Opportunistic Routing for Smart Grid With Power Line Communication Access Networks

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***Abstract*—Power line communications (PLCs) have recently absorbed interest in the smart grid since they offer communication capability in an easy and simple deployment. The main role of PLC access network (PLC-AN), which is constructed with medium and low voltage distribution networks, is to exchange control signals between substations and end users or to provide the Internet access to homes. Since a transmission signal of narrowband PLC penetrates electronic devices, a use of opportunistic routing (OR) can be a viable option in PLC-AN design. In this paper, we investigate the feasibility of OR use in PLC-AN and propose a customized OR for it, named PLC-OR, which uses static geographical information. For doing this, we formulate a bit-meter per second maximization problem and solves it in a distributed manner. Through simulations, we confirm that our proposed PLC-OR successfully reduces packet transmission time compared to the traditional sequential routing while achieving the same level of reliability in packet delivery.**

***Index Terms*—Access network, narrowband PLC, opportunistic routing, power line communications, smart grid.**

I. Introduction

THE RECENT momentum of replacing the aging power grid through combining the energy technology (ET) with the information and communication technology (ICT), which is called "smart grid," is bringing attention to the use of power line communications (PLC) as an appropriate networking technology within the grid. The smart grid requires advanced information, control, and communication technologies to support intelligent features such as electronic controlling, monitoring, self-healing, diagnosing, and an advanced metering infrastructure (AMI). The success of the smart grid heavily depends on fast and reliable data transmission since some smart grid applications should be performed in real time [1], [2]. There are ongoing debates on the actual roles of PLC for the smart grid, i.e., whether PLC can become the alternative of already-in-market wireless technology or not. However, there is no doubt that the smart grid will exploit multiple communication technologies to guarantee reliability, and that PLC has an advantage over the other communication systems because power line infrastructures exist everywhere.

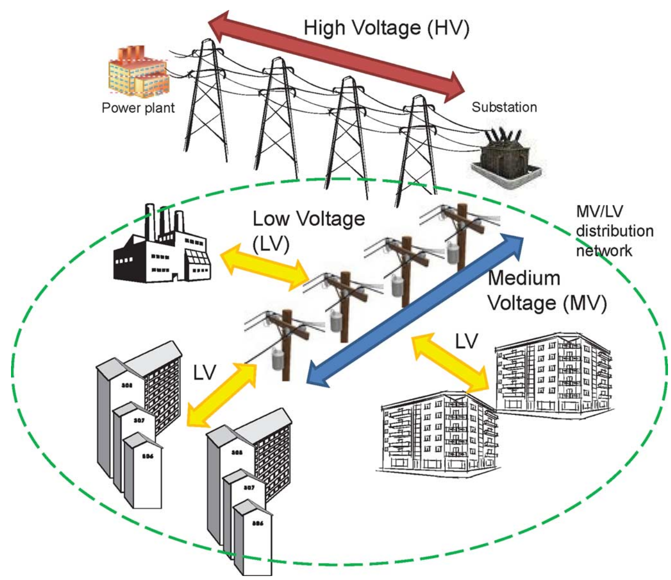

Fig. 1. HV, MV, and LV in a power network.

Power systems consist of four parts in general: generation, transmission, distribution and consumption. The power is generated and transported in high voltage (HV). Then, it is distributed over regional areas in medium voltage (MV) and low voltage (LV), and consumed in LV as shown in Fig. 1. PLC standards are designed to meet in-home (IH) multimedia or access network (AN) requirements [3]. They are targeting both high and low data rate communications for the Internet access to homes or for remote metering and load control applications in regional areas. In this paper, we focus on an AN which covers MV/LV distribution networks. As a candidate networking technology in the AN, PLC is attracting attention since it can support communication between power producing and consuming entities. Communication through PLC enables distributed, efficient and economical power management in the smart grid.

PLC-AN requires a routing functionality because an MV/LV distribution network covers a wide area and several intermediate nodes are involved in delivering a packet[1]. Since the characteristics of power line channels are different from those of wireless, simply adopting a traditional routing scheme cannot maximize the performance of power line networks [4]. Thus, it is necessary to design a PLC customized routing protocol which exploits power line characteristics.

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[1]It is different from PLC in-home where most of power devices are in one hop from each other.

Channel characteristics of power line and wireless media are different. Both of PLC and wireless channels show the multipath propagation property. In the wireless channel, fading is caused by the constructive and destructive combination of multipath signals, and incurs short-term signal fluctuations. Differently than this, fading in the PLC channel is caused by signal reflections in the branch-based grid topology [5] and signal attenuations at each capacitor bank and MV/LV transformer [6], [7]. In addition, noise characteristics of PLC and wireless channels are much different. The noise in the wireless channel is assumed to be dominated by thermal noise so that it can be modeled as additive white Gaussian noise (AWGN). On the contrary, the noise in the PLC channel can be modeled as colored background noise, narrowband interference and synchronous and asynchronous impulsive noises [8].

Recently, a number of researches on the routing functionality in PLC-AN have been performed [9]–[11]. In [9], flooding is shown to be an efficient routing scheme in PLC-AN when all nodes need to receive identical information from the network. However, neither all automation networks nor smart grid applications have the same requirements. Applications such as AMI, system breakdown sensing, and recharging systems for electric vehicles require point-to-point communications. Another researches on PLC-AN routing in [10], [11] have introduced geographic routing, which requires location information of each power device. Biagi *et al.* have briefly applied wireless routing schemes to the PLC-AN in [10] and extended those in [11]. However, they have not considered the case of multiple receivers.

Opportunistic Routing (OR) has emerged as a promising way of improving network performance by exploiting the broadcasting nature of wireless medium in ad-hoc and sensor networks. After finding a path from a source to a destination, traditional routing, or sequential routing, and OR differs in the way of relaying a frame hop by hop. The sequential routings deliver a frame with predetermined intermediate nodes decided before the transmission starts, and one dedicated next node is appointed to forward it. However in OR, multiple intermediate nodes, called a forwarder set, stochastically overhear the transmission from a sender. Then, a node with the closest to the destination, or with the largest improvement, rebroadcasts the frame. This forwarding process continues until the frame reaches the destination. It has been shown that OR improves network performance compared to traditional sequential routing schemes, in terms of end-to-end throughput, reliability, and the number of transmissions [12].

OR can be a good candidate in PLC-AN because of the penetration characteristic of PLC signals on power line. Therefore, in this paper, we argue the feasibility of OR in the PLC-AN and propose a PLC-AN customized OR, named PLC-OR. It uses topological information to build a routing table, and chooses a single route to the destination. Because of its use of a single route, PLC-OR does not suffer from duplicated reception at the final destination. Our PLC-OR also uses ACK based distribution coordination. To design our scheme, we first formulate a bit-meter per second maximization problem to select transmission rate, tone mapping pattern, and forwarder set. Then, we propose a locally operating algorithm which finds an optimal solution to the problem.

The rest of this paper is organized as follows. We first briefly overview narrowband PLC standards and OR in Section II. Then, our system model is described in Section III. We design a PLC-OR scheme in Section IV. After evaluating our proposed schemes in Section V, we conclude our paper in Section VI.

II. Background

A. PLC Standards

There are two approaches in PLC. The first one is a narrowband solution that operates below 500 kHz band at rates of up to hundreds kbps, and the second one is a broadband solution running at the band of 2–30 MHz with rates of up to a couple of hundred Mbps. Most of state-of-the-art PLC standards have employed the newest techniques for wireless systems such as orthogonal frequency division multiplexing (OFDM) and adaptive modulation and coding (AMC) [13], [14].

In PLC-AN, the narrowband solution is more appealing due to several reasons. First, it offers a longer transmission range as channel attenuation increases with the frequency [15]. Differently than the broadband solution, it does not have significant emission issues [5]. The narrowband signals can penetrate electrical devices, such as capacitor banks and transformers, while the broadband signals cannot [3].

Second, many of smart grid applications do not require data rates of hundreds of Mbps [5], [16]. Automated metering infrastructure (AMI), sensing/monitoring/controlling power devices, system malfunction recognition, and recharging control systems for electric vehicles are appropriate applications of the narrowband solution due to their moderate data rate requirements.

Finally, considering the OFDM technology in up-to-date PLC, the broadband solution requires higher complexity than the narrowband solution as it must support a larger number of subcarriers [3]. Therefore, the narrowband solution achieves a low-cost and wide-coverage network in MV and LV power grids. In this paper, we consider the narrowband solution for PLC-OR design.

Recently, several narrowband PLC standards such as G3-PLC, PRIME, ITU-T G.hnem, and IEEE 1901.2, aiming to support smart grid applications have been issued. They use OFDM, and AMC techniques to enhance throughput performance. In addition, to exploit PLC channel characteristics, adaptive tone mapping has been defined. It enables a transmitter to exclude some channels experiencing heavy interference from channel allocation, and to use higher modulation and coding (MCS) level.

Because of the multihop characteristic in PLC-AN, routing is essential for packet delivery. To the best of our knowledge, there is no previous investigation on the routing issue about new narrowband PLC standards that supports multiple transmission rates and adaptive tone mapping.

B. Opportunistic Routing

OR basically exploits the broadcasting nature of wireless medium where a transmission can be overheard by several neighbors. One of those who have overheard the transmission rebroadcasts the received frame toward the destination node, and this rebroadcasting continues until the frame reaches the destination. Since the forwarding continues as long as at least one neighbor receives the frame correctly, OR improves the reliability of a network. Furthermore, since there is a chance for a transmission to travel through multiple hops at a time,

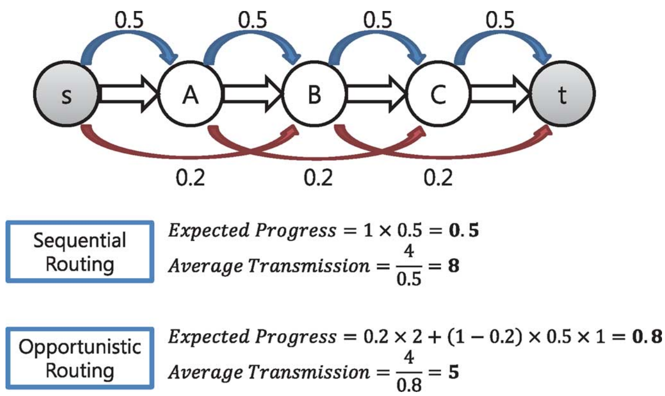


Fig. 2. The expected progress of sequential routing and OR.

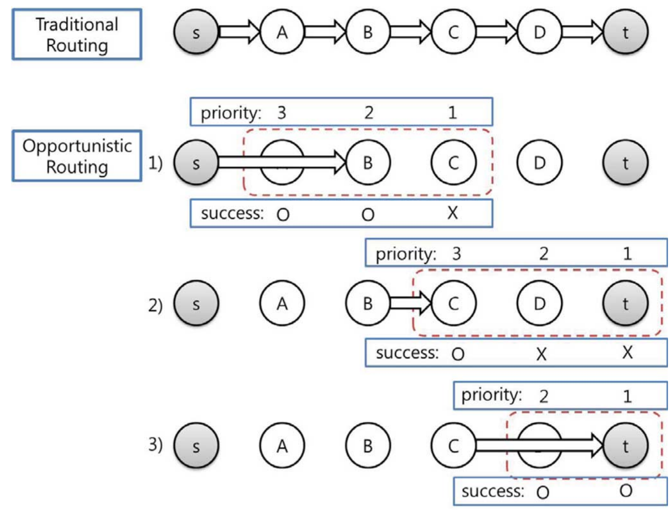


Fig. 3. An illustration of OR in a linear topology.

OR contributes to reducing the total number of transmissions required.

In Fig. 2, the difference between the traditional sequential routing and OR in the sense of expected progress of one transmission attempt and the average number of transmission attempts to reach the destination is shown. In this example, it is assumed that a transmission from a sender can be correctly received at one-hop neighbor with the probability of 0.5 and at two-hop neighbor with the probability of 0.2. In the sequential routing, since each transmission attempt aims to cross one-hop distance with the success probability of 0.5, the expected progress is 0.5. For a packet to reach the destination, it needs to cross four hops. So, in the sequential routing, it requires 8 attempts on average. However, in OR, a transmission can cross two hops with the probability of 0.2. And it crosses one-hop with the probability of 0.5 if given two-hop crossing has failed. The expected progress of an attempt is 0.8 in OR, leading to the reduced average number of attempts required.

The key design issues to achieve these goals are: forwarder set selection, prioritization, and duplicated transmission avoidance/suppression [12]. The forwarder set selection is to determine a set of candidates of the relaying neighbors. It should be done carefully toward the direction of the destination, i.e., having the routing progress. The prioritization is to give priorities among selected candidates so that one with the most routing progress in the set is selected as an actual relay. If the most progressive one fails to relay the frame, the second most one should be selected and so on. Finally, relaying should be performed in a way of reducing duplicated transmissions that degrade network performance due to the waste of network resource.

Fig. 3 shows an illustration of how the sequential routing and OR work. In both routings, a path from a source to a destination is decided priori with some metrics[2]. In the traditional routing, a frame travels through the predetermined route, passing through each node on the path in a sequential way. In OR, however, for each transmission, a forwarding set is selected first (dotted rounded square), and the node priority within the set is given in some way (upper square). According to the transmission result, i.e., success or failure, an actual relay will be chosen to forward the frame to the next forwarding set. In this example, OR requires three transmissions while the traditional routing needs five transmissions for the delivery. In general, OR requires a less number of transmissions or retransmissions. This is because in OR, relaying can be performed by some other neighbors when a specific neighbor fails to receive a sender's transmission. However, forwarder set selection, prioritization, and duplicated transmission avoidance/suppression require some processing. So, there exists a tradeoff between progressing gain and processing delay in OR protocol design.

Note that if the sender has only one neighbor node, OR performs the same as the traditional sequential routing. In addition, if a sender has no neighbor node, any routing scheme cannot deliver packets to the destination.

III. System Model

A. Narrowband Channel Model

In this subsection, we describe noise models and empirical channel measurement results of channel characteristics for narrowband PLC systems over the LV and MV power grid.

Since the bandwidth of narrowband PLC is only several kHz and OFDM technique divides the whole channel into several subchannels[3], a subchannel can be modeled as frequency flat while the whole bandwidth as frequency selective. If there is a narrowband noise source, the signal-to-noise ratio (SNR) of each subchannel can be different from each other. Since a power line acts as an antenna from a wireless system point of view, if there exist narrowband noises from wireless radio sources such as radio broadcasting/navigation and amateur radio, the band is severely interfered. This is called an interference from wireless to PLC or tone jammer. Also, if an electrical device periodically generates noise, called narrowband disturber, the band is also severely affected [8]. To get over these narrowband interferences, narrowband PLC standards have proposed to use adaptive tone mapping.

The empirical channel measurement results of narrowband PLC systems over the LV and MV grids are summarized as follows [6]–[8], [15]:

- The channel has not only frequency selective dependency but also position dependency on the LV and MV grid

[2]The decided path is shown as a line topology in this illustration.

[3]In this paper, we use the terms tone and subchannel interchangeably.

topology owing to impedance mismatches at the various branch points, transformers and open circuits [6].

- The channel attenuation increases with the distance in LV and MV lines. The mean channel attenuation in LV lines [15] is given by

$$\mu_{\mathrm{LV}}(f,D)=(0.0034D+1.0893)f+0.1295D+17.3481,$$

where f is the frequency in MHz and D is the distance in meters. Also, the mean channel attenuation in MV lines [15] is

$$\mu_{\mathrm{MV}}(f,D)=1.77f+0.01D+32.9.$$

- A capacitor bank attenuates signal strength more at higher frequencies. Each capacitor bank incurs about 10 dB attenuation in the narrowband signals between 10 kHz and 95 kHz [6].
- An MV/LV transformer shows a frequency selective characteristic in low frequency bands. It gives about 50 dB attenuation to the narrowband signals [7].
- PLC noise has a frequency selective characteristic and its energy profile varies significantly. The noise in MV lines is stronger than that in LV lines by around 10 dB in the 30–90 kHz band [9].

We model the SNR function of the narrowband signals that penetrates electrical devices with SNR degradation. We consider three channel models for MV and LV access networks according to the results of channel measurement: i) MV channel model without capacitor banks, ii) MV channel model with capacitor banks, and iii) LV channel model. Using $\mu_{\mathrm{LV}}(\cdot)$ and $\mu_{\mathrm{MV}}(\cdot)$ above, the signal-to-noise ratio (SNR) can be calculated as

$$\mathrm{SNR}_{\mathrm{dB}}(f,D)=P_r-\mu(f,D)-N(f),$$

where P_r is the transmit power spectral density and $N(\cdot)$ is the noise power spectral density. We use parameters, $P_r=-55$ dBm/Hz, $f=0.05$ MHz, $N(f)=-105$ dBm/Hz for MV access networks and $N(f)=-115$ dBm/Hz for LV access networks for the narrowband PLC systems [17]. For the channel model ii), the SNR is additionally lowered by 10 dB at each capacitor bank.

B. Network Model

We consider an electrical grid, represented as a communication network graph $\mathcal{G}=\{\mathcal{V},\mathcal{E}\}$, where $\mathcal{V}$ and $\mathcal{E}$ are the sets of vertices (nodes) and edges. The set of edges is defined $\mathcal{E}=\{(i,j)|p_{ij}<1-\epsilon\}$ where p_{ij} is a frame error rate (FER) and ϵ is an arbitrarily small positive real number. When there is a destination D, the distance improvement gain G_{ij} from node i to j is defined as $G_{ij}=d(i,D)-d(j,D)$ where $d(\cdot,\cdot)$ is the distance between the two nodes along the power line[4]. $\mathcal{N}_i$ is a neighbor candidate set of node i, that is $\mathcal{N}_i=\{j|(i,j)\in\mathcal{E}\text{ and }G_{ij}>0\}$. A ordered set $\mathcal{F}_i$ is a forwarder set of node i which is a subset of $\mathcal{N}_i$. M_i is a tone mapping pattern of node i, that is, $M_i=\{M_{i1},M_{i2},\ldots,M_{iM}\}$, where M_{il} is a tone mapping index of node i and subchannel l, and M is the number of subchannels. When $M_{il}=1$, the subchannel l is used, while it is not otherwise. The number of used tones at node i is $M^i=\sum_{l=1}^{M}M_{il}$.

[4]This function always returns positive value and $d(a,b)=d(b,a)$.

We assume that PLC-AN channel is frequency selective while each subchannel is frequency flat. According to the recent specification of narrowband PLC [3], [18], one frame is 2D interleaved into time and frequency. Assuming a perfect interleaving scheme, we obtain the FER as

$$p=1-\prod_{l=1}^{M}M_{il}\left(1-p_b^l\right)^{L/M^i}, \tag{1}$$

where L is the frame length in bits and p_b^l is the BER of subchannel l.

IV. Design of PLC-OR

In this section, we design a simple and practical OR protocol in PLC-AN, named PLC-OR under the most recent narrowband PLC standard of G3-PLC [3]. It can be easily extended to any other narrowband PLC standards since it only uses basic functions of G3-PLC.

A. Motivation

Although OR is attracting much attention owing to its improvement in network routing performance, it still has some obstacles to be tackled in general. OR gives performance enhancement in static topological environments such as sensor and mesh networks. In a network with mobility, such as mobile ad-hoc network (MANET), OR's performance gain is marginal due to frequent changes of the topology. Similarly, OR is not applicable when the physical channel condition varies rapidly even in static topology environments. It is because the decision on forwarder set selection and prioritization should be made again when channel changes, and this causes network-wide signaling overhead. Furthermore, isometric antennas and the broadcasting nature of the wireless channel incur duplicated frame delivery to the final destination since multiple path is generated when some neighboring nodes of a sender are not in the communication ranges of each other [12].

In PLC-AN, however, the problems mentioned above can be relatively easily resolved due to the following reasons. First, the topological structure in PLC-AN is completely static. Second, the MV/LV distribution grid that we are targeting has a radial topology [19]. Third, the average channel condition in PLC is relatively static compared to the wireless channel. Most fortunately, even though the channel response varies, relative channel conditions between sequentially connected nodes do not change. For example, the channel response between (s,A) is always better than that between (s,B) in Fig. 3 since the channel response (s,B) can be obtained by a serial cascade of (s,A) and (A,B) using the scattering matrix method in the radial topology [20], [21]. Therefore, the forwarder set and priority among them are unchanged unless intermediate nodes fail. Lastly, in the case that a forwarder set is selected along a physically connected line, which is excluded from other power lines, duplicated transmissions due to multi routes do not happen since all forwarders are in the communication range of each other.

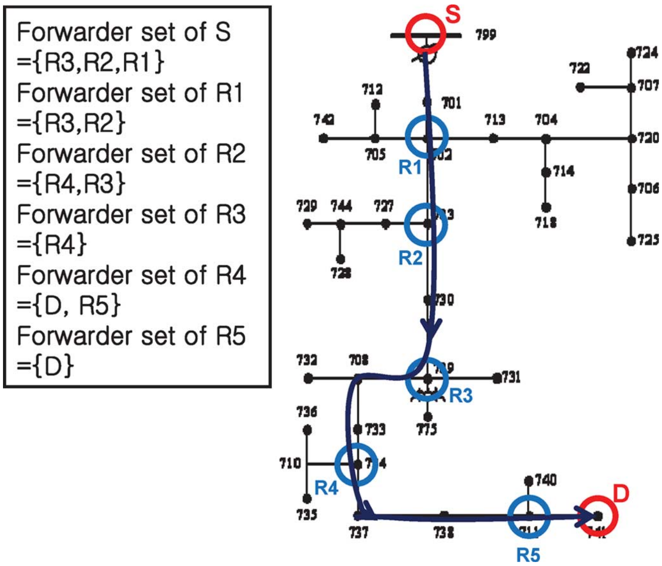


Fig. 4. An example of a path in IEEE 37 Node Test Feeder. Between the source and the destination, there are five relay nodes.

B. Default Path Selection

We assume that each node knows its own location and topology information a priori [10]. To prevent duplicated frame delivery, PLC-OR does not allow multipath routing, i.e., all the nodes in a forwarder set lie along the same route. Therefore, network coding which generally goes with OR is not required. This single path routing scheme guarantees that the sender and all the forwarder nodes are in the same transmission domain. To this end, Dijkstra's algorithm [22] is used to select a route between a source and a destination. The weight between the two nodes is the actual distance in meters so that the algorithm returns the shortest path between the source and the destination.

We also define a "Hello" message which is periodically transmitted. The "Hello" message is used by each node to maintain its neighbor list and update the FER. Although PLC channel has no moving elements, the channel response changes slowly. It is because load change at each branch results in impedance change [23]. The overhead for "Hello" message is about 15 ms [3] which is 0.15% when the message is broadcasted every 10 seconds.

With geographical information and the minimum distance default path selection algorithm, all the intermediate nodes in the route select the same route. When a forwarder correctly receives a frame and becomes a new sender, it knows the destination. The new sender looks for the shortest route to the destination using Dijkstra's algorithm. Since the new sender also has the topology information, the new shortest route to the destination is the same. Only the destination address is needed to find the same route.

Fig. 4 shows a specific path from a source to a destination in a topology constructed with 37 nodes. This topology comes from the Distribution Test Feeders [19], which is an actual feeder located in California. Using Dijkstra's algorithm, the minimum distance routing path is selected for the forwarder nodes in our proposed OR. There are five intermediate relay nodes placed along the path from S to D in this example.

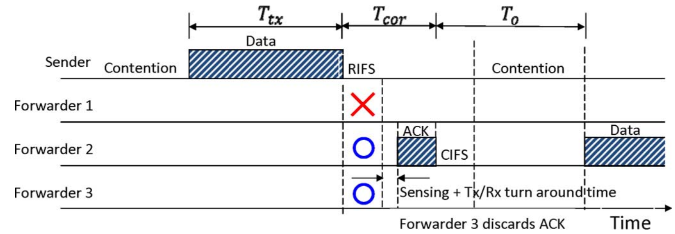


Fig. 5. An example of PLC-OR ACK transmission. $T_{\rm tx}$,$T_{\rm co}$, and $T_{\rm po}$ are actual transmission time, coordination delay of PLC-OR, and CSMA/CA protocol overhead time, respectively.

C. ACK-Based Coordination Scheme

Our proposed PLC-OR uses fast slotted acknowledgment (FSA) [24] which is an ACK based distributed coordination technique for priority differentiation. Relaying prioritization is realized by discriminated ACK timing in the MAC layer.

For channel access, G3-PLC uses the same carrier sensing medium access/collision avoidance (CSMA/CA) scheme as in IEEE 802.15.4. In G3-PLC, a sender gets a right to access the channel through contention by choosing a random backoff number. After the sender finishes its transmission, the intended receiver waits for the response interframe space (RIFS) interval and replies back to the sender with an ACK message. Then, a new contention starts after the contention interframe space (CIFS) interval.

In our proposed PLC-OR, the ACK transmission period for each forwarder node is reserved. The highest priority node gets the chance to transmit ACK immediately after RIFS, and the other nodes get the opportunities of being the actual relay node when the highest priority node fails to decode the frame. If the next priority node senses the channel idle for previously reserved ACK period and successfully decodes the frame, it becomes an actual relay. It notifies to the sender and the other possible relay nodes of becoming the actual relay through ACK message during the granted ACK period. After sensing ACK transmission of a higher priority node, all the other lower priority nodes stop their ACK transmissions. Note that in the G3-PLC standard, virtual carrier sensing (VCS) technique is adopted, so the ACK-based coordination scheme can be easily applied by setting the VCS period with some coordination time to a proper value. Since the VCS has a time limit, we define the maximum size of forwarder set as $K_{\max}$.

Fig. 5 presents a specific example of PLC-OR's coordination. In this example, the node with the first priority failed to receive the data frame successfully while the second and third ones succeeded. In the first ACK period, the highest priority node (Forwarder 1) does not transmit the ACK. Sensing that there is no ACK, the next priority node (Forwarder 2) knows that it is chosen as a relay, and sends ACK. The third node (Forwarder 3) senses the medium busy so that it discards its ACK transmission. As the sender has received the ACK, it knows that its transmission was successful and the relaying process is running as desired. The chosen relay (Forwarder 2) is then becomes a new sender and the same process will continue until the frame reaches the final destination.

A successful transmission at the jth forwarder node requires $T_j = T_{\rm tx} + T_{\rm co} + T_{\rm po}$, where $T_{\rm tx}$, $T_{\rm co}$, and $T_{\rm po}$ are actual transmission time, coordination delay of PLC-OR, and CSMA/CA protocol overhead time, respectively. The coordination delay is given as $T_{\rm co} = T_{\rm RIFS} + (j-1)T_s + T_{\rm ACK}$, where $T_{\rm RIFS}$ and T_s are RIFS time and sensing time, respectively. Similarly, the protocol overhead time is $T_{\rm po} = T_{\rm CIFS} + P\sigma$, where $T_{\rm CIFS}$ and σ are CIFS time and idle slot time, respectively. P is a random variable that describes a number of idle slots before starting a transmission.

Each transmission in PLC-OR requires more time than that in a traditional scheme due to the coordination overhead. The time required in the traditional scheme for each transmission is $T_{\rm tx} + T_{\rm RIFS} + T_{\rm ACK} + T_{\rm po}$, while that in PLC-OR needs $(n-1)T_s$ more. With the actual parameters in G3-PLC, the traditional scheme and PLC-OR scheme have 97.82 ms and 100.6 ms on average, respectively, assuming that $K_{\max} = 3$ [3]. Therefore, PLC-OR wastes about 3% more of time for each transmission. However, since the number of transmissions for a frame to get to the final destination in PLC-OR is much smaller than that in the traditional scheme, the total transmission time significantly decreases.

D. Rate, Tone Mapping Pattern, and Forwarder Set Selection Algorithm

After constructing the default path by Dijkstra's algorithm, each node i should select its transmission rate R_i, tone mapping pattern M_i, and forwarder set $\mathcal{F}_i$. We formulate it as a bit·m/s maximization problem as in [25]. That is, each node i tries to maximize

$$(\mathbf{P}) \quad \max \frac{L \sum_{j=1}^{|\mathcal{F}_i|} G_{ij}(1-p_{ij}) \prod_{k=1}^{j-1} p_{ik}}{T_{\rm out} \prod_{j=1}^{|\mathcal{F}_i|} p_{ij} + \sum_{j=1}^{|\mathcal{F}_i|} T_j (1-p_{ij}) \prod_{k=1}^{j-1} p_{ik}} \; (b \cdot m/s) \tag{2}$$

where L is the frame length in bits, $T_{\rm out}$ and T_j are medium holding times when all the forward nodes failed to decode the frame and when the jth priority forwarder node successfully received the frame, respectively. The control variables in $(\mathbf{P})$ are R_i, M_i, and $\mathcal{F}_i$ since p and T change as R_i and M_i vary.

The three control variables are discrete variables so the problem is a discrete and combinatorial optimization problem. The total number of possible combinations in $(\mathbf{P})$ is $J \cdot 2^M \cdot {}_N\mathrm{P}_K$ where J and M are the numbers of MCS levels and subchannels, respectively. N and K are the sizes of $\mathcal{N}_i$ and $\mathcal{F}_i$, respectively. Since $\mathcal{F}_i$ is an ordered set, the number of possible combination patterns is ${}_N\mathrm{P}_K$, not ${}_N\mathrm{C}_K$. To reduce the search space, we use a branch and bound algorithm.

The numerator of the problem $(\mathbf{P})$ is the expected packet advancement (EPA) proposed in [26]. As shown in their work, the EPA shows two lemmas which are priority rule and containing property.

Lemma 1: Replay Priority Rule (RPR): Given the elements of $\mathcal{F}_i$, M_i, and R_i, the optimal forwarder set $\mathcal{F}_i^*$ is achieved if and only if a closer node to the destination gets a higher priority.

Lemma 2: Forwarder Set Containing Property (FSCP): Let $\mathcal{F}_i^*(k)$ be the optimal forwarder set with k forwarders. When $\mathcal{N}_i$ is given, $\mathcal{F}_i^*(k-1) \subset \mathcal{F}_i^*(k)$, for all $1 \le k \le |\mathcal{N}_i|$.

Algorithm 1: Tx rate, tone mapping pattern, and forwarder set selection at node i

// Initialize
Forwarder Set F_i^*
Tone mapping M_{ij}^*
Rate R_i^*
for *Each tx rate* R_i **do**
  for *Tone mapping pattern* M_i *inquiry* **do**
    $F_i = \emptyset$
    Initialize $\mathcal{N}_i$
    $O_{max} = 0$
    repeat
      for *Each node* $n \in \mathcal{N}_i$ **do**
        $F_i = F_i \cup \{n\}$
        $O_{cur} =$ CalcObject(F)
        if $O_{cur} > O_{max}$ **then**
          $O_{max} = O_{cur}$
          $n^* = n$
        end
        $F_i = F_i - \{n\}$
      end
      $F = F \cup \{n^*\}$
      $\mathcal{N}_i = \mathcal{N}_i - \{n^*\}$
    until $|F_i| < K_{max}$ *and* $\mathcal{N}_i \neq \emptyset$
  end
  Choose maximum M_i and F_i
end
Choose maximum R_i^*, M_i^*, and F_i^*
Return R_i^*, M_i^*, and F_i^*

Owing to the use of RPR and FSCP, it becomes easier to select the forwarder set for $(\mathbf{P})$. The following lemma also leads our proposed algorithm to find the optimal tone mapping pattern. Let $M_i^*(n)$ be the optimal tone mapping pattern when n subchannels are on. The term'optimal' means that this tone mapping pattern gives the lowest FER in (1).

Lemma 3: Tone Mapping Containing Property (TMCP): Given a transmitter and receiver pair, $M_{ij}^*(n-1) = 0$ if $M_{ij}^*(n) = 0$.

Proof: We prove that $M_i^*(n)$ is simply achieved by removing the lowest $M-n$ SNR subchannels. This is proven by contradiction. Assume that there is a non-masked subchannel j which has a higher BER than a masked subchannel i. That is, $p_b^j > p_b^i$. According to (1), if we change the masked subchannel from i to j, the changed FER becomes lower than before. This is a contradiction. ■

According to TMCP, we need to use the same tone mapping pattern of $M_i^*(n)$, and then removing one more tone results in an optimal pattern to get $M_i^*(n-1)$.

With these three lemmas, we propose a searching algorithm to find the optimal values R_i^*, M_i^*, and $\mathcal{F}_i^*$, which has much lower complexity than the exhaustive search algorithm. Our proposed algorithm operates locally at each node since each node has detailed information to operate the algorithm. That is, $\mathcal{N}_i$, geographical information, and the routing path from a source to a destination as we assumed in Section IV-B.

Algorithm 1 is a pseudo code to obtain R_i^*, M_i^*, and $\mathcal{F}_i^*$. The repeat procedures (lines 9–21) find $\mathcal{F}_i^*$, given R_i and M_i. Owing to the use of RPR, the priority among candidate nodes in $\mathcal{F}_i^*$ shows the descending order in distance. CalcObject is a function of a forwarder set F which returns the objective function value defined in $(\mathbf{P})$, i.e., the expected improvement with F in unit of bit $\cdot$ m/s. Lines 10–18 select the best improvement node in $\mathcal{N}_i$ and put it into $\mathcal{F}_i$. This procedure repeats the maximum of $K_{\max}$ times or until there is no more neighbor candidate node. From FSCP, the result is $\mathcal{F}_i^*$, given R_i and M_i. For doing this, the maximum number of iterations is NK. The previous "for loop" of line 5 returns M_i^*. It starts from all tones on, and then removes one by one in an ascending order of SNR. From TMCP, this approach guarantees to obtain the optimal tone mapping with at most M iterations. The first "for loop" of line 4 tries all the possible rates, i.e., J times. At line 25, the algorithm chooses $\mathcal{F}_i^*$, R_i^* and M_i^* that maximizes the objective function from the iterations of $J \cdot M \cdot NK$.

V. Evaluations

In this section, we investigate the performance improvement of PLC-OR in terms of transmission time and reliability through simulations. We use the expected number of transmissions (ETX) [27] as the prioritization and the forwarder set selection metric. Dijkstra's algorithm is used for building a route from the source to the destination. The results are compared with those of shortest path routing (SPR) which is an optimal one among the traditional sequential routings[5], SPR with ETX link metric (SPR-ETX), and OR. SPR and SPR-ETX use both adaptive rate and tone mapping methods. SPR chooses a link with the best improvement among the links which packet reception ratios are greater than a certain threshold, i.e., 0.99. SPR-ETX chooses the best node as its next hop based on the ETX link metric. OR also uses the ETX as the prioritization and the forwarder set selection metric. OR does not use adaptive tone mapping, but simply use the whole bandwidth regardless of the narrowband interference. Note that OR is regarded as a simple application of wireless opportunistic routing to PLC-AN or beacon based routing (BBR) [11].

A. Settings

In G3-PLC specification, the maximum number of data symbols in one transmission is 252, and the channel sensing time is two symbols. With $K_{\max} = 3$, four symbols are needed to prioritize three forwarder nodes. So the maximum number of data symbols is 248[6]. The power line channel models in our simulation are described in Section III-A. We consider three density models: high, medium, and low densities. The distances between the two neighboring nodes in the three models follow the normal distributions with mean and standard deviation of (1 km, 0.5 km), (1.5 km, 0.75 km), and (2 km, 1 km), respectively. The maximum distance between the two neighbor nodes in high, medium, and low density modes are 2 km, 3 km, and 4 km, respectively. When a narrowband interference exists, it is assumed that the SNR of the corresponding subchannel is lowered by 10 dB [8].

We first measure the transmission time with the number of nodes in a simple chain topology. The length of the chain varies from one to 22 and the results are averaged. Then, we extend the simulation scenario to the IEEE 123 Node Test Feeder [19], which is suited topology for observing the effect of OR on an actual PLC-AN environment. In the IEEE 123 Node Test Feeder, one node located at the substation is selected as source, and a destination is randomly chosen among the other 122 nodes. The default path to each destination is selected by Dijkstra's algorithm. The closest and furthest distance nodes are one and 22 hops away, respectively, and the average distance of the pairs is 11.9 hops. Since the IEEE 123 Node Test Feeder is MV power network, we assume that there is an LV distribution network connected with each destination node in the IEEE 123 Node Test Feeder. There are consecutively connected 10 buildings through the LV power line, and the distance between two neighboring buildings follows normal distribution with mean 90 m and standard deviation 10 m [23]. The final destination of the packet is one randomly chosen building among the 10 buildings in the LV line.

B. Performance Results

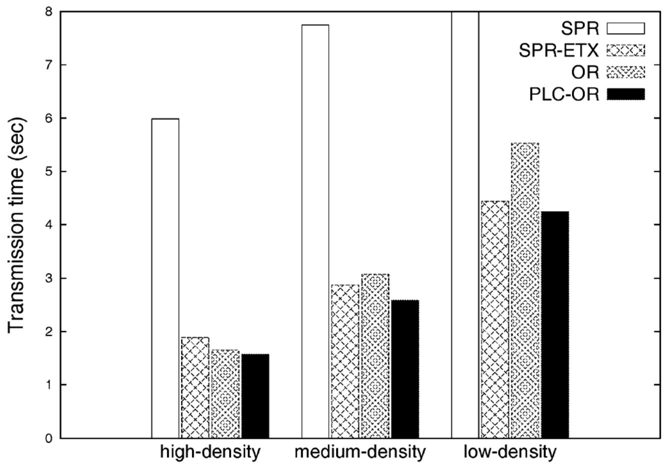
Fig. 6 shows the transmission time in seconds to reach the destination for the three density models without and with the narrowband interference. We use MV channel model in this simulation. The performances without the narrowband interference are shown in Fig. 6(a). SPR takes 8.86 seconds to reach the destination in the low density model. When the node density is low, most of the nodes have only one receiver. This is not the case in which the OR performs well, resulting in similar performances between SPR-ETX and PLC-OR. However, as the network gets denser, it shows better performance improvement. That is, the performance gains of PLC-OR over SPR-ETX in low, medium, and high density models are 4.4%, 10%, and 17%, respectively. In the low and medium density models, OR shows worse performance than SPR-ETX since the increased overhead of OR by having multiple receiver nodes has more impact on the performance.

Fig. 6(b) shows the performances without the narrowband interference. In the low and medium density models, the results of SPR are 10.27 and 8.97 seconds, respectively. When the narrowband interference exists, simple OR sometimes fails to deliver packets to the destination in the low and medium density models. Even in the high density model, OR performs worse than SPR-ETX due to the increase of error probability from the narrowband interference. However, SPR, SPR-ETX, and PLC-OR are not affect by the narrowband interference because of the adaptive tone mapping method. The performance gains of PLC-OR over SPR-ETX is almost the same as the case of without the narrowband interference. SPR shows the worst performance for all the cases. The other three routing schemes have performance gains over SPR about more than 50%. Our proposed PLC-OR reduces the total transmission time while achieving the same level of reliability of SPR.

To get a result of the IEEE 123 Node Test Feeder, simulations are performed 10 000 times and the averaged results are

[5]We use SPR1 in [10] which does not consider energy consumption.

[6]Higher $K_{\max}$ results in a less number of required data symbols.



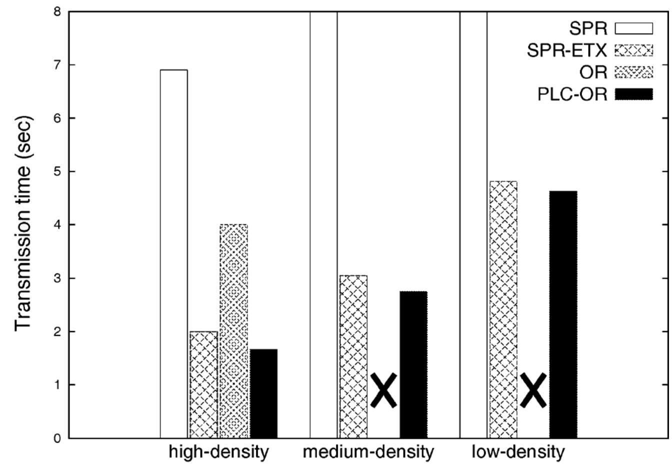


Fig. 6. Average transmission time in seconds in a chain topology for three density models. (a) Without narrowband interference. (b) With narrowband interference.

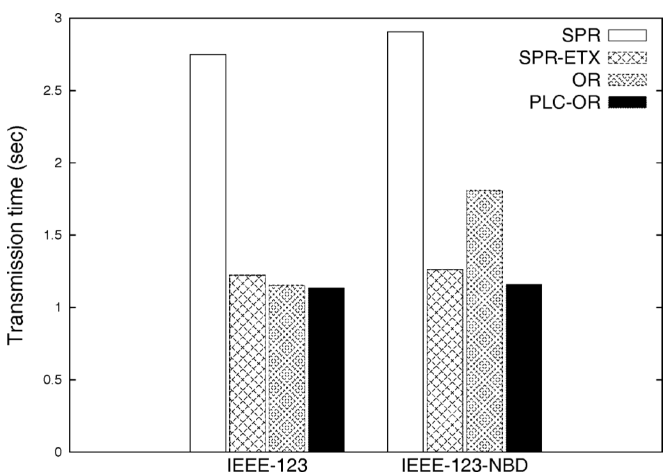


Fig. 7. Average transmission time in the IEEE 123 Node Test Feeder. NBD stands for the narrowband interferer.

shown in Fig. 7. It is also assumed that the narrowband interference exists in the grid network with the probability of 0.2 in the "IEEE-123-NBD" case. Since the actual distance between nodes in the IEEE model is similar with the high density model the general tendency is similar to that in the chain topology with high density. OR shows similar performance with SPR-ETX, but it performs worse than SPR-ETX with the narrowband interference since it has no interference cancelation scheme. PLC-OR performs best and shows about 60% and 8% gains compare to SPR and SPR-ETX, respectively. Compared with the results of the chain topology, the performance gain of our proposed PLC-OR increases with the MV/LV distribution network size.

VI. Conclusion and Future Works

With the recent proliferation of interest in the smart grid, power line communications (PLC) are attracting attention again as an appropriate networking technology for an access network (AN) covering a regional area of power systems. Narrowband solutions in PLC are appealing to the medium and low voltage distribution networks for applications of moderate data rates. Meanwhile opportunistic routing (OR) is a new routing paradigm that makes use of the broadcasting nature of the wireless channel. In this paper, we argued that, with the narrowband solution, OR can improve in routing performance by exploiting the penetrating characteristic of power signals in PLC-AN. Then, we design a PLC customized OR, named PLC-OR, which basically uses single path route selection and simple ACK-based coordination. It includes an algorithm to decide transmission rate, tone mapping, and forwarder set selection. Through simulations, it is shown that our proposed PLC-OR lowers the transmission time. The end-to-end delay is reduced by about 70% and 17% compared to the threshold based and ETX based sequential routings, respectively. A simple application of wireless OR to a PLC network has some gain over the threshold based sequential routing, but it performs worse than the ETX based one and experiences delivery failures in some cases.

A further extension of our work is to combine OR and cooperative transmission. In cooperative transmission, several nodes are enabled to simultaneously transmit a same packet to enhance throughput or reliability. If we properly control transmissions between forwarders, the combination of OR and cooperative transmission will lead to a better performance. Another extension of PLC-AN work is to cover the case of an interconnected grid that has multiple connections to other points of supply. Applying network coding in such an environment of multiple routes can be a good choice.

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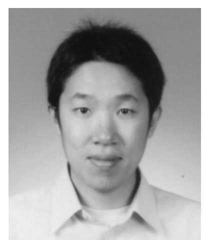

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