Cooperative Transmission Scheme Between PLC and WLAN to Improve TCP Performance

Adriano Muniz*, Kazuya Tsukamoto†, Kenji Kawahara†, Masato Tsuru†, Yuji Oie†
*†Department of Computer Science and Electronics, Kyushu Institute of Technology
680-4, Kawazu, Iizuka, Fukuoka, 820-8502 Japan,Tel:+81-948-29-7687
Email:*adriano@infonet.cse.kyutech.ac.jp,†tsukamoto,kawahara,tsuru,oie@cse.kyutech.ac.jp

***Abstract*—In-home networking based on Wireless LAN (WLAN) or Power Line Communication (PLC) provides convenience and mobility to the users because in both technologies there is no need to rewire a house. However, both PLC and WLAN suffer from different performance degradation problems due to their different communication media. This paper provides a cooperative transmission scheme between PLC and WLAN, which dynamically changes the communication media when either one of them becomes unfeasible, in order to improve the TCP performance when only PLC is employed. We showed through simulations that the proposed scheme effectively works by considerably improving the TCP throughput.**

***Index Terms*—PLC, WLAN, Cooperative transmission scheme, TCP throughput**

I. Introduction

Recently, the Internet-enable 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). 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 overcrowed 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) [1]. Moreover, this technology has been commercialized as a PLC-Ethernet Bridge by Panasonic Network Corporation in Japan [2].

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 [3]. Therefore, in this paper we 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.

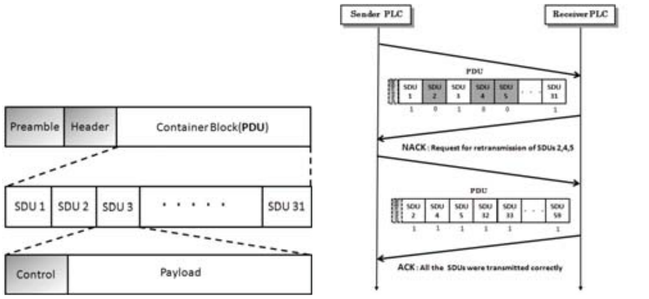
The rest of this paper is organized as follows. Section II gives a brief overview of PLC PHY/MAC specifications. Section III gives an explanation of the conducted experiments and the developed PLC network simulator. Section IV investigates the end-to-end flow level performance of Ethernet over PLC. Section V and VI describe the proposed scheme and its performance evaluation, respectively. Finally, some concluding remarks are drawn in Section VII.

II. HD-PLC PHY/MAC Specifications

In this section, we 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 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 [4].

HD-PLC operates in a frequency band that ranges from 2 to 30 MHz, and the maximum data rate is 210 Mbps. In addition, HD-PLC MAC structure is shown in Fig. 1(a). More specificallly, PLC sender modem creates a large MAC frame,



(a) MAC frame structure (b) Selective repeat ARQ procedure

Fig. 1. HD-PLC Media Access Control

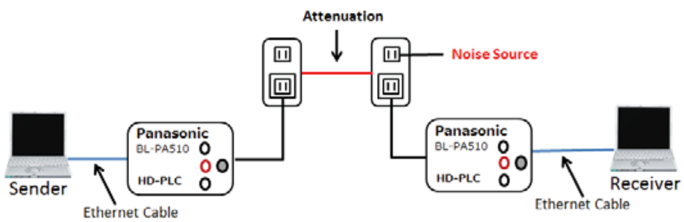


Fig. 2. PLC Experimental Topology

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).

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. 1(b) shows an example of the selective repeat ARQ procedure. In Fig. 1(b), the 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 [5]. 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).

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.

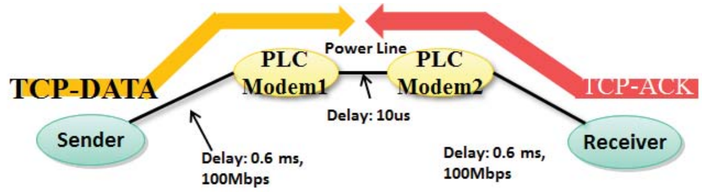


Fig. 3. Network TopologyI

TABLE I
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 II
WLAN Simulation Parameters

Transport Protocol	TCP New Reno/SACK
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

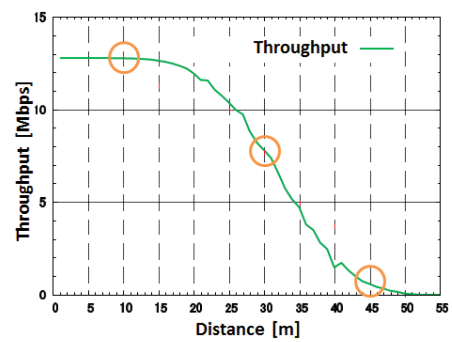
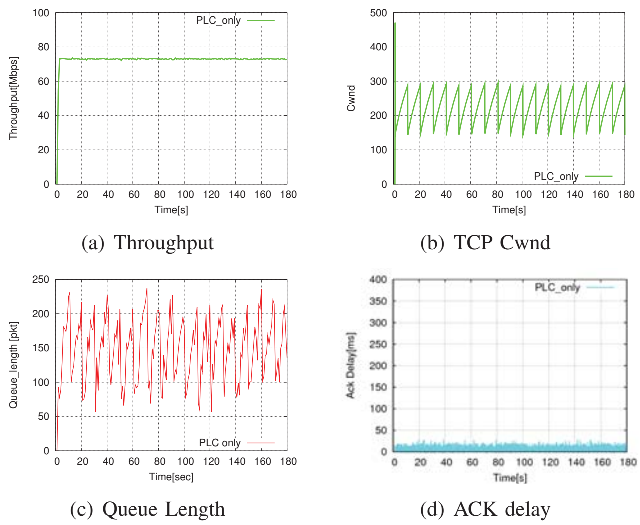


Fig. 4. WLAN Throughput vs. distance

A. PLC Environment

Fig. 2 shows the topology of the test-bed environment where we 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. We 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, the noise-sources we used in this work were fluorescent bulb and halogen lamp because of their peculiar characteristics and the way they influence the performance of in-home network.

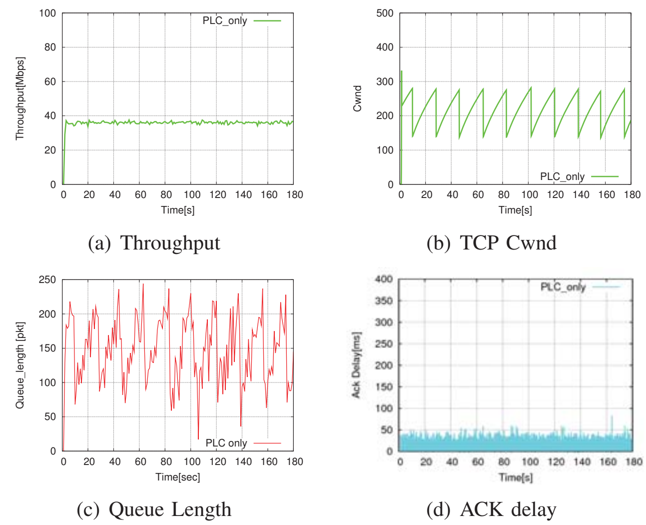
More specifically, we evaluated power line networks in three



(a) Throughput (b) TCP Cwnd

(c) Queue Length (d) ACK delay

Fig. 5. PLC (Good) - Error-Pattern: Light Bulb Att:15dB



(a) Throughput (b) TCP Cwnd

(c) Queue Length (d) ACK delay

Fig. 6. PLC (Normal) - Error-Pattern: Light Bulb Att:55dB

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 I.

Data transmission over high-speed PLC is provided by two PLC modems (i.e. PLC sender and PLC receiver modems). We used BL-PA510, a HD-PLC based modem provided by Panasonic Systems Network Corporation, in our experiments. That is, we 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.

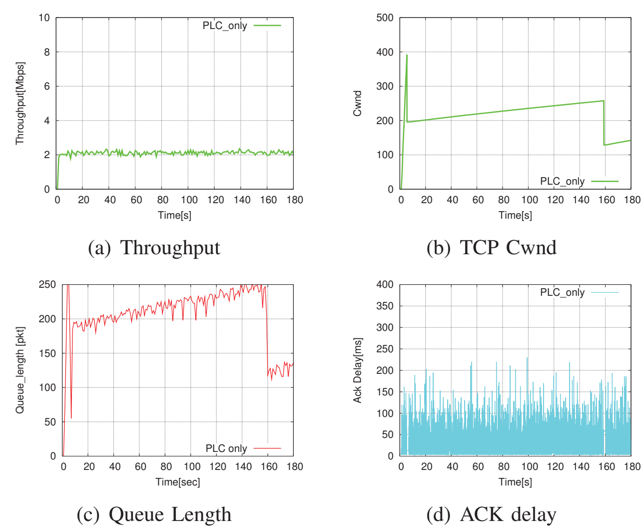
B. WLAN Environment

The performance of wireless networks is greatly affected by distance. In Fig. 4, which describes the simulation results for WLAN by using the parameters given in Table II, we demonstrated that the TCP throughput over wireless significantly degrades as the distance increases. Then, based on the simulation findings we validated the wireless parameters (i.e. Table II) that will be used afterwards in our extended NS2 network simulator module for PLC and WLAN.

IV. TCP PERFORMANCE OVER PLC NETWORK

In this section we 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 we obtained during our experiments for the fluorescent bulb 15dB, 55dB and halogen lamp 45dB noise sources are 17, 49 and 89%, respectively. We simulated the Ethernet over PLC by using the network simulator described in the previous section. Moreover, the simulation topology we used is shown in Fig. 3 and the simulation parameters are listed in Table I.

Fig. 7(a) shows that a hostile physical environment causes a drastic throughput degradation if compared to good and



(a) Throughput (b) TCP Cwnd

(c) Queue Length (d) ACK delay

Fig. 7. PLC (Poor) - Error-Pattern: Halogen Lamp Att:45dB

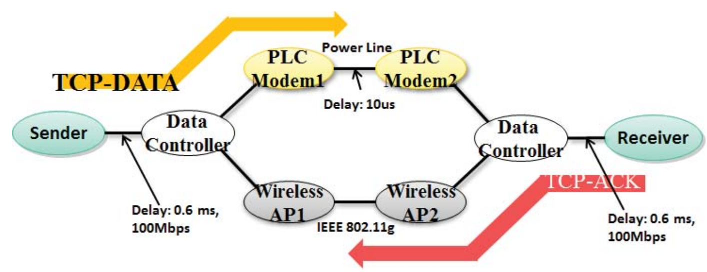
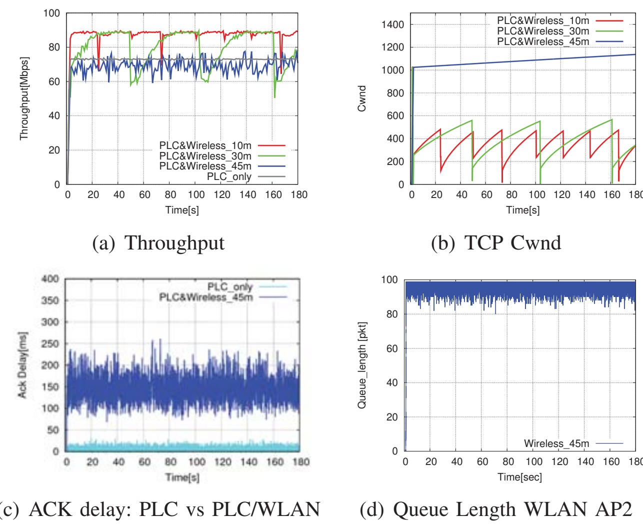


Fig. 8. Network TopologyII

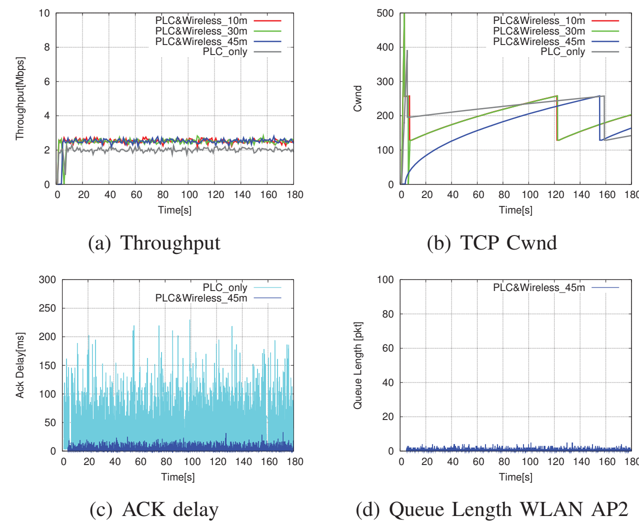
normal environmental conditions (Figs. 5(a) and 6(a)). That is, the poor communication environment of PLC link causes the drop of PLC-SDU more often. Then, the data retransmission mechanism employed by HD-PLC retransmits the dropped PLC-SDU as often as necessary until it is correctly transmitted to PLC modem2. Thus, different from Figs. 5(c) and 6(c) the transmit queue length stays constantly high and increases



(a) Throughput (b) TCP Cwnd

(c) ACK delay: PLC vs PLC/WLAN (d) Queue Length WLAN AP2

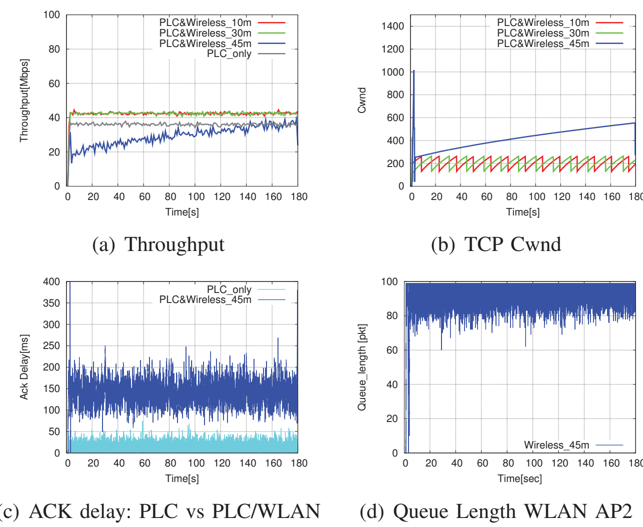
Fig. 9. PLC/WLAN - Error-Pattern: Fluorescent Bulb Att:15dB



(a) Throughput (b) TCP Cwnd

(c) ACK delay (d) Queue Length WLAN AP2

Fig. 11. PLC/WLAN - Error-Pattern: Halogen Lamp Att:45dB



(a) Throughput (b) TCP Cwnd

(c) ACK delay: PLC vs PLC/WLAN (d) Queue Length WLAN AP2

Fig. 10. PLC/WLAN - Error-Pattern: Fluorescent Bulb Att:55dB

slowly at PLC modem1 as shown in Fig. 7(c). Moreover, as the TCP-ACK, which refers to the acknowledgment packet sent by the receiver to the sender indicating that the data segment was successfully received, 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. 7(d)). Consequently, compared to the good and normal environment (Figs. 5(b) and 6(b), respectively), the congestion window (*cwnd*) for the poor environment shown in Fig. 7(b) increases at a constant rate slowly. As a result, since the *cwnd* does not increase efficiently the throughput is significantly degraded.

As far as we are aware, in most TCP variants the amount of data transmitted by the sender changes according to the ACK packet reception. That is, as the role that ACK packet plays in most TCP variants is similar, it will lead to similar problems to the ones we have considered in this study.

V. Cooperative Scheme between PLC and Wireless

Based on the results of PLC communication performance evaluation in section IV, we 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. 7(d). However, a huge TCP-ACK delay was not observed in neither good nor normal environmental conditions as shown in Figs. 5(d) and 6(d), respectively. Therefore, we propose a cooperative scheme between PLC and WLAN to improve the TCP performance inside a house.

Our proposed scheme consists of using the PLC environment to mainly send TCP-DATA, which refers to the data segments transmitted by the sender, because of its high data rate and TCP-ACK is sent through WLAN. Specifically, even though WLAN performance suffers from the effects of distance, in such communication environment the packets are not required to be concatenated before being transmitted as in PLC network. Thus, we propose that TCP-ACK is sent through WLAN unless its communication media becomes unfeasible. In case WLAN becomes unviable to maintain a good quality communication, we use PLC link to send TCP-ACK instead.

This 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 paper 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.

VI. Performance Evaluation

We dedicate this section to evaluate the performance of the proposed scheme. However, before evaluating our proposed dynamic cooperative scheme between PLC and WLAN, we first examine the communication performance when PLC and WLAN are statically employed. That is, we use PLC to send TCP-DATA to the receiver and only WLAN to send PLC-ACK to the sender. The overall goal of this evaluation is to find out the limitations of WLAN when these two technologies are cooperatively used under different network conditions for further considerations on the proposed scheme. We extended the module we had developed on NS-2 network simulator in our previous work [6]. The new 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 topology shown in Fig. 8 and the simulation parameters in Tables I and II.

A. Considerations concerning PLC/WLAN network conditions

1) PLC network condition is good/normal:

a) WLAN network condition is good/normal: Fig. 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).

b) 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 communication starts (Fig. 9(d)). Because of that, the TCP-ACK delay gets really higher than the one measured for PLC environment (Fig. 9(c)). Consequently, as shown in Fig. 9(b), the *cwnd* increases slowly thereby causing a lower TCP performance than when only PLC is considered. Note that we also obtained a not good TCP througput performane in case the physical environment is normal (i.e. Fluorescent Bulb Att: 55dB) and the WLAN network condition is poor (Fig. 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 transmitted and soon overwhelm the queue buffer at WLAN AP2 with the TCP-ACK packets during all the communication period (Fig. 10(d)). Consequently, there is a significant delay in delivering TCP-ACK to the sender (Fig. 10(c)). As a result, the *cwnd* shown in Fig. 10(b) does not increase efficiently causing a drastic low in TCP throughput performance.

2) PLC network condition is poor:

a) 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. 11(a)).

b) WLAN network condition is poor: Fig. 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. 7(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. 11(c)). Thereby, the *cwnd* for PLC increases too slowly (Fig. 11(b)) .

These findings have important implications on our proposed scheme because they 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, we proposed a dynamic cooperative scheme between PLC and WLAN as described in Section V.

B. Considerations concerning PLC/WLAN switching condition

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

What we 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 successively during all the communication period as seen in Fig. 13(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 we realized repeated simulations (i.e. 5 runs) and as shown in Figs. 13(d) and 14(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. 14(b)). We 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. 11(d)).

Furthermore, We 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. 13(a) and 13(b) show that in such circumstances, maximum packet retransmissions at WLAN AP barely occurs. Thus, on the basis of these results we opted for determining the successive number of 15 times of maximum packet re-

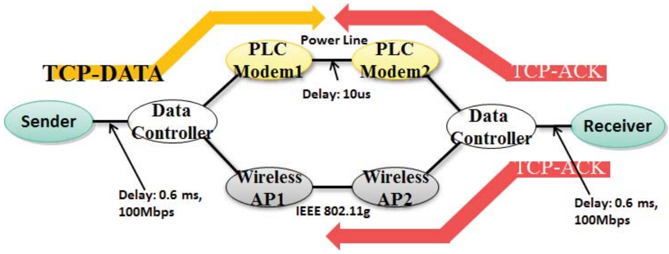
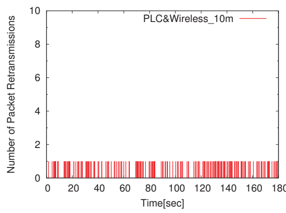
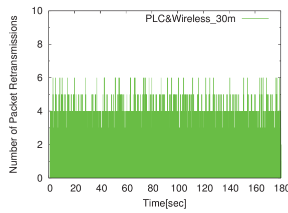


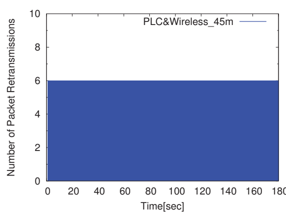
Fig. 12. Network TopologyIII



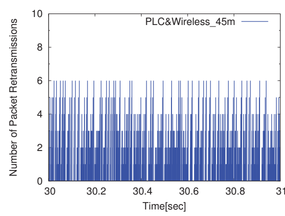
(a) Number of Packet Retransmissions



(b) Number of Packet Retransmissions



(c) Number of Packet Retransmissions



(d) Number of Packet Retransmissions 30s~31s

Fig. 13. PLC/WLAN - Number of Packet Retransmissions: Fluorescent Bulb Att:15dB

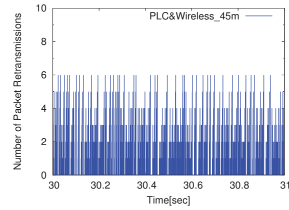
transmissions in 1-second period interval at WLAN AP as the threshold parameter (i.e. α equals 15) to change the TCP-ACK transmission from WLAN to PLC environment.

C. Considerations concerning the Proposed Dynamic Scheme

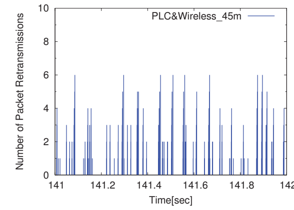
In order to evaluate the proposed scheme we made use of the network topology shown in Fig. 12 and the simulation parameters in Tables I and II. We consider two cases to perform the evaluation of the proposed scheme.

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. 15(a)). In the second case, we 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. 15(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.

Further studies will focus on the way of determining an appropriate α and investigate how it affects the in-home network performance.

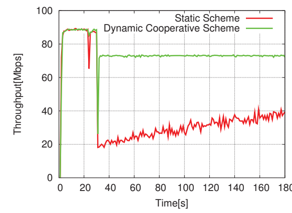


(a) Number of Packet Retransmissions 30s~31s

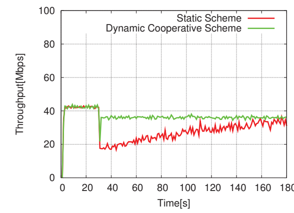


(b) Number of Packet Retransmissions 141s~142s

Fig. 14. 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

Fig. 15. Dynamic Cooperative Scheme Between PLC/WLAN

VII. Concluding Remarks

The contributions of this paper are as follows. First, we 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 we proposed a dynamic cooperative scheme between PLC and WLAN to improve the TCP performance inside a house. At last, we have implemented a new simulation module in NS-2 that combines the two networks and through the simulation results we have demonstrated the efficiency of the proposed scheme.

Acknowledgment

This work was partly supported by JSPS KAKENHI Grant Number 23500090.

References

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

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

[3] Y.-J. Lin, H. A. Latchman, S. Katar and M. K. Lee, A Comparative Performance Study of Wireless and Power Line Networks, IEEE Commun. Mag., 41(4), 54-63, Apr 2003.

[4] M. K. Lee, H.A. Latchman, R. E. Newman, S. Katar and L.Yonge, Field Performance comparison of IEEE 802.11b and HomePlug 1.0, *Proc.IEEE Conf. Local Comput. Netw.*, Tampa, Florida, USA, Nov.6-8, 2002, pp. 598-9.

[5] HD-PLC White Paper Ver.1.06, 27 Oct 2009. Available at http://www.hd-plc.org/

[6] A. Muniz, K. Tsukamoto, M. Tsuru, 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), Beijing, China, Mar 2012.