Frontiers of Information Technology & Electronic Engineering
www.zju.edu.cn/jzus; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Performance analysis for a two-way relaying power line network with analog network coding*

Yu-wen QIAN[†1], Meng TIAN[1], Xue JIANG[1], Hua-ju SONG[2], Feng SHU[1], Jun LI[1]

([1]*School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China*)

([2]*School of Biochemical and Environmental Engineering, Nanjing Xiao Zhuang University, Nanjing 210011, China*)

[†]E-mail: admon1999@163.com

Received Apr. 28, 2015; Revision accepted Aug. 10, 2015; Crosschecked Sept. 16, 2015

Abstract: In this paper, we investigate a two-way relaying power line communication (PLC) network with analog network coding. We focus on the analysis of the system outage probability, symbol error rate, and average capacity. Specifically, we first derive the probability density function (PDF) of the received signal-to-noise ratio (SNR) with a closed form, by exploiting the statistical properties of the PLC channel. Then with the help of this PDF, we develop the outage probability, symbol error rate, and average capacity with closed forms, based on the Hermite polynomial. Simulations show that the derived analytical results are consistent with those by Monte Carlo simulation.

Key words: Power line communication, Outage probability, Symbol error rate, Signal attenuation
doi:10.1631/FITEE.1500135 **Document code:** A **CLC number:** TN915.853

1 Introduction

Power line communications (PLCs) encounter a more hostile communication environment compared to conventional wire-line and wireless communications due to severe signal fading and impulsive noises. In the presence of impulsive noises in PLCs, the signal-to-noise ratio (SNR) falls drastically. Also, PLC channels vary quickly with the locations of transmitters, network topologies, and connected loads (Güzelgöz *et al.*, 2011). These negative factors severely affect the reliability of PLC systems, thereby imposing many unsolved challenges on reliable communications over long-distance power lines.

Recently, relay aided technologies have become an attractive solution for reliable communications in PLCs (Popovski and Yomo, 2007). In Zou *et al.* (2009), a PLC relay scheme for a multi-user scenario was designed to maximize the system throughput by optimizing both the channel and power allocations. Lampe and Han Vinck (2011) proposed a cooperative relaying communication approach based on fountain codes to alleviate the fading impacts on narrow-band PLC channels. In Kuhn *et al.* (2010), relay nodes were used to combine wireless local area networks (LANs) and PLC networks, which improves the robustness of the 'hybrid' networks. Opportunistic relay schemes were discussed in Tonello *et al.* (2010) for improving network capacity and extending communication ranges in power-line networks. Furthermore, the performance of PLC relaying systems has been analyzed (Balakirsky and Han Vinck, 2005). In Tan and Thompson (2011), transmit rates of two communication protocols were analyzed in a PLC relaying system according to the distance between the transmitters and relays. In Lampe *et al.* (2006), the outage probability was developed for a multi-hop PLC relaying network with distributed space-time block coding (DSTBC). In Cheng *et al.* (2013),

* Project supported by the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University, China (No. 2013D02) and the National Natural Science Foundation of China (Nos. 61271230 and 61472190)
ORCID: Yu-wen QIAN, http://orcid.org/0000-0001-9503-549X

the capacity bound of an amplify-and-forward based PLC relaying system has been derived and analyzed.

In this paper, we focus on a two-way relaying PLC system, where two sources exchange information with the help of an intermediate relay implementing analogue network coding. To the best of our knowledge, our work is the first of its kind to introduce network coding technology to PLC systems. We are particularly interested in analyzing both the outage probability (OP) and symbol error rate (SER) of this system, with the channel magnitudes being log-normally distributed. We first develop the probability density function (PDF) of the received SNR based on the distribution of PLC channels. Then based on this derived PDF, we derive the OP, SER, and average capacity performance of our PLC system. To obtain the closed forms of the OP, SER, and average capacity, we propose an approximated method based on the Hermite polynomial. Simulations show that the performance of the PLC system with the relay clearly outperforms that of the one without the relay.

2 PLC system with analog network coding

Consider the system shown in Fig. 1. Two terminals S_1 and S_2 communicate with each other through terminal R, which acts as a relay.

To use the two-way relaying scheme combined with network coding, our relay protocol employs a two-stage transmission scheme. In the first time slot, S_1 and S_2 send messages X_1 and X_2, respectively, to relay node R. The received signal at R can be written as

$$Y_R = h_1\sqrt{p_S}X_1 + h_2\sqrt{p_S}X_2 + n_1(t), \tag{1}$$

where h_1 is the fading amplitude of the channel between S_1 and R, h_2 is the fading amplitude of the channel between R and S_2, p_S is the transmitting power, and $n_1(t)$ is the noise signal with variance σ_0^2.

In the second time slot, the received signal is multiplied by the amplify-and-forward (AF) gain G at relay R, and then retransmitted to terminals S_1 and S_2. Under the total transmitting power constraint at the relay node, the gain G at the relay node is chosen to be

$$G^2 = \frac{1}{h_1^2 + h_2^2 + N_0}, \tag{2}$$

where $N_0 = p_S/\sigma_0^2$ is the average SNR. After receiving the superimposed information, the relaying terminal R broadcasts this signal directly to the two sources with power normalization. Since there is no decoding or detection at the relay node, the complexity is very low. Hence, the received signal at terminal S_2 is

$$Y_{R,S_2} = h_2G\left(h_1X_1 + h_2X_2 + n_1(t)\right) + n_2(t), \tag{3}$$

where $n_2(t)$ is the noise signal with variance σ_0^2.

X_1 and X_2 are signals transmitted at the first time slot. Therefore, S_1 and S_2 can perform network decoding and obtain the desired signal. After terminal S_2 has cancelled the self-interference signal X_2, the resulting received signal is

$$Y_{R,S_2} = h_2G\left(h_1X_1 + n_1(t)\right) + n_2(t). \tag{4}$$

The overall SNR at terminal S_2 can be written as

$$\gamma_{S_2} = \frac{\left(h_2Gh_1\right)^2}{h_2^2G^2N_0 + N_0}. \tag{5}$$

Substituting Eq. (2) into Eq. (5) yields

$$\gamma_{S_2} = \frac{1}{\sigma_0^2}\frac{h_1^2h_2^2}{\dfrac{p_S}{p_R}h_1^2 + \left(1 + \dfrac{p_S}{p_R}\right)h_2^2 + \dfrac{\sigma_0^2}{p_R}}, \tag{6}$$

where p_R is the transmitting power of the relaying node.

According to Dubey *et al.* (2014), the PLC channels are subjected to a mixture of Gaussian noise and impulsive noise. The two noises are independent. Hence, the variance of channel noise can be obtained by

$$\sigma_0^2 = \sigma_{\mathrm{G}}^2 + o\cdot\sigma_{\mathrm{I}}^2, \tag{7}$$

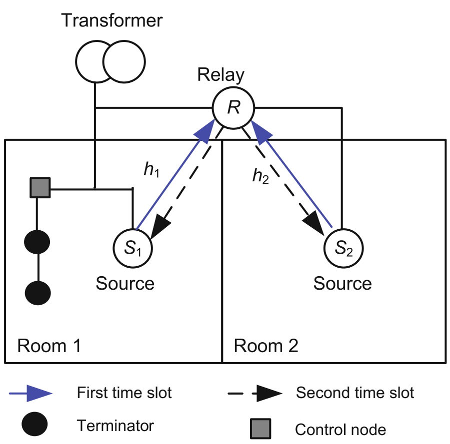

Fig. 1 In-home PLC amplify-and-forward relay system

where σ_{G}^2 and σ_{I}^2 are variances of the Gaussian noise and impulsive noise, respectively, and o is a constant.

For convenience of calculation, we use an equivalent SNR

$$\gamma_{\mathrm{eq}} = \frac{\gamma_1\gamma_2}{a\gamma_1 + b\gamma_2 + c}, \tag{8}$$

where $a = p_S/p_R$, $b = 1 + p_S/p_R$, $c = \sigma_0^2/p_R$, $\gamma_1 = h_1^2$, and $\gamma_2 = h_2^2$. Hence, the equivalent SNR as shown in Eq. (8) satisfies $\gamma_D = \gamma_{\mathrm{eq}}/\sigma_0^2$. In the following sections, we derive the probability distribution of the equivalent SNR.

3 Performance analysis of relay PLC system

In this section, we analyze the performance of the two-hop AF network system described in the previous section. We first characterize the statistics of the received SNR. Then, expressions of the outage probability, SER, and average capacity are derived.

3.1 Statistic properties of SNR

For a multi-path fading channel, the statistical model is more general when compared with the model with specific data. The statistical model of a PLC channel depends on the distributions of path amplitudes. According to Bumiller *et al.* (2010), the amplitude is given as

$$h = |g|\mathrm{e}^{-\alpha c\cdot\tau}, \tag{9}$$

where $|g|$ is a path constant, α and c are constants, and τ is a random variable following normal distribution with mean μ_τ and variance σ_τ^2. As shown in Fig. 1, nodes in PLC systems communicate with each other by only one power line. By Bumiller *et al.* (2010) and Dubey *et al.* (2014), the PDF of h is a log-normal distribution with PDF $f_h(x)$:

$$f_h(x) = \frac{1}{\sqrt{2\pi\sigma^2}x}\exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right), \tag{10}$$

where $\mu = \mu_\tau = 1 + \ln|g|$ and $\sigma^2 = \sigma_\tau^2$.

Because $\gamma_1 = h_1^2$ and $\gamma_2 = h_2^2$, we can obtain the PDF of γ_1 and γ_2 by

$$f_{\gamma_1}(x) = f_{\gamma_2}(x) = \frac{1}{2\sqrt{2\pi\sigma^2}x}\exp\left(-\frac{\left(\frac{1}{2}\ln x - \mu\right)^2}{2\sigma^2}\right). \tag{11}$$

The cumulative distribution function (CDF) of γ_1 and γ_2 would be written as

$$F_{\gamma_1}(x) = F_{\gamma_2}(x) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\ln x - 2\mu}{2\sqrt{2}\sigma}\right). \tag{12}$$

To analyze the performance of a two-way AF relay system, the CDF of the equivalent SNR γ_{eq} needs to be obtained. By Eqs. (8) and (11), the CDF of γ_{eq} is given by

$$\begin{aligned} F_{\gamma_{\mathrm{eq}}}(t) &= \Pr\left(\frac{\gamma_1\gamma_2}{a\gamma_1 + b\gamma_2 + c} < t\right) \\ &= \int_0^\infty F_{\gamma_1}\left(\frac{t\,(bx + c)}{x - at}\right) f_{\gamma_2}(x)\mathrm{d}x. \end{aligned} \tag{13}$$

3.2 Outage analysis

The outage probability is defined as the probability that the SNR of the receiver drops below the acceptable threshold γ_{th}. It is an important measure of quality of service of PLC networks, and can be obtained according to Theorem 1.

Theorem 1 (Outage probability) Let the amplitude of the PLC channel follow a log-normal distribution with mean μ and variance σ^2. The closed-form outage probability is given by

$$P(\gamma \le \gamma_{\mathrm{th}}) \cong 1/2 + \Psi_{\gamma_{\mathrm{eq}}}(\gamma_{\mathrm{th}}), \tag{14}$$

where γ_{th} is a threshold and $\Psi_{\gamma_{\mathrm{eq}}}(t)$ can be obtained from

$$\begin{aligned} \Psi_{\gamma_{\mathrm{eq}}}(\gamma) \approx& \frac{1}{2\sqrt{\pi}}\sum_{i=1}^{l} H_i \\ &\cdot \mathrm{erf}\left(\frac{\ln t\cdot \dfrac{b\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu} + c}{\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu} - at} - 2\mu}{2\sqrt{2}\sigma}\right), \end{aligned} \tag{15}$$

where s_i is the ith zero of the Hermite polynomial, H_i is the weight factor of the Hermite polynomial, and l is the order of the Hermite polynomial, set to be 100 in this study.

Proof We define the probability of instantaneous SNR below the threshold γ_{th} as

$$P_{\mathrm{out}} = P(\gamma \le \gamma_{\mathrm{th}}). \tag{16}$$

Substituting Eq. (13) into Eq. (16), we obtain the

CDF of $\gamma_{\rm eq}$ as

$$F_{\gamma_{\rm eq}}(\gamma_{\rm th}) = \int_0^\infty \left(\left(\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{\ln\gamma_{\rm th}\cdot\dfrac{bx+c}{x-a\gamma_{\rm th}}-2\mu}{2\sqrt{2}\sigma}\right)\right) \cdot\frac{1}{2\sqrt{2\pi}\sigma x}\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\right)\mathrm{d}x. \tag{17}$$

We rewrite Eq. (17) as

$$F_{\gamma_{\rm eq}}(\gamma_{\rm th}) = \int_0^\infty \frac{1}{4\sqrt{2\pi}\sigma x}\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\mathrm{d}x + \frac{1}{4\sqrt{2\pi}\sigma}\int_0^t\left(\frac{1}{x}\mathrm{erf}\left(\frac{\ln t\cdot\dfrac{bx+c}{x-at}-2\mu}{2\sqrt{2}\sigma}\right) \cdot\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\right)\mathrm{d}x. \tag{18}$$

We can conclude that the first item on the right side of Eq. (18) is 1/2. According to Abramowitz and Stegun (1970), we have the approximation

$$\int_{-\infty}^\infty f(x)\cdot \mathrm{e}^{-x^2}\mathrm{d}x \approx \sum_{i=1}^N H_i\cdot f(x). \tag{19}$$

Let $s=((\ln x)/2-\mu)/(\sqrt{2}\sigma)$. We define the second item on the right side of Eq. (18) as $\Psi_{\gamma_{\rm eq}}(t)$:

$$\Psi_{\gamma_{\rm eq}}(t)=\frac{1}{2\sqrt{\pi}}\int_{-\infty}^{\ln t}\mathrm{erf}\left(\frac{\ln t\cdot\dfrac{bs+c}{s-at}-2\mu}{2\sqrt{2}\sigma}\right)\mathrm{e}^{-s^2}\mathrm{d}s. \tag{20}$$

Combining Eqs. (19) and (20), Eq. (15) holds. Hence, we complete the proof of Theorem 1.

3.3 Symbol error rate

In this subsection, we derive the closed-form expression for the average symbol rate of the two-way AF relay system in Fig. 1. As McKay *et al.* (2007) suggested, the general SER expression for digital modulation is

$$P_{\rm SER}=mE_\gamma(Q(\sqrt{n\gamma})), \tag{21}$$

where $Q(x)=m/(\sqrt{2\pi})\cdot\int_x^\infty\exp(t^2/2)\mathrm{d}t$, and m and n are modulation-specific parameters related to the order and type of modulation, respectively. We rewrite the SER expression given in Eq. (21) as

$$P_{\rm SER}=\frac{m}{\pi}\int_0^\infty\left(\int_{\sqrt{nt}}^\infty \mathrm{e}^{-v^2}\mathrm{d}v\right)f_{\gamma_{\rm eq}}(t)\mathrm{d}t. \tag{22}$$

We apply integration by parts to Eq. (22), and have

$$P_{\rm SER}=\frac{m\sqrt{n}}{2\sqrt{\pi}}\int_0^\infty\frac{\mathrm{e}^{-nt}}{\sqrt{t}}F_{\gamma_{\rm eq}}(t)\mathrm{d}t. \tag{23}$$

Substituting Eq. (17) into Eq. (22), we obtain Eq. (24), which is shown at the bottom of this page.

According to Eq. (18), Eq. (24) can be transformed to be

$$P_{\rm SER}=\frac{m\sqrt{n}}{2\pi}\int_0^\infty\int_0^\infty\left(\frac{\mathrm{e}^{-nt}}{\sqrt{t}} \cdot\left(\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{\ln t\cdot\dfrac{bx+c}{x-at}-2\mu}{2\sqrt{2}\sigma}\right)\right) \cdot\frac{1}{2\sqrt{2\pi}\sigma x}\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\right)\mathrm{d}x\mathrm{d}t. \tag{25}$$

From Eq. (15), Eq. (25) can be transformed to

$$P_{\rm SER}\approx\frac{m}{\pi}\int_{-\infty}^\infty\left(\frac{1}{2}+\Psi_{\gamma_{\rm eq}}\left(\frac{q^2}{n}\right)\right)\mathrm{e}^{-q^2}\mathrm{d}q. \tag{26}$$

Then, the final average symbol error rate is given by

$$P_{\rm SER}\approx\frac{m}{2\pi}\frac{1}{2\sqrt{\pi}}\sum_{j=1}^l H_j\left(\frac{1}{2}+\sum_{i=1}^l H_i \cdot\mathrm{erf}\left(\frac{\ln q_j^2\cdot\dfrac{bn\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}+nc}{n\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-aq_j^2}-2\mu}{2\sqrt{2}\sigma}\right)\right), \tag{27}$$

where s_i and q_j are the ith and jth zeros of the Hermite polynomial, respectively.

$$P_{\rm SER}=\frac{m\sqrt{n}}{2\pi}\int_0^\infty\frac{\mathrm{e}^{-nt}}{\sqrt{t}}\left(\int_0^\infty\left(\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{\ln t\cdot\dfrac{bx+c}{x-at}-2\mu}{2\sqrt{2}\sigma}\right)\right)\frac{1}{2\sqrt{2\pi}\sigma x}\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\mathrm{d}x\right)\mathrm{d}t. \tag{24}$$

3.4 Average channel capacity

The average channel capacity is an important performance metric for a communication channel. It reveals the maximum amount of information that can be transmitted. According to the CDF of the SNR in Eq. (13), we can obtain Theorem 2.

Theorem 2 (Average channel capacity) In a two-way PLC AF relay system, the instantaneous capacity is given by Eq. (28) (at the bottom of this page), where s_i is the ith zero of the Hermite polynomial and H_i is the weight of the Hermite polynomial.

Proof The channel capacity can be expressed as

$$C(\gamma)=\mathrm{BW}\int_0^{\infty}\log_2\left(1+\frac{p_S}{\sigma^2}\gamma\right)f_{\gamma_{\rm eq}}(\gamma)\mathrm{d}\gamma, \quad (29)$$

where BW is the bandwidth of the transmitted signal.

Considering γ_1 and γ_2 as being independent and identically distributed, we can obtain $f_{\gamma_{\rm eq}}(\gamma)$:

$$f_{\gamma_{\rm eq}}(\gamma)=\int_0^{\infty}\frac{x-a\gamma}{2\sqrt{2\pi}\sigma\gamma(bx+c)}\exp\left(-\frac{\left(\frac{1}{2}\ln\frac{\gamma(bx+c)}{x-a\gamma}-\mu\right)^2}{2\sigma^2}\right)\cdot\frac{1}{2\sqrt{2\pi}\sigma x}\exp\left(-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}\right)\mathrm{d}x. \quad (30)$$

Let $s=((\ln x)/2-\mu)/(\sqrt{2}\sigma)$. Then

$$f_{\gamma_{\rm eq}}(\gamma)=\int_0^{\infty}\frac{\mathrm{e}^{2\sigma\sqrt{2}s+2\mu}+c}{2\sqrt{2\pi}\sigma(a\mathrm{e}^{2\sigma\sqrt{2}s+2\mu}-b)}\cdot\exp\left(-\frac{1}{2\sigma^2}\left(\frac{1}{2}\ln\frac{\gamma\left(b\mathrm{e}^{2\sigma\sqrt{2}s+2\mu}+c\right)}{\mathrm{e}^{2\sigma\sqrt{2}s+2\mu}-a\gamma}-\mu\right)^2\right)\mathrm{e}^{-s^2}\mathrm{d}s. \quad (31)$$

Eq. (31) can be transformed to Eq. (32), which is shown at the bottom of this page. Substituting Eq. (32) into Eq. (29) yields $\overline{C}$, as given in Eq. (33), which is also shown at the bottom of this page. By Abramowitz and Stegun (1970) and Eq. (33), Eq. (28) holds. This completes the proof of Theorem 2.

4 Simulation results

In this section, we present numerical results. The fading parameter σ for a PLC channel depends on the PLC network and frequency band. The value of σ increases with the increase of the number of the loads connected to the PLC network. When used for communication, σ is often represented on a dB scale, that is, σ (in dB) $=(10/\ln10)\sigma$. We have considered two different values of σ, 3 and 10, corresponding to good fading and bad fading, respectively. We build a Monte Carlo simulation model to compare its results with those found from the analytical model. Specifically, we average the performance in simulations over 1000 network cases, and the channel coefficients vary in each case. The impulsive noise parameter o is

$$\overline{C}=\sum_{i=1}^{l}\sum_{j=1}^{l}H_iH_j\log_2\left(1+\frac{p_S}{\sigma^2}\frac{\mathrm{e}^{2\mu+2\sigma v_j}\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}}{b\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}+c+a\mathrm{e}^{2\mu+2\sigma v_j}}\right)\frac{\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}\left(1-\frac{a\mathrm{e}^{2\mu+2\sigma v_j}}{b\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}+c+a\mathrm{e}^{2\mu+2\sigma v_j}}\right)}{b\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}+c}\cdot\frac{2a\sigma\mathrm{e}^{2\mu+2\sigma v_j}\left(b\mathrm{e}^{2\sqrt{2}\sigma s_i+2\mu}+c+a\mathrm{e}^{2\mu+2\sigma v_j}\right)-2\sigma\mathrm{e}^{2\mu+2\sigma v_j}}{\left(bs_i+c+a\mathrm{e}^{2\mu+2\sigma v_j}\right)^2}. \quad (28)$$

$$f_{\gamma_{\rm eq}}(\gamma)=\sum_{i=1}^{l}H_i\frac{\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-a\gamma}{2\sqrt{2\pi}\sigma(b\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}+c)}\exp\left(-\left(\frac{1}{2}\ln\frac{\gamma(b\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}+c)}{\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-a\gamma}-\mu\right)^2\Big/(2\sigma^2)\right). \quad (32)$$

$$\overline{C}=\int_0^{\infty}\log_2\left(1+\frac{p_S}{\sigma_0^2}\gamma\right)\sum_{i=1}^{l}H_i\frac{\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-a\gamma}{2\sqrt{2\pi}\sigma(b\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}+c)}\exp\left(-\left(\ln\frac{\gamma(2\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-1)}{\mathrm{e}^{2\sigma\sqrt{2}s_i+2\mu}-\gamma}-2\mu\right)^2\Big/(4\sigma^2)\right)\mathrm{d}\gamma. \quad (33)$$

3.27×10^{-3}, denoting the occurrence of the impulsive noise. Because we use only one power line as the communication medium, we set g in Eq. (9) as 1.

Fig. 2 shows the outage probability P_{out} versus the received SNR for the relaying PLC system with analog network coding. The computational curves are obtained using the approximate closed-form expression given by Eq. (13). The analytical results and simulation results are in good agreement. Note that the performance of the outage probability becomes worse with the increase of σ. However, for the same value of σ, the outage probability of the PLC system with relay is much better than that of the PLC system without relaying. The reason is that the outage performance of the PLC systems is affected by signal fading. The relay-aided PLC system achieves a better outage performance by alleviating signal fading.

Fig. 3 shows the average symbol error rate (SER) against the received SNR. We examine the SER in different modulations, including BPSK, 4-PAM, and 8-PAM. The SER of a channel is highly affected by the received SNR and fading parameter σ. The gap between SER of the relaying system and that of a direct communication system increases with the increase of SNR. At high SNR, the SNR performance of the PLC system with relaying is highly affected by the value of σ. When adopting the two-way relaying scheme with analog network coding, the SER performance of the PLC system is significantly improved. The reason is that the SER performance of the PLC system depends mainly on the noise, especially the impulsive one. The SER performance degrades sharply in a direct link system. However,

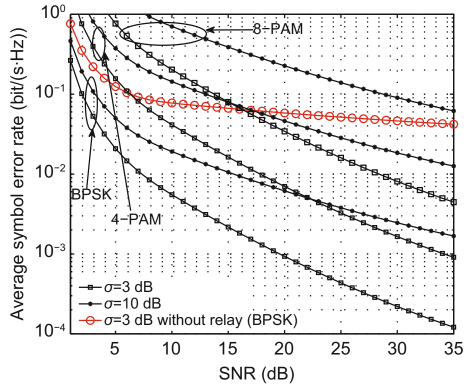

Fig. 3 Symbol error rate against average received SNR with σ=3 dB and σ=10 dB

when adopting a relay, the received SNR turns out to be larger, which improves the SER performance of the PLC system. Given the same transmission power, the minimum Euclidean distance in BPSK is larger than that in 4-PAM and 8-PAM, while the minimum Euclidean distance in 8-PAM is the smallest among the three modulation schemes. Hence, the BPSK system performs best, while the 8-PAM system performs worst.

Fig. 4 shows the curves of instantaneous channel capacity against the value of the transmit SNR of the PLC system. From Eq. (28), the average capacity is computed using the integral of the received SNR from zero to infinity. Thus, we select the transmit SNR as the horizontal axis. Several interesting conclusions can be drawn from Fig. 4. First, the computational curves obtained using Eq. (28) are found to agree well with the simulation curves, which validates the correctness of our verdict. Second, the two-way relay scheme outperforms the direct

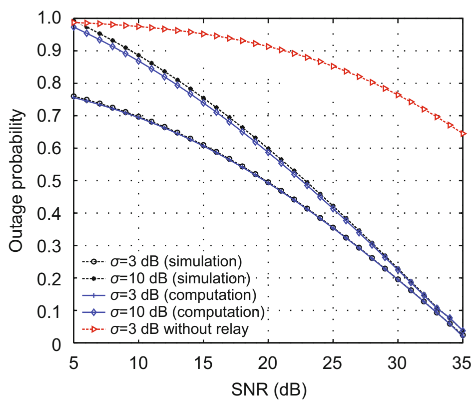

Fig. 2 Average outage probability against average received SNR with σ=3 dB and σ=10 dB

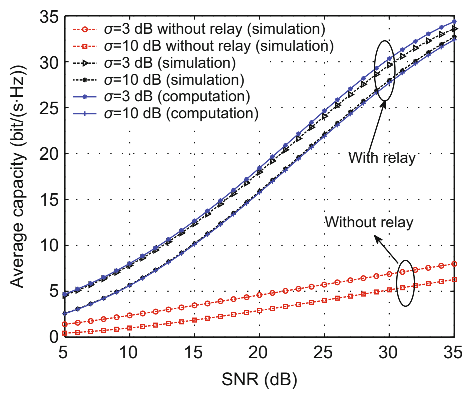

Fig. 4 Average system capacity against SNR with σ=3 dB and σ=10 dB

transmission scheme in terms of capacity. Third, the channel capacity of the relay scheme increases with the decrease of σ. Hence, at high value of SNR, the dominant factor of capacity is σ.

5 Conclusions

In this paper, the performance of the relaying PLC system based on analog networking is presented. The formula of the PDF of received SNR is derived. Then the outage probability, SER, and average channel capacity are calculated. Simulations verified the correctness of the derived expressions. We have also found that introducing a two-way relay can significantly improve the performance of a PLC system.

References

Abramowitz, M., Stegun, I.A., 1970. Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables (9th Ed.). Dover Publications, New York.

Balakirsky, V.B., Han Vinck, A.J., 2005. Potential performance of PLC systems composed of several communication links. Proc. IEEE Int. Symp. on Power Line Communications and Its Applications, p.6-8. [doi:10.1109/ISPLC.2005.1430456]

Bumiller, G., Lampe, L., Hrasnica, H., 2010. Power line communication networks for large-scale control and automation systems. *IEEE Commun. Mag.*, **48**(4):106-113. [doi:10.1109/MCOM.2010.5439083]

Cheng, X.L., Cao, R., Yang, L.Q., 2013. Relay-aided amplify-and-forward powerline communications. *IEEE Trans. Smart Grid*, **4**(1):265-272. [doi:10.1109/TSG.2012.2225645]

Dubey, A., Mallik, R.K., Schober, R., 2014. Performance analysis of a power line communication system employing selection combining in correlated log-normal channels and impulsive noise. *IET Commun.*, **8**(7):1072-1082. [doi:10.1049/iet-com.2013.0299]

Güzelgöz, S., Celebi, H.B., Arslan, H., 2011. Statistical characterization of the paths in multipath PLC channels. *IEEE Trans. Power Deliv.*, **26**(1):707-712. [doi:10.1109/TPWRD.2010.2080291]

Kuhn, M., Berger, S., Wittneben, I.H., *et al.*, 2010. Power line enhanced cooperative wireless communications. *IEEE J. Sel. Areas Commun.*, **24**(7):1401-1410. [doi:10.1109/JSAC.2006.874407]

Lampe, L., Han Vinck, A.J., 2011. On cooperative coding for narrow band PLC networks. *AEU Int. J. Electron. Commun.*, **65**(8):681-687. [doi:10.1016/j.aeue.2011.01.011]

Lampe, L., Schober, R., Yiu, S., 2006. Distributed space-time coding for multihop transmission in power line communication networks. *IEEE J. Sel. Areas Commun.*, **24**(7):1389-1400. [doi:10.1109/JSAC.2006.874419]

McKay, M.R., Grant, A.J., Collings, I.B., 2007. Performance analysis of MIMO-MRC in double-correlated Rayleigh environments. *IEEE Trans. Commun.*, **55**(3):497-507. [doi:10.1109/TCOMM.2007.892450]

Popovski, P., Yomo, H., 2007. Physical network coding in two-way wireless relay channels. Proc. IEEE Int. Conf. on Communications, p.707-712. [doi:10.1109/ICC.2007.121]

Tan, B., Thompson, J., 2011. Relay transmission protocols for in-door powerline communications networks. Proc. IEEE Int. Conf. on Communicatons Workshops, p.1-5. [doi:10.1109/iccw.2011.5963528]

Tonello, A.M., Versolatto, F., D'Alessandro, S., 2010. Opportunistic relaying in in-home PLC networks. Proc. IEEE Global Telecommunications Conf., p.1-5. [doi:10.1109/GLOCOM.2010.5683175]

Zou, H., Chowdhery, A., Jagannathan, S., *et al.*, 2009. Multiuser joint subchannel and power resource-allocation for powerline relay networks. Proc. IEEE Int. Conf. on Communications, p.443-449. [doi:10.1109/ICC.2009.5199210]