Performance Evaluation of Wireless Mesh Network Routing Protocols for Smart Grid AMI Networks

Yakubu Tsado and Kelum Gamage
Department of Engineering
Lancaster University
Lancaster, UK
y.tsado1@lancaster.ac.uk
k.gamage@lancaster.ac.uk

David Lund
HW Communications Ltd
Lancaster, UK
d.lund@hwcomm.ac.uk

Abstract— **Recent Advances in Wireless Mesh Networks (WMN) makes it one of the candidate communication technologies for Smart Grid Automatic Metering Infrastructure (AMI) because of its scalability and low cost of deployment. However, its capacity and multi-hoping performance in dynamic environment may not guarantee resilience and packet delivery reliability requirements of AMI. Theoretical and practical studies have shown that the multi-hoping capacity of a mesh network is constrained by increase in the number of nodes and number of hops in the network. In addition traffic requirements for smart meters will further compound WMN multi-hopping issues. In this paper, the performance of WMN when deployed for AMI is carried out using two wireless routing protocols; Hybrid Wireless Mesh Protocol (HWMP) and Optimised Link State Rout protocol (OLSR) in NS-3. Simulation results show that compared to the reliability requirement of AMI, there is need for improving the routing metric for both protocols. Furthermore, The Dynamic Link Exchange Protocol (DLEP) which allows layer 2 link estimation was proposed to enhance the route decision.**

Keywords—HWMP, OLSR; AMI; DLEP; Grid network Topology.

I. INTRODUCTION

Power monitoring and control system applications have long been in existence in the electrical grid system in a small scale and it was particularly for monitoring and managing the voltage levels and different components at the power distribution and generation level. Moving forward, the new and advanced power grid known as Smart Grid (SG) will extend monitoring and control on the electrical grid system by allowing a bi-directional flow of information and flow of electric power across different levels and devices in the electrical grid network. The expected outcome of this renovation is to improve load estimation, facilitate renewable power generation and allow consumer energy management capabilities. Support for data exchange for controlling power distribution, generation and consumption in smart grid does not only involve deploying existing wired and wireless communication systems in the power grid but also necessitates the improvement and development of communication systems to suit the stringent requirements for SG function. Wireless Mesh Network (WMN) was developed to guarantee connectivity by building a multi-hop wireless backbone to interconnect and extend backhaul access to isolated areas. It has become one of the candidate communication networks touted to be used as the main network or redundant network for data collection, management and control in Smart Grid [1].

Data collection applications such as Advanced Metering Infrastructure (AMI) will require the Utility companies to receive and respond to information on real time usage or pre-defined time schedules from the consumer side via smart meters [2]. AMI information have stringent requirements such that the reliability of information are required to be over 99 % [14]-[15]. Studies has revealed WMN has the potential to support ubiquitous and high speed broadband access to both urban and rural areas [3] as a result of its scalability, easy maintenance and low cost of deployment especially in the rural areas [4]. In order to validate the performance of WMN in urban and rural areas, an evaluation of proactive and reactive routing protocols in WMN was investigated in [3] to re-affirm its support for traffic exchange in both rural areas and urban areas. Nevertheless, the investigation did not consider a WMN for SG AMI with stringent Quality of Service (QoS) requirements. For example deploying WMN for smart metering will require multiple nodes to send different traffic types to a data collector which may affect packet delivery reliability, throughput and delay as a result of the following reasons [9]:

- Throughput for each node/meter transmitting to the data collector is limited by the channel capacity and the forwarding loads imposed by other nodes/meters.
- Shared resources in wireless network lead to serious contention problems as only one node can allow access of the wireless medium per time.
- Poor routing or path decisions as a result of routing metric being used by the routing protocol.

A lot of effort has been expended on IEEE 802.11 Medium Access Control (MAC) protocols to exploit physical layer techniques. However, in multi-hop WMN, performance also depends on the ability of the routing protocols to choose routes depending on the current network conditions. Route estimation in existing WMN are achieved through layer 3 and layer 2 properties of the network. Aside recent development in IEEE 802.11s which defines multi-hop forwarding at the link layer, most existing metric for WMN routing protocols source route decision information from layer 3. Different approaches have been developed to enhance route estimation and decision for AMI infrastructures [2] [8] [12]. This enhancement have mostly been designed to improve reliability and not necessarily the resilience of packet delivery in SG AMI. Wireless networks contain weak links and deploying the network for a complex AMI which requires high reliability, delay and throughput for packets of different sizes; there is a need to access layer 2 information for complex route calculations and better route decisions. The Dynamic Link Exchange Protocol (DLEP) developed by CISCO focuses on allowing link quality information exchange between router and connected radio devices. DLEP has been implemented on community networks and believe the implementation of DLEP on WMN for AMI will improve AMI packet delivery and throughput to a much greater extent. DLEP can be used to implement routing metric such as Extended Transmission Time (ETT) to access layer 2 information for a better performance of WMN based AMI.

In this article, an attempt is made to evaluate the performance of proactive routing protocols in WMN when deployed for AMI. The paper focuses on quantifying the packet delivery reliability, throughput and delay capabilities of IEEE 802.11s HWMP, and Optimised Link State Routing (OLSR) protocols for smart metering using simulations in NS-3 discrete network simulator. The simulation topology is made up of different grid size network with all the smart meters transmitting simultaneously to a data collector. The paper is organised as follows. Section II discusses background and related work on WMN routing protocol. Section III presents simulation results of our performance evaluation and recommendation. Finally, Section IV highlights the conclusion

II. BACKGROUND ON WMN ROUTING PROTOCOL

WMN diversify the capability of ad-hoc networks and it can be implemented using three types of architectures namely [11]: infrastructure, client and hybrid. The architectures allow nodes to communication with a gateway; in a peer to peer network among client devices; or in a hybrid of both. Realizing a seamless WMN based smart metering will necessitate new metric and design principles to enhance the capabilities of WMN. Akyildiz and Wang [11] highlighted scalability, mesh connectivity and Quality of services (QoS) as the critical design factors of WMN among which they also identified the most important and urgent ones to be scalability and security. Scalability can be achieved by developing new MAC, routing and transport protocols for WMN. Recent development in MAC protocols can only solve partial problems, new collaborative schemes between MAC protocols and routing protocols must be proposed to ensure that network performance of WMN does not degrade as the network size and traffic increases. An optimal routing protocol is expected to have multiple performance metrics, robustness and efficient routing with mesh infrastructures. In the following sub-sections, two well-known WMN routing protocols are discussed, highlighting their routing and path selection algorithms/metric.

A. Hybrid Wireless Mesh Protocol (HWMP)

HWMP protocol is a routing protocol which was specified as the routing protocol of IEEE 802.11s standard, HWMP together with the Air Link Metric (ALM) routing metric are the two path selection mechanism required to meet diverse requirements and allow efficient routing for different scenarios on the network [10]. HWMP allows On-demand routing and tree-based routing to run simultaneously. The On-demand routing protocol in HWMP is adopted for mesh nodes that experience a change in the network topology, while proactive tree-based routing protocol is an efficient choice for mesh nodes in a fixed network topology. The manner at which HWMP carries out its routing are briefly described as follows:

On demand Routing Mode

HWMP’s On-demand routing is specified based on the Ad-hoc Distance Vector (AODV) routing, it adopts its basic features but some extensions are carried out to enable it suit in IEEE 802.11s.

Proactive Routing Mode

The proactive tree-based routing of HWMP is applied when a root node is configured in the mesh network. A distance vector tree is built from the root node and maintained for other nodes to avoid unnecessary routing overhead for route path discovery and recovery. There are two mechanisms used for path selection in the proactive tree based routing mode. One is based on proactive path request PREQ and the other is based on Route announcement (RANN).

When RANN is used, the root node floods the network with RANN messages. This packet is then received and relayed by all the sub-nodes of the mesh network. When the sub-node needs to refresh a route to the root node, it sends a unicast PREQ to the root node while the root node replies with a unicast PREP on receiving the unicast PREQ. Thus the unicast PREP forms the new forward route from the sub-node to the root node. In the proactive PREQ, the root node broadcasts a proactive PREQ message periodically with an increasing sequence number. Each node may receive multiple copies of PREQ, each traversing different path from the root node to the receiving sub-node. The receiving sub-node updates its current route to the root node if the PREQ contain newer information. The new information is either a PREQ with greater sequence number, or a better metric.

Upon reception of route information from the root node, each mesh node will calculate the airtime cost metric using the formula shown below:

$$Ca = \left[O + \frac{Bt}{r}\right]\frac{1}{1-ef} \qquad (1)$$

Where O = channel access overhead, Bt = size of the transmission frame, r = data rate, and ef = error rate.

Though HWMP is considered suitable for smart grid AMI, this has resulted in many performance evaluation and modifications of HWMP. Authors in [8] highlighted route instability and the method of error rate calculation as problems which degrades performance of IEEE 802.11s network. They proposed a new error rate method which considers the MAC retransmission count of each packet as the value for calculating failure rate of the network. The route selection module was also modified to store multiple route paths in the routing table. A decentralized proactive root based routing for HWMP (DHWMP) was proposed in [12] to solve the difficulties of HWMP reactive mode routing. Similarly, in [2], the broadcasting of ARP was eliminated by extending the structure of the proactive PREQ of HWMP to address a dynamic MAC address mapping to ensure every node send its data to the root node neglecting any delay caused by ARP requests.

B. *Optimised Link State Routing protocol*

OLSR is an optimisation of the standard link state routing algorithm for mobile ad hoc networks (MANETS) and it can also be used for other wireless ad hoc and mesh networks. The key concept in OLSR protocol is the use of selected nodes known as Multi Point Relays (MPR) which reduces message and routing overheads caused by the flooding of broadcast and control messages in the network. The first draft of OLSR was documented in [5] (RFC 3626) as OLSR version 1 (OLSRv1) and an updated version has been documented in (RFC 7181) [6].

1. OLSR Version 1 (INRIA)

OLSRV1 was developed by the French National Institute for Research in Computer Science and Control (INRIA) and operates in a proactive manner by building tables from topology information exchanged between nodes periodically [5] (RFC 3626). OLSR optimisation is achieved in 3 stages. First, it selects neighbour nodes as MPR which are responsible for sending link state information, and also minimise the number of control traffic when flooding topology information. MPR's may choose to distribute partial link state information by reporting links between itself and its MPR selector. OLSRv1 relies on the optimised state information for route calculation (number of hops) to a destination which makes it well-matched for small and large networks. It comprises four types of periodic control messages namely: Hello message; Topology Control (TC) messages; Host and Network Association (HNA) messages; and Multiple Interface Declaration (MID) messages.

2. OLSR Version 2 (NIIGATA)

OLSRV2 is an updated version of OLSRv1 it retains the same mechanism and algorithm of OLSRv1. Updated attributes of OLSRv2 include four other protocols and specifications which allow it to: 1) extend addresses (i.e. accommodates both IPv4 and IPv6 addresses), 2) enhance the information base, 3) extend its signaling and 4) create better routes through the use of link metric instead of hop counts only as in OLSRv1. Metric-based routing supported by OLSRv2 allows each link to choose a link metric. OLSRv2 define the link metrics as additive, and the routes that are to be created are those with the minimum sum of the link metrics along that route. Link metrics are directional; the link metric from one router to another may be different from that on the reverse link and they are usually assessed at the receiver, same as on a wireless link that is the better informed as to link information. OLSRv2 makes use of its link layer information and notification when available and applicable [6] and information is sent using two types of control packets: Hello messages; T C messages (Topology Control messages)

The performance evaluation of OLSRv1 and OLSRv2 using the Qualnet 6.1 simulator with 100 nodes scenario was carried out in [7]. Results from comparing their performances shows that average end to end delay and jitter for OLSRv2 are much smaller than that of OLSRv1. Also, OLSRv2 showed lesser power consumption than OLSRv1 when implemented in the same charge scenario. In addition, it was observed that the packet delivery ration for OLSRv1 is over 10% higher than that of OLSRv2 when deployed in the same scenario. OLSRV1 was used for our simulation.

There hasn't been much work on carried out on the modification of OLSR for AMI applications. The possibility of introducing different routing metric for route selection in OLSR makes it suitable for AMI applications. Currently static route metric (hop count) and the extended transmission count (ETX) metric has been implemented in OLSR. ETX estimates the number of transmissions required to successfully send a packet over a link until an acknowledgement is received. However, IEEE 802.11 broadcast frames are sent at the network basic physical rate. These probes are usually smaller than data packets. Thus, ETX does not distinguish links with different capacities, and the loss probability of small probes differs from the loss probability of data packets [13]. The expected transmission time (ETT) metric is a progression of ETX, it combines loss rate of a link with the transmission rate (estimates the time a data packet needs to be successfully transmitted on a link). This leads to a reduced usage of the available electromagnetic spectrum, therefore, increasing the capacity of the whole network. Studies in [12] have shown that ETT out performs other metrics used in OLSR. However, calculating ETT on OLSR without access to the link layer is challenging.

III. PERFORMANCE EVALUATION

HWMP and OLSR model have been implemented in NS-3, our topology and evaluation of these protocols for AMI attempts to replicate a real AMI scenario. In this section the NS-3 environmental parameters and mesh topology used for the simulation of HWMP and OLSR protocol for AMI is presented. The environmental parameters and mesh topology were set for both protocols to allow a fair comparison. Results of the performance of these protocols for different grid sizes where also presented using some evaluation parameters.

A. *Simulation Setup*

While setting up the simulation for WMN based AMI in NS-3 network simulator, flow monitor module was used to collect a set of performance metric to enable the calculation of some parameters that will be used for performance evaluation. A grid topology was used because it is a common topology for mesh network and it can be used to represent distribution of houses in an urban area. Also, the grid topology is more reliable when extracting and comparing results than the randomly distributed nodes in WMN. The NS-3 YansWifi channel model was used with the Log distance path loss model, which assumes an exponential path loss over the distance from sender to receiver. It is designed for buildings, densely populated areas or suburban scenarios. Other parameters used for the simulation are presented in table 1.

A network of N x N mesh network with 802.11g configured on each node/smart meter was considered to represent the AMI network in a SG Neighbor Area Network (NAN). One of the nodes on the grid network act as the data collector, while an N x N -1 nodes act as smart meters sending data to the data collector. All smart meters on the network sends AMI data as a periodic Constant Bit Rate (CBR) message (i.e power report, billing information) every 15 seconds as shown in [8]. The smart meters transmission range was set to 120m and the nodes were placed at a distance of 100 meters apart from each other, this allows each meter to have a minimum of 2 and maximum of 4 neighbors. The smart meters were arranged as shown in figure 2, while the grid size was varied from 2 x 2 (4 nodes) grid size to 10 x 10 (100 nodes) grid size. The data collectors were situated at the last node, for example, in Fig. 1, the data collector was located at Mesh STA 9. All nodes were configured with a single interface and the simulation was run for simulation time equivalent of 1 day (86400 seconds) to give a practical representation of an AMI event for a day.

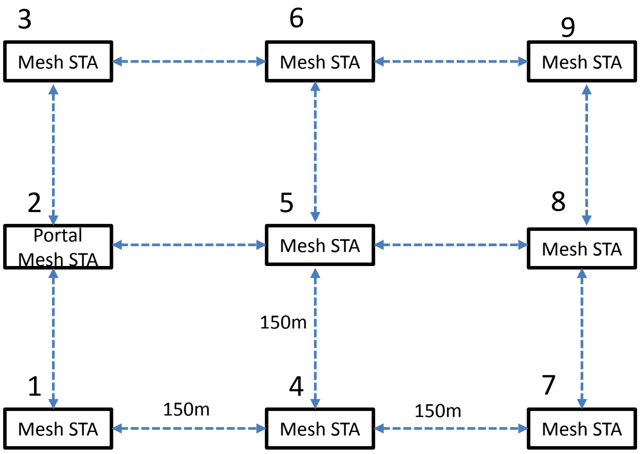

Fig. 1: A 9x9 grid mesh network for AMI

B. *Performance metric and Results*

Three performance metric that were used to assess the performance of HWMP and OLSRv1 in the network derived as follows: (1) Average end to end delay: The sum of the delay of all received packets at the destination divided by the number of received packets; (2) Average Packet Delivery Fraction (PDF): number of received packets at the destination divided by the number of transmitted packets; and (3) Throughput: total number of received bits at the destination for each grid size.

In evaluating the performance metric in an AMI scenario, we measured the delay, PDF and throughput of all nodes to the destination in other to get a better understanding of the performance of all the smart meters in the network.

Table 1: Transmission environment parameters

Path loss type	Log distance path loss
Reference distance	1 m
Exponent	2.7
Reference Loss	46.7 dB
CCA Threshold	-62
Energy detection Threshold	-89 dBm
Tx and Rx Gain	1 dB
Min and Max Tx level	18 dBm
Reception noise Figure	7 dBm

Findings from the metric evaluation is essential in understanding the support and performance of HWMP and OLSR in applications that are delay critical or require a high reliability. The results are presented from Fig. 2 to Fig. 5.

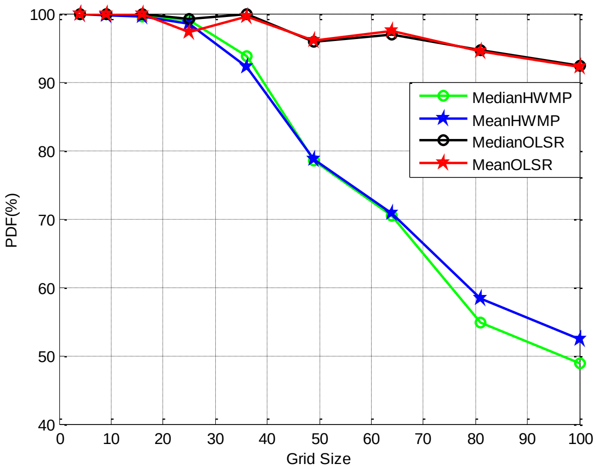

Fig. 2, Median and Mean PDF values of all nodes transmitting to a data concentrator for varying grid sizes using HWMP and OLSR routing protocol.

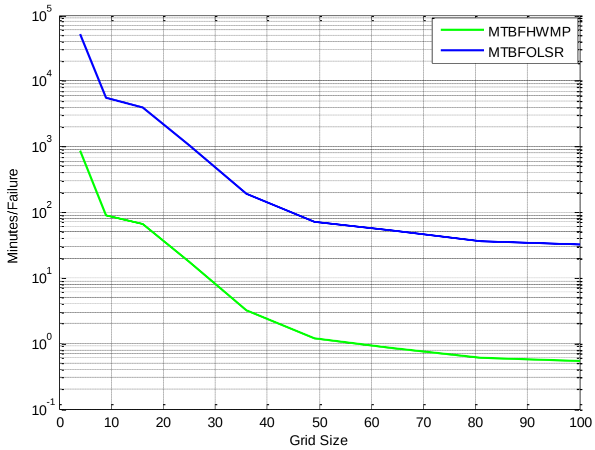

Fig. 3, Mean Time Between Failure (MTBF) on OLSR and HWMP for different grid sizes.

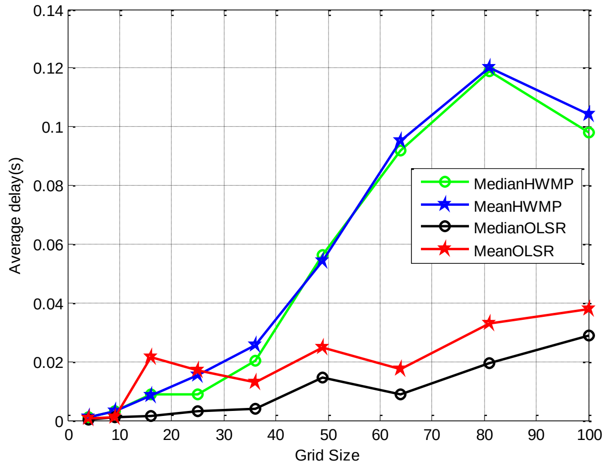

Fig. 4, Median and Mean delay values of all nodes transmitting to a data concentrator in varying grid size network using HWMP and OLSR protocol.

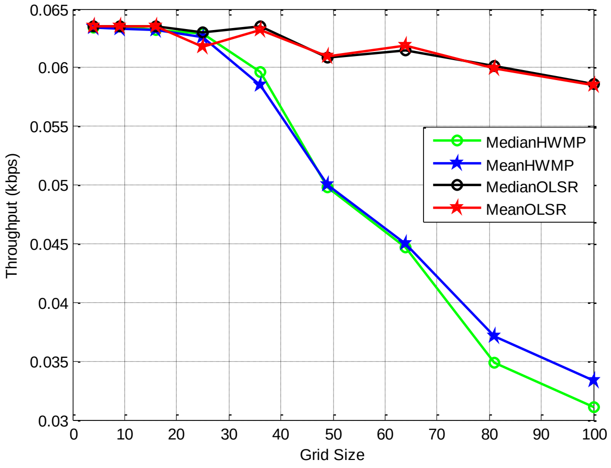

Fig. 5, Median and Mean throughput values of all nodes transmitting to a data concentrator in varying grid size network using HWMP and OLSR routing protocol.

Figure 2 depicts average PDF and the median PDF for all nodes transmitting to the data concentrator in a 2x2 to 10x10 grid size AMI network. This was presented to show the performance of all transmitting nodes in the grid network. From Fig. 2, it is observed that PDF for HWMP degrades much more rapidly than OLSR as the size of the grid increases. The PDF is for only 123 bytes of AMI data sent every 15 s to the data concentrator from each node. PDF on each node for both protocols could degrade more rapidly if the packet size or data sent from each node is larger as expected in a real smart meter scenario.

A decline in PDF can also lead to poor estimation of energy usage for demand side management applications. We considered each packet drop to represent a failure and estimated the Mean Time Between Failures (MTBF) on both protocols for each grid network size. Fig. 3 shows the failures per minute for each grid size. MTBF was calculated using the average PDF, however, some nodes in the network can experience failures/packet drops at lower time.

The median and average end to end delay to the destination for each grid size are also presented in Fig. 4. Both OLSR and HWMP routing protocol delays fall within 120 milliseconds. Throughput for all the grid sizes in Fig. 5 also shows a decline as the network size increases.

C. *Discussion and Recommendation*

The performance metric figures show that the decline ratio of HWMP is steeper decline than that of OLSR; nonetheless, performance of both protocol does not cut the mustard for SG AMI, especially when it is considered that only a low data application (AMI data of 123 bytes) was transmitted every 15 seconds. Hemce, the need to for enhancement of this protocols to meet the packet delivery reliability and resilience for SG application. In section II, we highlighted HWMP's route fluctuation and error rate calculation problems which causes packets to be transmitted through links with higher cost and dropped packets. Likewise, we stated the need for better route metric implementation in OLSR and highlighted the inability to access layer 2 information as a problem for implementing routing metric like ETT. Recent modification of HWMP and OLSR routing algorithms may improve performance but will not necessarily meet SG application requirements.

A solution for better access to the link layer information can be achieved by using DLEP. DLEP can communicate link characteristics to the routing protocols as they change. Implementing DLEP to support routing protocol decision making include identifying the link characteristic that can be measured at the MAC layer. DLEP plugins allow a user to mirror a layer 2 database from one application to another in order to enable optimal route selection, flow controlled communication and dynamic shaping of RF bandwidth in near real time to provide optimal use of actual bandwidth.

IV. CONCLUSION

In this paper, we presented an overview of two routing protocols (HWMP and OLSR) for an AMI based IEEE 802.11 WMN. We highlighted their limitations and carried out a performance evaluation for both protocols in a WMN based AMI using the NS-3 discrete network simulator. Simulation results showed that both protocols do not meet the reliability requirements SG AMI. The need for both protocol to use more layer 2 information for routing decision was emphasized. We recommended the implementation of Dynamic Link Exchange Protocol (DLEP) for layer-2 information exchange between a MAC layer and the upper layers. In the context of an AMI network node, DLEP will allow for an improved, more robust and scalable AMI WMN node with complex routing metrics that will improve resilience and reliability.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the ERDF through the Centre for Global Eco-Innovation, Lancaster University, UK.

REFERENCES

[1] J. C. Gao, Y. Xiao, J. Liu, W. Liang, and C. L. P. Chen, "A survey of communication/ networking in Smart Grids," Futur. Gener. Comp. Syst., vol. 28, pp. 391-404, 2012.

[2] N. Saputro and K. Akkaya, "An efficient ARP for large- scale IEEE 802.11s- based Smart Grid networks," ed, 2013, pp. 723-726.

[3] A. Zakaria, H. Mohamad, N. Ramli, and M. Ismail, "Performance evaluation of routing protocols in wireless mesh network," ed. <city/>, <country/>, 2013, pp. 1111-1115.

[4] A. Quadri, K. M. Hasan, M. Farhan, E. A. Ali, and A. Ahmed, "Next generation communication technologies: Wireless mesh network for rural connectivity," ed. <city/>, <country/>, 2011, pp. 1019-1023.

[5] T. Clausen, P. Jaqcquet, "Optimized link state routing (OLSR) RFC 3626," ed: .IETF Networking Group (October 2003) (2003).

[6] T. Clausen, C. Dearlove, and P. Jacquet, "Optimized Link State Routing Protocol (OLSR) Version 2," ed: Internet Engineering Task Force (IETF) Request for Comments: 7181. Category: Standards Track. ISSN: 2070-1721, April 2014.

[7] V. Dahiya, R. Sangwan, M. Duhan, and K. Dalal, "OLSRv2 Implementation and Performance Evaluation over OLSRv1 in MANET using Qualnet 6.1," International Journal on Scientific & Engineering Research, vol. 4, July 2013.

[8] J.-s. Jung, K.-W. Lim, J.-B. Kim, and Y.-B. Ko, "Improving IEEE 802.11s Wireless Mesh Networks for Reliable Routing in Smart Grid Infrastructure."

[9] M. Abolhassan, J. C. B. Wang, D. R. Franklin “On Indoor Multi-hopping capacity of Wireless Ad-Hoc Mesh Networks” IEEE International Conference on Mobile Adhoc and Sensor Systems. October 2007. 1-4244-1455-5/07/$25.00 c 2007 IEE

[10] M. E. Morote, “IEEE 802.11s Mesh Networking Evaluation under NS-3” Projecte Final de Carrera, April 2011.

[11] I. F. Akyildiz, X. Wang “A Survey on Wireless Mesh Networks” IEEE Radio Communications • September 2005.

[12] M. Singh, S. Lee, H. Lee, “Non-root based Hybrid Wireless Mesh Protocol for Wireless Mesh Networks”. International Journal of Smart Home Vol.7.No.2, March. 2013.

[13] M. E. M. Campista, P. M. Esposito, et al, “Routing Metric and protocols for Wireless Mesh Networks. IEEE networks. January/February 2008.

[14] K.M. Abdel-Latif, M.M. Eissa, A. S. Ali, O. P. Malik, and M. E.Masoud. "Laboratory investigation of using Wi-Fi protocol fortransmission line differential protection." Power Delivery, IEEETransactions on 24, No. 3 2009, pp. 1087-1094.

[15] D. Popa, M. Gillmore, L. Toutain, J. Hui, R. Ruben, and K. Monden 2014, Oct, 27) “Applicability Statement for the Routing Protocol for Low Power and Lossy Network (RPL) in AMI”