# Self-Motivated Relay Selection for a Generalized Power Line Monitoring Network

Jose Cordova and Xin Wang[1], Dong-Liang Xie[2], Lei Zuo[3]
[1] Department of Electrical and Computer Engineering, State University of New York at Stony Brook, USA
[2] Beijing University of Posts and Telecommunications, Beijing, China
[3] Department of Mechanical Engineering, State University of New York at Stony Brook, USA
jose.cordova@stonybrook.edu, xwang@ece.sunysb.edu, xiedl@bupt.edu.cn, lei.zuo@stonybrook.edu

***Abstract*—Efficient power line monitoring is essential for reliable operation of the Smart Grid. A Power Line Monitoring Network (PLMN) based on wireless sensor nodes can provide the necessary infrastructure to deliver data from the extension of the power grid to one or several control centers. However, the restricted physical topology of the power lines constrains the data paths, and has a great impact on the reporting performance. We discuss the features of power-lines and their impact on the performance of monitoring and transmissions. We present a comprehensive design to guide efficient and flexible relay selection in PLMNs to ensure reliable and energy efficient transmissions while taking into account the restricted topology of power-lines. Specifically, our design applies probabilistic power control along with flexible transmission scheduling to combat the poor channel conditions around power line while maintaining the energy level of transmission nodes. We evaluate the impact of different channel conditions, non-uniform topologies for a power line corridor and the effect of reporting events. Our performance results demonstrate that our data forwarding scheme can well control the energy consumption and delay while ensuring reliability and extended lifetime.**

## I. Introduction

Monitoring the states of the power-line infrastructure is an essential task for proper operation of an electric grid. Wireless sensor networks (WSN) are attractive for power line monitoring, due to their low cost, simplicity in implementation and low maintenance overhead. Various types of sensors are often deployed along the power lines and close to substations. To make preventive and corrective maintenance, sensed data such as voltage, current, temperature, and power-line strain among others need to be sent timely to the grid operators or various control units which may be located at different parts of the grid. However, some unique features of Power Line Monitoring Network (PLMN) make it difficult to ensure reliable data delivery.

First, the extension of the monitoring infrastructure can be in the order of several thousand meters. Such a large-scale node deployment makes replacement of batteries hard and even infeasible for large sections of the network in remote areas. This makes it critical for sensors to carefully manage their energy consumption to prevent loss of information or network disconnection.

Second, the network topology follows the layout of the electric grid, so sensing data are often transmitted linearly along the power line and through bottlenecks such as substations or power line crossings. Providing direct links between bottleneck points with substations using wide-area communications such as cellular links may help relieve the congestion, however, the lack of coverage in remote areas and the cost of service make cellular communications infeasible in many cases.

Third, transmissions along power lines are prone to loss, due to the strong noise around power line. Simply increasing the transmission power can help mitigate loss, however, it also compromises the network lifetime especially when the node density is low.

In this work, we consider the transmission of sensed data through local area network links such as ZigBee. Commercial off-the-shelf products may be applied in PLMN [1]. However, existing data forwarding schemes would perform poorly in a PLMN due to its restricted topology, low density of network nodes, as well as data transmissions at various frequencies and upon demand. Actively maintaining the routing path or periodically updating node states would lead to high energy cost. On the other hand, paths should be established upon need quickly for timely sending out important monitoring data. Common energy saving approaches that simply put node into periodic sleep may lead to significantly high delay in data transmissions. Despite a substantial amount of research work on energy-aware data transmissions, solutions such as [2] are often proposed for networks with high node density, which could provide alternative paths upon the energy depletion of sensors. This does not work in topology-restrictive PLMNs.

In light of above requirements and challenges, we present a comprehensive design to flexibly select relay nodes to ensure robust and reliable data transmissions in PLMN while conserving energy and extending the network lifetime. Instead of only considering a single power line corridor between two substations as done in some literature work, we consider a more general and larger-scale PLMN with several substations. The power line has a more general topology with non-uniform node distribution at a realistic node density. Finally, we consider sensors to be rechargeable and can harvest energy either from the power line itself or other source such as solar energy. Such sensors have recently become more available as they are well suited for monitoring applications.

Although sensor nodes in PLMN are generally static, the topology of the network can be dynamic due to the activity change of nodes (e.g., from on to off and vice versa). Also, nodes can become unreachable due to channel fading or power depletion. Different from existing single line-based schemes [3], our design supports flexible and robust information transmissions with paths constructed on demand. To alleviate the bottleneck effect, our scheme estimates the energy of nodes along the power lines beyond a single hop while keeping our scheme to work on demand and localized.

To guide relay selection, we propose a comprehensive cost metric which takes into account energy harvesting rate, distance advance and the expected energy consumption along two predicted hops on the line in the direction of destination. This allows relay selection to avoid overloading a small group of nodes which may quickly deplete their energy and result in network disconnection.

The rest of the paper is organized as follows. We present the related work in Section II, and motivation and our problem in Section III. In Section IV, we describe our basic data delivery algorithm for PLMN, and in Section V we propose an algorithm to ensure reliable data transmissions in PLMNs while maintaining the power level of nodes. Simulation results are presented in Section VI. We conclude the work in Section VII.

## II. Related Work

There exist a limited number of works on wireless network design for power line monitoring. Recently, [3], [4] proposed to select a set of overhead poles to place dedicated cellular links to alleviate traffic within the restricted linear topology of a power line. We identify two main limitations of such solutions. First, as introduced before, the installation and operational costs are a limiting factor when placing dedicated cellular links. In [3], the authors aim to minimize these costs while meeting delay and bandwith constraints. While this can be applied for areas with cellular coverage, the availability of service in remote areas is a limiting factor.

Second, the PLMN models assumed in existing work are often over-simplified, with one single power corridor, two substations and one control center. Such model under-estimates the impact of networking issues that arise due to topology. For example, there are increased traffic congestion and delay in sections where power lines meet, such as substations. Such sections also create energy bottlenecks, where nodes are more prone to energy depletion thus creating disconnected areas.

Also, in [3] authors assume substations are connected through a private network with optical fiber, then the destination of information is irrelevant and paths are fixed and defined offline. While this assumption is easily justifiable for a single power corridor, when information needs to be delivered to a specific substation without reaching the control center, a proper forwarding scheme needs to be designed to provide reliable paths as requested. Also, fixed paths that are reused constantly can produce disconnected areas when nodes deplete their energy. Moreover, offline solutions cannot react to link failures produced due to channel conditions or energy depletion.

Instead, our proposed scheme flexibly select relays based on demand, node energy levels and network topology. It can respond quickly to topology changes and link failure to ensure robust packet forwarding and low transmission delay. We consider that information can be delivered to any substation or node in the power line network upon request, hence paths are not fixed and may reach a desired location in the power grid over multiple transmission hops.

In [5] authors develop a WSN based solution for power line monitoring, aiming to not use direct cellular links. A topology tree is built by the exchange of several control messages. Paths may be recovered with the facilitation of constant control message exchanges at the cost of energy. Due to the difficulty of energy recharging for sensors deployed for power-line monitoring, our design specifically take into account the energy consumption and harvesting status to ensure nodes to keep a stable energy level while supporting robust packet forwarding.

There is also available literature on design guidelines for PLMNs. The survey presented in [6] presents characteristics, requirements and challenges of commercially available sensor nodes for PLMNs. Several features presented, such as the availability of different wireless technologies, nodes with energy harvesting capabilities or the feasibility of installing nodes on different locations, e.g. attached to overhead poles or clamped onto the power lines, give us guidelines to take into account when designing a PLMN solution.

The study in [7] includes an experimental characterization of the channel for three different common power grid locations. The tradeoff between optimizing network lifetime versus compromising coverage and reliability is explained. This work provides us with the characteristics of practical scenarios, which helps us design a relay selection scheme that can be applied to more realistic situations.

## III. Motivation and System Model

A PLMN is a sensor network with nodes deployed following the infrastructure of the power lines. The specific power line topology and features render the existing routing protocols to be inefficient in PLMNs. In this section, we first introduce the basic features of power-lines and their constraints to motivate our work, we then present our system model.

### A. Power Line Topology

PLMNs are composed of sections of nodes (linearly arranged along power lines) and the interconnection of these arrangements (at substations or crossings) ranging from hundreds of meters to kilometers.

In a simple model commonly assumed, a *power line corridor* is comprised of two substations and a power line of $n$ nodes, resulting in a network of $n + 2$ nodes. As shown in Fig. 1(a), nodes are evenly spaced and located on top of the overhead poles. Under this model, every monitoring node has only one possible neighboring node to forward its data to a specific substation.

As an alternative topology shown in Fig. 1(b), the distances between nodes are set arbitrarily. This can be the case for two reasons. First, the distance between poles may not be even due to the terrain constraints. For example, the distances between poles range from 0.5 to 1km in [3], [8], [9]. With Zigbee nodes transmitting up to 1.5km [10], there may exist up to 3 nodes in a distance space of 1km. Second, commercial sensor nodes often can be placed everywhere along a power line, e.g. clamped to the power line [1], [6].

In the logical topology shown in Fig. 1, the latter model, Fig. 1(b), has more than one neighbor for each direction towards a substation. Also, a substation (e.g., SS1) can be connected to more than one power line corridor [11]. The model in Fig. 1(a) is a special case of Fig. 1(b), where only one node can serve as a possible next-hop forwarder.

A logical diagram of a general PLMN is shown in Fig. 2, where a PLMN is a large-scale network with the interconnection of power line corridors that help relieve the linearity assumption of the network.

### B. Data Delivery in PLMNs

Data generated from powerline monitoring need to be sent out, either to a close-by substation, or to a data collection point such as a control center that may be located far away. Where the data should be delivered can be determined by the power grid operators. Sensor nodes can have a preset destination to deliver data, or dynamically determine a destination. In the latter case, the destination can be set based on the monitoring information for event handling or the status of a power line corridor (e.g., data traffic condition or remaining energy levels of sensors) for better transmission performance.

Delivering data from a sensor to a destination will traverse at least one power line corridor. With the model in Fig. 1(a), a naive forwarding scheme can relay a packet hop by hop over every node on the power line towards the destination. A general power line model shown in Fig. 2 allows for more forwarding options, but also calls for more careful routing design. Although sensors can be distributed unevenly in a more general power-line model, due to the physical layout of a power grid and its large coverage thus associated cost, the node density is generally low.

Following, we discuss the constraints and features of PLMN that impact the data delivery.

*1) Impact of PLMN topology and power-line features:* In PLMN, sensors are often attached to the poles or powerlines. Intuitively, static paths can be created, and data can be simply transmitted along a fixed path. However, using the same set of nodes over a long period will exhaust the node's energy and lead to the disconnection of large sections of the network. In addition, due to the restricted topology of powerline, channel fading or node inactivity (either due to failure or sleeping for energy saving) can cause network disconnection and consequently the loss of a large amount of data.

Existing routing schemes proposed either actively create and maintain a routing path [3]–[5] or find a routing path on-demand before data transmissions [12], [13]. As normal data transmission frequency is not high in power-line monitoring, actively maintaining the routing path would lead to high transmission overhead and energy consumption. In the case that the destination changes on demand based on events, the path maintenance is also unnecessary. On the other hand, upon events, monitoring data need to be sent to the operator quickly and reliably. Conventional on-demand routing schemes look for an end-to-end path before sending data, which not only introduces a high initial delay but also high overhead if a path search is invoked before each reporting period.

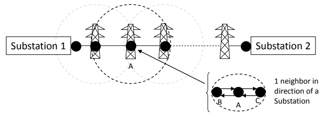
*2) Impact of the knowledge on power-line node states:* In contrast to the routing scheme that looks for the end-to-end path, a transmission scheme that selects local forwarders help to better cope with network topology changes, improve the transmission reliability and reduce the energy overhead. For example, in Fig. 1(b), node D sends a request message to SS3 which is heard by and has the relay selected from nodes B, C and F. Intuitively, the unselected nodes could go to sleep to save energy. However, if such decision is made without the knowledge of the states of other nodes, a sleeping node can disconnect a section of a power line corridor. In the previous example, although node F may not be selected as the forwarder for the destination SS3, node F is a critical node for B and C to reach SS1, e.g. in case of an event. Hence, F should consider the states of all power-line nodes within its reception range so monitoring data can be sent out timely. Particularly, due to the restricted topology, a sleeping node around substations and crossings may be needed for other nodes' transmissions.

Forwarders could be locally selected and reselected periodically. However, a periodic broadcast will be propagated in a cascade manner due to the power-line topology, which will increase the collisions and medium access time considerably. A similar behavior occurs when a group of nodes on a power line generate packets due to a detected event.

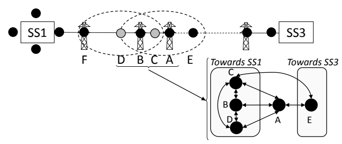
Apparently, local forwarder selection in existing routing schemes does not take advantage of the relative stability of the PLMN to make better local decisions. Estimating the states of a node's neighborhood in a section of the power line helps the node to identify a possibly disconnected or congested path. A node can also determine if it would volunteer to become a new relay when the current forwarder can no longer serve its role. This helps limit the number of explicit broadcast of relay requests to reduce the overhead and delay.

### C. System Model

In this work, we consider a PLMN consisting of wireless nodes deployed in a power grid composed of a control center, substations and power line corridors. We model the physical topology of a power line network as a combination of linear arrangements and interconnections of them. As power lines have widely different topology, our scheme is designed to be general so it can work under any physical arrangement. Every node in the network can generate data and transmit the data to




(a) Traditional power line corridor




(b) Generalized power line corridor

Fig. 1. Linear sections in a power grid: transmission lines.

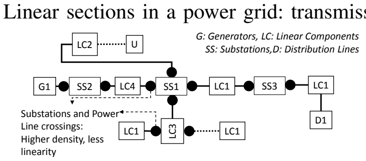



Fig. 2. General scenario of a PLMN

a destination which may change over time. Nodes can transmit data in the following ways:

- Power grid operators can set up a reporting period for sensors to send information to a substation or control center, which will be referred as *periodic monitoring*. For every period, all sensing nodes are required to schedule the transmissions and hence, paths should be discovered to not overload critical sections of the network.
- Sensor data can be generated upon detecting events, e.g. a measurement goes out of a predefined range, and this is called *event monitoring*. A sensor node needs to send event data immediately and reliably to a substation for grid operators to take proper preventive and corrective actions.

In our model, nodes are equipped with energy harvesters to continuously recharge the battery. The harvesting source can be the magnetic/electric field induced in the power line, solar energy, etc. However, the rate of energy replenishment is significantly lower than the energy consumption rate during the packet forwarding [1]. The consumption rate may be slowed down by controlling the transmission rate of each node. This, however, should not significantly compromise the monitoring performance, and particularly events data need to be sent out timely.

Given the restricted power-line topology, energy constraints of sensors and the knowledge on the states of nodes in the power-line corridors, the goal of this work is to design a reliable and energy efficient data delivery scheme for PLMNs. We propose a novel cost metric to facilitate the selection of relay nodes based on the estimated states of neighboring nodes, taking advantage of the relative stability of PLMNs. Given the low node density of a power line corridor, we further propose a probabilistic transmission power control algorithm to guarantee a certain level of transmission reliability while controlling the energy level and consumption.

Next, we present our design of a PLMN system that considers the aforementioned characteristics and attempt to address the conflicting design requests and challenges.

## IV. Basic Data Delivery in PLMN

The power line transmission is susceptible to strong noise, channel fading and node inactivity. To quickly transmit data upon need and ensure robust transmission in the presence of dynamic network topology, we consider a data delivery scheme which selects local relay nodes on demand. In this section, we first provide a sketch of the transmission scheme. We then propose a packet forwarding metric to facilitate efficient packet delivery in resource and topology constrained PLMN in Section IV-B, and present our forwarder selection scheme in Section IV-C. As we consider self-powered nodes which rely on energy harvesting to maintain the battery level, it is important to control the energy consumption. We discuss the activity control of sensor nodes for energy conservation in Section IV-D.

### A. Overview of the Transmission Scheme

In a PLMN, nodes continuously monitor the power-line conditions and deliver the data to selected destinations periodically or in response to events. To avoid unnecessary energy consumption, our scheme does not actively maintain a path to any substation.

In our design, packets can be delivered to any location in PLMN and the destination can change based on the need. For the simplicity of presentation, we consider that nodes are aware of their desired destination locations, which can be preset by the network operator, carried with query messages, or determined following some criteria on the event packets, e.g. closest substation. The locations of nodes can be configured at installation time or determined based on the locations of some seed nodes.

In order to determine the next-hop forwarding node for a data delivery, it is important to have a metric to facilitate the selection of forwarder or relay node among candidate ones. We formulate the forwarding metric taking into account the energy level of nodes, the forwarding distance, and the constraints of the power-line topology.

We consider two ways to initiate relay selection:

*1) Explicit Request:* When a network node $u$ intends to send packets to a substation $D$, if there is no relay node $w(D)$ cached, it will broadcast a *request* packet to its one-hop neighbors. To reduce the signaling overhead, we consider a self-selection scheme where a node receiving the request can self-determine if it can serve as a relay based on our proposed forwarding metric. Rather than being satisfied with only accepting the packets from $u$, a neighbor $v_i$ will also evaluate its capability of relaying the packets to the next hop in the forwarding metric. Once determining to be a packet forwarder, $v_i$ will broadcast a *reply* to indicate its interest of serving as a relay node upon the expiration of a backoff timer.

Once receiving an answer from $v_i$, $u$ sets $v_i$ as the next-hop forwarder for the substation $D$, i.e., $w(D)$. Other nodes can discard their *request* packets once overhearing the reply from $v_i$ or data forwarding from $u$. The latter can happen when the selected relay node is out of the transmission range of some neighbors of $u$. The ones not serving as packet relays can decide to take further actions, for example, to enter sleeping states if they meet certain condition (Section IV-D). For the next packet transmission towards $D$, there will not be an explicit request for $w(D)$.

*2) Implicit Request:* Once a forwarder is selected, future transmissions from $u$ towards $D$ will use $w(D)$. However, due to channel dynamics or energy depletion, the current $w(D)$ may not acknowledge the reception of a data packet, which would lead $u$ to perform retransmissions. Other neighbors regard the failed $u \rightarrow w(D)$ transmission attempt as an implicit request for finding forwarder. Neighbors follow the same procedure as done with the explicit requests to self-select relay nodes. Implicit requests help to reduce the number of *request* messages broadcasted as well as the delay in finding a new forwarder.

### *B. Design of Forwarding Metric*

Our forwarding metric considers both the energy level and forwarding distance. For a node to determine if it can serve as a candidate relay node, it first estimates the *energy advance* based on the potential energy consumption and replenishment during the packet forwarding process. It then estimates and incorporates the *distance advance* into the forwarding metric. To alleviate the topology constraints of powerline, both *energy advance* and *distance advance* consider upstream and downstream packet transmissions for better path selection.

*1) Energy Advance Estimation:* As a node on the power line generally has very few neighbors, the number of paths towards a substation is also limited. To prevent reducing even further the number of candidate paths and possible network disconnections, nodes will determine if they can forward packets according to their energy status. When a node $u$ has a packet to transmit to a destination $D$, it needs to determine among its neighbors a relay node $w(D)$. The capability for a neighbor $v_i$ to serve as a candidate forwarder is determined by $C(v_i)$, the *energy advance*.

A node estimates its *energy advance* based on its residual energy, expected energy replenished through harvesting, estimated energy to be consumed to receive and forward packets, and the energy consumption due to overhearing. A data forwarding *request* sent by a node $u$ includes the number of packets to transmit, $N_{u,D}^{REQ}$ and the average packet length $L_{u,D}^{data}$ in bits. With this information, node $v_i$ estimates how much energy is available and how it will be spent to forward $N_{u,D}^{REQ}$ packets if it serves as a relay. The time for $v_i$ to forward packets towards the destination $D$ can be estimated as:

$$E\left[T_{v_i}^{tx}\right] = \frac{\overline{L_{u,D}^{data}}}{r} N_{u,D}^{REQ}, \tag{1}$$

where the link rate $r$ can be estimated based on the channel condition measured by $v_i$ when receiving the request message from $u$. This estimation can vary during the actual transmission time due to channel dynamics and possible retransmissions. A selected neighbor $v_i$ will consume energy in receiving packets from $u$ and in overhearing other transmissions, which is the cost with respect to $u$, $u \rightarrow v_i$. Also, $v_i$ will have to *advance* the received packets towards the substation through one of its neighbors $w_j$, which is the cost with respect to the next hop, $v_i \rightarrow w_j$.

The metric $C(v_i)$ includes both types of energy costs. Hence, $v_i$ considers not only its current energy state, but also the energy to be consumed for forwarding the packetsW towards the destination (i.e., information on the 2-hop neighbors of the original request node $u$) to find a better path in the presence of the topology constraints of power lines. The *energy-advance* metric to be evaluated at each $v_i$ is:

$$C_{u,D}(v_i) = \frac{B_{v_i} + E\left[T_{v_i}^{tx}\right]\rho_{v_i} - \overline{L_{u,D}^{data}} N_{u,D}^{REQ} e_{v_i}^{tx} - OH_{v_i}}{B_{max}}, \tag{2}$$

where we have included the current battery level $B_{v_i}$, harvesting rate $\rho_{v_i}$, per bit transmission energy consumption $e_{v_i}^{tx}$ and the cost of overhearing. Manufacturers often provide an average power consumption value for reception state, $P_{rx}$. The estimated cost of overhearing can be calculated based on the reception power of the device, $P_{rx}$, and the expected time on reception state, $E[T_{v_i}^{rx}]$, as $OH_{v_i} = P_{rx} E\left[T_{v_i}^{rx}\right]$. As presented later in this section, common neighbors of $u$ and $v_i$ that receive the request of $u$ and reply from $v_i$ should go to sleep. Other neighbors of $v_i$, probably far from $u$, can remain awake. An awake node forwarding data for node $u$ can overhear packets during $E[T_{v_i}^{tx}]$ time. Then we have $E\left[T_{v_i}^{rx}\right] = E[T_{v_i}^{tx}]$. If there are other transmitters around, the overhearing energy should incorporate their energy consumption as well.

In (2), the amount of energy consumed to transmit a bit, $e_{v_i}^{tx}$, is a function of the transmission power $P_t$. For reliable transmissions, the metric also incorporates the energy consumed due to the possible number of retransmissions:

$$e_{v_i}^{tx} = \min\left(\frac{1}{PRR}, N_{max}^{retx}\right) E_t(P_t) \tag{3}$$

where PRR is the estimated rate of receiving the packet correctly, $N_{max}^{retx}$ is the maximum number of retransmissions allowed by the MAC layer. In section V, we will provide a methodology to select an appropriate power level, $P_t^*$, to meet certain reliability requirement while maintaining a controlled battery level.

*2) Energy-Distance Advance Estimation:* Once the *energy advance* has been determined, our metric further considers the advance a candidate $v_i$ can provide in terms of the *distance* towards $D$. A data forwarding *request* sent by node $u$ includes its position and the position of $D$. Different from other distance-based routing schemes, we consider two stages of distance advance: the distance advance when selecting the neighbor $v_i$ as the relay node, $d(u, v_i)$; and the distance between $v_i$ and its own next hop $w_j$ towards the substation $D$, $d(v_i, w_j)$. If $w_j$ has not been determined yet, we estimate the distance advance that $v_i$ can proportionate with its neighbors. For example, the average of the distances between each pair of $w_j$ and $v_i$ can be taken as the estimated distance.

If $R$ is the maximum transmission range of a node, the maximum distance advance a $v_i$ can provide to forward packets from $u$ to one of its neighbors is $2R$. The normalized *energy-distance advance* metric is:

$$C_{u,D}^{ADV}(v_i) = \left(\frac{d(u,v_i)+d(v_i,w_i)}{2R}\right) \times C_{u,D}(v_i). \quad (4)$$

We provide nodes with longer *distance advance* and higher remaining energy a higher priority to forward packets. Note that when the network has equally spaced nodes, the first factor in the above equation becomes a constant, which turns this approach into energy-based routing only.

### C. Forwarder Selection

A power line node which sends a transmission *request* normally has only a few neighbors. To avoid additional signaling for the sender to select a forwarder from responded nodes, in our design, a neighboring node will self-determine if it will serve as a relay node based on the forwarding metric estimated. A relay requester $u$ will set the node that responds the first as the forwarder $w(D)$. To avoid the reply collision from multiple responses, the response time will be jittered based on $C_{u,D}^{ADV}(v_i)$, where the node with a higher capacity of handling the packet forwarding will respond sooner. When receiving a *request*, a candidate $v_i$ calculates a backoff timer to *reply* to the request of transmission from $u$ to destination $D$, as:

$$T_{u,D}^{bf}(v_i) = (1 - C_{u,D}^{ADV}(v_i)) \times T_u^{bf} \quad (5)$$

The constant parameter, $T_u^{bf}$, is carried in the request message of node $u$ to define the maximum back-off interval similar to that in [14]:

$$T_u^{bf} = T_{ref} N_u^{ON} \quad (6)$$

The minimum time needed to send a *reply* message, $T_{ref}$, is used as the reference for setting the back-off timer. The number of nodes awake, $N_u^{ON}$, is based on the overheard transmissions when the node is awake and updated during every awake period. When nodes do not have any of the information, they can conservatively assume their 1-hop neighbors are all awake.

### D. Node Activity Control

In a generalized transmission line topology, such as the one shown in Fig. 1(b), not every node has to be used for every transmission. When a neighbor $v_i$ determines it is not the selected relay, $w(D)$, it can choose to conserve energy by entering the *sleep* mode in which it turns off its radio while allowing the energy harvesting component to replenish the energy more quickly. However, a sleeping node cannot respond to requests and become a forwarder when needed, e.g. quickly responding to *implicit requests* and events.

Monitoring nodes generally send reports every $\Delta T$ period. The transmission time $T_{u,w(D)}^{tx}$ for $u \rightarrow w(D)$ can be estimated using Eq. 1, and generally $E\left[T_{u,w(D)}^{tx}\right] << \Delta T$. Due to channel dynamics and packet loss, however, this estimation can be much smaller than the actual transmission time needed.

A $v_i$ that does not have packets to transmit can ideally sleep until the next period $\Delta T$. However, after $u$ finishes its transmission of a burst of data in $E\left[T_{u,w(D)}^{tx}\right]$ period, node $v_i$ and other nodes around may need to forward their data, either periodic reports or event packets. Then the expected transmission duration of $u$ is only a minimum time period a node $v_i$ can be kept idle, i.e., $T_{min}^{sleep} = E\left[T_{u,w(D)}^{tx}\right]$ within $\Delta T$.

To better estimate an appropriate sleeping duration, $v_i$ needs to determine how critical it is for power-line transmissions and also estimate the activity states of its neighbors. Following the physical arrangement of PLMNs, a node within a power line corridor can forward packets towards stations at two ends of the line, $D_L$ and $D_R$. Accordingly, a node $v_i$ can group its neighbors into two groups, $w_L$ and $w_R$, for nodes located in the direction of $D_L$ and $D_R$ respectively. For a destination $D_L$, we define the set of neighbors in $w_R$ that can forward packets in direction of $D_L$ without using $v_i$ as relay as:

$$N_L^c = \{w_i \in w_R \mid d(v_i, w_i) + min(d(v_i, \{w_L\})) \leq R\} \quad (7)$$

Similarly, $N_R^c$, is the set of neighbors that can advance packets towards $D_R$ without using $v_i$.

Using the size of these sets we can quantify how critical a node is within the power line. However, these nodes can fall asleep as well. To consider this situation, we will count only the nodes we estimate to be awake in each set. The power line estimator is:

$$\beta = \frac{1}{N_{v_i}} \left( \sum_{w_i \in N_L^c} I(w_i) + \sum_{w_i \in N_R^c} I(w_i) \right) \quad (8)$$

where, $I(w_i)$, is set to 1 if the node $w_i$ is estimated to be awake, and 0 otherwise. Note that when all nodes in $w_L$ can reach $w_R$, and vice versa, and also are all awake, the factor $\beta = 1$, allowing $v_i$ to go to sleep until the next report period of $u$ without compromising any transmissions around the power line. This estimator represents the portion of neighbors of $v_i$ that can respond to requests and events in place of $v_i$ in case it decides to sleep.

Compared to the minimum sleeping period $T_{min}^{sleep}$, a node with $\beta = 1$ can set itself to inactive state for an additional period: $T_{add}^{sleep} = \Delta T - T_{min}^{sleep}$. In the case none of the nodes in the sets $N_L^c$ and $N_R^c$ are awake or the sets are empty (i.e., when the network topology is very sparse), $v_i$ is a critical node, $\beta = 0$, and it should remain awake to listen for requests or *catch* event packets. The sleeping time of a node is expected to be proportional to $\beta$, i.e. $T_{v_i}^{sleep} \sim \beta \cdot T_{add}^{sleep}$.

Nodes with higher energy are expected to sleep a shorter time as follows:

$$E\left[T_{v_i}^{add}\right] = T_{add}^{sleep} \cdot \beta \cdot \left(1 - \frac{B_{v_i} + T_{min}^{sleep} \rho_{v_i}}{B_{max}}\right) \quad (9)$$

A node $v_i$ will decide its activity at the beginning of each $\Delta T$ period as: $E\left[T_{v_i}^{sleep}\right] = T_{min}^{sleep} + E\left[T_{v_i}^{add}\right]$, where the maximum time a node can be inactive is $\Delta T$. A node needs to determine its inactive time so that after $u$'s transmission, some transmission requests (either for periodic reports or events) generated during $T_{add}^{sleep}$ can be more timely forwarded by an active node on the power-line. The wake-up time thus the response speed of $v_i$ to these requests will be impacted by the activity of surrounding nodes and its energy level estimated at the end of the minimum sleeping period.

## V. Reliability in PLMN

Transmissions in outdoor monitoring applications follow a Log-Normal Shadowing Path Loss model, based on which authors in [7] analyze the effect of varying distances on the reliability. Varying the transmission power defines three *reliabilty regions* as well: 1) a disconnected region with very low PRR for small values of $P_t$, 2) a transitional region with variable PRR and 3) a connected region with high PRR for large values of $P_t$. To improve the reliability, $P_t$ can be increased to a value within the variable transitional region, to avoid unnecessarily high energy consumption, as long as it can guarantee a high probability of PRR.

The probability of having a PRR higher than a certain threshold, $p_{P_t}$, is related to the probability of having a high SNR at a given $P_t$:

$$p_{P_t} = P\left[PRR \geq PRR_{high}\right] \sim P\left[\gamma(P_t) \geq \gamma_U\right] \qquad (10)$$

where the parameter $\gamma_U$ corresponds to a high link quality, $PRR_{high}$, which is obtained using an analytical model relating SNR ($\gamma$) and PRR [15]. Unlike PRR, which does not increase with $P_t$ monotonically, the probability in (10) is an increasing function of $P_t$. Hence, given the set $P$ of available $P_t$ levels provided by hardware specifications, the transmission power that provides a high probability of achieving the desired link quality, $p_{P_t} \geq p_{TH}$, is:

$$P_t^* = \underset{\{P_t \in P | p_{P_t} \geq p_{TH}\}}{\arg\min} \left\{ \frac{1}{p_{P_t}} E_t(P_t) \right\} \qquad (11)$$

where $p_{TH}$ is the probability threshold to ensure the link reliability above $PRR_{high}$.

To maintain a sustainable energy level at a reliable $P_t^*$, we will divide time into windows of length $W$ and control the energy consumption within each window. PRR is estimated every $W$ period, i.e., $PRR_W$, and data are reported every $\Delta T$. A node under energy balanced operation in window $W$ should meet the following condition:

$$0 \leq B_0 + \sum_{i=1}^{W/\Delta T} H_i - \sum_{i=1}^{W/\Delta T} E\left[C_i(P_{TX})\right] \leq B_{max}, \quad (12)$$

where $B_0$ is the battery level at the beginning of $W$, $H_i = \Delta T \rho_i$ is the amount of energy harvested during the duration of slot $i$. The expected energy consumption, due to transmission and idle time, during each time slot $\Delta T$ is:

$$\begin{aligned} E\left[C_i(P_{TX})\right] = P_{TX} \cdot \frac{1}{PRR_W} \cdot E\left[T^{tx}_{w(D)}\right] + \\ \left(T^{sleep}_{min} + E\left[T^{sleep}_{v_i}\right]\right) \cdot P_{sleep} \end{aligned} \qquad (13)$$

When the link quality is below the requirement, i.e. $PRR \leq PRR_{high}$, a new $P_t^*$ should be selected using (11). Once the transmission power is selected, we will face two possible cases:

1) *Balanced energy condition is met:* As the goal is to guarantee the desired link quality $PRR_{high}$ for the next window $W$, we can set the transmission power for each slot in $W$ to $P_t^*$.
2) *Balanced energy condition is not met:* In this case, increasing the transmission power will lead to unbalanced energy operation. Simply maintaining the current $P_t$ or selecting a power smaller than $P_t^*$ does not guarantee the data delivery, which would also waste the transmission energy. Instead, we look for a longer reporting period $\Delta T$ by iteratively modifying the number of transmissions $W/\Delta T$ within the current time window until Eq. 12 is satisfied. As power line monitoring data have low reporting frequency, it requires very few iterations to find the new $\Delta T^*$.

Once transmissions have been performed, the node can enter a sleep mode following the procedure described in section IV-D. The increase of $\Delta T$ helps to harvest more energy and achieve reliability rather than wasting the power for unreliable transmissions.

## VI. Performance Evaluation

In this section, we evaluate the effectiveness of our algorithms for relay selection in PLMNs through extensive simulations and compare the performance with that of peer work. In the evaluation, all sensor nodes are powered by energy harvested from the transmission line [1], sharing common harvesting characteristics. Nodes are equipped with an extended-range transceiver, such as Xbee Pro [16], with range $R = 1.5km$, suitable for power line monitoring [10]. All nodes have the same battery capacity. Transmission and reception power are configured based on those in [16], where five power modes are specified.

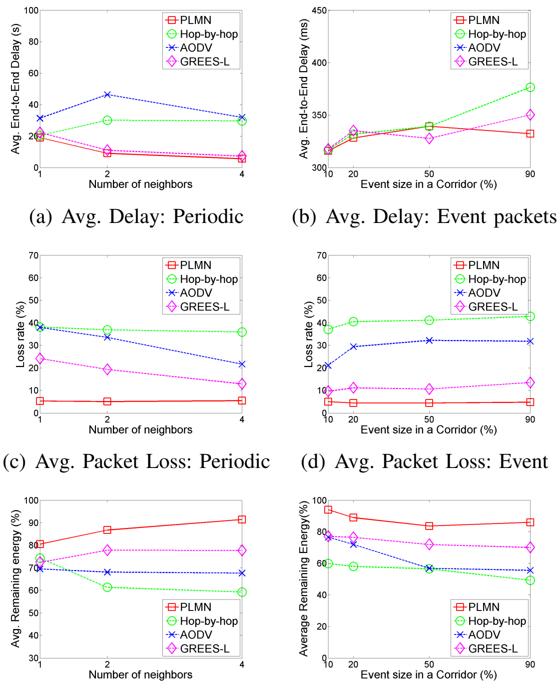
Monitoring data are expected to be sent to substations, located at the end of the corridors. Nodes in the network are assumed to be aware of the location of each substation in the network, which can be easily pre-configured. We have the packet length set to 64 bytes to carry the power-line parameters [17]. The monitoring cycle is set to 15 seconds [18], and within each cycle, a burst of five packets on average are sent. Common report periods of PLMNs range from seconds, several minutes up to every hour.

The following algorithms will be used for comparison:

- *AODV:* As a standard reactive on-demand solution, it is widely used in off-the-shelf ZigBee applications.
- *Hop-by-hop:* It uses a static route with every node on a power line to relay data. Many existing studies [3] assume the simple power-line model in Fig. 1(a) and take this type of linear forwarding.
- *GREES-L:* This geographic-based, energy and harvesting aware scheme proposed in [2] has similar goals as ours. We evaluate its performance in PLMN specific scenarios.

### A. Impact of Topology of the Power-Line Corridor

This section evaluates the network performance under the generalized power line corridor model described in Section III, we generate corridors containing different number of nodes with an average of 50 nodes. The non-uniform distributions of nodes on a power-line are generated using three different average distances between nodes ranging from 300m to 1km




(a) Avg. Delay: Periodic (b) Avg. Delay: Event packets

(c) Avg. Packet Loss: Periodic (d) Avg. Packet Loss: Event

(e) Avg. Energy Left: Periodic (f) Avg. Energy Left: Event

Fig. 3. Periodic (left column) and Event (right column) evaluations.

while following the low-density characteristic of the power line. Therefore, the number of neighbors a node has range from 1 to 4 per direction. To evaluate the effect of the arrangement of corridors in the generalized model we generate a PLMN with three lines and one crossing. This model can easily be extended to any power grid layout.

*1) Impact on Arrival Delay:* In Fig. 3(a), the delay is measured at one substation used as the destination for the three lines during *periodic monitoring*. The delay of AODV increases with the number of neighbors thus the potential collisions, while the delay of the static routes provided by Hop-by-Hop is also high as it does not consider the non-uniform node distribution to select more efficient relay nodes. PLMN can find better relay nodes to reduce the transmission delay taking advantage of increased number of candidate relay nodes in a neighborhood. GREES-L maintains a controlled average delay, however, it results in about 17% longer delay due to its selection of longer paths thus reduced transmission rate according to its cost metric.

*2) Impact on Reliability:* The reliability requirement is set at $PRR_{high} \geq 0.95$. Fig. 3(c) shows that our algorithm successfully meets the reliability requirement even with a smaller power. AODV controls the packet loss by looking for a new path with good quality, at the cost of increased energy and delay. GREES-L uses link quality as part of its cost function as well, resulting in a similar trend as that of our solution. However, its performance can be slightly lower because low link quality relays are only replaced when their cost is explicitly updated.

*3) Impact on Energy:* Fig. 3(e) shows that PLMN takes advantage of the increased number of candidate relay nodes in a varying power-line topology to adapt forwarders and node activity schedule according to the energy and power line conditions. We provided the peer schemes with a simple sleeping schedule: nodes sleep when they are not relay nodes. Using static paths, Hop-by-Hop reduces the sleeping time of nodes, resulting in increased energy consumption. Although AODV can generate routes on demand, the explicit and cascade transmissions of route request packets consume extra energy. GREES-L seems to also take advantage of the increment of neighbors in the line. However, its periodic transmission of *hello* messages increase the energy consumption.

### B. Impact on Event Monitoring

Event monitoring is a critical task in PLMNs. Events can be generated in a random location of a power line corridor and will be sensed by the nodes in the proximity of that location. Due to the physical connectivity of the power line, the event affects the whole corridor in a cascade manner. To model this characteristic of events in PLMN, we evaluate the impact of the *size of the event*. This corresponds to the percentage of nodes of a power line corridor that attempt to report an event.

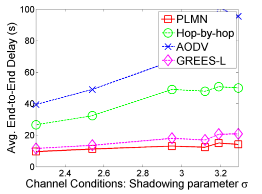
*1) Impact on Arrival Delay:* Different from the average delay of a monitoring cycle, Fig. 3(b) shows the average delay for *event packets* only. As the number of reporting nodes increases, AODV has to set up several requests to find routes, resulting in a significant delay increase, and the delay is even out of the range of the figure. Hop-by-hop experiences higher delay, due to the increased collisions and access time in its static path. Our proposed scheme can effectively support the sudden increase of reporting nodes due to random cascading events.

*2) Impact on Reliability:* In Fig. 3(d) we can see that our algorithm meets the reliability requirement for cascading event packets with its efficient power control and coordinative management of node activity, described in Sections V and IV-D respectively. The performance of GREES-L is compromised by the need of updated information from the neighbors. To report events, Hop-by-Hop uses the same routes as those for periodic monitoring, which does not consider the sudden traffic increase and thus performs poorly.

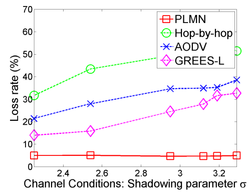
*3) Impact on Energy:* In Fig. 3(f) we see that algorithms that require explicit requests to set up paths, such as AODV, spend more energy due to the cascade of request packets. Nodes in GREES-L do not estimate the energy status of other nodes on the power line, leading to the local decision problem described in III-B and consequently the increased energy consumption as shown in the figure. In our algorithm, the node activity is controlled even under cascading events, maintaining a balanced energy operation as shown in the figure.

### C. Impact of Channel Conditions

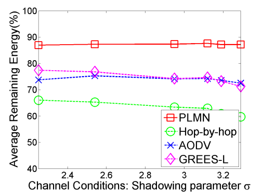
According to their locations, power line corridors can be affected for different channel conditions. As described in section V, the PLMN scenario follow the Log-Normal Shadowing model. As in reference, we consider non line of sight (NLOS) around a substation with $n = 3.51$. To evaluate the




(a) Average End-to-End delay




(b) Average Packet Loss




(c) Avg. Remaining Energy

Fig. 4. Impact of Channel Conditions in the PLMN scenario

impact of channel conditions, we consider different values of $\sigma$, the shadowing parameter, which reflects the levels of environmental fading in one of the three lines of the PLMN.

*1) Impact on Arrival Delay:* In Fig. 4(a), we can see that most algorithms maintain a constant trend of arrival delay. GREES-L and our proposed scheme also maintain a constant trend of low delay. Both algorithms take link quality into consideration to determine routes. With a large loss, AODV searches for a new path at the cost of increased delay, while Hop-by-hop performs several retransmissions when using bad links.

*2) Impact on Reliability:* Fig. 4(b) shows that our algorithm guarantees to meet the reliability requirement by using the probabilistic increment of transmission power described in Section V. Hop-by-Hop and AODV do not consider the reliability requirement and thus perform poorly. GREES-L estimates link quality in their cost metric periodically. However, it is not capable of improving the transmission reliability over low-quality links. .

*3) Impact on Energy:* In Fig. 4(c), our proposed PLMN algorithm maintains an energy level with its use of window-based transmission scheduling in Section V while meeting the reliability requirement. Peer algorithms waste considerable amount of energy, due to retransmissions on low quality links, with no guarantee of delivery.

## VII. Conclusion

We discuss a set of general scenarios for power line monitoring and consider realistic network characteristics for data delivery. By doing so, we identify various routing constraints in a PLMN, which are not addressed by general purpose WSN routing algorithms. To alleviate those constraints, we propose a comprehensive cost metric to guide efficient relay selection in PLMN. Our solution takes into account the energy and transmission states of nodes as well as the topology constraints of PLMN to enable robust data transmissions while ensuring lower delay and packet loss and extended network life time. Our algorithm takes advantage of the relative stability of the power line monitoring structure to locally find forwarding nodes and paths towards a destined substation. We provide simulation results for different power line scenarios. Compared to peer work, our proposed algorithm can achieve much better routing performance while ensuring network nodes to have lower and more even energy consumption.

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