SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

December 2016, Vol. 59 122305:1–122305:13
doi: 10.1007/s11432-016-5527-7

A reliable opportunistic routing for smart grid with in-home power line communication networks

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Received September 26, 2015; accepted November 25, 2015; published online June 13, 2016

Abstract The topology of in-home power line communication (PLC) networks varies frequently, which makes traditional routing algorithms failure. To solve this problem, an end-to-end transmission time for remaining path (TTRP) metric-based opportunistic routing (TTRPOR) is proposed. Since a local broadcasting scheme is adopted, the algorithm can find the optimal path for forwarding packets in a dynamic PLC network. The closed-form of the outage probability for a PLC channel is derived to estimate the TTRP. It is proved that the average throughput can achieve maximum as the metric TTRP is utilized to sort candidate forwarding nodes. Numerical results show that the end-to-end throughput of networks with TTRPOR, outperforms that of the network adopting DSR and EXOR, especially for the case of varying-topology in-home PLC networks.

Keywords smart grid, in-home network, narrowband PLC, opportunistic routing, power line communication

Citation 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(12): 122305, doi: 10.1007/s11432-016-5527-7

1 Introduction

Due to combining energy technology with information and communication technology, smart grid has the abilities of massive sensing, actuation, and management in the electricity grid. However, smart grid components are distributed in different places. Therefore, a robust data communication infrastructure needs to be constructed in smart grid. Power line communications (PLC), as a natural candidate technology for smart grid, has been widely investigated attributable to their advantages: easy-to-use, cost-efficiency and easy installation [1]. However, there are several problems on PLC networks [2]. When devices in PLC networks are usually turned on or off, impulsive noise and deep fading are often generated. Hence, links in PLC networks are highly unreliable in the presence of the impulsive noise and deep fading, which leads to a time-variant network topology. If routing algorithm cannot monitor the variation, the performance of the network would degrade seriously [3]. Therefore, an efficient and dynamic routing scheme is very useful and crucial for PLC networks.

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In recent years, many routing protocols have been developed for PLC networks. The original idea to design a routing protocol for PLC networks is inspired by those of mobile ad hoc networks [4, 5]. Researchers observed that many properties of PLC networks are similar to those of ad hoc networks, such as fast signal attention, hidden stations and exposed stations [6]. Naturally, the dynamic source routing (DSR), known as a frequently used routing protocol in ad hoc network, is introduced to PLC networks [7]. However, since there is no any effective optimization for the PLC network, this protocol does not achieve a good performance. To improve the performance, Refs. [8] and [9] introduce a geographic metric-based routing protocol, in which location information of nodes directs the packet forwarded to the correct direction toward the destination node. Ref. [10], however, suggests an optimal routing algorithm combining with channel allocation, which ensures the throughput of the users.

Another efficiency routing scheme for PLC networks is multiple-path routing, which can make use of the multi-path propagation property of the PLC channel. Multiple-path routing can achieve a better packet delivery rate and thus improves the stability of the networks [11]. However, the classic multiple-path routing ad hoc on-demand multi-path distance vector routing (AOMDV) is often used in small scale networks because of its huge memory requirement [12]. To solve this problem, the authors in [13] design a split multi-path routing (SMR) scheme for PLC networks. As a multi-path extension of DSR, the SMR makes an effort to improve the probability of successfully forwarding packets by finding two disjoint routers acting as forwarders. However, it is essential for SMR to probe forwarders by flooding packets in the entire network. To reduce the overhead, a method of location learning is proposed to control the broadcast in a PLC network with a master-slave structure [14]. Authors in [15] introduce a tangential connection clustering routing for PLC to reduce broadcasting. Unfortunately, the broadcasting control scheme can also cause performance deterioration to networks.

Opportunistic routing (OR) has emerged as a promising way of improving network performance by exploiting the broadcasting nature of the networks [16, 17]. In [18], authors investigate the feasibility of the use of OR in PLC and present a customized OR algorithm by adopting static geographical information as a metric. However, this method cannot meet the demand of dynamic topology of PLC networks [19]. In addition, the location information of a node may be unavailable to In-Home PLC networks.

In topology-varying networks, traditional metrics, such as geographical information, delivery rate, and the expected transmission count, are no longer effective. To improve the routing performance, more efficient metrics have been investigated for PLC networks with varying topology. For example, the length of PLC line is adopted by [20]. Ref. [21] uses states of PLC channels as metrics to design the routing algorithm. However, these algorithms cannot provide a guaranteed throughput for the PLC users.

In this paper, to guarantee QoS for the application used in in-home PLC networks, we study the opportunistic routing scheme for networks with a dynamic topology. The end-to-end transmission time is considered as routing metric, which can ensure the real network throughput for applications. As we update the candidate information periodically, the packet can be directed to the optimal path even though the topology of PLC network is dynamically changed. Our contributions in this paper are listed as follows.

- We adopt the end-to-end transmission time for remaining path (TTRP) as the routing metric, which can be calculated according to the derived outage probability of PLC channels.
- Based on TTRP, we propose an opportunistic routing scheme TTRPOR for in-home PLC networks with varying topology, in which packets can be forwarded to the paths with high throughput.
- With the help of the statistical methods and mathematic induction, we prove that the throughput can be maximized when TTRP is used as the priority to select and sort the candidate nodes for forwarding packets.
- Simulations show that the performance of the PLC system outperforms those of conventional routing algorithms.

The rest of this paper is organized as follows. The PLC system model is described in Section 2. A PLC-OR scheme is designed in Section 3. The proposed scheme is evaluated in Section 4, and Section 5 concludes the whole paper.

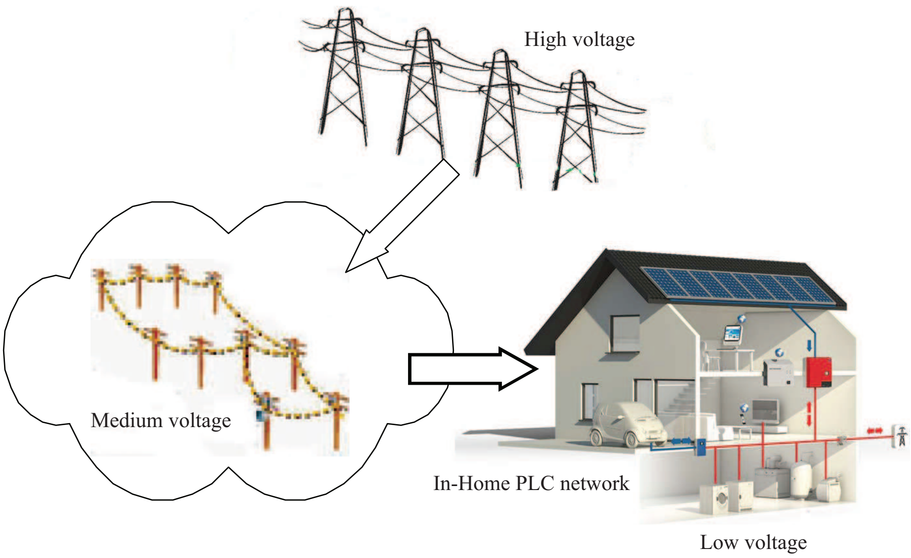

Figure 1 (Color online) The framework of power system.

2 Background

2.1 In-home PLC network

Figure 1 shows a power system consisting of four parts: generation, transmission, distribution and consumption. Generally, the power is generated and transported in high voltage (HV). The medium voltage (MV) and low voltage (LV) are used to distribute power over regional areas. Users access to the power systems by LV, in which systems PLC standards are often adopted to meet in-home (IH) requirements. In this paper, we focus on the IH which covers low voltage distribution networks.

However, compared with conventional communication channels, the channel of IH PLC has many disadvantages such as high noise, severe attenuation and multi-path effect. Moreover, since load in IH PLC network systems could change at any time, the topology of PLC networks is always unknown. And terminal impedance varies with different communication signal frequency. Due to these disadvantages in the IH PLC network systems, data concentrators (DC) may not always directly communicate with a meter unit [22]. To ensure the effectiveness of communication, some meter nodes must act as relays for the meters which located far from DC. Additionally, there are many sensors in smart grid, especially in IH PLC network. These sensors can perform as not only terminators but forwarding nodes. Then, the IH network can be taken as a sensor network, in which opportunistic is appropriate for adopting.

2.2 Opportunistic routing method

Opportunistic routing (OR) is based on the broadcasting transmissions of data packets. Since the forwarding continues as long as at least one neighbor receives the packet successfully, OR improves the reliability of the network.

In the OR scheme, the protocol selects a set of neighbor nodes as potential receivers for the next hop towards the destination. Neighbor nodes in the set are known as forwarding candidates, which are assigned a priority according to routing metric. These candidates are sorted by their priority in the candidate set in a descending order. When source node emits a batch of packets, the candidate forwarding node with the highest priority, is selected to forward packets. Consequently, given that some packets to be transmitted unsuccessfully, the second highest-priority node in the set acts as forwarding node to resolve unsuccessful packets. This process continues until 90% of the packets are successfully transmitted. The remaining 10% packets are sent by traditional routing, such as DSR.

In Figure 2, when $\mathcal{S}$ sends one packet to $\mathcal{D}$, the candidate forwarding node set of $\mathcal{S}$ is $F = \{u_1, u_2, u_3,$

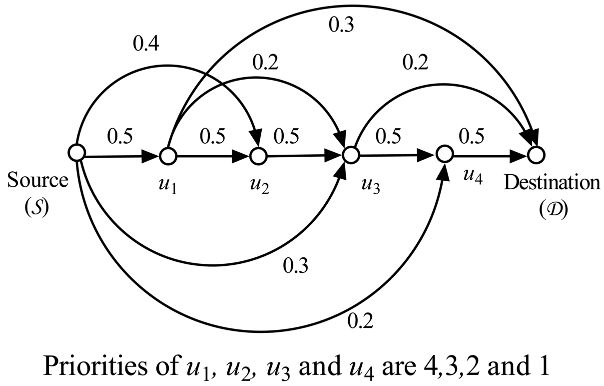

Figure 2 An illustration of OR approach. In the system, a node with larger priority number has a lower priority to forward packets. Thus, u_4 is of the highest priority.

$u_4\}$. u_4 is selected to forward packets from $\mathcal{S}$ due to its highest priority. Then, u_4 tries its best to forward packets $\mathcal{D}$. However, there are some unsuccessful packets during transmission. The second highest priority candidate node u_3 continues to forward these unsuccessful packets to $\mathcal{D}$. Packets failed to be forwarded by u_3 would be transmitted by u_2. The procedure will proceed until these packets are correctly received or all forwarding nodes cannot transmit these packets successfully. In OR scheme, relaying can be performed by some other forwarding candidates when the current forwarding candidate is unable to complete. Therefore, the total number of transmissions of OR is less than that of traditional routing methods, such as DSR and AOMDV.

3 Design of in-home PLC OR

3.1 System model and routing table

We consider an in-home PLC network scenario as shown in Figure 3, in which data communication devices are randomly distributed. Each device has one PLC modem, which acts as a terminal node or a relay node. There is only one central device at power meter or distributed transformer, which works as the master to manage the PLC network. In the network, terminal points and relays are taken as slaves. These slaves connect with the Internet and switch information through the master.

To ensure the throughput for in-home PLC networks, we construct a neighbor-path table (NPT) for each node to find the optimal routing to the destination $\mathcal{D}$ when initializing the network. Each entity in NPT is used to save the information of neighbor nodes and their corresponding optimal paths. The information of the neighbor node includes its name and the outage probability $p_{\rm out}$. The optimal path is the path with minimum transmission time from the neighbor node to $\mathcal{D}$, which is obtained by polling all the available paths. The information of the path is comprised by the time T of transmitting a packet through the path and the hops H in the path.

Nodes in PLC network are frequently connected and disconnected. This causes a dynamic change of the network topology. For the purpose of keeping path information in NPT up with the dynamic topology, we adopt a local broadcasting scheme. When a new node is connected to the network, it first emits the Hello packet to its neighbors. Neighbor nodes echo the new node with the path information after receiving the Hello packet. According to the path information, the new node builds its NPT. Neighbor nodes of the new node also add the path via the new node towards the destination into theirs NPTs except for those cycle paths.

In Figure 3, when the node u_{14} is added to the network, it polls its neighbors by broadcasting a Hello packet. Then, u_{24}, u_{25} and $\mathcal{S}$ return their path information to u_{14} for building its NPT. Similarly, when one node is out of work, its neighbors delete the path information via the node in their NPTs. In this way, variations of the network topology, such as nodes adding and leaving, can be perceived.

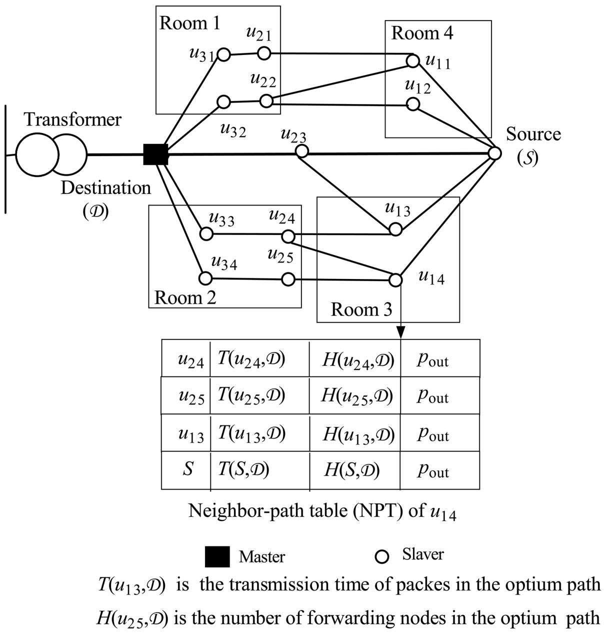

Figure 3 A typical in-home PLC network topology.

3.2 Routing metric

In order to favor routes with higher bit rate paths, we use end-to-end transmission time for remaining path (TTRP) as the metric to choose the path for a packet. To calculate TTRP, we first give the Lemma 1 to compute the point-to-point transmitting time for packets.

Lemma 1. The expected point-to-point transmitting time for a packet of a node can be given as

$$\mathrm{E}\left(T_{\text{p-p}}\right)=\sum_{i=1}^{M} i\cdot D_{\text{que}}\left(\frac{L}{V}+W_i\right)\cdot\frac{(1-p)^{i-1}p}{1-(1-p)^{M+1}},\tag{1}$$

where M is the threshold of retrying number for point-to-point transmission, and D_{que} is the queuing time, and W_i is time for back-off of the i transmission, and p is the probability of successfully transmitting packets, and V is the transmission rate, and L is the length of the packet.

Proof. The expected time required to transmit one packet is

$$\mathrm{E}\left(T_{\text{p-p}}\right)=\mathrm{E}\left(T|R<M\right),\tag{2}$$

where T is the time needed to transmit one packet, and R is the number of retries to transmit the packet. Hence, we have

$$\mathrm{E}\left(T_{\text{p-p}}\right)=\sum_{i=1}^{M} i\cdot D_{\text{que}}\left(\frac{L}{V}+W_i\right)\cdot\Pr\left(R_i(u)\right),\tag{3}$$

where R_i is the ith retries of node u to transmit a packet, and its probability is

$$\Pr\left(R_i(u)\right)=\frac{(1-p)^{i-1}p}{1-(1-p)^{M+1}}.\tag{4}$$

Then, Lemma 1 is proved.

In fact, the probability of successfully transmitting packets p can be computed by the outage probability p_{out} of the PLC channels, which is $p=1-p_{\text{out}}$. p_{out} can be estimated according to the distribution of the amplitude h of the PLC channel. According to Figure 3, nodes in the PLC system are communicating with each other by only one power line. In this case, the probability density function (PDF) of h is a lognormal distribution with PDF $f_h(x)$ [1], given as

$$f_h(x) = \frac{1}{\sqrt{2\pi\sigma^2}x}\mathrm{e}^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, \tag{5}$$

where μ is the mean of $\ln(x)$, which can be obtained from $\mu = 1 + \ln|g|$, and g is a path constant. σ is the variance of $\ln(x)$. According to [1], the PLC channels are subjected to the mixture of Gaussian noise and impulsive noise. The two noises are independent. Hence, the variances of channel noise can be obtained by

$$\sigma^2 = \sigma_{\mathrm{G}}^2 + c \times \sigma_{\mathrm{I}}^2, \tag{6}$$

where σ_{G}^2 and σ_{I}^2 are the variances of the Gaussian noise and impulsive noise, and c is a constant. As the received SNR of the PLC channel ρ can be expressed by $\rho = h^2$, the PDF of ρ can be expressed as

$$f_\rho(x) = \frac{1}{2\sqrt{2\pi\sigma^2}x}\mathrm{e}^{-\frac{\left(\frac{1}{2}\ln x-\mu\right)^2}{2\sigma^2}}. \tag{7}$$

The cumulative distribution function (CDF) of ρ is given as

$$F_\rho(x) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\ln x - 2\mu}{2\sqrt{2}\sigma}\right), \tag{8}$$

where $\mathrm{erf}\,(x) = \frac{2}{\sqrt{\pi}}\int_0^x \mathrm{e}^{-\eta^2}\mathrm{d}\eta$. We define the outage probability of SNR below threshold ρ_{th} as

$$p_{\mathrm{out}} = P(\rho \leqslant \rho_{\mathrm{th}}). \tag{9}$$

Hence, the outage probability of a PLC channel is

$$p_{\mathrm{out}} = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\ln \rho_{\mathrm{th}} - 2\mu}{2\sqrt{2}\sigma}\right). \tag{10}$$

Assuming that the length of the packet is large enough, the rate of packets losing is approximately equal to the outage probability.

Lemma 1 gives a method to calculate the average time to transmit a packet point to point. If we do not consider the retransmission, the end-to-end transmission time is the sum of the transmitting time of all the point-to-point in the path. However, retransmission of the end-to-end communication plays an important role in ensuring the stability of PLC networks. There is a threshold M of retrying number in point-to-point transmission. If the number of retransmissions is beyond M, the packet would be discarded. In the scenario, the source node retransmits the packet. Thus, end-to-end transmission time of a given path from $\mathcal{S}$ to $\mathcal{D}$ can be obtained by

$$T_{\text{E-E}}\,(S, D) = \sum_{m=1}^{\gamma}\sum_{n=0}^{H_m-1}\overline{T}_{\text{p-p}}\,(u_n), \tag{11}$$

where H_m means that the hops of the mth retry of the source node, and $\overline{T}_{\text{p-p}}\,(u_n)$ is average transmission time from u_n to its neighbor. γ is the number of transmissions for source node successfully delivering a packet to the destination.

From Eq. (11), the end-to-end transmission time is determined by the retransmissions and the number of node evolved in each retransmission. As a result, we define η_n as the probability that the packet successfully is transmitted via n nodes, then

$$\eta_n = \Pr(H_m > n) = \prod_{i=0}^{n}\left(1 - (1 - p_i)^M\right), \tag{12}$$

where p_i is the probability that ith node successfully transmits packets to the next node in the path. According to (11) and (12), the estimated end-to-end transmission time can be calculated by Theorem 1.

Theorem 1. Given a path form $\mathcal{S}$ to $\mathcal{D}$, the average end-to-end time to transmit a packet successfully over the path is

$$\mathrm{E}\left(T_{\text{E-E}}\right)(n)=\left(\frac{1}{\eta_H}-1\right)\sum_{k=1}^{H-1}\sum_{i=0}^{k}\mathrm{E}\left(T_{\text{p-p}}\left(u_i\right)\right)\times\left(\frac{\eta_i-\eta_n}{1-\eta_H}\right)+\sum_{n=1}^{H-1}\mathrm{E}\left(T_{\text{p-p}}\left(n\right)\right), \tag{13}$$

where H is the number of the hops of the path, and γ is the number for retries of successfully transmitting the packet.

Proof. Suppose the estimated time of transmitting a packet from node u to the destination $\mathcal{D}$ is $T_{\text{E-E}}(u)$, which can be given as

$$\mathrm{E}[T_{\text{E-E}}\left(u\right)]=\mathrm{E}\sum_{m=1}^{\gamma-1}\mathrm{E}_{\gamma}\left(\sum_{i=0}^{H_m}\overline{T}_{\text{p-p}}\left(u_i\right)\right)+\sum_{n=0}^{H-1}\overline{T}_{\text{p-p}}\left(u_n\right), \tag{14}$$

where H_m is the hops of the mth end-to-end retransmission, which value is from 0 to $H-1$, and $\overline{T}_{\text{p-p}}(u_n)=E\left(T_{\text{p-p}}(u_n)\right)$. The second item of (14) means the time for the last transmission, which is successful. The first item of Eq. (14) is the time responding for $\gamma-1$ unsuccessful transmissions. Hence, the expeced time for an unsuccessful transmission can be expressed as

$$\mathrm{E}_{\gamma}\sum_{i=0}^{H_m}\overline{T}_{\text{p-p}}\left(u_i\right)=\sum_{i=0}^{H_m}\mathrm{E}\left(\overline{T}_{\text{p-p}}\left(u_i\right)|H_m>i,m<\gamma\right). \tag{15}$$

According to the statistical method, we have

$$\mathrm{E}\left(\overline{T}_{\text{p-p}}\left(u_i\right)|H_m>i,m<\gamma\right)=\mathrm{E}\left(\overline{T}_{\text{p-p}}\left(u_i\right)\times I\left(H_m>i,m<\gamma\right)\right), \tag{16}$$

where I can be defined as

$$I\left(H_m>i,m<\gamma\right)=\begin{cases}1, & H_m>i,\ m<\gamma,\\ 0, & H_m\leqslant i\ or\ m=\gamma.\end{cases} \tag{17}$$

Hence, $\mathrm{E}\left(I\left(H_m>i,m<\gamma\right)\right)$ in Eq. (16) can be given as

$$\mathrm{E}\left(I\left(H_m>i,m<\gamma\right)\right)=\Pr\left(H_m>i,m<\gamma\right). \tag{18}$$

Combining (16) and (18) yields

$$\mathrm{E}\left(I\left(H_m>i,m<\gamma\right)\times\overline{T}_{\text{p-p}}\left(u_i\right)\right)=\mathrm{E}\left(\overline{T}_{\text{p-p}}\left(u_i\right)\right)\times\Pr(H_m>i,m<\gamma). \tag{19}$$

According to the statistics theory, $\mathrm{E}\left(\overline{T}_{\text{p-p}}(u_i)\right)$ in Eq. (15) can be transformed as

$$\mathrm{E}\sum_{i=0}^{H_m-1}\overline{T}_{\text{p-p}}\left(u_i\right)=\sum_{k=1}^{H-1}\sum_{i=0}^{k}\eta_i\overline{T}_{\text{p-p}}\left(u_i\right). \tag{20}$$

Combining (19) and (20) yields

$$\mathrm{E}\left(T_{\text{E-E}}\right)=\mathrm{E}\left(\gamma-1\right)\sum_{k=1}^{H-1}\sum_{i=0}^{k}\eta_i\overline{T}_{\text{p-p}}\left(u_i\right)\times P\left(H_m>i,m<\gamma\right)+\sum_{i=0}^{H-1}\overline{T}_{\text{p-p}}\left(u_n\right). \tag{21}$$

Since random variable γ obeys a geometric distribution, according to (12) we have

$$\begin{aligned}&\mathrm{E}\left(\gamma-1\right)\sum_{H_m=1}^{H-1}\sum_{i=0}^{H_m}\eta_i\overline{T}_{\text{p-p}}\left(u_i\right)P\left(H_m>n,m<\gamma\right)\\&=\left(\frac{1}{\eta_H}-1\right)\sum_{k=1}^{H-1}\sum_{i=0}^{k}\eta_i\mathrm{E}\left(T_{\text{p-p}}\left(u_i\right)\right)\left(\frac{\eta_i-\eta_n}{1-\eta_H}\right).\end{aligned} \tag{22}$$

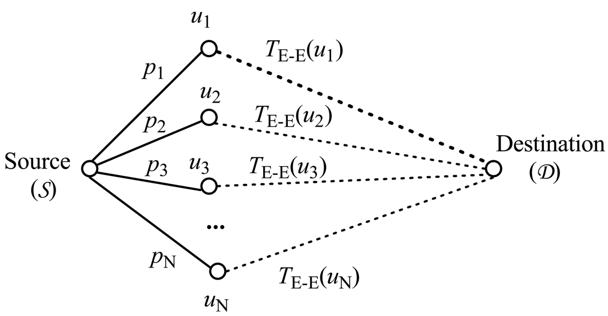

Figure 4 The forwarding nodes topology.

Combining (14) and (22), Eq. (13) is founded. Hence, Theorem 1 is proved.

The routing metric TTRP can be used to estimate the end-to-end transmission time, which can guide packets forwarded to the links with less TTRP. However, compute of the routing metric is very intensive. To reduce the complexity, we calculate the routing metric in NPT when initializing the network and changing topology. Thus, rather than computing TTRP for every transmission, the forwarding node consults NPTs to obtain TTRP for selecting and sorting forwarding nodes.

3.3 Forwarders sorting and selection

In this section, we use the metric TTRP as priority to sort forwarders. After sorting, we provide source node with a optimum forwarder list, so that the throughput can be improved. We define $ET_{S,F,D}$ as the expected throughput from $\mathcal{S}$ to $\mathcal{D}$ with a candidate node list $\boldsymbol{F} = \{u_1, u_2, \ldots, u_N\}$. In terms of Figure 4, we can calculate $ET_{S,F,D}$ by

$$ET_{S,F,D} = \sum_{i=1}^{N} \frac{L}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)} \times p_i \times \prod_{m=1}^{i-1} (1 - p_m), \tag{23}$$

where p_i is the probability of successfully delivering a packet from $\mathcal{S}$ to u_i.

Let $q_{S,i}$ be the probability that u_i is selected as the forwarding node, which is given as

$$q_{S,i} = p_i \prod_{m=1}^{i-1} (1 - p_m). \tag{24}$$

Thus, Eq. (23) can be transformed as

$$ET_{S,F,D} = \sum_{i=1}^{N} q_{s,i} \times \frac{L}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)}. \tag{25}$$

To illustrate the effectiveness of sorting forwarders according to TTRP, we give Theorem 2.

Theorem 2. Given a pair of source node and target node $(\mathcal{S}, \mathcal{D})$, and the forwarding node list of $\mathcal{S}$ is $\boldsymbol{F} = \{u_1, u_2, \ldots, u_N\}$, if $\boldsymbol{F}$ is sorted according to TTRP, the expected throughput achieves its maximum value.

Proof. Let the expected throughput with forwarder list $\boldsymbol{F}$ be $ET_{S,F,D}$, which can be given as

$$ET_{S,F,D} = L \sum_{i=1}^{N} \frac{q_{s,i}}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)}, \tag{26}$$

where $\boldsymbol{F}$ is sorted according to TTRP, namely $\mathrm{E}\left(T_{\text{E-E}}(u_j)\right) \geqslant \mathrm{E}\left(T_{\text{E-E}}(u_i)\right),\ i < j$. We assume that $\boldsymbol{F}^*$ is a forwarding node list with arbitrary order. The expected throughput with forwarding node list $\boldsymbol{F}^*$ can be given as

$$ET_{S,F^*,D} = L \sum_{i=1}^{N} \frac{q^*_{s,i}}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)}. \tag{27}$$

Then we should prove $ET_{S,F,D} \geqslant ET_{S,F^*,D}$. We prove the theorem by using the principle of mathematic induction.

(1) As $N = 1$, $ET_{S,F,D} \geqslant ET_{S,F^*,D}$ holds.

(2) Assume that Theorem 2 holds for $N = r$, where r is an integer. When inserting a new node into $\boldsymbol{F}$, we have $N = r + 1$. Without loss of generality, we separate $\boldsymbol{F}$ to two sorted lists $\boldsymbol{A} = \boldsymbol{F} - u_k$ and $\boldsymbol{B} = u_k$, where u_k is any node between u_1 to u_r. The sorted nodes list is $\boldsymbol{F}^* = \{\boldsymbol{A}, \boldsymbol{B}\}$, therefore

$$ET_{S,F^*,D} = L\left(\sum_{i=1}^{k-1} \frac{q_{S,i}}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)} + \sum_{i=k+1}^{r+1} \frac{q_{S,i}}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)(1-p_k)} + \frac{p_k \prod_{i=1}^{r}(1-p_i)}{\mathrm{E}\left(T_{\text{E-E}}(u_k)\right)(1-p_k)}\right). \tag{28}$$

In order to compare, we subtract $ET_{S,F^*,D}$ from $ET_{S,F,D}$,

$$ET_{S,F,D} - ET_{S,F^*,D} \approx \sum_{i=k+1}^{r+1} \left(\frac{1}{\mathrm{E}\left(T_{\text{E-E}}(u_k)\right)} - \frac{1}{\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)}\right) \frac{q_{s,i}}{(1-p_k)} > 0. \tag{29}$$

Therefore, $ET_{S,F,D} \geqslant ET_{S,F^*,D}$ holds for $N = r + 1$. This completes the proof of Theorem 2. According to Theorem 2, if we sort the forwarding nodes with TTRP, the network can achieve the highest throughput.

In general, more candidate nodes in the forwarder set can contribute to a higher throughput of the network. However, increasing the number of forwarding nodes leads to more system resource wasting. To select a proper length of forwarder set, we give Theorem 3.

Theorem 3. Given a source node $\mathcal{S}$ with N forwarding nodes, the forwarding node list of $\mathcal{S}$ is $\boldsymbol{F} = \{u_N, \ldots, u_2, u_1\}$. The increment of $ET_{S,F,D}$ reduces with the increase of N.

Proof. Let $\boldsymbol{F}_N$ denote the set of forwarding nodes with the cardinal N. We divide $\boldsymbol{F}_N$ into three ordered node sets $\Lambda_1, \Lambda_2, \Lambda_3$. After adding a node u_i into $\boldsymbol{F}_N$, we forge the new list of forwarding nodes $\boldsymbol{F}_{N+1} = \{\Lambda_1, u_i, \Lambda_2, \Lambda_3\}$. $\boldsymbol{F}_{N+2} = \{\Lambda_1, u_i, \Lambda_2, u_j, \Lambda_3\}$ is the list after adding another forwarding node u_j. To prove Theorem 3, we need to prove

$$\left(ET\left(\boldsymbol{F}_{N+1}\right) - ET\left(\boldsymbol{F}_N\right)\right) - \left(ET\left(\boldsymbol{F}_{N+2}\right) - ET\left(\boldsymbol{F}_{N+1}\right)\right) > 0. \tag{30}$$

We prove the problem in two cases in terms of the relationship between $\mathrm{E}\left(T_{\text{E-E}}(u_i)\right)$ and $\mathrm{E}\left(T_{\text{E-E}}(u_j)\right)$. In the first case, we consider $\mathrm{E}\left(T_{\text{E-E}}(u_j)\right) \geqslant \mathrm{E}\left(T_{\text{E-E}}(u_i)\right)$. We transform (30) into

$$\begin{aligned} &ET(F_{N+1}) - ET\{\Lambda_1, u_i, \Lambda_2, \Lambda_3\} \\ &\quad = (ET(\boldsymbol{F}_{N+2}) - ET\{\Lambda_1, u_i, \Lambda_2, \Lambda_3\}) + (ET(\boldsymbol{F}_{N+1}) - ET(\boldsymbol{F}_N)) > 0, \end{aligned} \tag{31}$$

where $ET\{\Lambda_1, u_i, \Lambda_2, \Lambda_3\}$ is the maximum value of ET with forwarder list $\{\Lambda_1, u_i, \Lambda_2, \Lambda_3\}$. Eq. (31) is further simplified as

$$\begin{aligned} ET\left(\boldsymbol{F}_{N+1}\right) - ET\{\Lambda_1, u_i, \Lambda_2, \Lambda_3\} &= \left(1 - \sum_{k\in\Lambda_1} q_k\right)\left(1 - \sum_{k\in\Lambda_2} q_k\right) \\ &\quad \cdot \left(\frac{1}{\mathrm{E}\left(T_{\text{E-E}}(u_j)\right)} - \frac{1}{\mathrm{E}\left(T_{\text{E-E}}(\Lambda_3)\right)}\right) > 0, \end{aligned} \tag{32}$$

where $\mathrm{E}\left(T_{\text{E-E}}(\Lambda_3)\right)$ is the expected end-to-end time to transmit packets for the source node with forwarding list Λ_3. Therefore, we prove the correctness of Eq. (27). Similarly, we can prove the second case, namely $\mathrm{E}\left(T_{\text{E-E}}(u_j)\right) \leqslant \mathrm{E}\left(T_{\text{E-E}}(u_i)\right)$. Then, we complete the proof of Theorem 3.

Theorem 3 shows that ET increases as the number of forwarding nodes increases. However, increment of network throughput in transport layer becomes smaller with the increase of the number of forwarding nodes.

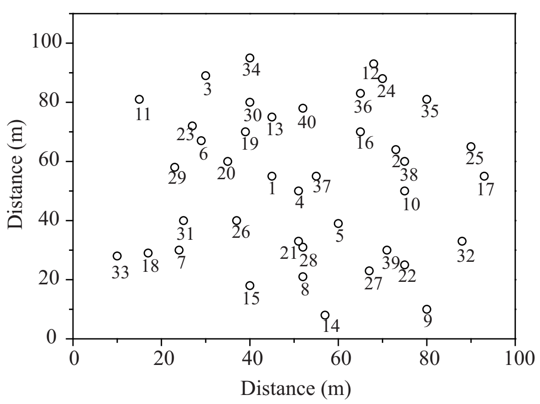

Figure 5 Layout of PLC network simulation.

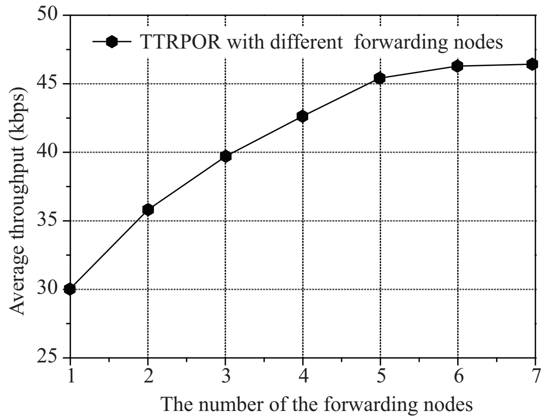

Figure 6 Throughput of signal hop by different forwarding nodes.

Table 1 ANT of routing algorithms

Hop number	DSR	EXOR	TTRPOR
1-hop	1.68	1.43	1.38
2-hop	2.56	2.01	1.78
3-hop	3.88	2.95	2.52
4-hop	5.95	4.02	3.26

3.4 Performance evaluation

We set up a 40-node PLC network in NS-2 according to the PLC transmission parameters in [6], as shown in Figure 5. These nodes are uniformly distributed within one 100 m×100 m rectangle region. The transmission range of one hop is selected as 25 m. The loss rate of each link varies from 0 to 60% randomly. Before simulation, we run initialization module to get the neighbor path table (NPT).

Figure 6 shows the curve of throughput versus number of forwarding nodes. The simulation result agrees well with the conclusion of Theorem 3. We observed that the throughput growth becomes slowly after the number of forwarding nodes is more than five. As a result, the number of forwarding nodes is selected as five in following simulations.

In the first experiment, we investigate the performance of the retransmissions characterized by average number of transmissions (ANT), which can be given by

$$\mathrm{ANT} = \frac{\sum_{i}^{P_{\mathrm{N}}} \sum_{j=1}^{T_{\mathrm{L}}} r_{i,j}}{P_{\mathrm{N}}}, \tag{33}$$

where P_{N} is the packet number, T_{L} is the number of links of the packet i transmitting on, and $r_{i,j}$ is the number of retries of packet i on link j. We send 5000 packets for 10 times with three routing protocols, DSR, EXOR and TTRPOR. The result is listed in Table 1.

The number of retransmissions per hop of the proposed TTRPOR is significantly less than those of EXOR and DSR. The average numbers of transmission per packet in whole network are about 3.26 times for the proposed method, 4.2 times for EXOR, and 5.95 by DSR, respectively. Obviously, the method proposed is very efficient. The reason is that by using the broadcasting feature of the network packets, the opportunistic routing scheme reduces retransmissions. Thus, The retransmissions of EXOR and TTRPOR is less than that of DSR. Additionally, the proposed algorithm adopts TTRP as its metric, with which packets can be forwarded to the links with high SNR leading to a small packet loss rate. Naturally, retransmissions in the network adopting TTRPOR is much less than that in EXOR.

In our second experiment, we switch off different proportions of nodes in the PLC network per 2 s. The scenario is similar to the situation that some lighters or switchers are turned off. The proportions

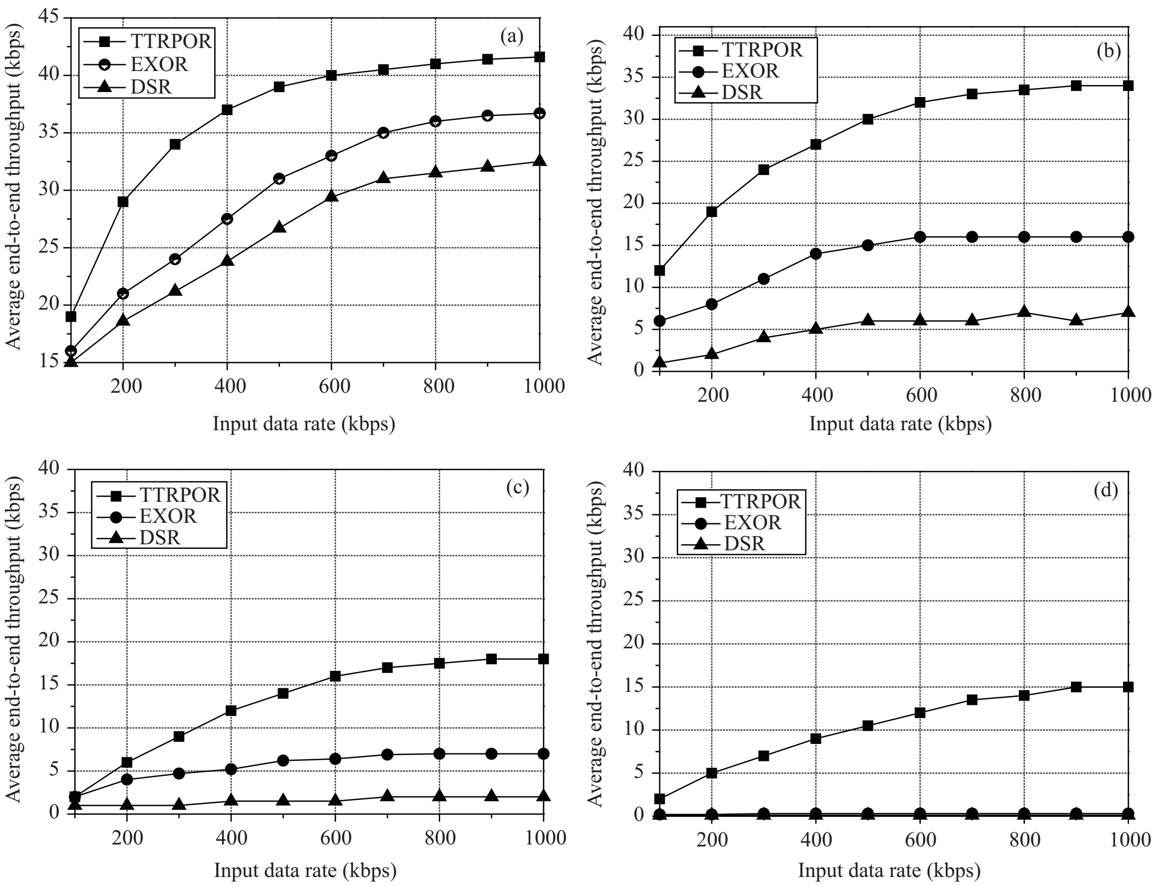

Figure 7 End-to-end throughputs with different proportions nodes dynamically turned off. (a) All nodes working; (b) one-third of nodes turned off; (c) two-fifth of nodes turned off; (d) two-third nodes turned off.

are selected as one-third, two-third and two-fifth. Figure 7 shows the average end-to-end throughput of the PLC network with the three routing algorithms.

The average end-to-end throughput of the TTRPOR outperforms that of the DSR and EXOR. From Figure 7(a), when the input data rate at source node is 1000 kb/s, the average end-to-end throughput of EATOR is about 11% higher than that of EXOR and about 20% higher than that of DSR. Since DSR requires the construction of routing table in every transmission, the end-to-end throughput of DSR is less than that of EXOR and TTRPOR.

From Figure 7, we also find the end-to-end throughput is highly affected by network topology when adopting EXOR and DSR. As one-third of nodes are dynamically turned off, the throughputs of the DSR and EXOR are decreased sharply. But it varies slightly in the network with TTRPOR. The reason is that some paths probed by DSR and EXOR now no long existed. For the same reason, when two-third and two-fifth of nodes fail, gaps between the curve of TTRPOR and those of DSR, EXOR tend to be larger. The average end-to-end throughput of the DSR and EXOR is very close to zero, while TTRPOR can still achieve an average throughput about 15 kb/s.

To evaluate the complexity of out routing algorithm, we adopt the total time of metric computation as the indicator. A thread is installed in the each node to count the time required for computing the routing metric. We collect the time from each node. The result is shown as Figure 8.

As shown in Figure 8, when one-third of nodes are dynamically turned off, the time of routing metric computation does not increase significantly for TTRPOR. By analysing the trace files of NS-2, we notice that it is needless to calculate TTRP in every transmission. Nonetheless, when one-third of nodes are turned off, DSR scheme probes the network frequently for reconstructing new source routes, which results in a dramatic increase the time for metric computing. As a result, the time to compute routing metric

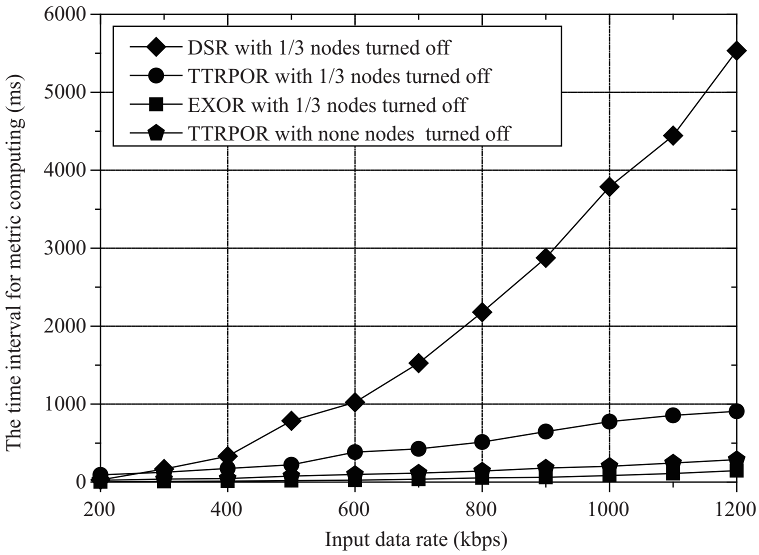

Figure 8 Curves of time to compute the routing metric versus nodes dynamically turned off.

for TTRPOR is much lower than that for DSR. Since EXOR does not update its metric even the network topology is changed, the total time spent on computing routing metrics is lower than that of TTRPOR. But for a static network, the total time used for metric computation for EXOR is very close to that of TTRPOR.

4 Conclusion

In this paper, we study an opportunistic routing scheme, which can perform well in in-home PLC networks with varying topology. A new routing metric of end-to-end transmission time for remaining path is proposed. The estimating method of TTRP is derived according to the outage probability of the PLC channel. It is proved that selection and sorting the forwarding nodes according to TTRP can maximize the throughput. Simulation results show a higher throughput can be achieved in the networks with TTRPOR by reducing the average number of retransmissions. Compared to EXOR and DSR, our proposed algorithm significantly improves throughput, especially for varying-topology in-home PLC networks.

Acknowledgements This work was supported in part by Open Research Fund of National Key Laboratory of Electromagnetic Environment, China Research Institute of Radiowave Propagation (Grant No. 201500013), Open Research Fund of National Mobile Communications Research Laboratory, Jiangsu Provincial Science Foundation Project (Grant No. BK20150786), Southeast University (Grant No. 2013D02), and National Natural Science Foundation of China (Grants Nos. 61501238, 61271230, 61472190).

Conflict of interest The authors declare that they have no conflict of interest.

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