Performance Analysis of Variable Smart grid traffic over ad hoc Wireless Mesh Networks

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***Abstract*—Recent advances in ad hoc Wireless Mesh Networks (WMN) has posited it as a strong candidate in Smart Grid's Neighbourhood Area Network (NAN) for Advanced Metering Infrastructure (AMI). However, its abysmal capacity and poor multi-hoping performance in harsh dynamic environment will require an improvement to its protocol stacks in order for it to effectively support the variable requirements of application traffic in Smart Grid. This paper presents a classification of Smart Grid traffics and examines the performance of HWMP (which is the default routing protocol of the IEEE 802.11s standard) with the Optimised Link State Routing (OLSR) protocol in a NAN based ad hoc WMN. Results from simulations in ns-3 show that HWMP does not outperform OLSR. This indicates that cross layer modifications can be developed in OLSR protocol to address the routing challenges in a NAN based ad hoc WMN.**

Keywords— HWMP; OLSR; Routing protocol; Traffic Classification; Smart grid; QoS requirement; NAN.

I. INTRODUCTION

The new and advanced power grid, (also known as Smart Grid), will extend monitoring and control on the electrical grid by allowing a bi-directional flow of information and electricity across the electrical grid network [1]. Amongst several available communication technologies, the ad hoc Wireless Mesh Network (WMN) has been acknowledged as a communication technology well suited to the requirements of Smart grid's Neighbourhood Area Networks (NAN). This is due to its extended coverage (through its multi-hopping capabilities), low latency, high throughput and Quality of Service (QoS) functionalities, which can enable data transportation hop-by-hop from the traffic sources (i.e., Smart meter on each household) to the backhaul distribution. However, it is important to highlight that WMN technologies were only developed to support multimedia applications such as voice, video, web browsing and node mobility. In contrast, Smart Grid's application performance requirements are quite different; they have strict transport and QoS requirements in terms of latency, data rate and packet delivery such that it will allow high reliability of critical functions (up to 99.9999 % reliability which correspond to total outage period shorter that one second per year) [2] [3]. Hence the need to undertake a detailed performance analysis in order to investigate whether a conventional ad hoc WMN is able to meet these requirements when deployed in Smart Grid NAN. This will provide a good understanding of the development areas in the design of an efficient and reliable NAN based ad hoc WMN for AMI.

Performance of multi-hop ad hoc WMN is hinged on the ability of the routing protocols choosing reliable paths to a destination. Normally, paths are selected through the link metrics used by the routing protocols to estimates the current network conditions on each path. For this reason, a number of reliable routing protocols such as: i) Routing Protocol for Low Power and Lossy Networks (RPL) by Winter et al [4], ii) Geographic routing, ii) Dynamic Source Routing (DSR) protocol, and the Hybrid Wireless Mesh Protocol (HWMP); have been classified for routing in NAN domain [5]. Nonetheless, modifications of these protocols and other routing protocols are still being carried out to suit Smart Grid's application traffic characteristics. For example, performance evaluation and reliability improvement of HWMP (IEEE 802.11s standard) was carried out for Smart grid in [6] and [7] which resolves the original problems of HWMP. Given that HWMP works at the MAC layer, it is worth exploring and modifying other protocols that work at the network layer. This is to enable the design of network layer and routing protocols for smart meters with a network management perspective.

The Optimised Link State Routing protocol (OLSR) is an established proactive routing protocol that works at the Network layer. It mostly uses the Extended Transmission Count (ETX) as its link metric and has been implemented on several devices despite it deficiencies in certain areas. In order to carry out modifications on OLSR for Smart grid data characteristics, a performance analysis of the IEEE 802.11s standard protocol (HWMP) and OLSR models on ns-3 network simulator is carried out in a NAN based ad hoc WMN for Advanced Metering Infrastructure (AMI). The key contributions of this paper is to classify AMI application traffic based on delay and reliability requirements as well as evaluate the performance of each of the traffic class on a NAN based ad hoc WMN using HWMP and OLSR protocols. The paper is organized as follows: Section II presents AMI traffic classification based on delay and reliability requirements. Section III discusses the background of the routing protocols. Simulation and performance evaluation of each traffic class is presented in section IV, while section V highlights the conclusion.

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II. CLASSIFICATION OF SMART GRID APPLICATION TRAFFIC

This section explores common traffic scenarios for AMI applications and categorises them in to four application classes. This is because it is important to study the traffic supported by routing protocols, which can be periodic, real-time or near real-time with strict reliability and low latency. Reliability and low latency requirement can be a challenging feat for ad hoc WMN, especially, when it is required for variability of application traffics. In this section, a classification of AMI traffics in terms of packet delivery reliability and delay requirements across a network are presented.

A. *Traffic classification based on network driven requirements*

AMI application traffics can be characterized in terms of data or network driven performance needs [8]. The packet delivery performance in time and reliability domain used for classification of Wireless Sensor Network (WSN) application in [8] is adopted in this paper to classify Smart Grid AMI traffic. Performance in time domain (delay sensitive) relates to the time taken for data to be received at the destination and reliability domain (loss sensitive) relates to how much data is received at the destination. Latency requirement of a traffic type such as delay is used to measure time domain performance, while reliability domain performance is dependent on how much data is required to be delivered. The traffic classification are presented as follows:

- Delay-tolerant, Loss-tolerant Class. The AMI application traffic categorised in this class are those that are not affected by high traffic delay and losses. An example of these application types are best effort traffic types such as periodic AMI data from Home Area Network (HAN) devices, which are used to monitor or estimate electricity usage in a household (sent every 15 seconds and require a latency less than 3 seconds) [9] [10]. These applications can still function as desired even if data losses are incurred and/or data delivery time or latency is prolonged.
- Delay-tolerant, Loss-intolerant Class. The AMI applications in this class are those that must be delivered at the destination but can tolerate delays in delivering data [8]. Example of this application is the Power quality data (sent every 3 seconds and has a latency of less than 3 seconds). Power quality information must be accurate for better load estimation and determining the fitness of power to consumer devices within seconds. High reliability at the expense of delay must support by the communication network.
- Delay-sensitive, Loss-tolerant Class. Most SG traffic require very high reliability, a certain amount of loss rates may be acceptable in this class but data must arrive in a timely manner (little percentage of Losses tolerable) [11]. Examples of applications in this class are Mobile Work Force tracking traffic, video surveillance and software updates. Support for delay is critical on this traffic.
- Delay-sensitive, Loss-intolerant Class. The application traffic in this class demand strict time and reliability performance. Example of applications in this class include Real Time Pricing (RTP), EV charging traffic, Distribution Automation (DA), and Wide Area Measurement (WAM) which involve monitoring the distribution line and transformers. This can also apply to event-triggered information reporting an incident (fault) and/or information from an actuator to carry out a particular task.

B. *Traffic profile for simulation*

The application traffic type in each class is modeled using their expected packet sizes and delay objectives in User Datagram Protocol (UDP) traffic profiles. Four different traffic profiles sending variable packet sizes within short intervals over several hops to the data concentrator as shown in Table 1 are used to represent each traffic class presented in the previous sub-section. They include: 1) billing/AMI data information sent every 15 seconds represents Delay-tolerant, Loss tolerant class; 2) power quality measurement sent every 0.5 seconds represent the Delay-Tolerant, Loss-intolerant class; 3) Software update sent every one second represents Delay-sensitive, Loss-tolerant class; and 4) WAM data sent every 0.1 second represents Delay-sensitive, Loss-intolerant class.

TABLE 1. TRAFFIC CHARACTERISTICS

Traffic Characteristics	**Priority**	**Example**
Delay Tolerant Loss Tolerant	4	UDP IPv4 CBR 123 bytes/15s
Delay Tolerant Loss Intolerant	3	UDP IPv4 CBR 3000 bytes/3s
Delay Sensitive Loss Tolerant	2	UDP IPv4 CBR 1024 bytes/1s
Delay Sensitive Loss Intolerant	1	UDP IPv4 CBR 48 bytes/0.1s

III. BACKGROUND ON OLSR AND HWMP

The category of routing protocols which require nodes maintaining tables that represent the entire network (proactive) are known to perform best in static networks. Therefore, proactive protocols have been mostly proposed for routing in NAN based WMN since smart meter networks are static nodes. Performance evaluations of a number of routing protocols have been carried out in NAN for AMI. The focus in this paper is HWMP and OLSR, which work at the MAC layer and Network layer respectively. Both protocols are discussed in the following sub-sections:

A. *Hybrid Wireless Mesh Protocol (HWMP)*

The HWMP is the multihop default routing protocol for IEEE 802.11s WLAN mesh networking. It was developed for the purpose of allowing interoperability between devices from different vendors; HWMP serves as a common path selection protocol for every device that is compliant of IEEE 802.11s standard. It uses the Air Link Metric (ALM) routing metric for path selection to enable efficient routing in a dynamic network environment [12]. The term hybrid is due to the fact that HWMP allows On-demand (reactive) routing and tree-based (proactive) routing to run simultaneously. In proactive tree-based routing, 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 path discovery and recovery. In HWMP, when a node needs a path to a given destination, it broadcasts a route request message requesting a route to that destination. The route request message is processed and forwarded by all mesh points to the originator of the route discovery. The destination node, or an intermediate node that owns a path to the destination, answers with a unicast reply message indicating the route requested. On receiving this information, the forward path to the destination from each mesh node is set up using the airtime cost metric expressed in the equation below [7].

$$Ca = \left[Oc + Op + \frac{Bt}{r} \right] \frac{1}{1 - ef} \quad (1)$$

Where, Oc = channel access overhead, Op = MAC protocol overhead Bt = size of the transmission frame, r = data rate, and ef = error rate.

Due to the requirements of variable application traffic, a number of improvements and modification have been carried out in HWMP to support these applications in Smart Grid[6, 13]. They include: i) modifying the route selection mechanism to reduce route fluctuations, ii) local route recovery mechanism by using alternative routes, iii) calculation method of the air cost metric that considers Smart grid's data characteristics, and iv) a mechanism to tackle the ARP broadcast storm problem in 802.11s-based NANs by piggybacking the MAC address resolution in the proactive rote request of HWMP. However, performance evaluation was carried out on the conventional HWMP.

B. *Optimised Link State Routing protocol*

OLSR is an upgrade 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. There are several documentation on OLSR protocol functions and operation which can be found in [14] [15]. OLSR protocol is also metric based routing that allows the calculation of link quality by different link metrics. Several proposed link metrics and cross layer metrics to improve routing and capture the best paths in other to increase the performance of WMN have been integrated with OLSR.

Performance evaluation was carried out on OLSR because it is a well-known routing protocol for WMN that have been implemented on several network simulation tools and Commercial off the shelf Terminal (CoT) devices. This will enable more research through experimental setup of NAN scenarios as well as allow the integration and implementation of modifications to suit application traffic on real test bed for Smart Grid. The work carried out in this paper, considers different load and flow rates for AMI application traffic through simulation and examine the performance of the two routing protocols.

IV. SIMULATION AND PERFROMANCE EVALUATION

The environmental parameters and mesh topology were set for both protocols to allow a fair comparison. Each of the application traffics specified in Table 2 were transmitted over the network and results of the performance of both protocols for varying grid sizes of NAN based ad hoc WMN are also presented.

A. *Simulation Setup*

The experimental set up used in this study is similar to the set up used in [16]. The simulation was carried out in ns-3 and all the evaluation parameters were extracted using the flow monitor module. A summary of the simulation parameters is presented in Table 2. The choice of employing the transport control protocol (TCP) or UDP is a trade-off between efficiency (throughput and delay) and delivery guarantees with flow control. Therefore, given that the transmission of metering information is characterized by short transaction that do not require persistent connection between the Smart meter nodes and the data concentrator, it is more suitable to use UDP.

All smart meters on the network simultaneously transmit their AMI information as a UDP Constant Bit Rate (CBR) message to the data concentrator. The NAN topology is shown in Fig. 1 and each of the application traffic profiles presented in Table 1 were transmitted from all smart meter nodes to the data concentrator. The grid size was varied from 4-by-4 (16 nodes) to 11-by-11 (121 nodes) grid sizes. The smart meter nodes were also configured with a single interface and the simulation time equivalent of 1 day (86400 seconds) was used for each grid size to give a representation of an AMI event for a day.

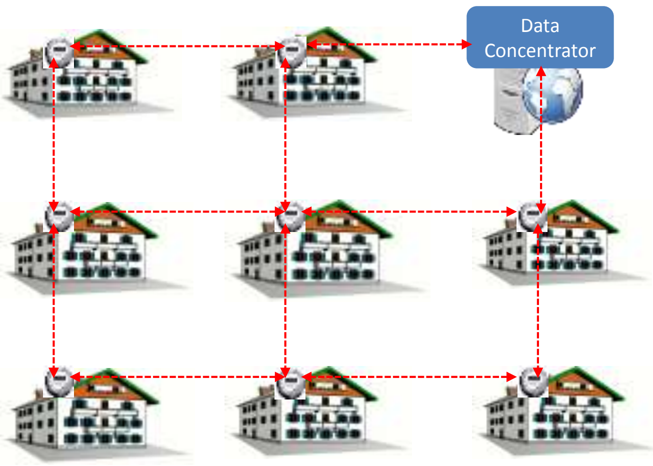


Fig. 1. A 3 by 3 NAN based ad hoc Wireless Mesh Network

B. *Performance metric*

The metric that were used to assess the performance of HWMP and OLSR in the network are:

1) Average end-to-end (ETE) delay: These metric indicates the average ETE delay of each packet that is successfully delivered to the data concentrator from a smart meter.

$$ETE_{ave} = \frac{D}{R_x} \qquad (2)$$

2) Average Packet Delivery Ratio (PDR): percentage of the average ratio of successfully received packets at the data collector to the number of transmitted packets.

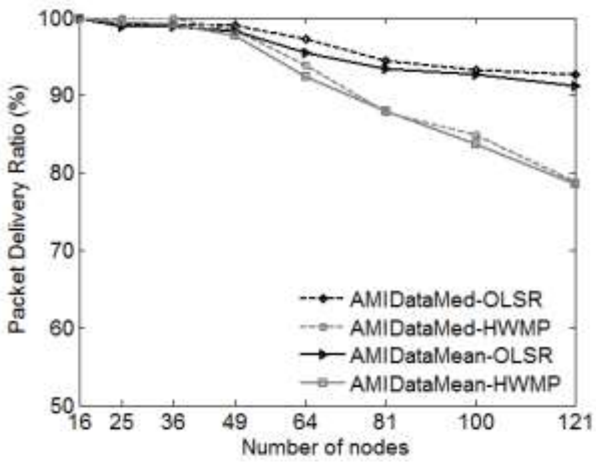
$$PDR_{ave} = \frac{R_x}{T_x} \qquad (3)$$

TABLE 2. NODE AND ROUTING PROTOCOL PARAMETERS

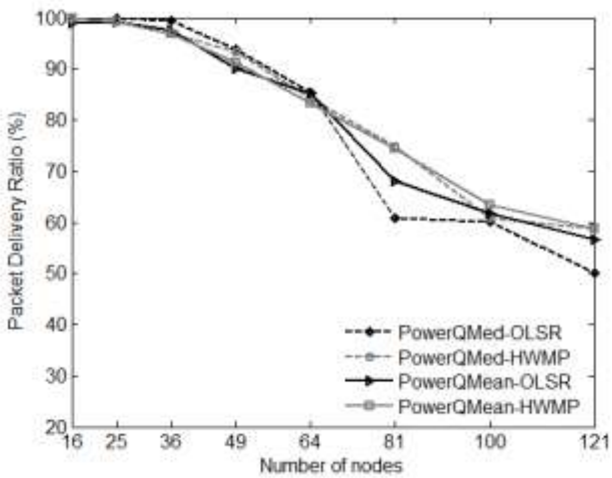
Parameters	**HWMP**	**OLSR**
Route metric	Air Link Metric (ALM)	Hop count/ETX
Simulation time (s)	86400	86400
Tx Range (meters)	120	120
Distance btw nodes (m)	100	100
Exponent	2.7	2.7

C. Results & Discussion

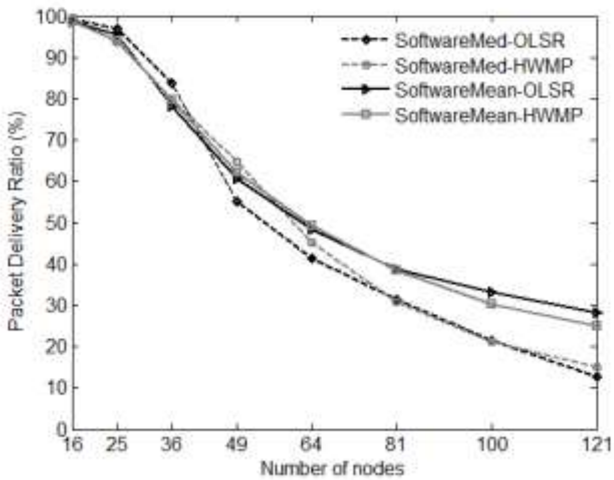
Fig. 2 depicts the mean and median PDR for smart meters transmitting to a data concentrator for varying grid size of 16 to 121 nodes. The degradation in PDR as the grid network size scales is as a result of increased interference, packet drops and number of hops traversed by the packet. Fig. 2a to 2d also show PDR performance of OLSR and HWMP for four different SG applications traffic profile. From PDR results in Fig. 2a, it is observed that after showing a higher PDR from 16 to 49 grid size, average PDR for HWMP degrades much more rapidly than OLSR as the size of the grid increases for the AMI data traffic profile. The steepness in the degradation of HWMP can also be attributed to the large overheads generated by HWMP as well as the PREQ travel distance from the data concentrator (root node) as the network scales. This demonstrates a clear indication of the advantage of OLSR's MPR in achieving better reliability across larger multi-hop network [17] [18]. Fig. 2b, 2c, 2d, represent the PDR's of power quality measurement, software update and WAM applications traffic profiles respectively. These applications they have less transmission interval (higher packet generation rate) between packets and the margin in PDR degradation between the two protocols is narrowed down. Reliability in WMN is impacted by both MAC layer factors and non-MAC layer factors such as packet generation rate, packet sizes, hop counts, traffic load and number of flows.



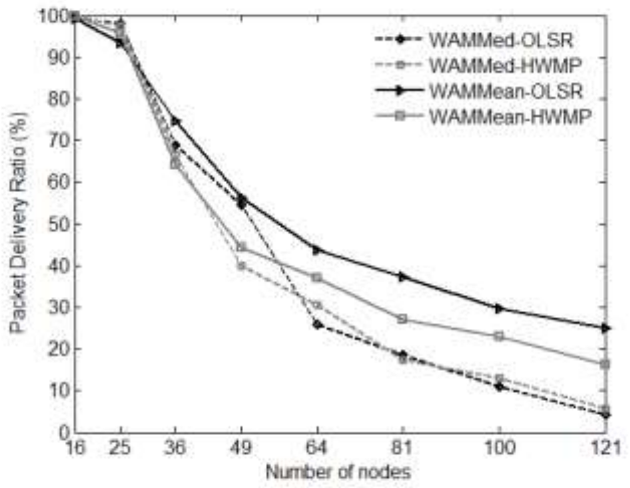
a) PDR for AMI data traffic



b) PDR for power quality measurement traffic.



c) PDR for Software updates traffic



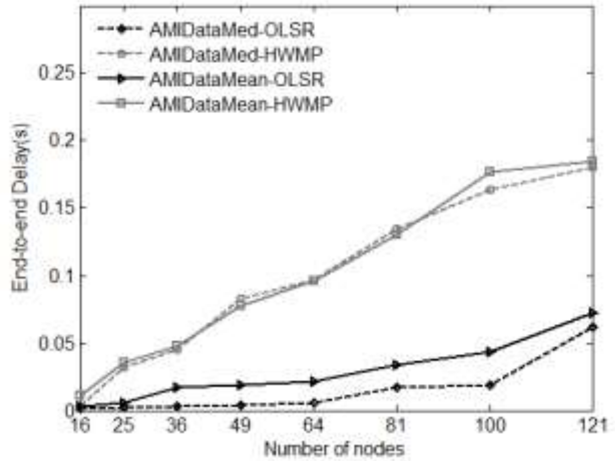
d) PDR for WAM traffic

Fig. 2. Mean and median PDR for AMI applications on varying grid sizes using OLSR and HWMP

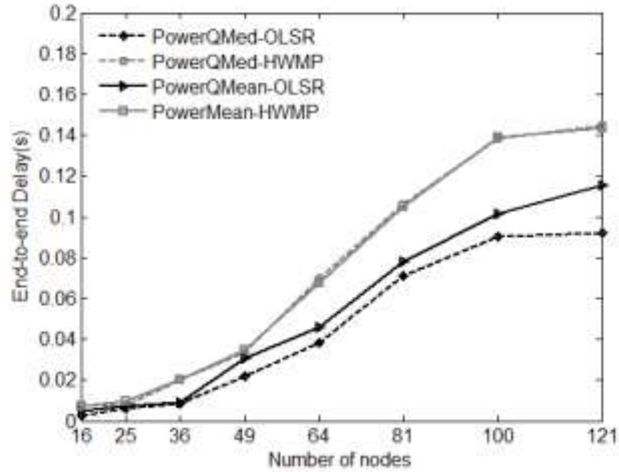
A high packet generation rate results in higher collision probability and dropped packets in the network. This is evident in Fig. 2d, where WAM application with a packet size of 48 bytes, generating packets at (26pkts/sec) has a lower average PDR at 36 grid size on both protocols than software update application which has a packet size of 1024 bytes packets. Though a difference of 10% loss rate between WAM applications and software update is observed in average PDR at a grid size of 36, the difference reduces as the grid size increases. It can be concluded that high packet generation levels have a high impact on packet losses for small packet sizes than a large packet size with less transmission rates. It was also observed that the PDR of nodes further away from the destination recorded higher packet losses than nodes closer to the receiver, which is as a result of packet drop at the intermediate nodes and the increased interference that causes packet losses at the medium as packets multi-hop through the network. PDR results in Fig. 2b and Fig 3b are similar to that of HWMP Grid results obtained in [7], which used a similar traffic profile as the power quality measurement data.

The median and average ETE delay of all smart meters transmitting to the data concentrator for varying grid sizes are presented in Fig. 3. It is observed that the ETE delay of OLSR is consistently lower than HWMP for AMI data, power quality and software update traffic. This is not the case for the WAM traffic, which has a high packet generation rate. Results for WAM application also indicate higher ETE delay on both protocols.

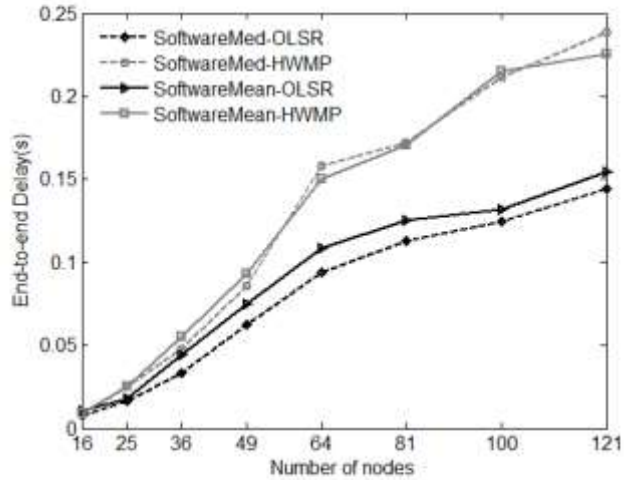
Performances of both protocols are acceptable for NAN in a small grid sized network. However, modifications of the protocols will be required to enable better performance in large grid sized network. OLSR has been known to perform better in large networks as a result of the use of MPR nodes. Hence, network layer management and cross layer solutions can also be explored in OLSR to improve performance in larger grid sized networks and also tackle the multiple challenges of smart grid application traffic.



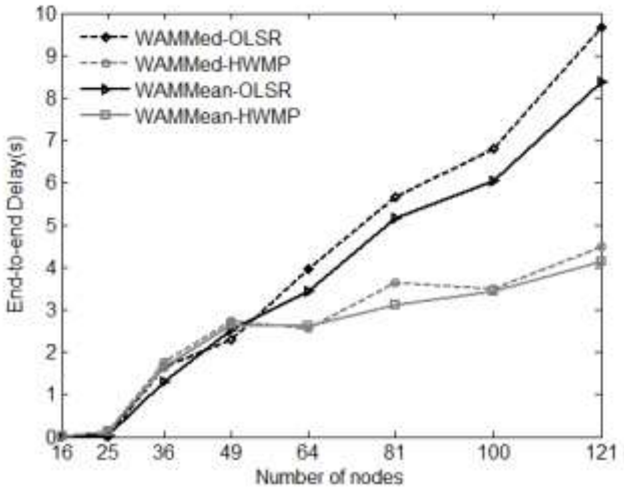
a) ETE delay for AMI data traffic



b) ETE delay for power quality measurement traffic



c) ETE delay for Software updates traffic



d) ETE delay for WAM traffic

Fig. 3. Mean and median ETE delay for AMI application traffic on varying grid sizes using OLSR and HWMP.

This modifications include: cross layer QoS routing and resource reservation techniques; that can guarantee reliability of packets by leveraging the characteristics of delay and loss tolerant application traffics to guarantee the delivery of critical application packet.

V. Conclusion

In this paper, the classification of AMI traffic according to their variable network requirements was presented. Following the traffic classification, a performance evaluation of two routing protocols (HWMP and OLSR) is carried out in ns-3 for a grid topology NAN based ad hoc WMN. The performance of each traffic class was carried out for varying WMN grid sizes. Based on the topology and parameters used in the simulation, results show that the performance of OLSR protocol is the same or, in some cases, marginally out performs the IEEE 802.11s standard default protocol. Thus, OLSR protocol can be used to explore cross layer network management options and QoS routing in NAN for AMI applications.

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