Influences of Periodically Switching Channels Synchronized with Power Frequency on PLC Equipment

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***Abstract*—The regulation on power line communication (PLC) has been eased in Japan, and the frequency band between 2 and 30 MHz can be used for in-home PLC. Several different types of commercial PLC equipment are available in the market. Almost all of them include PLC adapters that interconvert Ethernet signals and power line signals. An in-home network can easily be constructed by using these PLC adapters because there are many power outlets in every room. However, there are various factors that tend to destabilize the communication among PLC adapters. These factors involve time-varying channel response and noise characteristics, which are both synchronized with the power frequency. In particular, it has been observed that the noise in a power line varies more significantly than the channel response. Therefore, many PLC adapters contain certain features to mitigate the time-varying noise in a power line. We show a number of examples of more significant variations in the channel response synchronized with the power frequency due to the switching regulators used. This paper deals with such a time-varying channel response synchronized with the power frequency. We show that the performance of the PLC adapters suffers due the time-varying channel response and analyze its influences on the PLC adapters.**

***Index Terms*—Power line communication, periodically switching channel, cyclo-stationary noise, switching regulator, PLC equipment.**

I. INTRODUCTION

THE use of indoor power lines to set up an in-home network is an attractive prospect because indoor power lines have already been installed in homes as a commercial power supply network. Therefore, part of the power line communication (PLC) can be achieved by integrating power supply and communication on an indoor power line. In October 2006, the regulation on PLC in Japan was changed to allow the use of indoor power lines for communication purposes in a frequency range of 2–30 MHz. Consequently, several vendors started supplying PLC equipment such as PLC adapters on a commercial basis. Almost all PLC adapters in use in Japan comply with one of the three following PLC technologies. The technology HomePlug AV (HPAV) [1], [2] has been released by HomePlug Alliance (HPA). The technology UPA [3] has been released by Universal Powerline Association (UPA). The technology HD-PLC [4], [5] has been released by HD-PLC Alliance. These three technologies do not ensure interoperability with each other. In addition, PLC adapters employing the same technology but by different vendors may not necessarily communicate with each other. Therefore, the IEEE P1901 Working Group aims to define medium access control (MAC) and physical (PHY) layer specifications for coexistence and interoperability between all classes of PLC devices [6]. This proposal is expected to be approved in 2008.

Commercial PLC adapters are designed to overcome the various limitations of PLC. One such limitation is the variation of the characteristics of the channels synchronized with the power frequency. The noise in a power line has a cyclic nature [7], [8]. Therefore, power line noise is said to be *cyclo-stationary* [7]. Cañete *et al.* showed that the channel response of power line channels also varies and is synchronized with the power frequency [9], [10]. The cyclic nature of the channel response is *linear periodically time-variant (LPTV)* [9]. It is more considered that power line noise variations are more significant than the variations in the channel response. As a result, many commercial PLC adapters contain a feature to mitigate the impact of cyclo-stationary noise [1], [4], [11], [12]. In addition, in order to clarify the correlation between PLC adapters and the inherent nature of power line channels, benchmark estimation and bandwidth estimation methods have been developed [13]–[15]. For example, Lin *et al.* showed that cellphone chargers caused serious degradation of the bandwidth of the PLC adapters [15].

In this study, we investigate the influences of some switching power devices on PLC adapters. We show that some types of switching regulators, including cellphone chargers, trigger serious time-varying channel responses synchronized with the power frequency over the entire bandwidth of the commercial PLC adapters. Some of these time-varying channel responses have steeper and more significant variations than cyclo-stationary noise. We present the user datagram protocol (UDP) throughput of typical PLC adapters on power line channels for a case in which a cellphone charger is connected. Furthermore, we investigate a more robust PLC adapter design so

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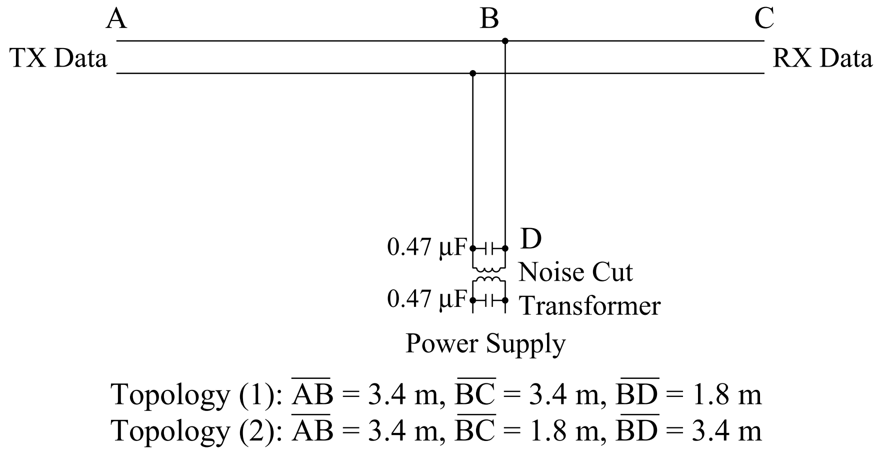


Fig. 1. Two fundamental power line topologies using a residential power line cable, VVF-1.6×2C.

that the adapter can withstand such time-varying channel responses; in order to obtain such a design, we perform short-term Fourier transform (STFT) analysis of PLC signals on power line channels.

The remaining paper is organized as follows: Section II presents reference power line channels and the measurement of the frequency response of these channels. We show serious time-varying characteristics of the channel response, which is synchronized with the power frequency. Section III shows the influences of serious time-varying channel responses synchronized with the power frequency in PLC adapters and presents a robust PLC adapter design. Section IV concludes the paper.

II. MEASUREMENT OF POWER LINE CHANNELS

A. Reference Power Line Channels

In this section, we introduce some reference power line channels dealt with in this paper. We consider two fundamental power line topologies and ten reference power line channels. Figure 1 illustrates the target power line topology with VVF-1.6×2C, which is a vinyl insulation and vinyl sheath flat (VVF) cable; this VVF cable consists of two conductors of diameter 1.6 mm and is the most popular residential power line cable in Japan. A, B, C, and D are the transmitting port, branch point, receiving port, and power supplying (or electrical short) port, respectively. *Topology (1)* is a power line topology with $\overline{AB} = 3.4$ m, $\overline{BC} = 3.4$ m, and $\overline{BD} = 1.8$ m. *Topology (2)* is power line topology with $\overline{AB} = 3.4$ m, $\overline{BC} = 1.8$ m, and $\overline{BD} = 3.4$ m. Topology (1) results in flat fading and Topology (2) results in frequency selective fading, as described in Section II-B.

Five reference power line channels take off from each topology. A reference power line channel with Topology (k) is denoted as *Channel (k-ℓ)* for $\ell = 1$, 2, 3, 4, and 5. ℓ represents the state at the receiving port C as follows:

- $\ell = 1$.
  A cellphone charger is not connected at the receiving port C.
- $\ell = 2$.
  A cellphone is connected through a cellphone charger at the receiving port C and is rapidly charging.
- $\ell = 3$.
  A cellphone is connected through a cellphone charger at the receiving port C. It is on and its charging is complete.
- $\ell = 4$.
  A cell phone is connected via the cell-phone charger at the receiving port C. It is off and its charging is complete.
- $\ell = 5$.
  A cellphone charger is connected at the receiving port C, but a cellphone is not connected.

The time variation of Channel (k-ℓ) is dependent on ℓ, as mentioned in Section II-C.

When a cellphone charger is not connected, the reference power line channels, that is, Channels (k-1), become static channels. When a cellphone charger is connected, the reference power line channels, that is, Channels (k-ℓ) except $\ell = 1$, become time-varying channels synchronized with the power frequency.

B. Frequency Response of Static Channels

Figure 2 illustrates the frequency responses of Channels (1-1) and (2-1), measured by a network analyzer. This figure shows that Channels (1-1) and (2-1) are flat and frequency selective fading channels, respectively, and Channel (2-1) has a deep dip at 24.3 MHz. The frequency responses of Channels (1-1) and (2-1) can roughly be approximated by the theory of multipath power line channels [16]–[18]. The attenuation amount of Topology (1) from 2 to 30 MHz is 3.60 dB, and the attenuation amount of Topology (2) is 4.24 dB. The fluctuation in the frequency responses of Channels (1-ℓ) and (2-ℓ) for all values of ℓ except $\ell = 1$ could be observed by

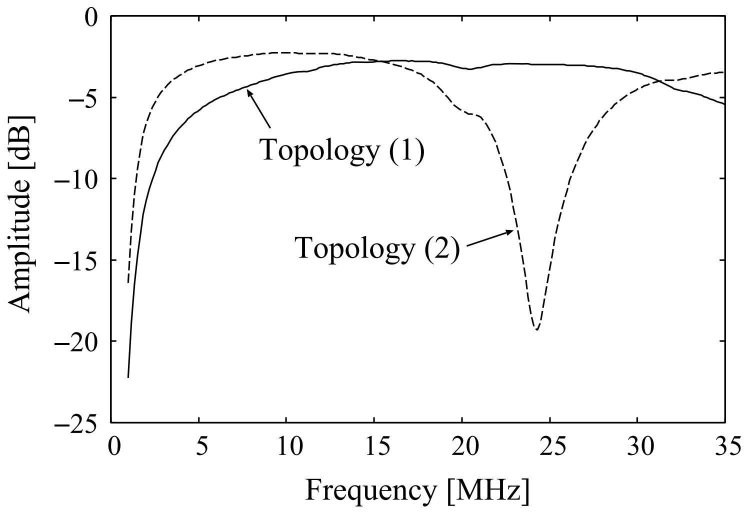


Fig. 2. Frequency response of two static power line channels. The sweep time of the network analyzer is 88 ms and, the averaging number is 16.

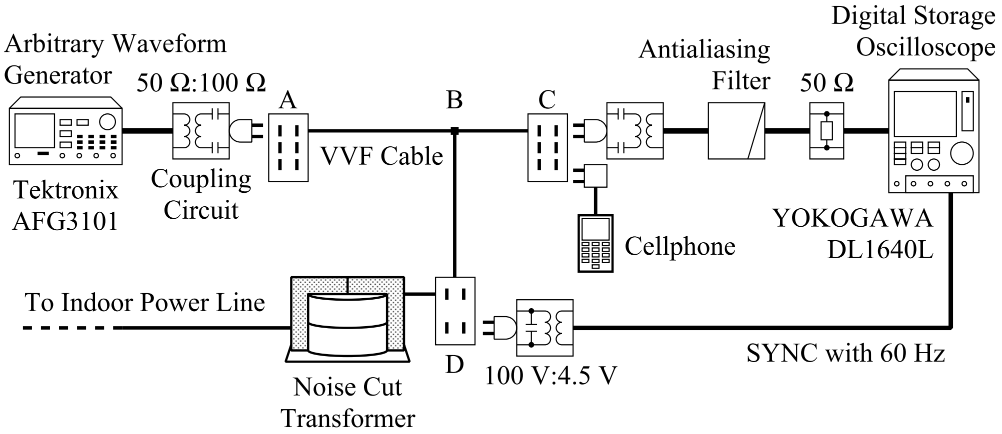


Fig. 3. Measurement system for time-varying channels synchronized with the power frequency.

measuring the response with a network analyzer, even on averaging up to 16 times. This is because the frequency responses of Channels (1-ℓ) and (2-ℓ) except for $\ell = 1$ have significant time variations; in other words, a time-varying channel response is observed when a cellphone charger is connected at the receiving port C.

C. Time-frequency Analysis for Time-varying Channels

The time-varying nature of a reference power line channel when a cellphone charger is connected to the channel can be observed by using a network analyzer; however, characteristics, such as cycle of fluctuation, cannot be investigated by the network analyzer. Therefore, we present a measurement and analysis method that allows the investigation of variation in the frequency responses of the reference channels when a cellphone charger is connected. Figure 3 illustrates a measurement system for time-varying channels synchronized with the power frequency.

The signal $p(t)$ with a duration T of 40.96 μs is designed so as to minimize

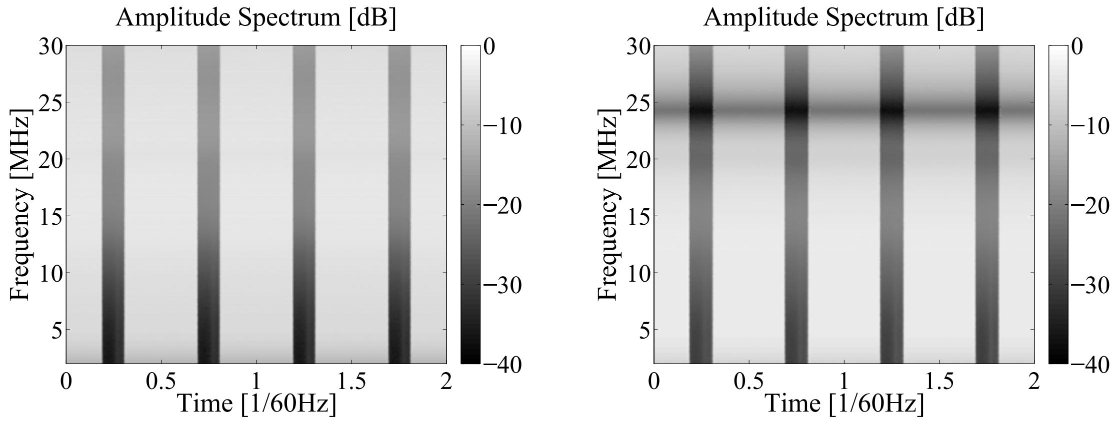
$$\max\{p(t_i)^2 | 0 \leq i < N\}, \tag{1}$$

subject to the condition that the one-sided amplitude spectrum $|P(f)|$ is flat in the frequency range of 2–30 MHz and zero otherwise, where N is equal to 3072, t_i is equal to iT/N, and $P(f)$ is the Fourier transform of $p(t)$, in order to overcome the effect of quantization errors of measurement instruments. The signal

$$x(t) = \sum_{i=0}^{\infty} p(t - iT) \tag{2}$$

is transmitted from an arbitrary waveform generator. The transmitted signal $x(t)$ passes through the power line channel, and the signal $y(t)$ is received by a digital storage oscilloscope. The frequency response $H(t, f)$ with a time resolution T can be obtained by analyzing the correlation between $x(t)$ and $y(t)$.

When a cellphone charger is connected, the frequency responses $H(t, f)$ of the reference channels alternate



(a) Channel (1-2). (b) Channel (2-2).

Fig. 4. Time-frequency analyses of time-varying power line channels within two power cycles while rapidly charging a cellphone.

between two different values according to the power supply voltage. They can be expressed as

$$H(t,f) = \begin{cases} H_{\mathrm{Low}}(f), & |v_{\mathrm{ac},\theta}(t)| \le V_{\mathrm{thr}}, \\ H_{\mathrm{High}}(f), & |v_{\mathrm{ac},\theta}(t)| \ge V_{\mathrm{thr}} + \Delta V, \end{cases} \tag{3}$$

for the power-frequency signal

$$v_{\mathrm{ac},\theta}(t) = \sqrt{2} V_{\mathrm{ac}} \sin(2\pi f_{\mathrm{ac}} t + \theta), \tag{4}$$

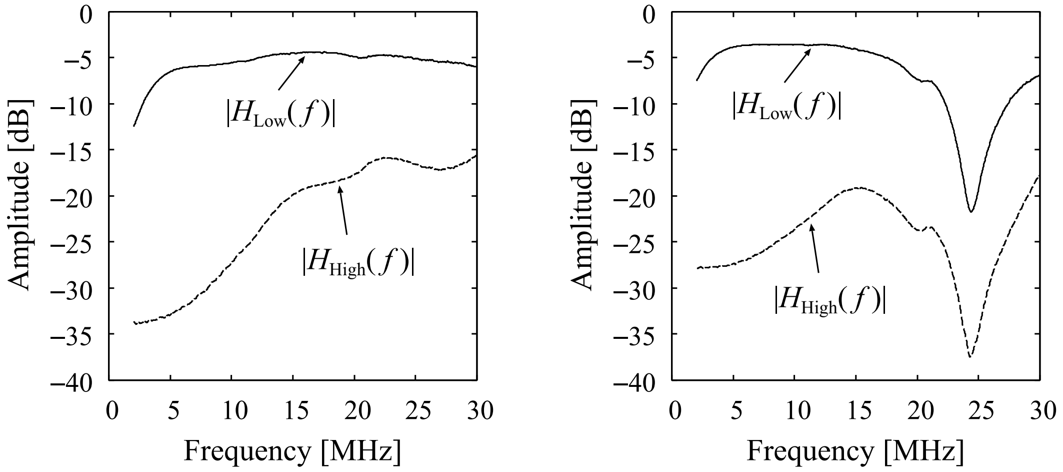
where $V_{\mathrm{ac}} > 0$ represents the power voltage, which is 100 V in Japan; $f_{\mathrm{ac}} > 0$ represents the power frequency, which is 60 Hz in western Japan; $-\pi/2 \le \theta < \pi/2$ represents the phase difference of the actual power supply voltage $v_{\mathrm{ac},0}(t)$, which has a rising edge at $t = 0$; $V_{\mathrm{thr}} > 0$ represents a threshold voltage; and $\Delta V \ge 0$ gives the transient duration from $H_{\mathrm{Low}}(f)$ to $H_{\mathrm{High}}(f)$. The channel response $H(t,f)$ is called a *periodically switching channel* if ΔV is negligibly small, that is, the transient duration is small and $H_{\mathrm{Low}}(f)$ is considerably different from $H_{\mathrm{High}}(f)$ for any frequency f.

Figures 4(a) and 4(b) show time-frequency analyses of the frequency responses for Channels (1-2) and (2-2). It should be noted that the unit on the horizontal axis is the power cycle and the 0 power cycle indicates a rising edge of commercial power supply. As shown in these two figures, Channels (k-2) are periodically switching channels and $H_{\mathrm{High}}(f)$ experiences heavier attenuation than $H_{\mathrm{Low}}(f)$.

The amplitude spectra $|H_{\mathrm{Low}}(f)|$ and $|H_{\mathrm{High}}(f)|$ are shown in Figs. 5(a) and 5(b), respectively. The difference between $|H_{\mathrm{Low}}(f)|$ and $|H_{\mathrm{High}}(f)|$ is large in both Topology (1) and Topology (2) for any frequency f. In particular, $|H_{\mathrm{Low}}(f)|$ is 20 dB larger than $|H_{\mathrm{High}}(f)|$ in both Topology (1) and Topology (2) if f is less than 10 MHz. The frequency responses of a static power line channel with Topology (1) and Topology (2) shown in Fig. 2 is nearly identical to $|H_{\mathrm{Low}}(f)|$ of Channels (1-2) and (2-2) shown in Figs. 5(a) and 5(b), respectively. As a result, it is concluded that the impedance magnitude of a cellphone charger while it is rapidly charging a cellphone is nearly infinity. The heavy attenuation of $|H_{\mathrm{High}}(f)|$ degrades the performance of the PLC adapters; when a cellphone charger is not connected, the amplitude spectrum is almost the same as $|H_{\mathrm{Low}}(f)|$ with the same power line topology.

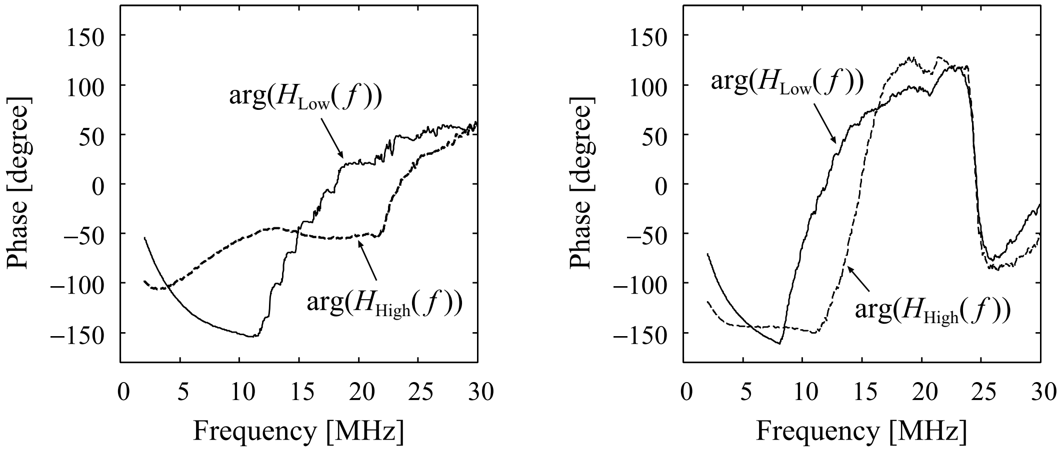
The phase spectra $\arg(H_{\mathrm{Low}}(f))$ and $\arg(H_{\mathrm{High}}(f))$ are shown in Figs. 6(a) and 6(b), respectively. It should be noted that in the analysis, the timing recovery is performed at the receiving end, i.e., for the signal $y(t)$. Therefore, $\arg(H_{\mathrm{Low}}(f))$ and $\arg(H_{\mathrm{High}}(f))$ would not be the actual phase spectra of Channels (1-2) and (2-2). However, it will be sufficient to understand the difference between $\arg(H_{\mathrm{Low}}(f))$ and $\arg(H_{\mathrm{High}}(f))$. As shown in Figs. 6(a) and 6(b), the difference between $\arg(H_{\mathrm{Low}}(f))$ and $\arg(H_{\mathrm{High}}(f))$ on Channel (2-2) is larger than that on Channel (1-2). The communication quality of PLC adapters may suffer due to the switching of different phase spectra shown in Fig. 6(b) if the modulation scheme is sensitive to it.

The modeling of periodically switching channels synchronized with power frequency is effective for evaluating the performance of existing PLC adapters and designing robust PLC adapters against periodically switching channels. There are many proposals for the modeling of the transfer function over power line channels—the multipath model obtained by fitting the parameters from channel measurements [16], [17]; the multipath model obtained by tracing the cable loss, reflection, and transmission coefficients [18]; the cascaded two-port network model obtained by using multiconductor-transmission-line (MTL) theory [19], [20]; and the transfer function model obtained by taking into consideration loads, distances, and interconnection nodes [21], [22]. Any transfer function model of power line channels is effective for describing $H_{\mathrm{Low}}(f)$ and $H_{\mathrm{High}}(f)$. Therefore, a simulator for periodically switching channels synchronized with the power frequency is feasible if V_{thr}, ΔV, and θ are precisely estimated. Hayasaki *et al.* proposed a simulator for periodically switching channels synchronized with the power frequency on the basis of the abovementioned concept [23].



(a) Channel (1-2). (b) Channel (2-2).

Fig. 5. Amplitude spectra of periodically switching channels while rapidly charging a cellphone.



(a) Channel (1-2). (b) Channel (2-2).

Fig. 6. Phase spectra of periodically switching channels while rapidly charging a cellphone.

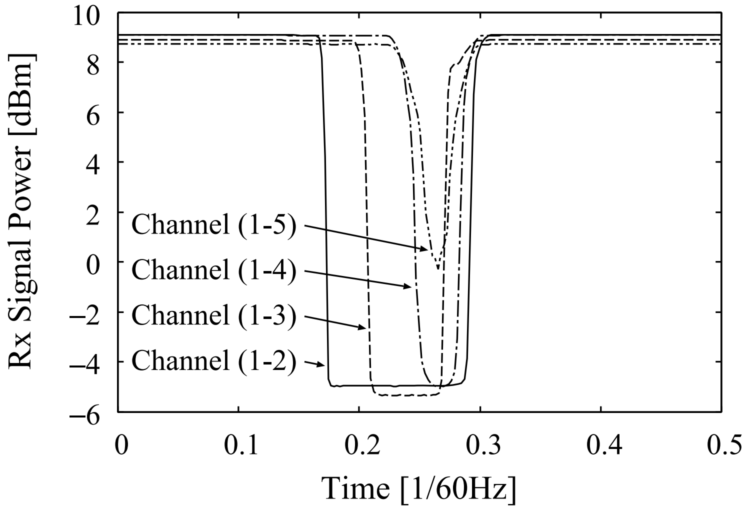


Fig. 7. Time-variations of received signal power for the state of a cellphone charger. The transmitted signal power is 14.5 dBm.

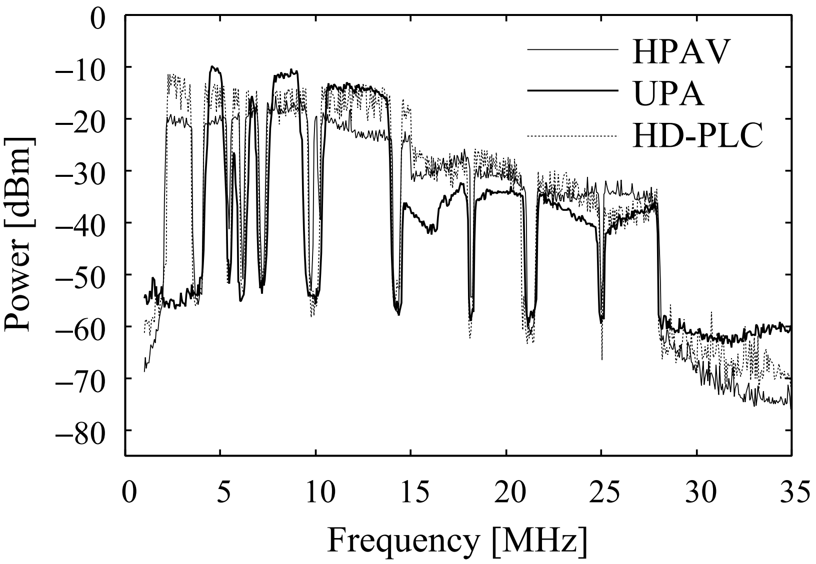


Fig. 8. Power spectra of the PLC adapters. The spectrum analyzer is set to MAX HOLD, and the RBW is 10 kHz.

TABLE I
ATTENUATION RATIO FOR THE STATE OF A CELLPHONE CHARGER, OBTAINED FROM MEASUREMENTS.

ℓ	1	2	3	4	5
$A_{k,\ell}$	0	0.26	0.18	0.13	0.12

The difference between in $V_{\rm thr}$, ΔV, and θ for a case in which a cellphone charger is connected, is investigated for $\ell = 2$, 3, 4, and 5. Figure 7 shows the plot of the received signal power on the half of power cycle for $\ell = 2$, 3, 4, and 5, where the transmitted signal power is 14.5 dBm. It is shown that the switching time of the frequency responses is dependent on the state of the cellphone charger. Further, the switching time of the frequency responses is independent of the topology of the power line channels. The ratio of the duration in which $|v_{{\rm ac},\theta}(t)|$ is larger than $V_{\rm thr}$, that is, the frequency response is not $H_{\rm Low}(f)$ in the half of power cycle is called the *attenuation ratio* and is denoted as $A_{k,\ell}$ for Channel (k-ℓ). Table I shows the attenuation ratio $A_{k,\ell}$ for the state ℓ of a cellphone charger, obtained from the measurements.

The abovementioned switching of frequency responses is deterministic, unlike cyclo-stationary noise. The deterministic property of periodically switching channels may help us improve the performance of the existing PLC adapters.

III. INFLUENCES OF PERIODICALLY SWITCHING CHANNELS ON PLC EQUIPMENT

In this section, the influences of periodically switching channels synchronized with power frequency on commercial PLC adapters are investigated. A pair of HomePlug AV (HPAV) adapters, a pair of UPA adapters, and a pair of HD-PLC adapters are considered in the experiment. Let us denote pairs of HPAV, UPA, and HD-PLC adapters as *HPAV*, *UPA*, and *HD-PLC*, respectively.

Figure 8 shows the power spectra of all PLC adapters measured by using a spectrum analyzer. The measurement data are obtained by using MAX HOLD, which records the maximum value in the measurement period, since PLC adapter signals are burst signals and not continuous signals. RBW stands for resolution bandwidth. The power of all the PLC adapters in the frequency range of 15–30 MHz is about 10 dB lower than that in the frequency range of 2–30 MHz. This is because the regulation value of common-mode current from 15 to 30 MHz is 10 dB lower than that from 2 to 15 MHz. The notches in the power spectrum for HD-PLC are slightly deeper than those of the other PLC adapters; this is because the wavelet orthogonal frequency division multiplexing (OFDM) is employed for HD-PLC as a multicarrier modulation scheme [4], [5], which leads to steep and deep notches, whereas in the case of HPAV and UPA, OFDM is employed [1], [3].

From Fig. 8, it can be observed that UPA does not allocate subcarriers for data transmission from 2 to 4 MHz unlike HPAV and HD-PLC. When the frequency is less than 15 MHz, the power of UPA is larger than that of HPAV and HD-PLC; when the frequency is greater than 15 MHz, the power of UPA is less than that of HPAV and HD-PLC. Thus, each vendor manufactures PLC adapters in a different manner. Further, the power supply AC cable of HPAV is 1.6 m in length while that of UPA is 1.2 m in length. HD-PLC has no power supply AC cable. Therefore, the performance of the PLC adapters shown in the experiment does not indicate the superiority of the communication schemes used in them. The objective of this study is to investigate the influences of periodically switching channels synchronized with the power frequency and thereby determine a robust design for PLC adapters for periodically switching channels. Note that the periodical switching of the frequency responses is only one aspect of power line channels.

A. UDP Throughput

We measure the UDP throughput of all the PLC adapters over Channels (1-1), (1-3), (2-1), and (2-3). It is difficult to measure the UDP throughput while rapidly charging a cellphone because long-term measurements will lead to state variations and identical states cannot be guaranteed.

Figure 9 shows a measurement system for UDP throughput for the PLC adapters. The transmitting and receiving PCs use the Linux OS on an Intel Pentium 4, 1.5 GHz CPU with 256 MB memory. We employ a TCP/UDP bandwidth measurement tool, *Iperf* [24], in order to measure the UDP throughput of PLC adapters on the target power line channels (here, TCP stands for transmission control protocol).

Figure 10 shows the UDP throughput of PLC adapters on Topology (1). Figure 11 shows the UDP throughput of PLC adapters on Topology (2). The configuration of the experiment is as follows: The offered load ranges from 1 Mbps to the maximum rate of the network information card (NIC), which is approximately 95 Mbps, at intervals of 1 Mbps. The transmission time is 10 s for each offered load, and the sleep time between packet transmissions is 10 s. The UDP buffer size is 216 Kbyte which is the maximum in the experiment, and the UDP datagram size is 1470 bytes. The 1470 bytes of UDP datagram size may be optimal for all PLC adapters as a result of transmission tests of UDP datagrams with different sizes.

From Figs. 10 and 11, we can observe that in the case of HPAV, there is less degradation and there are no fluctuations in the throughput with the periodically switching channels synchronized with the power frequency. This is because HPAV has a countermeasure to reduce the cyclo-stationary noise [1], [11], [12], which is synchronized with the power frequency. Both the periodically switching channel and cyclo-stationary noise have the same periodicity, which is half the power cycle. Therefore, the countermeasure against cyclo-stationary noise will work well, even for a periodically switching channel. However, a further enhancement of PLC adapters will be expected since the phenomenon of periodically switching channel is deterministic and can be learned before the establishment of communication. On the other hand, large fluctuations in the UDP throughput of HD-PLC are observed when connecting a power-on cellphone via a cellphone charger, as shown in Figs. 10 and 11 although the maximum UDP throughput of HD-PLC is the highest among all PLC adapters. This phenomenon for HD-PLC may result from the short sleep time or transmission time because such fluctuations in HD-PLC are not observed in an experiment in which the sleep time and transmission time are set to 30 s and 60 s, respectively. Note that the master of UPA is connected to the receiving port C in Fig. 9 because the measurement of the UDP throughput sometimes fails if the slave of UPA is connected to the receiving port C.

TABLE II
AVERAGE UDP THROUGHPUT OF THE PLC ADAPTERS. THE OFFERED LOAD IS THE MAXIMUM RATE OF THE NIC, THE NUMBER OF TRIALS IS 10, AND THE TRANSMISSION TIME FOR EACH TRIAL IS 60 S.

	HPAV	UPA	HD-PLC
$R_{1,1}$	82.0 Mbps	76.8 Mbps	93.5 Mbps
$R_{1,3}$	59.6 Mbps	43.0 Mbps	67.2 Mbps
$R_{2,1}$	82.7 Mbps	65.8 Mbps	85.8 Mbps
$R_{2,3}$	56.9 Mbps	35.4 Mbps	63.6 Mbps
R_{F}	0.99	0.85	0.93
R_{T}	0.71	0.55	0.73

The average effect of the measurement results is obtained by extending the transmission time and increasing the number of trials. The measurement results that take into consideration the average effect are shown in Table II. The offered load is set to the maximum rate of the NIC, and the number of trials is 10. The transmission time is 60 s for each trial and the sleep time between trials is 30 s. The UDP throughput on Channel (k-ℓ) in Table II is denoted as $R_{k,\ell}$. The ratio of UDP throughput on Topology (2) to that on Topology (1) is given as

$$R_{\mathrm{F}} = \frac{R_{2,1} + R_{2,3}}{R_{1,1} + R_{1,3}}, \tag{5}$$

in order to investigate the robustness of frequency selective fading. The ratio of UDP throughput on periodically switching channels to that on static channels is given as

$$R_{\mathrm{T}} = \frac{R_{1,3} + R_{2,3}}{R_{1,1} + R_{2,1}}, \tag{6}$$

in order to investigate the robustness of time selectivity.

From Table II, it can be observed that HD-PLC can totally achieve higher average UDP throughput than HPAV and UPA. This is because wavelet OFDM, which is the multicarrier modulation for HD-PLC, does not have any guard interval (GI). Instead, the value of R_{F} for HD-PLC is slightly less than that for HPAV, that is, HD-PLC is somewhat susceptible to frequency selective fading. The higher UDP throughput of HD-PLC can also be observed by comparing the positional relation between HPAV and HD-PLC of Topology (1) in Fig. 10 with that of Topology (2) in Fig. 11. This result may also be attributed to the difference in the multicarrier modulation schemes. OFDM can resolve inter-symbol interference (ISI) and inter-channel interference (ICI) almost completely by removing GI if the maximum delay spread is less than the duration of GI. However, wavelet OFDM does not remove ISI and ICI completely because it does not have a GI. On the other hand, from the value of R_{T} in Table II, it can be observed that UPA is definitely susceptible to periodically switching channels. This phenomenon would be caused by the difference in the MAC protocols. The token passing scheme is used in the case of UPA [3], whereas a hybrid scheme of time division multiple access (TDMA) and carrier sense multiple access with collision avoidance (CSMA/CA) synchronized with power frequency is used in the case of HPAV and HD-PLC [1], [4]. Thus, the

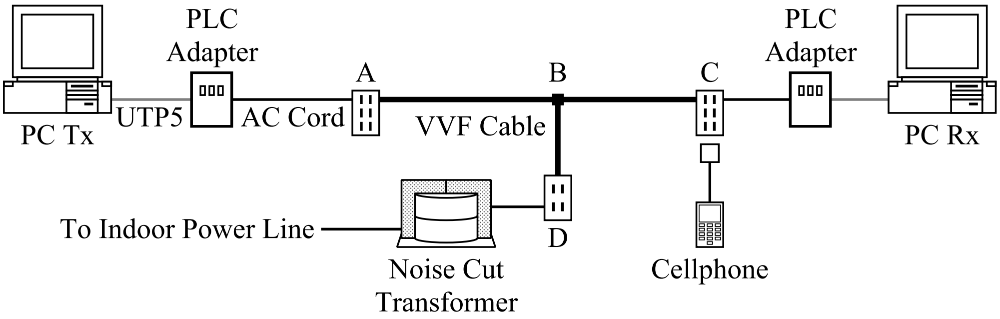


Fig. 9. The measurement system of UDP throughput for the PLC adapters.

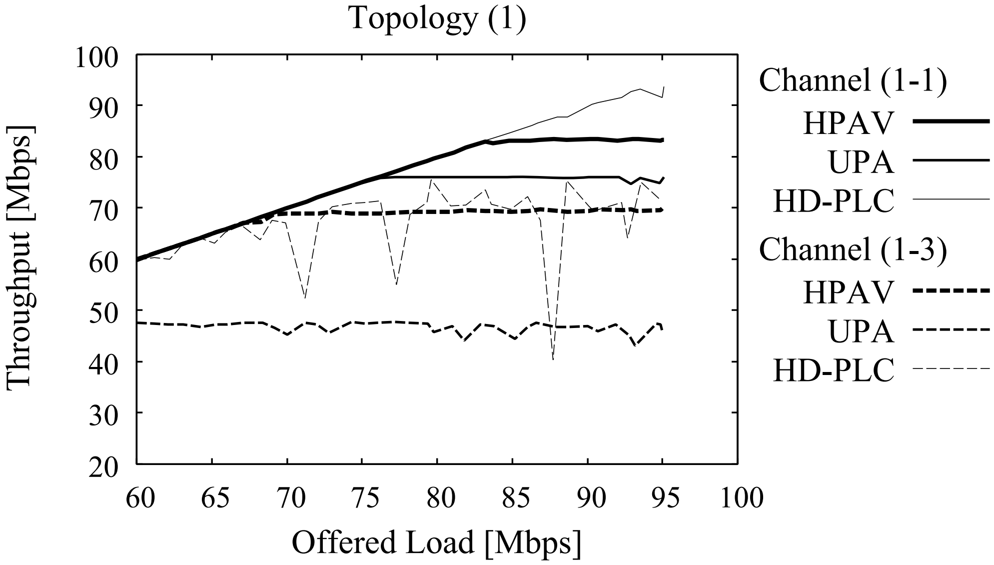


Fig. 10. UDP throughput of PLC adapters over Channels (1-1) and (1-3).

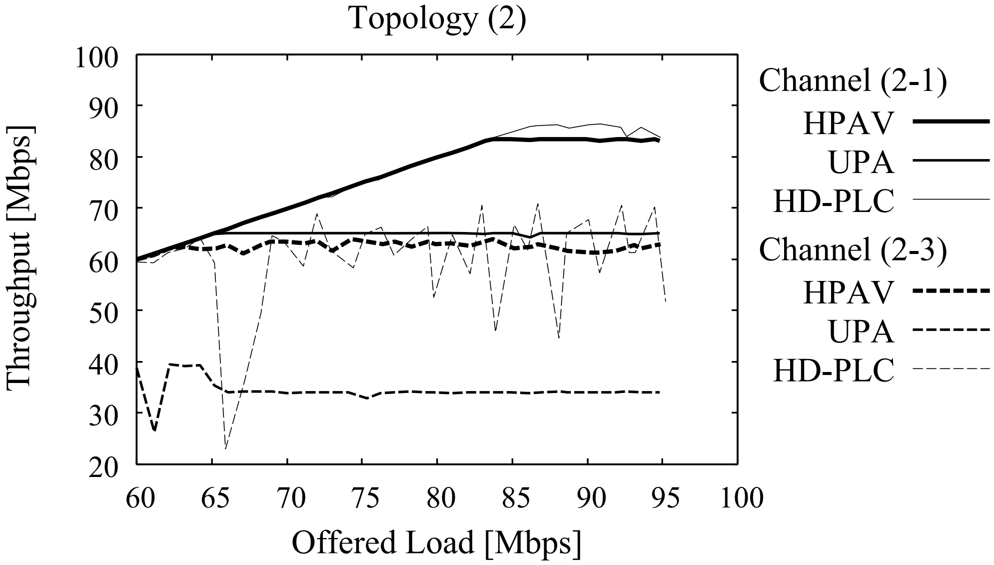


Fig. 11. UDP throughput of PLC adapters over Channels (2-1) and (2-3).

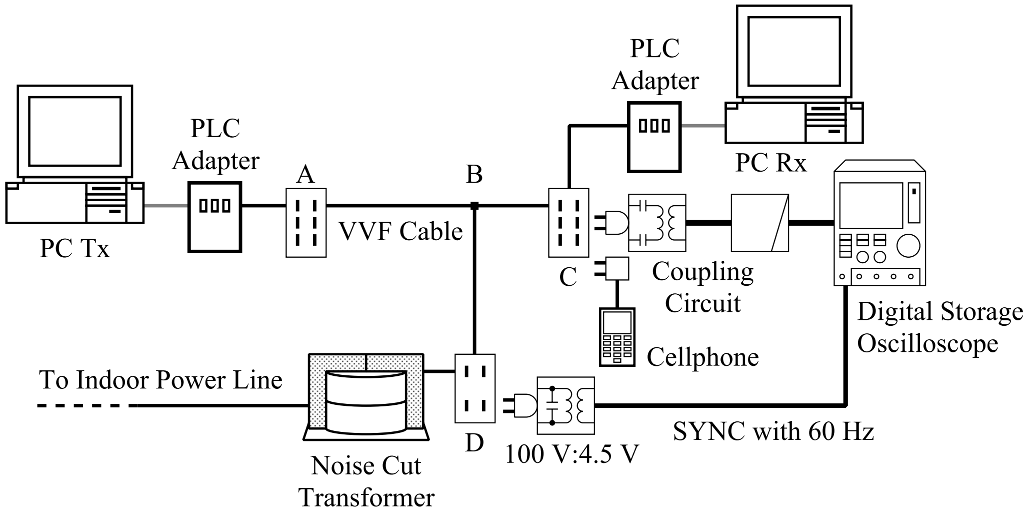


Fig. 12. Measurement system of data packets on the power line between two PLC adapters.

countermeasure to mitigate cyclo-stationary noise would work well in the case of HPAV and HD-PLC. Note that the fluctuations in UDP throughput for HD-PLC, shown in Figs. 10 and 11, cannot be observed in the experiment that provided the values listed in Table II. HD-PLC may be incompatible with the setting parameters, such as the transmission time and the sleep time, of the experiment in which the UDP throughput shown in Figs. 10 and 11 were obtained.

Let us recall that the attenuation ratio, $A_{k,3}$, is equal to 0.18, as shown in Table I. The switching parameters such as $V_{\rm thr}$, ΔV, and θ will be estimated at the receiver since they are deterministic. We consider a simple scheme that transmits data within the range of $H_{\rm Low}(f)$ and does not transmit any data otherwise. For example, in the case of HPAV and Channel (1-3), the simple scheme can achieve

$$R_{1,1}(1 - A_{1,3}) = 67.2 \text{ Mbps} > 59.6 \text{ Mbps} = R_{1,3}, \tag{7}$$

if it works ideally. Therefore, it is possible to obtain a higher throughput in the case of PLC adapters by optimizing the PHY and MAC layer.

B. STFT Analysis of PLC Signals

In this section, we investigate the transmission characteristic of signals from the PLC adapters via Channel (2-2) by STFT analysis in order to capture the influences of periodically switching channels on the electric data packets. Figure 12 illustrates the measurement system of data packets on the power line between two PLC adapters. Iperf is employed to ensure data traffic with a constant bit rate between two PCs.

Figures 13, 14, and 15 show the results of STFT analyses of HPAV, UPA, and HD-PLC for an offered load of 50 Mbps on Channel (2-2). In all figures, the horizontal axis corresponds to one power cycle and zero indicates a rising edge of power supply voltage. The attenuation region can be observed in both time and frequency, and it is around 0.25 and 0.75 on the horizontal axis and 24 MHz for all the figures.

The long and aggregated MAC frame can be clearly observed for all the figures. The attenuation duration, in which $H(t, f)$ is equal to $H_{\rm High}(f)$, is comparable to or less than the length of the aggregated MAC frame. A robust modulation and coding scheme, by which erroneous received data can be recovered, should be exploited in the attenuation region, whereas an efficient modulation and coding scheme, by which many bits can be received correctly per unit time, should be exploited in the non-attenuation region. As shown in Figs. 13 to 15, switching parameters such as $V_{\rm thr}$ and θ are deterministic and will be estimated for the PLC adapters. There are two challenging issues that arise in the case of periodically switching channels— how to estimate and track the switching parameters precisely and quickly and how to optimize the modulation and coding scheme and the MAC frame length on the basis of the estimated switching parameters.

The beacon and token for PLC adapters are investigated. HPAV transmits a beacon packet regularly, and its cycle corresponds to 2 power cycles. This can be confirmed by observing the received signal when there is no communication between PLC adapters. Further, HD-PLC transmits a beacon packet regularly and its cycle corresponds to approximately 2.8 power cycles. Hence, HPAV and HD-PLC have an almost silent period if they do not establish any communication. In particular, HPAV is scheduled to transmit the beacon packets when the channel condition is good in order to overcome cyclo-stationary noise [12]. HD-PLC may also be scheduled in a similar manner. On the other hand, the token packets of UPA are sent and received at frequent intervals. The number of round trips of the token packets is more than 10 in one power cycle, even when the adapters do not communicate with each other.

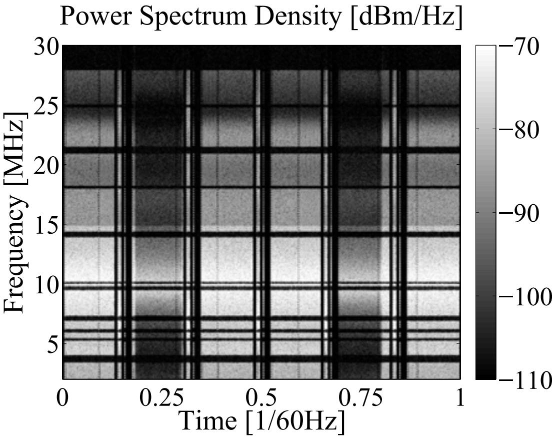


Fig. 13. STFT analysis of HPAV for an offered load of 50 Mbps on Channel (2-2).

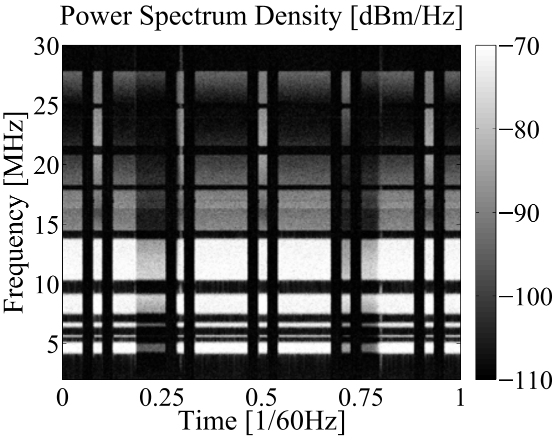


Fig. 14. STFT analysis of UPA for an offered load of 50 Mbps on Channel (2-2).

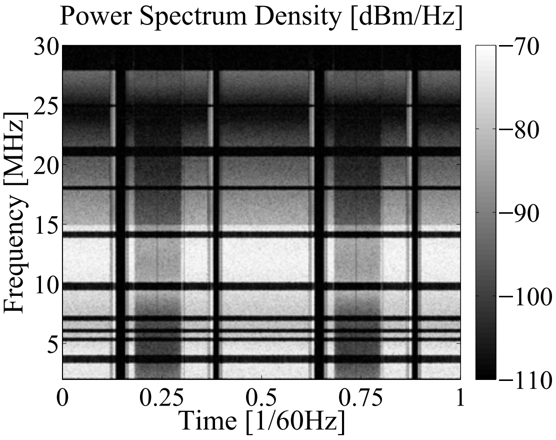


Fig. 15. STFT analysis of HD-PLC for an offered load of 50 Mbps on Channel (2-2).

IV. CONCLUSION

We have shown a number of examples of more significant time-variation of the channel response synchronized with the power frequency due to some types of switching regulators. The frequency responses of the power line channels alternate between two values and are synchronized with the power supply voltage if a switching power device is connected to the power line and the transient duration is extremely small. A channel with such a response is called a periodically switching channel in this paper. We have investigated the influences of periodically switching channels on commercial PLC adapters. The degradation of UDP throughput for HPAV and HD-PLC PLC adapters is not a matter of concern because these two technologies have a feature to mitigate cyclo-stationary noise.

The periodically switching channels are different in character from cyclo-stationary noise: Periodically switching channels are a a deterministic phenomenon whereas cyclo-stationary noise has a random nature. Therefore, it is possible to enhance the performance of the existing PLC adapters on periodically switching channels.

We would like to emphasize that the objective of this study is to investigate the influences of periodically switching channels on PLC adapters and present a novel study on periodically switching channels. We hope that the results presented in this paper will provide useful insights into the design of in-home power line communication.

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