

A Testbed Based Performance Evaluation of Smart Grid Wireless Neighborhood Area Networks Routing Protocols

Juan Pablo Astudillo León ^{a,1}, Luis J. de la Cruz Llopis ^a

^a*Department of Network Engineering, Universitat Politècnica de Catalunya (UPC),
Barcelona, Spain.*

Abstract.

Smart Grid networks have a data communication network associated with the electrical energy distribution infrastructure. This network connects all the subscribers' homes with the data control centers of the supplying companies, which in turn have access to the global Internet network. They are in charge of transporting the needed information between the elements that comprise the electricity network and the control centers. A part of these networks is the so-called Neighborhood Area Networks (NANs), which transports the data from the subscriber's home to some data concentrators. This article presents a comparison of the performance of different routing protocols that can be used in this part of the data network, when a wireless technology is selected. For this comparison, a hardware testbed has been implemented, with a simple initial configuration, which allows the comparison of the OLSR v1, OLSR v2 and HWMP protocols. The numerical results are presented in terms of network throughput, protocol overhead, number of retransmissions, network transit and packet transfer times.

Keywords. Smart Grid Neighborhood Area Networks, wireless mesh networks, wireless ad hoc networks, OLSR, HWMP, hardware testbed.

1. Introduction

The evolution of the traditional electric system towards the Smart Grid (SG) has attracted research in different areas. For instance, the improvement of the performance of the SG data communication network has focused the work of numerous research groups. In a near future, many services will be provided by this communications network such as control messages, maintenance, billing and all sort of user-generated applications. Some of these services are of crucial importance for the proper functioning of the electricity distribution network, and therefore must be transmitted with the highest level of reliability, security and availability.

The Smart Grid data communication network is comprised in different parts, where each one of them fulfills different purposes. The different smart meters (SM) devices and other hemo appliances are interconnected through the Home Area Network (HAN). Be-

¹Corresponding Author: Book Production Manager, IOS Press, Nieuwe Hemweg 6B, 1013 BG Amsterdam, The Netherlands; E-mail: bookproduction@iospress.nl.

January 2020

sides, the HANs are interconnected by the Neighborhood Area Network (NAN), where wired (Power Line Communications (PLC)) and wireless (Wireless Adhoc or Mesh Networks) technologies have been considered. Finally, a wired or wireless backbone allows the interconnection between the NANs and the control centers.

The goal of this work is the evaluation, by means of a hardware testbed, of some multi-hop wireless network technologies (and specifically their routing algorithms) in the context of the Smart Grid Neighborhood Area Networks (SG NANs). For this purpose, a comparison will be made between two wireless network technologies: the classical ad hoc networks [1] in multi-hop mode and operating with the OLSR (Optimized Link State Routing) routing protocol [2, 3], and the mesh networks as defined also in the environment of the IEEE WLAN networks [4] (previously known as IEEE 802.11s) operating with their own HWMP routing protocol (Hybrid Wireless Mesh Protocol).

The rest of the paper is organized as follows. In Section 2, some related work is presented. Section 3 describes the testbed configuration, and section 4 presents and analyzes the obtained results. Finally, the conclusions are summarized in Section 5.

2. Related work

Most of the research involving routing protocols for Smart Grid Neighborhood Area Networks is performed through network simulations. For instance, authors in [5] present a modification to the Optimized Link State Protocol (OLSR) aiming to satisfy the required level of reliability in NANs. They provided an adapted quality of service to the different data traffics through a combination of different basic metrics. The same authors had previously presented in [6] a performance evaluation and comparison of OLSR and HWMP (IEEE 802.11s) routing protocols, together with a classification of the main AMI application traffics.

In [7], authors present a multigate communication network, based on IEEE 802.11s for Smart Grids where more than one gateway is taken into account, together with real-time traffic scheduling and a multi-channel routing protocol. Furthermore, the authors propose a heuristic backpressure scheme, where every node evaluates the state of its neighbors before selecting one of them as the best next hop. On the other hand, authors in [8] propose the HWMP-NQ protocol which is a modification of the basic HWMP to provide different quality of service (QoS) requirements based on each smart grid data application. To this end, the computation of the airtime link metric is modified. Another modification of the airtime link metric calculation method was presented in [9]. The authors focused their work to give more importance to the upstream communication from smart meters to the concentrator. They also highlight the need for congestion control mechanisms when the network size is increased. With this goal in mind, a congestion control mechanism, which takes into account possible emergencies in the network, and applies also multi-channel allocation and traffic differentiation techniques, is presented in [10].

Some of the same authors of [9] make in [11] a study of the HWMP routing protocol, to identify its weakness, both from the HWMP protocol itself (route instability and route recovery) and from the integration with Smart Grid networks (oversimplified calculation of airtime link metric and the need of traffic differentiation). Here, a modification of the airtime link metric computation is also proposed, as well as a proposal for

January 2020

the path selection mechanism. A new path selection mechanism is presented in [12] for the HWMP in conjunction with a multi-channel allocation. In this work, the paths are assigned differentially according to the quality of service demanded by every traffic.

When using physical hardware, several routing protocols for multi hop wireless networks are studied and evaluated in Community Networks [13] [14] [15]. The platform mainly used to conduct experiments in Community Networks is the Community Lab testbed [16]. In another work, authors in [17] present the implementation of a OpenWRT OS based testbed for Content Centric Networks (CCN). They analyze the performance of Optimized Link State Routing (OLSR) protocol in an indoor scenario. For the evaluation, they considered hop count, delay and jitter metrics. Their experimental results show that the nodes in the testbed were communicating smoothly with low values of delay and jitter.

In this paper we present a comparison of the performance of different routing protocols used in wireless mesh networks (OLSRv1, OLSRv2 and HWMP) in the context of SG NANs. This comparison has been made through experiments carried out on a real network platform, where the network nodes have been implemented on Linux embedded devices.

3. Testbed configuration

As previously said, in order to measure and compare the performance of the different routing protocols in a context of SG NANs, a testbed consisting of a series of Linux embedded devices acting as smart meters nodes has been implemented. In this first series of experiments, we have opted for a linear chain topology, in which the number of intermediate nodes between the source and the destination (data concentrator) of the information is increased (see Figure 1, where every smart meter or station STA is represented together with its coverage area). As will be seen in the results section, increasing the number of hops implies an increase in the use of all the channels of the network under study, with the consequent degradation of the quality of service parameters.

In this first work on the hardware platform, it has been chosen to focus the study on the performance obtained based on the use of different routing protocols. For this, a simple network configuration has been taken into account in which only the first node acts as the source of data, modeling the different home appliances that can be found inside homes. In future works the results will be generalized, considering more complicated network topologies, and including the possibility of having all the network nodes acting as generators and relays of data flows.

3.1. Testbed setup

The measurement setup is based on up to four smart meters (STAs) and one data concentrator. These devices have placed in our lab to model a linear chain topology network. Each device consists of a Raspberry PI 3 device configured either in mesh or ad hoc mode according to the experiment. In mesh mode, each node is configured as a mesh station (MSTA) with the same mesh ID and channel. On the other hand, in ad hoc mode, each node is configured with the same ESSID and channel. In addition, every node has a connection to its direct neighbors one hop away. Hence, it is necessary to ensure the devices do not have connections with the nodes two hops away as presented in Figure 1.

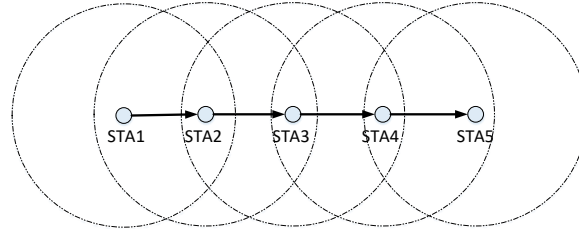


Figure 1. Linear Chain topology.

3.2. OLSRv1, OLSRv2 and HWMP implementations

The OLSRv1 and OLSRv2 implementations were downloaded from the OLSR.org project [18]. OLSR.org has two major projects and a minor one. The first one is the OLSRv1 [2] implementation called *olsrd* and the second is the *OLSR.org Network Framework* (OONF) project. The latter contains the implementation of NHDP [19] and OLSRv2 protocols [3] called *olsrd2*. The Dynamic Link Exchange Protocol (DLEP), which aims to extract information from the radio for the design of new metrics, is also implemented in OONF as *DLEP*. On the other hand, the mesh implementation (HWMP) does not need any additional libraries to be installed at the physical devices.

3.3. Testbed controller

The testbed implemented is based on a network controller developed in *Python*. It is implemented and running in the first network node (STA1). The controller automatically generates the data flows among the information source (leftmost STA) and the destination (rightmost STA). In order to generate these data flows, the network tool *Iperf3* was also installed in the controller (see Figure 2). In this work, these flows simulate the data generated by SG NAN applications that do not need a reliable connection being established, and so, the UDP protocol has been selected. Each data flow is based on the target throughput, the number of runs, routing and transport protocols, and the number of intermediate nodes. In addition, the controller transmits control packets to the rest of the network nodes in order to save the results generated by *iperf3*, and to enable also traffic captures in every node to get all the exchanged traffic. To carry out the experiments, the parameters shown in Table 1 were configured.

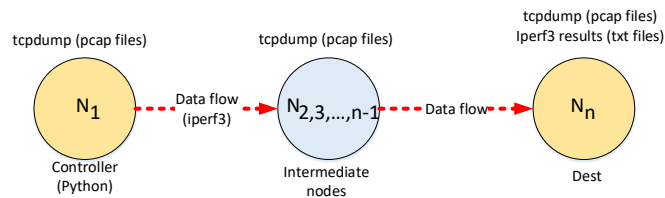
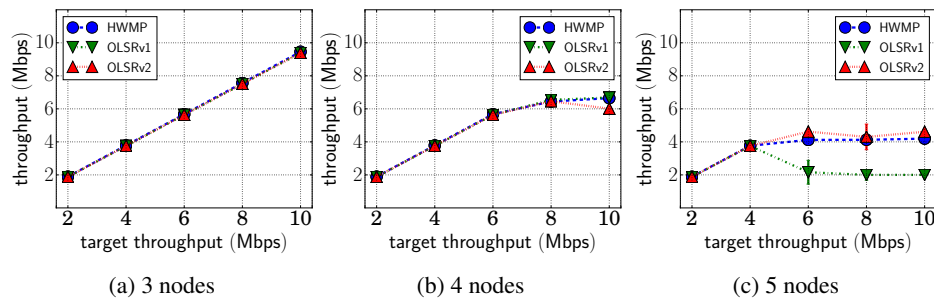


Figure 2. Testbed controller.

Table 1. Parameters configured

Parameter	Value
Physical layer	802.11g.
Main scenarios to be evaluated	3, 4 and 5 STAs (including the data concentrator)
Separation between nodes	1 m.
Transmission power	1 dbm.
Target throughput	2, 4, 6, 8, 10 Mbps.
Number of runs per protocol	50.
Run time	100 s.
Confidence Interval (CI)	95%.

**Figure 3.** Throughput measured on the destination node.

4. Experimental results

Several runs were conducted in order to evaluate the network performance in terms of network throughput, protocol overhead, network transit time, MAC layer retransmissions and packet transfer time. To evaluate all the network performance parameters, the whole traffic was captured (*pcap files*) through the *tcpdump* network utility.

4.1. Network throughput

The throughput represents the number of bits per second received correctly. The obtained measured includes all the layer headers except for the physical layer (Radio Tap Header v0). The headers taken into account for the throughput measurement are listed in Table 2. Figure 3 shows the delivered throughput (and its 95% confidence interval) for different network sizes (3, 4, and 5 nodes), for different target throughput (2, 4, 6, 8 and 10 Mbps), and for the three protocols under evaluation (OLSRv1, OLSRv2 and HWMP). It can be observed how as the network size is increased, it becomes more congested, and therefore, the throughput decreases. However, the throughput decrement is lower when the OLSRv2 and HWMP protocols are used. It must be kept in mind that, when using wireless channels, each additional node in the network causes an increase in the use of channels in its coverage area, which in turn extends to more distant areas of the network

Table 2. Protocol header sizes (Bytes)

Protocol	OLSRv1	OLSRv2	HWMP
IEEE 802.11 QoS Data Frame	26	26	38
Logical-Link Control	8	8	8
IPv4	20	20	20
UDP	8	8	8

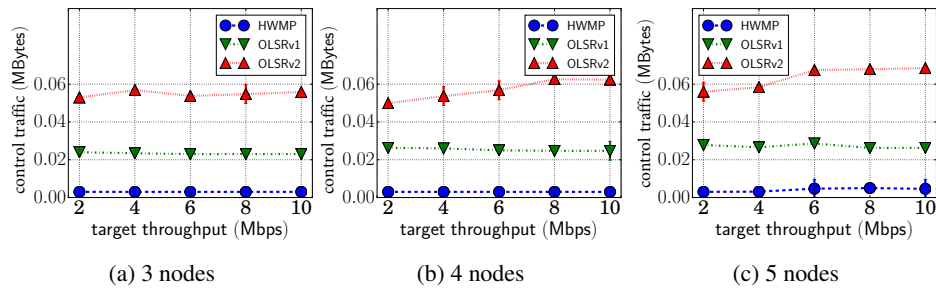
4.2. Control traffic

All the nodes transmit periodically some control traffic to keep the network topology. Table 3 presents the message types used by each protocol. Our developed network tool identifies the routing protocol, management frames and signaling messages. Therefore, according to the port number and message type, we calculate the amount of control traffic used by each routing protocol. For all the experiments, the routes lifetimes has been set with their default values.

Table 3. Message types

OLSRv1	ID	OLSRv2	ID	HWMP	ID
HELLO	1 or 201	HELLO	0	PREQ	130
TC	2 or 202	TC	1	PREP	131
MID	3	DSCP	192	PERR	132
HNA	4				

Figure 4 shows how the HWMP protocol loads the network with less control traffic for all the evaluated network sizes. On the other hand, the OLSRv2 protocol uses more control traffic due to its implementation (olsrd2) uses additional signaling for the Neighborhood Discovery Protocol (NHDP) and Dynamic Link Exchange Protocol (DLEP). Besides, olsrd2 has also implemented the extension proposed by [20] to use multiple routing topologies. To this end, a Differentiated Services Code Point (DSCP) message is sent periodically.

**Figure 4.** Protocol overhead measured on the destination node.

4.3. Number of retransmissions

In this subsection, the number of MAC layer retransmissions is evaluated. For this purpose, our network tool analyzes the *Frame Control field* at each frame received and verifies whether the *Retry* flag is set to 1 or not. If this flag is set to 1, the received frame is a retransmitted frame. The results are shown in Figure 5. It can be seen that the number of retransmissions is similar for all the protocols, and for all the different network sizes. In particular, Figures 5b and 5c show that there is no more free time for (re)transmissions (congested network) when the target throughput exceeds the value of 8 and 6 Mbps respectively. Therefore, they are blocked by the medium access mechanism itself.

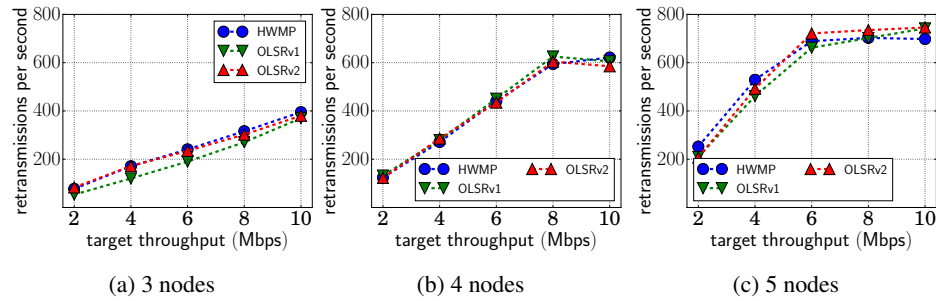


Figure 5. Number of retransmissions measured on the MAC layer.

4.4. Network transit time

The transit time is the time that packets need to go from the source to their destination through the intermediate nodes. It must be taken into account that the application fragments the datagrams into several data blocks when their size exceeds the maximum transfer unit (MTU). Therefore, each datagram will have a unique identifier and each fragment has an offset value that will be used in the receiver to reassemble the datagram. The use of the datagram identifier together with the offset value is used as a single identifier in our network tool to calculate the transit time of each datagram. The results are depicted in Figure 6. As it can be observed, as the number of intermediate nodes increases, the transit time also increases. However, the HWMP shows a lower increment of this parameter.

4.5. Packet transfer time

The transfer time represents the total time elapsed from the packet arrival and departure times at one network node. The measurements are based on the schematic shown in Figure 7. For this purpose, ICMP messages have been used, where the ICMP Request or Reply are generated at the first STA or last STA respectively. Among the different components of the transfer time (packet headers processing, queuing, medium access and transmission times), in this section we are interested in the evaluation of the processing time. In this sense, only one ICMP message is generated every two seconds to avoid queuing delays and MAC layer retransmissions. On the other hand, as shown also in Figure 7,

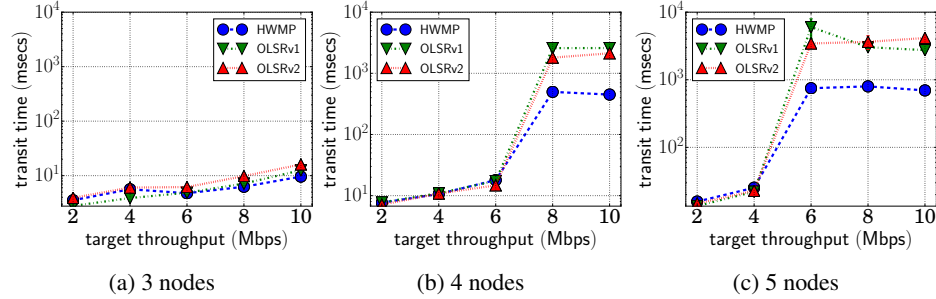


Figure 6. Network transit time.

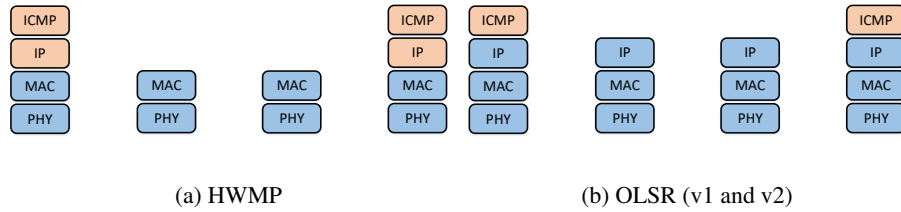


Figure 7. Layers involved in packet retransmission.

with OLSRv1 and OLSRv2 the PHY, MAC and IP layers are involved in forwarding the packets, while with HWMP the IP layer is not necessary.

For all the experiments, the same hardware/software and workload configurations have been used. The objective is that each of the intermediate nodes maintains the same execution time of the processing tasks. For this calculation, the end nodes are not considered since they add processing time for the generation of ICMP Request and Reply messages. Table 4 shows the protocols and packet headers lengths. The transfer time estimation is based on the analysis of 2000 traffic captures (*pcap files*) per protocol.

Table 4. Packet headers length (Bytes)

Protocol	ICMP (Request)			ICMP (Reply)		
	OLSRv1	OLSRv2	HWMP	OLSRv1	OLSRv2	HWMP
Radiotap	13	13	13	36	36	36
QoS Data	26	26	38	30	30	42
LLC	8	8	8	8	8	8
IPv4	20	20	20	20	20	20
ICMP	64	64	64	64	64	64
Total	131	131	143	158	158	170

The results obtained are shown in Figure 8. As can be seen, HWMP exhibits the minimum transfer time as expected, given that fewer communication layers are involved to retransmit the data frames. It is important to note that in the transfer time analyzed, in addition to the processing time, the times corresponding to the access mechanism (interframe spaces, backoff and acknowledgment times) are also included. Therefore, as a future line of work, our network tool will be extended to allow the evaluation of just the

January 2020

process time. The main objective is to obtain a model for this time that could be included in network simulations.

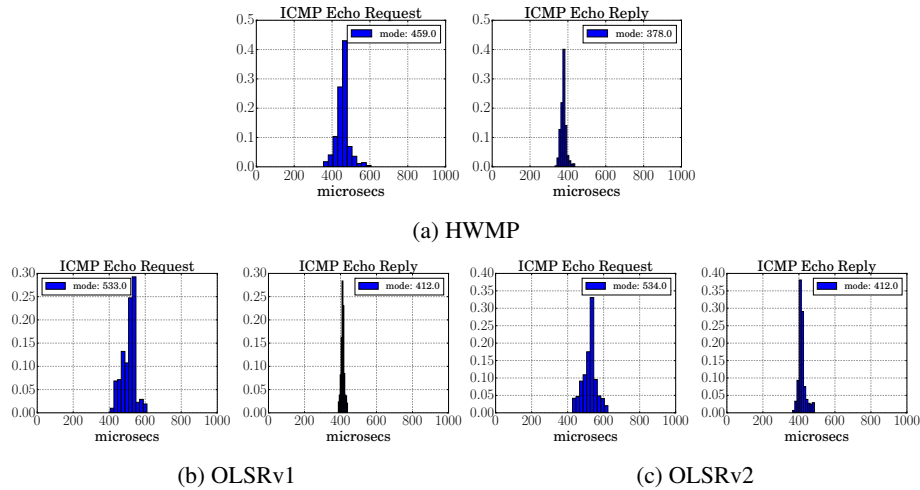


Figure 8. Transfer time (pdf)

5. Conclusions

This work is focused on the evaluation of the network performance of different wireless network routing protocols in the context of Smart Grid Neighborhood Area Networks. The evaluation is carried out by means of a hardware testbed based on Linux embedded devices. Each device represents a wireless smart meter, with the first one generating data flows to the data concentrator. A network controller was developed to drive the tests, managing the data flows generation and capturing all the exchanged traffic through different network utilities. Finally, the controller analyzes and processes all the traffic and events generated for all the protocols under evaluation.

OLSR and HWMP protocols were evaluated in terms of throughput, transit time, protocol overhead and transfer time. The obtained results have allowed quantifying the performance that can be expected from a wireless multi-hop network in terms of throughput and network transit time when it is built by Linux embedded devices. This can be very useful if we are planning to develop such a Smart Grid data communication network. Besides, a slight improvement in performance has been observed when using the HWMP protocol. Future works will be focused on more complex network topologies, where all the nodes act as information sources and packet relays.

Acknowledgment

This work was supported by the Spanish Research Council under project MAGOS (TEC2017-84197-C4-3-R), and Juan Pablo Astudillo León is the recipient of a full scholarship from the Secretaría de Educación Superior, Ciencia, Tecnología e Innovación (SENESCYT), Ecuador.

References

- [1] "IEEE Computer Society", *IEEE Std 802.11-2016. IEEE Standard for Information technologyâ€”Local and metropolitan area networks. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.*, New York, 2016.
- [2] T. Clausen and P. Jacquet, "Optimized Link State Routing Protocol (OLSR)," *Internet Engineering Task Force (IETF)*, vol. 4, p. 75, 2003. [Online]. Available: <https://www.ietf.org/rfc/rfc3626.txt>
- [3] T. Clausen, C. Dearlove, P. Jacquet, and U. Herberg, "The Optimized Link State Routing Protocol Version 2," Tech. Rep. 7181, apr 2014. [Online]. Available: <https://tools.ietf.org/html/rfc7181>
- [4] IEEE Computer Society, *IEEE Std 802.11s, IEEE Standard for Information Technologyâ€”Local and metropolitan area networksâ€”Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications. Amendment 10: Mesh Networking.*, New York, 2011.
- [5] Y. Tsado, K. Gamage, B. Adebisi, D. Lund, K. Rabie, and A. Ikpehai, "Improving the Reliability of Optimised Link State Routing in a Smart Grid Neighbour Area Network based Wireless Mesh Network Using Multiple Metrics," *Energies*, vol. 10, no. 12, p. 287, feb 2017. [Online]. Available: <http://www.mdpi.com/1996-1073/10/3/287>
- [6] Y. Tsado, K. A. A. Gamage, D. Lund, and B. Adebisi, "Performance analysis of variable Smart Grid traffic over ad hoc Wireless Mesh Networks," in *2016 International Conference on Smart Systems and Technologies (SST)*. IEEE, oct 2016, pp. 81–86. [Online]. Available: <http://ieeexplore.ieee.org/document/7765637/>
- [7] H. Gharavi and B. Hu, "Multigate Communication Network for Smart Grid," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1028–1045, jun 2011. [Online]. Available: <http://ieeexplore.ieee.org/document/5768102/>
- [8] X. Deng, L. He, X. Li, Q. Liu, L. Cai, and Z. Chen, "A reliable QoS-aware routing scheme for neighbor area network in smart grid," *Peer-to-Peer Networking and Applications*, vol. 9, no. 4, pp. 616–627, jul 2016. [Online]. Available: <http://link.springer.com/10.1007/s12083-015-0331-5>
- [9] J.-S. Jung, K.-W. Lim, J.-B. Kim, Y.-B. Ko, Y. Kim, and S.-Y. Lee, "Improving IEEE 802.11s Wireless Mesh Networks for Reliable Routing in the Smart Grid Infrastructure," in *2011 IEEE International Conference on Communications Workshops (ICC)*. IEEE, jun 2011, pp. 1–5. [Online]. Available: <http://ieeexplore.ieee.org/document/5963578/>
- [10] J. P. Astudillo León and L. J. De la Cruz Llopis, "Emergency aware congestion control for smart grid neighborhood area networks," *Ad Hoc Networks*, vol. 93, p. 101898, 2019.
- [11] J. Kim, D. Kim, K.-W. Lim, Y.-B. Ko, and S.-Y. Lee, "Improving the reliability of IEEE 802.11s based wireless mesh networks for smart grid systems," *Journal of Communications and Networks*, vol. 14, no. 6, pp. 629–639, dec 2012. [Online]. Available: <http://ieeexplore.ieee.org/document/6412861/>
- [12] J. P. Astudillo León and L. J. De la Cruz Llopis, "A joint multi-path and multi-channel protocol for traffic routing in smart grid neighborhood area networks," *Sensors*, vol. 18, no. 11, p. 4052, 2018.
- [13] Freifunk, "Freifunk is a non-commercial initiative for free wireless networks." [Online]. Available: <https://freifunk.net/en/>
- [14] "Athens wireless metropolitan network." [Online]. Available: <http://awmn.net/content.php>
- [15] Funkfeuer. [Online]. Available: <https://www.funkfeuer.at/>
- [16] L. Navarro, R. B. Vinas, C. Barz, J. Bonicioli, B. Braem, F. Freitag, and I. Vilata-i Balaguer, "Advances in wireless community networks with the community-lab testbed," *IEEE Communications Magazine*, vol. 54, no. 7, pp. 20–27, jul 2016. [Online]. Available: <http://ieeexplore.ieee.org/document/7509374/>
- [17] A. Barolli, T. Oda, L. Barolli, and M. Takizawa, "Experimental results of a raspberry pi and olsr based wireless content centric network testbed considering openwrt os," in *2016 IEEE 30th International Conference on Advanced Information Networking and Applications (AINA)*, March 2016, pp. 95–100.
- [18] OLSR.org. [Online]. Available: <http://www.olsr.org/>
- [19] T. Clausen, C. Dearlove, and J. Dean, "IETF RFC 6130, Mobile Ad Hoc Network (MANET) Neighborhood Discovery Protocol (NHDP), IETF, 2011," 2011. [Online]. Available: <https://tools.ietf.org/html/rfc6130>
- [20] C. Dearlove and T. Clausen, "Multi-Topology Extension for the Optimized Link State Routing Protocol Version 2 (OLSRv2), RFC 7722 (Experimental)," Tech. Rep. 7722, 2015. [Online]. Available: <http://www.ietf.org/rfc/rfc7722.txt>