SCIENCE CHINA
Information Sciences

• LETTER •

August 2021, Vol. 64 189301:1–189301:3
https://doi.org/10.1007/s11432-019-2839-y

The opportunistic relaying scheme design and symbol error rate analysis for PLC networks in smart homes

Linlin SUN[1], Jiahui YAN[1], Yuwen QIAN[1*], Feng SHU[1] & Xiangwei ZHOU[2]

[1]*The School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing* 210094*, China;*
[2]*The Division of Electrical and Computer Engineering, Louisiana State University, Baton Rouge,* 70803*, USA*

Received 26 September 2019/Revised 28 December 2019/Accepted 19 March 2020/Published online 24 May 2021

Citation Sun L L, Yan J H, Qian Y W, et al. The opportunistic relaying scheme design and symbol error rate analysis for PLC networks in smart homes. Sci China Inf Sci, 2021, 64(8): 189301, https://doi.org/10.1007/s11432-019-2839-y

Dear editor,

Power line communication (PLC) is treated as a retrofit technology, transmitting messages via conductors without extra infrastructure, which reduces the cost of implementation and maintenance [1]. Therefore, PLC is extensively adopted in smart grid applications. However, PLC encounters a hostile communication environment caused by the fast signal attenuation and severe impulsive noise [2]. These factors limit the reliability of PLC networks in long-distance transmission. In general, reliability is a key factor for PLC networks, measured with the symbol error rate (SER). Thus, the research on SER analysis for PLC networks has attracted great attention.

The analysis on SER for PLC networks mainly focuses on two aspects, the multi-path effect and the impulsive noise [3]. For instance, Ref. [4] has developed a signal attenuation channel model over multiple paths based on the distance to analyze the performance for the PLC channel. However, the channel model is developed with specific data, which cannot be generalized easily. To solve the problem, the authors of [5] have modelled the PLC channel with a statical approach to derive the received signal-to-noise rate (SNR) and SER. Recently, a number of researches have focused on the impulsive noise, which is another important factor leading to symbol errors in PLC networks [6, 7]. Among these research works, the Bernoulli-Gaussian model is a practical one, where the PLC system is shifted between two states: the impulsive noise state and Gaussian noise state [7].

To reduce the SER, relaying technologies have been introduced into PLC networks. For example, Ref. [8] investigated a relay-based communication protocol to solve the inefficiency problem in long-distance PLC communications. Recently, opportunistic relaying technologies have become an attractive solution for reliable wireless communications. However, to the best of the authors' knowledge, the design of the opportunistic relaying schemes for the PLC network is rarely reported. Moreover, there is little literature analyzing SER for an opportunistic relaying PLC network.

In this study, an efficient opportunistic decode-and-forward relaying model is designed for the PLC network in smart homes. Then, we model the PLC channel with the log-normal fading under the Bernoulli-Gaussian noise. Based on the channel model, we derive an approximate expression for the cumulative distribution function (CDF) of the received SNR. By using the Tailor extension and Gaussian approximation, we develop the approximate closed-form expression for average SER of the opportunistic relaying PLC network with the derived CDF of received SNR.

System model. As shown in Figure 1(a), we design a typical PLC network for smart homes, which is composed of several sub-circuits. These sub-circuits independently connect with a switcher, denoted by $\mathcal{K}$, to obtain a power supply from the power grid. To bring safe power utility and convenient maintenance for smart home users, we adopt a single-phase transformer to isolate the sub-circuits, which is suitable for smart home users owning to its cheapness and small size. Owing to the isolation with the transformer, transmitting signals over power lines in different sub-circuits do not interfere with each other. Furthermore, to cope with the unstable PLC communications, relaying nodes are installed in the sub-circuits to improve transmission reliability. As shown in Figure 1(b), we construct a corresponding logical structure for the in-home PLC network shown in Figure 1(a). In the PLC network, a source node $\mathcal{S}$ in the lighting sub-circuit is selected to communicate with the destination node $\mathcal{D}$ located in the heating sub-circuit via several relaying nodes $R_1, R_2, \ldots, R_M$. In our opportunistic relaying communication scheme, we dynamically select relaying nodes with the highest forwarding efficiency in different time slots as the optimal relaying node to forward messages.

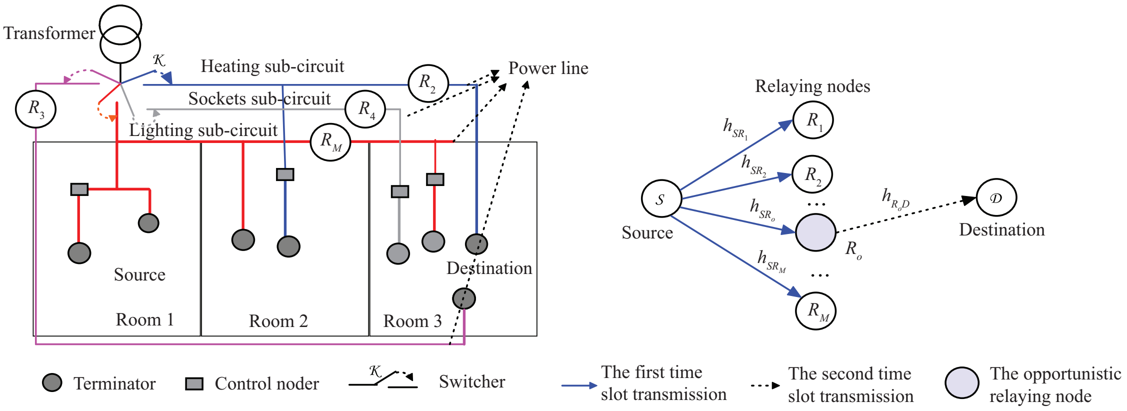
Then, we implement a relaying protocol by adopting a two-stage transmission scheme. In the first time slot, $\mathcal{S}$ transmits messages to relaying nodes R_i for $i = 1, 2, \ldots, M$. Thus, the received signal at R_i is

$$y_{R_i} = \sqrt{P} h_{SR_i} x_S + n_{SR_i}, \tag{1}$$

where P is the transmission power, h_{SR_i} is the fading of the

---

[*] Corresponding author (email: admon@njust.edu.cn)



(a) (b)

Figure 1 (Color online) (a) A typical relaying PLC network designed for smart homes; (b) the logical structure of the PLC network.

PLC channel between $\mathcal{S}$ and R_i, x_S represents the transmitted signal with transmitting power being one, and n_{SR_i} represents the noise sample.

Suppose R_o is selected as the optimal relaying node. Thus, the transmitted signals are forwarded to $\mathcal{D}$ via R_o in the second slot. In this study, we let the transmit power of each relaying node to be P, being equal to the transmit power of $\mathcal{S}$. In this scenario, the received signal at $\mathcal{D}$ can be given as

$$y_D = \sqrt{P} h_{R_oD} x_{R_o} + n_{R_oD}, \tag{2}$$

where h_{R_oD} is the fading of the PLC channel between R_i and $\mathcal{D}$, x_{R_o} is the decoding result of x_S based on y_{R_o}, and n_{R_oD} is the receiving noise sample at $\mathcal{D}$.

In this study, we select the optimal relaying node $\mathcal{R}_o$ with the max-SNR criterion, given as

$$o = \arg \max_{i=1,\dots,M} \{\gamma h^2_{R_iD}\}, \tag{3}$$

where $\gamma \triangleq \frac{P}{\sigma_0^2}$ denotes the transmit SNR.

According to Figure 1(a), we consider there is only one power line between any two nodes in the proposed relaying PLC network. From [5, 9], the probability density function (PDF) of the PLC channel fading follows a log-normal distribution, given by

$$f_h(x) = \frac{1}{\sqrt{2\pi\sigma_h^2}x} \mathrm{e}^{-\frac{(\ln x - \mu_h)^2}{2\sigma_h^2}}, \tag{4}$$

where $\ln(x)$ follows a normal distribution with the mean μ_h and variance σ_h^2. To simplify analysis, we suppose that h_{SR_i} and h_{R_iD} are independent, and identically follow the log-normal distribution with PDF f_h. In addition, we assume the transmission power of the PLC channel as one, i.e., $\mathbb{E}[h^2] = 1$. Add to that, the noise variance σ_h^2 in (4) is

$$\sigma_h^2 = \sigma_G^2 + p\sigma_I^2 = \sigma_G^2(1 + p\eta), \tag{5}$$

where $\eta = \frac{\sigma_I^2}{\sigma_G^2}$ denotes the ratio of impulsive noise power to thermal noise power and p is the parameter of Bernoulli sequence.

SER analysis. We derive the closed-form expression for the average SER of the in-home PLC network. First of all, the CDF of the received SNR at relaying nodes and destination are derived. Then, we develop the expression of the average SER based on the derived CDF.

From (1) and (2), R_o is given by

$$\gamma_{SR_o} = \frac{P}{\sigma^2} h^2_{SR_o} = \gamma h^2_{SR_o}. \tag{6}$$

Since h_{SR_o} follows a log-normal distribution given by (4), γ_{SR_o} also log-normally distribute with parameters $\mu_\gamma = 2\mu_h + \ln \frac{P}{\sigma^2}$ and $\sigma_\gamma = 2\sigma_h$. Thus the PDF of γ_{SR_o} can be given by

$$f_{SR_o}(x) = \frac{1}{\sqrt{2\pi\sigma_\gamma^2}x} \mathrm{e}^{-\frac{(\ln x - \mu_\gamma)^2}{2\sigma_\gamma^2}}. \tag{7}$$

Accordingly, the CDF of γ_{SR_o} can be obtained as

$$F_{\gamma_{SR_o}}(x) = 1 - Q\left(\frac{\ln x - \mu_\gamma}{\sigma_\gamma}\right), \tag{8}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \mathrm{e}^{-\frac{y^2}{2}} \mathrm{d}y$ is a Gaussian Q-function.

According to (3), the received SNR at destination is

$$\gamma_{R_oD} = \max\left\{\frac{P}{\sigma^2} h^2_{R_1D}, \dots, \frac{P}{\sigma^2} h^2_{R_MD}\right\}. \tag{9}$$

Since h_{SR_o} and h_{R_iD} $(i = 1, 2, \dots, M)$ identically follow the log-normal distribution, the CDF of γ_{RD} can be expressed by combining (8) with (9) as

$$F_{\gamma_{R_oD}}(x) = \left(1 - Q\left(\frac{\ln x - \mu_\gamma}{\sigma_\gamma}\right)\right)^M. \tag{10}$$

To derive the average SER, we consider that the transmitting signal is modulated with binary phase shift keying (BPSK). Thus, given the received SNR, the conditional SER for each time slot can be written as [9]

$$\Pr(e|x) = p_0 Q(\sqrt{x\alpha_0}) + p_1 Q(\sqrt{x\alpha_1}), \tag{11}$$

where $p_0 = 1 - p$, $p_1 = p$, $\alpha_0 = 1 + p\eta$, and $\alpha_1 = \frac{1+p\eta}{1+\eta}$.

Later on, with the Tailor extension and Hermite polynomial, we derive the average SER from the source to the optimal relaying node as

$$S_{SR_o} = \sum_{j=1}^{N} w_j \sum_{i=0}^{1} \frac{p_i}{\sqrt{\pi}} \left(1 - Q\left(\frac{\ln \frac{\alpha_i t_j^2}{2} - \mu_\gamma}{\sigma_\gamma}\right)\right), \tag{12}$$

where N denotes the Hermitian polynomial order, w_j is the jth weight factor, and t_j represents the jth zero of the Hermit polynomial.

In addition, we use exponential function and fitting constants, denoted by P_1, P_2, and P_3, to approximate the Gaussian function. Then, the expression of average at destination node $\mathcal{D}$ can be derived as

$$\begin{aligned}
S_{R_oD} = & \frac{\sigma_\gamma}{4\sqrt{2}} \sum_{i=0}^{1} p_i \sum_{k=0}^{K} C_{1,k} \sqrt{\frac{\alpha_i}{\rho_{1,\alpha_i}}} \\
& \times \exp\left(\frac{\rho_{2,\alpha_i}^2 - \rho_{1,\alpha_i}\rho_{3,\alpha_i}}{\rho_{1,\alpha_i}}\right)\left(1 - \operatorname{erf}\left(\frac{\rho_{2,\alpha_{\mathrm{i}}}}{\sqrt{\rho_{1,\alpha_{\mathrm{i}}}}}\right)\right) \\
& + \frac{\sigma_\gamma}{4\sqrt{2}} \sum_{i=0}^{1} p_i \sum_{k=0}^{K} C_{1,k} \sum_{m=0}^{M} I_m \sqrt{\frac{\alpha_i}{\beta_{1,\alpha_i}}} \\
& \times \exp\left(\frac{\beta_{2,\alpha_i}^2 - \beta_{1,\alpha_i}\beta_{3,\alpha_i}}{\beta_{1,\alpha_i}}\right)\left(1 - \operatorname{erf}\left(\frac{\beta_{2,\alpha_{\mathrm{i}}}}{\sqrt{\beta_{1,\alpha_{\mathrm{i}}}}}\right)\right),
\end{aligned} \tag{13}$$

where ρ_{1,α_i}, ρ_{2,α_i}, ρ_{3,α_i}, β_{1,α_i}, β_{2,α_i}, and β_{3,α_i} are

$$\begin{aligned}
&\rho_{1,\alpha_i} = -MP_1 + W_{1,\alpha_i}, \quad \rho_{2,\alpha_i} = -\frac{MP_2}{2} + W_{2,\alpha_i}, \\
&\rho_{3,\alpha_i} = -MP_3 + W_{3,\alpha_i}, \quad \beta_{1,\alpha_i} = -mP_1 + W_{1,\alpha_i}, \\
&\beta_{2,\alpha_i} = -\frac{mP_2}{2} + W_{2,\alpha_i}, \quad \beta_{3,\alpha_i} = -mP_3 + W_{3,\alpha_i}, \\
&W_{1,\alpha_i} = -\frac{\sigma_\gamma^2}{C_{3,k}^2}, \quad W_{2,\alpha_i} = \frac{\sigma_\gamma}{4} - \frac{\sigma_\gamma(\mu_\gamma - C_{2,k})}{C_{3,k}^2}, \\
&W_{3,\alpha_i} = -\frac{(\mu_\gamma - C_{2,k})^2}{C_{3,k}^2} - \frac{\mu_\gamma - \alpha_i}{2},
\end{aligned}$$

and $C_{1,k}$, $C_{2,k}$, and $C_{3,k}$ are fitting constants.

By applying the law of total probability, we can approximate the closed-form of average SER as

$$A_{\mathrm{SER}} = S_{SR_o} + S_{R_oD} - S_{SR_o}S_{R_oD}, \tag{14}$$

where S_{SR_o} and S_{R_oD} are derived in (12) and (13), respectively.

References

1 Ferreira H, Lampe L, Newbury J, et al. Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines. Hoboken: Wiley, 2010

2 Qian Y W, Zhang C, Xu Z W, et al. A reliable opportunistic routing for smart grid with in-home power line communication networks. Sci China Inf Sci, 2016, 59: 122305

3 Shlezinger N, Shaked R, Dabora R. On the capacity of MIMO broadband power line communications channels. IEEE Trans Commun, 2018, 66: 4795–4810

4 Zimmermann M, Dostert K. A multipath model for the powerline channel. IEEE Trans Commun, 2002, 50: 553–559

5 Qian Y W, Yan J H, Guan H B, et al. Design of hybrid wireless and power line sensor networks with dual-interface relay in IoT. IEEE Int Things J, 2019, 6: 239–249

6 Rahman M J, Lampe L. Interference alignment for MIMO power line communications. In: Proceedings of International Symposium on Power Line Communications and Its Applications, Austin, 2015

7 Agrawal N, Sharma P K, Tsiftsis T A. Multihop DF relaying in NB-PLC system over rayleigh fading and bernoulli-laplacian noise. IEEE Syst J, 2019, 13: 357–364

8 Ezzine S, Abdelkefi F, Cances J, et al. Capacity analysis of an OFDM-based two-hops relaying PLC systems. In: Proceedings of Vehicular Technology Conference, Glasgow, 2015

9 Dubey A, Mallik R K. PLC system performance with AF relaying. IEEE Trans Commun, 2015, 63: 2337–2345