Green Data Transmission in Power Line Communications

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***Abstract*—This paper presents a green data transmission approach to enhance the energy efficiency of power line communications (PLC) by jointly utilizing signal detection and resource allocation techniques. Due to the awareness of the interference as enabled by the signal detection function, the proposed PLC system can adaptively adjust the transmission parameters. Furthermore, given a power budget, a performance optimization algorithm is proposed that maximizes the energy efficiency of PLC by optimally choosing the signal detection duration and the transmit power. Simulation results show that the proposed system can not only mitigate the effects of interference, but also considerably improve the energy efficiency of PLC when compared with the existing PLC systems.**

***Index Terms*—Green data transmission, Power line communications, Energy efficiency, Energy detection.**

I. Introduction

Power line communication (PLC) has received growing attention in many applications, e.g., smart grids. Using the power grid as a communication medium for transmitting signals, however, presents significant challenges. The PLC channel exhibits strong frequency-selective fading with deep notches at some frequencies [1]. Orthogonal frequency-division multiplexing (OFDM) techniques can enhance the PLC system performance. One of the crucial issues in OFDM transmission is the allocation of the power resources to the subchannels [2]. The optimal bit/power loading can be achieved by using the water-filling principle [3]. Nevertheless, the influence of interference has not yet been addressed with respect to the system energy efficiency. In PLC, radio signals of wireless communication systems, which share frequency bands with PLC, can be coupled to the power line, leading to high power and narrowband interference. Consequently, the energy efficiency of PLC decreases. Therefore, it is critical to deal with the interference for saving energy.

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To mitigate interference, blocking filters can be employed for absorbing unnecessary signals on the power line. In addition, if one knows what radio operations are located in the vicinity of PLC, the effects of interference can be minimized by carefully choosing the operating frequencies and transmission power on PLC. A simple frequency avoidance approach is the so-called fixed frequency notching that avoids using the non-essential and unpleasant frequencies based on the databases. Another approach is called agile frequency avoidance which monitors frequency bands and dynamically avoids the interference. However, there is a significant concern that such frequency avoidance approaches would not essentially reduce the interference potential to PLC. This is because the frequencies that can be used by PLC are highly limited, and the frequency avoidance is equivalent to wasting spectral resources on which all communication systems rely.

This paper proposes a green data transmission approach that fully exploits the spectral resources by jointly utilizing signal detection and resource allocation techniques. Different from the agile frequency avoidance, the proposed system adapts transmission parameters to mitigate interference, rather than passively avoids interference. The signal detection techniques are used for detecting the presence/absence of interference, and the transmit power is adapted based on signal detection result. Specifically, in the proposed system, we divide one frame into two time slots, i.e., a blind transmission time slot, and an awareness transmission time slot. In the former slot, the default transmit power is used for data transmission. Meanwhile, the signal detection is performed for detecting interference. In the latter slot, we adopt a high transmit power if the signal detection result shows that the interference is absent. Otherwise, we use a low transmit power. Moreover, given a power budge, we present an optimization algorithm that maximizes the energy efficiency of PLC by jointly optimizing the signal detection duration and the transmit power.

The rest of the paper is organized as follows. Section II introduces the system model of PLC. Section III proposes a green data transmission system for PLC. Simulation results are presented in Section IV, with conclusions given in Section V.

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II. System Model

Suppose that a PLC system consists of a transmitter (Tx) and a receiver (Rx) while Tx transmits signals to Rx using OFDM techniques. Let $\Omega = \{1, 2, \cdots, N\}$ denote the set of subchannels, W_n denote the bandwidth of the subchannel n, and H_n denote the channel frequency response between Tx and Rx. The channel state information (CSI) is estimated by using a channel estimation scheme, e.g., training bits [4], [5]. Thus, the frame length T can be carefully chosen such that the channel power gain, i.e., $G_n = |H_n|^2$, remains constant within one frame. Using the noise model in [6], the PLC noise is cyclostationary additive Gaussian with zero mean and variance N_n which is synchronous to the AC voltage of mains. Based on the CSI, the optimal power allocation vector can be obtained by using the water-filling approach, i.e., $\vec{P} = [P_1, P_2, \cdots, P_N]$. In practice, PLC shares the frequency bands with wireless communication systems. As the power line is unshielded and can be good antenna that receives signals transmitted from wireless communication systems, the radio signal of wireless systems act as the interference to PLC. In this paper, we model the on/off status of the interference as two hypotheses $\mathcal{H}_{0,n}$ (absence of interference) and $\mathcal{H}_{1,n}$ (presence of interference). Suppose that the interference follows Gaussian distribution, the instantaneous transmission rate of the PLC in the non-interference case and the interference case, i.e., $R_{0,n}$ and $R_{1,n}$, can be given by [7]

$$R_{0,n} = W_n \log_2\left(1+\frac{G_n P_n}{N_n}\right), R_{1,n} = W_n \log_2\left(1+\frac{G_n P_n}{Q_n + N_n}\right) \quad (1)$$

respectively, where Q_n denotes the interference power as received at Rx. The average throughput on the subchannel n can be given by

$$\mathbb{E}[R_n] = \Pr(\mathcal{H}_{0,n}) R_{0,n} + \Pr(\mathcal{H}_{1,n}) R_{1,n} \quad (2)$$

where $\Pr(\mathcal{H}_{0,n})$ and $\Pr(\mathcal{H}_{1,n}) = 1 - \Pr(\mathcal{H}_{0,n})$ denote the probabilities of the non-interference case and the interference case occurring on the subchannel n, respectively.

The expected power consumption in one frame can be modeled as the sum of the amplifier power consumption and the constant power dissipation in the processing circuit, i.e., $\mathbb{E}[\varpi_n] = P_{\rm A} + P_{\rm cc}$, where $P_{\rm A}$ denotes the amplifier power consumption and $P_{\rm cc}$ denotes the other constant circuit power per subchannel. As shown in [8], $P_{\rm A}$ will determine the transmission power by: $P_n = \eta P_{\rm A}$, where η denotes the power efficiency of the power amplifier. The average energy efficiency measures the quantity of information transmitted from Tx to Rx per unit energy use. Thus, the average energy efficiency on the subchannel n, i.e., $\mathbb{E}[E_n]$, can be defined by using (2)

$$\mathbb{E}[E_n] = \frac{\mathbb{E}[R_n]}{\mathbb{E}[\varpi_n]} = \frac{\Pr(\mathcal{H}_{0,n}) R_{0,n} + \Pr(\mathcal{H}_{1,n}) R_{1,n}}{P_{\rm A} + P_{\rm cc}}. \quad (3)$$

It can be seen from (3) that the energy efficiency decreases due to the existence of interference.

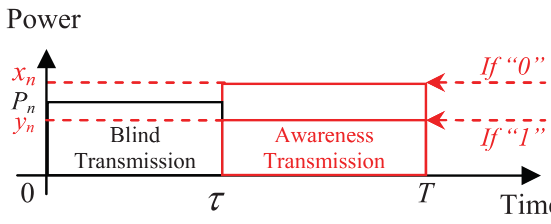

Fig. 1. Frame structure of the proposed green data transmission PLC system.

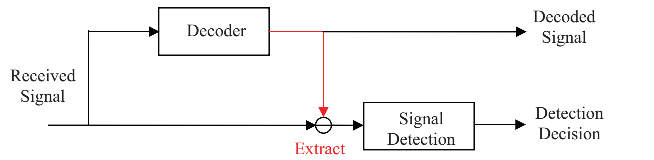

Fig. 2. Receiver structure of the proposed green data transmission PLC system.

III. Green Power Line Communications

In this section, we develop a green data transmission system for enhancing the energy efficiency of PLC systems. The purpose is to achieve high energy efficiency even if PLC suffers strong interference with high power level.

A. System Description

We consider a PLC system in which each frame (with length T) consists of a blind transmission duration (τ) and an awareness transmission duration ($T-\tau$), as shown in Fig. 1. In the blind transmission duration, the default transmit power P_n (i.e., optimal transmit power under the water-filling approach) is adopted at Tx for data transmission and the signal detection technique is used for detecting the interference on the power line. We note that the signal detection and data transmission can be performed in the same time. This is because the PLC Rx can firstly decode the signal sent by the PLC Tx, strip it away from the received signal, and use the remaining signal to perform signal detection, as depicted in Fig. 2. In the awareness transmission duration, we change the transmit power of Tx based on the signal detection result, i.e., using the transmit power x_n ($x_n \geq P_n$) if the signal detection result is $\mathcal{H}_{0,n}$ (non-interference), and using the transmit power y_n ($y_n \leq P_n \leq x_n$) if the signal detection result is $\mathcal{H}_{1,n}$ (presence of interference).

Because an energy detector [9] does not require any prior information about the interference, this paper considers the use of energy detector for detecting the interference. By comparing the received signal energy S_n with the detection threshold Λ_n, the probabilities of false alarm and detection under the energy detection approach can be written as [10]

$$\begin{aligned} P_{{\rm f},n} &= \Pr(S_n > \Lambda_n | \mathcal{H}_{0,n}) = \Phi\left(\left(\frac{\Lambda_n}{N_n} - 1\right)\sqrt{\tau f_{\rm s}}\right) \\ P_{{\rm d},n} &= \Pr(S_n > \Lambda_n | \mathcal{H}_{1,n}) = \Phi\left(\left(\frac{\Lambda_n}{N_n} - \gamma_n - 1\right)\sqrt{\frac{\tau f_{\rm s}}{2\gamma_n + 1}}\right) \end{aligned} \quad (4)$$

where $\Phi(x) = \frac{1}{2} - \frac{1}{2}{\rm erf}(\frac{x}{\sqrt{2}})$ in which the error function ${\rm erf}(x) = \frac{2}{\pi}\int_0^x e^{-t^2}dt$, $f_{\rm s}$ ($f_{\rm s} \geq 2W_n$) is the sampling rate, and $\gamma_n = \frac{\mathbb{E}[Q_n]}{N_n}$ (dB) is the interference-to-noise ratio. It is more meaningful to consider $P_{\mathrm{d},n} \in [\frac{1}{2}, 1]$ and $P_{\mathrm{f},n} \in [0, \frac{1}{2}]$; thus, the detection threshold $\Lambda_n \in [N_n, N_n(\gamma_n + 1)]$.

In practice, there will be nontrivial probabilities of false alarm and missed detection. Consequently, there are four different cases regarding the signal detection result and the actual on/off status of interference, resulting in four different instantaneous transmission rates:

$$\begin{aligned} R^0_{0,n}(x_n) &= W_n \log_2\left(1 + \tfrac{G_n x_n}{N_n}\right), \\ R^0_{1,n}(x_n) &= W_n \log_2\left(1 + \tfrac{G_n x_n}{Q_n + N_n}\right), \\ R^1_{0,n}(y_n) &= W_n \log_2\left(1 + \tfrac{G_n y_n}{N_n}\right), \\ R^1_{1,n}(y_n) &= W_n \log_2\left(1 + \tfrac{G_n y_n}{Q_n + N_n}\right) \end{aligned} \quad (5)$$

where the first subscript of R describes the actual status of interference, and the superscript of R describes the signal detection result ("0" for absence and "1" for presence of interference). As τ is reserved for the blind transmission using the default transmit power P_n, while the remaining time slot $T - \tau$ is used for awareness transmission, the average throughput of the proposed PLC system can be written as

$$\begin{aligned} \mathbb{E}[R'_n](\tau, x_n, y_n) = &\frac{\tau}{T}\mathbb{E}[R_n] + \frac{T-\tau}{T}\big(a_n R^0_{0,n}(x_n) + b_n R^1_{0,n}(y_n) \\ &+ c_n R^0_{1,n}(x_n) + d_n R^1_{1,n}(y_n)\big) \end{aligned} \quad (6)$$

where $a_n \triangleq \Pr(\mathcal{H}_{0,n})(1 - P_{\mathrm{f},n})$, $b_n \triangleq \Pr(\mathcal{H}_{0,n})P_{\mathrm{f},n}$, $c_n \triangleq \Pr(\mathcal{H}_{1,n})(1 - P_{\mathrm{d},n})$, and $d_n \triangleq \Pr(\mathcal{H}_{1,n})P_{\mathrm{d},n}$.

In the awareness transmission duration, we should also consider the electromagnetic compatibility regulations of the PLC system. In such a scenario, the average transmit power has a constraint: $(a_n + c_n)x_n + (b_n + d_n)y_n \le \Gamma_n$, where Γ_n denotes the average transmit power constraint on the subchannel n. Next, we consider the energy consumption of the proposed PLC system. In the blind transmission duration τ, the energy consumption consists of the amplifier power consumption $P_{\mathrm{A}} = \frac{P_n}{\eta}$, the signal detection power P_{ss} ($P_{\mathrm{ss}} \ll P_n$), and the constant circuit power P_{cc}. In the awareness transmission duration, the energy consumption is comprised of the amplifier's power consumption ($\frac{x_n}{\eta}$ or $\frac{y_n}{\eta}$) and the constant circuit power P_{cc}. Therefore, the average power consumption of the proposed system can be written as

$$\begin{aligned} \mathbb{E}[P'_n](\tau, x_n, y_n) = &\frac{T-\tau}{T}\left((a_n + c_n)\frac{x_n}{\eta} + (b_n + d_n)\frac{y_n}{\eta} + P_{\mathrm{cc}}\right) \\ &+ \frac{\tau}{T}\left(\frac{P_n}{\eta} + P_{\mathrm{ss}} + P_{\mathrm{cc}}\right). \end{aligned} \quad (7)$$

Finally, in the proposed system, the average energy efficiency of subchannel n can be given by

$$\mathbb{E}[E'_n](\tau, x_n, y_n) = \frac{\mathbb{E}[R'_n](\tau, x_n, y_n)}{\mathbb{E}[P'_n](\tau, x_n, y_n)}. \quad (8)$$

B. Optimization Problem Formulation

To save energy, we should improve the energy efficiency of the PLC system , i.e., increasing the quantity of information transmitted from Tx to Rx per unit energy. In this paper, we try to answer the following two questions: 1) for the same average power consumption, whether the average throughput of the proposed PLC system is greater than that of the traditional PLC system, and 2) for a given power budget, how can we maximize the average throughput of the proposed PLC system.

TABLE I
OPTIMIZATION ALGORITHM FOR IMPROVING THE ENERGY EFFICIENCY OF THE PROPOSED PLC SYSTEM.

Initialize: $S = \emptyset$ and $F = \emptyset$.
For $\tau = 0 : T$ **do**
a). Obtain the possible optimal transmit power $x^\dagger_n$ and $y^\dagger_n$ in (10) by using the subgradient method in (12).
b). Store the above solution $S = S \bigcup \{x^\dagger_n, y^\dagger_n\}$.
c). Calculate the objective function $f_0(\tau, x^\dagger_n, y^\dagger_n)$ in (9).
d). Merge new result $F = F \bigcup \{f_0(\tau, x^\dagger_n, y^\dagger_n)\}$.
End
Output: $\tau^\star = \arg_\tau \max F(\tau, x^\dagger_n, y^\dagger_n)$. $(x^\star_n, y^\star_n) = S_{\tau=\tau^\star}$.

As shown in Section II, the average power consumption of the traditional PLC system is $\mathbb{E}[\varpi_n] = \frac{P_n}{\eta} + P_{\mathrm{cc}}$. To make the average power consumption identical, we can let $\mathbb{E}[\varpi_n]$ and $\mathbb{E}[P'_n]$ in (7) to be equal. After simple manipulation, we obtain: $\frac{\tau\eta}{T-\tau}P_{\mathrm{ss}} + (a_n + c_n)x_n + (b_n + d_n)y_n = P_n$. Therefore, the energy efficiency enhancement problem can be reformulated to the following optimization problem:

$$\begin{aligned} \max_{\tau, x_n, y_n}: \ & \tfrac{\tau}{T}\mathbb{E}[R_n] + \tfrac{T-\tau}{T}\big(a_n R^0_{0,n}(x_n) + b_n R^1_{0,n}(y_n) \\ & + c_n R^0_{1,n}(x_n) + d_n R^1_{1,n}(y_n)\big) \\ s.t.: \ & (a_n + c_n)x_n + (b_n + d_n)y_n - \Gamma_n \le 0 \\ & (a_n + c_n)x_n + (b_n + d_n)y_n + \tfrac{\tau\eta}{T-\tau}P_{\mathrm{ss}} - P_n = 0. \end{aligned} \quad (9)$$

where the inequality denotes the average transmit power constraint, and the second constraint guarantees that the average power consumption in both the traditional system and the proposed system are identical.

It can be proved that the above optimization problem is a convex optimization problem regarding to τ, x_n, and y_n, respectively. It is important to note that, due to the dependence of the probabilities on the signal detection duration τ, the optimization problem of (9) with respect to τ is complicated and there is no closed-form expression for the solution of τ. However, as τ lies in the interval $[0, T]$, we can easily find the optimal signal detection time $\tau^\star$ by using one-dimensional exhaustive search within the interval $[0, T]$. In Table I, we present an algorithm that can choose the optimal signal detection time $\tau^\star$ and the optimal transmit power, i.e., $x^\star_n$ and $y^\star_n$.

Theorem 1: For the same average power consumption, the proposed PLC system has greater average throughput than that of the traditional PLC system. In other words, the proposed PLC system can achieve higher energy efficiency when compared with the traditional PLC system.

Proof: If $\tau = 0$, then $P_{\mathrm{f},n} = P_{\mathrm{d},n} = \frac{1}{2}$. In such a scenario, the second constraint of (9) becomes $x_n + y_n = 2P_n$. Therefore, the traditional PLC system is a special case of the proposed PLC system by letting $\tau = 0$ and $x_n = y_n = P_n$, i.e., $\mathbb{E}[R'_n](0, P_n, P_n) = \mathbb{E}[R_n]$. Further, as $\mathbb{E}[R'_n](\tau, x_n, y_n)$ is a concave function with respect to τ, x_n, and y_n, we have

$\mathbb{E}[R_n'](\tau^\star, x_n^\star, y_n^\star) \geq \mathbb{E}[R_n'](0, P_n, P_n) = \mathbb{E}[R_n]$. $\square$

Remark 1: Given the same energy budget, the proposed PLC system adjusts the transmit power to higher level once the interference is detected to be present; otherwise, it changes to lower transmit power. This adaptive scheme provides an advantage of flexibility in adapting the transmit power to the presence/absence of interference, thereby maximizing the benefits of unit energy use.

C. Optimal Transmit Power

As shown in Table I, the key parameters of the proposed system are the possible optimal transmit power that maximize the average throughput in (9) when τ is a particular number within $[0, T]$. Next, we concentrate on solving these optimal transmit power. For simplicity, we rewrite the optimization problem in (9) as:

$$\begin{aligned} \max_{x_n, y_n}: \quad & f_1(x_n) + f_2(y_n) \\ s.t.: \quad & A_n x_n + B_n y_n - \Gamma_n \leq 0, \\ & A_n x_n + B_n y_n - \Theta_n = 0 \end{aligned} \tag{10}$$

where $f_1(x_n) \triangleq a_n R_{0,n}^0(x_n) + c_n R_{1,n}^0(x_n)$, $f_2(y_n) \triangleq b_n R_{0,n}^1(y_n) + d_n R_{1,n}^1(y_n)$, $A_n \triangleq a_n + c_n$, $B_n \triangleq b_n + d_n$, and $\Theta_n \triangleq P_n - \frac{\tau\eta}{T-\tau} P_{ss} > 0$.

Using Slater's condition [11], we know that solving the dual optimization problem is equivalent to solving the primal optimization problem of (10). Introducing dual variables λ and ν, we can form the Lagrangian function: $L(x_n, y_n, \lambda, \nu) \triangleq f_1(x_n) + f_2(y_n) - \lambda(A_n x_n + B_n y_n - \Gamma_n) - \nu(A_n x_n + B_n y_n - \Theta_n)$. Then the dual optimization problem is given by:

$$\begin{aligned} \min_{\lambda,\nu}: \quad & D(\lambda,\nu) \triangleq F_1(\lambda,\nu) + F_2(\lambda,\nu) + \Gamma_n \lambda + \Theta_n \nu \\ s.t.: \quad & \lambda \geq 0 \end{aligned} \tag{11}$$

where $F_1(\lambda,\nu) \triangleq \sup_{x_n}(f_1(x_n) - (\lambda+\nu)A_n x_n)$ and $F_2(\lambda,\nu) \triangleq \sup_{y_n}(f_2(y_n) - (\lambda+\nu)B_n y_n)$.

To solve the dual problem, we adopt the subgradient method as

$$\begin{cases} x_n^{(k)} = x_n^\dagger(\lambda^{(k)}, \nu^{(k)}), & y_n^{(k)} = y_n^\dagger(\lambda^{(k)}, \nu^{(k)}) \\ \lambda^{(k+1)} = \left[\lambda^{(k)} - \xi^{(k)} g_1^{(k)}\right]^+, & \nu^{(k+1)} = \left[\nu^{(k)} - \rho^{(k)} g_2^{(k)}\right]^+ \end{cases} \tag{12}$$

where $[x]^+ = \max(0, x)$, the step size $\xi^{(k)}$ and $\rho^{(k)}$ are small positive parameters, $g_1^{(k)} = -A_n x_n^{(k)} + \Gamma_n \leq \Gamma_n$ and $g_2^{(k)} - B_n y_n^{(k)} + \Theta_n \leq \Theta_n$ are subgradients, and $x_n^\dagger(\lambda,\nu)$ and $y_n^\dagger(\lambda,\nu)$ are the solutions of the following two subproblems:

$$\begin{aligned} &\textbf{Subproblem 1}: \quad \max_{x_n \in \mathbb{R}^+} \left(f_1(x_n) - (\lambda+\nu)A_n x_n\right) \\ &\textbf{Subproblem 2}: \quad \max_{y_n \in \mathbb{R}^+} \left(f_2(y_n) - (\lambda+\nu)B_n y_n\right). \end{aligned} \tag{13}$$

Solving these two independent subproblems, we obtain $x_n^\dagger(\lambda,\nu)$ and $y_n^\dagger(\lambda,\nu)$ as

$$\begin{aligned} x_n^\dagger(\lambda,\nu) &= \arg\max_{x_n \in \mathbb{R}^+} \left(f_1(x_n) - (\lambda+\nu)A_n x_n\right) \\ &= \left[\frac{G_n - \ln(2)(Q_n + 2N_n)(\lambda+\nu) \pm \sqrt{\Delta_x}}{2\ln(2)G(\lambda+\nu)}\right]^+ \\ y_n^\dagger(\lambda,\nu) &= \arg\max_{y_n \in \mathbb{R}^+} \left(f_2(y_n) - (\lambda+\nu)B_n y_n\right) \\ &= \left[\frac{G_n - \ln(2)(Q_n + 2N_n)(\lambda+\nu) \pm \sqrt{\Delta_y}}{2\ln(2)G_n(\lambda+\nu)}\right]^+ \end{aligned} \tag{14}$$

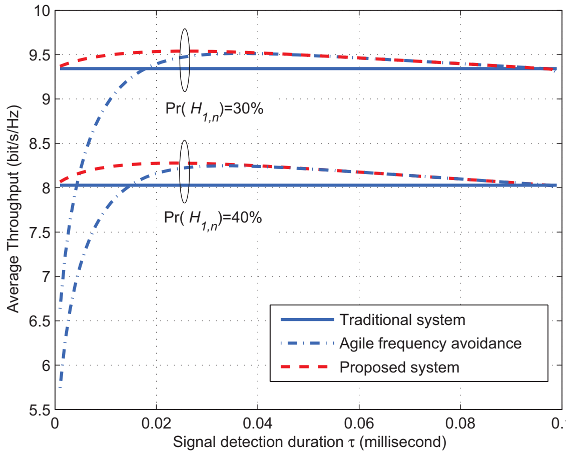

Fig. 3. The relation between the signal detection duration τ and the average throughput for different PLC systems. The influence of the probability of interference occurring is also shown. The average transmit power constraint is $\Gamma_n = 40$ dBm.

where $\Delta_x = \ln^2(2)Q_n^2(\lambda+\nu)^2 - 2\ln(2)G_n Q_n(\lambda+\nu)(1 - \frac{2a_n}{A_n}) + G_n^2$ and $\Delta_y = \ln^2(2)Q_n^2(\lambda+\nu)^2 - 2\ln(2)G_n Q_n(\lambda+\nu)(1 - \frac{2b_n}{B_n}) + G_n^2$.

IV. Simulation Results

In simulations, the frame length T is chosen to be 0.1 ms, and OFDM techniques are adopted with the number of sub-channels $N = 1024$ based on IEEE standard 1901 [12]. The multipath signal propagation model [13] is used to generate the channel frequency response. We set the number of propagation paths $L_n = 4$, the weighting factor $w_n = [0.4589, 0.5823, 0.3391, 0.1706]$, the attenuation vector $[6.4070 \times 10^{-4}, 8.2114 \times 10^{-56}, 9.0067 \times 10^{-11}, 1.3941 \times 10^{-5}]$, and the path delay vector $[0, 8.4623, 3.7019, 3.8323] \times 10^{-5}$. The central frequency of the subchannel is $f_n = 60$ kHz, while the bandwidth of the subchannel is $W_n = 10$ kHz. The default transmit power is $P_n = 40$ dbm which is also used for the data transmission in the blind transmission slot. We consider that the class-A power amplifier is used that has the efficiency of 20%, i.e., $\eta = 20\%$. The constant circuit power is set to be $P_{cc} = 23$ dBm, while the power consumption for signal detection is $P_{ss} = 20$ dBm. We consider the interference received by Rx from wireless systems, i.e., $Q_n = -60$ dBm. The noise is generated using the noise model in [6], with average power level $N_n = -110$ dbm. The sampling rate is chosen to be $f_s = 20$ kHz. The energy detector is used for performing signal detection, where the detection threshold is set to be $\Lambda_n = 4N_n$. The signal detection decision is made by comparing the signal energy with the detection threshold.

Fig. 3 shows the average throughput of different PLC systems when the signal detection duration τ and $\Pr(\mathcal{H}_{1,n})$ vary. It can be seen that the proposed PLC system yields throughput gain over the other systems, whereas the gain varies as the signal detection duration τ changes. The average throughput of the proposed system is maximized when $\tau \approx 0.02$ ms. Further, we can see that the average throughput of all systems decreases as $\Pr(\mathcal{H}_{1,n})$ increases. This is due to the fact that

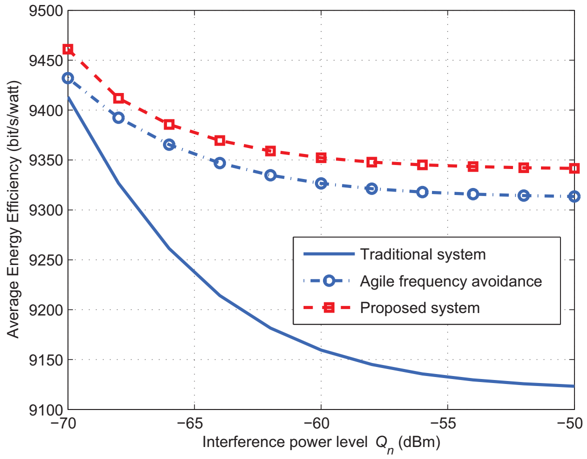

Fig. 4. The average energy efficiency of different PLC systems when the interference power level Q_n varies. The probability of the interference occurring is $\Pr(\mathcal{H}_{1,n}) = 0.3$, while the average transmit power constraint is set to be $\Gamma_n = 40$ dBm.

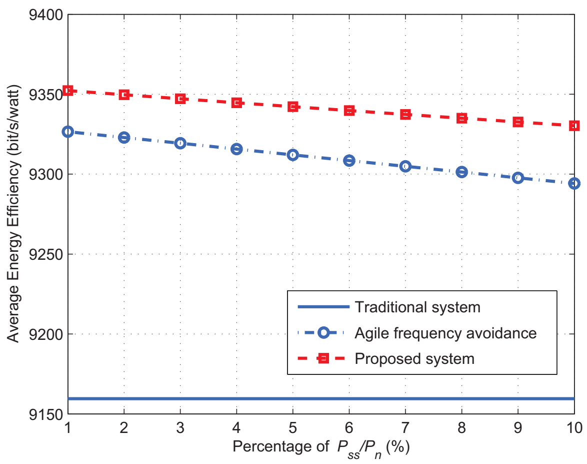

Fig. 5. The average energy efficiency of different PLC systems when the signal detection power $P_{\rm ss}$ varies. The probability of the interference occurring is $\Pr(\mathcal{H}_{1,n}) = 0.3$, and the average transmit power constraint is $\Gamma_n = 40$ dBm.

the presence of interference can significantly deteriorate the communication performance.

Fig. 4 describes the influence of the interference power Q_n on the system energy efficiency. It can be seen that the average energy efficiency of all PLC systems decreases as Q_n increases. Both the agile frequency avoidance PLC system and the proposed system outperform the traditional PLC system. The performance gain increases as Q_n increases. This is because, as Q_n increases, it is becoming easier (i.e., taking less time) for detecting the presence of interference. Furthermore, as we can see in Fig. 4, if a specific energy efficiency is required, the proposed system can tolerate higher interference power level than that of the traditional system or the agile frequency avoidance system.

Fig. 5 compares the average energy efficiency of different PLC systems when the power consumption for signal detection $P_{\rm ss}$ varies. It shows that both the agile frequency avoidance system and the proposed system become more energy-efficient when the power consumption of the signal detection function decreases. The proposed system is less sensitive to the growth of the signal detection power than the agile frequency avoidance system.

V. Conclusions

In this paper, we have proposed a green data transmission system for improving the energy efficiency of PLC. It has been shown that the proposed PLC system is more energy efficient than the traditional PLC system. This is due to the fact that the proposed system is aware of the existence of interference thanks to the signal detection function. Compared to the traditional PLC system and the agile frequency avoidance system, the proposed system can achieve higher energy efficiency due to its capability of exploiting spectral resources. Moreover, we have presented a performance optimization algorithm that can maximize the energy efficiency of PLC by choosing the optimal signal detection duration and the optimal transmit power. Simulation results have shown that the proposed system can not only improve the energy efficiency of PLC, but also enhance the robustness against the interference.

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