Feasibility, Challenges, and Performance of Wireless Multi-Hop Routing for Feeder Level Communication in a Smart Grid

Babak Karimi
Electrical Engineering and Computer Science
Wichita State University, KS, USA
bxkarimi@wichita.edu

Vinod Namboodiri
Electrical Engineering and Computer Science
Wichita State University, KS, USA
vinod.namboodiri@wichita.edu

Visvakumar Aravindhan
Electrical and Computer Engineering,
Clemson University, SC, USA
varavin@clemson.edu

Ward Jewell
Electrical Engineering and Computer Science,
Wichita State University, KS, USA
ward.jewell@wichita.edu

ABSTRACT
In a Smart Grid communication network at the power distribution level, several technologies have been suggested to meet communication needs. In this work these technologies are compared with an explanation of why wireless communication technologies may be most suitable. A wireless mesh network architecture is proposed to meet communication requirements of the power distribution system. Subsequently, a performance evaluation exploring connectivity and end-to-end delay when routing packets in this mesh architecture is done for the power grid topology. Optimizations are proposed to enhance overall communication performance, with specific recommendations made on node density, antenna transmission power levels, and application data rate.

Categories and Subject Descriptors
B.8.2 [Performance Analysis and Design Aids]; C.0 [GENERAL]; System architectures; C.2.0 [General]: Data communications; C.2.1 [Network Architecture and Design]: Network communications, Network topology, Wireless communication; C.3 [SPECIAL-PURPOSE AND APPLICATION-BASED SYSTEMS]: Real-time and embedded systems; J.7 [COMPUTERS IN OTHER SYSTEMS]: Command and control, Industrial control, Consumer products, Real time.

General Terms
Design, Performance, Experimentation, Verification.

Keywords
Smart Grid, Power Distribution Level, Wireless Communication, Multi-Hop Routing.

1. INTRODUCTION
The need for improved communication at the power distribution level takes on greater importance with the introduction of the Smart Grid approach. Significant work has been done on power system communication needs and applications, IEC 61850 and DNP 3 standardize communication within the substation. ANSI C12.22 networking standards were built for advanced metering infrastructure [1]. Even though 80% of consumer interruptions are attributed to distribution component failure (at the feeder level), obtaining reliable information is still a challenging task. This is due to lack of component monitoring in the distribution system and the communication infrastructure. As a result, failure/abnormality analysis is done by harvesting information from the components at the substation level. A significant amount of work in analyzing such data [2]-[5] has been done, but even investigating the entire feeder using the data from substations (beginning or end of a feeder) will not capture all the necessary information.

Due to the non-trivial nature of failures/abnormalities, the exact prediction and location of a failure, independent of the feeder model, is still in premature stages. By improving the communication infrastructure, a vital ingredient for the Smart Grid, a more reliable approach could be taken to better manage assets. In addition to asset and outage management tasks, communication will also aid in better energy management and tariff-related information.

The motivation for this paper is to propose a wireless mesh architecture for meeting the communication requirements between the control center and smart meters deployed in residences and commercial end points. This work considers wireless communication as a medium for feeder-level communication. It identifies the requirements for distribution feeder communication and explores the feasibility of wireless communication. Specific contributions of this work include the following:

i. Encourages the design choice of using a wireless medium for communication at the feeder level.
ii. Compares and contrasts various wireless technologies, and identifies a feasible subset for the envisioned architecture.
iii. Evaluates how existing communication protocols designed for wireless mesh networks perform for network topologies expected in the power grid.
iv. Provides direction on how the wireless mesh architecture should be deployed to meet application requirements and optimize communication performance.

This rest of the paper is organized as follows. In Section 2 we motivate wireless communication as the medium of choice for meeting communication requirements at the distribution level of the Smart Grid and how our work compares to prior work. We compare the suitability of different current wireless technologies...
and present details of our proposed wireless mesh architecture in Section 3. In Section 4 we evaluate connectivity and end-to-end delay in characteristic topologies of the power grid. Subsequently in Section 5 we optimize other aspects of the topology in terms of node density, antenna transmit power, and application data rate. Finally, in Section 6, we demonstrate the utility of our proposed architecture through evaluations on a real-world power distribution level topology.

2. WIRELESS COMMUNICATION IN SMART GRID

In this section, we provide the motivation for choosing a wireless communication medium over other possible communication technologies. Furthermore, we compare our contributions to prior work in this area.

2.1 Choice of Communication Medium

A Smart Grid communication network is an emerging technology that allows power utility companies to access electricity usage data and services remotely, regardless of their geographic position. Real-time monitoring of transmission and distribution lines for protection against natural disasters or even malicious attacks are all reasons to have a secure, reliable, and scalable network in Smart Grids. Several last-mile options are available for getting a Smart Grid network to be operational. Broadband technologies like Digital Subscriber Line (DSL), Fiber Options (FTTX), and Power Line Communication (PLC) are all examples of last-mile options for consideration. Here, we will explain the limitations of the above-mentioned technologies due to their fixed nature and inflexibility.

When distribution feeders (section 3.3 describes and depict the feeder level communication architecture) are considered, PLC is well-suited, because it is a no-cost medium for the utility and is spread along the distribution system. PLC has the potential to transmit data at a maximum rate of 11 Kbit/s, when it has well-suited, because it is a no-cost medium for the utility and is feeder level communication architecture) are considered, PLC is work in this area.

The distribution system will be affected by voltage transients and harmonics consistently which are unpredictable, therefore this is prone to high disturbance. High-frequency signal (BPL) needs to be extended, and the nodes located on the feeder would be able to communicate with the control center.

The disadvantages of wireless communication would be interference due to the presence of buildings and trees, which could result in multi-paths; this could be avoided with improved receivers and directional antennas, which might increase the cost. Another major concern with a wireless medium is easy accessibility, which could result in security issues. This could be avoided by using secure protocols. Rural feeder sections would be long, and the range of communication could become a concern; however, directional antennas could mitigate this issue.

2.2 Impact of Interference Due to Transmission Lines on Wireless Medium

One of the concerns in using wireless communication along power lines is the interference from high-voltage transmission lines. Electromagnetic noise generated around high-voltage power lines is an undesirable disturbance, which can affect wireless data transmission. This noise can be observed as an additive signal to the original one, and it can interrupt, obstruct, degrade, or limit the performance of communication systems. According to [11] this noise is due to the following:

Discharges between line components: This occurs only in power lines less than 70 kV. This type of noise is generated in insulators, in metallic parts, or in faulty or not properly installed equipment. The noise tends to dominate the frequency spectrum between 10 and 20 MHz. Its effects can be controlled by ensuring a correct power line installation and proper maintenance.
Corona effect: This affects power lines over 110 kV and tends to dominate the frequency spectrum between 10 and 30 MHz. It is generated due to partial discharges in areas with a very high electric field and causes acoustic noise, electric current, energy loss, radio interference, and mechanical vibrations.

In [11], it was concluded that the radio interference generated by high-voltage lines diminishes logarithmically with the distance to the power line and with increasing frequency. Therefore, it is recommended that communication modules be operated at frequencies greater than 100 MHz. A selection of wireless communication technologies like WiFi, ZigBee, or WiMax, which operate in the GHz range, could be utilized in the distribution system with minimal interference.

2.3 Prior Work

Recently, many attempts have been made to deploy wireless technologies in a Smart Grid. Some of them involved metering options and how to read their data, some focused on sensor networks and receiving their data, and others were based on feeder-level communication. As one work that considered most last-mile options for telecommunication in a Smart Grid, [12] talks about backhaul solutions for the distribution network. Recall from Section 2.1 that one approach for interconnecting a Smart Grid is using Power Line Communication. The authors of [13] considered PLC in low- and medium-voltage distribution grids to connect network nodes (e.g., meters, actuators, sensors) through multi-hop transmission. They investigated the application of geographic routing protocols and gauged their performance with respect to energy consumption and transmission delay. They investigated the use of Beacon Less Routing (BLR), Implicit Geographic Forwarding (IGF), and Beacon-Based Routing (BBR). They also included Shortest Path Routing (SPR) and flooding as benchmark schemes. In fact, they used Greedy Perimeter Stateless Routing (GPSR) as a general geographic algorithm and BLR, IGF, and BBR as approaches of this algorithm to see which one achieved a performance close to that of SPR. What is remarkable in this paper is that SPR assumed perfect knowledge of instantaneous link qualities and relied on a centralized optimization. BBR performed better than IGF, assuming that the frequency of hello messages was set commensurate with the network (connectivity) dynamics.

The connectivity of smart meters and their connectivity in Smart Grids is another subject with a significant body of work. The authors in [14] proposed a unified solution for Advanced Metering Infrastructure (AMI) integration with a Distribution Management System (DMS). They found that a challenge of the integration of AMI and DMS is that it entails different communication protocols and requirements for handling various meter information models. They claimed that by caching and delivering meter data back and forth between DMS and AMI systems, the proposed solution architecturally isolates the two systems, minimizes the influence of the AMI meter data load on DMS systems, and vice versa. Leon et al. proposed a two-layer wireless sensor network for transmission towers, mainly to reduce the cost of operation while overcoming the limitations of a wireless communication range [15]. Muthukumar et al. proposed a wireless sensor network for distribution-level automation [16].

While the prior work above discusses how to design a network, some researchers have looked beyond. For example, [17] discussed one of the key components of a future Smart Grid called load leveling, i.e., shifting the demand in time so as to match the available supply and in so doing improving utilization of resources and reducing the reliance on environment-unfriendly reserve sources of energy as much as possible. The challenge here is in achieving such load leveling, and this work elaborates on how existing techniques from networking research could be potentially applied to solve these problems. Regarding connectivity of home area networks to smart meters, [18] studied the connection of a home-area sensor network to an energy management unit. They proposed the Appliance Coordination (ACORD) scheme, which uses an in-home Wireless Sensor Network (WSN) and reduces the cost of energy consumption. The cost of energy increases at peak hours; hence, reducing peak demand is a major concern for utility companies. With this scheme, they aimed to shift consumer demands to off-peak hours. Appliances use the readily available in-home WSN to deliver consumer requests to the Energy Management Unit (EMU). EMU schedules consumer requests with the goal of reducing the energy bill. The authors of [19] described an approach to modeling wireless communications at the link layer of the power grid, which first identifies the various applications utilizing a specific link. Second, it translates the requirements of these applications to link traffic characteristics in the form of a link-layer arrival rate and average message size. Third, it uses a coverage analysis to determine the maximum range of the technology under an outage constraint and for a given set of channel propagation parameters. Finally, using the link traffic characteristics and coverage area determined above, it employs a Medium Access Control/Physical (MAC/PHY) model to measure link performance in terms of reliability, delay, and throughput.

Some researchers believe that wireless communication is not enough to meet the entire needs of Smart Grid communication. The authors in [20] describe a hybrid Wireless-Broadband over Power Lines (W-BPL) technology. They believe that this combination is suitable for rural and remote areas. The hybrid approach employs BPL technology for the transmission of communication signals via the medium voltage (MV) grid and wireless technology for providing broadband access to end users. They showed the advantages and opportunities of this approach in a case study of Larissa, a rural area in central Greece. This network offers broadband access and Smart Grid applications along a 70 km MV power grid.

In this paper, we focus on feeder-level communication requirements and challenges. Having chosen the wireless communication medium for the grid, our goal is to compare different technologies and pick one, considering the characteristics of the grid. After identifying a suitable technology, we determine the best architecture for it and optimize it for parameters like transmit power and receiver sensitivity of individual nodes, distance between nodes, protocol data rate, and other factors that specify the network’s performance. We study network performance by first selecting a suitable routing protocol and then use it as the basis for evaluating other parameters mentioned above.

3. WI-FI MESH NETWORK ARCHITECTURE

3.1 Essential Features

In our envisioned wireless communication architecture, the following features are essential for end-to-end communication:
**Security:** Since the network is for a large nationwide electric grid, protecting connectivity and keeping its data confidential are critical. Design choices in developed protocols should include aspects for secure communication. Several reliable security solutions have been proposed and tested in different wireless architecture like mesh.

**Low latency:** Since grid functionality can be critical, having fast and real-time reaction (matter of milliseconds) in the case of an abnormal event is vital. The communication architecture should strive for high-priority, low-latency alerts during abnormality.

**Fixed stations (and few mobiles):** In the power grid infrastructure, almost all nodes are fixed. Therefore, the communication architecture does not have to factor in node mobility explicitly. However, the ability to support mobility for some nodes would be helpful for situations like a maintenance vehicle trying to connect to the network through the grid.

**Low overhead:** Excessive use of control packets and multiple nodes trying to send the same information constitute high overhead. This reduces available bandwidth for data traffic and can result in higher latencies for critical alert packets. Therefore, it is necessary to ensure that overhead is kept low.

**Scalability:** The network of wireless nodes is expected to be quite large considering the scale of towers from the substation to residential units. This scale could vary from 1 kilometer up to hundreds of kilometers. The communication architecture must work equally well for a small network as for a large network.

We leave the issue of security for future work; in this paper we propose an architecture and evaluate it with respect to the other four features mentioned above.

### 3.2 Selection of Appropriate Wireless Technology

Among the choices of wireless technologies, WiFi (peak bandwidth 54 Mbps), WiMAX (peak bandwidth 100 Mbps), and cellular data service (peak bandwidth 10 Mbps) are compared in Table 1. Based on the information in this table, WiFi mesh seems to be the superior technology for Smart Grid communications at the feeder level, and WiMAX could be used as a gateway for long-haul communication based on availability and cost considerations. Taking into account the above considerations, a final architecture could be as shown in Figure 1. For WiFi, unlicensed frequency bands are preferred, due to cost benefits and additional robustness that could be possible by leveraging community WiFi networks.

Among the unlicensed bands, we chose the 2.4 GHz range because of its greater communication range when compared to higher-frequency bands. Our focus in this work will be on the mesh architecture, leaving long-haul communications for future work.

#### 3.3 Architecture

In general, there are two possible architectures of a WiFi network: infrastructure mode and infrastructure less (ad-hoc) mode [21]. In the proposed communication architecture, the goal is forwarding packets to the next available node. So it is more likely to behave in ad-hoc mode where no central base station exists in a long chain of transmission or distribution lines. There is no central node for controlling communication between nodes. The ad-hoc mode operation of WiFi can be used in the formation of a mesh network among all nodes.

<table>
<thead>
<tr>
<th>Customer Need</th>
<th>WiMAX</th>
<th>Wi-Fi Mesh</th>
<th>GSM/UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Range</td>
<td>Rural 4 km, Urban 500–900 m</td>
<td>200–400 m, 1–2 mi</td>
<td></td>
</tr>
<tr>
<td>Maximum Data Rate</td>
<td>70 Mbps</td>
<td>54 Mbps</td>
<td>20–800 kbps</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>2–11 GHz and 10–66 GHz</td>
<td>2.4 GHz and 5 GHz</td>
<td>700 MHz–2.1 GHz</td>
</tr>
<tr>
<td>Band License</td>
<td>Free and Licensed</td>
<td>Free</td>
<td>Licensed</td>
</tr>
<tr>
<td>Flexibility</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Robustness</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

![Figure 1. Proposed WiFi Mesh Architecture.](image-url)
In a multi-hop wireless network, a source node relies on intermediate nodes on a routing path to forward packets toward the destination. Therefore, a data packet should pass several hops to reach the destination. A Smart Grid network at the distribution level is expected to have this behavior. Each item (poles, smart meters, control center computers, etc.) can be a source, destination, or intermediate node to send, route, or receive a data packet. Also, each entity in these networks can be connected to more than one other entity. For example, a smart meter in a residence area can be connected to two or three distribution line poles in its vicinity.

This interconnectivity in a network is said to be mesh connectivity. Because of this similarity, the envisioned Smart Grid network is called a multi-hop mesh network. Multi-hop architecture will ensure that the necessary redundancy is available upon the failure of a master node. A typical range using 2.4 GHz with a stock antenna is 300 feet outdoors, which fits the typical distance between distribution poles.

3.4 Possible Application Scenarios

**Fault location:** Having an established wireless mesh topology has the benefit of speeding up the location of a fault or failure in the network. Each pole could have sensors monitoring the power lines that could then communicate to nodes on the mesh network. Such capability enables immediately reporting any event and its geographic location in a matter of seconds.

**Bi-directional communication:** All appliance parts of consumers’ Advanced Metering Infrastructure (AMI) could be connected to the network via smart meters. This requires bidirectional communication: control commands from the control center of the utility to smart meters, and load profiles and logs from smart meters to the control center.

4. PRELIMINARY EVALUATION OF PROPOSED MESH ARCHITECTURE

The vision of using a collection of cost-effective, fixed wireless nodes that form a mesh network is evaluated here. We base the feasibility of the architecture on connectivity and end-to-end delay. The transmit power used by each mesh node has the largest impact on connectivity, and hence will be the focus of our preliminary evaluations here. We begin by describing our experimental setup, and subsequently examine impact of antenna transmit power levels on end-to-end delay.

4.1 Experimental Setup

**Simulation environment:** Simulations are carried out in the open-source network simulator-2 (NS ver-2.31) [22], which allows abstraction of all communication protocols and their performance evaluation for different network topologies and configuration of various network traffic types.

**Traffic model:** Continuous bit rate (CBR) traffic sources are used. The source-destination pairs are the first and last nodes of the network. Small data rates of the order of Kbps are used which we believe are typical for Smart Grid scenarios. The measurement data (e.g., synchrophasor measurements) may send continuous data, but the packet size is expected to be small. Any asset management data with a moderate packet size would typically not be continuous, and thus, again requiring only a small data rate.

**Network Topology:** The nodes are placed using linear topology (mimicking electric poles on a distribution line) on a 10 km long scenario, each node separated by 100 meter distance from its neighbors, unless we are varying node density. An example linear topology is shown in Figure 2. The first node, or Node (0) represents the control center, which is located at the furthest left part of the topology. The destination, or Node (n), is assumed to be the node from which the control center is requesting information (for example a smart meter).

![Figure 2. Simulation Scenario Schematic.](image)

Performance of the message delivery is analyzed in this work. For all simulations, a fixed antenna model is used. The transmit power is set to be fixed at 0.28 Watt, providing a range of 100 meters in our simulator, which is consistent with practical values for WiFi.

**Performance measures:** The following performance measures are used for the routing protocol:

- **Packet delivery fraction (PDF):** This is the ratio of packets delivered to packets sent by the traffic generator.
- **Average end-to-end packet delay:** This is the average of delays of each successfully received packet from the source node to the destination.
- **Node density:** This term is used to describe the number of nodes within a certain geographic length.

**Selection of Routing Protocol:** Ad hoc routing protocols that we can use for our mesh architecture can be divided into two main categories: reactive (on-demand) and proactive (table-driven). Other possible categories include location-based routing (e.g. [23] and prediction based routing [24]). There has been extensive prior work on evaluating routing protocols for ad hoc networks. (e.g. [25], [26] and [27]). We picked Ad Hoc On-Demand Distance Vector (AODV) routing protocol [28] as the representative of routing protocols in this work due to prior evaluation results [29] and our own comparisons with proactive routing protocols. In on-demand routing protocols, routes are created as and when required. When a source wants to send to a destination, it invokes route-discovery mechanisms to find the path to the destination. These discovered routes time-out after a fixed duration, requiring new routes to be created to replace them.

For our evaluations we had to modify some default parameters of the AODV protocols to support a topology that spans many thousands of meters with route lengths expected to many hundreds of hops. For example, the default network diameter for AODV in NS2 is 30 hops; we modified it to be larger than the number of hops expected in long chain topologies.

4.2 Transmit Power Effect on Coverage Range and End-to-End Delay

Increasing the transmit power of a node’s antenna would be possible in the event of failure of any node along a route. Typically, we envision using directional antennas, in comparison to Omni-directional antennas, for nodes to allow maximum range and to reduce interference among nodes and with other wireless networks in the vicinity. To perceive the idea of interference among nodes, or contention, an understanding of the implementation of the concept of physical carrier sense in the IEEE 802.11 standard for WiFi [30] is needed. Usually a node
that wishes to transmit a packet must first assess the channel. If the energy detected on channel is greater than a Carrier-Sense Threshold (CSTresh), the station must assume that the channel is busy, and defer. Thus, a small CSTresh implies that even nodes quite far away from a transmitting node shall detect the channel as busy, and defer. On the contrary, a large carrier-sense threshold implies that only nodes very close to a transmitter shall assess the channel as busy. Recall that carrier-sense range (CSRange) is the distance from the transmitter up to which nodes assess the channel as busy, and thus CSTresh and CSRange possess an inverse relationship with each other. A larger CSRange implies more space is "reserved" by a transmission as a "guard zone" to avoid interference/collisions. A smaller CSRange implies there can be more concurrent transmissions, but chances of collision are higher.

To observe this property, a simulation is performed that evaluates the effect of antenna’s transmit power on carrier-sense range with a fixed receiver sensitivity (default NS2 value of 3.65e-10 Watt), and the delay between source and destination of packets. The simulation scenario is shown in Figure 3. Here we just assumed a simple 2 nodes communicating in 100 meter distance but it could be any other scenario.

Figure 3. Simulation Scenario Scheme.

This simulation is performed using AODV routing protocol starting with a power of 0.5 mW, which results in a 200 meter CSRange, and continuing the simulation to reach a power of 450 mW, which results in a CSRange of 1,094.8 meters. Increasing the transmit power any more will provide the same behavior as output results in PDF and delay. Figure 4 represent the results of these experiments.

The results from this experiment show us that we can take advantage of increasing an antenna’s transmit power in the event of a failure, such as collapsing of a pole. Increasing the transmit power helps to increase the communication radius (Figure 4![Error! Reference source not found.]), and consequently the Smart Grid wireless communication remains operational. Figure 4(a) shows how increasing the transmit power will affect the delay and transmission range. Initially with increasing transmit power, the delay also increases due to greater interference among nodes. However, as the transmit power reaches a point where it has reduced the number of hops from source to destination, the delay decreases.

4.3 End-to-End Delay

In this section, we study the average end-to-end delay in a linear chain topology when multiple sources are involved for various transmit power levels. Five sources in a ten-node scenario were used, with each node 100m apart. Results in Figure 5 indicate a cyclical pattern due to the competing impact of transmit power on interference levels and delay. As we increase the transmit power, the delay initially decreases due to a reduction number of hops to the destination. Subsequently, the delay suddenly increases after a transmit power value due to increasing contention among multiple flows. As the transmit power keeps on increasing, however, the delay again decreases when the shorter routes provide more benefits than the penalty due to increased contention among nodes.

Figure 5. Transmit Power vs. Average of Delays Plot.

In any scenario, there could be multiple optimal transmit power values depending on requirements; For example, the best value could depend on the wireless router power supply. If the power is obtained from a battery, then the best transmit power could be the local minimum point on the plot above. But if the supply is from a power line or a source that is not limited, then we can afford to use higher transmit powers to reduce delays, in which case the optimal transmit power would be the absolute minimum point on the overall delay plot. Again, these transmit powers are only for this specific experiment; results could vary for other scenarios that vary the number of nodes and amount of data rate.

5. FEASIBLE OPERATING CONDITIONS FOR MESH ARCHITECTURE

Motivated by previous simulation results, a further study was conducted to determine feasible data rates, node density, and length of node chain. As a first step, it was decided to determine the appropriate node density when deploying the proposed
wireless mesh architecture. Data rates of 0.01 and 0.5 Mbps were used. Actual distribution level data communication would be in this range, since the requirement is to transmit only the power system operation information in a secured manner. Packet delivery fraction and delay for these two cases are plotted in Figure 6.

![Figure 6](image1.png)

(a) Delay

(b) Packet Delivery Fraction

**Figure 6. Comparison of 0.01 and 0.5 Mbps Communication.**

The drop seen for node densities of 20 to 21 in Figure 6(a) is due to a sudden decrease in the number of hops taken by the AODV routing protocol from the source to the destination. This protocol considers all possible paths from the source to the destination and picks the one that can reach the destination with the least delay, which typically is the route composed of the shortest number of hops. As node density increases, there is a certain point at which the routes taken can skip over some nodes on the path to the destination. From Figure 6(a), it can be seen that node density of 10 nodes per km performs better for both 0.01 Mbps and 0.5 Mbps cases. The smaller the node density, the cheaper the feeder-level communication in terms of number of nodes that needs to be deployed. Therefore, this work suggests using the minimum possible node density of 10 nodes per km as the best option. A 100% data delivery fraction is a critical component for reliable communication. From Figure 6(b), it can be seen that this can be achieved when the data rate is 0.01 Mbps but not when the data rate is 0.5 Mbps.

Further analysis was done for delay and packet delivery for data rates between 0.01 and 1 Mbps. To compare the effect of node densities, both 10 and 15 nodes per km were simulated. Figure 7 shows the simulation results for these cases.

From Figure 7(a) and (b), it could be seen that when the data rate exceeds 0.15 Mbps, the delay increases significantly, and the packet delivery fraction decreases from 100%. The selection of 10 nodes per km is validated in this plot, since increasing the node density to 15 nodes per km would decrease performance. Based on this simulation for a reliable communication, the data rate should not exceed 0.15 Mbps with a node density of 10 nodes per km.

![Figure 7](image2.png)

(a) Delay

(b) Packet Delivery Fraction

**Figure 7. Simulation Results for Different Data Rates.**

As the final step, it is important to determine the appropriate length of a single WiFi chain. Using a node density of 10 nodes per km and data rates of 0.1 and 0.15 Mbps the length of the feeder is varied from 1 to 25.5 km. The simulation results are plotted in Figure 8.
Since distribution feeders are much longer than 100 meters, a long chain of linear nodes are required. Simulation results showed that although the results are satisfying in small chains (two- to ten-node scenarios), a greater increase in the number of nodes results in a decrease in performance. As part of future work, we plan to explore the theoretical limitations network capacity for long chain topologies.

6. EVALUATION OF A REAL-WORLD POWER DISTRIBUTION TOPOLOGY

Our final goal in this paper is to show that, given the chosen or feasible parameter values in section 5, we expect good performance in terms of communication in a real-world Smart Grid topology.

Figure 9 shows the abstracted topology of the power distribution system that we took from a local utility company. All connections are bi-directional, and all can either send or receive data packets. We evaluated the scenario where the source (Node 0) sends packets to the shown destination.

Table 3 shows some values used in the simulation settings and obtained results. We can conclude that the performance obtained in terms of delay and PDF was satisfactory and bodes well for utilizing wireless mesh architecture for communication at the distribution level of the smart grid.

### Table 2. One Feasible Configuration for the WiFi Mesh Architecture

<table>
<thead>
<tr>
<th>Property</th>
<th>Feasible Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node Density</td>
<td>10 nodes /km</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>0.28 Watt</td>
</tr>
<tr>
<td>Data Rate</td>
<td>0.15 Mbps</td>
</tr>
<tr>
<td>WiFi Chain Length (Linear Topology)</td>
<td>25 km</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from the Power Systems Engineering Research Center (PSERC), as well as contributions from the industrial and academic members of the PSERC T-39 Project, “Communication Requirements and

---

Image of the graphs and table is included in the text, along with relevant text content.
Integration Options for Smart Grid Deployment,” and from the U.S. Department of Energy Project DE-FG36-08GO88149, “Sustainable Energy Solutions.”

REFERENCES


