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Improved Noise Reduction Scheme for Smart Grid Applications

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***Abstract*— In this paper, we propose clipping scheme and equalizer as methods to reduce the effects of impulsive noise and channel attenuation in power line communication (PLC) system. Clipping is cutting off the amplitude of the received signal over threshold level without its phase change in order to reduce noise effects. The equalizer compensates for effects of PLC channel. The performance is evaluated in terms of bit error rate (BER). From simulation results, it is confirmed that the proposed clipping scheme has slightly better performance than conventional PLC system. The results of the paper can be applied to PLC systems for smart grid.**

***Index Terms*— Power line communication, Noise reduction, smart grid, bit error rate.**

I. INTRODUCTION

Over the past few years, the electric power industry, state and federal regulators, government agencies, and universities have been considering with how to best update the aging electric power infrastructure. The general consensus is that the updated power grid not only must secure the future reliability of the power system in light of the increasing demand for electricity, but it also must operate with greater efficiency overall. From these considerations, the smart grid technology has attracted public attention. The goal of the smart grid is to use advanced, information-based technologies to increase power grid efficiency, reliability, and flexibility and reduce the rate at which additional electric utility infrastructure needs to be built [1], [2]. Besides this, explosive increase of demands for high quality of multimedia and convenient access has led to research a variety of communications technologies. To support the smart grid and meet the customer's desire, communication technologies should be considered fast data rate, reliable reception and access in anywhere.

As one of the promising candidates for smart grid, power line communication (PLC) is a leading technique because of its advantages. The most striking point is using the existing power line infrastructure, so installation cost is lower than other communication system. Besides this, communication service can be available everywhere outlets exist [1]. Since power line, however, have been made for electricity distribution purpose, its channel characteristic is very hostile for data transmission. There are lots of devices with variety impedance in PLC network, so this cause multipath environment. Also, impulsive noise is generated by random joint of each device, which sometimes exceeds power spectral density (PSD) of background noise by 50dB [2]. Because these are critical to the system performance, it needs

In this paper, we propose clipping scheme and equalizer as a method to overcome above issues. Clipping is cutting off amplitude of the received signal over threshold level and the equalizer compensates effects of PLC channel.

This paper is organized as follows. In Section II, we describe the PLC system and the channel model of PLC system is presented in Section III. The proposed PLC system model considered in this paper is described in Section IV. The performance of the proposed interference cancellation scheme is analyzed in Section V. Simulation results are shown in Section VI. Finally, applications and concluding remarks are given in Section VII and Section VIII.

II. POWER LINE COMMUNICATION SYSTEM

PLC is one of the promising communication technologies. This technology literally transmits data on electric power from a small number of sources (the generators) to a large number of sinks (the consumers) in the frequency range of 50-60Hz [3]. PLC technology begins to receive explosive attention in the smart grid and the home networking industry because of its several attractive advantages. The most useful advantage of them is a national-wide power line infrastructure. It is very robust and can be utilized anywhere using electricity. This point approaches low installation cost since it uses existing line as communication path [4], [5].

These days, PLC technology is mainly employed for access network and in-home communications networks. It also receives high attention in smart grid industry because other technologies typically spend the high cost about 50% of the investments making network infrastructure [4]. This type of PLC technologies is called, "last-inch" access. The development of the "last inch" by Home networking companies in the form wireless network adapters and power-line adapters is gradually leading to widespread home networking; i.e., a wide array of devices connected inside the home in an intra-home network.

Broadband PLC systems are applied to the telecommunications access area represent and alternative communications technology for the realization of the so-called "last-mile" access. This concept is the use of PLC technology to provide broadband Internet access through ordinary power lines. PLC subscribers are connected to the network by plugging PLC modems that ensure data transfer over low-voltage supply grids into any outlet in an equipped building high speed Internet access [3], [4].

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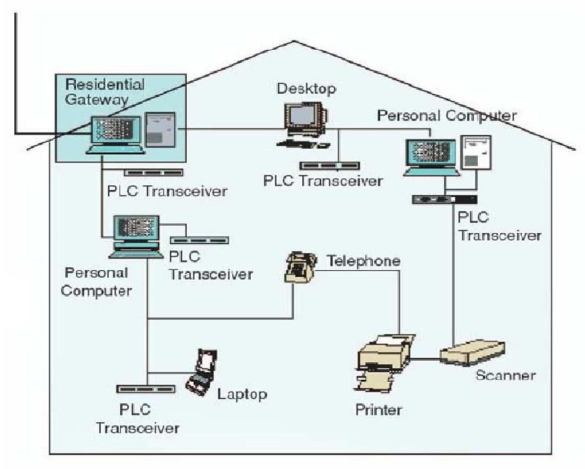

Fig. 1. Last-inch access

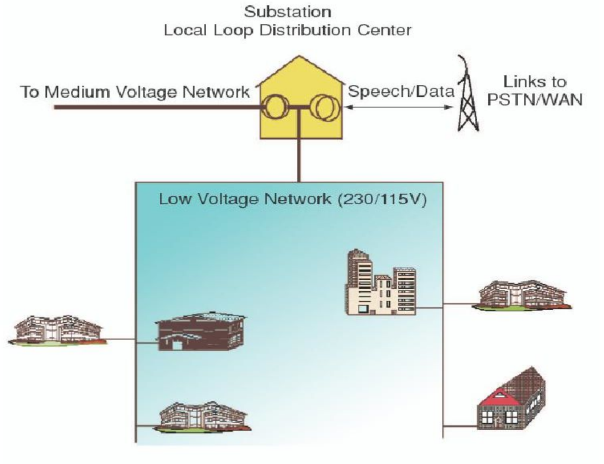

Fig. 2. Last-mile broadband access.

Power line is originally, however, designed for power delivery, not for data transmission. Therefore, there are many difficulties in data communication with power line. Varying impedance, considerable noise which includes white noise as well as impulse noise, and high levels of frequency-dependent attenuation are the representative issues.

First off, the PLC channel between any two outlets in a home has the transfer function of an extremely complicated line network because of being made of various conductor types, terminating in varying impedance, and being joined randomly. Over such a transmission medium, the amplitude and phase response may vary widely with frequency. Hence, some of the signals arriving at the receiver undergo little loss over some frequency, while another cannot be recognized over other frequencies at all. Second, there are reflection and multipath fading in PLC channel similar to wireless channel. The signal may be propagated along a line- of-sight (LOS) and suffer from reflections and delays due to the impedance mismatch with electric devices at the terminal. It causes multipath fading and high levels of frequency-dependent attenuation. Third is a noise issue. Among noise types in power line channel, there are asynchronous impulsive noise of which PSD may be as much as 50dB above the background noise spectrum. Thus, it can be wiping out blocks of data symbols during high data transmission at certain frequencies [3-5].

III. CHANNEL MODEL

A. Channel Model

The power line medium is an unstable transmission channel owing to the variance of impedance caused by the variety of appliances that could be connected to the power outlets. The impedance is mainly influenced by the characteristic impedance of the cables, the topology of the considered part of network and the nature of the connected electrical loads [6]. Hence signal reflection occurs at the impedance mismatching part, so that we should notice that signal propagation does not only take place along a direct line-of-sight path between transmitter and receiver, but additional paths (echoes) must also be considered. The result is a multipath scenario with frequency selective fading [7-10]. In this paper, we employed the multipath model proposed by M. Zimmermann and K. Dostert [11] and its scenario is described in Fig. 3. Multipath scenario is studied by a simple example which can be easily analyzed in Fig. 3.

The PLC channel has only one branch and is made of the parts AB, BC, and BD with the lengths l_{AB}, l_{BC}, and l_{BD} and the characteristic impedances Z_{AB}, Z_{BC}, and Z_{BD}.

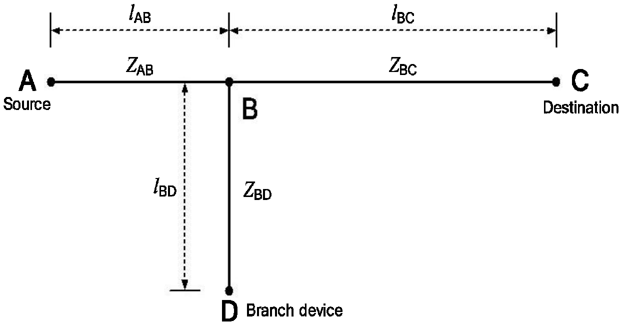

Fig. 3. Multipath scenario.

In order to simplify the considerations, the terminals and lines connecting directly are assumed to be matched, which means impedance of device A and B is equal to line impedance of Z_{AB} and Z_{BC}, respectably.

Although an infinite number of propagation paths are possible in principle due to multiple reflections, we consider just four paths in the channel. Each path i has a weighting factor g_i (which is a product of transmission and reflection factors), representing the product of the reflection and transmission factors along the path. All reflection and transmission factors at power lines are basically less or equal to one. This is due to the fact that transmission occurs only at joints, where the load of a parallel connection of two or more cables leads to resulting impedance being lower than the characteristic impedance of the feeding cable. Thus, the weighting factor g_i is also less or equal to one.

The more transitions and reflections occur along a path, the smaller the weighting factor g_i will be. Moreover, longer paths exhibit higher attenuation, so that they contribute less to the overall signal at the receiving point. Due to these facts, it is reasonable to approximate the basically infinite number of paths by only N dominant paths, and to make N as small as possible. Thus, the delay τ_i of a path can be shown as

$$i \quad \frac{d_i \quad r}{c_0} \quad \frac{d_i}{v_p},$$

where the dielectric constant ε_r of the insulating material, the speed of light c_0, and the lengths d_i of the cables. The losses of cables cause an attenuation increasing with length and frequency.

Noise Model

Fig. 4 illustrates a noise block diagram in PLC channel. The signal $s(t)$ is transmitted over PLC channel with the impulse response $h(t)$ and the various noises added to the signal passed the channel. Then, the received signal $r(t)$ is arrived at the receiver [7]. The noises can be typified into five categories: colored background noise, narrow-band noise, periodic impulsive noise synchronous or asynchronous to the main frequency (50~60Hz), and asynchronous aperiodic impulsive noise.

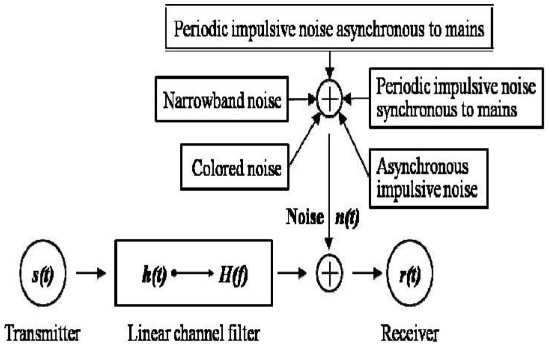

Fig. 4. Multipath scenario.

Some noise among them rarely has properties similar to the easily analyzed white Gaussian noise of the receiver [13], [14]. The background, narrow-band, and periodic asynchronous noise may be summarized as background noise since their properties are typically stationary over periods of seconds and minutes or sometimes even for hours. However, asynchronous impulsive noise and periodic synchronous impulsive noise are varying rapidly for microseconds to milliseconds. Therefore, it is necessary to set up impulsive noise model.

To establish impulsive noise model, we consider Middleton's Class A noise mode. For the Class A noise model [15], [16], the observed process is assumed to have two independent components:

$$z(t) \quad z_G(t) \quad z_P(t). \qquad (2)$$

The first term, $z_G(t)$, is a stationary background Gaussian noise component. The second term, $z_P(t)$, is the impulsive component of the interference and is represented by

$$z_P(t) U_l(t, \;), \quad {}_{l} \qquad (3)$$

where U_l denotes the l_{th} waveform from an interfering source and θ represents a set of random parameters that describe the scale and structure of the waveform. The arrival time of these independent impulsive events at the observer is assumed to be governed by a Poisson process. In addition, the waveforms add non-coherently when they overlap in time. Under these assumptions, probability density function (pdf) of the Class A noise as is given by

$$z \quad \frac{m}{2} \quad \frac{z^{2}}{2} \quad 2 \quad {}_{m\;0} \quad 2_{m} \quad {}_{m}$$

$$_{m} \quad e^{A} \quad \frac{A^{m}}{m!}, \qquad (5)$$

where m denotes the number of impulsive noise occurrence and A is called the impulsive index, which is the product of the average rate of impulsive noise and the mean duration of typical impulse.

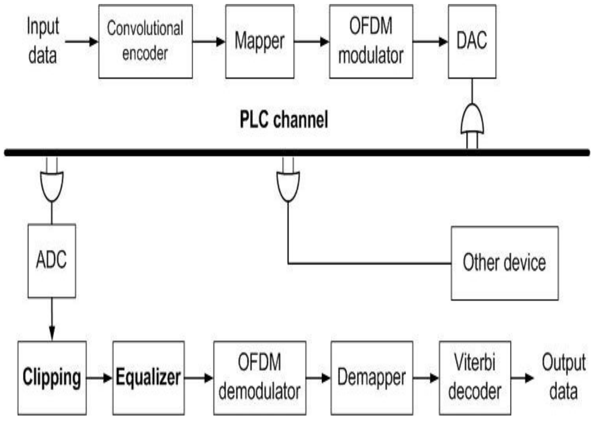

Fig. 5. Block diagram of proposed PLC system model.

IV. SYSTEM MODEL

PLC system model considered in this paper is illustrated in Fig. 5. Binary data stream is modulated by channel coding at the convolutional encoder. The channel coding compensates for the effect of channel fading. Then, the phase shift keying (PSK) modulated signal is changed serial signal to a number of parallel frames. Each frame is loaded subcarriers and summed up through inverse fast Fourier transform (IFFT). This signal is converted to analog at the digital-to-analog converter (DAC) and then transmitted via power lines. The received signal experienced a variety of noises changed to digital signal again at the analog-to-digital converter (ADC). Next, channel and impulsive noise are mitigated through the clipping and equalizer block. Finally, the received signal is recovered as the original data stream via FFT and demodulator.

PLC has hostile transmission channel due to the variance of impedance caused by a variety of appliances that could be connected to the power outlets. Hence signal reflection occurs at the impedance mismatching part, so that additional paths must also be considered. The result is a multipath channel with frequency selective fading [7]. In this paper, we employed the multipath channel model proposed in [11], and its impulse response is given as

$$H(f) \underset{i\;1}{\overset{N}{}} g_i \, e^{(a_o \quad a_1 f^{k}) d_i} \, e^{j2f(d_i/v_p)}, \qquad (7)$$

where, g_i is weighting term, $e^{(a_0 \; a_1 f_k) d_i}$ is attenuation term, and $e^{-j2\pi f(d_i/v_p)}$ is delay term.

V. NOISE REDUCTION SCHEME

A. ZF Receiver

In order to reject the interference, we consider the zero forcing (ZF) linear detectors which satisfy the condition shown below.

$$W_{ZF} H = I, \tag{8}$$

where $W_{ZF} = \left(H^H H\right)^{-1} H^H$ is the ZF decoding matrix, ^{H} denotes Hermitian transpose, H is channel matrix and I is identity matrix. The receiver can obtain the estimated signal by using ZF equalization, which is given by

$$\hat{X} = W_{ZF} Y, \tag{9}$$

where $\hat{X}$ is an estimate matrix of the transmitted signal. If the determinant of H is not zero so that there exists the inverse matrix of H, the decoding matrix can be expressed as

$$W_{ZF} = H^{-1}. \tag{10}$$

The ZF algorithm is ideal when the channel is noiseless. However, when the channel is noisy, the ZF algorithm will amplify the noise greatly where the channel has small magnitude in the attempt to invert the channel completely.

B. MMSE Receiver

In order to minimize the power of noise component, we employ the minimum mean square error (MMSE) algorithm, which is given by

$$W_{MMSE} = \underset{W_{MMSE}}{\arg\min}\, E\left\| W_{MMSE} Y - X \right\|_F^2, \tag{11}$$

where W_{MMSE} is the MMSE decoding matrix and $\|\cdot\|_F$ represents the Frobenius norm.

$$W_{MMSE} = \left(H^H H + \frac{1}{\lambda} I\right)^{-1} H^H, \tag{12}$$

where λ is signal-to-noise ratio (SNR).

The MMSE algorithm can be used to reject the interference with varying the decoding matrix in accordance with SNR. Besides, it prevents the noise component from being amplified.

C. Clipping Technique

The orthogonal frequency division multiplexing (OFDM) signal with long symbol period is more robust to impulsive noise because the impulse noise energy is spread over N subcarriers. If techniques mitigating impulsive noise, however, are not considered, it can still significantly affect the performance of OFDM systems, especially in a hostile medium such as power lines. In order to overcome the effect of impulsive noise, clipping technique is often employed in practical applications owing to its simplicity [17]. A clipping block is used at the front-end of OFDM receiver before demodulating. The most attractive point is that clipping changes only the amplitude of the signal over specific threshold level without changing its phase. Therefore, the received signal with clipping can be expressed as below.

$$y_n = \begin{cases} r_n, & |r_n| \le T_c \\ T_c e^{j\arg(r_n)}, & |r_n| > T_c \end{cases}, \quad n = 0, 1, \ldots, N-1, \tag{13}$$

where T_c denote the clipping threshold.

VI. SIMULATION RESULTS

In the paper, the size of data frame and CP length is 3072 and 336 samples each, and 30 packets are transmitted. Simulation is conducted at the case that the number of power line branches N_{br} is 3 and 5. The length of main line is fixed as 40m and length of the branches are determined randomly in the range of 2 to 10m every packet. It is also random that the state of each device at the end of branch is on or off. In the attenuation term of PLC channel model, the parameter k, a_0, and a_1 are set as 1, 0 m^{-1}, and 7.8×10^{-10} s/m, respectively [11]. In Middleton's Class A noise model, the parameters A and Γ are set as 0.1 each. It is also assumed devices in the end of branch lines are randomly on/off. We employ BPSK, QPSK, and 16QAM as a modulation scheme and simulate two cases that one has no channel coding, but the other includes convolutional code. The clipping scheme and equalizer are applied to all of the case. As an equalizer, ZF scheme is used.

A. Channel Response

Fig. 6 and Fig. 7 illustrate channel responses. As we mentioned above, PLC channels suffers from frequency selective fading. It can be also confirmed the magnitude of the channel is attenuated as the frequency increases. Also, as the number of branches increase, the channel state is getting poor because the reflection between devices and lines or branch lines and main lines often occurs. Since the reflection causes many paths and even inter-symbol-interference (ISI), it seriously affects PLC channel.

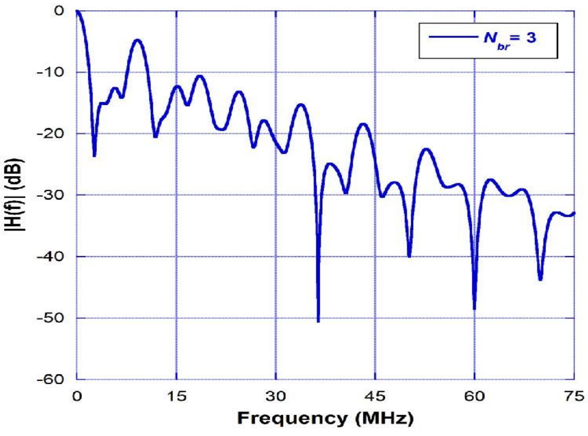

Fig. 6. Channel response. (N_{br} =3)

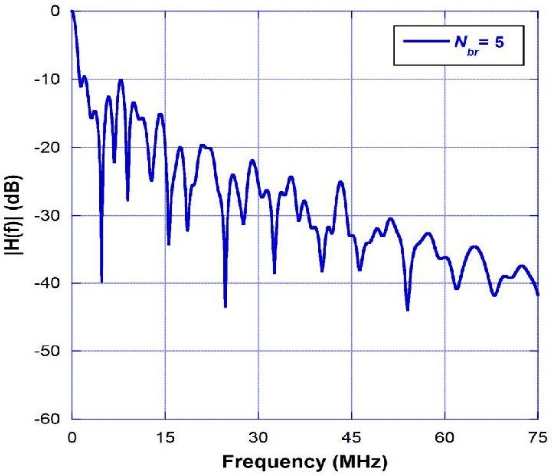

Fig. 7. Channel response. (N_{br} =5)

B. Error Performance of Proposed PLC System

Fig. 8 shows bite error rate (BER) for PLC system without channel coding. In the general cases with no clipping, BPSK, QPSK, and 16QAM illustrate 25dB, 28dB, and 32dB BER performance at 10^{-3}, respectively. In the event of applying clipping scheme, the performance for all cases increases around 0.5~0.6dB. Therefore, we confirm clipping improves the system performance slightly.

Fig. 9 shows BER performance in the case applying convolutional code to PLC system. At bit error rate 10^{-3}, overall system performances are improved approximately 6dB and there is 0.4~0.7dB additional improvement in terms of the effect of clipping. Therefore, BER performance for BPSK, QPSK, and 16QAM is 18.5dB, 21.3dB, and 25.6dB at the above point, respectively.

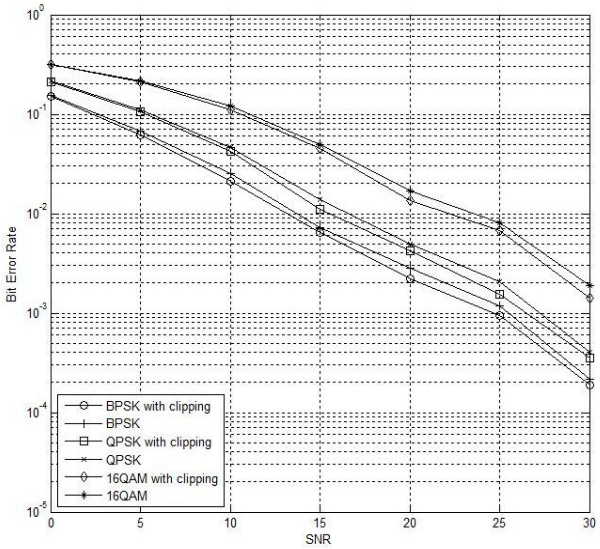

Fig. 8. Performance of the uncoded-PLC system employing noise reduction scheme in PLC channel.

VII. SYSTEM APPLICATIONS

To realize an efficient smart grid, it is necessary that communication technologies support it. The PLC has been known to be very promising enough among various candidates for the smart grid communications because it just uses existing power line infrastructure.

The PLC requires just low installation cost and network charge. Moreover, it has advantage that is easy to combine with other technologies such as visual light communication (VLC), Bluetooth, Zigbee, UWB and so on. These days, communications for the smart grid should cover from simple control signal transmission such as auto meter reading (AMR), distribution automation system (DAS), energy management service (EMS), home area network (HAN), and supervisory control and data acquisition (SCADA), intelligent building system (IBS), smart energy (SE) technology, and plug-in hybrid electric vehicle (PHEV) to high capacity multimedia content transmission like real time movie and voice service, parking management service, building information providing service and so on. Therefore, the proposed scheme can be properly applied to those application based on PLC environment because of its advantages we have continuously mentioned. Fig. 10 illustrates simple application example for home network of the proposed system.

Since the Clipping technique reduces impulsive noise generated by the electronic sources of various home appliances, we can enjoy the internet and home network service without any disturbance, using the printer and the fax at the same time. Also, the billing for electricity can be accurately achieved due to improved network reliability, so that it is possible not only to make flexible electricity bill plans, but also to build a robust back-bone network instead of optical fiber or cable. Therefore, the proposed scheme satisfies customers and providers with the diverse services.

CONCLUSIONS

In this paper, we analyzed and simulated the performance of PLC systems using the clipping and the equalizer. We confirmed that the BER performance of PLC systems with clipping scheme was slightly improved in comparison with the normal case without clipping. The performance improvement was also demonstrated in the case applying convolutional code. Therefore, we confirmed the clipping scheme is good for mitigating impulsive noise in PLC system, even though it increase BER performance slightly. The results of this paper can be applied to reduce impulse noise in the PLC system for smart grid.

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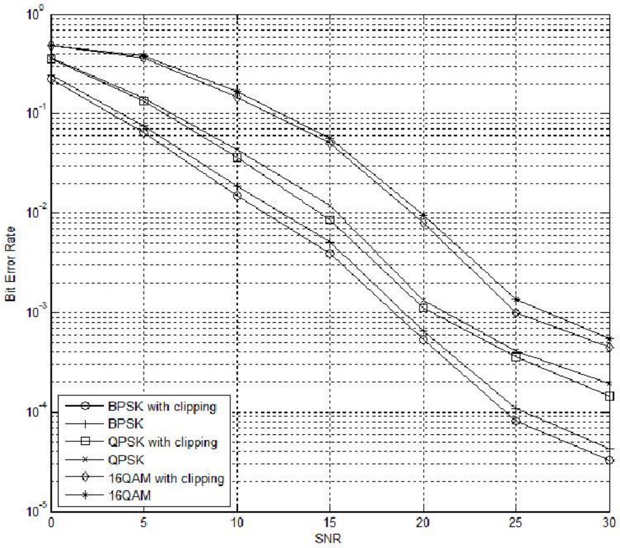

Fig. 9. Performance of the coded-PLC system employing noise reduction scheme in PLC channel. (Convolutional code)

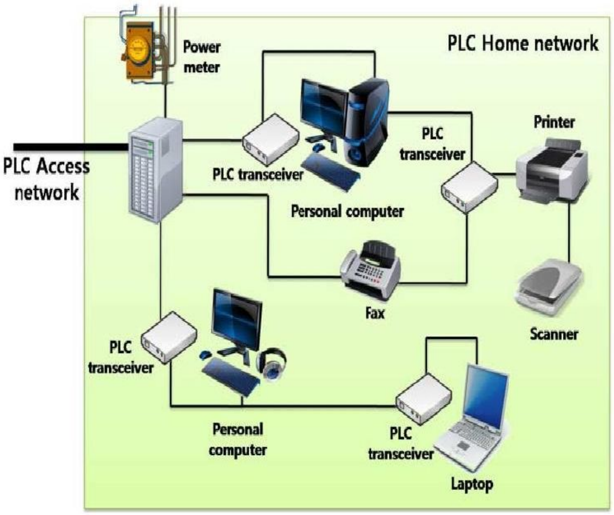

Fig. 10. Application example of the proposed scheme