throughput performance degradation occurs at a hostile physical environment, that can be explained by the data retransmission mechanism employed by HD-PLC. Then, I investigate how the distance can influence on the TCP throughput performance on WLAN. The findings confirm that the TCP throughput over WLAN significantly degrades as the distance increases. Last, considering that both PLC and WLAN suffer from different degradation factors and have scope for improvement I propose a dynamic cooperative transmission scheme between these two technologies. More specifically, the proposed scheme consists of using PLC to mainly send TCP-DATA and TCP-ACK is sent through WLAN, which does not require the packets to be concatenated before being transmitted as in PLC network, unless its communication media becomes unfeasible. In that case we use PLC link to be used to send TCP-ACK instead. After a thorough investigation under different and practical network conditions the findings have led to conclude that despite of CBR cross-traffic on the WLAN link and the coexistence of two bidirectional flows, the scheme showed to be very effective in terms of throughput performance. That is due to the fact that TCP inherently has a robust characteristic against TCP-ACK loss.

The results discussed in Chapter 4 are mainly taken from [MTTO13] and Chapter 5 from [MTK+13] and [MTKO14].

Chapter 2

IEEE 1901 (PLC) and IEEE 802.11 (Wireless LAN) Technologies

2.1 IEEE 1901 (PLC) Technology

Power Line Communications (PLC), as the name suggests, is a technology that enables the data transmission through power lines. The PLC system consists of devices called PLC modems, which have two interfaces. That is, one specific interface to provide the power supply and transmission over power lines and the other one is the Ethernet interface to connect to different communication devices like routers or computers. PLC can be used for different applications such as home automation and internet access. This technology is possible because compared to the electrical voltage, a data signal's voltage is small and considerably fast. Then, since the waves have different frequencies there is no cross interference when they are combined. Because of that, the overlapping signals are devided and the PLC modem is able to extract the data signal which enables to send data signals through power lines. Moreover, the used frequency and modulation scheme have a considerable impact on the performance efficiency of the broadband services. The PLC technology I consider in this dissertation is HD-PLC, the modulation method it uses is Wavelet-OFDM and a more detailed explanation about this modulation method can be found in Section 2.1.1.

The communication process has been globally standardized and organized into seven hierarchical layers known as Open System Interconnection (OSI) network reference model in order to make the interoperability of different data communication systems possible. From the seven layers, the first 3 layers are in charge of enabling data transmission over different communication networks, transport layer (Layer 4) provides end-to-end communication between final hosts through a network, session layer (Layer 5) allows applications on devices at each end to establish, manage and terminate connections through the network, presentation layer (Layer 6) formats and encrypts data to be sent out on the network and the application layer (Layer 7), which is the closest layer to the end user, provides an interface to the user operates a device connected to the network. In the context of the OSI model, as seen in Fig. 2.1, PLC networks correspond to the first two layers: Physical layer (Layer 1), which carries the PLC signal, and the data link layer (Layer 2), which plays an important role in providing methods to efficiently utilize the available resource and deal with the physical layer channel impairments experienced in power lines through the Media Access Control (MAC) and Logical Link Control (LLC) sublayers, respectively. Network layer (Layer 3) is responsible for ensuring the communication between the power line transmission medium and the user interface and provide IP routing support as well.

2.1.1 HD-PLC PHY/MAC Specifications

In this section I explain about the HD-PLC PHY specifications and its transmission control and error recovery mechanism.

The IEEE 1901 standard defines two modulation schemes. The FFT-based OFDM (Orthogonal Frequency Division Multiplexing) and the wavelet-OFDM. The one used by HD-PLC is wavelet-OFDM, which is a technique developed by Panasonic Systems Network Corporation. This modulation scheme uses 220 carriers and symbol lengths of 8.192 μs. Wavelet-OFDM achieves highly efficient transmission because it appropriately modulates

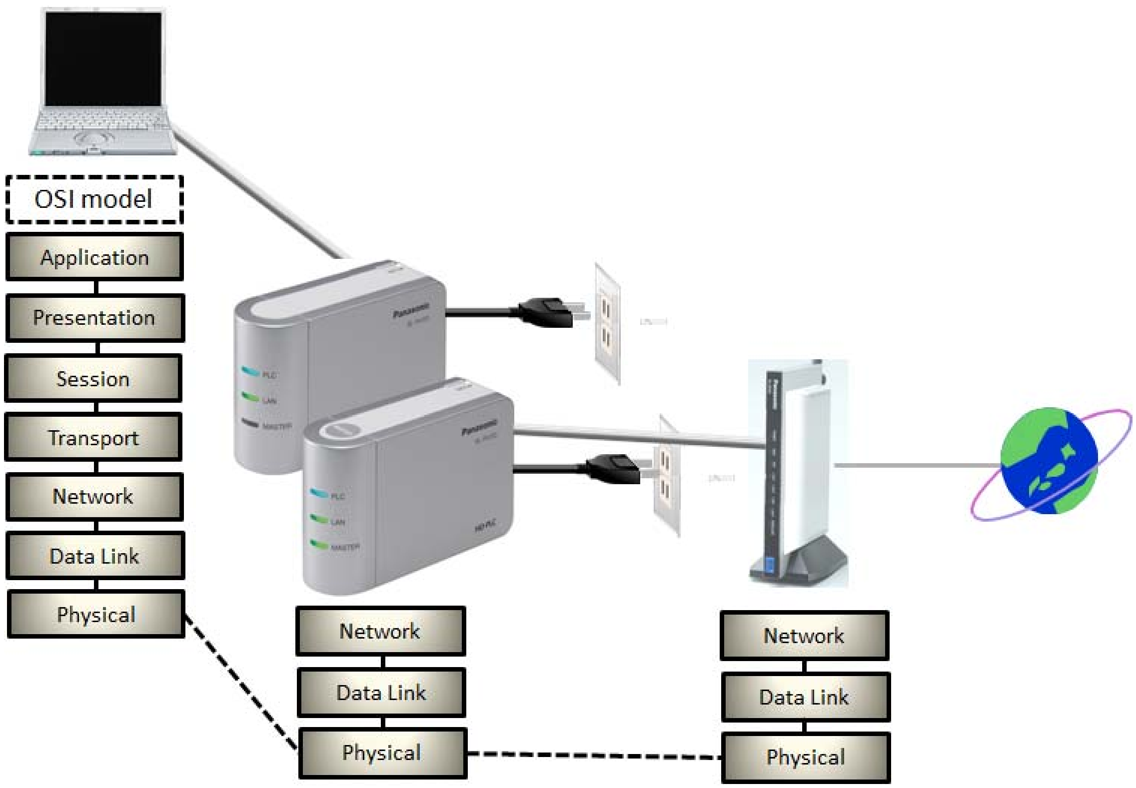


Figure 2.1: PLC technology architecture in the OSI model

the sub-carrier and there is no need to include the overhead of GI (guard intervals). Therefore, the wavelet-OFDM modulation scheme may be more efficient than FFT-based OFDM scheme [LLN+02].

HD-PLC operates in a frequency band that ranges from 2 to 30 MHz, and the maximum data rate is 240 Mbps. In addition, HD-PLC MAC structure is shown in Fig. 2.2. More specificallly, PLC sender modem creates a large MAC frame, which is denoted by PLC-protocol data unit (PLC-PDU), to send data over high-speed PLC. The PLC-PDU consists of concatenated PLC-service data units (PLC-SDUs), which are Ethernet MAC frames with the objective of reducing overhead. Note that PLC-PDU is dispatched whether the maximum number of 31 SDUs are concatenated or the maximum transmission timer of 5ms expires. HD-PLC uses a hybrid MAC composed of TDMA and CSMA in each beacon cycle in order to provide Quality of Service (QoS).

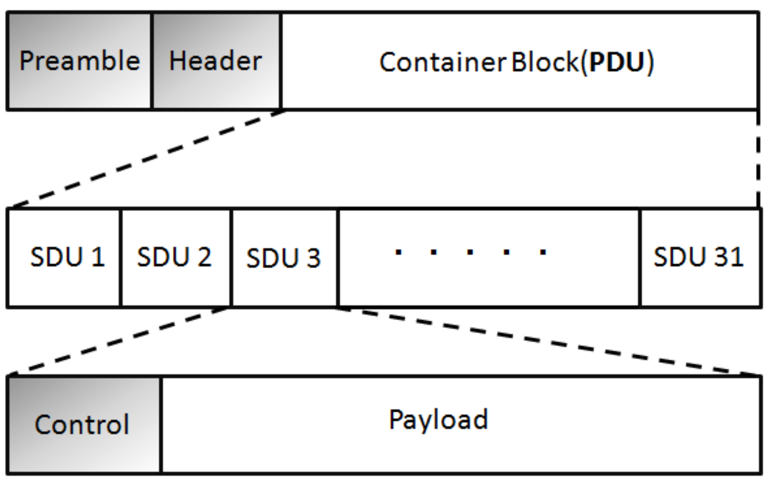


Figure 2.2: HD-PLC MAC Structure

Since power line is subject to many adverse factors that degrade the communication performance. HD-PLC technology employs an error recovery mechanism, which is called selective repeat Automatic Repeat reQuest (ARQ), in order to improve the transmission efficiency. Fig. 2.3 shows an example of the selective repeat ARQ procedure. In Fig. 2.3, the

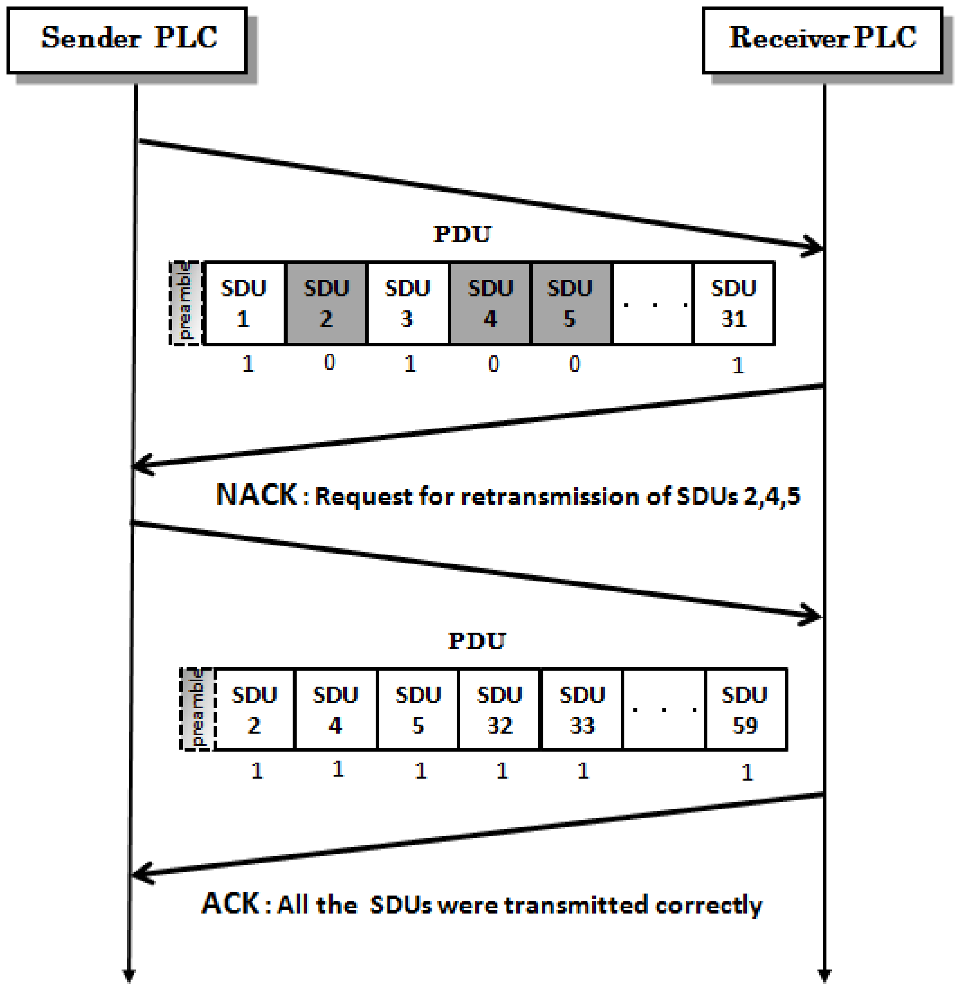


Figure 2.3: SDU Retransmission Mechanism

receiver recognizes the existence of errors in SDUs 2,4,5 in the frame (PLC-PDU) transmitted by the PLC sender. Then, the receiver therefore sends a Negative ACKnowledgment (NACK) to request the retransmission of SDUs 2,4,5. After receiving NACK from the receiver, the sender sends PLC-PDU including the requested PLC-SDUs and the new SDUs loaded in the transmit queue of PLC sender modem, up to the maximum number of SDUs per PDU [PLC09]. The PLC receiver then returns ACKnowledgment (ACK) if no error is detected. The transmission can be efficiently improved by this selective ARQ scheme because only the SDUs with errors are retransmitted instead of retransmiting the whole frame (PLC-PDU).

2.1.2 Half-Duplex Transmission Scheme

In addition, it is also important to note that HD-PLC employs a half-duplex transmission mechanism where the transmission rights among the active PLC modems alternately switch. For instance, let's assume that PLC modem1 sends a PLC-PDU to modem2. After receiving the PLC-PDU and 50μs have elapsed, PLC modem2 sends a PLC-ACK back to PLC modem1. Then, when PLC modem1 receives the PLC-ACK from PLC-modem2, the transmisssion right is given to PLC modem 2 and after a silent period of 200μs has elapsed, the next PLC-PDU is sent by PLC modem2 as seen in Fig. 2.4. Nevertheless, in case PLC modem2 has no PLC-PDU to send the transmission right returns to PLC modem1 as shown in Fig. 2.5 and so on.

2.2 IEEE 802.11 (Wireless LAN) Technology

Since the first WLAN standard called 802.11 created in 1997 by the Institute of Electrical and Electrocnic Engineers (IEEE), Wireless LAN technology has made great progress over the last few years as can be seen in Table 2.1, which describes the standards proposed so far with their respective speed and frequency band. Moreover, the WLAN technology is

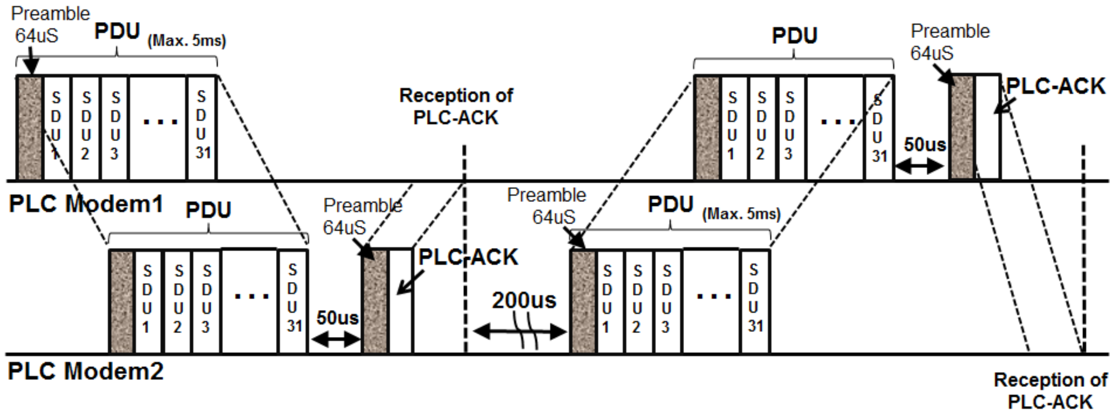


Figure 2.4: HD-PLC Half-Duplex Transmission Mechanism: Case I

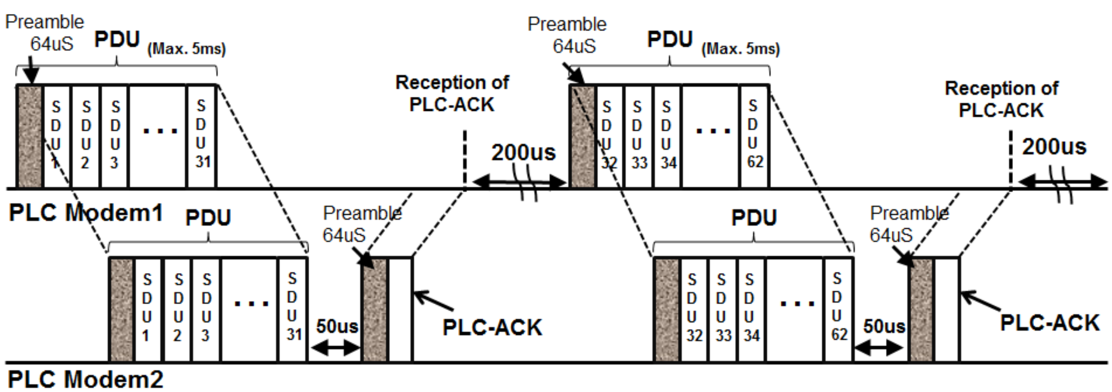


Figure 2.5: HD-PLC Half-Duplex Transmission Mechanism: Case II

also supported by the recent approved IEEE 1905.1 standard that enables the combination of WLAN with other wired network technologies inside home as shown in Fig. 2.6. This section will give an explanation of the Medium Access Control (MAC) layer of WLAN for further understanding of the study presented in chapter 5.

Table 2.1: 802.11 Standards

IEEE Standard	*Speed*	*Frequency band*
802.11	1 Mbps 2 Mbps	2.4GHz
802.11b	11 Mbps	2.4GHz
802.11a	up to 54 Mbps	5GHz
802.11g	up to 54Mbps	2.4GHz
802.11n	up to 600Mbps	2.4/5GHz
802.11ac	up to 6.93Gbps	5GHz

Figure 2.6: IEEE 1905.1 Standard

2.2.1 Medium Access Control (MAC) Layer

The MAC layer determined by The 802.11 standard has as main objective to coordinate the access of the shared wireless frequency band. The 802.11 MAC protocol differs from the

Ethernet one because it has to deal with the fact that radio, which is a wireless transmission media, is mostly half-duplex (i.e. it cannot send and listen for noise burst on a single frequency simultaneously) [Gas05]. Because of that, the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol deployed by Ethernet is not applicable to wireless. Instead, 802.11 deploys the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In order to coordinate the multiple access to the wireless medium by multiple users the distributed coordination function (DCF) is provided. DCF enables the mobile nodes (MN) to sense the medium before sending a frame. That is, if a mobile node is sending a frame, the other MNs wait until the channel is idle. In order to reduce the collision probability among the multiple MNs when the medium becomes idle, the DCF makes use of a random back off timer that demands that the MNs wait a random period of time before trying to access the medium again as seen in Fig. 2.7. Moreover, because of the lossy wireless channels a two-way handshake procedure (DATA/ACK) is deployed in order to confirm whether or not the transmitted data frames were successfully received by the receiver. In case the sending node does not receive an ACK after a certain period of time, the sending node will assume that a collision occurred and the frame will be retransmitted. Nevertheless, the carrier sense mechanism cannot be performed when MNs cannot reach each other due to the distance or the influence of an obstacle. This issue is called hidden terminal problem and is described in Fig. 2.8. IEEE 802.11 MAC employs a Request to Send (RTS) / Clear to Send (CTS) reservation scheme to mitigate this problem. That is, firstly a node with a packet to send will send a RTS frame to the receiver and the receiver will send back a CTS frame if it is not currently busy indicating that the sender can send the data frame. The RTS/CTS frames carry a duration field, which reserves the medium for a fixed amount of time period called Network Allocation Vector (NAV). Once RTS/CTS exchange is detected by all the nodes located within reaching distance, NAV avoids other nodes from accessing the medium until the transmission is completed as shown in Fig. 2.9. Due to the significant amount of overhead produced by RTS/CTS mechanism, it is worth to use it only for large size packets. Therefore, in my simulation settings the RTS/CTS mechanism is not activated because WLAN is used only to send ACK packets, which are very small packets.

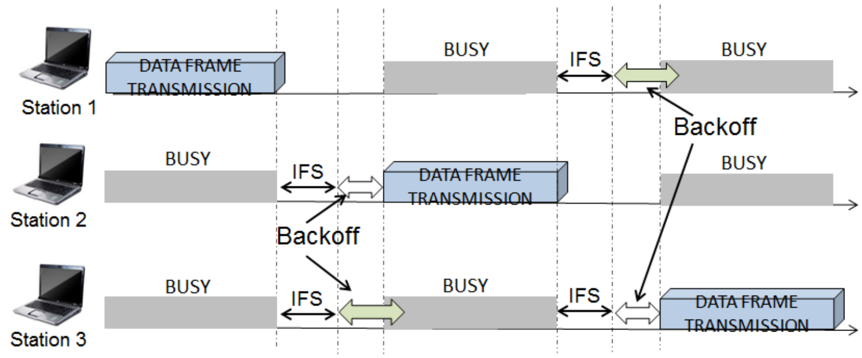


Figure 2.7: CSMA/CA

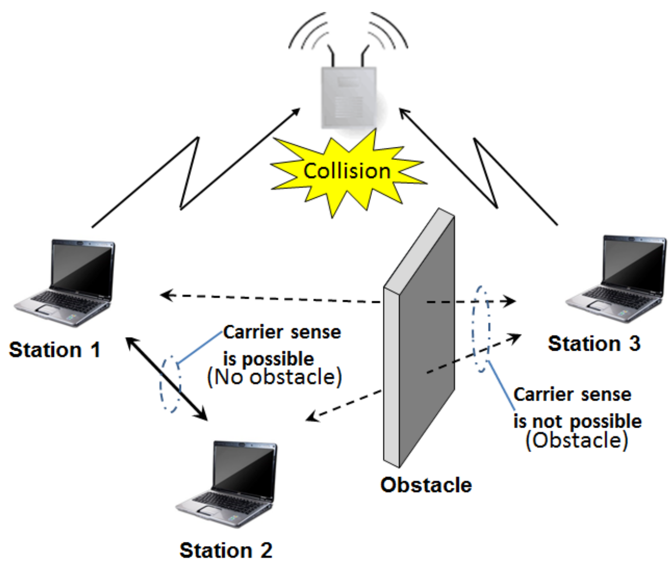


Figure 2.8: Hidden Terminal Problem

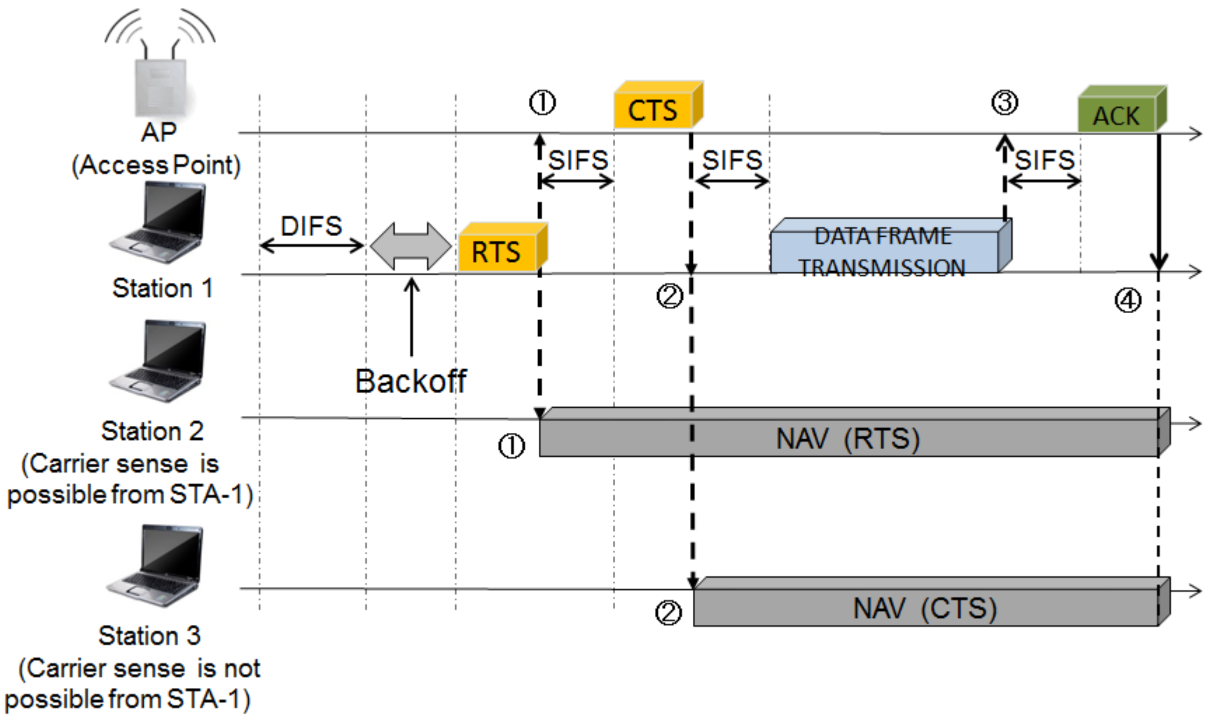


Figure 2.9: RTS/CTS

Chapter 3

TCP: Transmission Control Protocol

Transmission Control Protocol (TCP) was mainly designed to provide a mechanism for delivering data reliably over an unreliable communication medium. Both TCP and UDP transport protocols run over the IP network [Pos81a], which provides only best effort service without any guarantees that the packet will be delivered to its final destination, despite the fact that different from UDP, TCP provides a byte-stream, connection-oriented, reliable service. That is, a a connection is established between two parties before the data transmission. This process is known as a three-way handshake and involves the exchange of three messages between the client and the server as illustrated in Fig. 3.1 . First, the client (active particpant) chooses a sequence number = x and sends a connection request segment to the server (the passive participant). Then, the server replies with an ACK segment that acknowledges the client's sequence number (Ack=$x+1$) and informs its own initial sequence number, y. Finally, the client replies with a third segment that acknowledges the server's sequence number (ACK=$y+1$). That is the reason why most Internet applications rely on TCP to deliver data reliably across the network.

Once TCP is discussed throughout this dissertation, in this chapter I will discuss two of the key techniques that TCP uses to achieve high performance by avoiding network overwhelming and congestion collapse across the network.

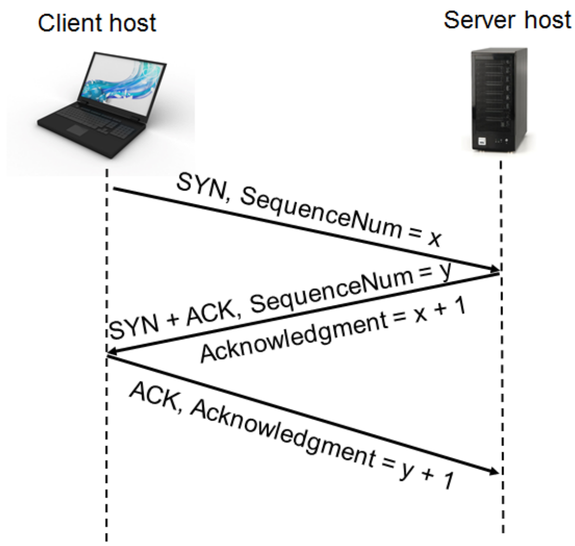


Figure 3.1: TCP three-way handshake

3.1 Flow Control

The TCP standard [Pos81b] defines a sliding window based flow control to properly adequate the data transmission rate of the sender host to that of the receiver host in order to prevent the overhelming of the receiving host which can be probably caused due to the fact the receiving host has either a heavy traffic load or a lower processing power compared to the sending host. In this section I will explain about the TCP flow control and its mechanisms. The sliding window determines the number of unacknowledged packets that the sender host can send to the receiver host by analysing two factors: The size of the sender buffer, the size and available space of the receiver buffer. First, before starting the data transmission the sender buffers all data and assign a sequence number to each buffered byte. When establishing a connection, the receiver communicates the sender about the available buffer size for incoming packet. Then, based on this information the maximum number of unacknowledged packets that a sending host can send is determined and the packets are transmitted to the receiver. Finally, as soon as the sender receives a delivery confirmation through acknowledgment (ACK) packet for at least one data packet, a new bunch of packets is transmitted and the window slides forward along the sender's buffer to send more data as shown in Fig. 3.2. Regarding the way that the receiver acknowledges data delivery, there are the cumulative ACK and selective ACK (SACK). The former indicates that all segments with smaller sequence number have already been successfully delivered. The latter, the receiver informs to the sender the data that have been delivered, then the sender needs to retransmit only the segments that have been lost.

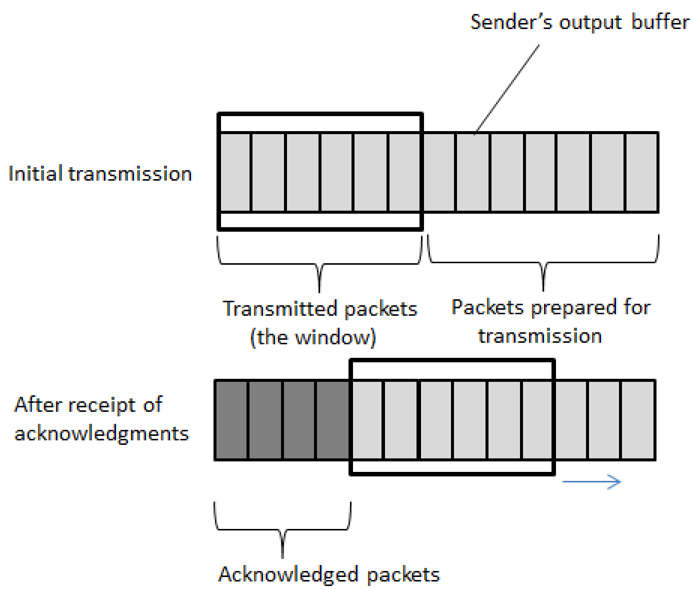


Figure 3.2: Sliding Window concept

3.2 Congestion Control

In the previous section I explained that by using the flow control mechanism a sending node is able to slow down data transmission in case its peer cannot keep up. However, in this section I will explain about congestion control, a mechanism that TCP uses to treat the drawback when TCP senders and receivers are asked to carry more data than the network between them is able to handle. Consequently, packets are forced to be dropped affecting the communication performance.

The basic congestion control mechanism supported by TCP includes the following algorithms: Slow Start, Congestion Avoidance, Fast Retransmit and Fast Recovery, where the first two algorithms are used by the TCP sender to control the amount of data sent out on the network and the other two are used to resend what seems to be packet loss without waiting for Retransmission Timeouts (RTOs). Note that in the literature RTO is also referred as timeout period. In this dissertation I make use of both terms. [Tan11]

In TCP communication, the TCP sender determines the amount of data to be transmitted to the TCP receiver based on the window size (*wnd*), which indicates the maximum amount of transmittable data without receiving ACK packets. *Wnd* is decided by choosing the minimum value between the congestion window (*cwnd*), which is a variable that limits the amount of data a TCP host can send, and advertised window (*awnd*), which is the TCP receiver's buffer capacity. That is, *Wnd = min(cwnd,awnd)*.

3.2.1 Slow Start

At slow start phase, TCP doubles the default initial congestion window *cwnd* at every Round Trip Time (RTT) upon the receiving of the acknowledgment by the receiver. That is, *cwnd* increases the sending rate according to the RTT. For instance, if the RTT is large the number of allowable in-flight packets indicated by *cwnd* at TCP sender will increase as well. This behavior continues until the *cwnd* reaches the slow start threshold (ssthresh). At this point, the TCP sender enters into congestion avoidance phase in order to reduce the sending rate of packets as shown in Fig. 3.3. A more detailed explanation of the congestion avoidance phase is detailed in the following section.

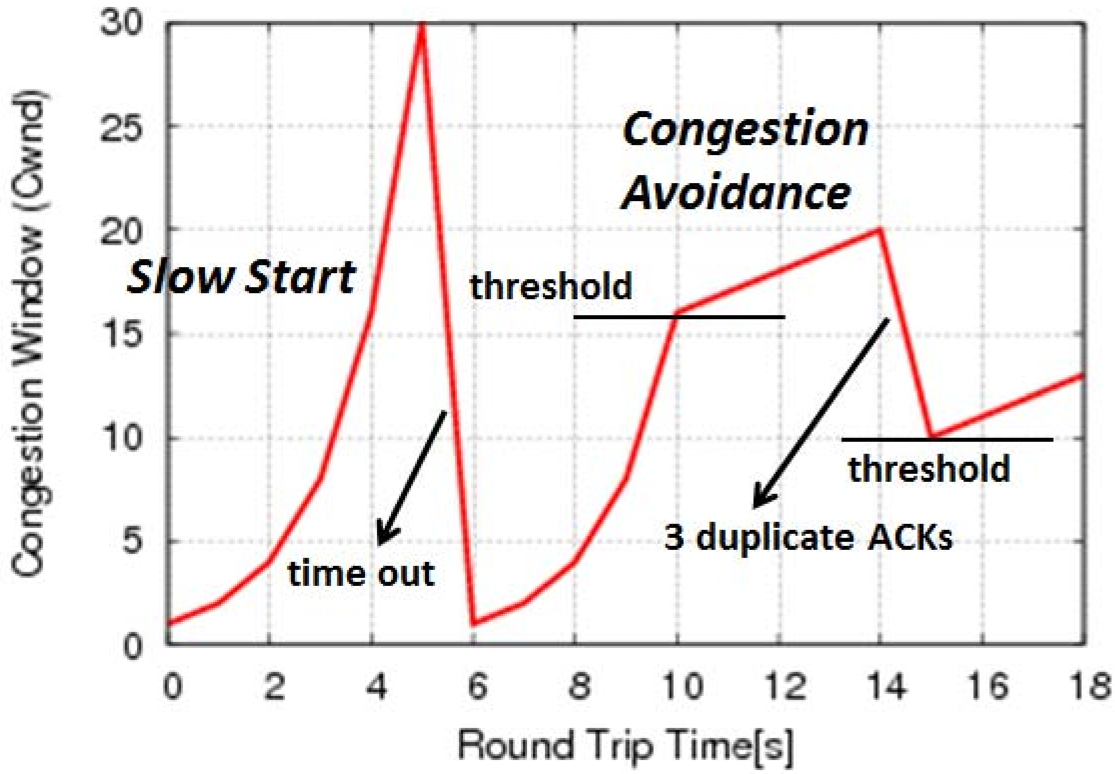


Figure 3.3: Slow Start & Congestion Avoidance

3.2.2 Congestion Avoidance

During congestion avoidance, TCP increases the *cwnd* linearly per RTT. This linear increase continues until the occurence of packet loss implied by duplicate ACKs or the retransmission timer expires. If congestion was indicated by a time out, the *cwnd* is reset to one segment and the TCP sender is switched to slow start mode. However, in case the congestion was indicated by duplicate ACKs, fast retransmit and fast recovery algorithms are implemented.

3.2.3 Fast Retransmit

When three or more duplicate ACKs are received by the TCP sender, it assumes that packet loss occured and instead of waiting for the retransmission timer expire, the lost packet is retransmitted and the TCP sender enters the fast recovery algorithm. As the name suggests, the main purpose of the fast retransmit is to resend dropped packet as soon as it notices that the congestion caused packet loss.

3.2.4 Fast Recovery

The fast recovery algorithm is invoked right after the fast retransmit. When the TCP sender enters the fast recovery, the ssthresh is set to half of the current *cwnd* and the *cwnd* is set to the sshthresh plus three. The purpose of the fast recovery is not to reduce the injection of data abruptly and keep high throuhgput performance under moderate congestion. However, it is important to note that in any circumstances, whenever retransmission timeout occurs, the ssthresh is set to half of the current *cwnd*, *cwnd* is set to one and the TCP sender is put into the slow start phase.

3.3 TCP Variants

The fast growth of the Internet over the years has increased the amount of traffic demand and that has led to a problem called congestion collapse. Therefore, numerous efforts have been done and many solutions have been proposed to prevent congestion problem in networks. The very first TCP variant was Old-Tahoe, this variant only detects packet loss through timeout. In the late 1980s, TCP Tahoe introduced the first congestion control mechanism called fast retransmit. That mechanism was implemented by simply reducing *cwnd* to its initial value (i.e. 1SMSS) in case any loss was detected forcing the connection to slow down. However, once this approach forces the TCP sender to get back to the point where it was through slow start, it can cause the underutilization of the available network bandwidth.

Then, to solve this problem, the reinitialization of slow start was reconsidered and a new version of TCP called TCP Reno was developed by incorporating a fast recovery algorithm to Tahoe.

It has been found that TCP Reno suffers from performance degradation because it is not able to recover from multiple packet losses in a window of data. Thus, to address this problem a new enhanced version of TCP Reno called TCP New Reno has been developed. That is, TCP New Reno stays in the fast recovery until all the packets that were transmitted during the start of this phase have been acknowledged or until timeout occurs.

In [TAM08] it was made a comparative study between TCP NewReno and the other previous TCP variants and it was proved that it outperforms the other ones in terms of performance. Therefore, in this work regarding the traditional TCP I made use of TCP variant NewReno.

Chapter 4

Network-Supported TCP Rate Control for the Coexistence of Multiple and Different Types of Flows on IP over PLC

4.1 Introduction

Power Line Communication (PLC) is a technology that makes use of existing power lines for data transmission. It is already in use but still questioned regarding whether or not it can offer a viable alternative to the predominant existing Wi-Fi and wired Ethernet technologies for in-home networking. Moreover, considering PLC and Wi-Fi, it is known that both of them face difficulties to provide a better communication quality to the users inside a large house because of their degradation factors [LLKL03].

It is expected that PLC will be widespread worldwide because of the acceptance of IEEE 1901 standard for power line communications [STD10] in September 2010 and the recent start of certification of PLC-related devices that comply with such standard [PLC09]. In addition, despite of the diversified number of broadband power line technologies and their interoperability issue [GKL$^+$10], in July 2011 HD-PLC Alliance announced that the world first IEEE 1901 compliant LSI is now ready to deploy to the market [PLC]. Thus, although PLC has not reached the mass market diffusion so far, there has been a great progress to accelerate the adoption of IEEE 1901 standard compliant products in the world.

The necessity of improving the electric grid infrastructure and the management of energy transmission and distribution has motivated a global push for Smart Grids. Among the many types of communication technologies that Smart Grid will probably make use of, PLC is a very good candidate because of its features and continuous improvement over the past few years [LZGY12] [VBL+10]. This is confirmed by the great progress that PLC has made for supporting Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI) applications [GSW11]. Those are the reasons why I believe PLC is a promising technology on which to base the in-home-network.

Furthermore, nowadays it is increasing the demands for more convenience at in-home-network and in PLC there is nothing else to be built or installed in a house because the infrastructure needed to deploy this technology is already installed. However, like Wi-Fi, which faces problems such as interference, overcrowded spectrum and Ethernet that faces construction cost problems, PLC has its drawbacks as well. The fluctuations of source impedance, power level attenuation and the background noise caused by the electrical appliances are among the main ones. In order to overcome the above-mentioned problems related to PLC and get better communication performance, the authors proposed in [MMT+10] a TCP rate control method that was shown to be effective on an IP over PLC network environment. Nevertheless, in such environment neither large difference in RTTs of coexisting flows nor cross-traffic was addressed. Therefore, in this chapter I take as reference the network-supported TCP rate control scheme for high-speed power line communications environment [MMT+10] and make a comparative study to investigate the end-to-end flow-level performance of IP over PLC through an unstable Internet environment (i.e. more realistic situation). Then, I propose a new scheme to deal with the unfair bandwidth allocation caused by the coexistence of multiple TCP flows and VoIP applications, whose voice quality depends on many parameters, such as one-way delay, jitter, packet loss rate, codec, voice data length [CXVR09]. Regarding the QoS requirements for VoIP applications, I restricted the investigations to one-way delay because in my view the time needed for a packet to cross the network from a source to the destination host is the key parameter that should be mainly investigated.

This chapter starts with a brief explanation of the related works in Section 4.2. In Section 4.3 I explain about the experiments I have made and the simulator of PLC network I have developed. The previous scheme is described in Section 4.4, then I address the throughput unfairness problem in coexisting multiple TCP flows and VoIP end-to-end delay problem in TCP/VoIP flows. I dedicate Section 4.5 to describe detailed procedure of my proposed scheme. In Section 4.6 I demonstrate the effectiveness of the proposed scheme through simulation results. Finally, Section 4.7 summarizes the contributions.

4.2 Related Work

The majority of the previous studies and works on PLC networks have been done on PHY/MAC layer. However, just a little attention has been given to the evaluation of these networks from an end-to-end perspective.

In literature [ZM11] the construction of a PLC Test Bed with 5 nodes was described. With the objective of identifying the MAC and PHY limitations of this equipment, tests including uplink and downlink of TCP and UDP traffic simulated by iperf were realized.

In literature [MMT+09] the authors propose a scheme to estimate an achievable throughput for TCP communication limited to the home network and adaptively control the transmission rate of TCP to prevent buffer overflow at the PLC Sender.

Mizutani et al. [MMT+10] extends the work presented in literature [MMT+09] to a network-wide where the clients are connected to the servers related to a different network through Internet. However, to the best of my knowledge there are no studies that have focused on the evaluation of IP over PLC under adverse aspects like network congestion and cross traffic that contributes to the instability (e.g. large and variable RTT) of the flows in the Internet environment from an end-user perspective.

Thus, my research mainly differs from [MMT+10] in the following aspects: In order to investigate the above-mentioned adverse aspects in an Internet environment (i) I evaluate both multiple TCP and TCP/VoIP flows behavior with large difference in round trip time (RTT) and (ii) the existence of cross-traffic for a certain amount of time during the communication period. Based on the obtained results, I propose a new scheme to solve the problems.

4.3 Simulation of PLC Network

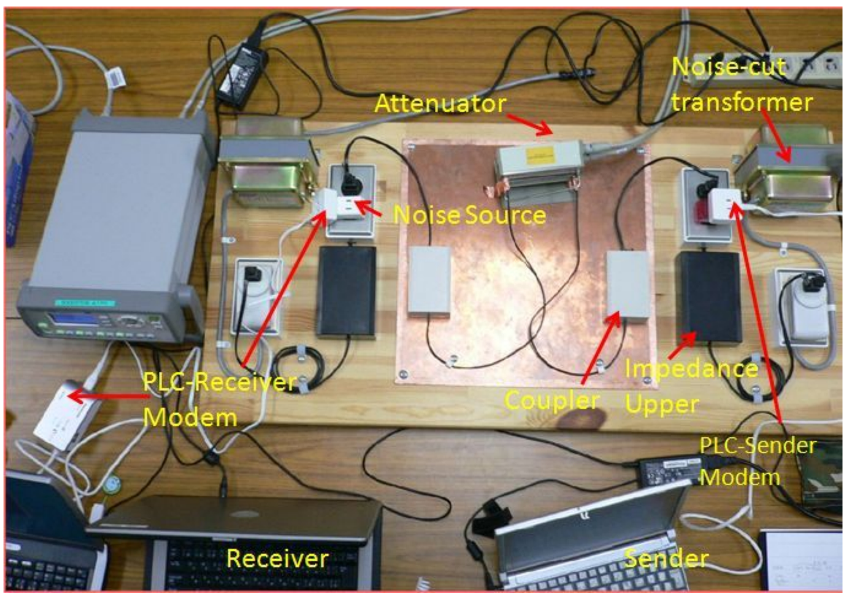


Figure 4.1: Experimental Environment

4.3.1 Experimental Environment

Since there is no standard model of auto-tuned PHY rate and packet-level error patterns over PLC, I first conducted preliminary experiments using real production-level PLC modems

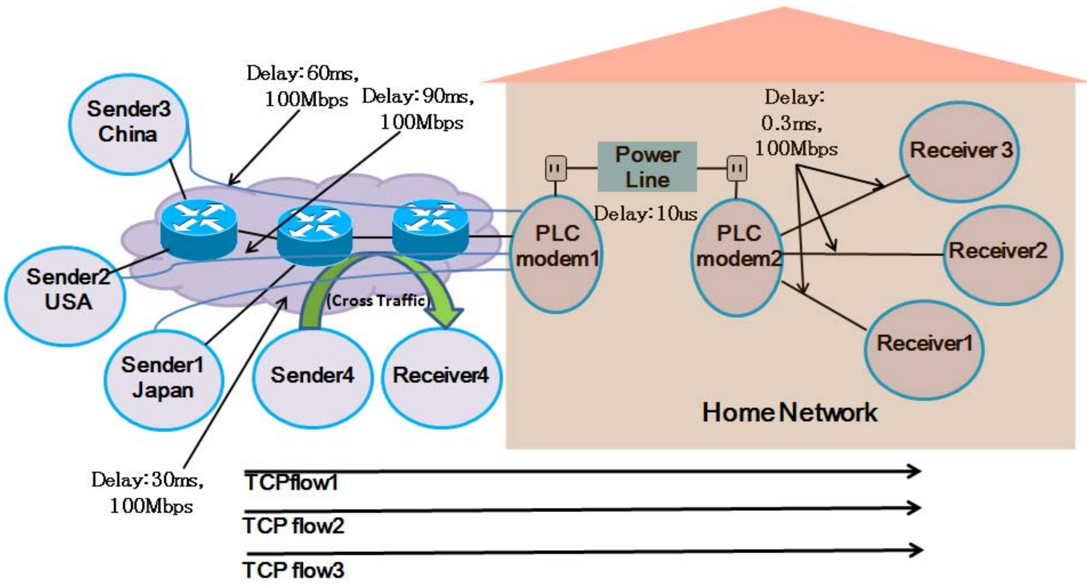


Figure 4.2: Network Topology I

Table 4.1: Simulation Parameters

Transport Protocol	TCP NewReno/SACK, UDP
PLC bandwidth (Phy_Rate)	18.62 Mbps
Internet bandwidth	100Mbps
Buffer Size	256 packets
Packet Size	1500 bytes
Delay	Sender1(JAPAN)-PLC_modem1 30[ms] Sender2(USA)-PLC_modem1 90[ms] Sender3(CHINA)-PLC_modem1 60[ms] PLC_modem2-Receiver 0.3[ms]
Error Pattern	Inverter Light Att:45dB

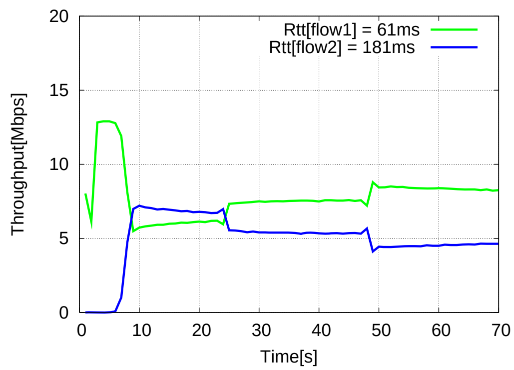
on a test-bed environment to experimentally obtain those essential parameters for realistic simulation settings. That is, the objective of my study is not to modify the HD-PLC standard but to investigate the end-to-end flow-level performance of IP over PLC without changing the features of BL-PA510, a HD-PLC based modem provided by Panasonic Systems Network Corporation, which was used in my experiments.

The experiment was realized with the use of an experimental environment that avoids interference from outside noise. The experimental environment is shown in Fig. 4.1, where the sender and receiver communicate to each other through the PLC-Sender modem and PLC-Receiver modem. We added different levels of attenuation and some types of noise-source to the power line to measure the packet-level error rate and the PHY rate over PLC under different situtations. However, the pattern that I used to be simulated by the simulator was the combination of the packet-level error rate and PHY rate for inverter light with the attenuation level 45dB because it significantly impacts the performance of home network. Note that in order to validate the accuracy of the simulator, during the experiments the throughput and *wnd* were measured by using Iperf [IPE] and Web100 [WEB], respectively. In this work I would rather give attention to an unstable communication environment than a stable one because PLC network is subject to many degradation factors.

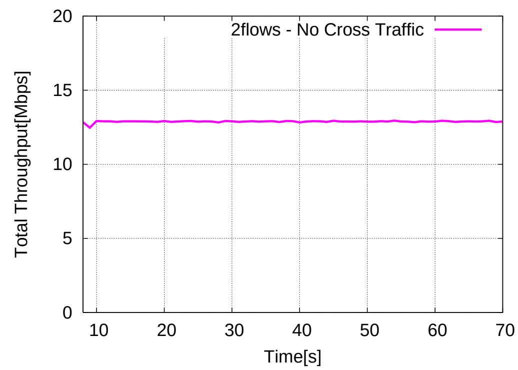
4.3.2 Simulation

The network topology used in my study is shown in Fig. 4.2 , and the parameters used are given in Table 4.1.

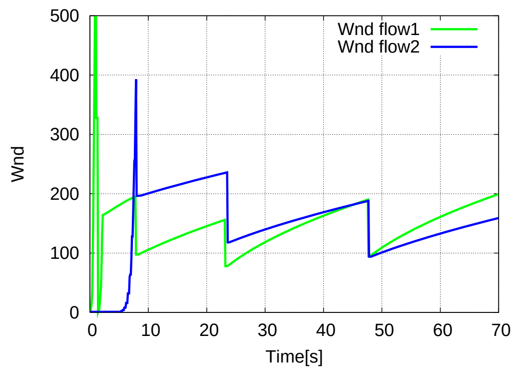
I assume that sender1 is located inside Japan, sender2 is in the USA and sender3 is in China. Then, the propagation delays implemented in my study between sender1, sender2, sender3 and the PLC_modem1 are 30 ms, 90 ms and 60 ms, respectively. In addition, the propagation delay assumed between receiver1, receiver2, receiver3 and the PLC_modem2 is 0.3 ms, and I further assume the Internet and the PLC bandwidth to be 100 Mbps and 18.62 Mbps, respectively.



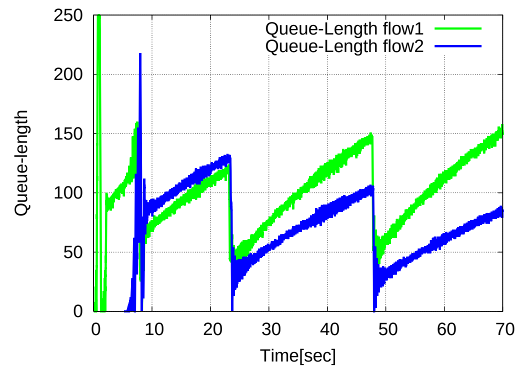
(a) Throughput



(b) Total Throughput



(c) Wnd

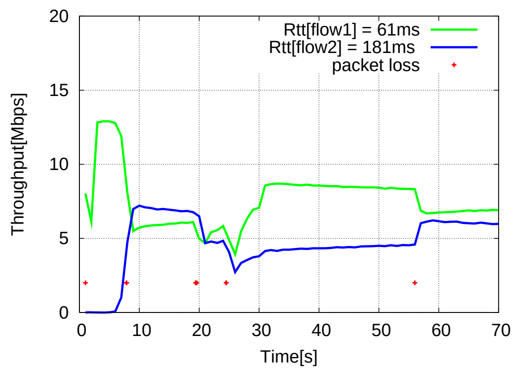


(d) Queue Length

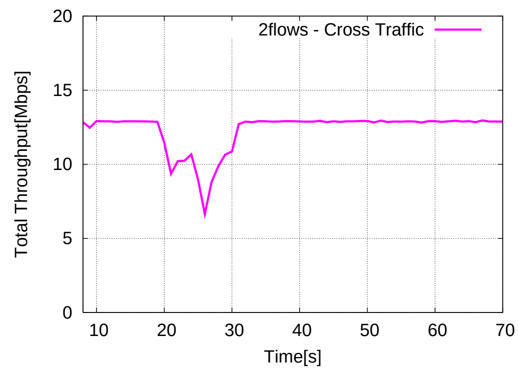
Figure 4.3: TCP NewReno/SACK: 2TCP flows (w/o cross traffic)

I developed a module on the NS-2 network simulator [NS2], which is a discrete event-driven network simulator directed to the networking research community. Besides, the data (Phy_rate and packet level error rate) previously obtained in the PLC experimental environment (Fig. 4.1) were loaded in my NS-2 module. Thus, I could simulate the realistic behavior of how data are sent through power line communication under different power level attenuation and different noise sources.

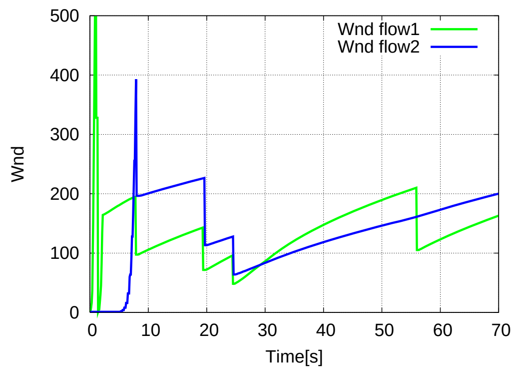
We set packet size as 1500 bytes TCP communication. Besides, I added CBR cross traffic with rate of 90 Mbps that is injected along the communication path between sender4 and receiver4. Moreover, I assumed large RTT difference among the coexisting flows in order to simulate the behavior of a real Internet environment. That is, I make use of the



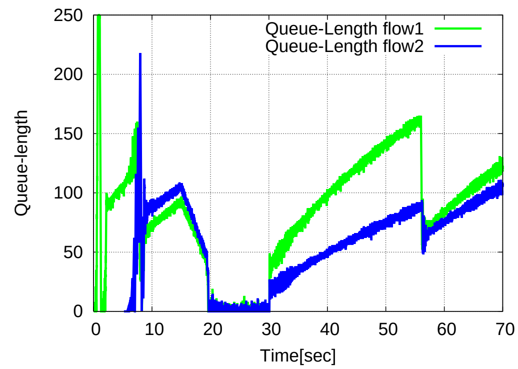
(a) Throughput



(b) Total Throughput



(c) Wnd



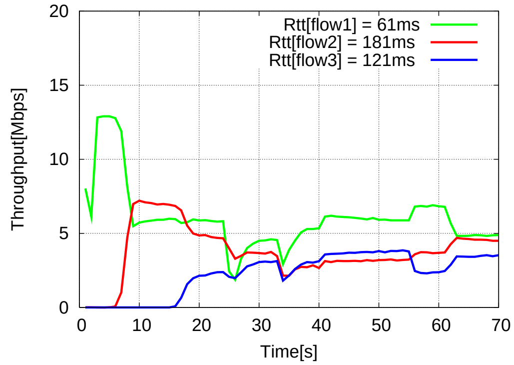
(d) Queue Length

Figure 4.4: TCP NewReno/SACK: 2TCP flows (w/ cross traffic)

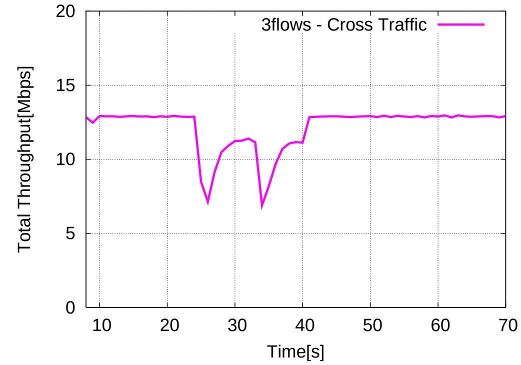
network topology shown in Fig. 4.2, which describes a scenario where the maximum of 3 TCP flows coexist on IP over PLC network with the presence of CBR cross traffic in the Internet environment.

4.4 A Previous Scheme - Network Supported TCP Rate Control Scheme For High-Speed PLC Environment

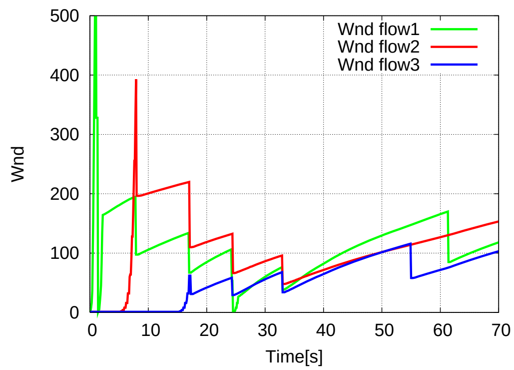
This reference scheme was proposed by Mizutani et al. [MMT+10] with the purpose to extend the work in literature [MMT+09] in order to maximize the throughput over PLC



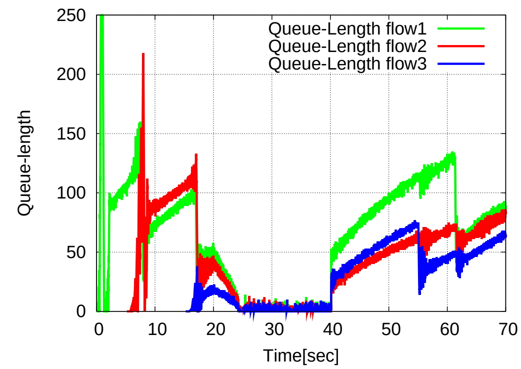
(a) Throughput



(b) Total Throughput



(c) Wnd

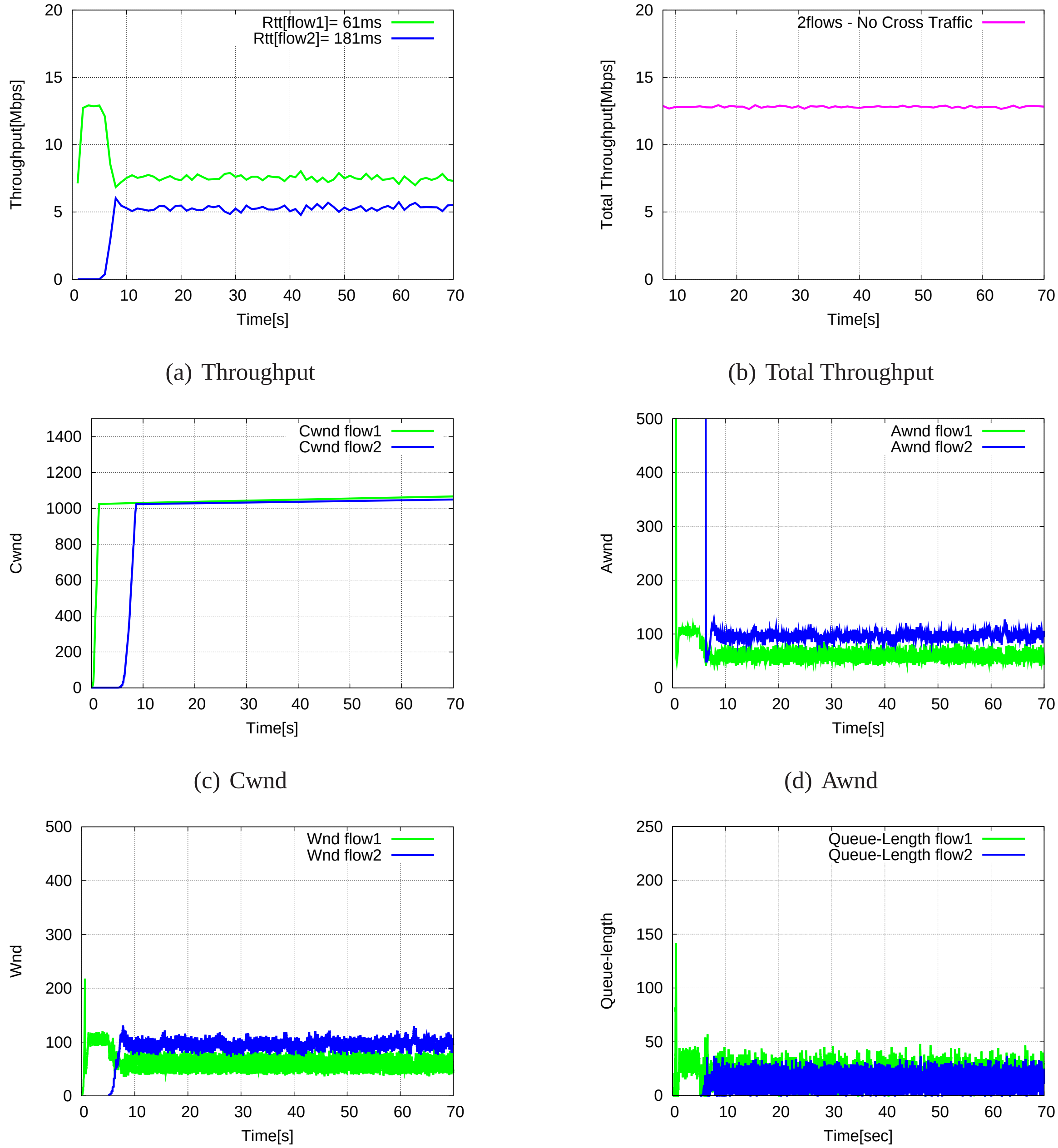


(d) Queue Length

Figure 4.5: TCP NewReno/SACK: 3TCP flows (w/ cross traffic)

connected to an environment where neither RTT difference nor cross traffic over the Internet was taken into consideration. The scheme is the same idea of the TCP protocol. In TCP, the receiver informs its buffer-capacity to the sender through *awnd* every time the receiver sends the TCP-ACK. Therefore, the sender's window-size *wnd* will take the smallest value between congestion window *cwnd* and advertised window *awnd* to provide a way to avoid network congestion and overflow of the receiver side.

The scheme in discussion modifies the *awnd* for each TCP-ACK packet in PLC_modem1 only in case the value set by the the receiver is larger than the desired one calculated by the PLC_modem1. This approach can safely provide a way to determine the appropriate window size *wnd* of the sender according to the transmission condition on the PLC.



(a) Throughput

(b) Total Throughput

(c) Cwnd

(d) Awnd

(e) Wnd

(f) Queue Length

Figure 4.6: Previous Scheme: 2TCP flows (w/o cross traffic)

4.4.1 Problem in Coexisting Multiple TCP Flows

For a comparison purpose, I evaluate both TCP NewReno/SACK and the reference scheme [MMT+10] to see how competing flows consume the network bandwidth in network topol-

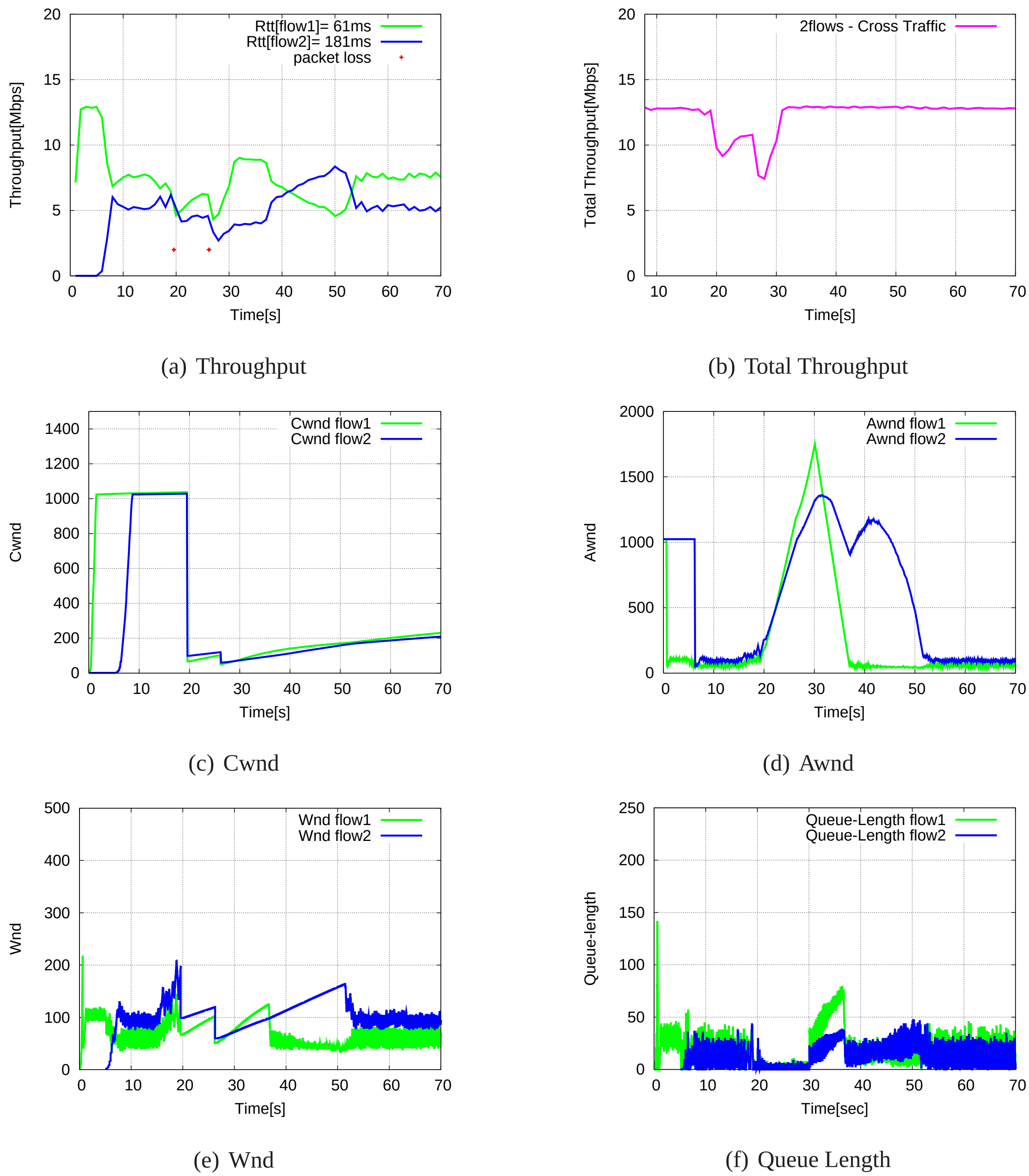
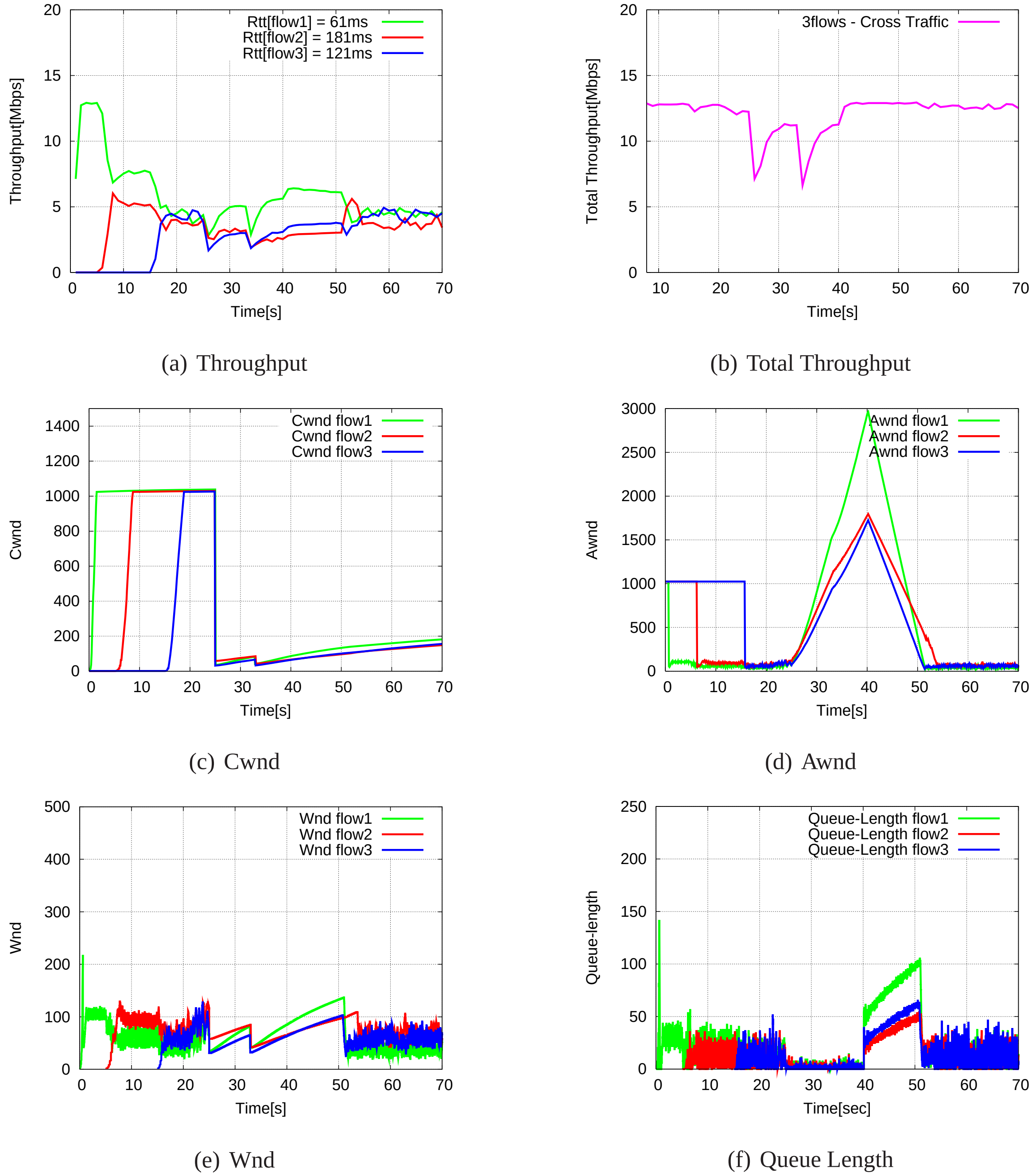


Figure 4.7: Previous Scheme: 2TCP flows (w/ cross traffic)

ogy I (Fig. 4.2). I focus on the scenario where two flows coexist, under an unstable environment (Inverter 45dB) connected to the Internet in order to simplify the performance problems



(a) Throughput (b) Total Throughput

(c) Cwnd (d) Awnd

(e) Wnd (f) Queue Length

Figure 4.8: Previous Scheme: 3TCP flows (w/ cross traffic)

of the existing scheme. In addition, I assume that Sender 1 and 2 are connected to the Internet and there is a large RTT difference between them with the existence and non-existence

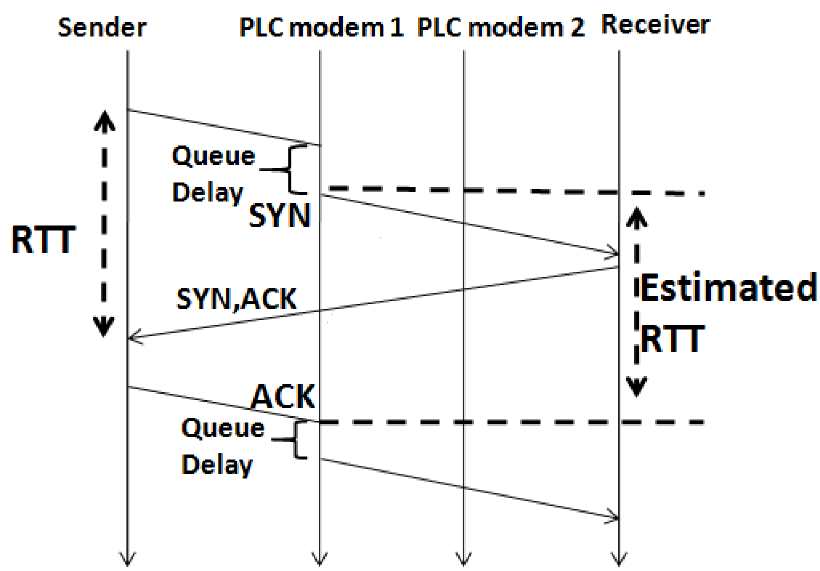


Figure 4.9: Estimation of RTT

of cross traffic.

The reference scheme [MMT+10] is made up of four phases. First, the RTT for each flow is measured during the connection establishment. Second, the previously obtained estimated RTT is utilized to calculate the maximum number of transmitted SDUs within the RTT period for each flow (*Sample_Awnd[i]*). Then, as shown in Equation (1), which is referred in [MMT+10], the appropriate amount of data transmission (*awnd*) is determined based on the estimated RTT and the number of coexisting TCP flows to maintain an adequate transmit queue length of PLC_modem1. Finally, a dynamic adaptation scheme of *awnd* is implemented in order to adjust the amount of information that must be sent by the TCP sender according to the network conditions. Therefore, besides monitoring the transmit queue length of PLC_modem1, it has the function of updating and returning the appropriate *awnd* value of each flow to the TCP sender. The pseudocode for the existing dynamic adaptation scheme of *awnd* can be found in Fig. 4.10

Another important function implemented was the estimation of the RTT between the sender and the receiver based on a passive measurement technique [JID+04]. The idea behind this technique is to estimate the RTT by using the SYN and ACK packets in a measurement point (e.g. PLC modem 1). More specifically, that happens during the connection establishment when the PLC modem 1 records both the TCP SYN packet departure time and the TCP ACK packet arrival time of each flow when they pass through this measurement point. Then the RTT estimation is calculated based on the difference between the TCP ACK packet arrival and TCP SYN packet departure time. The sketch of this estimation RTT technique is shown in Fig. 4.9

However, this technique estimates the RTT period of a flow only during the three-way handshake (i.e., only during the connection establishment). After that, RTT can dynamically vary because of factors like network congestion and route change during the communication. Thus, a scheme that can also deal with the appearance of those negative elements during the communication period is necessary.

$$Awnd[i] = Sample\_Awnd[i] \times \frac{\frac{1}{RTT[i]}}{\sum_{i=1}^{N} \frac{1}{RTT[i]}} \tag{4.1}$$

if $Queued\_pkt[i] \geq \frac{L}{N}$ **then**

  $Awnd[i] = Awnd[i] - \frac{1}{\frac{L}{N}}$

else

  $Awnd[i] = Awnd[i] + \frac{1}{\frac{L}{N}}$

end if

Figure 4.10: Previous Algorithm for Dynamic Adaptation of *awnd*

where L: The maximum number of SDUs in a PDU in the current condition, N: The number of TCP flows coexisting, and $Queued\_pkt[i]$: The number of SDU packets of the i-th flow remaining in Transmit queue of PLC modem 1.

The metrics I use to evaluate the simulation results are the throughput, congestion window (*cwnd*), advertised window (*awnd*), window size(*wnd*) and the queue length of PLC_modem1.

Problems in RTT difference

We assume that flow2 begins the communication 5 s after flow1 does. Taking into consideration the performance evaluation for the traditional TCP NewReno/SACK, Fig. 4.3(c) shows that even though flow2 changes to the congestion avoidance right after the communication starts, it maintains a high *wnd* value and increases gradually. Because of this, flow1 obtains low throughput for a considerable amount of time. However, to clarify the cause of the throughput unfairness (Fig. 4.3(a)) between flow1 and flow2, I also investigated the queue length for each flow at the PLC_modem1 (Fig. 4.3(d)). By comparing Figs. 4.3(c) and 4.3(d), I observed that the queue length is constantly high. More specifically, as flow1 occupies more than 70% of the queue length at the moment the flow2 starts the communication, the frames belonging to flow2 tend to be dropped because of buffer overflow. That is the reason why flow2 enters into the congestion avoidance phase very soon.

However, flow2 is superior to flow1 in terms of throughput until the second buffer overflow occurs as shown in Fig. 4.3(d). Fig. 4.3(c) shows that when the second buffer overflow occurs, the *wnd* of flow 1 increases gradually and faster than flow2. As a result, the queue length (Fig. 4.3(d)) for flow1 becomes higher, thereby leading to a higher throughput during the rest of the communication period.

The buffer overflow at PLC sender modem only occurs when I evaluate the traditional TCP New Reno/SACK. Note that in TCP communication, TCP sender determines the amount of data to be transmitted to the TCP receiver based on its *wnd*. That is, as the traditional TCP employs a congestion control mechanism with the objective to avoid network congestion and overflow at the receiver side, it is common the occurrence of buffer overflow along the network path between TCP sender and receiver. Consequently, since TCP is not aware of the PLC network condition, the amount of information transmitted by the TCP sender based on

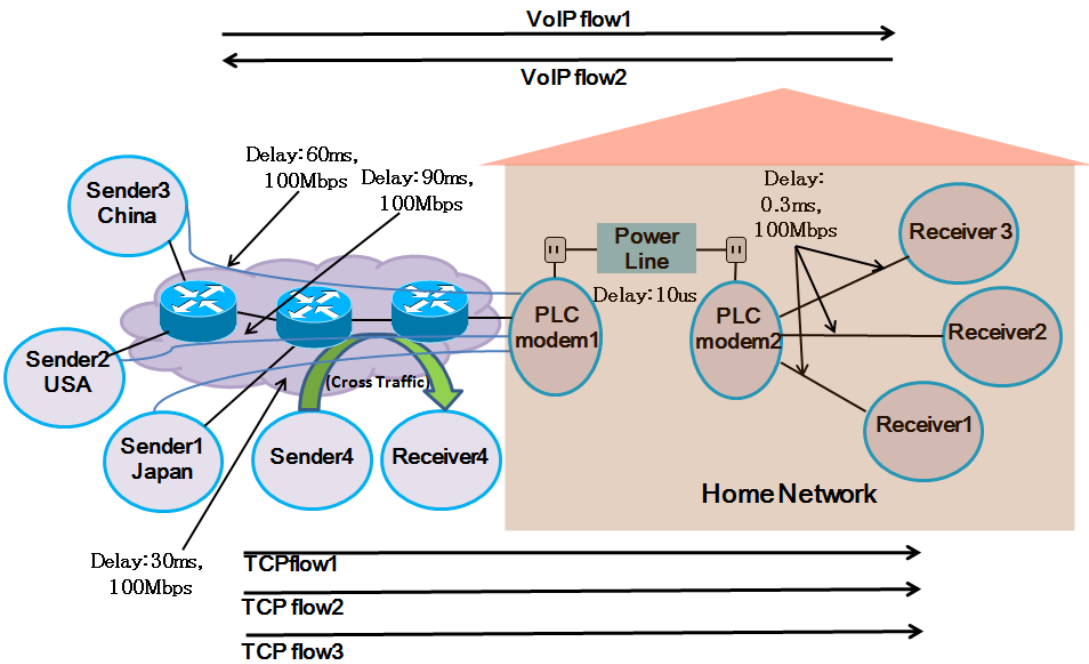
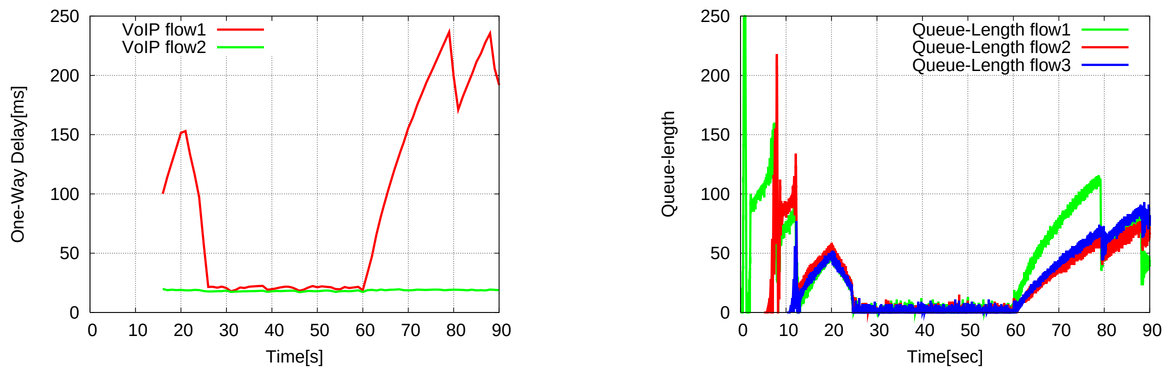


Figure 4.11: Network Topology II

wnd can unknowningly exceed the maximum PLC network capacity.

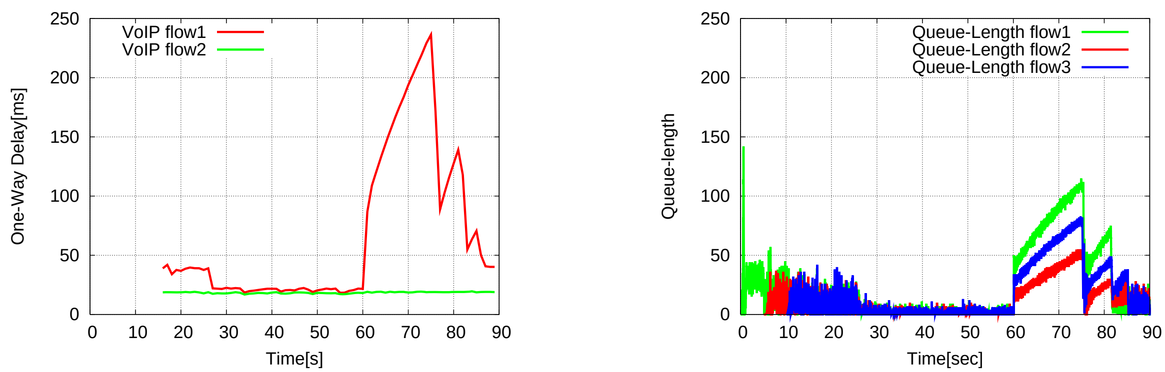
Regarding the previous scheme, Fig. 4.6(a) shows the throughput for the coexistence of *2 flows with large RTT and without cross traffic*. The result shown in Fig. 4.6(a) highlights the flow with small round trip time consumes a large of network bandwidth. That is, the flow with smaller RTT (e.g. flow1) reaches high throughput during all the communication time even after the second flow starts the communication in 5 s, consequently causing a not friendly allocation of the available bandwidth.

Furthermore, these findings show that the existing dynamic adaptation scheme is not effective when there is a considerable RTT difference between the flows. That is, this method does not update the *awnd* value considering the RTT period. The key problem in such circumstances is that once the *awnd* is not accurately modified for each TCP-ACK packet in PLC sender modem, the sender will not determine an appropriate *wnd* (Fig. 4.6(e)) as long as *awnd* (Fig. 4.6(d)) is smaller than *cwnd* (Fig. 4.6(c)).



(a) End-to-End Delay (b) Queue Length

Figure 4.12: TCP NewReno/SACK: VoIP/3TCP flows (w/ cross traffic)



(a) End-to-End Delay (b) Queue Length

Figure 4.13: Previous Scheme: VoIP/3TCP flows (w/ cross traffic)

Problems with the existence of heavy Cross-Traffic

We also evaluated the traditional TCP NewReno/SACK and the existing scheme in the worst-case scenario, where besides the RTT difference, CBR cross traffic with rate of 90 Mbps is also injected along the communication path between sender4 and receiver4. In this scenario, the coexistence of 2 and 3 flows are analyzed. When 2 flows coexist, the cross traffic comes into the communication path in 15 s and leaves in 30 s. However, in case of 3 flows I assume that the cross-traffic is injected in 20 s and leaves in 40 s. Considering TCP NewReno/SACK, I observed that during the cross-traffic, the *Queued_pkt* (transmit-queue in PLC_modem1) becomes very low (Figs. 4.4(d) and 4.5(d)). Nevertheless, when the cross traffic leaves the queue length gets extremely high. That is due to the gradual *wnd* increase of each flow (Figs. 4.4(c) and 4.5(c)) without any particular control. Therefore, the throughput unfairness is shown in Figs. 4.4(a) and 4.5(a).

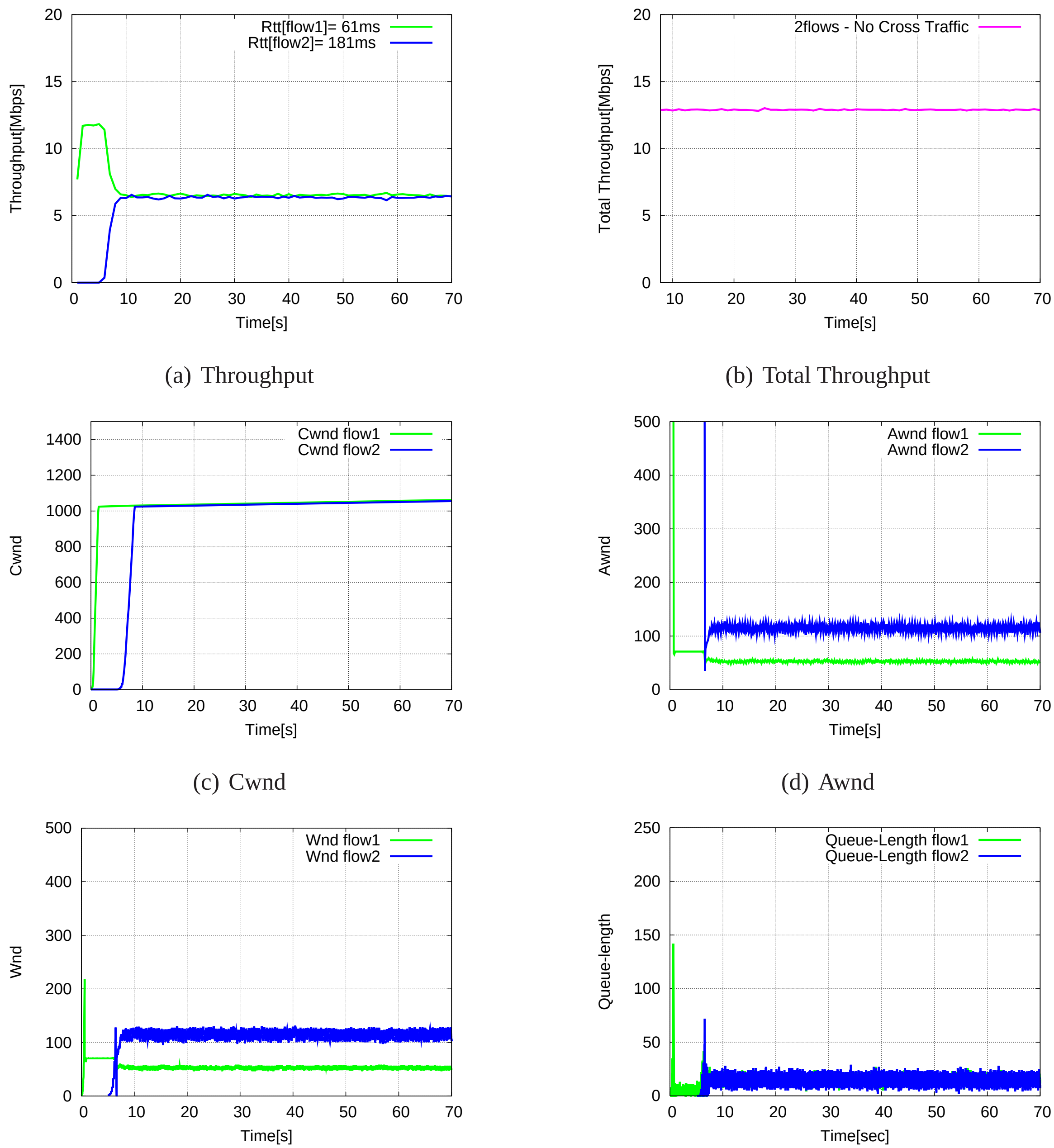
Turning to the existing scheme, We observed that during the cross-traffic, the *Queued_pkt* (transmit-queue in PLC_modem1) becomes very low as well (Figs. 4.7(f) and 4.8(f)) and because of the condition imposed by this scheme ($Queued\_pkt[i] < \frac{L}{N}$), *awnd* keeps on increasing unnecessarily as shown in Figs. 4.7(d) and 4.8(d). During this time interval, the existing scheme does not work properly. However, when the cross traffic leaves, the amount of information passing through PLC network increases and the transmit queue at PLC_modem1 starts being occupied again.

Hence, Fig. 4.7(d) shows that the *awnd* of the first flow decreases immediately after the cross traffic leaves, because the increasing speed of *wnd*(Fig. 4.7(e)) of each one of the flows, which is determined by the *cwnd* in such situation, is different. Consequently, the queue length is not occupied by each flow with the same frequency. Thereby, leading to the *awnd* decreasing delay of flow2. Fig. 4.8(d) highlights that for the coexistence of 3 TCP flows, the same procedure will occur when cross traffic leaves the communication path. Furthermore, as expected, Figs. 4.7(e) and 4.8(e) demonstrate that *wnd* receives the minimum value between *cwnd* (Fig. 4.8(c)) and *awnd* (Fig. 4.8(d)) (i.e.,*Wnd = min (cwnd,awnd)*).

In short, as Figs. 4.7(a) and 4.8(a) suggest, the reference scheme suffers from the throughput instability problem for coexisting multiple flows in such environments.

4.4.2 Problem in Coexisting Multiple TCP and VoIP Flows with no QoS

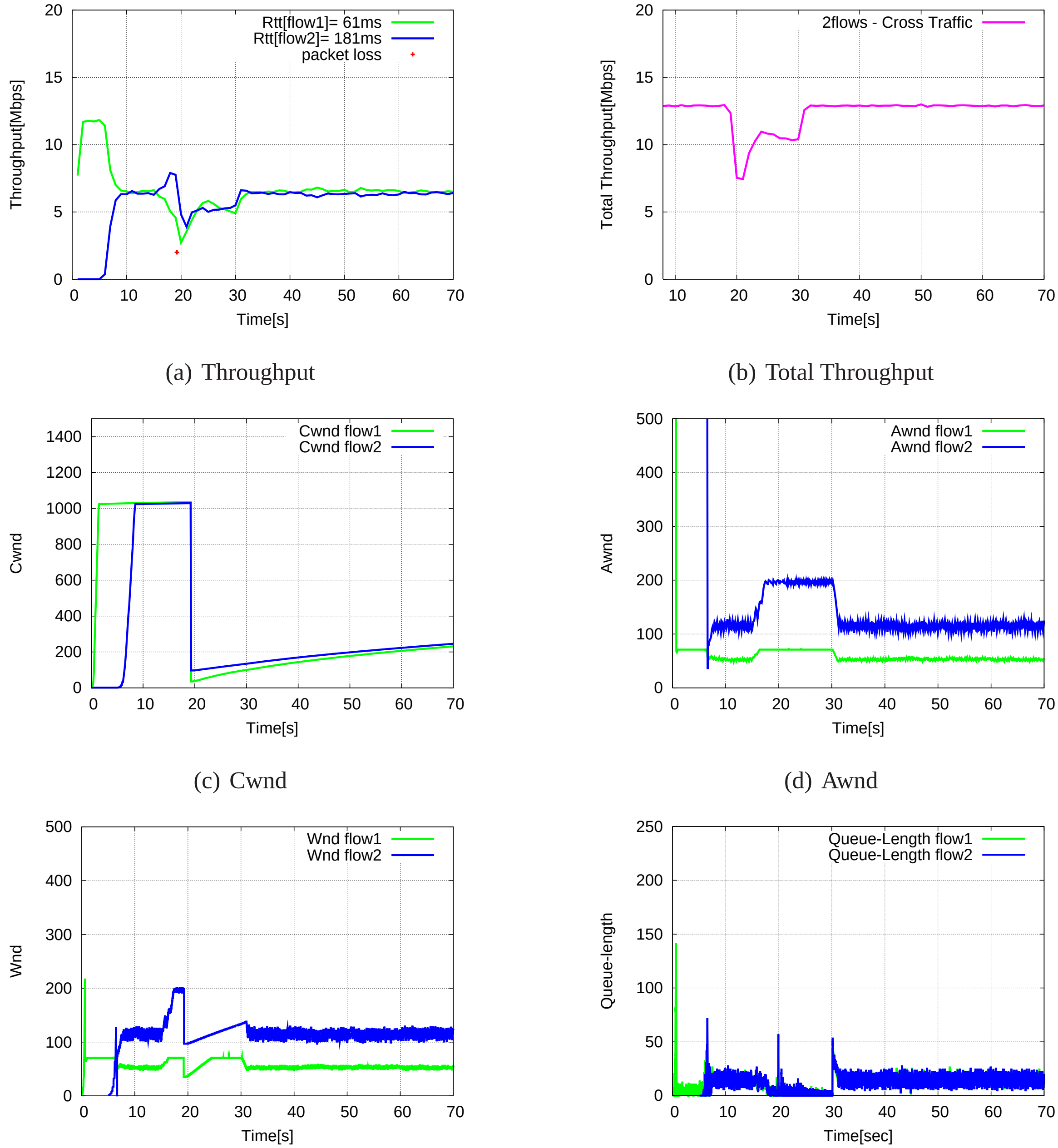
In this section, considering that some PLC solutions may still not provide QoS (Quality of Service) management support, I focus on the network topology II (Fig. 4.11), where 3 TCP flows coexist with 2 bi-directional VoIP flows without QoS. We assume that Sender 1, 2 and 3 are connected to the Internet and Receiver 1, 2 and 3 are limited to the home network. In



(e) Wnd (f) Queue Length

Figure 4.14: Proposed Scheme: 2TCP flows (w/o cross traffic)

addition, I also assume the existence of heavy cross-traffic (90 Mbps) on the Internet. Both TCP flows and VoIP flow 1 pass through PLC modem 1 in the same direction. As a result,



(a) Throughput

(b) Total Throughput

(c) Cwnd

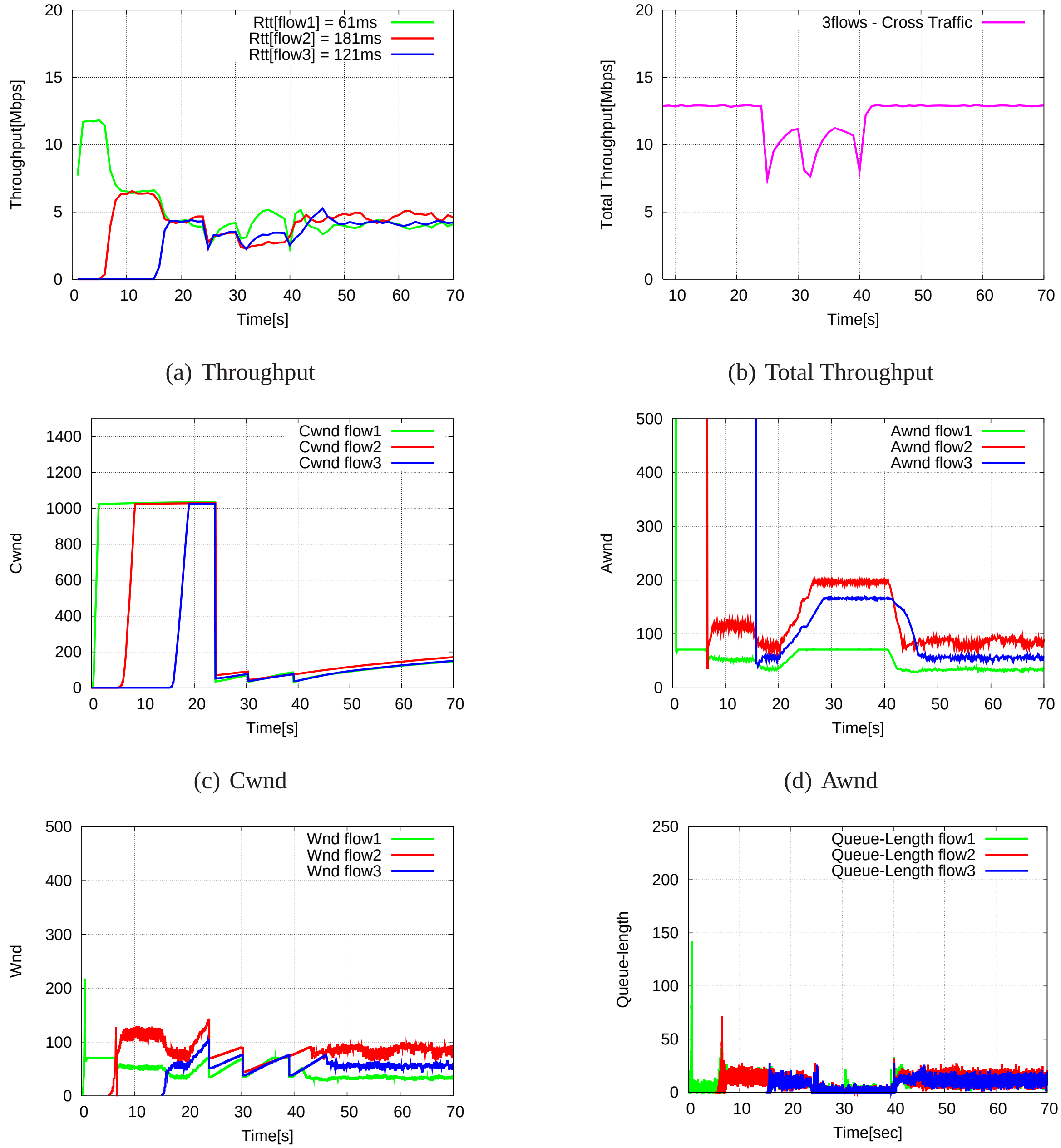
(d) Awnd

(e) Wnd

(f) Queue Length

Figure 4.15: Proposed Scheme: 2TCP flows (w/ cross traffic)

VoIP flow 1 delay goes over 150 ms for some period and shows to be inconstant (Figs. 4.12(a) and 4.13(a)). Regarding both traditional TCP NewReno and the existing scheme, they could



(a) Throughput

(b) Total Throughput

(c) Cwnd

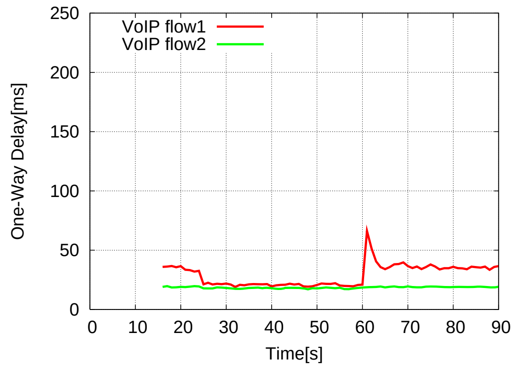
(d) Awnd

(e) Wnd

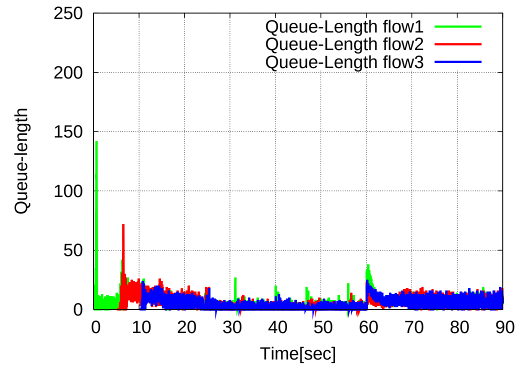
(f) Queue Length

Figure 4.16: Proposed Scheme: 3TCP flows (w/ cross traffic)

not keep the queue length short Figs. 4.12(b) and 4.13(b). In case of the existing scheme, since it could not employ a properly controlled *awnd* for each TCP flow, the *awnd* unneces-



(a) End-to-End Delay



(b) Queue Length

Figure 4.17: Proposed Scheme: VoIP/3TCP flows (w/ cross traffic)

sarily increases during the cross traffic.

Therefore, VoIP flow 1 in such circumstances does not satisfy the QoS requirements for VoIP applications according to the ITU-T recommendation Y.1541 [ITU11].

4.5 Fairness Scheme For the Bandwidth Allocation

The dynamic adaptation of *awnd* in response to the change in the network condition implemented in the previous scheme [MMT+10] makes PLC_modem1 increase and decrease *awnd* gradually based on the change in the Transmit queue length. In that case, the scheme obtained excellent throughput performance because in the studied environment was not assumed adverse situations like large RTT difference between the flows and cross-traffic. That is, the estimated RTT did not differ a lot from one flow to the other. Consequently, the dynamic adaptation occured smoothly.

However, when I bring this work to an Internet environment where there are large RTT variations between the flows caused by adverse factors such as network congestion and the existence of cross traffic. The existing scheme faces throughput unfairness problems as shown in Figs. 4.6(a) and 4.7(a). Thus, I propose a new fairness scheme for the appropriate bandwidth allocation in this heterogeneous network. The RTT estimation is also made during

if $Awnd[i] \leq Sample\_Awnd[i]$ **then**

    if $Queued\_pkt[i] \leq \frac{L}{N}$ **then**

        $Awnd[i] = Awnd[i] + \frac{2^{\rho[i]}}{Awnd[i]}$

    else

        $Awnd[i] = Awnd[i] - \frac{2^{\rho[i]}}{Awnd[i]}$

    end if

else

    $Awnd[i] = Awnd[i] - 2^{\rho[i]-1}$

end if

Figure 4.18: Proposed Algorithm for Dynamic Adaptation of *awnd*

the connection-establishment time (Fig. 4.9) and the appropriate calculation of *awnd* is the same of the previous scheme [MMT+10] shown in Eq.1.

In literature [CF04], a TCP algorithm called TCP Hybla was proposed to solve the RTT-unfairness problem in heterogeneous networks with both long and short RTT connections (e.g. satellite and wired, respectively). This algorithm modifies the New Reno's Slow Start and Congestion Avoidance to make them semi-independent of RTT. That is, It was proposed considering the fact that in TCP New-Reno the congestion window size is inversely dependent on RTT. Consequently, a flow with a shorter RTT has advantage compared to one with longer RTT.

The new scheme has been proposed based on this algorithm mainly because they gave special importance to the degradation problem of TCP throughput with New Reno standard congestion control. On the other hand, my proposed TCP rate control scheme does not change the TCP congestion control. It only makes some necessary modifications at the PLC_modem1 based on the transmission condition on the PLC. The pseudocode for the proposed adaptation scheme of *awnd* can be found in Fig. 4.18

A similar scaling factor ρ that was proposed by TCP Hybla algorithm is also applied in my scheme. However, the mechanisms under investigation in my study are different. In order to determine the ρ value, first I make use of the RTT estimation done by PLC_modem1 for each flow during the connection establishment time. Then, to obtain a normalized performance to the flow with the lowest RTT, I calculate $\rho[i]$ by using the equation $\rho[i] = \frac{RTT[i]}{RTT_{ref}}$, where RTT[i] is the RTT of each flow and RTT_{ref} is the smallest RTT among the coexisting flows, which is called the reference RTT.

Let me explain how my scheme, which is described in Fig. 4.18, works in two different cases where the ”large RTT difference” and the ”existence of cross-traffic” are addressed. First of all, I use the Eq.1 referred in [MMT+10] to calculate the initial *awnd* of each flow.

In the first case, let's assume there is a large RTT difference between two coexisting flows and there are no adverse factors that make RTT fluctuates, such as cross traffic. In such circumstances, lines 1 to 7 of the proposed algorithm (Fig. 4.18) is used. We compare the queue length condition (i.e. $Queued\_pkt[i]$, which is the number of SDU packets of the i-th flow remaining in the transmit queue) to the maximum number of SDUs in a PDU $[L]$ determined by HD-PLC standard divided by the number of TCP flows $[N]$. Then, although the estimated RTT is not updated according to the network conditions, my proposed scheme compensates for this drawback by using the following equation $\frac{2^{\rho[i]}}{Awnd[i]}$. Note that as previously explained, the scaling factor ρ is decided after the RTT estimation of each flow and not updated afterwards. That is, by using scaling factor ρ and *awnd* I can make the increasing and decreasing rate change not only proportionally with the RTT of each flow, but also gradually because *awnd* avoids scaling factor ρ from receiving a large value. Because of that, the available network resource at PLC network (i.e. Queued buffer at PLC modem 1) will be used efficiently. In this way, *awnd* is updated. That is, in case $Queued\_pkt[i] \leq \frac{L}{N}$, *awnd* is increased by $Awnd[i] = Awnd[i] + \frac{2^{\rho[i]}}{Awnd[i]}$, otherwise it is decreased by $Awnd[i] = Awnd[i] - \frac{2^{\rho[i]}}{Awnd[i]}$. As a result, the awnd is dynamically updated based on the queue length condition at PLC modem 1.

In the second case, let's assume both large RTT difference and the existence of cross traffic. In such circumstances, the RTT is expected to fluctuate considerably. The changes in the RTTs will influence on the amount of information that is sent through the network path. More specifically, when cross-traffic is addressed in the Internet environment the number of SDUs that pass through the PLC network decreases substantially. For that reason, the scheme proposed by authors in [MMT+10] increases *awnd* unnecessarily (Fig. 4.8(d)). In addition, since *awnd* determines the *wnd* as long as it is lower than *cwnd*, the entire approach becomes invalidated during the time it increases unnecessarily, thereby exceeding $Sample\_Awnd$. Thus, their approach is not well suited for such circumstances. To solve this problem, in my proposed scheme, I implemented an upper bound limit control. As indicated in lines 8 to 10 of the proposed algorithm (Fig. 4.18), if *awnd* is higher than $Sample\_Awnd$ I hold it back by using the equation: $Awnd[i] := Awnd[i] - 2^{\rho[i]-1}$. $2^{\rho[i]-1}$ shows to be an efficient method to decrease *awnd* based on the RTT of each flow because it determines the rate at which *awnd* should be decreased. That is, $\rho - 1$ is used in order to not make *awnd* decrease suddenly and consequently affect the throughput performance of the flows in the network. In details, for each flow there will be a different decreasing rate based on different RTTs of individual TCP flows. In addition, it is worth noting that the decreasing rate mentioned here is only used in case $Sample\_Awnd$ is exceeded.

As a result, I have got to keep the balance in terms of network resource allocation between the competing flows even in a critical network condition.

4.6 Performance Evaluation

We dedicate this section to examine the performance of the proposed scheme in the same environment (Fig. 4.2), where up to three TCP flows coexist on the same unstable PLC network connected to the Internet under adverse situations. In my previous work [MTTO12], I only evaluated the existence of two coexisting TCP flows. However, in this study, I present a deeper evaluation of my scheme to clarify its effectiveness. Thus, I consider not only two but the coexisting of three TCP flows and VoIP as well.

In case of 2 TCP flows, I assume that TCP flow2 starts the communication 5 s after the TCP flow1 starts. Figs. 4.14(a) and 4.15(a) show that when TCP flow2 starts the communication, there is no loss in terms of throughput compared to TCP flow1. That is, PLC_modem1 modifies *awnd* (Figs. 4.14(d) and 4.15(d)) according to the transmission conditions of PLC and passes the modified *awnd* information to the TCP sender through TCP ACK in order to make control of the window size (*wnd*) of TCP. Furthermore, In such cirmcunstances, it must be emphasized that both existing and proposed schemes keep the queue length short (Figs. 4.6(f) and 4.14(f)).

When cross-traffic is injected along the communication path in 15 s and leaves in 30 s, the upper bound limit employed by my approach works well by limiting the maximum *awnd* value necessary for each flow without degrading their throughput performance as shown in Fig. 4.15(a). Consequently, Fig. 4.15(f) when compared to Fig. 4.7(f) shows that my scheme keeps the transmit queue length stable even in a critical situation, when both large RTT differences and heavy cross-traffic are considered simultaneously. Moreover, different from the *wnd* in Fig. 4.14(e), which consists of the lower value between *cwnd* and *awnd* (Figs. 4.14(c) and4.14(d)), in the presence of cross-traffic *wnd* (Fig. 4.15(e)) is reduced to half of the minimum value between *cwnd* and *awnd* (19.2s). That is due to the packet loss with duplicate acks. We can see that such packet loss occurs with less frequency in Fig. 4.15(a) than in Figs. 4.4(a) and 4.7(a).

In this worst-case scenario, when I consider 3 TCP flows, my findings for *awnd* and *queue-length* in Figs. 4.16(d) and 4.16(f) emphasizes the validity of my scheme. After all the performance evaluation made so far, it is also fundamental to note that the objective of obtaining the throughput fairness between the coexisting flows in the above-mentioned situations did not cause side effects in terms of total throughput.

Figs. 4.3(b), 4.4(b), 4.5(b) and Figs. 4.6(b), 4.7(b), 4.8(b) show the total throughput results for TCP NewReno/SACK and the existing scheme, respectively. My findings confirm that when compared to my proposed scheme, there was no degradation in the total throughput as can be seen in Figs. 4.14(b), 4.15(b) and 4.16(b). In sum, these results have led us to conclude my proposed scheme obtained the throughput fairness without degrading the maximum communication performance.

In addition, the VoIP end-to-end delay problem addressed when 3 TCP/VoIP flows coexist in Section 5.2 was also solved as shown in Fig. 4.17(a). In Fig. 4.17(b), the new scheme keeps the transmit queue length very low and stable, even with the existence of cross traffic (20 s - 60 s). Hence, I could maintain the VoIP end-to-end delay very low during all the communication period.

Finally, I can affirm based on these results that my proposed dynamic adaptation of *awnd* determines the appropriate *wnd* (Figs. 4.14(e), 4.15(e) and 4.16(e)) according to the network conditions. That is, in case its value is lower than the *cwnd* one (Fig. 4.16(c)). As a result, the throughput fairness among multiple coexisting TCP flows is achieved efficiently (Figs. 4.14(a), 4.15(a) and 4.16(a)). Furthermore, my proposed scheme guarantees a satisfactory VoIP one-delay latency even in an unstable Internet environment.

4.7 Conclusion

In this study, I have proposed a new scheme to allocate the available bandwidth fairly when multiple TCP flows coexist over heterogeneous networks (i.e. IP over PLC Network connected to the Internet) in a realistic environment.

The contribution of this work is three-fold. First, it treats the large RTT difference that can occur between coexisting flows. Second, the proposed scheme copes with the existence of heavy cross traffic that significantly influences the RTT values, and thus yield a drastic performance imbalance. Finally, I also show that even though QoS is not taken into consideration in my study, when TCP/VoIP coexist in an unstable environment, my scheme mitigates the degradation in network performance and fulfills the necessary one-way delay QoS requirement for VoIP flows based on ITU-T Recommendation Y.1541 [ITU11]. Therefore, through the simulation results I could show that my proposed rate control scheme can efficiently cope with the coexisting of multiple and different types of flows passing through the Internet.

In this study, I addressed TCP communication and the coexistence of TCP and VoIP without QoS. However, in the Internet there are many other types of applications, such as video-on-demand (VoD) and real-time streaming. Further studies are needed to analyze whether or not my proposed approach fulfills the requirements of those applications in case QoS management was not provided.

Chapter 5

Cooperative Transmission Scheme Between PLC and WLAN to Improve TCP Performance

5.1 Introduction

Recently, the Internet-enabled home appliances like TV and HDD recorder have made people's lives more convenient. That is, once those appliances are connected to the Internet, they can have access to content-on-demand service which is provided by a server (e.g. AcTVila [AcT]). Thus, many home-networking technologies have been competing to meet the needs of the services provided to the users in a residence. Since wired networks demand the installation of new wires and that makes it costly, the candidates for providing convenient home-networking are mainly Wireless LAN (WLAN) and Power Line Communication (PLC).

WLAN, such as 802.11g, is the key technology used in indoor environment at present due to the advantages of providing connectivity without the use of cables and allowing mobility to the users. However, the increasing popularity of this technology has overcrowded spectrum in the 2.4GHz and the interference caused by some household appliances (e.g. cordless phones and microwaves) have contributed to its performance degradation.

PLC enables high speed data and voice transmission over the existing electrical wiring. Since there are outlets everywhere in a house, the cost, effort and time to deploy and maintain PLC network can be substantially lower than wired or wireless LAN. Thus, PLC emerges as a potentially desirable candidate to become the preeminent in-home network technology. However, communication performance over PLC is often degraded by physical environmental factors, such as source impedance, power level attenuation and the background noise generated by electrical appliances when plugged into the power outlet.

PLC technology has gained strength lately with its international standardization. The PLC technology under investigation in our study is HD-PLC (High-Definition Power Line Communication). HD-PLC has been approved as IEEE 1901 standard (IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications) [STD10]. Moreover, this technology has been commercialized as a PLC-Ethernet Bridge by Panasonic Network Corporation in Japan [PLC].

Both PLC and WLAN suffer from different degradation factors related to their communication media that hinder a better quality of data delivery to the end-user [LLN+02]. Therefore, in this chapter I propose a cooperative scheme between these two technologies (i.e. PLC and WLAN) by considering their communication characteristics in order to improve the TCP throughput performance in a home network. In addition, I investigate how both bidirectional flows and cross-traffic impact on the proposed scheme.

The rest of this chapter is organized as follows. Section 5.2 gives an explanation of the conducted experiments and the developed PLC network simulator. Section 5.3 investigates the end-to-end flow level performance of Ethernet over PLC. Sections 5.4 and 5.5 describe the proposed schemes and their performance evaluation. Finally, some concluding remarks are drawn in Section 5.6.

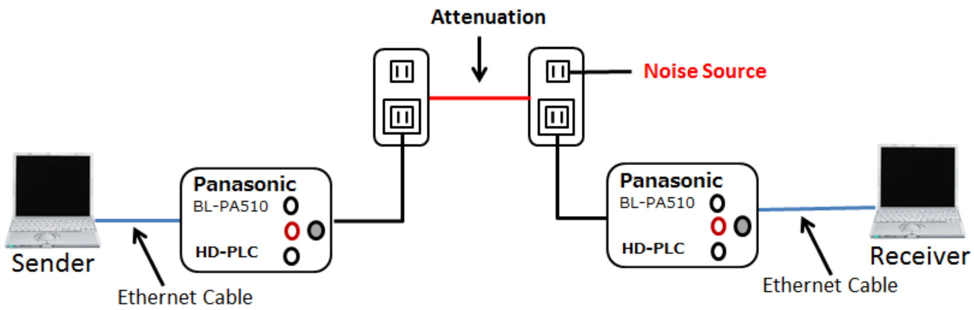


Figure 5.1: PLC Experimental Topology

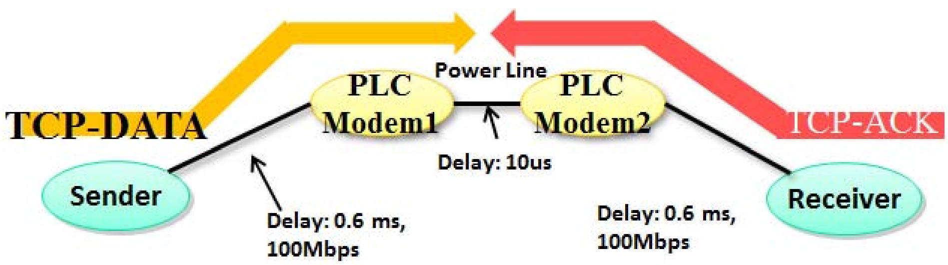


Figure 5.2: Network TopologyI

Table 5.1: PLC Simulation Parameters

Transport Protocol	TCP New Reno/SACK
Buffer Size	256 packets
Packet Size	1500 bytes
Error Pattern	Fluorescent Bulb Att:15/55dB Halogen Lamp Att:45dB
Phy_Rate (Mbps)	Fluorescent Bulb 15dB: 121.46 (Good) Fluorescent Bulb 55dB: 67.57 (Normal) Halogen Lamp 45dB: 8.36 (Poor)

Table 5.2: WLAN Simulation Parameters

Wireless LAN	IEEE 802.11g
Data Rate	54Mbps (Fixed)
WLAN AP Distance	10m (Good) 30m (Normal) 45m (Poor)
RTS/CTS	Active (Threshold: 1500Bytes)
Buffer Size	100 packets

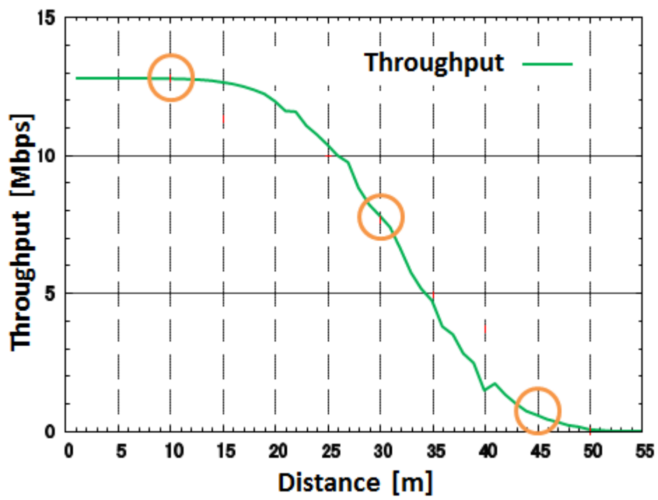


Figure 5.3: WLAN Throughput vs. distance

5.2 Experiment and Simulation of PLC and WLAN

5.2.1 PLC Environment

Fig. 5.1 shows the topology of the test-bed environment where I conducted preliminary experiments. It is worth noting that the experiment was carried out in an environment that avoids interference from outside noise to not affect the results. I added different types of attenuation (i.e. 15/35/45/55 dB) and noise-source to the power line (i.e. cell phone, inverter light, fluorescent bulb, halogen lamp) with the purpose of measuring the packet-level error rate and the PHY rate over PLC under different combinations that can occur in a house. However, in this work I evaluated power line networks in three different conditions according to the PHY data rate. That is, good, normal and poor conditions represented by fluorescent bulb 15/55dB and halogen lamp 45dB patterns, respectively, as shown in Table 5.1.

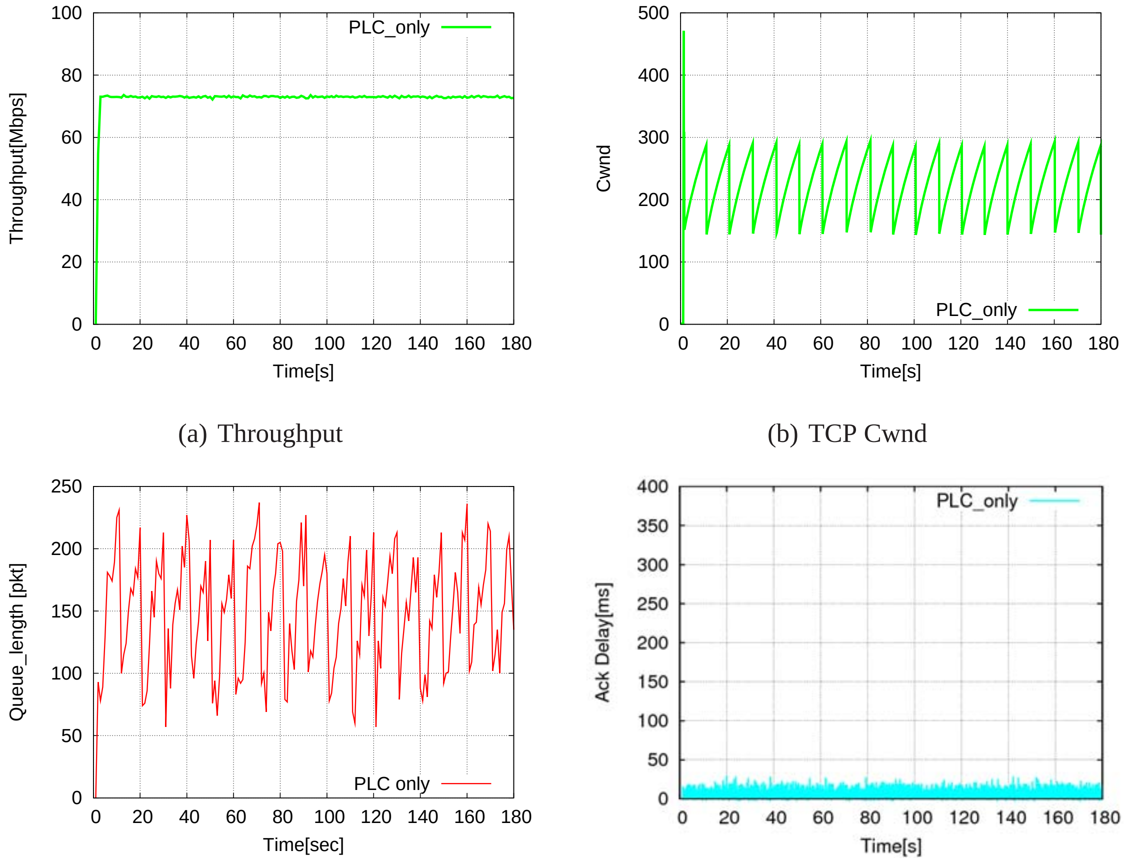
Data transmission over high-speed PLC is provided by two PLC modems (i.e. PLC sender and PLC receiver modems). I used BL-PA510, a HD-PLC based modem provided by Panasonic Systems Network Corporation, in our experiments. That is, I made experiment with real production-level PLC modem and then used the obtained data (i.e. packet-level error rate and PHY rate) in our simulator to obtain a realistic simulation setting without modifying the HD-PLC standard.

5.2.2 WLAN Environment

The performance of wireless networks is greatly affected by distance. In Fig. 5.3, I demonstrated that the TCP throughput over wireless significantly degrades as the distance increases. Then, based on the simulation findings I validated the wireless parameters (i.e. Table 5.2) that will be used afterwards in our extended NS2 network simulator module for PLC and WLAN.

5.3 TCP performance over PLC network

In this section I investigate how the physical environment of a home under good, normal and poor conditions (i.e. fluorescent bulb 15dB, 55dB and halogen 45dB, respectively) influences on the communication performance in the home network. Note that the packet error ratio I obtained during our experiments for the fluorescent bulb 15dB, 55dB and halogen lamp 45dB



(a) Throughput (b) TCP Cwnd

(c) Queue Length (d) ACK delay

Figure 5.4: PLC (Good) - Error-Pattern: Light Bulb Att:15dB

noise sources are 17, 49 and 89%, respectively. I simulated the Ethernet over PLC by using the network simulator described in the previous section. Moreover, the simulation topology I used is shown in Fig. 5.2 and the simulation parameters are listed in Table 5.1.

Fig. 5.6(a) shows that a hostile physical environment causes a drastic throughput degradation if compared to good and normal environmental conditions (Figs. 5.4(a) and 5.5(a)). That is, the poor communication environment of PLC link causes the drop of PLC-SDU more often. Then, the data retransmission mechanism employed by HD-PLC retransmits the dropped PLC-SDU as often as necessary until it is correctly transmitted to PLC modem2. Thus, different from Figs. 5.4(c) and 5.5(c) the transmit queue length stays constantly high

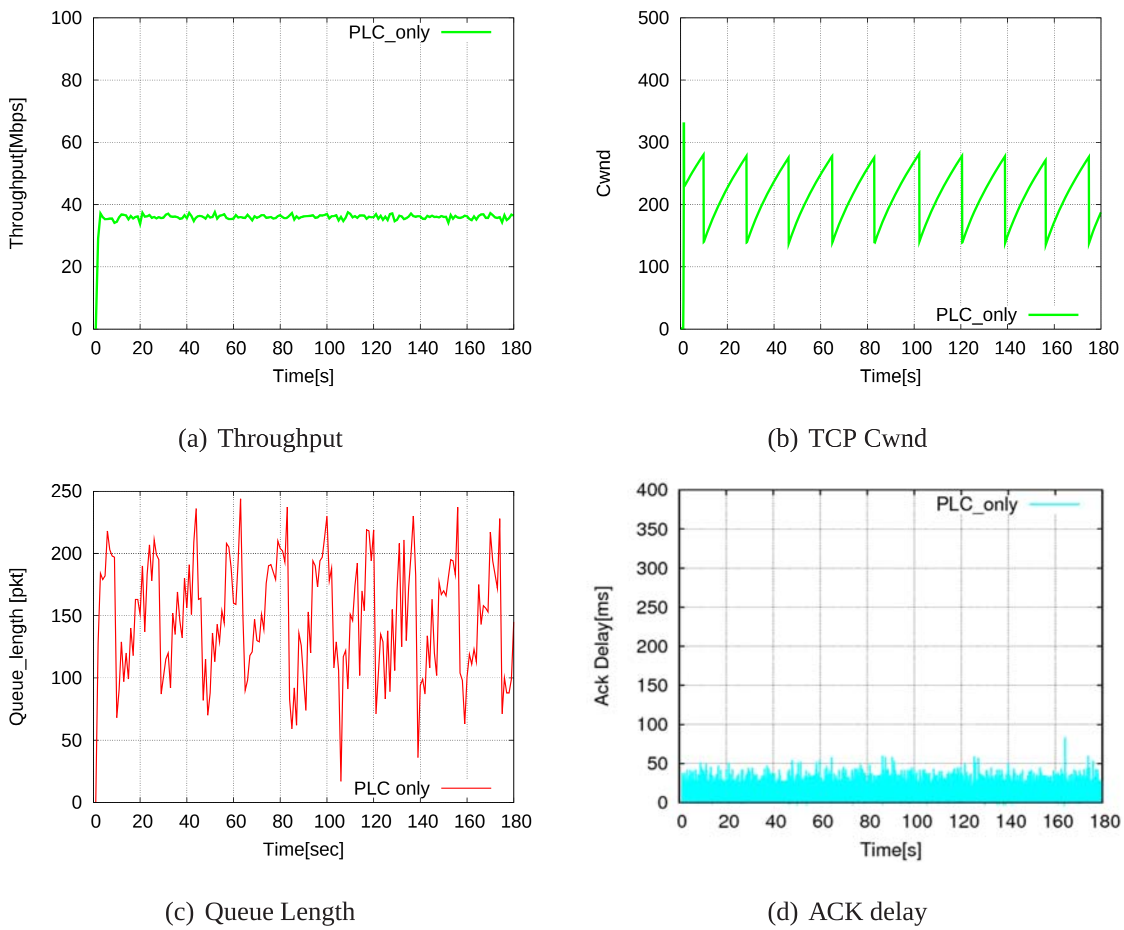
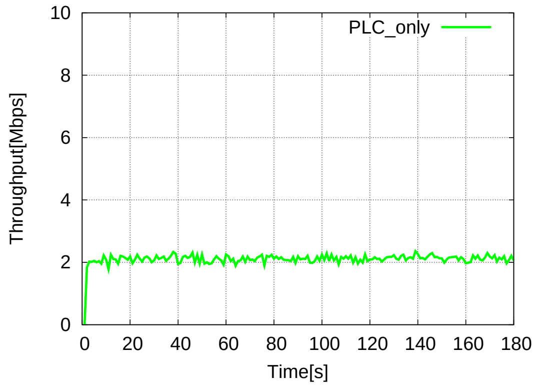
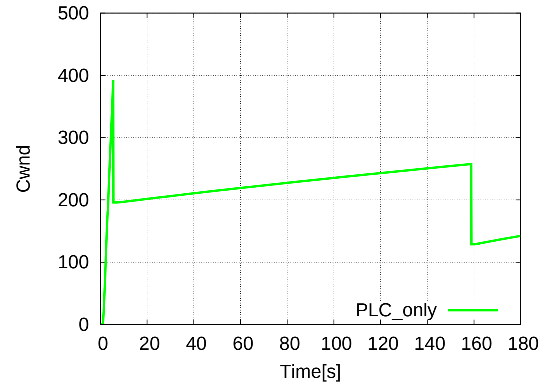


Figure 5.5: PLC (Normal) - Error-Pattern: Light Bulb Att:55dB

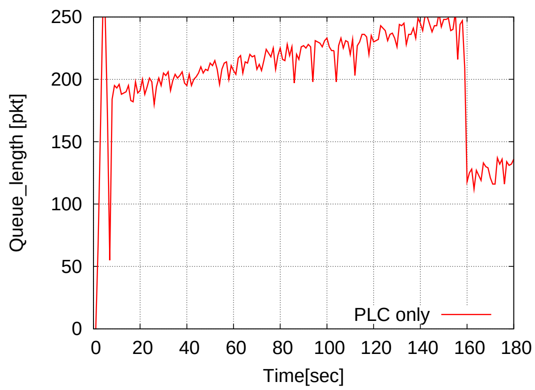
and increases slowly at PLC modem1 as shown in Fig. 5.6(c). Moreover, as the TCP-ACK are queued in the transmit queue at PLC modem it is handled as PLC-SDU and then concatenated into a PLC-PDU. For that reason, TCP-ACK will be delivered to the sender with a considerable delay (Fig. 5.6(d)). Consequently, compared to the good and normal environment (Figs. 5.4(b) and 5.5(b), respectively), the congestion window (*cwnd*) for the poor environment shown in Fig. 5.6(b) increases at a constant rate slowly. As a result, since the *cwnd* does not increase efficiently the throughput is significantly degraded.



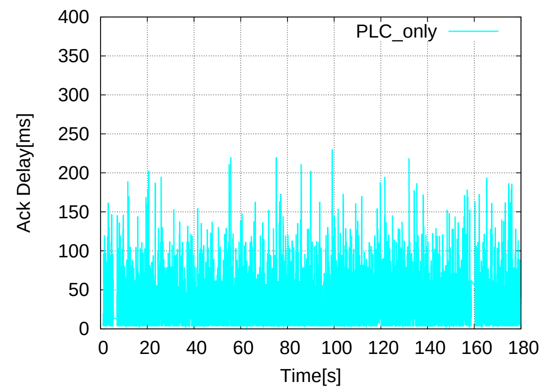
(a) Throughput



(b) TCP Cwnd



(c) Queue Length



(d) ACK delay

Figure 5.6: PLC (Poor) - Error-Pattern: Halogen Lamp Att:45dB

5.4 Static Cooperative Scheme between PLC and WLAN

Based on the results of PLC communication performance evaluation in Section 5.3, I found out that when the physical environmental conditions get worse, the TCP throughput gets considerably lower. That is because the TCP-ACK packets are concatenated as PLC-SDUs at the transmit queue of PLC modem as well. Consequently, the TCP-ACK delay in poor environment is extremely high as seen in Fig. 5.6(d). However, a huge TCP-ACK delay was not observed in neither good nor normal environmental conditions as shown in Figs. 5.4(d) and 5.5(d), respectively. Therefore, I propose a cooperative scheme between

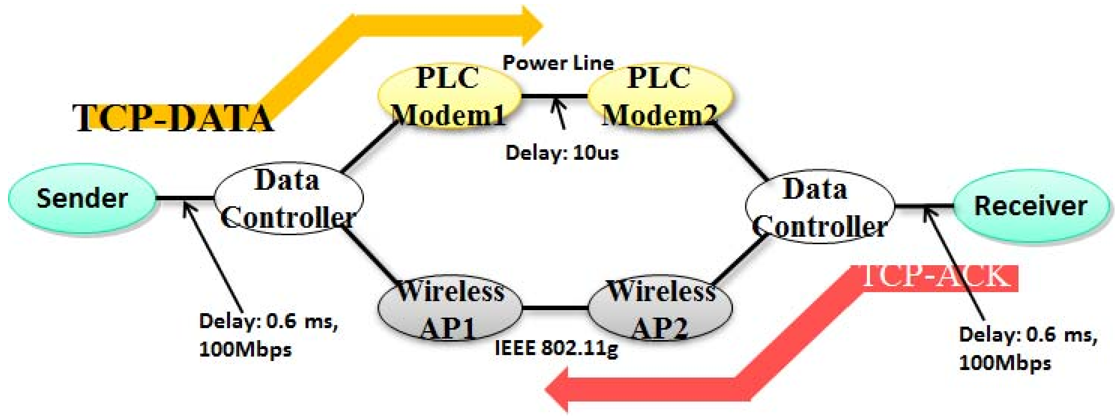


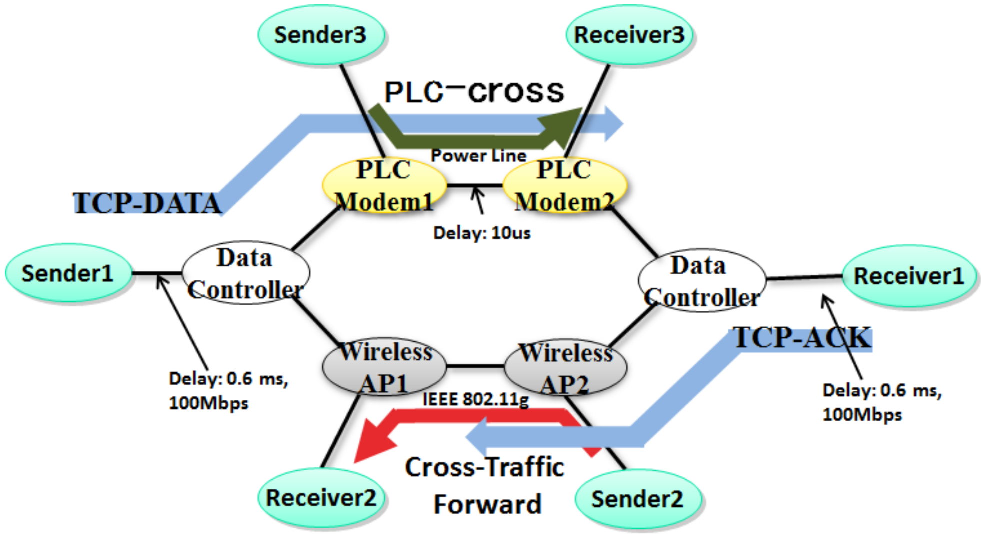
Figure 5.7: Network TopologyII

PLC and WLAN to improve the TCP performance inside a house.

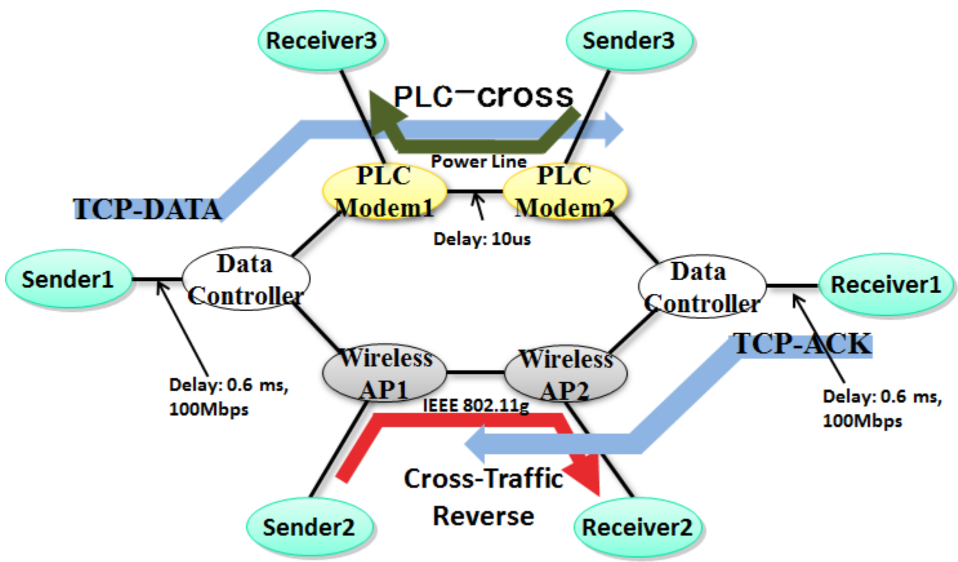
In addition, TCP inherently has a robust characteristic against TCP-ACK loss. That is, if for some reason a TCP-ACK is lost, the subsequent TCP-ACK that arrives at the TCP sender will indicate that the other previous segments were certainly received by the TCP receiver (i.e. the effect of cumulative TCP-ACK). WLAN realizes the packet transmission without performing packet concatenation. For this reason, I propose that TCP-ACK is sent through WLAN in order to avoid a high ack delay that is caused due to the excess packet concatenation mechanism and the half-duplex method employed by HD-PLC technology.

5.4.1 Performance Evaluation

I dedicate this section to evaluate the performance of the proposed scheme where PLC and WLAN are statically employed. The overall goal of this evaluation is to find out the limitations when these two technologies are cooperatively used under different network conditions in different scenarios as described below. I extended the module I had developed on NS-2 network simulator in our previous work [LLKL03]. The new module consists of the implementation of a data controller which covers not only PLC but also WLAN. In our simulation



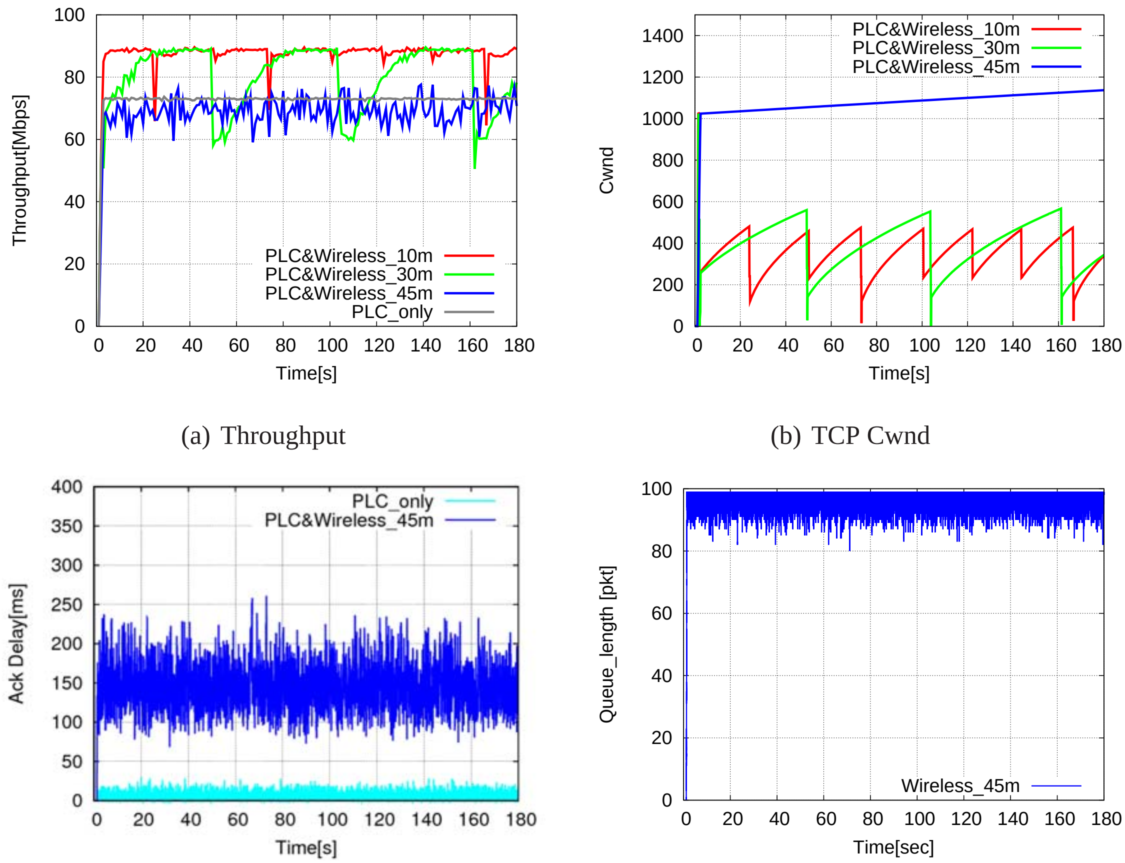
(a) One unidirectional flow (Cross-Traffic - Forward)



(b) One unidirectional flow (Cross-Traffic - Reverse)

Figure 5.8: Network Topology I

experiment I used the network topology shown in Fig. 5.7 and the simulation parameters in Tables 5.1 and 5.2.



(a) Throughput

(b) TCP Cwnd

(c) ACK delay: PLC vs PLC/WLAN

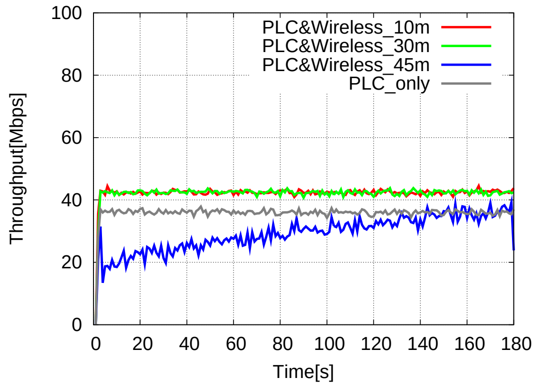
(d) Queue Length WLAN AP2

Figure 5.9: PLC/WLAN - Error-Pattern: Fluorescent Bulb Att:15dB

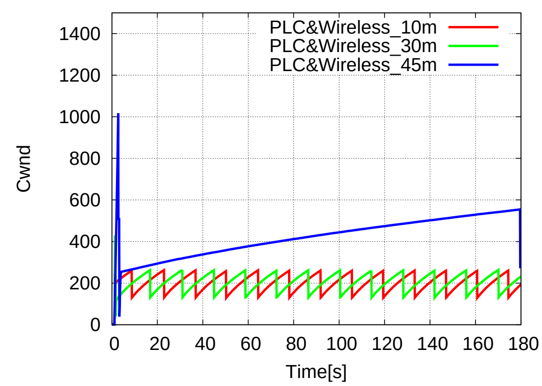
Scenario I: PLC network condition is good/normal

WLAN network condition is good/normal Fig. 5.9(a) shows that when the physical environment is good (i.e. Fluorescent Bulb Att:15dB) and the WLAN conditions are either good or normal (i.e. 10m, 30m, respectively), the static cooperative use of PLC/WLAN is superior in terms of TCP throughput performance compared to PLC only (i.e. when only PLC environment is used).

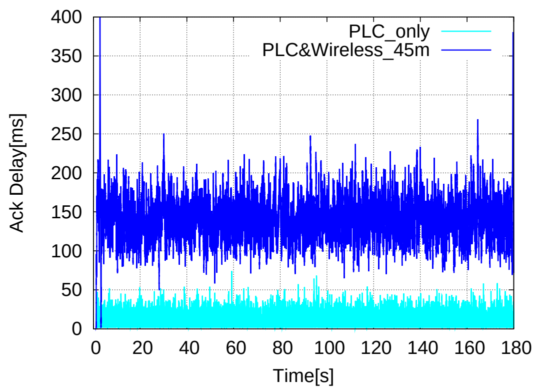
WLAN network condition is poor However, when network condition in WLAN becomes poor (i.e. 45m), the queue length in WLAN AP2 gets fully occupied right after the commu-



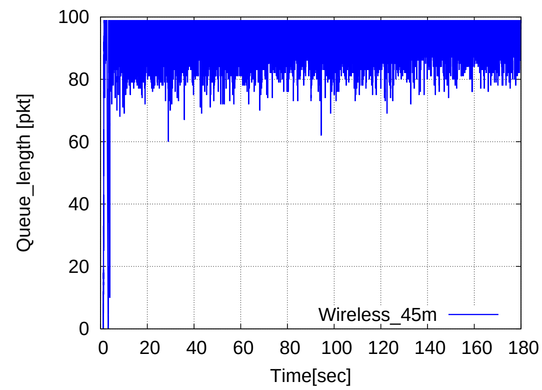
(a) Throughput



(b) TCP Cwnd



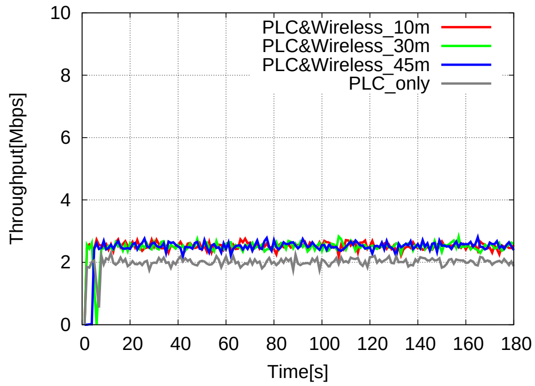
(c) ACK delay: PLC vs PLC/WLAN



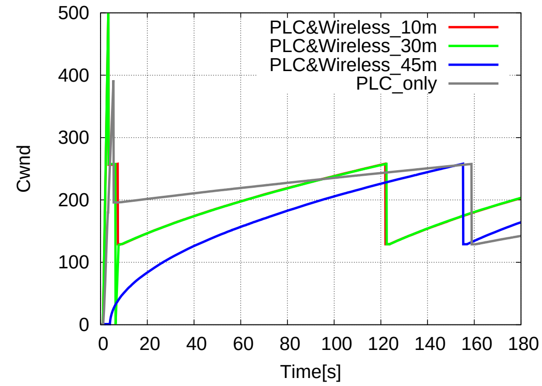
(d) Queue Length WLAN AP2

Figure 5.10: PLC/WLAN - Error-Pattern: Fluorescent Bulb Att:55dB

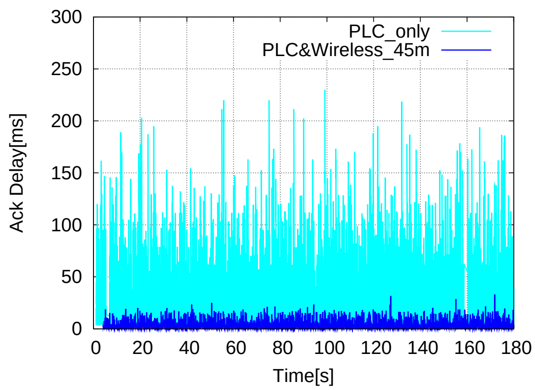
nication starts (Fig. 5.9(d)). Because of that, the TCP-ACK delay gets really higher than the one measured for PLC environment (Fig. 5.9(c)). Consequently, as shown in Fig. 5.9(b), the *cwnd* increases slowly thereby causing a lower TCP performance than when only PLC is considered. Note that I also obtained a not good TCP throughput performance in case the physical environment is normal (i.e. Fluorescent Bulb Att: 55dB) and the WLAN network condition is poor (Fig. 5.10(a)). The reason is similar to the one above explained when the physical environment is good. That is, once the physical environment is good or normal the packets sent through its environment do not need to be retransmitted repeatedly like in a severe physical environment (i.e. Halogen lamp Att:45dB). Thus, the data is smoothly



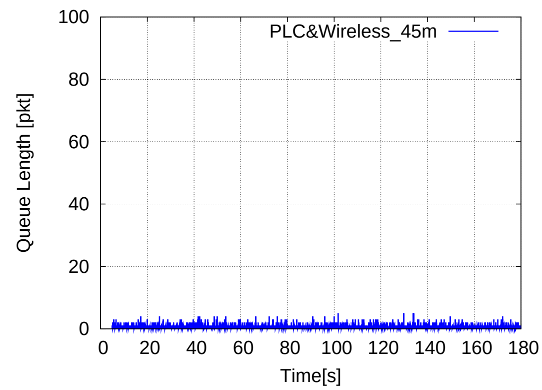
(a) Throughput



(b) TCP Cwnd



(c) ACK delay



(d) Queue Length WLAN AP2

Figure 5.11: PLC/WLAN - Error-Pattern: Halogen Lamp Att:45dB

transmitted and soon overwhelm the queue buffer at WLAN AP2 with the TCP-ACK packets during all the communication period (Fig. 5.10(d)). Consequently, there is a significant delay in delivering TCP-ACK to the sender (Fig. 5.10(c)). As a result, the *cwnd* shown in Fig. 5.10(b) does not increase efficiently causing a drastic low in TCP throughput performance.

Scenario II: PLC network condition is poor

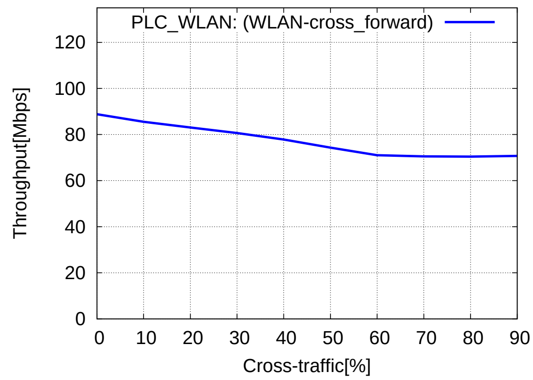
WLAN network condition is good/normal Once PLC environment is considered to be poor, the PHY throughput at PLC environment is considerably low. For that reason, the amount of data sent through PLC is small. Then, the amount of TCP-ACK sent through WLAN is also reduced. As a result, the thoughput performance over good and normal WLAN network conditions are basically the same (Fig. 5.11(a)).

WLAN network condition is poor Fig. 5.11(a) shows that when both the physical environment (i.e. Halogen lamp Att:45dB) and the network condition in WLAN are poor, they achieve higher throughput than when only PLC is used, possibly because the transmit queue at PLC modem1 is constantly high (Fig. 5.6(c)) caused by the frequent packet retransmission. Because of that, the TCP-ACK delay is higher than then the static cooperative use of PLC/WLAN (Fig. 5.11(c)). Thereby, the *cwnd* for PLC increases too slowly (Fig. 5.11(b)) .

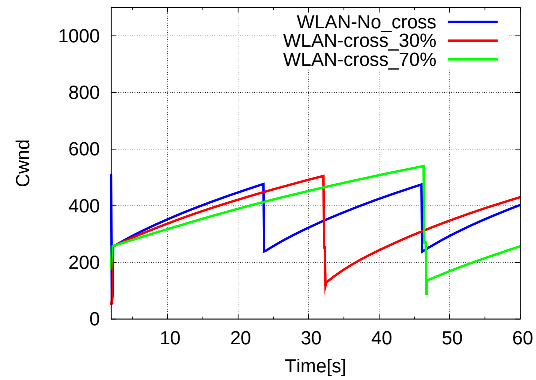
Scenario III: One unidirectional flow with cross-traffic on WLAN

Cross traffic - Forward direction Fig. 5.12(a) shows that when the physical environment is good (i.e. Fluorescent Bulb Att:15dB) and the WLAN condition is good (i.e. 10m) in an environment where the existence of cross-traffic in a forward direction (i.e. the cross-traffic flows from sender 2 to receiver 2 as seen in Fig. 5.8(a)) is also considered on WLAN environment, the cooperative use of PLC/WLAN achieves a high TCP throughput performance during all the communication period.

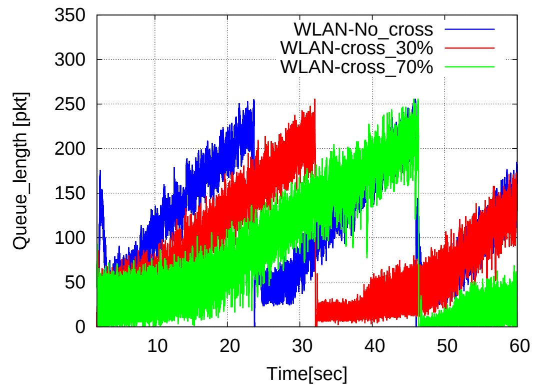
Although a great number of TCP-ACK packets were dropped at WLAN AP2 because of the existence of cross-traffic at WLAN (Fig. 5.12(e)), the packets sent from WLAN AP2 were received at TCP sender with no packet-loss on WLAN link (Fig. 5.12(d)), that is due to the fact that as both TCP-ACK packets and UDP packets are sent on the same direction, collision in the WLAN link does not occur. Because of that, the queuing delay at WLAN AP2 does not increase drastically even with the existence of heavy cross traffic (Fig. 5.12(f)) thereby not causing large variations in RTT (Fig. 5.12(g)). Furthermore, in traditional TCP the congestion control mechanism consists of two phases: slow start and congestion avoidance. At slow start phase, TCP doubles the default initial *cwnd* at every RTT. While at the congestion avoidance phase, TCP increases the *cwnd* linearly. That is, *cwnd* increases the



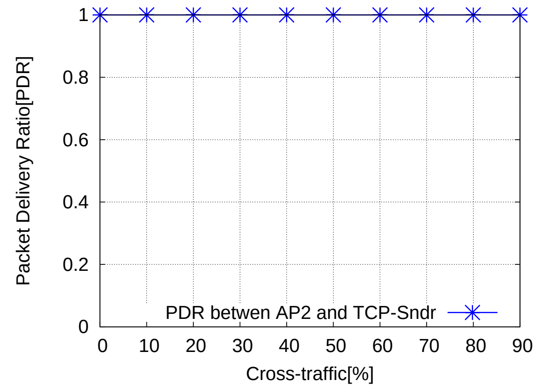
(a) Throughput



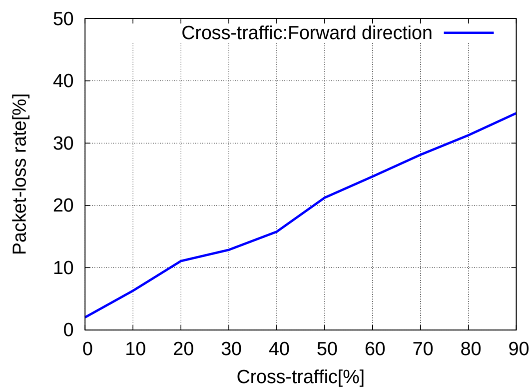
(b) TCP Cwnd



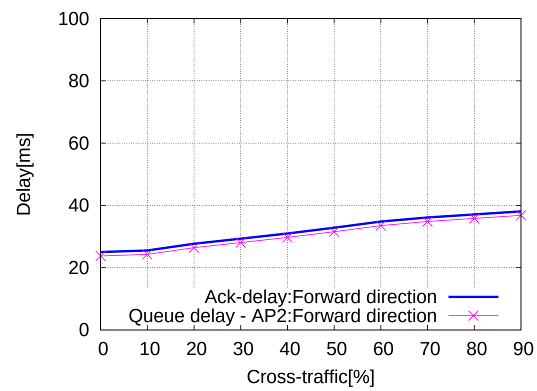
(c) Queue Length



(d) Number of Packets - WLAN AP2

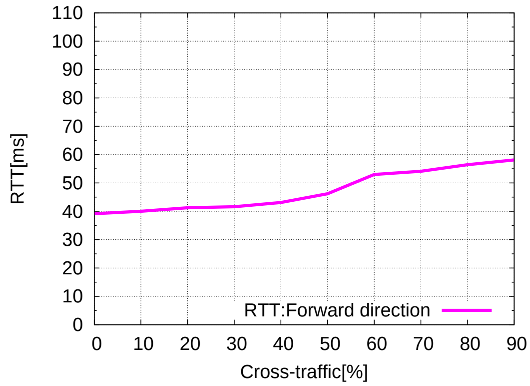


(e) Packet-loss rate - WLAN AP2



(f) Ack Delay - Forward Direction

rate according to the RTT. As a result, as shown in Figs. 5.12(b) and 5.12(c) respectively, the *cwnd* increases efficiently and the queue length at PLC-modem1, which is occupied by



(g) RTT - Forward Direction

Figure 5.12: One unidirectional flow (Forward direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

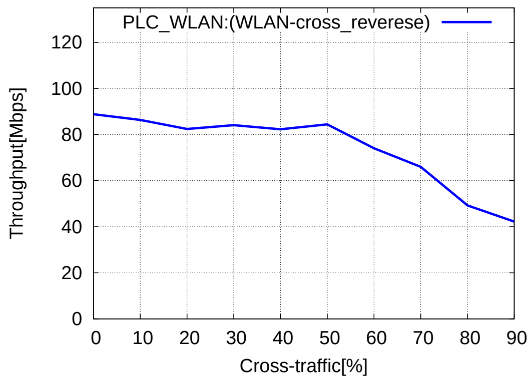
TCP-DATA packets, is occupied considerably fast even when 70% of cross-traffic is injected on the WLAN path. Thus, there is no drastic low in TCP throughput performance even under the existence of heavy cross-traffic.

Cross traffic - Reverse direction In order to make a thorough investigation of the proposed scheme in many different circumstances, the cross-traffic in reverse direction, which is sent from sender 2 to receiver 2 as shown in Fig. 5.8(b), was also considered in WLAN communication environment. Through Fig. 5.13(a), it is important to note that when the cross-traffic load reached 60% or more of the total available bandwidth of the WLAN link in such circumstances, a higher performance degradation was observed when compared to the one in forward direction. That is probably because WLAN is being overcharged with a high collision rate caused due to the CBR cross-traffic in reverse direction of the TCP-ACK packets thereby causing a great number of TCP-ACK packet losses on WLAN link (Fig. 5.13(e)). In addition, note that the packet delivery ratio from the WLAN AP2 to the TCP sender substantially falls off as the cross-traffic load increases (Fig. 5.13(d)). It seems likely that this is the reason why the number of packet retransmissions in WLAN increases and the queuing delay at WLAN AP2 gets higher as well (Fig. 5.13(f)).

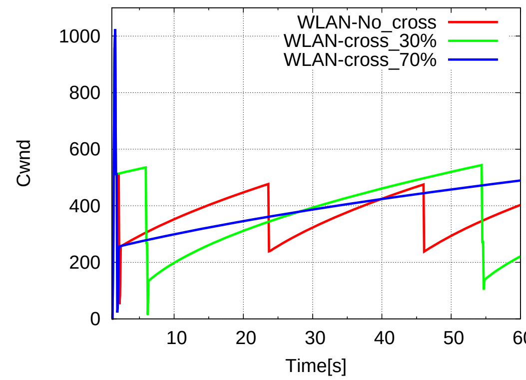
As far as I am aware such increase in the waiting time at WLAN AP2 results from the retransmission of packets in carrier sense multiple access with collision avoidance (CSMA/CA), which is delayed based on the amount of time derived from the slot time and the number of attempts to retransmit them. That is, CSMA/CA tries to prevent collisions by exploiting the random waiting time.

In details, regarding the WLAN 802.11g technology, which is the one I make use of in our work, the initial and maximum contention window *(CW)* are 15 and 1023 slots respectively and the slot duration is 9 μs. Moreover, in case of TCP-ACK, which is packet of short size, the retransmission limit is 7 times [WLA99]. Then, considering the exponential backoff algorithm employed by 802.11 technologies, after n collisions, the *CW* is chosen by a random number between 0 and $2^n - 1$ and then multiplied by the slot time (i.e. $CW = (2^n - 1) * slottime$). Based on that, the average and maximum exponential backoff time for the maximum number of 7 retransmissions are 9.1 ms and 18.2 ms, respectively. In addition, these retransmissions of HOL (Head of Line) packet further increase the waiting time of all the packets waiting behind HOL packet, i.e., due to HOL blocking. That explains why the ack delay and the RTT shown in Figs. 5.13(f) and 5.13(g) increase as the number of retransmission attempts increases.

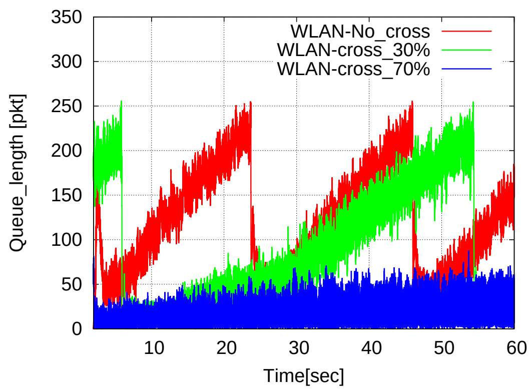
Consequently, the *cwnd* does not increase efficiently in case of 70% of cross-traffic as shown in Fig. 5.13(b), because of the frequent TCP-ACK losses on WLAN link. Thus, the TCP-DATA packets do not occupy much of the queue length at PLC-modem1 (Fig. 5.13(c)). However, even if there is a high packet loss rate on WLAN link caused by the existence of cross-traffic, our proposed scheme attains an excellent throughput performance unless RTT increases drastically.



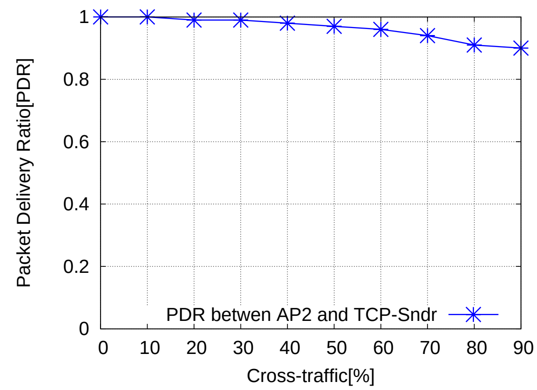
(a) Throughput



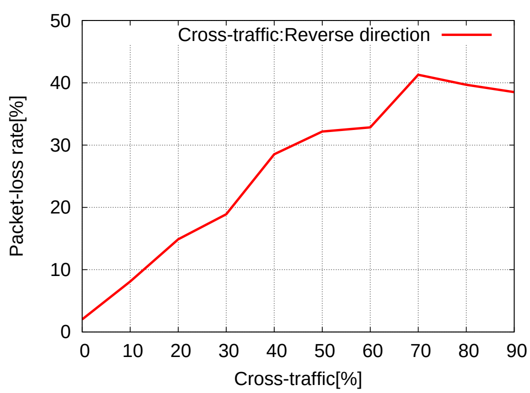
(b) TCP Cwnd



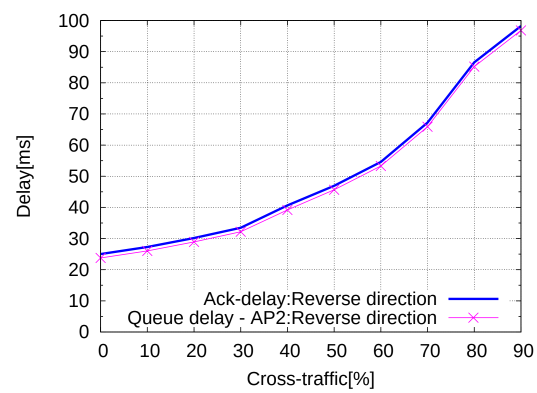
(c) Queue Length



(d) Number of Packets - WLAN AP2



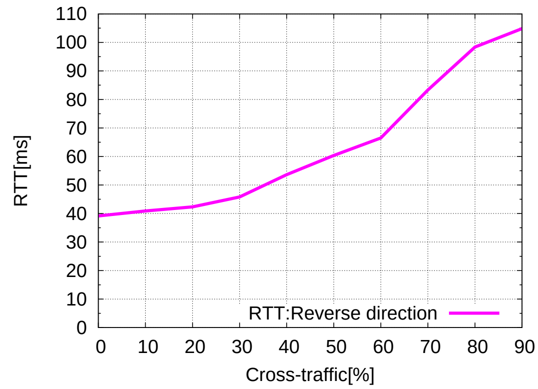
(e) Packet-loss rate - WLAN AP2



(f) Ack Delay - Reverse Direction

Scenario IV: One unidirectional flow with cross-traffic on PLC

Cross traffic - Forward direction It was also evaluated how the cross-traffic on the PLC environment in forward direction (i.e. the cross-traffic flows from sender 3 to receiver 3 as



(g) RTT - Reverse Direction

Figure 5.13: One unidirectional flow (PLC Cross-Traffic Reverse direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

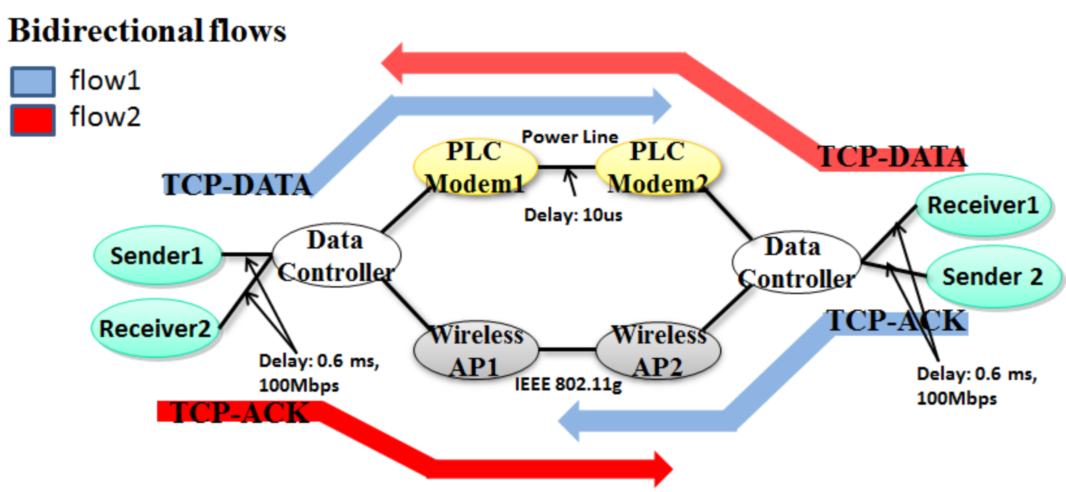
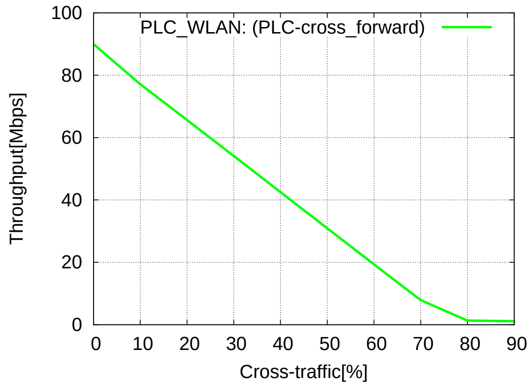


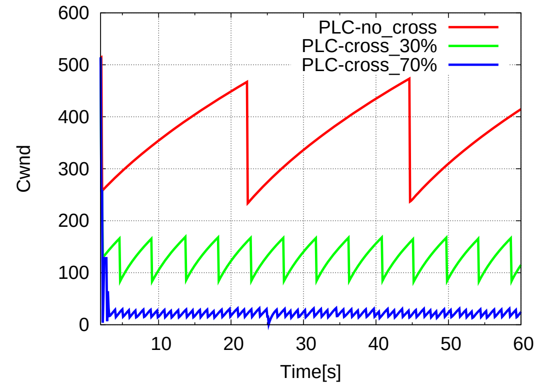
Figure 5.14: Network Topology II

shown in Fig. 5.8(a)) effects the throughput performance of the PLC/WLAN hybrid proposed scheme. Fig. 5.15(a) shows that there is a drastic decrease on the throughput performance right after the communication starts. We believe that the existence of cross-traffic in forward direction contributes to the transmit queue at PLC modem1 to be constantly high and overwhelmed (Fig. 5.15(c)). Consequently, as in the proposed scheme the PLC environment is used to send the TCP-DATA, most of these packets will be discarded and the TCP-sender halves *cwnd* multiple times (Fig. 5.15(b)). As a result, the *cwnd* does not have an efficient increase causing a drastic low in TCP throughput performance proportionally to cross-traffic load on the PLC network path.

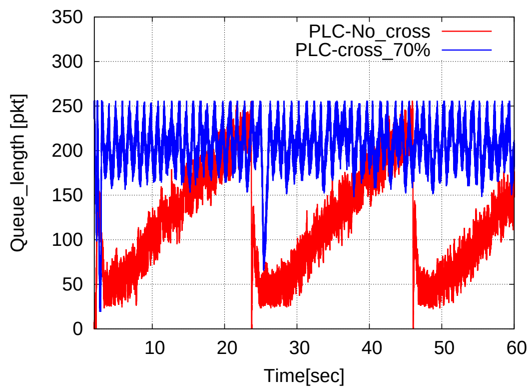
Cross traffic - Reverse direction Different from the cross-traffic in forward direction on PLC path, which caused a constant throughput performance degradation, when the cross-traffic is sent on reverse direction (Fig. 5.8(b)) and its traffic load reaches 40% of the available bandwidth of PLC link the throughput remains stable (Fig. 5.16(a)). As mentioned in Section 2.1.2, because of the half-duplex transmission scheme that HD-PLC employs, the transmission rights to all the PLC modems switch at every 50 μs and the utilization of the available bandwidth of PLC network is effected by the way PLC-PDU is dispatched (i.e. the arrival of 31 SDUs or the expiration of 5ms). When a certain amount of cross-traffic comes from an opposite direction, the transmit queue of PLC modem 2 will be constantly high and consequently the transmission right is certainly given to it. Although it will promptly send the 31 SDUs already loaded in the queue (i.e. one PDU), the transmission right surely returns to PLC modem1. Because of that, as shown in Fig. 5.16(b), the *cwnd* increases efficiently even under a severe network environment (i.e. 70% of cross-traffic) thereby occupying the queue length at PLC modem1 fastly (Fig. 5.16(c)). As a result, the throughput performance is kept constantly high and it does not lower than half of its total throughput unless 30% or more of cross-traffic is injected on the PLC communication path.



(a) Throughput



(b) TCP Cwnd

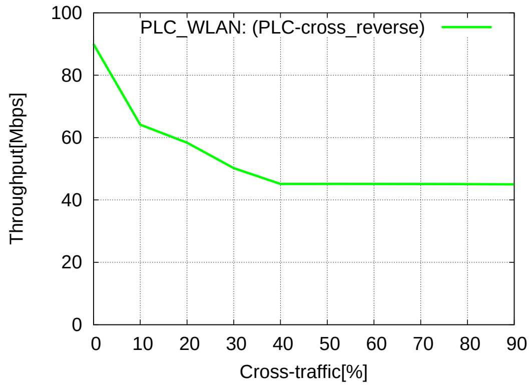


(c) Queue Length

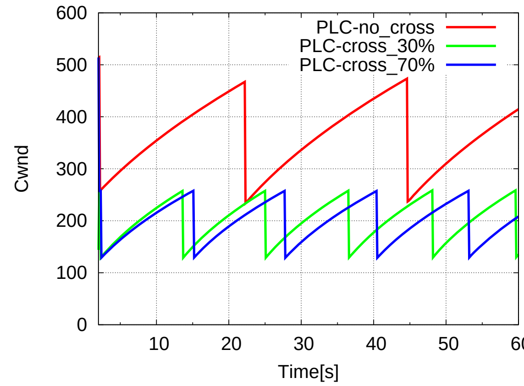
Figure 5.15: One unidirectional flow (PLC Cross-Traffic Forward direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

Scenario V: Two bidirectional flows

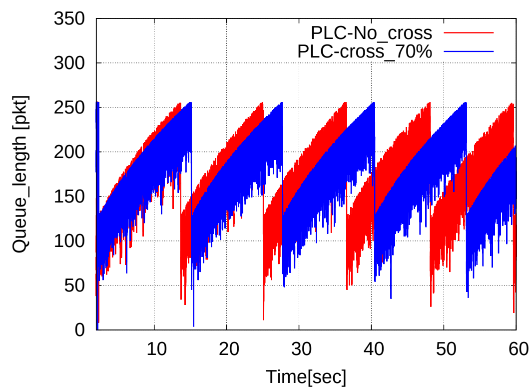
Taking into account the fact that two flows can coexist over PLC network in a bidirectional direction, in this section I show how two competing flows consume the network bandwidth based on network topologies shown in Fig. 5.14 and the simulation parameters in Tables 5.1 and 5.2. Figs. 5.17(a) and 5.17(b) show that the throughput performance in PLC/WLAN for each flow is reduced to half if compared to the one obtained in case of only one flow under same network conditions. Furthermore, it is interesting to note that the proposed



(a) Throughput



(b) TCP Cwnd



(c) Queue Length

Figure 5.16: One unidirectional flow (PLC Cross-Traffic Reverse direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

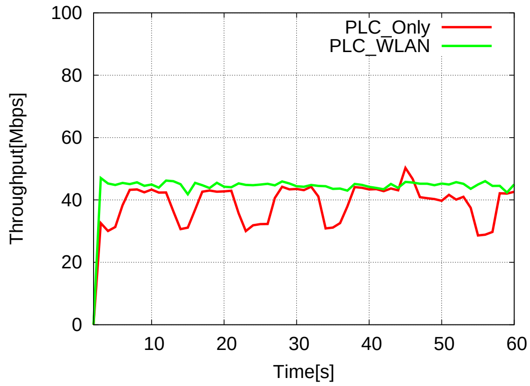
PLC/WLAN cooperative scheme outperforms the PLC-only throughput performance in this case as well. As expected, when PLC network condition is good, although PLC technology employs the packet concatenation mechanism and TCP-ACK is also handled as PLC-SDU, the *cwnd* increases efficiently (Figs. 5.17(c) and 5.17(d)). However, as shown in Figs. 5.17(e) and 5.17(f) the queue-length at both PLC modems tends to queue more packets thereby causing a slight performance degradation compared to when PLC and WLAN are cooperatively used.

This result has further strengthened the validity of our scheme when multiple flows coexist in bidirectional way by fairly allocating the available network resource between them.

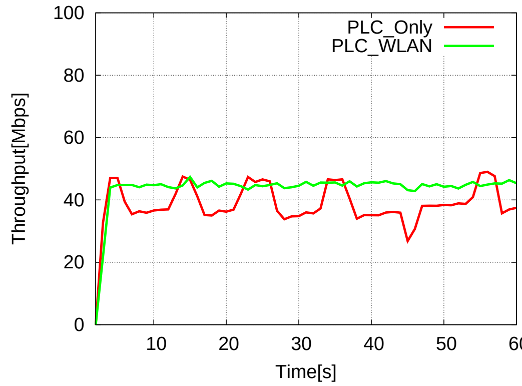
5.5 Dynamic Cooperative Scheme between PLC and WLAN

After a thorough evaluation of the proposed static cooperative transmission scheme under practical network environment the findings of this study shown in scenarios III, IV and V have led to conclude that despite of the fact that CBR cross-traffic was injected on the WLAN link and the coexistence of two bidirectional flows, the scheme showed to be very effective in terms of end-to-end throughput performance and robust against TCP-ACK packet losses. On the other hand, the results obtained in scenarios I and II showed that in two situations where the WLAN is poor and the PLC is either good or normal, the TCP performance is lower than when only PLC is deployed. These findings point toward the idea that a dynamic scheme would be indispensable due to the fact that both PLC and WLAN network conditions can change frequently. Therefore, I proposed a dynamic cooperative scheme between PLC and WLAN.

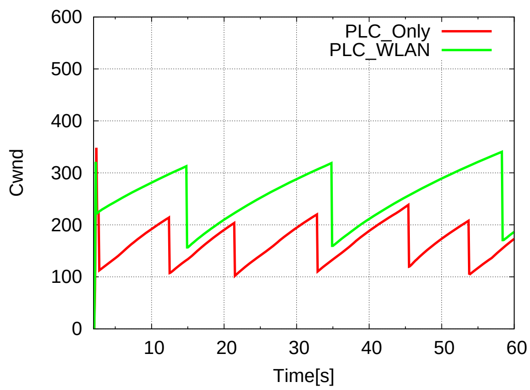
The dynamic process of choosing which communication media will be used to send TCP-ACK is done by monitoring the maximum number of retransmission of the ACK packet in WLAN every second during the communication period. That is, if the maximum retransmission times (i.e. 6 times) occurs successively exceeding the threshold of α times, which is a parameter determined in this chapter as part of our scheme, TCP-ACK is then transmitted through PLC because it is assumed that the network condition in WLAN is very poor. Note that during this time, the WLAN continues to be monitored every second during the communication period. Then, as soon as the communication media becomes feasible to send data again, the TCP-ACK will be sent through WLAN. More details on why α times was chosen as our threshold parameter will be given in the next section.



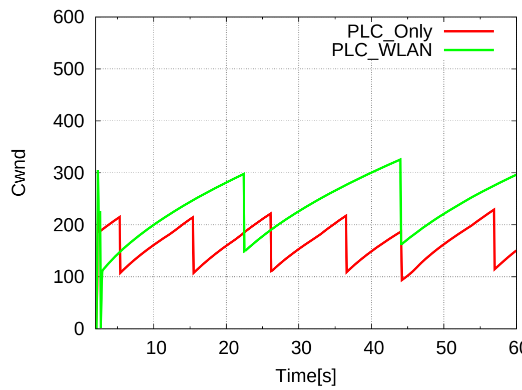
(a) Flow1: Throughput PLC/WLAN



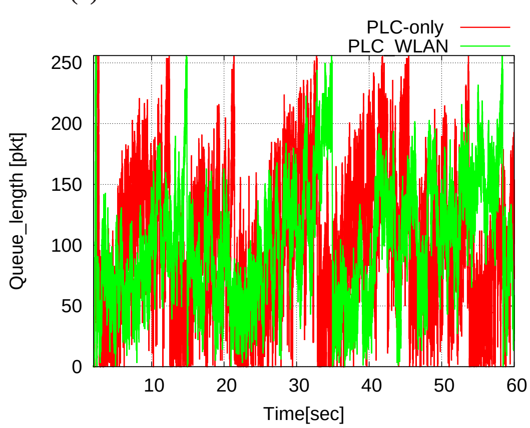
(b) Flow2: Throughput PLC/WLAN



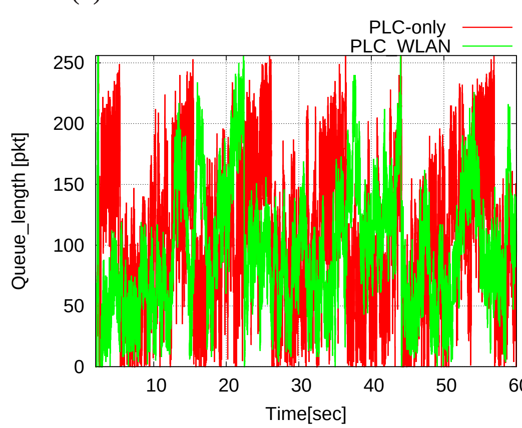
(c) Flow1: Cwnd PLC/WLAN 10m



(d) Flow2: Cwnd PLC/WLAN 10m



(e) Flow1: Queue-Length PLC Modem1



(f) Flow2: Queue-Length PLC Modem2

Figure 5.17: Two bidirectional flows - Error-Pattern: Light Bulb Att:15dB WLAN 10m

5.5.1 Considerations concerning PLC/WLAN switching condition

Based on the results of the static cooperative use of PLC and WLAN, I made a thorough investigation of what conditions I could take into consideration to decide what communication media I should use as the most appropriate one in a way TCP-ACK achieves the sender without too much delay.

What I have learned from these detailed investigation results is that when physical environment is either good or normal (i.e. Fluorescent lamp Att:15dB, 55dB) and WLAN condition is poor (i.e. 45m), the maximum number of packet retransmissions (i.e. 6 times) occur successivelly during all the communication period as seen in Fig. 5.19(c). That indicates that packets are constantly discarded causing a substantial TCP throughput degradation. To have a more precise information of how often the number of maximum number of packet retransmission occurs in such circumnstances I realized repeated simulations (i.e. 5 runs) and as shown in Figs. 5.19(d) and 5.20(a), in such networks more than 30 packets are discarded in 1-second period interval due to their maximum number of retransmissions. However, when both physical enviroment and WLAN conditions are poor (i.e. halogen lamp Att:45dB and 45m, respectively), the number of maximum packet retransmissions occurs intermittently but does not exceed 15 times in a 1-second period interval (Fig. 5.20(b)). I believe that due to the low PHY throughput at poor physical environment the amount of data that passes through WLAN AP2 is reduced. Thus, the queue buffer at WLAN AP2 is constantly low (Fig. 5.11(d)).

Furthermore, I also examined the maximum number of packet retransmissions when physical environment is good and WLAN condition is either good or normal (i.e 10m and 30m). Figs. 5.19(a) and 5.19(b) show that in such circumstances, maximum packet retransmissions at WLAN AP barely occurs. Thus, on the basis of these results I opted for determining the successive number of 15 times of maximum packet retransmissions in 1-second period interval at WLAN AP as the threshold parameter (i.e. α equals 15) to change the TCP-ACK transmission from WLAN to PLC environment.

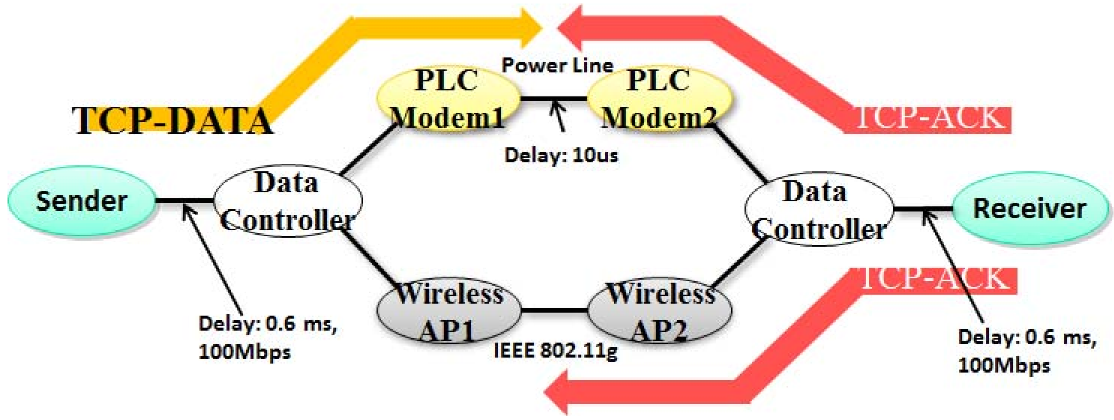
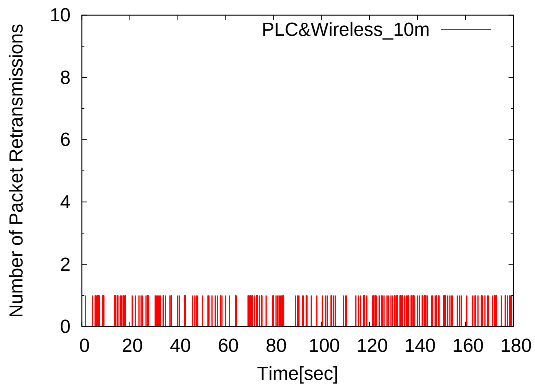


Figure 5.18: Network TopologyIII

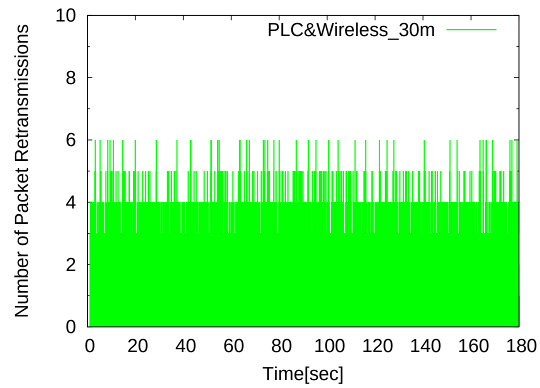
5.5.2 Considerations concerning the Proposed Dynamic Scheme

In order to evaluate the proposed scheme I made use of the network topology shown in Fig. 5.18 and the simulation parameters in Tables 5.1 and 5.2. I consider two cases to perform the evaluation of the proposed scheme.

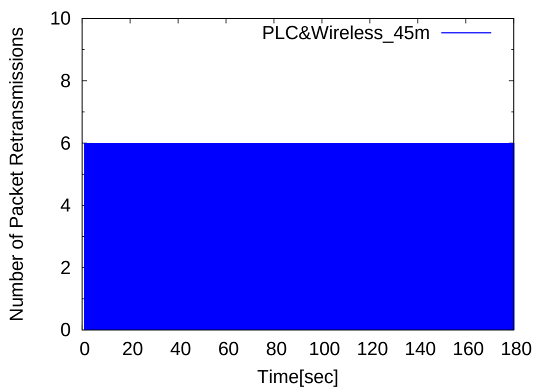
In the first case, let's assume that the physical environment is good and the network condition in WLAN starts good and becomes poor at 30 seconds. Consequently, TCP throughput drastically decreases (Fig. 5.21(a)). In the second case, I consider the physical environment to be normal and when the WLAN network condition turns to be poor at 30 seconds, TCP throughput also substantially falls off (Fig. 5.21(b)). However, when our proposed scheme is employed in both cases, the scheme detects when WLAN is unfeasible to send data and dynamically changes the communication media from WLAN to PLC, thereby improving throughput performance considerably by choosing the appropriate communication media to send TCP-ACK.



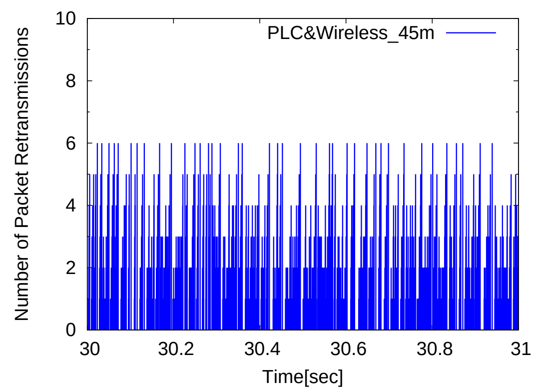
(a) Number of Packet Retransmissions



(b) Number of Packet Retransmissions

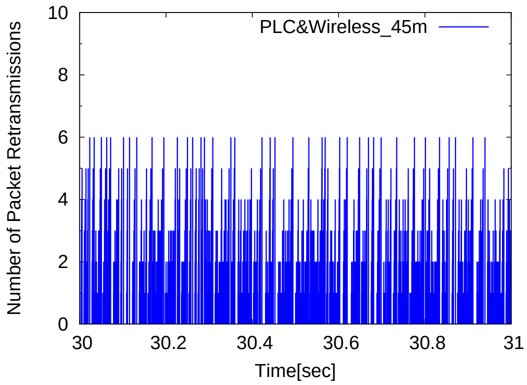


(c) Number of Packet Retransmissions

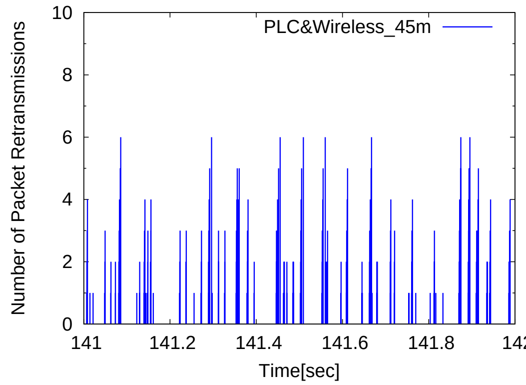


(d) Number of Packet Retransmissions 30s31s

Figure 5.19: PLC/WLAN - Number of Packet Retransmissions: Fluorescent Bulb Att:15dB

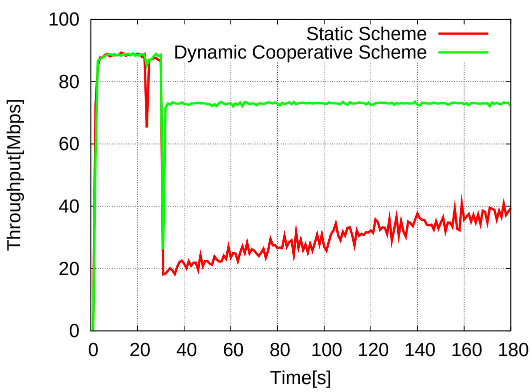


(a) Number of Packet Retransmissions 30s31s

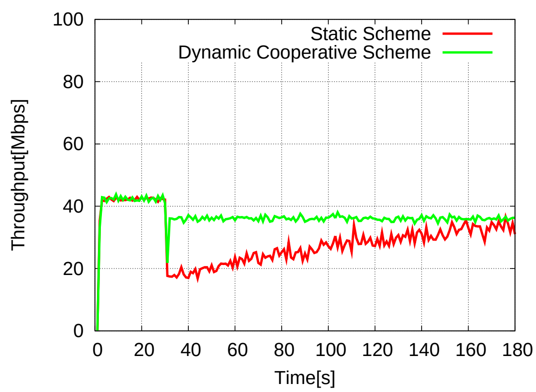


(b) Number of Packet Retransmissions 141s142s

Figure 5.20: PLC/WLAN - Number of Packet Retransmissions: Fluorescent Bulb Att:55dB (a) and Halogen lamp Att:45dB (b)



(a) PLC noise source: Fluorescent Bulb 15dB and WLAN: 45m



(b) PLC noise source: Fluorescent Bulb 55dB and WLAN: 45m

Figure 5.21: Dynamic Cooperative Scheme Between PLC/WLAN

5.6 Conclusion

The contributions of this study are as follows. First, I have evaluated the end-to-end TCP performance on PLC and WLAN under different network conditions through experiments and simulations. Then, considering that both technologies have significant scope for improvement I proposed a static cooperative scheme between PLC and WLAN to improve the TCP performance inside a house. Nevertheless, in some network conditions where the WLAN became poor while the PLC was either good or normal the TCP throughput suffered a huge performance degradation. Because of that, I proposed a dynamic cooperative scheme between PLC and WLAN based on their network conditions. At last, I have implemented a new simulation module in NS-2 that combines the two networks and through the simulation results I have demonstrated the efficiency and the limitations as well of the proposed schemes.

Chapter 6

Concluding Remarks

The permanent growth of the use of Internet over the years has led to the need of the development of new solutions to support the great growth of data traffic and the demands of new applications in terms of throughput, propagation delay and low bit error rate. Although WLAN is the most widely used in-home network technology nowadays, it has shown limitations to meet the requirements to deliver applications such as streaming of audio and video with high quality to the end-user because of its limited wideband and performance. However, with the ratification of the IEEE 1901 standard, PLC has emerged as a promising in-home network technology mainly due to its high data rate and easy connectivity. Thus, in this dissertation I have investigated the communication performance over PLC connected to the Internet when multiple flows coexist in terms of bandwidth allocation and total TCP throughput. Moreover, once PLC is one of the technologies supported by the IEEE 1905.1 standard, which defines an abstraction layer that enables the aggregation of heterogeneous wireless and wired home networking technologies to form a unique home network, I have also proposed a scheme to combine PLC and WLAN with the objective of improving the TCP throughput performance in a residence and consequently offer a better data transmission quality to the end-user.

In Chapter 2, I first briefly described the PHY specifications of the investigated broadband high-speed power line communication technology (i.e. HD-PLC) and gave a detailed explanation of the error recovery mechanism and half-duplex mechanism that it employs. Moreover, I explained how the protocols implemented by IEEE 802.11 MAC layer coordinate the multiple access of the shared wireless frequency band and deal with the hidden terminal problem. Then, in Chapter 3, I provided an explanation about the flow and congestion control mechanisms deployed by Transmission Control Protocol (TCP) because the understanding of TCP and its mechanisms is of fundamental importance to know how the flow-level performance investigation of TCP over PLC was carried out. Next, I handled the unfair bandwidth allocation problem when multiple flows coexist on IP over PLC network connected to the Internet in Chapter 4. Finally, in Chapter 5, I investigated the TCP throughput performance degradation issue of both PLC and WLAN technologies in a house and then proposed a scheme in order to improve it by aggregating both network technologies.

In Chapter 4, I focused on the evaluation of IP over PLC network connected to the Internet from an end-to-end perspective because these days most of the services and applications are delivered to the end-user through the cloud (e.g. Video on demand service AcTVila). That is, I considered the existing of multiple flows passing through the Internet over PLC and first analysed the end-to-end TCP throughput performance of each flow. The majority of existing studies have proposed layer-2 approaches to increase the efficiency of data communication over PLC, but just a few of them have focused on layer-4. Compared to existing studies where a layer-4 approach has been proposed to improve the TCP throughput performance my study showed to be the only one that tried to simulate a realistic Internet network environment because I considered that each flow had a different RTT regarding their location and the existence of cross traffic over Internet as well. Under this network scenario I ran simulations by using an existing scheme and found out that it was not efficient in such network circumstances because the unfair bandwidth allocation issue occured. Then, to solve this problem I proposed a new scheme to dynamically adjust *awnd* to support the large RTT difference between the flows and the existence of cross-traffic in the Internet environment. That is, the *awnd* for each ACK was modified for each TCP-ACK packet in PLC-sender modem only in case the value set by the TCP receiver was larger than the desired one calculated by the PLC modem. Through simulations I showed that the *awnd dynamic adaptation scheme* determined the appropriate *wnd* of the TCP sender according to the network circumstances including the transmission condition on the PLC. As a result, TCP performance degradation problem was avoided and the TCP throughput fairness was achieved. In addition, in case QoS was not considered and TCP/VoIP coexisted in such environment, the scheme mitigated the network performance degradation and coped with the one-way delay QoS demand for VoIP flows based on ITU-IT Recommendation Y.1541.

In chapter 5, I focused on how to improve the TCP throughput performance inside a residence in which numerous factors contribute to its degradation based on what network technology is being deployed. PLC and WLAN, which are supported by the IEEE 1905.1 standard, were the two technologies I covered in this study. HD-PLC, which is provided by Panasonic Systems Network Corporation, was the PLC technology I investigated. In order to make an accurate evaluation of PLC network, the investigation consisted of experiments and simulations. That is, first preliminary experiments were carried out with real production-level PLC modems (i.e HD-PLC modem) in a test-bed environment where different levels of attenuation and some types of noise-source were injected to the power line with the objective of measuring the packet-level error rate and the PHY rate over PLC under different situations. Then, those obtained parameters were loaded in the simulator to obtain realistic simulation settings. Through simulations I evaluated how good, normal and poor enviromental conditions impact on the power line networks. The simulation results showed that a drastic throughput performance degradation ocurred in a hostile physical environment due to two reasons. First, once TCP-ACK was also handled as a PLC-SDU in the transmit queue of PLC modem it was delivered to the TCP sender with high delay. Second, the number of packet drops (i.e. PLC-SDU) occurred more often and the data retransmission mechanism employed by HD-PLC retransmitted the dropped PLC-SDUs as often as necessary until it was transmitted to the destination correctly. In case of WLAN, I investigated how the distance influenced on the WLAN through simulations and I confirmed through the simulation results that it has a significant and direct impact on the throughput performance degradation. Therefore, taking into consideration the fact that both technologies suffer from different degradation factors I proposed a dynamic cooperative scheme between them without making any changes to their PHY/MAC specifications. The scheme consisted of sending TCP-DATA through PLC in order to maximize the utilization of its high data rate and TCP-ACK was sent through WLAN to avoid the packet concatenation deployed by PLC and achieve the TCP sender without a considerable delay, unless WLAN became unfeasible. Through simulation results I showed that the scheme worked efficiently even in the worst case scenario where heavy CBR cross-traffic was considered on the WLAN link. That made me conclude not only its efficiency but also how robust the scheme is in adverse situations, that can be explained because TCP inherently has a robust characteristic against TCP-ACK loss.

This dissertation focused on the evaluation of end-to-end TCP throughput performance of PLC and in methods to improve its efficiency in order to guarantee a better quality of data delivery to the end-user not only restricted in a house but also connected to the outside world through the Internet. However, the following investigation and issues remain for future work. Regarding the first, I hope that further investigations will prove the efficiency of my scheme in case TCP flows coexist with other kinds of applications besides VoIP such as Video on Demand (VoD) and real streaming satisfying their respective requirements. In addition, in case of the latter, the dynamic proposed cooperative scheme presented in Chapter 5 with the objective of combining PLC and WLAN techologies did not propose a way to check when the PLC was unfeasible and dynamically change to WLAN. Instead, it only checked when the WLAN was in good or bad transmission condition (i.e. By the number of maximum number of packet retransmissions) as the dynamic changing parameter to send TCP-ACK through either WLAN or PLC to avoid delay in its delivery. In addition, this study has only investigated how to dynamically combine two of the four technologies covered by the recently approved IEEE 1905.1 standard. Despite of the limitation and issues, I believe that the findings and methods proposed in this dissertation represent an excellent intial step forward in how to aggregate heterogeneous network technologies that use different communication media to increase the data transmission efficiency.

Bibliography

[AcT] "AcTVila", Available at `http://actvila.jp`.

[CF04] C. Caini and R. Firrincieli, "TCP Hybla: A TCP enhancement for heterogenous networks", *International J. Satellite Communications and Networking*, Vol. 22, pp. 547–566, 2004.

[CXVR09] H. T. Cruz, J. A. Xool, L. E. Vargas, and D. T. Romman, "An introduction to VoIP: End-to-end elements and QoS parameters", in Shigeru Kashihara, editor, *VoIP Technologies*. InTech, Janeza Trdine 9, 51000 Rijeka, Croatia, 2009.

[DS2] "DS2", Available at `http://www.ds2.es`.

[Ech] "Echelon Corporation", Available at `http://www.echelon.com`.

[Eva01] G. Evans, *CEBus Demystified: The ANSI/EIA 600 User's Guide*, McGraw-Hill, 2001.

[Gas05] M. S. Gast, *802.11 Wireless Networks: the Definitive Guide*, O'Reilly, 2nd edition, 2005.

[GKL+10] S. Galli, M. Koch, H. A. Latchman, S. Lee, and V. Oksman, "Industrial and International Standards on PLC-based Networking Technologies", in H. Ferreira, L. Lampe, J. Newbury, and T. Swart, editors, *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines*, chapter 7. John Wiley and Sons, New York, NY, 1st edition, 2010.

[GSW11] S. Galli, A. Scaglione, and Z. Wang, "For the grid and through the grid: The role of power line communications in the smart grid", *Proc. IEEE*, Vol. 99, No. 6, pp. –, Jun 2011.

[HP005] "HomePlug AV White Paper", Available at `http://www.homeplug.org`, Aug 2005.

[HPA] "HomePlug Power Line Alliance", Available at `http://www.homeplug.org`.

[IPE] "Iperf", Available at `http://iperf.sourceforge.net`.

[ITU10] "Recommendation ITU-T G.9972, Coexistence mechanism for wireline home networking transceivers", Jun 2010.

[ITU11] "Recommendation ITU-T Y.1541: Network Performance Objectives for IP-Based Services", Dec 2011.

[JID+04] S. Jaiswal, G. Iannaccone, C. Diot, J. Kurose, and D. Towesly, "Inferring TCP Connection Characteristics Through Passive Measurements", in *Proceedings of 23rd Annual Joint Conference of the IEEE Computer and Communications Societies*, Hong Kong, Mar 2004.

[KKK03] H. Koga, N. Kodama, and T. Konishi, "High-speed Power Line Communication System based on Wavelet OFDM", IEEE International Symposium on Power Line Communications and its Applications (IEEE ISPLC2003), May 2003.

[LLKL03] Y. J. Lin, H. A. Latchman, S. Katar, and M. K. Lee, "A Comparative Performance Study of Wireless and Power Line Networks", Vol. 41, pp. 54–63, Apr 2003.

[LLN+02] Y. J. Lin, H. A. Latchman, R. E. Newman, S. Katar, and M. K. Lee, "Field Performance Comparison of IEEE 802.11b and HomePlug 1.0", in *Proc. IEEE Conf. Local Comput. Netw.*, pp. 598–599, Tampa, Florida, USA, Nov 2002.

[LNL+03] M. K. Lee, R. E. Newman, H. A. Latchman, S. Katar, and L. Yonge, "HomePlug 1.0 Powerline Communication LANs- Protocol Description and Performance Results", *International Journal of Communications Systems*, Vol. 16, pp. 447–73, May 2003.

[LRC03] G. Lee, R. D. Rao, and Y. Cern, "Demonstration of the technical viability of PLC systems on medium and low-voltage lines in the United States", Vol. 41, pp. 108–112, May 2003.

[LZGY12] J. Liu, B. Zhao, L. Geng, and Z. Yuan, "Current Situations and Future Developments of PLC Technology in China", IEEE International Symposium on Power Line Communications and its Applications (IEEE ISPLC2012), Mar 2012.

[MMT+09] M. Mizutani, Y. Miyoshi, K. Tsukamoto, M. Tsuru, and Y. Oie, "Network-Supported TCP Rate Control for High-speed Power Line Communications", The Second International Workshop on Information Design (WIND'09), Nov 2009.

[MMT+10] M. Mizutani, Y. Miyoshi, K. Tsukamoto, M. Tsuru, and Y. Oie, "Network-Supported TCP Rate Control for High-speed Power Line Communications Environment", *Elsevier Simulation Modeling Practice and Theory (SIMPAT)*, Vol. 19, pp. 69–83, Jan 2010.

[MTK+13] A. Muniz, K. Tsukamoto, K. Kawahara, M. Tsuru, and Y. Oie, "Cooperative Transmission Scheme Between PLC and WLAN to Improve TCP Performance", 2013 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM2013), Aug 2013.

[MTKO14] A. Muniz, K. Tsukamoto, K. Kawahara, and Y. Oie, "An Effectiveness Evaluation of PLC/WLAN Cooperative Transmission Scheme under Practical Network Environment", The 8th International Workshop on Advanced Distributed and Parallel Network Applications (ADPNA2014), Sep 2014.

[MTTO12] A. Muniz, K. Tsukamoto, M. Tsuru, and Y. Oie, "Network-Supported TCP Rate Control for the Coexistence of Multiple Flows in IP over PLC", IEEE International Symposium on Power Line Communications and its Applications (IEEE ISPLC2012), Mar 2012.

[MTTO13] A. Muniz, K. Tsukamoto, M. Tsuru, and Y. Oie, "Network-Supported TCP Rate Control for the Coexistence of Multiple and Different Types of Flows on IP over PLC", *IEICE Transactions on Communications*, Vol. E96-B, No. 10, pp. 2587–2600, Oct 2013.

[NS2] "The Network Simulator 2 - ns-2", `http://www.isi.edu/nsnam/ns/`.

[PLC] "HD-PLC High Definition Power Line Communication", Available at `http://www.hd-plc.org`.

[PLC09] "HD-PLC Specifications White Paper", Available at `http://www.hd-plc.org`, Nov 2009.

[Pos81a] J. Postel, "RFC791 - Internet Protocol", *RFC*, 1981.

[Pos81b] J. Postel, "RFC793 - Transmission Control Protocol", *RFC*, 1981.

[STD10] "IEEE Standard for Broadband Over Power Line Networks: Medium Access Control and Physical Layer Specifications, IEEE Std.1901-2010", Sep 2010.

[STD13] "IEEE Standard for a Convergent Digital Home Network for Heterogeneous Technologies, IEEE Std.1905.1-2013", 2013.

[TAM08] H. A. Torkey, G. M. Attiya, and I. Z. Morsi, "Performance Evaluation of End-to-End Congestion Control Protocols", *Minufya Journal of Electronics Engineering Research (MJEER)*, Vol. 18, No. 2, pp. 99–118, Jul 2008.

[Tan11] A. S. Tanenbaum, *Computer Networks*, Pearson, 5th edition, 2011.

[VBL+10] I. B. Valmala, G. Bumiller, H. A. Latchman, M. V. Ribeiro, A. S. Escalona, E. R. Wade, and L. W. Yonge, "Systems and Implementations", in H. Ferreira, L. Lampe, J. Newbury, and T. Swart, editors, *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines*, chapter 8. John Wiley and Sons, New York, NY, 1st edition, 2010.

[WEB] "The Web100 project", Available at `http://www.web100.org`.

[WLA99] "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", Sep 1999.

[X10] "X10 Powerline Carrier Technology", Available at `http://www.x10.com/x10-basics.html`.

[ZM11] B. Zarikoff and D. Malone, "Construction of a PLC test bed for networking and transport layer experiments", IEEE International Symposium on Power Line Communications and its Applications (IEEE ISPLC2011), Apr 2011.