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An Effectiveness Evaluation of PLC/WLAN Cooperative Transmission Scheme under Practical Network Environment

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***Abstract*—With the approval and publication of the IEEE 1905.1 standard in 2013, which was designed to enhance the in-home network technology interoperability, the future in-home networking tends to provide the integration between multiple home network technologies including IEEE 1901 - Broadband over Power Line Networks with the objective of achieving a ubiquitous coverage within the home. So far, we have proposed a cooperative transmission scheme between two of these technologies, Power Line Communication (PLC) and Wireless LAN (WLAN). In this scheme, the PLC technology devotes to send TCP-DATA packets by maximally utilizing its high data rate, whereas the WLAN technology devotes to send TCP-ACK packets with small size. In order to have the proposed scheme evaluated in a more realistic network environment, its performance should be investigated under the cases where bidirectional TCP flows coexist and adverse factor that influences on the communication performance such as cross-traffic exist in both PLC and WLAN as well. Therefore, in this paper we investigate how both bidirectional flows and cross-traffic impact on the proposed scheme. Through simulation results, regarding the first case we have shown that the attained performance is higher than the one obtained when only PLC environment is used. Moreover, in the latter one it has been observed that despite of the presence of heavy cross-traffic in the WLAN link the scheme does not have considerable performance degradation because of its robustness against TCP-ACK packet loss.**

***Index Terms*—PLC, WLAN, Cooperative transmission scheme, Robustness**

I. Introduction

People's lives have become more convenient in the last few years with the Internet-enable household appliances like TV and HDD recorder. That is, once those appliances are connected to the Internet they can provide content-on-demand service like AcTVila, which has its server hosted in Japan and is already being used worldwide, to the end-users. Because of this fast progress in information technology in terms of services provided to the users in a residence the home-networking technologies are competing to meet their requirements. Among the existing home-networking technologies, Wireless LAN (WLAN) and Power Line Communication (PLC) are the ones that can provide convenient home-networking because they do not need installation of new wires.

PLC technology is currently an emerging in-home-network technology because of not only its features but also the approval of the IEEE 1901 standard (IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications) [1]. The PLC technology under investigation in our work is HD-PLC (High-Definition Power Line Communication), which has been commercialized as a PLC-Ethernet Bridge by Panasonic Network Corporation in Japan. [2].

Like current WLAN family, which faces drawbacks such as interference, fading channel, overcrowded spectrum and so forth, PLC faces some problems as well. Among the main ones, we can mention the fluctuations of source impedance, power level attenuation and the backgroud noise caused by the household appliances. That is, the communication performance in both PLC and WLAN is negatively effected by different degradation factors [3]. Therefore, in our previous paper we proposed a cooperative scheme between these two technologies (i.e. PLC and WLAN) by considering their communication media characteristics. Specifically, the TCP-ACK was proposed to be sent by WLAN in order to return it as fast as possible to the TCP sender by avoiding the packet concatenation mechanism employed by PLC technology and the TCP-DATA was proposed to be sent by PLC technology with the objective of maximizing the TCP-DATA packet transmission rate by utilizing its high data rate transmission capacity and packet concatenation mechanism [4].

At present, WLAN is the key technology used in indoor environment because it provides mobile connectivity to the end-users. Therefore, many users already make use of it to access many different kinds of applications. Besides, recently PLC has been spread as a home-networking technology with great potential to be explored. Hence, competition to access the network resource among multiple flows in such technology is also expected. Nevertheless, in our previous work we did not investigate the end-to-end throughput performance under an unstable practical network environment. That is, the existence of cross-traffic in both PLC and WLAN was not taken into consideration. Therefore, with the objective to have the proposed scheme evaluated in a more realistic network environment (i.e. the existence of adverse factor such as cross-traffic), in this paper we investigate how both bidirectional flows and cross-traffic impact on the proposed scheme.

The rest of this paper is organized as follows. Section II gives a brief overview of PLC PHY/MAC specifications.

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TABLE I
PLC Simulation Parameters

Transport Protocol	TCP New Reno/SACK
Buffer Size	256 packets
Packet Size	1500 bytes
Error Pattern Phy_Rate	Fluorescent Bulb Att:15dB Fluorescent Bulb 15dB: 121.46 Mbps (Good)
TCP Throughput	Fluorescent Bulb 15dB: 73.01 Mbps

TABLE II
WLAN Simulation Parameters

Transport Protocol	TCP New Reno/SACK
Wireless LAN	IEEE 802.11g
Phy_Rate	54Mbps (Fixed)
WLAN AP Distance RTS/CTS	10m (Good) Active (Threshold: 1500Bytes)
TCP Throughput	12.9 Mbps (Good)
Buffer Size	100 packets

Section III gives an explanation of the conducted experiments and the developed PLC network simulator. Section IV and V describe the cooperative transmission scheme in detail and its performance evaluation under different scenarios, respectively. Finally, some concluding remarks are drawn in Section VI.

II. HD-PLC PHY/MAC Specifications

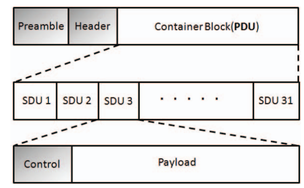
In this section, we explain about the HD-PLC PHY specifications and its transmission control.

HD-PLC maximum PHY data rate is 210 Mbps and the frequency band it operates ranges from 2 to 30 MHz. Data transmission over PLC is provided by two modems (i.e. PLC sender and PLC receiver modems), which are connected via Ethernet MAC frames in which the data unit is called PLC-service data unit (PLC-SDU). In the connection process between PLC modems, PLC sender modem creates a large MAC frame which is denoted by PLC-protocol data unit (PLC-PDU) as shown in Fig. 1(a). The deployment of PLC-PDU reduces overhead during the communication. That is, PLC-PDU, which consists of concatenated PLC-SDUs, is dispatched whether the maximum number of SDUs are concatenated or the maximum transmission timer of 5ms expires [5].

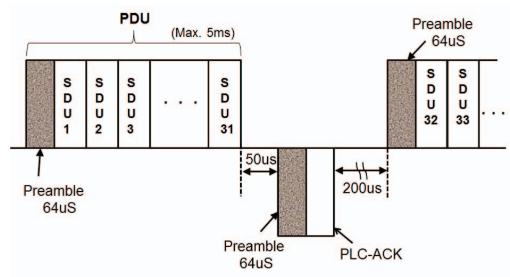
In addition, it is also important to note that HD-PLC employs a half-duplex transmission mechanism, which is shown in Fig. 1(b), where the transmission rights among the active PLC modems alternately switch at every 50μs. For instance, let's assume that PLC modem1 sends a PLC-PDU to modem2. After receiving 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, after a silent period of 200μs and the switch time for transmission right of 50μs have elapsed, the next PLC-PDU is sent by PLC modem2. In case PLC modem2 has no PLC-PDU to send the transmission right returns to PLC modem1 and so on.

III. Experiment and Simulation of PLC and WLAN

In this section we explain how the experiment and simulation were performed in order to evaluate both PLC and WLAN under different network conditions.



(a) HD-PLC MAC frame structure



(b) Half-Duplex Transmission Scheme

Fig. 1. HD-PLC MAC frame Sctructure and Half-Duplex Transmission Mechanism

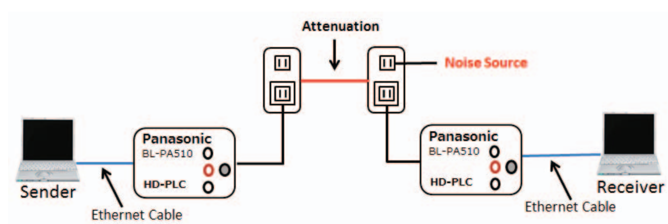


Fig. 2. PLC Experimental Topology

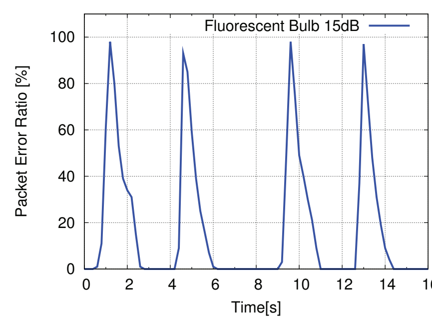
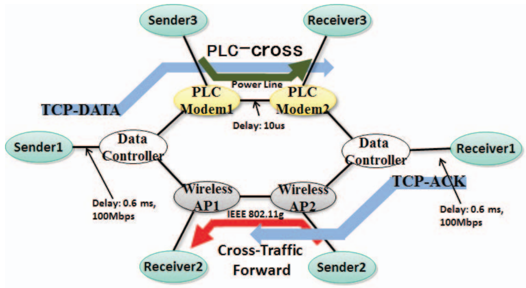


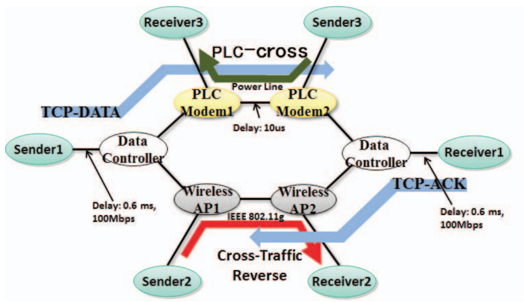
Fig. 3. Packet Error Ratio Pattern

A. PLC Environment

In [4], we made experiments with real production-level PLC modem with the purpose of measuring the packet-level error rate and PHY rate over PLC technology under different conditions that can possibly occur in a home-network. It is fundamental to mention that the preliminary expirements were carried out in a test-bed environment that avoids interference from outside noise to not have any kind of impact on the results (Fig. 2).

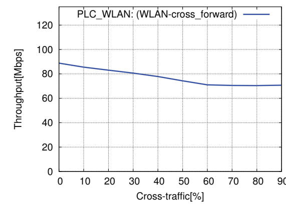


(a) One unidirectional flow (Cross-Traffic - Forward)

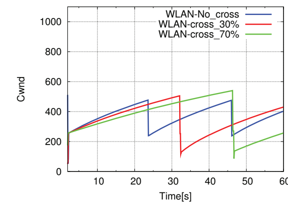


(b) One unidirectional flow (Cross-Traffic - Reverse)

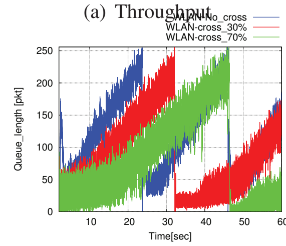
Fig. 4. Network Topology I



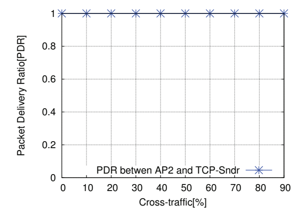
(a) Throughput



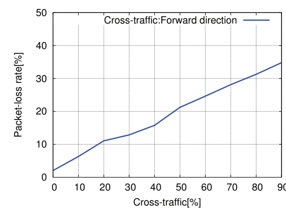
(b) TCP Cwnd



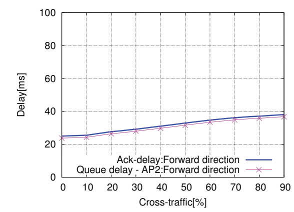
(c) Queue Length



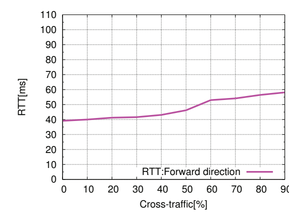
(d) Number of Packets - WLAN AP2



(e) Packet-loss rate - WLAN AP2



(f) Ack Delay - Forward Direction



(g) RTT - Forward Direction

Fig. 5. One unidirectional flow (Forward direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

Nevertheless, since the objective of this work is to mainly evaluate how both cross-traffic and bidirectional flows influence on the end-to-end TCP throughput performance we made use of the packet error ratio pattern for fluorescent bulb 15dB shown in Fig. 3 (i.e. a good PLC network environment with low level attenuation).

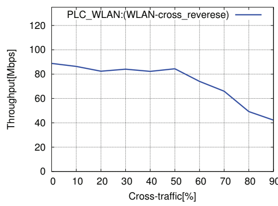
B. WLAN Environment

The WLAN parameters we will use later on in our extended NS2 network simulator module for PLC and WLAN were validated through simulations [4] and they are described in Table II. As stated previously, our main goal is to evaluate how cross-traffic and bidirectional flows impact on the end-to-end TCP throughput performance. That is the reason why in our work not only the evaluated environment for PLC is good but also the one for WLAN. (i.e. the distance of 10m between the APs).

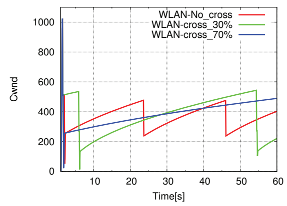
IV. Cooperative Scheme between PLC and WLAN

As was discussed in Section II, PLC network employs a packet concatenation mechanism and the half-duplex method. Furthermore, as far as we are aware in such technology TCP-ACKs are concatenated as PLC-SDUs at the transmit queue of PLC modem as well. On the other hand, considering that in most TCP variants the amount of TCP-DATA, which refers to the segments transmitted by the TCP sender, changes according to the number of received TCP-ACK packets. That is, as the role that TCP-ACK packet plays in most TCP variants is similar, quick delivery of TCP-ACK packets is essential for improving the TCP throughput performance. However, when the TCP-ACK packets are sent through PLC under critical communication environment the TCP throughput performance drastically decreases due to the increase in the delay of TCP-ACK packet. Therefore, in our proposed scheme PLC technology devotes to send TCP-DATA to maximize the TCP throughput performance because of its high data rate and TCP-ACK is sent through WLAN, which does not require packet concatenation.

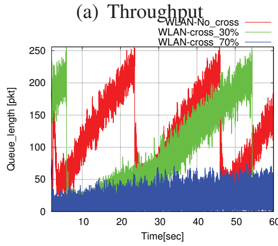
In addition, TCP inherently has a robust characteristic against TCP-ACK loss. That is, if for some reason a TCP-ACK is lost, the subsequent TCP-ACK that arrives at the TCP sender will indicate that the other previous segments were certainly received by the TCP receiver (i.e. the effect of cumulative TCP-ACK). WLAN realizes the packet transmission without performing packet concatenation. For this reason, we 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.



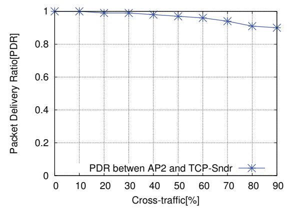
(a) Throughput



(b) TCP Cwnd

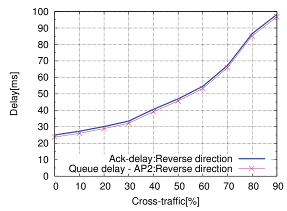


(c) Queue Length

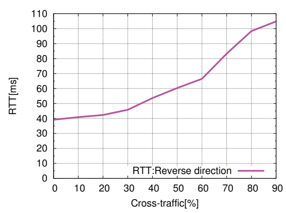


(d) Number of Packets - WLAN AP2

(e) Packet-loss rate - WLAN AP2



(f) Ack Delay - Reverse Direction



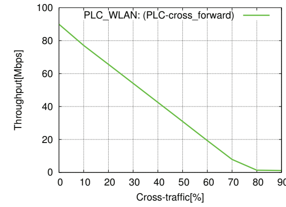
(g) RTT - Reverse Direction

Fig. 6. One unidirectional flow (Reverse direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

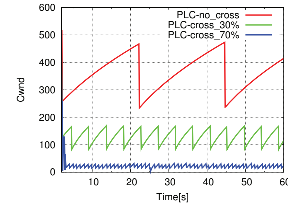
V. TCP Performance Over PLC/WLAN Hybrid Networks

We dedicate this section to evaluate the performance of the proposed scheme. That is, once we use PLC to send TCP-DATA because an improvement in throughput can be obtained due to its concatenation mechanism and WLAN to send PLC-ACK to the sender fastly, the overall goal of this evaluation is to find out the limitations when these two technologies are cooperatively used under different network conditions in three different scenarios as described below. We used the same module we had developed on NS-2 network simulator in our previous work [6]. This module consists of the implementation of a data controller which covers not only PLC but also WLAN. In our simulation experiment we used the network topologies shown in Figs. 4(a), 4(b), 9 and the simulation parameters in Tables I and II.

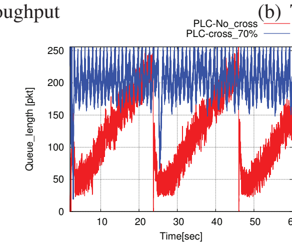
Before we get into the explanation of the evaluation of the scheme in question, it is important to note that the TCP throughput results described in this paper are the averaged throughput values obtained from 30 to 60s in order to avoid an unstable measurement due to any instability which can probably occur in the beginning of the transmission.



(a) Throughput

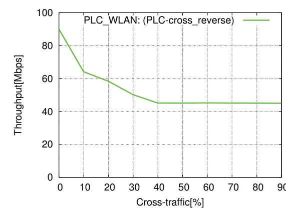


(b) TCP Cwnd

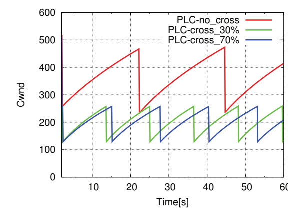


(c) Queue Length

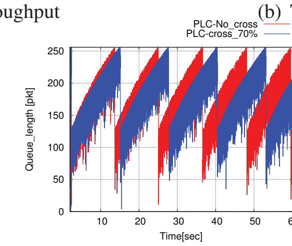
Fig. 7. One unidirectional flow (PLC Cross-Traffic Forward direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m



(a) Throughput



(b) TCP Cwnd



(c) Queue Length

Fig. 8. One unidirectional flow (PLC Cross-Traffic Reverse direction) - Error-Pattern: Light Bulb Att:15dB WLAN 10m

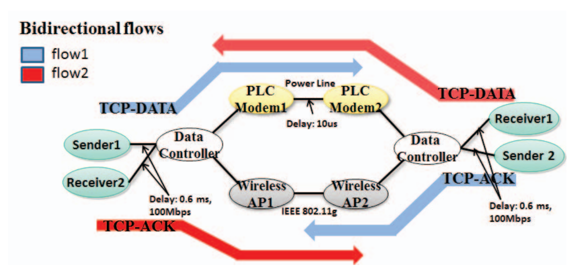
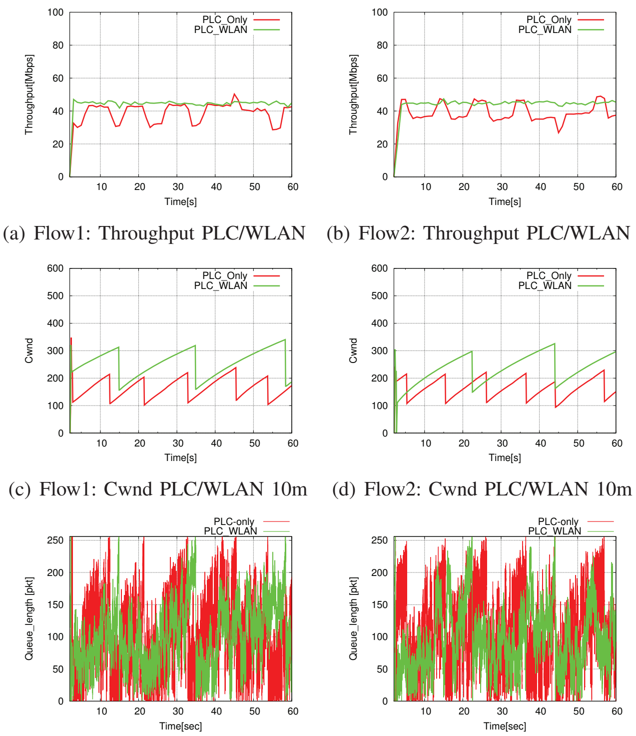


Fig. 9. Network Topology II



(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

Fig. 10. Two bidirectional flows - Error-Pattern: Light Bulb Att:15dB WLAN 10m

A. Scenario I: One unidirectional flow with cross-traffic on WLAN

1) Cross traffic - Forward direction: Fig. 5(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. 4(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(e)), the packets sent from WLAN AP2 were received at TCP sender with no packet-loss on WLAN link (Fig. 5(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(f)) thereby not causing large variations in RTT (Fig. 5(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 rate according to the RTT. As a result, as shown in Figs. 5(b) and 5(c) respectively, the *cwnd* increases efficiently and the queue length at PLC-modem1, which is occupied by 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.

2) 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. 4(b), was also considered in WLAN communication environment. Through Fig. 6(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. 6(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. 6(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. 6(f)).

As far as we 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 we 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 [7]. 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. 6(f) and 6(g) increase as the number of retransmission attempts increases.

Consequently, the *cwnd* does not increase efficiently in case of 70% of cross-traffic because of the frequent TCP-ACK losses on WLAN link. 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.

B. Scenario II: One unidirectional flow with cross-traffic on PLC

1) 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 shown in Fig. 4(a)) effects the throughput performance of the PLC/WLAN hybrid proposed scheme. Fig. 7(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. 7(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. 7(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.

2) 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. 4(b)) and its traffic load reaches 40% of the available bandwidth of PLC link the throughput remains stable (Fig. 8(a)). As mentioned in Section II, 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. 8(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. 8(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.

C. Scenario III: Two bidirectional flows

Taking into account the fact that two flows can coexist over PLC network in a bidirectional direction, in this section we show how two competing flows consume the network bandwidth based on network topologies shown in Fig. 9 and the simulation parameters in Tables I and II. Figs. 10(a) and 10(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 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. 10(c) and 10(d)). However, as shown in Figs. 10(e) and 10(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.

VI. Concluding Remarks

Considering that PLC technology faces TCP throughput degradation problems because it employs a packet concatenation mechanism and a half-duplex transmission method, we have proposed a cooperative transmission scheme between PLC and the most widely used home-networking technology nowadays, WLAN. That is, PLC technology is used to send TCP-DATA because of its high data rate with the objective of maximizing the TCP-DATA packet transmission rate while WLAN technology devotes to send TCP-ACK in order to avoid a high TCP-ACK delay that can influence negatively on the communication performance and because of the cumulative TCP-ACK mechanism, which provides robustness against TCP-ACK loss.

After a thorough evaluation of our proposed scheme under practical network environment the findings of this study 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.

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