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Improving the Reliability of Optimised Link State Routing Protocol in Smart Grid's Neighbour Area Network

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Centre for Global Eco-Innovation

Declaration

I, Yakubu Tsado, hereby declare that this thesis has been written by me and contains extracts from several published papers/articles, which I am a joint author. The work presented in this thesis was carried out at the University of Lancaster between October 2012 and October 2016 and has not been submitted in any previous application for a higher degree.

Yakubu Tsado

Dates ………………………………..

Signature of candidate ………………………..

I, Doctor Kelum Asanga Akurugoda Gamage, hereby certify that the candidate has fulfilled the conditions of the resolution and regulations appropriate for the degree of Doctor of Philosophy in the University of Lancaster and that the candidate is qualified to submit this thesis in application for that degree.

Signed …………………………………………………………

Date ………………………………………………………………

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Abstract

A reliable and resilient communication infrastructure that can cope with variable application traffic types and delay objectives is one of the prerequisites that differentiates a Smart Grid from the conventional electrical grid. However, the legacy communication infrastructure in the existing electrical grid is insufficient, if not incapable of satisfying the diverse communication requirements of the Smart Grid. The IEEE 802.11 ad hoc Wireless Mesh Network (WMN) is re-emerging as one of the communication networks that can significantly extend the reach of Smart Grid to backend devices through the Advanced Metering Infrastructure (AMI). However, the unique characteristics of AMI application traffic in the Smart Grid poses some interesting challenges to conventional communication networks including the ad hoc WMN. Hence, there is a need to modify the conventional ad hoc WMN, to address the uncertainties that may exist in its applicability in a Smart Grid environment.

This research carries out an in-depth study of the communication of Smart Grid application traffic types over ad hoc WMN deployed in the Neighbour Area Network (NAN). It begins by conducting a critical review of the application characteristics and traffic requirements of several Smart Grid applications and highlighting some key challenges. Based on the reviews, and assuming that the application traffic types use the internet protocol (IP) as a transport protocol, a number of Smart Grid application traffic profiles were developed. Through experimental and simulation studies, a performance evaluation of an ad hoc WMN using the Optimised Link State Routing (OLSR) routing protocol was carried out. This highlighted some capacity and reliability issues that routing AMI application traffic may face within a conventional ad hoc WMN in a Smart Grid NAN.

Given the fact that conventional routing solutions do not consider the traffic requirements when making routing decisions, another key observation is the inability of link metrics in routing protocols to select good quality links across multiple hops to a destination and also provide Quality of Service (QoS) support for target application traffic. As with most routing protocols, OLSR protocol uses a single routing metric acquired at the network layer, which may not be able to accommodate different QoS requirements for application traffic in Smart Grid. To address these problems, a novel multiple link metrics approach to improve the reliability performance of routing in ad hoc WMN when deployed for Smart Grid is presented. It is based on the OLSR protocol and explores the possibility of applying QoS routing for application traffic types in NAN based ad hoc WMN. Though routing in multiple metrics has been identified as a complex problem, Multi-Criteria Decision Making (MCDM) techniques such as the Analytical Hierarchy Process (AHP) and pruning have been used to perform such routing on wired and wireless multimedia applications.

The proposed multiple metrics OLSR with AHP is used to offer the best available route, based on a number of considered metric parameters. To accommodate the variable application traffic requirements, a study that allows application traffic to use the most appropriate routing metric is presented. The multiple metrics development is then evaluated in Network Simulator 2.34; the simulation results demonstrate that it outperforms existing routing methods that are based on single metrics in OLSR. It also shows that it can be used to improve the reliability of application traffic types, thereby overcoming some weaknesses of existing single metric routing across multiple hops in NAN. The IEEE 802.11g was used to compare and analyse the performance of OLSR and the IEEE 802.11b was used to implement the multiple metrics framework which demonstrate a better performance than the single metric. However, the multiple metrics can also be applied for routing on different IEEE wireless standards, as well as other communication technologies such as Power Line Communication (PLC) when deployed in Smart Grid NAN.

List of Common Acronyms

- 3GPP: 3rd Generation Partnership Project
- AHP: Analytical Hierarchy Process
- ALM: Air Link Metric
- AMI: Advanced Metering Infrastructure
- AMR: Automatic Meter Reading
- AODV: Ad Hoc On-Demand Distance Vector
- AP: Access Point
- ARP: Address resolution Protocol
- AVL: Automatic Vehicle Location
- BAN: Building/Business Area Network
- BPLC: Broadband Power Line Communication
- CBR: Constant Bit Rate
- COSEM: Companion Specification for Energy Metering)
- DA: Distribution Automation
- DER: Distributed Energy Resources
- DGM: Distributed Grid Management
- Distributed Autonomous Depth-First Routing (DADR)
- DLMS: Device Language Message Specification
- DNP3: Distributed Network Protocol
- DOE: Department of Energy
- DOS: Denial of Service
- DR: Demand Response
- DSM: Demand Side Management
- DSSS: Direct Sequence Spread Spectrum
- EDCA: Enhanced Distributed Channel Access
- EFW: Expected Forwarding Counter
- EPT: Expected Path Throughput
- ETE: End-to-end delay
- ETX: Expected Transmission Count
- EV: Electric Vehicle
- EVCC: EV Charging Controller
- EVCS: EV Charging Station

- FAN: Field Area Network
- GOOSE: Generic Object Oriented Substation Event
- GSSE: Generic Substation State Event
- HAN: Home Area Networks
- HEMS: Home Energy Management Systems
- HWMP: Hybrid Wireless Mesh Protocol
- HYDRO: Hybrid Routing Protocol
- IAN: Industrial Area Networks
- ITU: International Telecommunication Union
- LBS: Location-Based Services
- LLN: Lossy and Low power Networks
- LTE: Long Term Evolution
- M2M: Machine to Machine
- MAC: Media Access Control Layer
- MANET: Mobile Ad hoc Networks
- MCDM: Multi-Criteria Decision Making
- MD: Minimum Delay
- MDMS: Meter Data Management Systems
- ML: Minimum Loss
- MMS: Manufacturing Message Specification
- NAN: Neighbour Area Network
- NBPLC: Narrow-Band Power Line Communication
- NGN: Next Generation Networks
- NIST: National Institute of Standards and Technology
- ns: network simulator
- OFDM: Orthogonal Frequency Division Modulation
- OLSR: Optimised Link State Routing Protocol
- PDR: Packet Delivery Ratio
- PHEV: Plug-in Hybrid Electronic Vehicles
- PHY: Physical Layer
- PLC: Power Line Communication
- PMU: Phase Measurement Unit
- PREP: Path Reply
- PREQ: Path Request
- QoS: Quality of Service

- RLMT: Route Link Metric Type
- RLMTV: Route Link Metric Type Value
- RLMTW: Route Link Metric Type Weight
- RPL: Routing Protocol for Low Power and Lossy Networks.
- RTU: Remote Telemetry Unit
- SCADA: Supervisory Control and Data Acquisition
- SGIP: Smart Grid Interoperability Panel
- TETRA: Terrestrial Trunk Radio
- USN: Ubiquitous Sensor Network
- UTC: Utility Telecom Council
- VPN: Virtual Private Network
- WACS: Wide Area Control Systems
- WAM: Wide Area Measurement
- WAMS: Wide Area Monitoring Systems
- WAN: Wide Area Networks
- WAPS: Wide Area Protection Systems
- WASA: Wide Area Situational Awareness
- WIMAX: World Interoperability for Microwave Access
- WLAN: Wireless Local Area Network
- WMN: Wireless Mesh Network
- WPAN: Wireless Personal Area Networks
- WPM: Weighted Product Model
- WPMS: Weighted Product Model Score
- WSM: Weighted Sum Model
- WSMS: Weighted Sum Model Score

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Chapter 1

1.Introduction

1.1. Overview

The traditional electric power infrastructure has remained unchanged since its inception. It has been a strictly hierarchical system for decades of operation, where power flows in one direction from generating plants towards the consumer load (as shown in Figure 1-1). This system of power generation and supply is rapidly approaching its limitations. As a result, the level of satisfaction currently expected by both the consumer and supplier is restrained for various reasons including:

i) the growth in demand for electricity driven by increase in population, electrical/digital equipment, automated manufacturing and the anticipated introduction of Electrical Vehicles (EV's);
ii) the open loop method of operation in the existing grid, where the control centre has very limited or no near real-time information about the dynamic change in load and operating condition of the electrical system.

The increasing load, poor visibility and lack of situational awareness have made the grid susceptible to frequent disturbances that may lead to cascading failures (Farhangi, 2010). These failures can easily create numerous levels of risk, both in grid components and at the consumer end. This underscores the necessity of reliable and secure power and information transfer in all directions.

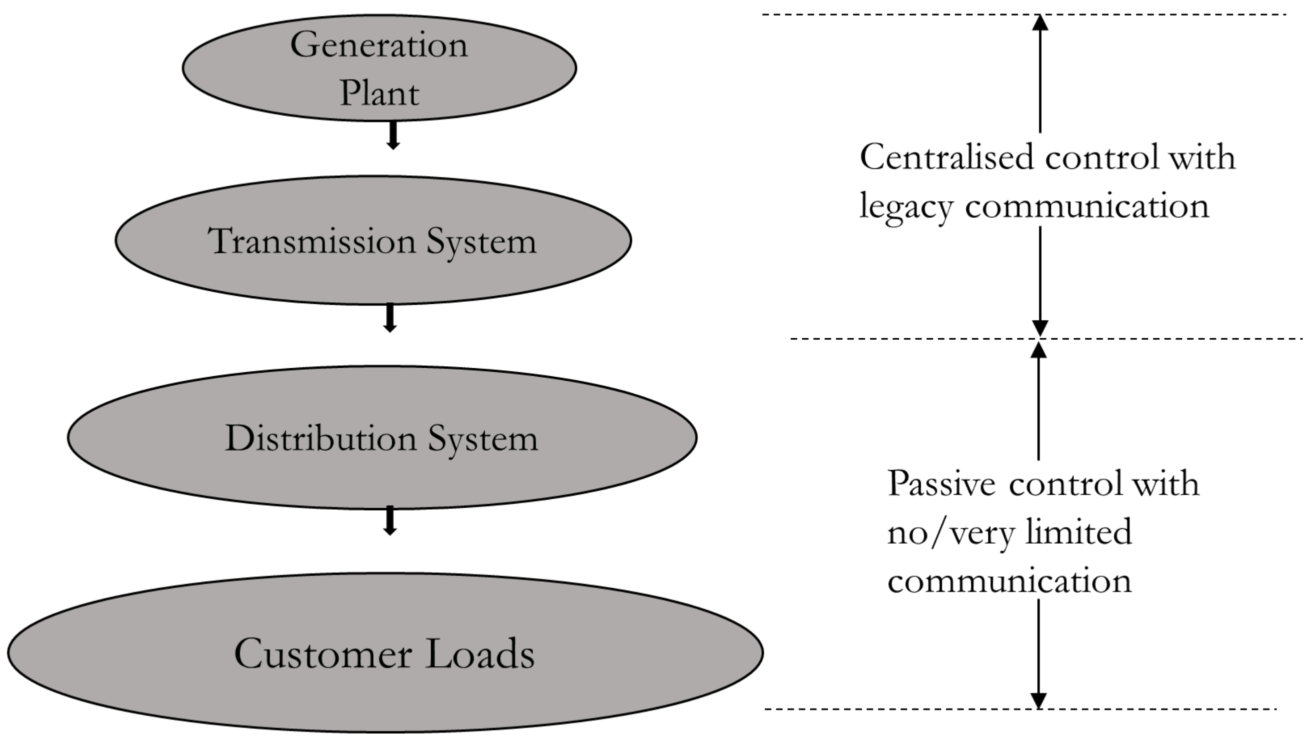


Figure 1-1: The unidirectional power flow in existing electricity grid

Furthermore, the growing awareness of the adverse effects of climate change and environmental risk has led to the reduction of greenhouse gas emissions from power generation. The cost of generation associated with energy sources from fossil fuel depletion and nuclear energy has also brought about a shift towards renewable energy sources like solar and wind power. This is evident in the fact that many countries have set targets for the generation and integration of renewable energy. For example, according to a report 'U. K. Renewable Energy Road Map' released by the Department of Energy and Climate Change (DECC) in 2011 (Department of Energy & Climate Change (DECC), 2011), the UK has set a target to deliver 15 % of its total energy consumption from renewable sources by 2020. The target is already being achieved; in the 4th quarter of 2015, the renewables' share of electricity generation was a record 26.9 %, up 5.0 % from the 4th quarter of 2014 (James Hemingway). This is a reflection of high renewable power generation on low overall power generation.

In addition, EVs, which will feed off the electrical grid, are also being considered promising solutions to reduce carbon emission and the dependence on fossil fuel. An increase in the adoption and usage of EVs is expected to become a major load to the grid in the near future. For instance, since the introduction of the Plug-in Car Grant in January 2011, there have been 63,100 eligible cars registered (Element Energy Limited, 2010). If EVs are adopted by all end users, additional peak electricity demand on the UK national grid is expected to be up to 1.5% by 2020 and 10% by 2030 (Element Energy Limited, 2010). The integration of EVs with the existing grid reserves, reverses the direction of the power flow since they are also expected to act as storage devices that can feed power back to the grid.

The Smart Grid aims to address all the shortcomings of the existing electrical grid by integrating information and communication technologies to support and augment the performance of existing electrical power networks. In a more detailed description, the U. S. Department of Energy (DoE) defines Smart Grid as "a distributed and automated energy delivery network that provides a two-way flow of electricity and information as well as enables near-instantaneous balance of supply and demand by incorporating the benefits of distributed computing and communications". Thus, a robust communication infrastructure must act as a key enabler for Smart Grid. This would differentiate it from the conventional grid, by allowing the exchange of information between its components for data acquisition monitoring, control, and protection of applications.

There have been inconsistencies in the market structure, motivation and definition of what constitutes a Smart Grid. Its implementation is still in the early stages and most commercially deployed applications are limited to smart meters, which carry out remote meter reading/billing. Utility companies are now considering the deployment of other potential applications and reliable communication networks. This is why it is necessary to conduct a comprehensive study to properly assess the feasibility and performance of a potential communication technology for Smart Grid and identify areas of modification to improve communication reliability.

1.2. Background

It is important to mention that Smart Grid is not a destination in itself. It is a journey motivated by ambitious goals such as energy savings, efficient and sustainable power supply, reduction of greenhouse gas emissions and attaining satisfactory levels of security and quality of energy supply (Balmert and Petrov, 2010). Achieving Smart Grid goals will involve a set of functionalities within the generation, distribution and consumer premises rather than a deployment of individual appliances or technologies (Tsado et al., 2015b).

The present electrical grid incorporates different types of systems, devices and communication media with specific procedures for exchanging data. For example, the Supervisory Control and Data Acquisition (SCADA) system with Remote Telemetry Unit (RTU) and Programmable Controllers, are used on the power grid for monitoring and control purposes. These are mostly based on proprietary protocols and wired communication networks such as cables using Modbus protocols, Power Line Communication (PLC) and fibre optic (Nordell, 2008). This is because wired networks were considered suitable for the high capacity and high-reliability transmission that were required at the time. With the growing portfolio of Smart Grid applications has come the need for ubiquitous sensing and communication by Utility operators that can provide sufficient measurement and bandwidth for supporting the large number of devices and their traffic requirements.

Expanding the existing wired communication to serve the large number of homes and businesses for utility purposes is highly time and cost prohibitive. Instead, wireless standards such as IEEE 802.11 and IEEE 802.15.4g are being considered essential technologies for Smart Grid. However, this will introduce new complexities and vulnerabilities such as security and coordination of different technologies (communications and electricity) which have diverse capabilities and characteristics that are not well defined (Gao et al., 2012) (Ancillotti et al., 2013a). To help with the development of expanding the communication network, the power industry is gradually adopting different terminologies for partitioning the command and control layers of Smart Grid. Examples include the Home Area Network or HAN (used to identify the network of communicating loads, sensors, and appliances beyond the smart meter and within customer premises); Neighbor Area Network or NAN (used to identify network of integrated field components that form logical gateways between distributed substations and a customer’s premises); and, lastly, Wide Area Network or WAN (used to identify the network of upstream utility assets, including control centres, distributed storage, power plants and substations) (Farhangi, 2010).

There are also efforts to develop communication network architecture or framework required to tie together the diverse applications and heterogeneous communication technologies that will be deployed on these network partitions.

Smart Grid communication has been researched with different media techniques, including wireless, coaxial, PLC or hybrid combinations of these technologies. However, the choice of technology has been largely determined by cost and personal interest. Among contemporary wireless technologies, the IEEE 802.11 ad hoc wireless mesh network will play an important role in meeting the existing and future communications needs for Smart Grid, especially in partitions, which involve Local Area Networking (LAN) such as NAN. This is because it has several advantages, they include, extended coverage, low-cost, low latency and Quality of Service (QoS) support; it has also been implemented to bridge seamlessly with several other wireless standards and wired technologies.

The IEEE 802.15.4g wireless standard has made outstanding progress in HAN, and plans to extend its capabilities to the area of NAN are being explored. However, there are various problems, one of which is its limited data rates, which will not provide the required bandwidth capacity for NAN. Aside from providing high bandwidth, IEEE 802.11 Wireless LAN (WLAN) standards are considered candidates for NAN because they provide high-speed and easy-to-deploy wireless backbone services. They also possess outdoor deployment properties where the network may support a number of different applications and services, which are essential requirements of a NAN communication network (Zhang et al., 2011). They can be deployed as Wireless Mesh Networks (WMN) which are capable of self-organisation, self-configuration, and self-healing as well as transmit using a multi-hop environment (Akyildiz et al., 2005). The IEEE 802.11 has increasing throughput, Physical (PHY) Layer data rates and the ability to provide extended transmission range and reliability when deployed as ad hoc WMN, where a node can send information to a destination across multiple hops. However, reliability in 802.11 ad hoc WMN is not only dependent on the throughput and data rate capabilities, but also the ability of the routing protocols to find reliable paths to a destination.

Since the NAN partition of the Smart Grid conveys information from meters to the Utility operation centres; ad hoc WMN networks must have sufficient capabilities to support and satistfy the different application traffic requirements of users. A number of existing protocols, which include the Routing protocol for Low Power Lossy Networks (RPL) and the Hybrid Wireless Mesh Protocol or HWMP (IEEE 802.11 standard protocol) have been considered and modified for routing in NAN (Sabbah et al., 2014). Most of these protocols have been designed to support specific Smart Grid traffic patterns (i.e. point to point or P2P, point to multipoint or P2MP and multipoint to point or MP2P) in near real-time and non-real time using single best effort path to a destination. In addition, most of the routing protocols used are fitted with a single metric such as the Expected Transmission Count (ETX) for path discovery to a destination. Single metrics may not be efficient in providing guarantees for requirements such as delay and Packet Delivery Ratio (PDR). This can lead to congestion since it will require Smart meters to send all application traffic to the destination through a single path. It is, therefore, necessary to steer the design and modification of routing protocols for NAN based WMN towards the perspective of network management that will consider cross-layer QoS routing and adaptively support the requirement for different application traffic types.

1.3. Research Aim and Motivation

In IEEE 802.11 ad hoc WMN technology, routing protocols determine the path needed for data flow to the destination. Therefore, when ad hoc WMN is deployed for communication in NAN, the efficiency of the network and Smart Grid is dependent on the routing protocols. When designing a routing protocol for Smart Grid, it is most important to study the application traffic to be supported and the link metric for path selection. As one of the conventionally used and deployed routing protocols in ad hoc WMN, the Optimised Link State Routing (OLSR) protocol can be used to significantly extend the reliability of the Smart Grid NAN, by allowing fast and reliable communication over a wide neighbourhood coverage area. It is worth noting here that the conventional ad hoc WMN with OLSR routing protocol was only developed to support multimedia applications such as voice, video, web browsing and node mobility. In contrast, the communication network for smart grid applications has to support machine-to-machine communication (M2M), which is autonomous in nature and triggered by time or event. For instance, it must support information exchange between a large number of smart meters, intelligent electronic devices (IEDs) and sensors/actuators with limited or no human intervention. Moreover, each application operating on any of these M2M devices has different characteristics and traffic requirements, depending on their mode of operation (e.g. Normal/periodic, alert, fault). For example, while the meter reading traffic from a smart meter is fairly delay-tolerant, the demand management traffic from the same device is much more delay sensitive; likewise, the traffic priority of a demand management event and a substation event is quite different. Therefore, the coexistence of monitoring, control and reporting traffic poses additional challenge of providing strict QoS differentiation within a multi-service Smart Grid communication network.

A number of studies have been conducted into the performance of routing protocols for ad hoc WMN in the Smart Grid environment. Most of them have concentrated on the IEEE 802.11s standard protocol (HWMP) and RPL. To the best of our knowledge, there has not been much research on evaluation and modification of OLSR protocol for Smart Grid communication. The aim of this thesis is to offer an in-depth study on Smart Grid NAN communication over an ad hoc WMN using OLSR and improve its reliability for variable Smart Grid applications. To fulfil this aim, it first conducts a detailed review on network components/partitions as well as the application characteristic and traffic requirements of several Smart Grid applications. For each network component, it highlights potential communication technologies and their challenges. Based on the review and having identified ad hoc WMN as a front runner for NAN component of the Smart Grid, a traffic classification and modelling of traffic profiles using transmission interval and delay requirements is presented. Subsequently, an experimental setup and a series of simulation studies (using smart meter as the traffic source) are conducted to identify and highlight QoS and capacity issues that application traffic will face within a NAN based ad hoc WMN using OLSR as its routing protocol. A key solution to the observed issues is to provide an adaptive QoS for routing targeted applications, as routing protocols with single link metric such as ETX, used for path selection are deficient in guaranteeing reliable QoS for variable Smart Grid applications. Amongst the different existing routing approaches, the focus of this thesis is mainly on the use of multiple metrics with OLSR to improve reliability of ad hoc WMN when they are deployed for NAN communication. As a result, a network architecture for smart meters communicating in a NAN based WMN that will incorporate the multiple metrics algorithm is proposed. The possibility of combining multiple metrics with OLSR protocol, through the Analytical Hierarchy Process (AHP) algorithm is also explored to provide adaptive QoS for variable applications. An implementation of multiple metrics OLSR in a NAN based ad hoc WMN is then presented and results are compared with other existing OLSR link metric versions.

It is important to note that this thesis focuses on packet delivery reliability of Smart Grid applications in NAN using predefined or modelled Smart Grid application traffic profiles. Though conventional telecommunication applications such as voice over IP (VOIP), streaming multimedia, and the Internet may also be present in a Smart Grid, they were not considered. Additionally, while security is a key issue in a large and complex cyber-physical system such as the Smart Grid, it is also not within the scope of this thesis.

1.4. Scope of Research

There has been a lot of research and modification on existing protocols for reliable routing of multimedia applications without necessarily considering Smart Grid scenarios and their application traffic. This thesis explores the use of OLSR routing protocol in Smart Grid's NAN, based on ad hoc WMN. It attempts to improve its reliability by implementing a multiple metrics OLSR through the use of AHP algorithm. This implementation is expected to improve WMN routing by selecting good quality links and also enable adaptive QoS guarantees for variable Smart Grid traffic types.

1.5. Contribution of the Thesis

The contribution of this thesis can be summarised in twofold. The first contribution is the design of traffic profiles and a performance evaluation of ad hoc WMN using the OLSR protocol in Smart Grid NAN. This was achieved through an experimental and simulation evaluation of OLSR protocol in a NAN based ad hoc WMN scenario. The second contribution is the case study and simulation evaluation of multiple metric OLSR through the use of the AHP, a Multi Criteria Decision Making (MCDM) algorithm. It is designed to support target application level QoS requirement using different OLSR link metric versions to enable good quality links to a destination. Each chapter has a section which lists its specific contribution. However, a summary of the key contribution of each chapter of this thesis is highlighted as follows:

- Chapter 2 provides an in-depth review on Smart Grids communication components and traffic for different applications that will utilise the communication components. The chapter also explores the use of the International Telecommunications Union (ITU)'s Ubiquitous Sensor Network architecture (USN) architecture for Smart Grid and presents the available communication technologies which can be deployed within the USN schematic layers for a secure and resilient communication, including a study of their pros and cons, vulnerabilities and challenges. This contribution has been published in the Computer Communication Journal (Elsevier).
- Chapter 3 makes a case for the use of OLSR routing protocol in NAN based WMN, by carrying out an evaluation of conventional OLSR protocol through experimental setup and simulation, to demonstrate its multi-hopping capabilities in a NAN based ad hoc WMN scenario. Its delay, PDR and throughput performance were compared with the IEEE 802.11 standard HWMP, which shows that HWMP does not outperform OLSR. The results obtained from the performance evaluation of OLSR protocol in a NAN based ad hoc WMN network scenario using Smart Grid application traffic profiles have been published in the International Conference on Smart Systems and Technologies (SST) 2016.
- Chapter 4 presents a case study on the modification of OLSR protocol to improve reliability and QoS support for Smart grid's application traffic types using multiple metrics with AHP algorithm and Pruning. Given that OLSR is only responsible for informing nodes about the best path to a destination, the study shows that the use of AHP with multiple metrics can inform nodes on better paths to a destination for a particular application traffic. The contribution of this study was presented and published in the IEEE Second International Smart Cities Conference (ISC2) 2016.
- Chapter 5 develops a multiple metrics OLSR in ns-2 to adaptively support QoS for targeted Smart Grid applications. This enables the transmission of target application types through the best paths chosen by the multiple metric and AHP algorithm to the data concentrator. Results for transmitting

Smart Grid application traffic types using the multiple metric OLSR with AHP shows an improvement in performance in terms of reliability and delay compared to other conventional OLSR link metric types.

1.6. List of Publication

At the start of this research in October 2012, Smart Grid was still a fledgling concept. The supporting company was highly interested in communication technologies that support cross-layer techniques, which involves multi-hopping and routing over extended distance within the Low Voltage (LV) and Medium Voltage (MV) areas. The company has also been involved in PLC technologies. Therefore, the author was compelled to review and explore other communication technologies, especially PLC. This led to the publication of papers establishing possible scenarios and their impact within the MV and LV area of communication. The majority of the papers were published in peer-reviewed conferences to keep pace with ongoing research activities in Smart Grid. The complete list of published and submitted articles related and unrelated to this thesis write up are presented as follows:

Article/Publications Related to the thesis write-up

- Communication Technologies for Smart Grid Ubiquitous Sensor Network System submitted and presented at the "IEEE 4th International Conference on Power Engineering, Energy and Electrical Drive" Istanbul, Turkey on May 12 – 18, 2013.

- Resilient Wireless Communication Networking for Smart Grid Building Area Network (BAN) submitted and presented at the "IEEE International Energy Conference (EnergyCon)" Dubrovnik, Croatia, May 13 – 16, 2014.

- Performance Evaluation of Wireless Mesh Network routing protocol for Smart Grid networks presented at the "IEICE Information and Communication Technology Forum Manchester UK, June 3 – 5, 2015".

- Resilient Communication for Smart Grid Ubiquitous Sensor Network: State of the Art and Prospects for Next Generation. Elsevier Journal for Computer Communication, July 2015.

- Performance Analysis of Variable Smart Grid traffic over ad hoc Wireless Mesh Networks presented at the "International Conference on Smart Systems and Technologies (SST)" Osijek, Croatia, October 12 -14, 2016.

- Multiple Metrics-OLSR in NAN for Advanced Metering Infrastructures presented at the "IEEE Second International Smart Cities Conference (ISC2)" Trento, Italy, September 12 – 15, 2016.

- Improving the Reliability of Optimised Link State Routing in a Smart Grid Neighbour Area Network based Wireless Mesh Network Using Multiple Metrics. energies Journal "Volume 10, issue 3, 2017".

Other Publications generated as part of this research

- Challenges of Time-critical Applications in Narrow Band Power Line Communication (NBPLC) Deployed for Smart Grid. Faculty of Science and Technology Christmas Conference 2013 Poster Presentation.

- Performance of Time-Critical Smart Grid Applications in Narrow Band Power Line Communication submitted and presented at the "7th IET international conference on Power Electronics, Machines and Drives (PEMD)" Manchester 8 - 10 April 2014.

- Narrowband PLC channel Modelling for Smart Grid Applications submitted for the "9th IEEE/IET International symposium on Communication systems, Networks and Digital Signal Processing, CSNDSP14" Manchester, UK July 23 – 25 2014.

1.7. Thesis Outline

This section outlines the remaining chapters of this thesis as follows:

Chapter 2

The main focus of Chapter 2 is to present an overview of network components/partitions that constitute a Smart Grid communication network and the different applications that will utilise the network components. In particular, it describes the Home Area Network (HAN), Neighbour Area Network (NAN), Field Area Network (FAN) and Wide Area Network (WAN), which is the focus of this thesis. Furthermore, an overview of the adaptation of the ITU's USN is also presented to tie together the networking components and make them functional. This is followed by an in-depth review of available conventional communication technologies that can be deployed within the USN architecture layers, together with a study of their pros and cons and challenges. Based on factors highlighted for the choice of Smart Grid communication technology, the IEEE 802.11 ad hoc WMN is considered as the communication technology for Smart Grid NAN. The routing protocols for Smart grid NAN which are the building blocks of the work in subsequent chapters are then discussed.

Chapter 3

This Chapter presents a classification of Smart Grid traffic and examines the performance of HWMP (which is the default routing protocol of the IEEE 802.11s standard) with the OLSR protocol in a NAN based ad hoc WMN. An experimental setup of ad hoc WMN for NAN was implemented using Commercial Off The Shelf (COTS) devices to observe the performance of Smart Grid traffic over a real ad hoc WMN implementation. The ns-3 simulation was then used to simulate a larger network of Smart meters in a NAN scenario. Results from simulations in ns-3 show that HWMP does not outperform OLSR. This allows the possibility of exploring the modification of OLSR protocol to address the routing challenges and improve reliability in a NAN based ad hoc WMN.

Chapter 4

A case study of the performance of three OLSR link metric versions is carried out on a grid topology wireless mesh NAN using the ns-2 network simulator. The two best performing metrics were used to demonstrate the possibility of combining multiple metrics with the OLSR protocol, through the AHP decision-making algorithm to improve link quality and fulfil the QoS routing requirements of targeted AMI application traffic.

Chapter 5

This Chapter presents a multiple-metric OLSR route framework which is designed for cross-layer and multiple metric routing decision in NAN based ad hoc WMN. The framework uses multiple OLSR link metric versions to support Smart grid application level QoS requirements, by allowing different applications to use different paths provided by the OLSR link metric types. This is aimed at allowing or enabling appropriate route decisions for target Smart Grid application traffic at the network layer. The chapter also analyses the multiple metrics framework and evaluates its performance on a NAN scenario using the ns-2 simulation.

Chapter 6

The Chapter summarises the main contributions of the thesis and discusses the findings from the study. This includes issues found and steps taken to get around or provide solutions to the problems. It also includes some thoughts on future research direction.

Chapter 2

2. Communication Technologies for Smart Grid: Background and Literature Review

2.1. Introduction

The next generation electrical grid or Smart Grid is envisioned to use a combination of existing communication technologies for advanced monitoring, control and protection to enable active customer participation and management capabilities, integrate distributed energy resources, and implement self-healing functionalities. This is in contrast to the proprietary communication technique for control and monitoring currently used in the existing electrical grid. A system of converged pervasive communication, comprising different heterogeneous networks, is the key enabler to a complex, multidimensional energy delivery system that allows information exchange among a large number of distributed devices over a vast geographic area.

Smart Grid communication is classified as M2M communication, since it involves information exchange between two or more end devices and a remote server situated at a substation or control centre with very little or no human interaction. Smart Grid M2M communication will provide interaction for a set of applications within power generation, distribution and consumer premises with the aim of achieving important goals such as: improving load estimation, facilitating and integrating renewable power generation and enabling consumer energy management capabilities. The communication network must be resilient (i.e. traffic must be able to mitigate failures in the network) and able to guarantee certain Quality of Service (QoS) requirements which include latency, bandwidth and throughput, before these functionalities can be successfully carried out. Since most existing communication technologies vary in their ability to provide a certain QoS, they will have to be deployed at different levels of Smart Grid network to provide optimal flexibility and scalability.

Presently, most commercially available Smart Grid applications are limited to smart metering and non-real time demand side management. However, Smart Grid's ambitious goals go far beyond these two applications to include Electronic Vehicle Charging (EVC), power quality measurement and other applications to be developed. Utility companies are now considering the implementation of other prospective applications and develop a much more reliable, resilient and future-proof network to satisfy current and future communication needs.

In order to properly study the performance of communication technologies in Smart Grid, it is very important to acquire detailed knowledge about their architecture and how all application traffic will strive when these technologies are deployed. The aim of this chapter is to provide a detailed overview of Smart Grid communication systems and key Smart Grid applications, as well as their traffic requirements and characteristics. The chapter also explores the adaptation of ITU's USN architecture and attempts to review available communication technologies for Smart Grid. Finally the key research challenges and performance requirements for Smart Grid communication technologies are presented.

The focus of the study is then placed on routing in Smart Grid's NAN with emphasis on ad hoc WMN and the OLSR protocol which is the research area of this thesis.

2.2. Legacy in the Electrical Grid

Since its inception, the traditional electrical grid involves large centralised generation of electrical energy from different energy sources, mainly fossil fuels, transmitted in bulk over long distances through high voltage transmission lines to a distribution substation. The electricity is then distributed to end users at low voltages (< 240 V). There have been a lot of technological advances in power generation from nuclear, gas turbines and renewable energy sources (solar and wind energy) (Erlinghagen and Markard, 2012), however, transmission and distribution, which are core parts of the electricity sector has experienced very little or no change over the last 100 years (Bauknecht, 2011). This is evident in the fact that even in societies with advanced technologies, the only way utility companies know there is an outage is when a customer calls in to report it. The utility electrical grid has become more unreliable over the years, characterised by frequent brownouts and blackouts. These not only seriously affect the lives of consumers, but also cause substantial economic losses.

Zeng Bo et al (Bo et al., 2015) presented a comprehensive list of recent blackouts and summarised their causes into four categories, namely: environment, inadequate grid structure, management (i.e load forecasting errors) and market aspect (regulatory and tariff system).

Recent awareness of the cost of generation and risks associated with energy sources from fossil fuel depletion and nuclear energy has accelerated the shift towards renewable energy sources. However, renewable energy sources challenge the existing grid architecture, which is not able to cope with a large share of intermittent and possibly decentralised energy sources. Thus, the energy sector is poised for transformation to a Smarter and intelligent grid in order to achieve long term sustainability and reliability. This will not only involve the shift to renewable energy, but also the development of infrastructure that can cope with: a) transmission losses, b) integrating multiple energy sources, and c) enhanced efficient energy distribution and consumption.

Smart Grid transforms the electrical grid from a centralised producer controlled network to one that is more decentralised and consumer interactive. Based on the perception of the utility companies and research community, Table 2-1 presents the changes expected in the existing electrical grid as a result of Smart Grid. The utility companies desired capabilities of the future Smart electrical grid are discussed in the next subsection.

Table 2-1: Comparison of Todays Grid and Future Smart Grid (Farhangi, 2010)

Today's Electrical Grid	**Future Smart Grid**
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralised Generation	Distributed Generation
Blind & Manual Restoration	Self-Monitoring and Self-Healing
Few Sensors	Sensors everywhere possible
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices
No Energy Management Capabilities	Energy Management Capabilities

2.2.1. Distributed Energy and Automation

Nearly 90% of all power outages and disturbances have originated from the distribution network (Glover et al., 2012). This means that the shift towards the Smart Grid should start at the distribution system, which is the bottom of the chain. In Smart Grid, the specification of distributed generation over centralised generation is subject to requirements related to the renewable energy and other distributed power sources, as well as their effect on the power-system operation.

This is especially so where the intermittent energy sources such as wind and photovoltaic (PV) power generators constitute a significant part of the total energy capacity. Electricity storage and power electronics technologies are key drivers in distributed generation and integration of renewable energy sources. The rising demand for electricity and the cost of expanding generation also mean that these technologies are required to help manage demand and protect revenue **(Farhangi, 2010)**. For example, the electricity produced in periods when demand is low should attract low generation cost and provide good conditions for intermittent renewable energies to be stored. The stored electricity can then be made available for distribution to consumers in periods of higher demand and high-generation cost, or when there is no available generation. This can only be achieved with the development of novel electricity storage facilities and fast semiconductor switches with real-time computer controllers that can implement advanced and complex control algorithm (Carrasco et al., 2006).

2.2.2. Key Utility Applications

A plethora of new applications with variable requirements and features for energy integration and capacity building are expected to emerge in Smart Grid operations. For the purposes of this section, only a selected set of applications which have drawn significant attention from the utility industry and research community is considered. These applications have been classified by the United States (US) Department of Energy (DOE) into six functional categories (Saputro et al., 2012). The following subsections discuss the characteristics and traffic requirements of these applications and highlight their key challenges:

2.2.2.1. Advanced Metering Infrastructure (AMI)

AMI is regarded as the most fundamental and crucial part of Smart Grid. It is expected to link consumers and power utility companies and provide the foundation for future distribution automation and other Smart Grid functionalities. The system-wide measurement and visibility enabled by AMI will enhance the utilities' system operation and asset management process. AMI is designed to read, measure, and analyse the energy consumption data of consumers through smart meters to allow for dynamic and automatic electricity pricing.

Automatic Meter Reading (AMR) is the simplest form of AMI applications, which according to IEC 61968-9 refers to a technique of collecting meter readings, grid events and alarm data from designated meters remotely, using communication systems. However, AMI functions extend far beyond that of AMR. It requires two way communication and spans through all the network components of Smart Grid from private networks WAN. Other advanced applications supported by AMI include using the two way communication systems on meters to send information about customer price, load management, Meter Data Management Systems (MDMS) and Home Energy Management Systems (HEMS) (Wenpeng, 2009). AMI can also be used to monitor power quality, electricity produced or stored by Distributed Energy Resource (DER) units and interconnected Intelligent Electronic Devices (IED) (Ancillotti et al., 2013a). In addition, AMI is also expected to support customer switch between suppliers and help detect and reduce electricity theft. Electricity theft has plagued many utility companies especially in developing countries. Authors in (Anas et al., 2012) have shown that smart meters in efficient and secure AMI infrastructure can be used to address or minimise electricity theft issues.

2.2.2.2. Demand Side Management (DSM)

DSM is the action that influences the quantity or pattern of energy consumption by end users. These actions may include targeting reduction of peak demand by end users during periods when energy supply systems are constrained. In the UK, the duration of peak demand times/periods are affected by factors such as weather and holidays which makes it vary for different quarter in a year. However, in most cases, they are between 6.30 am to 9.30 pm (Pout et al., 2008). Energy peak management does not necessarily decrease the amount of total energy consumption, but it will reduce the need for investments on power generation sources or electricity spinning reserves at peak periods (Wang et al., 2011) (Palensky and Dietrich, 2011) (Davito et al., 2010). DSM programs include the following activities:

- Demand Response (DR) - DR enables the utility operator to optimally balance power generation and consumption, either by offering dynamic pricing programs or implementing various load control programs. This includes programmes aimed at reducing energy consumption during peak usage hours by encouraging customers through various incentives to limit their usage or shift them to other periods. Examples of incentives based on DR:
    I. Direct Load Control: utility or grid operator gets free access to customer processes.
    II. Emergency demand response programs: voluntary response to emergency signals.
    III. Capacity market programs: customers guarantee to pitch in when the grid is in need.
    IV. Demand bidding programs: customers can bid for curtailing at attractive prices
- Time based load management - This is achieved through dynamic pricing which helps to reduce energy consumption during peak hours and encourage customers to limit energy usage or shift demand to other periods. Examples of Time based load management include:
    I. Time of Use (TOU) - Achieved by dividing the day in to contiguous blocks of hours with varying prices. The highest price is allocated to the on-peak block.
    II. Real Time Pricing (RTP) - The price is tied to the real market cost of delivering electricity and may be varied hourly.
    III. Critical Peak Timing (CPT) – a less predetermined variant of TOU (only applied on a relatively small number event days).
    IV. Peak Time Rebates (PTRs): Electricity rebates given to customers for minimising power usage during peak periods.
- Conservation of energy through load control programs, this involves performing remote load control programs where communicating networks are used to control usage of appliances remotely to use less energy across many hours. The remote load control programs can be classified into the following:
    I. Interruptible Loads – refers to loads such as water pumps, dryers and dish washers that can be interrupted during peak periods and shifted to another time. However, simple

load control signals to interrupt and reschedule the load process are required to ensure that when the waiting period of the load is over, the rebound of the load to the grid does not cause additional congestion (Palensky and Dietrich, 2011).

II. Reducible Loads – refers to loads that can be reduced to lower levels for certain periods of time. Examples of this type of loads include – refrigerators and air conditioners which can have their thermostats adjusted to higher temperatures to reduce load.

III. Partially Interruptible Loads – as the name implies, refers to loads that can be partially interrupted over peak periods by limiting the run-time cycle. Examples of the loads that can have their runtime cycles reduced are washing machines.

2.2.2.3. Wide Area Situational Awareness (WASA)

WASA involves near real-time monitoring, protection and control of the power grid across large geographical areas. It requires collating information on the description of the current state of the power grid in the area concerned. The information is then analysed in order to diagnose the current situation, or predict the evolution of the power grid state under different operational conditions and energy control strategies (Zhang et al., 2010) (Terzija et al., 2011) (Johnson et al., 2011). WASA application traffic requires very high frequency or granularity of information in order of milliseconds, collected from the transmission networks and electric substations, about the state of the power grid (Wang et al., 2011). The information is used to provide timely prevention of power disruption and to optimise the performance of the grid. WASA information is also used to implement monitoring (Wide Area Monitoring Systems or WAMS), Control (Wide Area Control Systems or WACS) and for Protection (Wide Area Protection Systems or WAPS) (Khan and Khan, 2013). This is achieved by using hundreds of Phase Measurement Units (PMU) to provide accurate system state measurements in near real-time. GPS is used to provide a timestamp for each measurement (Phadke and Thorp, 2008).

2.2.2.4. Distributed Energy Resource (DER) and Storage

These are applications which contain information that enable efficient integration of energy resources from renewable sources to the power grid, to complement bulk generation. DER may reside at the transmission, distribution or even at end user systems and will require applications or incentives in the case of end user DER to channel the energy resources into the grid at appropriate times. Applications for efficient use of energy storage are also necessary to allow storage of surplus electricity at a given time for distribution thereafter, or to compensate for the energy generation fluctuation from renewable sources.

2.2.2.5. Electric Vehicle (EV) Monitoring and Control:

This involves monitoring the activities of plug-in electric or hybrid electronic vehicles (PEV or PHEV) that are expected to enhance or replace fossil fuel transportation systems. Electric Vehicles (EV) use one or more electric motors which are powered by a rechargeable storage device in the vehicle. The connection of the storage device on an EV to the electrical grid to recharge is called Grid to Vehicle (G2V) flow. In the event where an EV is connected to the electrical grid to discharge electric power back to the grid when it is not being used, the process is known as Vehicle to Grid (V2G).

EV charging systems must be well managed, as high concentrations of charging requests within a short period can cause severe overloading in the distribution network. Smart charging concepts that enable controlled charging have been proposed to mitigate the problem of overloading the distribution circuit (Khan and Khan, 2013) (Sortomme et al., 2011). They incorporate DR programs known as “demand dispatch”, which aggregate a large number of controllable loads like EVs to improve the energy efficiency of the grid by optimally balancing its load supply profile. The key instrument behind smart charging is a centralised EV charging controller (EVCC) which is located at the utility control centre. The EVCC is responsible for coordinating each energy transfer session in real-time to accommodate the time-varying nature of the total available power and the number of EVs being charged. In order to accomplish this, the EVCC sends control signals to the EV charging station (EVCS). It also receives the state of charge (SoC) of the battery from the EVCS through the communication networks. It is important to note that fast and reliable transfer is a key requirement for EV charging systems. This is because, the SoC update messages are very critical for EV charging applications, since the controller relies on them to adjust the charging rate. They are also delay sensitive because the charger may remain idle and energy may only be transferred (hence, wasted) until a status against the SoC update message is received (Khan et al., 2013).

2.2.2.6. Distributed Grid Management (DGM)

This encompasses the various Smart Grid automation technologies for real-time information and remotely controlled devices. This also provides utility companies with a comprehensive suite of applications and tools for efficient, reliable and cost effective management of distribution networks. The applications involve technologies that can integrate different grid applications such as Substation Automation, Video Surveillance, SCADA and Automatic Vehicle Location (AVL) used for directing workforce to locate faults that need to be repaired (Seal and Uluski, 2012).

In the substation automation domain, the IEC 61850 (CODE, 2003) and the Distributed Network Protocol version 3 (DNP3) /IEEE 1815 (Majdalawieh et al., 2007) are the most widely adopted communication standards. The IEC 61850 standard is more widely used because it covers almost all aspects of the substation automation, including real-time high bandwidth protection and control applications. The DNP3 only provides communication specifications for low-bandwidth monitoring and control operations. IEC 61850 is designed to run over a standard communication network based on the Ethernet and IP standards. It also defines five traffic types to differentiate among applications and prioritise their traffic flows (Sidhu and Gangadharan, 2005). The first three types are time-critical and are used in the protection and control of the substation, they include: Sampled Values (SV), Generic Object Oriented Substation Event (GOOSE), and Generic Substation State Event (GSSE). The remaining types are: Time Sync and Client-Server Manufacturing Message Specification (MMS). Table 2-2 illustrates the Smart Grid variable application latency and network bandwidth requirement. Across the network components, Smart Grid application requirements, including criticality factors such as bandwidth and latency, differ from one application to the next, as illustrated in Table 2-2. Deploying different communication technologies in Smart Grid network components to enable functionalities of all the utility applications will require seamless interoperability among these technologies as well as support QoS for different traffic classes. Therefore, the criticality of each application must be enabled through the resilience of the integrated network components and their capabilities to deliver application data with the most appropriate QoS.

Table 2-2: Smart grid applications network bandwidth and latency requirement (Locke and Gallagher, 2010) (Khan and Khan, 2013) (Tsado et al., 2015b)

Smart Grid Applications	**Network Requirement (Throughput)**	**Traffic Type**	**Latency**	**Criticality**
AMI (Billing, Metering)	10 - 100 kbps/node, 500 kbps backhaul	Periodic	2 - 15 s	Low
DSM (DR, Dynamic Pricing and Load Control)	14 - 100 kbps per node per device	Periodic/Random	500 ms to several min	Medium,/High
WASA (WAMS, WAPS, WACS)	600 - 1500 kbps	Random	20 - 200 ms	High
EV Monitoring	9.6 – 56 kbps, 100 kbps is a good target	Random	2s – 5 min	High
DGM	9.6 – 100 kbps	Periodic/Random	0.1 – 2 s	High/Medium
Video surveillance	15 – 128 kbps, camera	Random	1 s	Medium
Operational telephony	8 kbps, call	Random	1 s	High
SCADA	1.8 – 9.6 9.6 kbps	Random	< 0.5	High
DER and storage	9.6 - 56 kbps, depending on the number of energy sources	Periodic/ Random	0.02 – 15 s	High

2.2.3. Data Management

Integration of distributed generation and ever increasing utility applications bring a huge amount of growth in the volume of data that must be managed by the utility company. The evolution of Smart Grid drives has led to a massive increase in the deployment of sensor and actuators (IEDs for SCADA and smart meters), this has resulted in accumulation of enormous sums of data associated with these devices. In order to extract the most value from Smart Grid's data, it is essential for utility companies to develop a data management strategy that takes into account collection, correlation, and analysis of data from disparate sources for conversion into actionable information for grid management and business functions.

Snart Grid's data analysis includes customer analytics, asset analytics and financial analytics, and the practical techniques to support these data analytics are just emerging. The electrical grid will not be smart from just storing real-time household usage data, unless knowledge patterns are generated in real-time and humans can convert this into actionable processes. For example, suppliers should be able to determine house hold utility profiles (or demand profiling) from gas and electricity usage and adjust costs appropriately for billing purposes. This is why novel techniques are being explored to analyse collected data readings in order to identify and explain electricity usage patterns. The techniques include recent advances in data mining and machine learning algorithms for handling and capturing useful patterns on Smart Grid's data.

Smart Grid's data refers to volume, velocity and variety of data, and researchers have begun to explore some of these efforts (Han et al., 2013) (Bryant et al., 2005) (Feller et al., 2013). Currently, it has been observed that data processing with single machines is inhibited by resources (memory and processor speed). An alternative cost-effective solution being explored is horizontally scaling several machines over low-cost networks and storage.

Apart from data security and privacy concerns, other technological challenges of data management include the variability of communication standards due to encoding of data in different specifications and propriety formats. Hence, a typical Smart Grid management system must consist of the following:

- Data Storage Systems: A database for processing Smart Grid's data and providing quick response to data queries. This can be carried out using traditional data base systems such as MySQL and Oracle. However, there have been calls for more open, distributed application development environments such as the Hadoop distributed file system and the in-memory multicore processing to achieve Smart Grid's real time goals and accelerate data processing and calculation (Arenas-Martìnez et al., 2010).

- Data types and handling methods: Data available for processing at the utility companies ranges from structured data to semi-structured and unstructured data. Data with a specific format like meter data, temperature, voltage and geographical coordinates are referred to as structured data, while, unstructured data refers to pictures, audio and video files. The use of middleware systems and complex event processing is required for handling and processing synchronous and asynchronous (event) data in an efficient manner, to deal with information which requires quick response (Budka et al., 2014).
- Data Quality: Accuracy, timeliness, and relevance to specific task being performed are some of the characteristics of good-quality data. Thus, the degree of quality required is significantly dependent on the application data being analysed. For example, in billing applications, a periodic data feed with hourly updates or less would suffice. Whereas, in power flow state estimation and voltage control applications, it is critical to have quality data in a timescale of seconds to minutes, since real-time computations are being made using these quality data at a resolution of 50 or 60 samples per second.

2.2.4. End-to-End Communication

A reliable and effective communication infrastructure with low latency all through the Smart Grid network is required to coordinate and integrate the DER with DGM and the consumer. As earlier stated, Smart Grid network infrastructure is expected to be heterogeneous with seamless interoperability, to successfully meet performance requirements and achieve Smart Grid functionalities. Although a consensus about the architecture and scope of a highly cross-functional infrastructure for Smart Grid has not been reached, some sub-networks have been widely accepted across several domains on the electrical grid. Communications network viewpoint of IEEE P2030 provides sub-network components that interconnect the Smart Grid generation and distribution as well as the transmission and customer premises to form an end-to-end Smart Grid communication model. Derived from (IEEE Standards Association, 2011) and (Saputro et al., 2012), Figure 2-1 shows a communication model for information transmission from home, business and field areas to the control centres. Smart Grid end-to-end communication network is made up of sub-networks which are described briefly in the following sub sections.

2.2.4.1. Home Area Networks (HAN)

HANs are private networks located in the customer premises or domain, which can be used to implement home automation and HEMS. These systems allow monitoring and control of applications for user comfort and efficient management of in-home appliances (Saputro et al., 2012). They also provide access to in-home appliances by allowing every home device to send their power readings over the network to the home meter or gateway outside the house, for Automatic Metering Infrastructure (AMI) applications. HANs are similar to other private networks such as: (1) Industrial Area Networks (IANs) is a communication network coupling and monitoring industrial equipment to provide user comfort, DR and energy management capabilities; (2) Building/Business Area Network (BANs): a network of automation implemented to support a building or business premises.

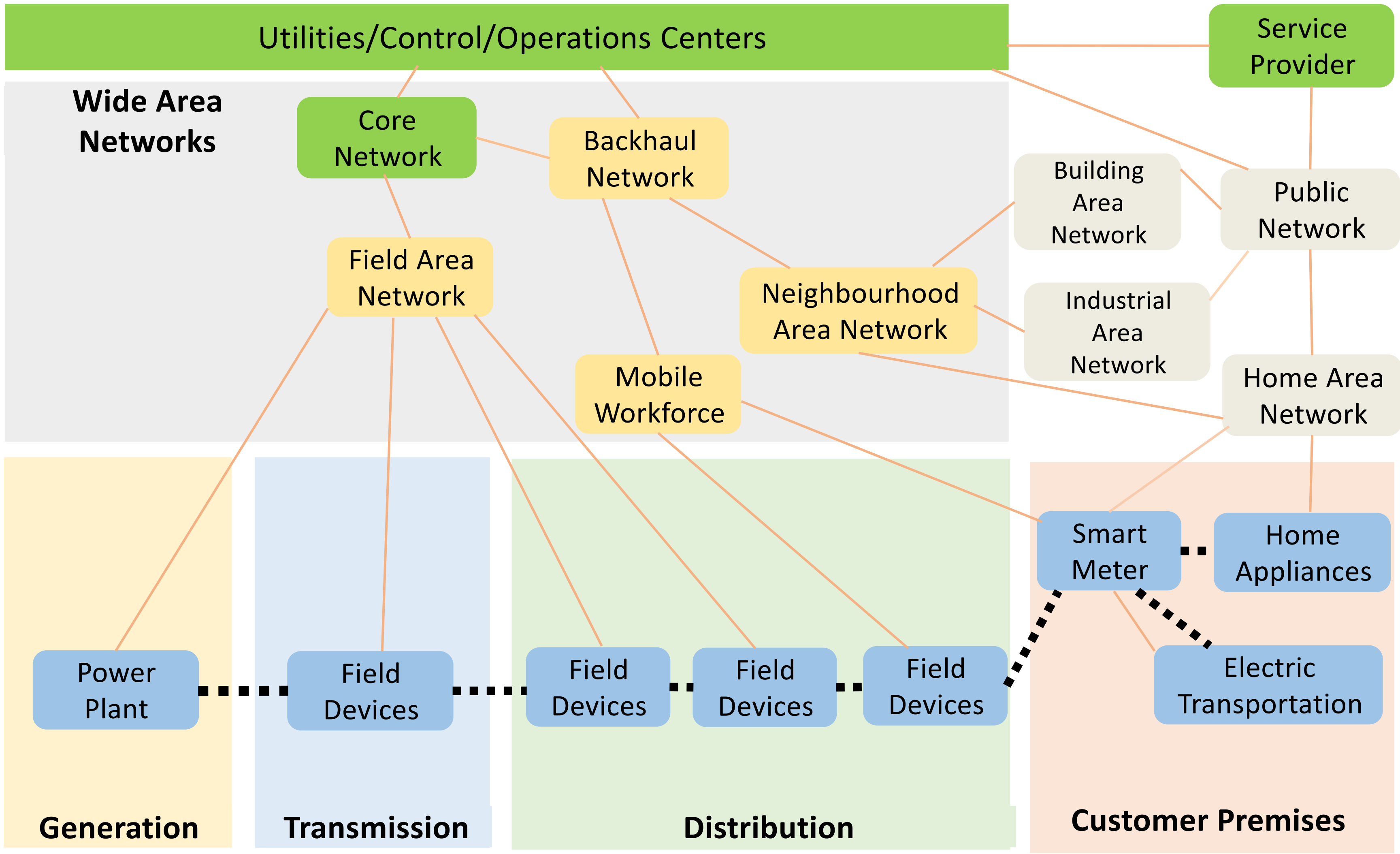


Figure 2-1: Network components for end-to-end communication in Smart Grid (Saputro et al., 2012)

2.2.4.2. Neighbour Area Networks (NAN)

NAN can be regarded as a logical AMI system that connects customer premises and the utility control centre. NAN can be said to involve networks of multiple HANs that deliver the metering data to data-concentrators and deliver control and information data to HANs. Many wireless metering gateways of home/field areas may connect to each other to form a possible wireless mesh network (Gao et al., 2012). For example, smart meters acting as gateways for in-home application data can be used as wireless mesh nodes to transfer information. Smart meters are the major constituent of NAN, acting as the interface between private networks and Utility control centres. NAN end points are either smart meters at the customer end or data concentrators to a group of smart meters at the utility end, which send the aggregated information to the MDMS via a backhaul network (Khan and Khan, 2013).

2.2.4.3. Field Area Network (FAN)

A FAN is a network of field devices such as feeder equipment, transformers, switches and circuit breakers in the transmission and distribution substations that facilitate information exchange between utility control centres. High voltages are usually converted to low voltage as required by homes, businesses and industries. The electricity supplies to customer premises are carried out through the distribution feeder equipment which includes transmission lines and cable poles. Smart Grid FANs will include RTUs, PMUs and Programmable controllers to perform substation automation functions. Automation functions using this terminal unit may be carried out according to embedded logic, or by an external operator/utility command which overrides the internal or local commands. FAN is also responsible for communicating to the utility control, information on DER/micro grids which are connected to the distribution grid (Wang et al., 2011) (Ancillotti et al., 2013a) and (Khalifa et al., 2011).

2.2.4.4. Wide Area Networks (WAN)

WANs are the largest networks for communication to/from data centres. WAN connects smart metering gateways, NANs and FANs with core utility systems and the distribution control system. WAN comprises two types of networks: Backhaul and Core networks (Saputro et al., 2012). Backhaul networks are used to connect NAN to the Core network while the Core network is used to connect the metro network of the utility and substations. WAN coverage spans over thousands of square miles and is used to deliver the large amount of data collected by the highly dispersed Smart Grid network components to the control centre.

2.2.4.5. Mobile Workforce Networks

Mobile Workforce networks are used to provide routine maintenance and operation services by the utility workforce/employees. The network requirements include broadband connectivity that will enhance VOIP, Virtual Private Network (VPN) and geographic information system (GIS) based applications for asset management and logistics. In addition, in-vehicle applications and fleet telematics such as Automatic Vehicle Location (AVL) and location-based services (LBS) with global positioning system (GPS) based tracking and navigation are expected to be integrated with the Mobile Network Work Force.

2.3. Smart Grid Communication Architecture

Understanding the smart grid architecture is vital for identifying and addressing the needs and requirements of the complex end-to-end communication. The most widely accepted Smart Grid architectures are:

1) A model for Smart Grid information networks proposed by the US National Institute of Science and Technology (NIST) architecture (Locke and Gallagher, 2010), which identifies actors, communication pathways, domain interactions, potential applications and capabilities enabled by the interactions in Smart Grid;

2) CEN-CENELEC-ETSI Smart Grid Coordination Group proposed a Smart Grid Architecture Model (SGAM) Framework which aims to offer support for the design of Smart Grids use cases with an architectural approach, allowing for a representation of interoperability viewpoints in a technology neutral manner, both for current implementation of the electrical grid and future implementations of the Smart Grid, and (CEN-CENELEC-ETSI, 2012);

3) The IEEE 2030-2011 standard which provides guidelines regarding Smart Grid architecture and interoperability reference model (SGIRM) (IEEE Standards Association, 2011). SGIRM uses a system-level approach to provide guidance on interoperability among various components of communication, power systems and information technology platforms in the Smart Grid.

The views on communication model shared by the aforementioned research bodies and authors describe and support heterogeneous communication for a functional Smart Grid. However, these models have not presented a coherent heterogeneous end-to-end communication architecture and structure for Smart Grid. Zaballos et al (Zaballos et al., 2011) proposed a communication paradigm based on Smart Grid network requirements to support end-to-end information flow between the application domains in Smart Grid. This paradigm aims to achieve end to end integration of all communications required by Smart

Grid, using the International Telecommunication Union's (ITU) Ubiquitous Sensor Network (USN) architecture. The network architecture successfully adapts and applies the ITU-Telecommunication Standardisation Sector USN Next Generation Network (ITU-T USN /NGN) system to Smart Grid architecture to allow better management of QoS and facilitate interoperability with other technologies. The USN based heterogeneous communication architecture for Smart Grid is adopted in this research as the platform for seamless and efficient end-to-end Smart Grid communication.

2.3.1. Adaptation of USN layers for Smart Grid

Integrating the actions of consumers and generators in an electrical grid will involve a system of distributed sensor nodes that will interact with themselves as well as with the electrical infrastructure to provide and process information extracted from the physical world. Applications of sensor nodes can be assigned to any of the following three useful elements in Smart Grid applications (ITU-T Technology Watch Briefing Report Series, February 2008):

- Detection – e.g., measure temperatures of transformers, pressure, sound, humidity and motion of intruders on electrical equipment.
- Tracking – e.g., household items or equipment, supply and distribution of electricity, plug in electrical vehicles in intelligent transport systems.
- Monitoring – e.g., monitoring of inhospitable environments such as volcanoes, hurricanes and storms that may affect the grid.

To achieve communication over long distances, sensor networks may require routing and multi-hop protocols which can increase delay and reduce the reliability of the communication network. Adapting the USN architecture for Smart Grid sensors network will allow communication over long distance and provide reliable heterogeneous communication systems, which define interoperability with a NGN as the Smart Grid backbone (Zaballos et al., 2011). Figure 2-2 shows the proposed schematic model of USN architecture applied to Smart Grid. USN's capabilities to support requirements for AMI have been discussed in ITU Telecommunications standardisation sector (ITU-T) Question 25/16, "Framework of USN applications and services for smart metering (F.USN-SM)". Zaballos et al (Zaballos et al., 2011) also discussed a similar approach but with emphasis on a network architecture that will integrate all the communications requested by Smart Grid applications in a single system. The schematic model in Figure 2-2 depicts communication between the USN sensor networking layer through the access network to the USN applications and services. The description of smart grid activity in each layer together with the required network component is presented in the following sub-section.

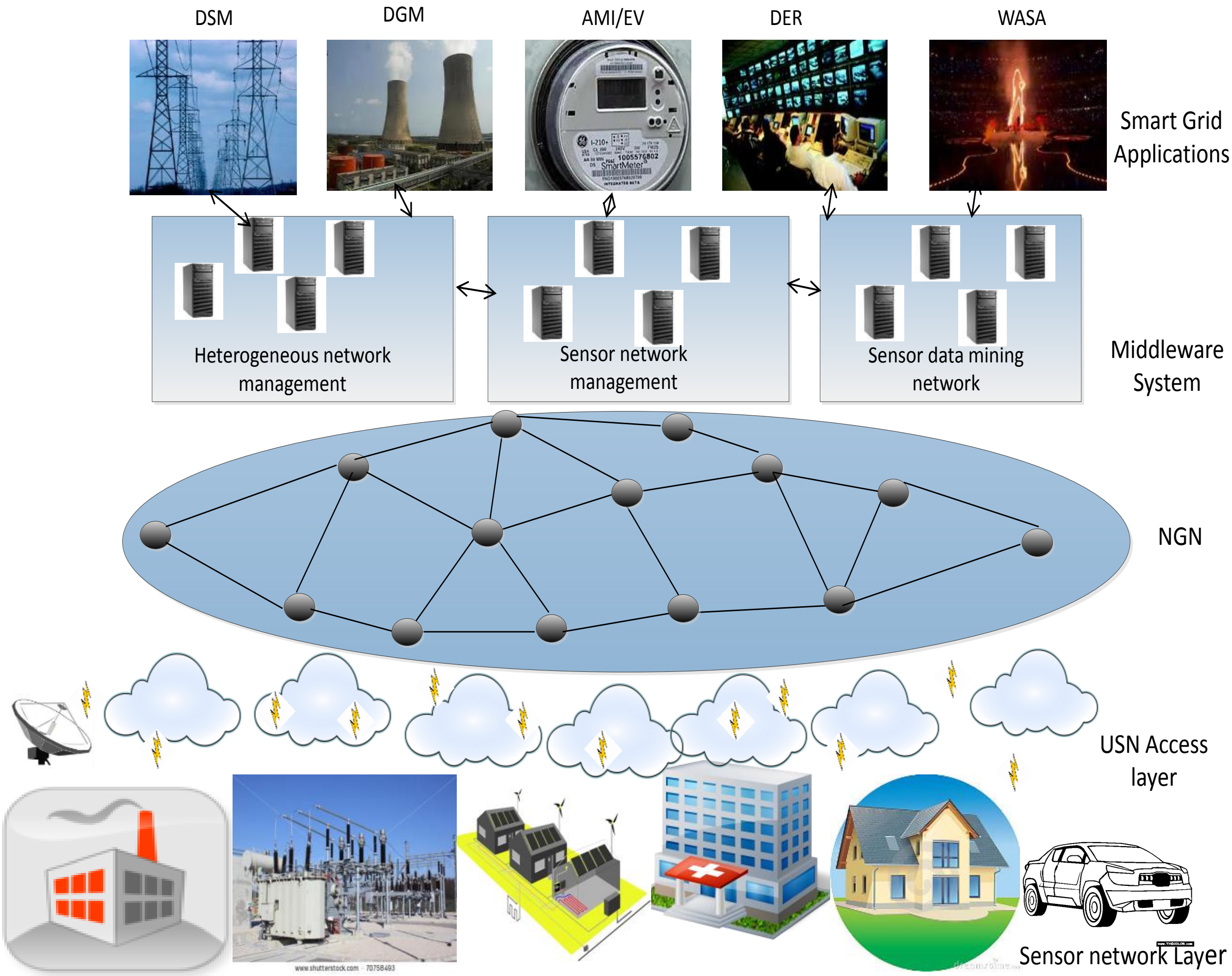


Figure 2-2: Schematic layers of the USN sensor network applied to Smart Grid

2.3.2. USN Sensor Network Layer

The areas of the electricity system where tracking, monitoring, detection and physical quantities are measured are the FANs, IANs, BANs and HANs. Energy management and automation of equipment and appliances in residential and institutional buildings, industrial facilities, transmission lines, substations and distribution systems require the use of sensors and actuators. A network of interconnected sensor nodes are expected to measure and exchange sensed data within BANs, IANs, FANs and HANs through wired or wireless processing. The data is then communicated to other networks through USN gateways or Access Point (AP). For example, in HAN, appliances and related fittings can be monitored through the activities of sensor nodes and communicated to the sensor gateway or APs which is mostly smart meters. As discussed earlier, the aim of home automation and energy management is to enable control and monitoring signals from appliances and basic services. A similar interconnection of sensor nodes is also expected in the FAN, which comprises substation monitoring, control and protection of distribution and transmission systems. The schematic layers of the USN architecture and the corresponding smart grid network components are presented in Figure 2-3.

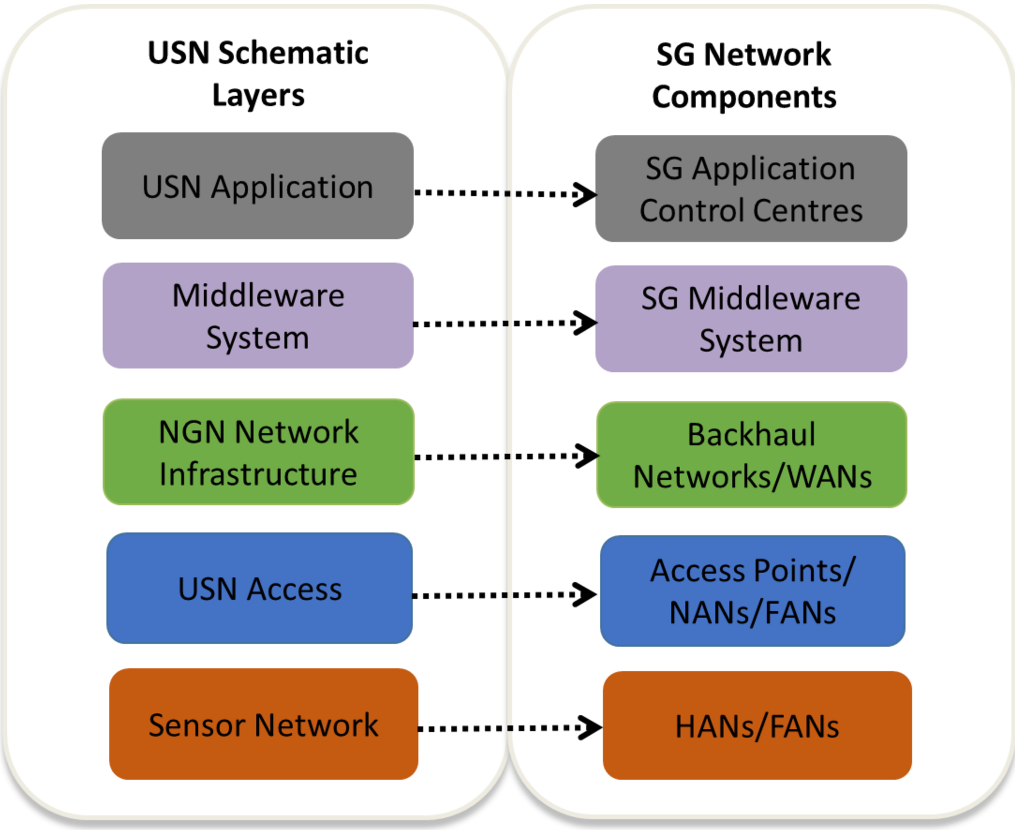


Figure 2-3: USN layers with corresponding Smart Grid network components.

2.3.3. USN Access Network Layer

Access networks involve USN intermediary or "sink nodes" collecting information from a group of sensors or sensor networks that will facilitate communication with a control centre or with utilities. For example, transmitting information received from smart appliances in HAN to the Utilities/AMI control centre through smart meters or NANs. Similarly in FANs, field devices such as RTUs and Programmable Logic Controllers can be used to send information about the electrical grid to external operators or utilities. The information can be sent by field devices transmitting information to the utility/control centres through WANs or backbone networks connected to FANs. Smart meters and RTU's can serve as APs/gateways and have WANs provide the links to Utilities, DMS, AMI, and other Smart Grid applications control centres.

2.3.4. USN Next Generation Network (NGN) layer

In simple terms, the USN NGN is a backbone network infrastructure expected to perform only data transport to enhance two-way communication between the sensor nodes and the USN access network. Selection of a common transport layer based on the internet protocol (IP) for smart grid is being considered by many authors and research groups (Gomez and Paradells, 2010), however achieving this goal requires a number of developments to successfully encapsulate legacy protocols within IP, whilst addressing the need for strict QoS. The development of protocols for sensor networks, as well as internetworking with backbone network infrastructures such as NGN, is one of the most important standard issues for USN (ITU-T Technology Watch Briefing Report Series, February 2008). For this purpose, ITU-T's recommendation in Y.211 defines a generic end-to-end architecture for the QoS resource control in NGNs. It aims to provide QoS management of new end-to-end services and multimedia communications through diverse NGNs. The ITU NGN model has also suggested an Open Service Environment (OSE) capability (T-REC, 2008) that will allow the creation of enhanced and flexible services based on the use of standard interfaces, reuse, portability, and accessibility of services.

2.3.5. USN Middleware Layer for Smart Grid

The middleware system is a software layer running above the communication network which enables communication and data management services for distributed applications. In (Ancillotti et al., 2013a), the middleware system was described as a major component of Smart Grid communications because it provides standard interfaces between applications and Smart Grid devices. Middleware solutions also provide different sets of abstraction and programming interfaces to applications, which include distributed objects, event notifications, distributed content management and synchronous/asynchronous communication functions (Ancillotti et al., 2013a) (Kim et al., 2010).

In the context of the USN architecture, middleware is responsible for translating information between the NGN and USN application layers, which refers to the Smart Grid application and control centre. USN has different standardisation activities which have underscored the role of middleware in an efficient heterogeneous operation system between various sensors and communication technologies. Without a middleware system, direct interaction between components in the Smart Grid communication architecture will lead to a large number of use cases and make the system more complex. This is because direct communication with Smart Grid applications through different communication technologies will necessitate consideration of several different specifications.

One method of alleviating the complexity of such a system is by using fewer communication standards in the middleware. The middleware can also provide a level of abstraction from the complexity and heterogeneity of the communication networks and management of distributed applications by providing an API that encapsulates the access to technologies being used. A USN architecture middleware solution is preferable to having a heterogeneous Smart Grid communication on direct application-to-application connections. A middleware communication bus is illustrated in Figure 2-4.

The Electronics and Telecommunications Research Institute's (ETRI) Common System for Middleware of Sensor Networks (COSMOS) was recommended as a middleware for the smart grid USN architecture (Zaballos et al., 2011). COSMOS is designed to provide integrated data processing over multiple heterogeneous sensor networks based on sensor network abstraction (called the sensor network common interface) and to support real field applications (Kim et al., 2008). However, enhancement of COSMOS using a service oriented middleware system is required to access devices (sensor nodes) and also support criticality and QoS for Smart Grid applications (Martínez et al., 2013) (Zhou and Rodrigues, 2013).

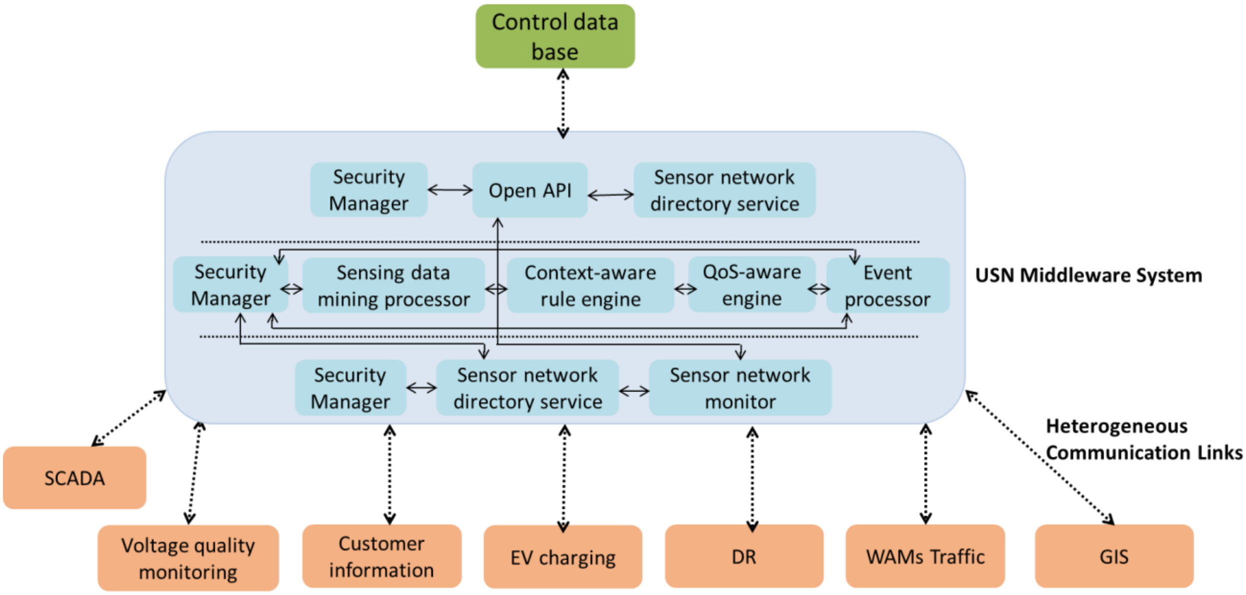


Figure 2-4: USN Middleware communication bus

2.4. Smart Grid Communication Technologies

Heterogeneous communication simply implies that wireless and wired media technologies will co-exist within the Smart Grid USN architecture. This section presents the current state of available wired and wireless communication technologies that may be used in the Smart Grid USN architecture. A summary of their characteristics as well as their pros and cons are also discussed.

2.4.1. Wireless Communication Technologies

The feasibility of communication without a tangible connection between nodes is one of the most important characteristics of wireless communication. This characteristic can ensure continued communication of application data for wireless nodes, even when electrical infrastructure (poles and cables) are displaced, by providing redundant communication paths for nodes affected in the network (Aravinthan et al., 2011). Another important advantage of wireless technologies is that it provides long distance coverage. Wireless technologies such as Wireless Personal Area Networks (WPAN) and WLAN with lower coverage areas can increase their range of communication through multi-hop networks. Both single and multi-hop networks together with backhaul wireless technologies can provide a dedicated network for smart grid communication. Hybrid network architecture of WIMAX and Wireless Mesh Network (WMN) presented in (Gungor and Lambert, 2006), describe a group of electrical utility subscribers clustered into wireless mesh domains, each of which can be easily managed by a control centre using different wireless standards communication. Heterogeneous layer wireless communication standards can also be deployed in NAN/FAN to minimise cost and overcome the range issues with sensor nodes, by using different wireless communication standards. Most wireless communication standards are easily classified based on their transmission range. Other means by which these standards differ are in areas of bandwidth, frequency ranges and mode of networking topologies. They can operate as:

i) Single-hop networks, also called infrastructure-based wireless network which refers to a client and server or master and slave communication, it features a central connection point referred to as hub nodes that could be an AP, network hub, switch or router communicating with several nodes in the network.
ii) Multi-hop networking, network coverage area is often much larger than radio range of single node(s), neighbouring nodes can be used as relays to reach some destination nodes. The two most mature and consolidated examples of networking technologies using multi-hop communications are WMN and Wireless Sensor Networks (WSN). Larger networks based on multi-hop networking such as ad hoc network paradigm can also be configured to carry out WMN.

2.4.1.1. IEEE 802.15 (WPAN) Standard

Technologies that address mid to high data rates for voice, PC and LANs can be reused to implement local Smart Grid networks. No other standard meets the unique needs of sensors and control devices as well as the IEEE 802.15.4 (zigbee) (Sidhu et al., 2007). WPAN supports star, tree, and mesh topologies and has standardised 'layers' that facilitate and trade-off features such as low-cost, easy implementation, short-range operation, adequate security and very low power consumption. Power consumption also varies depending upon the topology being used. Zigbee operates on the 2.4 GHz, 915 MHz and 868 MHz frequency band with direct-sequence spread spectrum (DSSS) multiple access technique and offers data rates of 20-250 kbps over distances of about 10m. The routing protocol used is hinged on the network topology that is deployed (Gomez and Paradells, 2010). A number of zigbee routing protocols matching the needs of the HAN have been implemented, they include 6LoWPAN, WirelessHART and Enhanced least-hop first routing protocol.

Zigbee is suitable for Wireless Sensor Networks (WSN) and a good candidate for the sensor network layer such as HAN and FAN where there is an interaction between sensors and power grid equipment (Bou-Harb et al., 2013). Thus, it will find application in Smart Grid operations such as the control of home appliances in HAN, direct load monitoring and control in a substation. Low running cost of implementation and low power consumption can be considered as advantages of Zigbee.

2.4.1.2. IEEE 802.11 (WLAN) Standard

IEEE 802.11 standards also known as Wireless Fidelity (WiFi), is a wireless communication technology which defines a set of PHY and MAC layer specification for implementing WLANs. The success of the standard is attributed to: i) unlicensed operating frequency of 2.4 GHz and 5 GHz bands; ii) The use of flexible access schemes based on CSMA/CA principles and iii) The availability of low-cost radio interface. The standard consists of IEEE 802.11a/b/g /n PHY layer modes operating in the 2.4 GHz and 5 GHz band. Until 2013, the highest data rates were supported by the 802.11n standard, which integrates OFDM-based transmission of 802.11a/g with multiple-input multiple-output (MIMO) antennas to boost the transmission rate to 150Mbps from 54Mbps. However, experimental studies have indicated that outdoor ranges can be up to 300 m for 802.11n based radio (Ancillotti et al., 2013a). In 2013 the IEEE 802.11ac was released with data rates of 500 Mbps. The IEEE 802.11ax standard which targets a data rate of 10 Gbps is expected to be released in 2019 (Sidhu et al., 2007). Other WiFi standards suitable for smart grid are 802.11e which offers QoS features and 802.11s standard which defines a mechanism to support multi-hop transmissions and build wireless mesh network on top of the 802.11 physical layer. IEEE 802.11p WiFi standard is also a key enabling technology for Smart Grid Vehicle-to-Grid (V2G) systems because it supports wireless access in vehicular environments.

IEEE 802.11 networking in Smart Grid mostly comprises single hop infrastructure and mesh multi-hop network. The benefit of using Wireless Mesh Network (WMN) topologies is the redundant paths provided by the wireless backbone between the sender and receiver, which eliminates single point failures and bottleneck links in the network. These alternative routes result in increased communication reliability and robustness against problems that may occur in the network due to path loss or RF interferences. 802.11 single hop networking in Smart Grid provides wireless connection to the end user through the deployment of Wi-Fi APs. Ensuring full coverage of an area, requires the deployment of a large number of APs, connected through a backbone link to a Smart Grid control centre. The growth and pervasiveness of WLAN has helped the technology to grow in to consumer electronics devices such as Internet telephony, music streaming, gaming and in-home video transmission. IEEE 802.11s defines how wireless devices such as sensors can be connected to create ad hoc WMN networks over the PHY layer of the IEEE 802.11 a/b/g/n.

As for any wireless technology, the IEEE 802.11 is also vulnerable to threats such as traffic analysis, passive/active eavesdropping; man in the middle attack and session hijacking, that can lead to Denial of Service (DoS); and replay attacks. WLAN is a potential technology for HAN and FAN, however, it is faced with the challenge of poor reliability when multiple users access the network. WLAN will find application in the sensor network layer of the USN architecture. WLAN can be deployed for Substation automation and protection, monitoring and control of remote distributed energy resources and redundant link for distribution automation systems. Other areas include enhanced transformer differential protection Communication aided line protection, and Inter-substation communication (Parikh et al., 2010). The capability of 802.11 to meet the data rate requirement of Smart Grid applications is its major advantage, however, there are concerns of limited availability of industrial WLAN equipment. Furthermore, WLAN security mechanisms are well known to be vulnerable. Security considerations must be improved to provide additional protection.

2.4.1.3. IEEE 802.16 (WIMAX) Standard

World Interoperability for Microwave Access better known as WIMAX is an IEEE 802.16 approved standard for wireless wide band access. WIMAX supports long distance (7-10 km) broadband (100 Mbps) wireless communication. It was conceived as a complementary technology to IEEE 802.11 because it supports a connection-oriented control of channel bandwidth and thousands of simultaneous users over wider areas and makes ubiquitous internet possible. WIMAX also operates on licensed frequency band with QoS mechanism, which is more sophisticated compared to 802.11e and supports point to point, point to multipoint or mesh and hybrid (multi-hop relay) topologies. WIMAX is considered for long and short distance communications in Smart Grid and can find application in core and backhaul network components of Smart Grid. WIMAX has also been deployed for real-time pricing; AMR and outage detection and restoration applications (Parikh et al., 2010).

High data rates are considered as the advantage of WIMAX, nonetheless, the high cost of WIMAX equipment such as Radio frequency tower and spectrum license that may be required is a limitation.

2.4.1.4. LTE and 3GPP cellular networks

Cellular network technology has constantly evolved to achieve performance and scalability breakthrough across different network generations, with varying cell site ranges for different deployment scenarios. It covers huge number of devices and provides ubiquitous coverage worldwide. Third-generation (3G) and fourth-generation (4G) cellular technology Long Term Evolution (LTE) operational frequency bands vary in different countries; higher data transmission rates may reach 768 kb/s - 100MB/s, while the distance depends on the availability of cellular service coverage. The cellular network enables topologies that facilitate non interrupted data flow and can also receive and transmit data from Ethernet and other wired and wireless interfaces (Parikh et al., 2010). This means that its USN architecture makes it suitable for adoption for NAN communication mechanism or the USN access layer.

Both WIMAX and 3GPP cellular networks have very good coverage and are most suitable for WAN transmission links between the USN access layer and the application layer systems. Customers will have to pay for using their services and the cost may be higher if a particular QoS (or critical service level) is required for Smart Grid traffic. LTE and 3GPP cellular can also be deployed as SCADA interface for remote distribution substation and monitoring of remote DERs and wide coverage. Indeed, high data rates are considered as the advantages of LTE and 3GPP cellular technologies. Recent developments on Critical features such as: LTE in unlicensed spectrum, LTE enhancements for M2M communication, and enhanced multi-user transmission techniques, have been added to the 3GPP standards, which is available in 3GPP release 13 of 2016. This will strengthen its capability for Smart Grid. However, the technology is faced with limitation such as: (1) Call establishment may take time and delay, (2) Drop calls experienced in the network as a result of congestion, poor radio coverage and radio interference can hinder data exchange of critical applications, and (3) QoS capability is available within 3GPP standards but there is no evidence of its thorough implementation, or use beyond basic prioritisation (for consumer) methods.

2.4.1.5. Terrestrial Trunk Radio (TETRA) communications

TETRA is targeted primarily at the mobile radio's need for critical communication from applications such as public safety (police, security services, military services, ambulance and fire departments). However, it has also attracted the attention of utility companies. TETRA's operating frequency is between 380 MHz to 470 MHz in the EU and 806 MHz and 912 MHz in Asia, defining 5 MHz band for emergency services and 10 MHz band for civil services. The standard operates is full duplex and defines 24 kHz carrier spacing for both uplink and downlink channels (Equipment).

The main objective of TETRA is to have standard interfaces, facilities and services such as guaranteed interoperability, versatility, efficiency, robustness and security. It is a standard solution for groups that use both Private/Professional Mobile Radio (PMR) and Public Access Mobile Radio (PAMR). It takes its features from several technology areas such as mobile radio, digital cellular telephone, paging and wireless data. TETRA Enhanced Data services (TEDs) have evolved from TETRA to address the needs of data extensive applications (Equipment). TETRA is applicable for USN access network for smart meters. It is known to have good penetration through walls, which makes it suitable for the sensor network layer (HAN and HEMS). TETRA can also provide WAN links between USN access networks and the application layer and will find applications in smart metering or connecting residences to the grid.

The challenge of using TETRA in Smart Grid is its low throughput, licensing and equipment cost. However, its advantages that will enhance its deployment for Smart Grid are its resilience to critical communication and long range transmission capability, which is as a result of its low transmission frequency.

2.4.2. Wired Communication Technologies

In terms of reliability, security and bandwidth, wired technologies are considered superior to wireless technologies because cables are easier to protect from interference and eavesdroppers. Furthermore, the equipment and cost of maintenance is cheaper compared to wireless solutions. Consequently, utility operators preferred wired communication technologies because they were considered the most reliable option for a communication network. The most important wired technologies that are used in smart grids are:

2.4.2.1. Power Line Communication (PLC)

PLC is a process of data transmission through the electric power grid cables. It was initially intended to monitor faults on distribution lines, but has now gained a lot of attention and development over the years for communication in Medium and Low voltage network of the electrical grid. PLC is categorised as Broadband Power Line Communication (BPLC) and Narrow Band Power Line Communications (NBPLC) according to the frequency of operation. NBPLC operates in frequency bands of 9 - 148.5 kHz in Europe and 450 kHz in the US and delivers bit rates from 2 kbps to 500 kbps (Adebisi et al., 2011). On the other hand, BPLC provides throughputs between 10- 300 Mbps and can be used in home LAN and USN access networks. The power line carrier provides a harsh environment for data transmission which leads to continuously changing channel conditions. This brings about varying throughput to ensure a required QoS (Zaballos et al., 2011).

Research and pilot projects have been initiated to investigate and develop communication platforms for Smart Grid applications (Adebisi et al., 2011). A combination of Zigbee and PLC will provide a good concept of interconnecting sensor nodes in LV and MV levels of the grid. These solutions can be considered for Smart Grid applications such as AMI, SCADA and video surveillance. PLC is suitable technology for the USN sensor network, USN access network and the NGN, because it is potentially accessible to every customer and can reach every location on the grid, even where there are underground cables that are not readily accessible by wireless communication technologies.

PLC also has the advantage of being owned by the grid operator which allows control of the communication network. Other advantages of PLC technology include low-cost of implementation and no license fees or service overhead from providers, as well as the permanent connection accessibility compared to other technologies.

The down side of PLC is that signals cannot propagate across electrical transformers and high technical efforts are still required for improvement of this technology and to address these limitations. In addition, data rate limitations of NBPLC may affect transmitting information from the USN NGN layer to the application layer or utility because of the large volumes of data that may be involved. In most PLC network deployments, transmissions over transformers have been carried out using a bridge (coaxial or optical cable) over the transformer.

2.4.2.2. Digital Subscriber Lines (DSL) communications

DSL refers to a family of technologies that carry out digital transmission over telephone lines. The technology is currently being used to provide broadband internet services to clients. The DSL technology family include the basic Asymmetric DSL (ADSL), ADSL2^{+}, ADSL2^{++} and the Very High bit rate DSL (VDSL or VHDSL). As the name implies VDSL provides faster data transmission in short distances of up to 52 Mbps downstream and 16 Mbps upstream over copper wire and up to 85 Mbps down and up link on coaxial (Ancillotti et al., 2013a). The second generationVDSL2 systems are expected to improve on existing ones with achievable data rates of 100 Mbps on both up and down link, at a range of 300 m. The key advantage of using DSL for Smart Grid technologies is the possibility of interconnecting residential areas with control centres, thereby avoiding installation cost of deploying their own private network. However, it will attract a running cost or rental fee to the DSL communication operators.

2.4.3. Optical Wireless Communication for Smart Grid

Optical wireless communication are technologies which transmit in unguided propagation media, through the use of optical carriers, such as light, infrared, and ultraviolet band. Some Optical wireless communication sub categories, fibre optics and visible light communication in particular, will find application in Smart Grid.

2.4.3.1. Optical Fibre communication

Transmission of data through pulses of light over optical fibre has been used by many communication applications and forms the main backbone of the internet that we all use daily. Optical fibres offer benefits over copper cables because they have very low interference and attenuation, which enables transmission of data over long distances, making them suitable for high demand applications. The fibre optic cable distance coverage is an average of 100 km compared to 2 km distance coverage by copper before the signal is boosted or regenerated (Witcher). Fibre-optic is a potential candidate for Smart Grid applications because it is immune to electromagnetic interference, reliable, has low latency and high data capacity, all of which are desirable features of Smart Grid NAN and WAN communication technology (Lévesque and Maier, 2012). It is also suitable for the USN access network and NGN layers of the USN architecture for Smart Grid.

Security concerns relate mainly to the physical intrusion onto the fibres. Once an intruder gains access to the fibre, information is easily compromised. Tight physical access control to fibre needs to be implemented (Witcher). The major factors affecting its deployment are high cost of installation, which may not be an issue if the running cost and maintenance cost are considered over a period of time. Applications of fibre-optics for Smart Grid operations are in areas of inter-substation communication. They can also be installed along transmission lines and underground facilities to provide communication links with back end systems. Despite the high data rates and throughput provided by fibre-optics technologies, cost of implementation and installation is a limitation that can hinder its deployment for Smart Grid.

2.4.3.2. Visible Light Communications (VLC)

VLC is a sub-category of optical wireless communications, including Infrared and Ultra Violet communications. VLC communications take place by modulating the intensity of the LED light in such a way that it is undetectable to the human eyes, then using a photo sensitive detector as a receiver to demodulate the light signal into electronic form (Chang et al., 2012). In simple terms, it adds communication to the original purpose of LED light, which is illumination.

VLC can serve as an alternative to radio wave wireless technologies because of the growing challenges of radio wave communications such as: (i) increase in demand of spectrum and congestion in communication channels (ii) inefficient usage of power and (iii) reduce health risks associated with radio frequency signals on humans (Bhalerao et al., 2013) (Bhalerao and Sonavane, 2014). Current and potential application of VLC are in areas of transport systems, smart traffic systems, dangerous and extreme environments, real-time audio and video transmission, hospitals, public and industrial sector (Bhalerao et al., 2013) (Bhalerao and Sonavane, 2014) (Hou et al., 2015). With regards to Smart Grid it can find application in HEMs, HANs and distribution grid management. VLC is still new and technical enhancements and standardization activities are still being carried out on physical and medium access layers such as the P802.15.7 IEEE draft standard published in November 2010. VLC can transmit signals of up to 500 Mbps for a distance of 5 meters and at low data rates, it can transmit up to a distance of 1 to 2 km. The Home Gigabit Access Project (OMEGA) in 2010 enabled the transmission speed of 1 Gbps via a heterogeneous network which included VLC, Infrared and PLC.

The advantages of VLC when deployed for Smart Grid is that it is license-free and it is not associated with any charges. It also has low-cost front end devices as well as an unregulated huge bandwidth for point to point communications. In addition, VLC can be combined with other communication technologies such as PLC to increase data rate and communication distance. Since VLC is still in its early stages, there are many severe technical limitations such as multipath distortion and interference from sunlight etc. The ongoing VLC research activities and standardisation can be extended towards its consideration for Smart Grid deployment.

A summary of the characteristics of all the communication technologies discussed in this section is presented in Table 2-3. The table classifies the communication technologies that can be deployed as LANs are as Local, while those that can be deployed across a long distance are classified as backhaul.

Table 2-3: Characteristics of Smart Grid communication technologies

Communication technology standards	Local or backhaul System	Maximum data rate	Approximate coverage	Potential smart grid application
IEEE-802.11 (WLAN)	Local	11 - 600 Mbps	Up to 300 m	HEMS, DSM, DA and protection
IEEE-802.15.4 (Zigbee)	Local	20 -250 kbps (2.4 GHz) 40 kbps (915 MHz)	10 -100 m	HEMS, DER, AMI
IEEE-802.16 (WIMAX)	Backhaul	Up to 1 Gbps for fixed users	30 -100 km	AMI, WASA, AMI,
3GPP CELLULAR (3G, 4G: LTE, LTE advanced)	Backhaul	500 Mbps up link 1Gbps down link	10-100 km	WASA, EV, AMI
Optical Fibres	Backhaul	155-2448 Mbps up, 1.244-2.448 Gbps down	Up to 60 km	WASA, Distributed Grid Management
PLC (NB-PLC & BPLC)	Local and Backhaul	1-500 kbps (NB-PLC) 1-10 Mbps	NB-PLC: over 150 km BB-PLC: ~ 15 km	AMI, Electric transportation monitoring, DSM, Distributed Grid Management
TETRA	Local and Backhaul	170 kbps	10 -50 km	AMI, DSM
Digital Subscriber Line (DSL)	Backhaul	256 kbps – 200 Mbps down	Up to 7 km	AMI, DSM
Visible Light Communication (VLC)	Local	10 kbps-500 Mbps	Over 5 meters	HEMS, Distribution grid management

2.5. Communication Technologies for NAN

Smart Grid's major applications and their basic networking components have been discussed in previous sections. It is evident that a heterogeneous communication network is required for Smart Grid, and it needs to support a wide range of traffic sources with significantly varying QoS requirements. The USN architecture for Smart Grid proposed in section 2.3 also identified the NGN as a key layer to support QoS for varying Smart Grid traffic. The NGN does not require the creation of new communication technologies; instead, it refers to enhancing and retrofitting the existing technologies to efficiently carry out Smart Grid functionalities. In this section, the factors that determine the choice of communications technology is presented. Based on these factors, a communication technology is selected for the NAN sub-network component of Smart Grid, which is the main area of study in this thesis. Some of the key challenges of the selected technology in Smart Grid are also presented.

2.5.1. Factors that determine choice of communication technologies

The selection of communication technologies to be deployed at different Smart Grid network components will depend on technical and economic factors. This section describes the economic and technical factors necessary for the selection of communication technologies to be deployed at the appropriate elements of the Smart Grid USN.

2.5.1.1. Economic Factors

- Accessibility: Ease of access or the degree to which a communication technology is available to be deployed for Smart Grid networking purposes. Monitoring and controlling electrical components may be located in remote areas with limited accessibility, i.e. underground feeder cables and meters. Consideration for this limitation must be put in place when deploying Smart Grid communication technology.

- *Ownership*: Due to the heterogeneous nature of the Smart Grid, the communication network infrastructure may span across different owners. They could be public, private or even have a combination of public and private ownership of Smart Grid communication networks and devices.

- *Installation*: This has impact on cost, challenges and risks associated with setting up a communication network. Some communication infrastructures are expensive or take time to install. Assessing the practicalities associated with installation will influence a utility or grid operator in their decision upon which technologies and mechanisms to use for Smart Grid communications.

- *Running cost*: This is the cost or amount of money expended to operate and manage a communication network over a period of time. It has a huge impact as it recurs throughout the lifetime of the technology.

2.5.1.2. Technical Factors

- *Latency*, in Smart Grid, latency can be defined as the time between when a state occurred and when it was acted upon by an application (Kansal and Bose, 2012). Many critical applications have tight delay constraints such that the latency requirement corresponds with a physical reaction time (i.e. control signals may be required to switch a relay to mitigate a short circuit failure within a defined time). Among different types of delays, communication delays that consist of transmission delays, propagation delays, processing delays and queuing delays add up to Smart Grid latency. If these delays exceed a required time window the information may not serve its purpose, therefore delays must be examined to understand the overall behaviour of the communication network. For example, application classes like WAM systems comprise hundreds of PMU's deployed at various locations in a national electrical grid system. Measurements from PMU's are first collected by a PMU data concentrator (PDC) via a local communication network, and then sent to the central control network (CCN) located at the utilities core network via the backhaul communication networks. Communications between PMU's and PDC must be within a strict delay (< 1s) (Khan and Khan, 2013). Similarly, in distribution automation, the IEDs deployed in substations are required to send their measurements to data aggregators within 4 ms, while communications between data aggregators and utility control centres also require a network latency ⩽8–12 ms (IEEE Standard Association 1646, Feb. 25, 2005).

- *Bandwid*th, is measure of the width of a range of frequencies measured in Hz. The ranges of frequencies (i.e. difference between the upper and lower frequencies) are used as boundaries by which data is transmitted in different communication technologies. Every wireless and wired Smart Grid communication system has a frequency band for transmitting data. Bandwidth and packet sizes affects data throughput.

- *Reliability & Resilien*ce: The ability of a communication network to absorb or mitigate disruptions in the network. Disruptive challenges on the network could be man-made (power failure, hacker) or natural (weather effects). An operationally resilient network for Smart Grid is expected to continue delivering essential services even under adverse operating conditions, and should rapidly recover full operational services once the conditions improve (Tsado et al., 2015a). This will bring about stability of the Smart Grid system, which requires a guaranteed data delivery system. Other failures that can affect communications include time-out, network and resource failures (Ramírez and

Céspedes, 2015). A time-out failure occurs if the time spent in detecting, delivering and taking action in response to a control message exceeds the timing requirements (Wang and Leung, 2011). A network failure occurs when there is a failure in one of the layers of the protocol suite employed for communication (i.e., failure originating in a logical level, which prevents packets from reaching their destination. This can occur even if the physical link is operational and may be caused by factors such as noise and interference). A resource failure means that one end node (i.e., sender or receiver) has failed. The mechanisms utilised for reliability measurements is the Packet Delivery Ratio (PDR), which is defined as the ratio between the number of packets received and the number of packets sent (Ramírez and Céspedes, 2015).

- *Throughput*: Throughput is the actual measure of the amount of data a network channel can deliver when delay is considered. It is measured by calculating the average rate of successful data delivery over a communication channel, measured in bits per second (bps). The Smart Grid network must take in to consideration the throughput of the network being deployed for Smart Grid in order to ensure the application data requirements are met. Node processors of communication networks must be able to provide data volumes for supported applications. For example, PMU's are deployed jointly with Transient fault recorder (TFR) and they generate data volumes about transient fault, voltage swings and trends of 100 MB daily (Khan and Khan, 2013).

2.5.2. Requirement for NAN Communication

NAN is the most critical segment that connects utilities and customers in order to enable primarily important Smart Grid applications. Therefore, the communication network must be able to deal with the huge volume of variable application data and important control signal, from and to millions of devices installed at the customer premises. Networking a huge number of devices that are distributed over large geographical areas requires technologies that are scalable, self-configurable and robust to node and link failures. They must also be able to support different types of traffic that require a wide range of reliability and latency for Multipoint-to-Point (MP2P) and Point-to-Multiplepoint (P2MP) traffic.

As a result of the pervasive nature of Smart Grid and the aforementioned requirements, communication technologies such as WSN, ad hoc WMN and PLC are well suited for NAN. While PLC has several advantages, disadvantages such as its inability to reach devices that are turned off and its extensive signal attenuation gives room to explore wireless alternatives. Although the wireless sensor network standard (IEEE 802.15g) has made outstanding progress in HAN communications, efforts to extend its capabilities to NANs poses many problems. The most critical of them is that it is only capable of providing a maximum data rate of 1 Mbps within one hop range (IEEE Standards Association, 2012).

Networks based on this standard may also suffer from heavy interference when deployed with networking system such as the IEEE 802.11 which have higher data rates and transmission power. In contrast to HANs, NANs require outdoor deployment properties, where the network may support a number of different applications and services in a multi-hop environment.

WMN based on WLAN technologies, particularly IEEE 802.11s standard, have been considered as candidate technologies to provide a high-speed and easy-to-deploy wireless backbone for Smart Grid NAN (Zhang et al., 2011). This is because they are capable of self-organising, self-configuration and self-healing. Other unique features of WMN such as the enhanced distributed channel access (EDCA) which differentiates traffic types can also be used to provide priorities for variable application traffic types in NAN.

2.5.3. Routing Protocols for NAN

Since routing protocols play significant roles in selecting reliable paths to destination in WMNs, routing protocols for NAN based WMN must have sufficient capabilities to support QoS routing and the different requirements of user applications. The default routing protocol for 802.11s (Hybrid Wireless Mesh Protocol or HWMP) is considered to be suited to static mesh routing; which is also a characteristic of NAN. However, like many other static routing protocols, HWMP may pose various problems if implemented in Smart Grid NAN without any modifications. The following subsections present a number of routing protocols that have been classified and are currently being modified for routing in NAN domain. In order to keep the scope of this section limited, only a brief description of the routing protocols are discussed.

Ad Hoc On-Demand Vector (AODV)

AODV routing protocol was originally designed for Mobile Ad Hoc Networks. Its routing process is composed of three phases: (1) the discovery phase which involves a route sending Route Request Packet (RREQ) from source to destination. Each RREQ has a sequence number of every intermediate node in the network which is used to determine whether to forward a packet to the next hop or reply with a Route Reply (RREP) instead; (2) second phase has to do with updating the destination sequence number in the routing tables of intermediate nodes; and (3) data sending then takes place (Bennett and Wicker, 2010). Due to previous research modifications, AODV can be used for routing in NAN as shown in (Farooq and Jung, 2013) (Toimoor, 2013). For example, in (Toimoor, 2013), the authors modified the protocol, such that selected nodes are provided with more intelligence, which contributed to lower latency, compared to the original AODV and made it useful for AMI applications (DR and EV).

Routing Protocol for Low Power and Lossy Networks (RPL) by Winter et al (Winter, 2012)

RPL is distance-vector protocol that can support a variety of data link protocols. It is regarded as the most mature and commercially viable solution for routing in Low power and Lossy Networks (LLN) and has been proposed by the Engineering Task Force (IETF) to enable real time meter readings and real time remote utility management in AMI. However, RPL nodes suffer from severe unreliability problems when tasked with meeting the stringent reliability requirements of AMI (Ancillotti et al., 2013b). This is mainly because RPL lacks a complete knowledge of link qualities and may sometimes select suboptimal paths with highly unreliable links. Thus, further research is required to improve the RPL route selection process in order to increase routing reliability.

Geographic routing

Geographic routing is a distance vector routing protocol which adopts a combination of weighted link metrics and geographical proximity to route data packets. It considers packet forwarding by making use of node position information provided by GPS devices instead of building network addresses and routing tables. Through the knowledge of neighbours' locations, each node selects the next hop that is closer to the destination (Sabbah et al., 2014) (Iyer, 2011). It can be adopted and used with a combination of weighted link metrics. For example in (Lichtensteiger et al., 2010), a WMN system architecture called Geo-Mesh was proposed for energy management applications in NAN, using RF mesh networks.

Dynamic Source Routing (DSR)

DSR protocol is an on-demand routing protocol that uses the concept of source routing. It requires a node to maintain a route cache, which contains source routes that are known by all other nodes. The route cache is continually updated as the nodes learn new routes to the source node. It is based on the RFC 4728 (Johnson et al., 2007). In (Kevre and Shrivastava, 2014) an evaluation of DSR and AODV in a grid-based cluster network was carried out. It considered energy consumed in transmission mode, received mode, idle mode and residual battery capacity (remaining battery after simulation). Results show that AODV has a better consumption of energy than DSR, while the residual battery capacity showed similar values for both protocols.

Distributed Autonomous Depth-First Routing (DADR) (Iwao et al., 2010)

DADR is a proactive distance vector protocol that uses a control mechanism to provide the best available paths for each destination. It also utilises Depth First Search algorithms for path recovery in cases of link failures (Herberg et al., 2013) (Yi et al., 2015). As the data forwarding occurs, all the information learned is used to update the routing table, which happens during periodic “Hello” message exchange among neighbouring nodes. In, a simulation scenario which involved about 2000 smart meters was presented, which showed capability of learning new routes in indoor and outdoor environments and low overheads in large scale networks. The study also showed that packet latency in a flat mesh network is affected by the several hops that data packets traverse to reach the destination.

Hybrid Routing Protocol (HYDRO) (Dawson-Haggerty et al., 2010)

HYDRO is a hybrid link state routing protocol for LLN that provides centralised control. It uses the Directed Acyclic Graphs (DAG) similar to that used by RPL to provide multiple reliable paths to a border router. Each node builds its default route table by adding its neighbouring nodes toward a border router. The entries in the route table are ordered following an ETX metric. There is an expectation of high reliability level with HYDRO protocol, especially for power quality applications, due to the use of multiple and alternative routes. However, there are no considerations for security support and other routing metrics need to be considered to test HYDRO's capability of supporting various AMI applications.

HWMP,

The Hybrid Wireless Mesh Protocol (HWMP) is the multihop default routing protocol for IEEE 802.11s WLAN mesh networking. It was developed to allow interoperability between devices from different vendors; HWMP serves as a common path selection protocol for every device that is compliant with IEEE 802.11s standard. The term hybrid denotes the use of both reactive and proactive approaches in the routing scheme. HWMP results from an adaptation of AODV called Radio-Metric AODV, which, unlike AODV, works on layer 2 and uses a radio-aware routing metric. HWMP is discussed in more detail in Chapter 3. There have been modifications of the IEEE 802.11s standard routing protocol Hybrid wireless mesh network protocol (HWMP) (Jung et al., 2011) (Saputro and Akkaya, 2015), which considered the use of HWMP in a smart grid deployment by reducing the broadcast storm caused (Address Resolution Protocol) and utilising the air cost (failure rate of each node calculated by MAC retransmission count of each packet) as a performance metric. This new method gives more priority to retransmission of small packets, as they are likely to have fewer bit errors. As a consequence, the protocol becomes more adapted for the NAN domain and improves reliability for the applications that are part of the smart grid architecture.

2.5.4. Key Research Challenge

Many Smart Grid applications require highly reliable message delivery within specified delay, as they act as triggering points for the underlying monitoring, protection and control. As a result, all protocols that will coexist in the network must support different traffic patterns (i.e. P2P, P2MP, and MP2P).

However, not all the aforementioned routing protocols support the different Smart Grid traffic patterns. The performance and functionality of the applications traffic has to be determined in objective terms (e.g. message delivery success rate) against a set of predefined QoS attributes, such as delay and packet-loss for each individual packet. Most protocols also consider a single path metric such as the ETX for discovering paths, which may not be efficient in guaranteeing delay and PDR requirements.

Thus, the routing protocols have to be designed with a network management perspective to support real-time and non real-time communications. The routing protocols in WMN also have to be aware of the status of the intermediate nodes (e.g., their available capabilities and resources) and the requirements of the targeted applications. Furthermore, QoS differentiation in existing communication networks is normally achieved through resource reservation and traffic prioritisation. Specifically, various approaches can be employed to prioritise important delay critical data over loss critical data. For instance, many MAC layers (e.g., 802.11e and 802.16) support the specification of different traffic categories and use scheduling algorithms to provide bandwidth differentiation (Wu et al., 2012, Piro et al., 2012). However, MAC-based solutions are generally limited to providing QoS guarantees on single communication links.

For this reason, there is an increasing awareness that a fully-fledged cross-layer QoS-based architecture, as well as QoS-aware routing that allows selecting network routes with sufficient resources for requested QoS parameters, is needed to guarantee and satisfy the different end-to-end requirements of Smart Grid applications (Ramírez and Céspedes, 2015). More research is also needed to study network performance under multimode communications. For example, P2MP and MP2P utilise multiple paths simultaneously, which may increase interference and possibly cause congestion. The research in this thesis concentrates on improving routing in NAN based WMN using the Optimised Link State Routing (OLSR) protocol to adaptively support requirements for targeted Smart Grid application.

2.5.5. Why Optimised Link State Routing (OLSR)

OLSR is a well-known routing protocol for WMN that have been implemented on several network simulation tools and COTS devices. Several proposed link metrics and cross-layer metrics to improve routing and capture the best paths in order to increase the performance of WMN have been integrated with OLSR. While most of the proposed protocols have solved particular issues for multimedia applications, they have not been implemented for Smart Grid AMI applications traffic. Therefore, the thesis focuses on studying the performance of OLSR, when deployed as the routing protocol in NAN based ad hoc WMN for AMI. It also attempts to improve OLSR reliability, as well as adaptively support requirements for different Smart Grid applications through the implementation of multiple OLSR link metric versions.

2.6. Chapter Summary

This chapter started by presenting the legacy in the electrical grid and its evolvement towards a smarter and intelligent grid. A study and classification of the applications, communication network components and requirements that will support the utility companies' desired grid functionality was then presented. In section 2.3, the adaptation of ITU's USN architecture was proposed as the platform for a heterogeneous communication in Smart Grid. The communication technologies that can be deployed within the USN schematic layers together with their pros and cons was also presented. It was identified in section 2.5 that the choice of communication technologies does not only depend on utility budget and policies (economic factors) but also the capability of the communication technology to meet certain requirements such as security, latency and other technical factors of Smart Grid application. The focus of the research is shifted towards the communication technologies in Smart Grid NAN which considers the IEEE 802.11 WMN as the candidate communication technology. The key research challenges relating to reliability of routing variable application traffic in NAN based on WMN were presented. Finally, studying and improving the performance of OLSR routing protocol was highlighted, and thus, outlined as the research focus of this thesis.

Chapter 3

3. Traffic Classification and Performance Analysis of Ad-hoc WMN routing protocols in NAN for AMI.

3.1. Introduction

In Chapter 2, the ad hoc WMN was acknowledged as a communication technology well suited to the requirements of Smart grid's NAN. This is due to its extended coverage (through its multi-hopping capabilities), low latency, high throughput and QoS functionalities, which can enable data transmission hop-by-hop from the traffic sources (i.e., smart meter in 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 as discussed in Chapter 2 they have strict transport and QoS requirements in terms of latency, data rate and packet delivery. For example, the UTC (Utility Telecom Council) and Verizon communications suggested that the required latency will be in the range of tens of milliseconds to 15 seconds and reliability requirements will be in the range 99 % to 99.99% for some types of data traffic (United States Department Of Energy, 2010) (Chenine et al., 2007). Although this is difficult to achieve in WMN, it is necessary to undertake a detailed performance analysis to investigate whether a conventional ad hoc WMN is able to meet these requirements when deployed in 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.

In the previous chapter, key Smart Grid applications and candidate communication technologies were reviewed. However, to keep the scope of the work focussed, only applications such as the AMI application traffic that use the smart meter as their traffic source are selected for investigation in this chapter. This is because smart meters are the major constituents of NAN, which will act as the interface between the private networks in HAN and the utility control centres.

With the development of AMI applications, several routing protocols have been proposed, however, in this chapter our focus is OLSR and HWMP standard. It is assumed that the smart meters will not have any resource and energy constraints. Therefore, we do not consider routing approaches that are geared towards low-power devices such as RPL.

In order to evaluate performance of ad hoc WMN deployed in a NAN for AMI, a grid topology WMN and Log distance path loss algorithm was used to represent NAN in an urban area, four AMI traffic profiles were also generated based on different packet sizes and transmission intervals. The profiles were then transmitted to a data concentrator, while varying the ad hoc WMN grid sizes (which increases the number of hops to a destination) in order to evaluate performance. In addition, the performance analysis of routing capabilities of the WMN, in terms of packet delivery and delay support for the different AMI traffic in a NAN environment was carried out.

Specifically, emphasis is placed on evaluating the performance of IEEE 802.11s HWMP and the OLSR routing protocols. These two were considered because, while the former is the ad hoc WMN standard, the latter can be implemented on real hardware for evaluation and testing. In addition, since most ad hoc WMN nodes are static in an AMI network, proactive routing protocols are used because they provide faster convergence time in static ad hoc WMN.

Smart meters and nodes are used interchangeably in this chapter. The simulation for evaluating the performance of both HWMP and OLSR protocols were developed using the well-known ns-3 network simulator, which has been widely used by researchers to analyse networks and protocols. The ns-3 is an open source discrete event network simulator, which allows a user to add new features or modify existing ones, i.e., propose new algorithms and modifications of protocols. It was used to develop, generate and transmit AMI application traffic types over the NAN based ad hoc WMN to a data concentrator.

The rest of the chapter is structured as follows. Section 3.2 gives a brief overview of the two routing protocols (HWMP and OLSR). Section 3.3 develops the AMI application traffic classes and models. Section 3.4 presents the experimental implementation of ad hoc WMN for AMI application traffic, while the simulation study on NAN for AMI applications is presented in section 3.5. Finally Section 3.6 highlights the chapter summary.

3.2. Ad hoc WMN Routing protocols

There is often confusion about the difference between a wireless ad hoc network and WMN. A wireless ad hoc network is one that has a cooperative connection between other wireless devices without the intervention of any centralised infrastructure. The wireless devices serve as client devices to perform routing functions in order to forward data from themselves or for other nodes to form arbitrary network devices. A good example of the wireless ad hoc network is WSN. On the other hand, a WMN is characterised by dedicated wireless routers which carry out the function of routing packets through the network using static nodes/client devices without any routing functionality connecting them to wireless routers (Morote, April 2011). An example of this type of WMN is the broadband community networks. Both networks make use of ad hoc networking protocols that are standardised by IETF MANET working group. In this thesis, WMN refers to a number of static wireless devices that establish a cooperative connection of IEEE 802.11 network and are fully meshed or able to send data across multiple hops (i.e. each node can forward data belonging to themselves or for other nodes) to a destination through the help of routing protocols. Figure 3-1 shows an example of an ad hoc WMN with node S sending data to node D.

Routing protocols play a significant role in WMNs and their performance is hinged on the link metric used. The category of routing protocols that involve every node maintaining tables that represent the entire network (proactive) is known to perform best in static networks. Therefore, proactive protocols have been mostly proposed for routing in NAN for AMI, since smart meters are static. For example, each node in a network maintains a table of routes to reach other nodes. The decision on the best route to reach each node used by the routing protocol is calculated from the network parameter measured by the link metric.

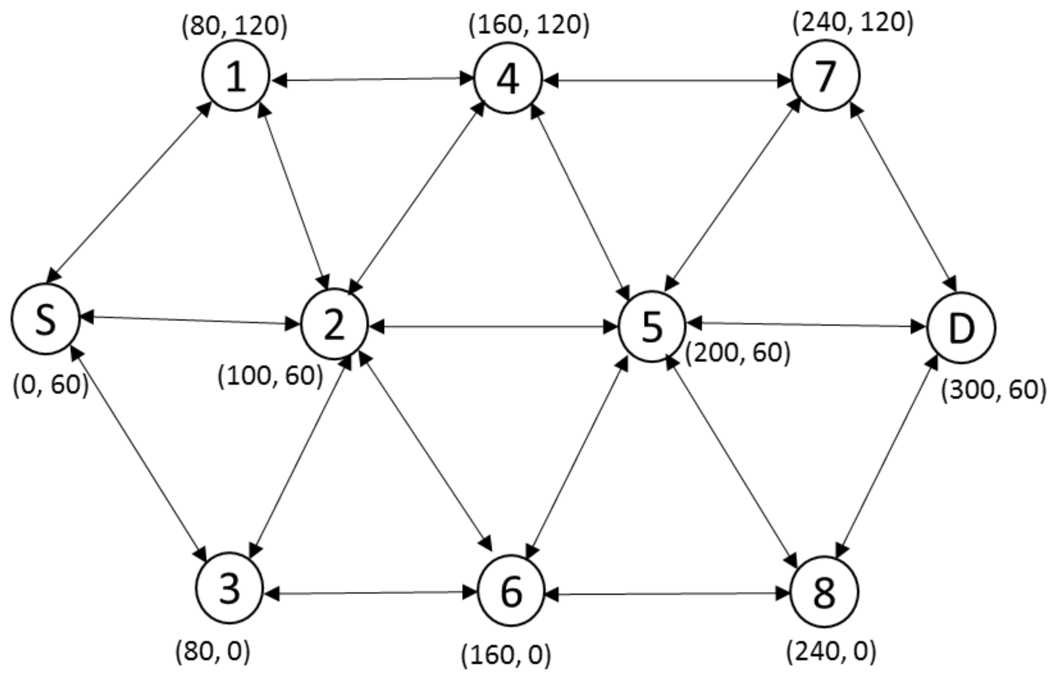


Figure 3-1: An example of Ad hoc Wireless Mesh Network Topology

The two proactive routing protocols HWMP and OLSR evaluated in this chapter work at the MAC layer and Network layer respectively. They are presented in the following subsections.

3.2.1. Hybrid Wireless Mesh Protocol (HWMP)

HWMP routing protocol has been specified as the IEEE 802.11s mesh networking standard HWMP uses the Air Link Metric (ALM) routing metric for path selection to meet the diverse wireless network requirements and enable efficient routing in a dynamic network environment (Morote, April 2011). HWMP allows both On-demand routing and tree-based routing to run simultaneously. 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. HWMP's On-demand routing is specified based on the AODV routing. It adopts AODV's basic features but some extensions are carried out to enable it suit IEEE 802.11s standard.

However, our emphasis is on the proactive 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 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 and the root node replies with a unicast path reply (PREP). 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 a 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 contains new information. The new information is either a PREQ with greater sequence number, or a better metric. Upon receipt of route information from the root node, each mesh node will calculate the airtime cost (Ca) metric using the formula shown below (Morote, April 2011) (Saputro and Akkaya, 2014):

$$C_a = \left(O_{ca} + O_p + \frac{B_t}{r}\right)\frac{1}{1-e_{fr}} \qquad 3.1$$

where O_{ca} and O_p are constants quantifying the channel access overhead, and MAC protocol overhead respectively. B_t is the number of bits in a probe frame and r is the transmission rate (in Mbps). e_{fr} is the frame error rate.

HWMP is considered suitable for smart grid AMI. This has resulted in many performance evaluations and modifications. Authors in (Kim et al., 2012) highlighted route instability and the method of error rate calculation as problems that degrade reliability performance of IEEE 802.11s networks. The IEEE 802.11s did not set a specific way of measuring or calculating e_{fr} (error rate), authors in (Kim et al., 2012) proposed a new method of measuring e_{fr} as shown in equation 3.2. The method considers the MAC retransmission count of each packet as the value for calculating failure rate of the network.

$$e_{fr} = \frac{M_n \times \frac{1}{P_n}}{R_{max}} \qquad 3.2$$

Where M is total number of MAC level retransmissions made by node n, P is the total number of data frames transmitted by node n, and R_{max} is the maximum retransmission count allowed.

In addition, it has been acknowledged that a single smart grid infrastructure can provide services to various applications that may be simultaneously transmitting various data types in the network. Equation (3.2) was modified to equation (3.3) below to enable the network to give various penalties to the airtime cost calculation when considering different sizes of each packet.

$$e_{fr} = \frac{\sum_{i}^{P_n} M_i \times \left(1 - \frac{B_i}{B_{max} + B_i}\right)}{P_n R_{max}} \qquad 3.3$$

Where B_i is the size of data frame i in bytes, B_{max} is the biggest size of data frame in the network, it was configured with a size 1024 bytes which is the default MAC Protocol Data Unit (MPDU) size.

Authors in (Jung et al., 2011) considered this method more beneficial for Smart Grid. The route selection module of HWMP was also modified to store multiple route paths in the routing table. Furthermore, in (Saputro and Akkaya, 2014) and (Saputro and Akkaya, 2015), the broadcasting of Address Resolution Protocol (ARP) was eliminated by extending the structure of the proactive PREQ of HWMP to address a dynamic MAC address mapping and to ensure every node sends its data to the root node neglecting any delay caused by ARP requests. Simulation results of this approach showed significant reduction in end-to-end delay without negatively impacting the PDR and throughput. Though optimisations carried out for HWMP have shown improvement in packet reliability and delay, improvements have not addressed QoS and prioritization or support for targeted application traffic. Therefore, it is worth exploring other routing options for NAN based ad hoc WMN communications.

3.2.2. Optimised Link State Routing protocol

OLSR is an upgrade of the standard link state routing algorithm for mobile ad hoc networks (MANETS). 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 (Clausen and Jaqcquet, 2003) (RFC 3626) as OLSR version 1 and an updated version of this draft has been documented in (RFC 7181) (Jacquet and Herberg, 2014).

OLSR reduces the overhead of flooding Link State information by enabling the forwarding of information from fewer nodes. A broadcast from node N is only forwarded by its multipoint relays. The MPR’s of node N are its neighbours, so that each two-hop neighbor of N is a one-hop neighbour of at least one multi point relay of node N. Multipoint relays are chosen by each node transmitting its neighbor list in periodic beacons so that all nodes can identify their two hop neighbours. The OLSR process of disseminating route messages through selected MPR's is illustrated in Figure 3-2. The figure shows that the shaded nodes are selected by OLSR as MPR nodes. For example, if node 1 is sending information to 10, the packets are forwarded through the shaded nodes (nodes selected as MPRs) along the path to node 10.

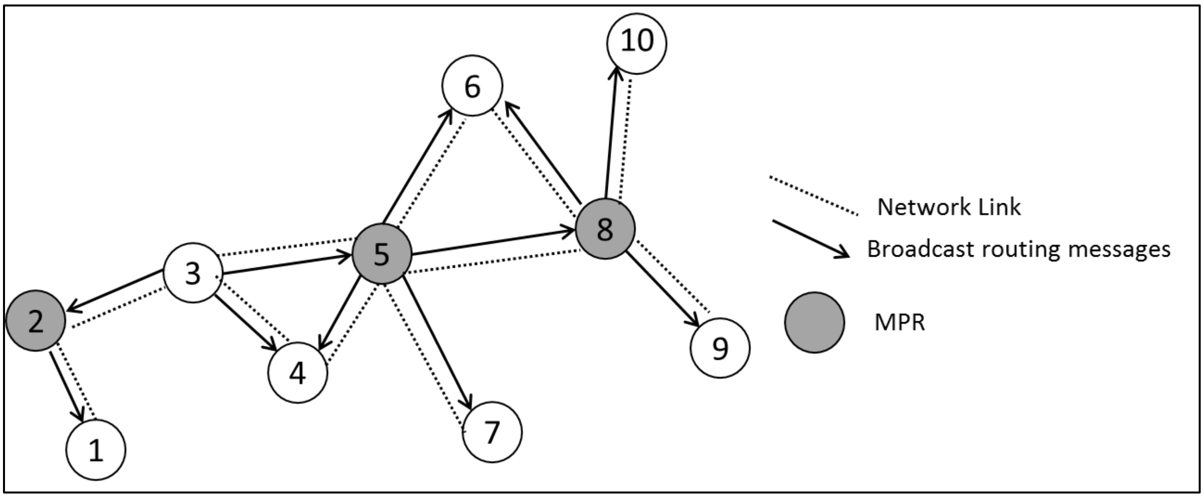


Figure 3-2: Selection of MPRs in OLSR routing protocols

OLSR version 2 is an updated version of OLSR version 1 which it retains the same mechanism and algorithm of OLSR version 1. Updated attributes of OLSR version 2 include four other protocols and specifications which allow it to: 1) extend addresses (i.e. accommodate both IPv4 and IPv6 addresses); 2) enhance the information base; 3) extend its signaling; and 4) create better routes through the use of link metrics instead of hop counts only as in OLSR version 1. Metric-based routing supported by OLSR version 2 allows each link to choose a link metric. OLSR version 2 defines 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. They are usually assessed at the receiver, in the same way 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 (Jacquet and Herberg, 2014). Information is sent using two types of control packets: Hello messages; T C messages (Topology Control messages). The OLSR source code that runs on existing wireless devices use two either of the following type of routing metrics:

1) Hysteresis routing metric: As specified in the Request for Comment (RFC) document for OLSR, Hysteresis is used to calculate the link quality between nodes to stabilise the network in the presence of many alternative routes. Link hysteresis is calculated using an alternative iterative process. If q_n is the link quality after n packets and h is the hysteresis scaling constant between

0 and 1, then the received link quality for each consecutive successful packet is defined by the following equation:

$$q_n = (1-h)q_{(n-1)} + h \qquad 3.4$$

2) ETX routing metric: ETX proposed in (De Couto et al., 2005), estimates the number of transmissions required to successfully send a packet over a link until an acknowledgement is received. The packet loss probability is measured in both directions, since in wireless networks based on IEEE 802.11 protocol, the destination must acknowledge each received data frame. For example, if (i, j) are wireless links established between NAN devices i and j; P_{ij} and P_{ji} signifies the packet loss probability between the wireless link (i, j) in forward and reverse directions respectively. The probability of successful transmission Ps between the wireless link (i, j) is therefore computed as $Ps_{(i,j)} = (1 - P_{ij}) \cdot (1 - P_{ji})$. The expected number of transmissions necessary to deliver the data packet considering both its transmission and successful acknowledgement as required by the IEEE 802.11 protocol can be evaluated as (Paris et al., 2013), (Campista et al., 2008):

$$\text{ETX} = \frac{1}{Ps_{(i,j)}} = \frac{1}{(1-P_{ij})\cdot(1-P_{ji})} \qquad 3.5$$

There have been a number of modifications on link metric variations implemented in OLSR protocol, it also has the advantage of wide implementation on various hardware devices, which means that practical tests can be carried out for AMI application traffic on ad hoc WMN. The next section presents different traffic classifications for AMI applications.

3.3. Communication over NAN

This section explores common traffic scenarios for AMI applications and categorises them in to four application classes. Application traffic from AMI nodes or smart meters will not just measure consumption data for billing purposes, but also generate traffic for consumer interaction. These can be periodic, real-time or near real-time and may require high reliability and low latency from any network deployed for AMI. Reliability and low latency can be challenging for ad hoc WMN, especially when considering varying application traffic has different packet sizes, transmission interval and latency requirements, which are often prerequisites in AMI for efficiency and functionality of Smart Grid as a whole. In this section, a comprehensive list of Smart Grid application traffic and their classification in terms of their reliability and latency requirements is presented.

3.3.1. Classification of Smart Grid Application traffic

More generic application characteristics are often used for classification of Smart Grid applications. For example, a popular method of classifying traffic is how they send data (periodic/aperiodic) or the data volume they generate. Application traffic types can also be characterised in terms of performance needs, i.e. they may require data-driven or network-driven performance (Suriyachai et al., 2012). Data-driven performance depends on the packet content, thus information accuracy and fidelity are design concerns. In contrast, network-driven performance depends on packet delivery being timely or reliable. In the context of classifying Smart Grid application traffic in this section, the performance in time and reliability domain used for classification of WSN applications in (Suriyachai et al., 2012) is adopted for classifying Smart Grid traffic. Performance in time domain relates to the time taken for data to be received at the destination. Parameters such as delay and jitter can be used to quantify performance aspect of time domain. While reliability performance depends on how much or ratio of data received at the destination node. Delivery ratio and packet loss rate are measurements often used to represent reliability performance. In addition, the performance in time and reliability are interdependent. For example in some Smart Grid applications data delivered late can be considered as lost data. Likewise as seen when retransmissions are employed, additional time for data transmission can be used to improve reliability. As delay and loss can be used as a pair of network-driven performance metric, the Smart Grid application traffic are classified based on such pairing as follows:

- **Delay-tolerant, Loss-tolerant Class**. The Smart Grid application traffic categorised in this class are those that can accept high data transport delay and loss. Examples of applications that are performance independent of losses and delays are those which require best effort such as software updates and periodic AMI data from HAN devices, which are used to monitor or estimate electricity usage in a household. The data could be sent every 15 seconds and require a latency more than 3 seconds (Luan et al., 2010) (Gungor et al., 2013) (Martinez et al., 2004), where data delivery requirements can be relaxed in both time and reliability domains. These applications can still function as desired even if data losses are incurred and/or data delivery time or latency is prolonged. A network can leverage the properties of this type of application traffic to guarantee QoS requirements for other critical application traffic.
- **Delay-tolerant, Loss-intolerant Class**. Smart Grid applications in this class are those that tolerate large delays in data delivery but data must eventually be delivered at the destination (Suriyachai et al., 2012). An example of this application is the Power quality data (Power report) which is sent every 3 seconds and has a latency of less than 3 seconds). Power quality information must be accurate for better load estimation and to determine the fitness of power for consumer devices, in order of seconds. In order to accommodate this traffic class, data delivery can be relaxed in the time domain but must obey a stringent requirement in the reliability domain.

- **Delay-sensitive, Loss-tolerant Class**. Most Smart Grid traffic requires very high reliability, a certain amount of loss rate may be acceptable in this class but data must arrive in a timely manner (little percentage of Losses tolerable) (Römer, 2004). Examples of applications in this class are Mobile Work Force traffic, video surveillance. To accommodate applications traffic in this class, the data delivery of this traffic must be tailored to obey a strict requirement in time domain but can be relaxed in the reliability domain.
- **Delay-sensitive, Loss-intolerant Class**. The application traffic in this class demand strict performance in both time and reliability domains. Example of applications in this class include Real Time Pricing (RTP), Synchrophasor reporting, Distribution Automation (DA), EV charging and Wide Area Measurement (WAM) which involves 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. These are critical application traffic because of the strict delivery and delay requirement (in tens of milliseconds), which must be guaranteed in any communication system deployed for Smart Grid. A summary of the traffic classification discussed in this section is presented in Table 3-1.

Table 3-1: Smart Grid Application Traffic Classification

Applications traffic	Transmission Interval (s)	Application Size (Bytes)	Reliability (%)	Latency (ms)	Characteristics
Periodic AMI (data from HAN nodes)	15	123	99.0 – 99.99	100 – 200 (<15 s)	Delay Tolerant Loss Intolerant
Power quality data (Power report)	3	512	98.0	< 3 s	Delay Tolerant Loss Intolerant
RTP (Real Time Pricing)	900 (15 mins)	210	99.0 – 99.99	100 - 200	Delay sensitive Loss Intolerant
EV Monitoring/charging	Event based	48	99.0 – 99.99	2000 - 5000	Delay sensitive Loss Intolerant
WAM	0.04, 0.1	48	99.0 – 99.99	< 10	Delay sensitive Loss Intolerant
Video surveillance	Event based	1024	98.0	< 100	Delay sensitive Loss Tolerant
Synchrophasor reporting	0.04, 0.1	48	99.0 – 99.99	40 - 100	Delay sensitive Loss Intolerant
Distribution Automation	0.04, 0.1	48	99.0-99.99	< 1000 (20-200)	Delay sensitive Loss Intolerant
Demand Management	Event based	200	99.0	1000 - 5000	Delay Tolerant Loss Intolerant
Trip/Block Signal	Event triggered	48	99.0 – 99.99	< 50	Delay sensitive Loss Intolerant
Event/Alarm Reporting	Event triggered	48	99.0	< 1000	Delay sensitive Loss Intolerant
AMR	300 (5 min)	400	98.0	< 2000	Delay Tolerant Loss Tolerant
Firmware/Software		≤ 1MB	98.0	Days	Delay Tolerant Loss Tolerant

3.3.2. Traffic profiles for simulation

A communication network for AMI comprised a large number of devices or smart meters, which have to collect the measurement of each residential and commercial meter within the network area deployed for AMI. For example, the smart grid priority action plan 2 (PAP2) released by the U. S. National Institute of Standards and Technology (NIST) (Locke and Gallagher, 2010), indicates that meter density per Km^2 for rural, suburban, and urban areas are 100, 800, 2000 respectively. Therefore, it will be required of the ad hoc WMN deployed for NAN communication to provide network access to the smart meters, sending variable application traffic within short intervals over several hops to the data concentrator.

Four different traffic profiles shown in Table 3-2 are used to represent the variable AMI application traffic sent from smart meters in NAN networks. They include: 1) billing information sent every 15 seconds represents Delay-tolerant, Loss-tolerant class; 2) power quality measurement sent every 0.5 seconds represents the Delay-tolerant, Loss-intolerant class; 3) video surveillance 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. IPv4 with UDP is used for all profile cases, with the smart meters transmitting upward towards the data concentrator. The application traffic is modelled as Constant Bit Rate traffic (CBR) utilising the user datagram protocol (UDP) at the transport layer.

Normally, the choice between the transmission control protocol and UDP is a trade-off between efficiency (throughput and delay) on one hand, and reliability (delivery guarantees) with flow control on the other hand. UDP brings about efficiency and support for real time applications. Therefore, it is more beneficial to employ UDP for a network of smart meters, given that transmission of metering information is typically characterised by short transactions that do not require persistent connection between data concentrators and the smart meters.

Table 3-2: Traffic profiles Characteristics

Traffic Characteristics	Application Type	Example	Direction	Delay Objective
Delay Tolerant Loss Tolerant	AMI data	UDP IPv4 CBR 123 bytes/15s	Up	< 15 seconds
Delay Tolerant Loss Intolerant	Power Quality	UDP IPv4 CBR 512 bytes/0.5s	Up	< 3 seconds
Delay Sensitive Loss Tolerant	Video Surveillance	UDP IPv4 CBR 1024 bytes/1s	Up	< 100 milliseconds
Delay Sensitive Loss Intolerant	WAM data	UDP IPv4 CBR 48 bytes/0.04s	Up	< 10 milliseconds

3.4. Implementation of ad hoc WMN for AMI

Primarily, the causes of packet losses in WMNs are classified as: (1) channel induced factors, which include the random bit error from signal attenuation, shadowing, multipath fading and noise; (2) interference induced factors, which include interfering nodes in or out of the mesh network and operating within the same channel (frequency) as the desired transmission; and (3) node induced factors, which refers to the kernel configurations and Central Processing Unit (CPU) type. Ad hoc WMN in NAN will involve packet transmission from every smart meter upward (MP2P) and transmission to every smart meter downward (P2MP) which also results in packet losses due to congestion on forwarding intermediate smart meter nodes.

An experimental implementation of ad hoc mesh network is carried out using low-cost COTS Terminals configured with OLSR routing protocol, to provide a better understanding of the multi-hopping capabilities and behaviour of ad hoc WMN when deployed in NAN for AMI. The COTS devices are used to represent smart meter nodes transmitting the smart grid traffic profiles in Table 3-2 to the destination. This is done to evaluate the performance of a conventional ad hoc WMN, using OLSR in a real wireless multi-hop environment. The aim is to evaluate the packet loss when smart meters send traffic to a destination across multiple hops. In NAN based ad hoc WMN, the intermediate or forwarding smart meters are expected to transmit their AMI data as well. Therefore, an evaluation of reliability is carried out when the intermediate or forwarding smart meter nodes are transmitting packets.

3.4.1. Components used for Experimental setup

During the experimental setup of ad hoc WMN, a number of hardware and software components were used in configuring and extracting results from the COTS devices used to represent smart meter nodes.

3.4.1.1. Hardware Components

The major hardware device used in setting up ad hoc WMN for analysing performance of AMI application traffic profile is the Google Nexus 7 (a 7" screen tablet developed by Asus in July 2012) COTS device. This device was used for the experiment because it enables node mobility (for varying the distance between nodes), has a high processor speed (a quadcore processor) and long battery life. It also uses the IEEE 802.11a/g/n standards for Wi-Fi communication which gives an option to operate in different Wi-Fi mode during implementation and supports the open source android operating system which enables configuration of the tablet. Other information on features of Nexus 7 can be found in .

3.4.1.2. Software Components

The nexus device configuration involved downloading and installing some free software, which include: CyanogenMod, OLSR Daemon (OLSRd) and iperf. They were installed to enable the configuration of ad hoc network, allow multi-hopping of traffic through an intermediate node to a destination node, and also enable the extraction of evaluation parameters. The free software is further described as follows:

CyanogenMod software:

CyanogenMod is a free software built on android that greatly extends the capabilities of android devices to support ad-hoc, OLSRd routing and multi-hop communication. More information about the CynogenMod software can be found in (Google play Apps). The version used in the implementation is 10.2-20130919-NIGHTLY-grouper released in 2013.

OLSRd

OLSRd is an open source link state routing protocol implementation of OLSR for MANET. This is developed by the OLSR.org Network Framework (OONF) that is optimised for MANET on embedded devices like COTS terminals, smart phones or normal computers. The software was installed in on the nodes to enable it update link tables on all the nodes in the network. More information on how the OLSRd updates its tables can be found on their website (OLSR.org). Version 0.6.6 was used on the experimental devices.

Iperf

Iperf is a network testing tool that can create TCP and UDP data streams and measure the throughput of a network that they are being transmitted on. It is written in C and also measures the network performance including delays and packet loss. The iperf used to extract the network performance from the ad hoc setup was obtained by downloading iperf for android on Google play. The transmitting nodes were configured as client and the receiving nodes as server.

3.4.2. Experimental setup and Node configuration

The configuration steps are presented in Figure 3-3. Though ad-hoc network capability exists in the android operating system, it is not supported by default (it is turned off).

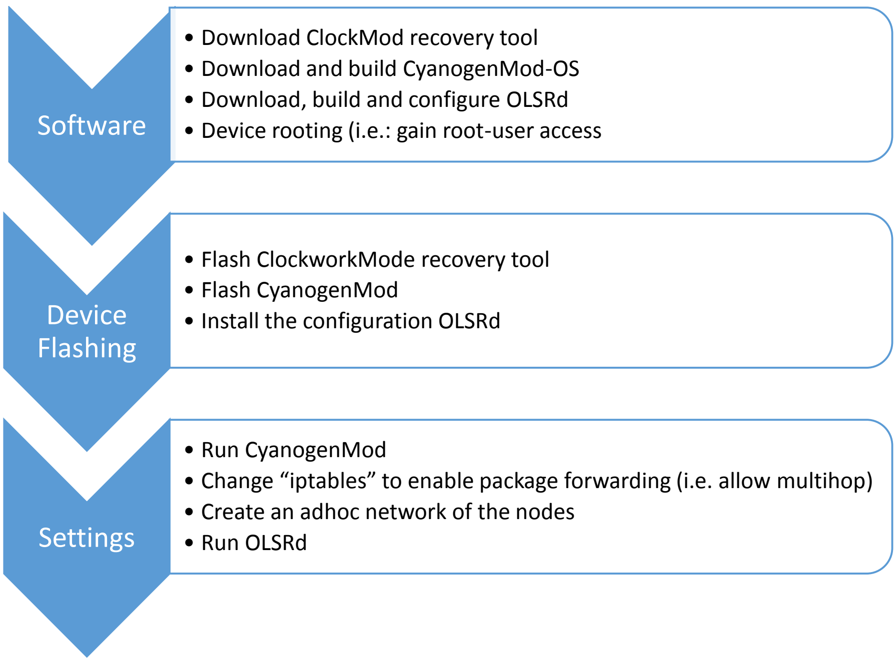


Figure 3-3: Steps for android device configuration on ad-hoc model

Turning ad-hoc capability on for multi-hopping and to run OLSRd on the Nexus device involved rooting the device to access and authorise the network drivers in order to activate OLSRd and multi-hopping. After rooting the device, the android operating system is configured to enable the devices to facilitate the creation of an ad-hoc network, by broadcasting the SSID (Service Set Identifier) and BSSID (Basic Service Set Identifier) of the network to join the already established ad-hoc network. An ad-hoc network of 5 nodes was set up with IP address of 10.2.70.108, 10.2.70.106, 10.2.70.105, 10.2.70.104, and 10.2.70.102 as shown in Figure 3-4.

The experiment was carried out in a building area and each COTS device was set to 802.11g PHY layer. OLSRd routing was also enabled on all devices used in the ad-hoc network. Nodes which represent smart meters were placed in a chain topology designed so that they can only route through one intermediate node to the destination (data concentrator) as shown in Appendix A. The node (android device) with IP address 10.2.70.108 was set as the data concentrator and packets where transmitted from varying nodes to the data concentrator for 1 hop, 2 hops, 3 hops and 4 hops.

The test was carried out to demonstrate smart meters sending data to a data concentrator node when the intermediate smart meters between the transmitting smart meter and the data concentrator are not transmitting (nodes are passive) and when the intermediate smart meters are transmitting data (nodes are active). The active intermediate smart meter setup represents a real smart metering scenario in a NAN. The test was carried out to evaluate the performance of ad hoc networks in a smart metering scenario and to show the effect of congestion as a result of transmission on the intermediate smart meters. Iperf was used as the network-testing tool to generate packets for each application class and to measure the packet delivery metric at the destination node. Using iperf allowed for setting the datagram sizes and packet generation interval which represents the various AMI application traffic profiles. The packet losses recorded at the destination node were used to estimate the packet delivery ratio. All nodes on the network send AMI information as a periodic UDP Constant Bit Rate (CBR) message.

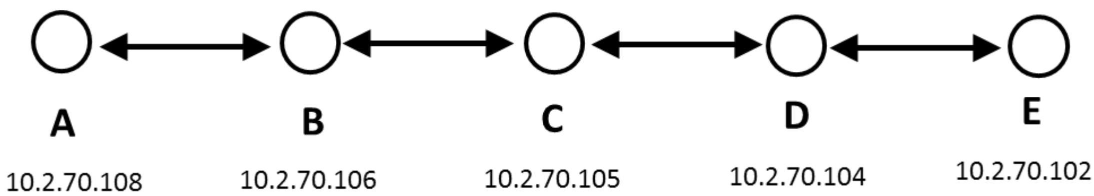


Figure 3-4: Node chain topology with 1 hop to 4 hop routes

3.4.2.1. Snapshots samples of Node Configuration

Figure 3-5 shows the snapshot of a network configuration of a smart meter node. It shows the configuration of a smart meter node with an IP address and gateway of 192.168.0.4. In order to enable the creation of ad hoc networking, Cyanogenmod operating system had to be installed on the devices instead of the original android/nexus operating system. Consequently, the ad hoc network is established over a mesh topology to enable communication between nodes and across multiple hops in the network.

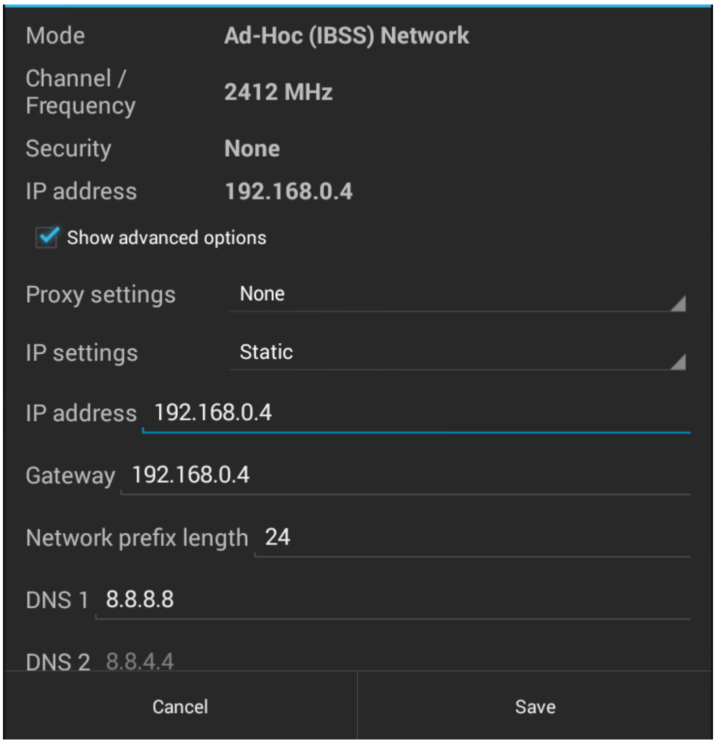


Figure 3-5: Network configuration snapshot on Nexus 7 device

A snapshot of OLSRd showing the neighbours connected to the smart meter node (Nexus 7) configured with an IP address of 192.168.0.4 is presented in Figure 3-6. The snapshot shows that a smart meter node configured with an IP address of 192.168.0.5 is connected directly to smart meter node 192.168.0.4 and another smart meter node configured with an IP address of 192.168.0.6 has a two hop connection with smart meter node 192.168.0.4.

Figure 3-6: OLSRd on smart meter node 4 showing single hop and two hop connection with smart meter node 5 and smart meter node 6

The OLSRd is not responsible for forwarding traffic, it only provides information about the routes. In order words, OLSRd only inform the smart meter nodes on how to reach other smart meters nodes that are not in direct communication range by hopping through a number of intermediate smart meter nodes (hops). The route calculations depends on the size of the network and the measurement of the link quality among other parameters, taking into account the configuration of the network and OLSRd. In order for an intermediate smart meter node to forward traffic to a destination, a rule must be added in its IP-Table. This rule forces the network driver to forward the traffic instead of dumping it. A screen shot of the IP table of smart meter node 192.168.0.4 is presented Figure 3-7. The IP forward profile variable of smart meter node 192.168.0.4 is set to "Yes" as shown on the screen shot in Figure 3-7. This is to enable it forward all traffic sent to the node. The OLSR port is also set as 698 to enable the node transmit all the state messages.

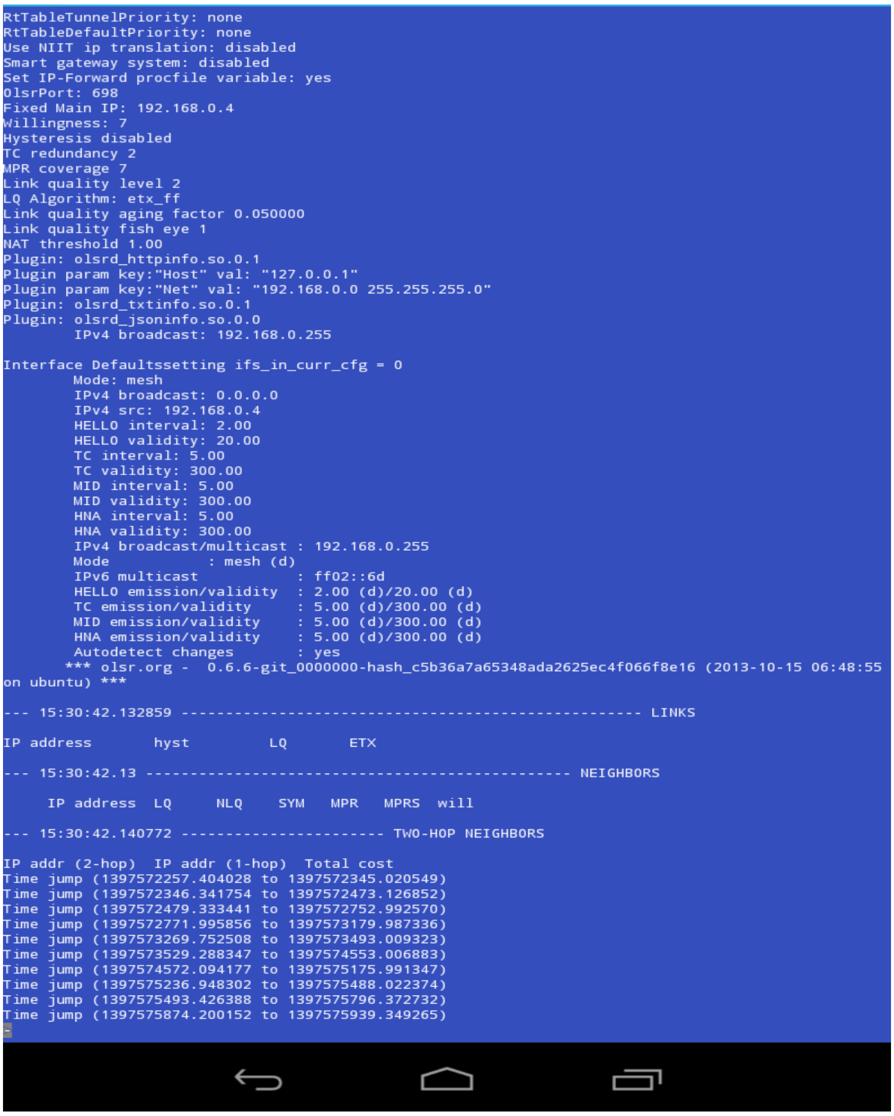
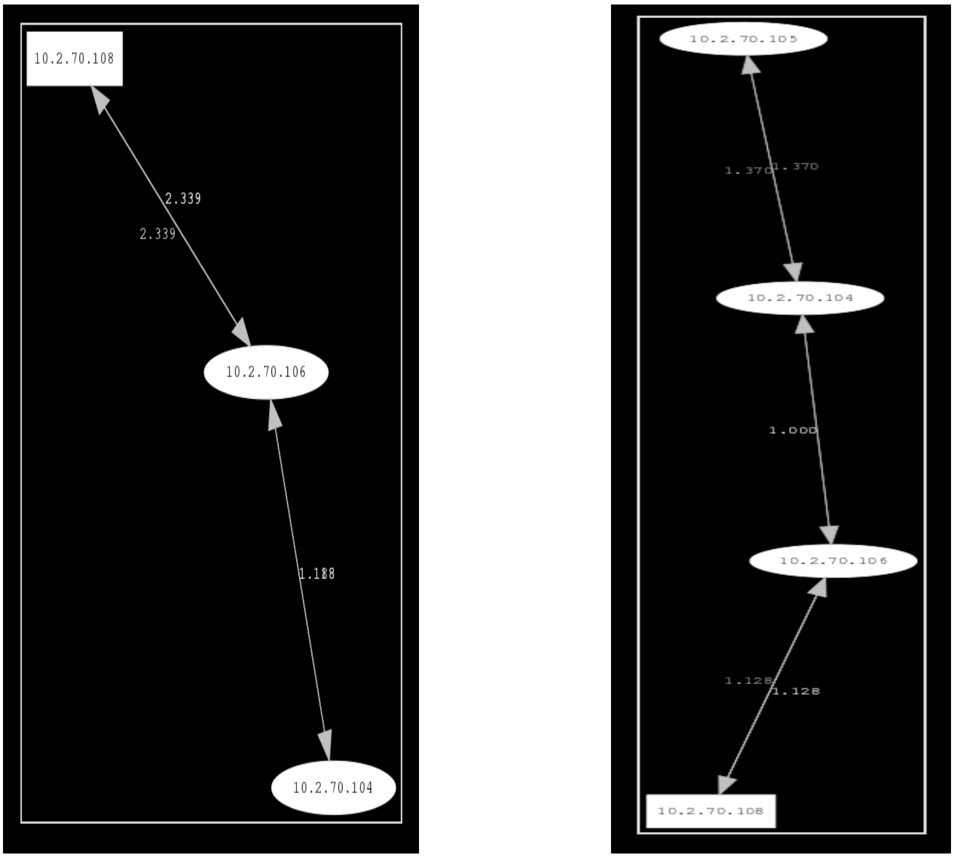


Figure 3-7: IP-Table for smart meter node 192.168.0.4

A caption of the smart meter nodes connection and communication in a chain topology using the Linux ImageMagick is presented in Figure 3-8. It shows a caption of the ad-hoc network set up of 2 hops and 3 hops with IP address of 10.2.70.108, 10.2.70.106, 10.2.70.105, and 10.2.70.104.



A B

Figure 3-8: Chain topology for 2 hop and 3 hop experimental setup

3.4.3. Performance Evaluation metric

The metrics that were used to assess the network performance of the experimental setup of ad hoc WMN using OLSR were derived as follows:

(1) Average end-to-end (ETE) delay: ETE delay indicates the amount of time required to successfully transmit all the bits of each packet from a transmitting smart meter node to the destination (data concentrator). The average ETE was measured by dividing the sum of ETE delay for all successfully transmitted packet by the total number of packets.

$$\text{ETE}_{ave} = \frac{D}{N_R} \qquad 3.6$$

where D = DelaySum (sum of all delays for each packet), N_R is Number of packets successfully delivered.

(2) Average PDR: this is the ratio of packets that are successfully delivered at the data concentrator compared to the number of packets that have been sent by each smart meter node.

$$\text{PDR}_{ave} = \frac{N_R}{N_T} \quad 3.7$$

where N_R is number of packets successfully delivered, and N_T is number of packets transmitted by all sending nodes.

(3) Throughput: this a measure of the actual amount of data that can be delivered when delay is considered. It is the average rate of successful delivery divided by the duration of transmission.

$$\text{Throughput}_{\text{ave}} = \frac{Nbits_R}{TL_R - TF_T} \quad 3.8$$

where $Nbits_R$ is the rate of successful delivery in Mbps, TL_R the time last packet was received and TF_T is the time first packet was transmitted and $TL_R - TF_T$ is the duration of transmission.

3.4.4. Results and Discussion

The results obtained from the experimental implementation of testing the performance of Smart Grid traffic profiles on a conventional ad hoc WMN are presented in Figure 3-12. It shows the average PDR comparison between transmissions across the multi-hop setup when the intermediate nodes are active or passive. Each of the test was run for a duration of 500 seconds to represent a period of the day where all applications are transmitting simultaneously. The results show the effect of multi-hops and congestion which occurs as a result of interference in the network and congestion due to the intermediate nodes transmitting and forwarding data packets. When the intermediate nodes are passive, Figure 3-12 to Figure 3-12 show that the number of packet loss increases with the number of hops. This is because interference increases in wireless medium with more hops and the forwarding process for multi-hop flows further increases packet drop at the receive queue. Packet losses also increase with the number of hops in the active intermediate node mode, though, there are more packet losses in the active intermediate node mode than the passive mode.

Another observation is that the degree of packet loss with increasing number of hops is higher for application traffic with high packet generation rate and packet size on both passive and active intermediate nodes. For example, the PDR for WAM traffic profiles transmitting a packet size of 48 bytes every 0.04 seconds (25packets per second) and video traffic transmitting a packet size of 1024 bytes every second are below 70% and 60% respectively at the 4th hop, compared to the application traffic of the other two that are above 85% at the 4th hop.

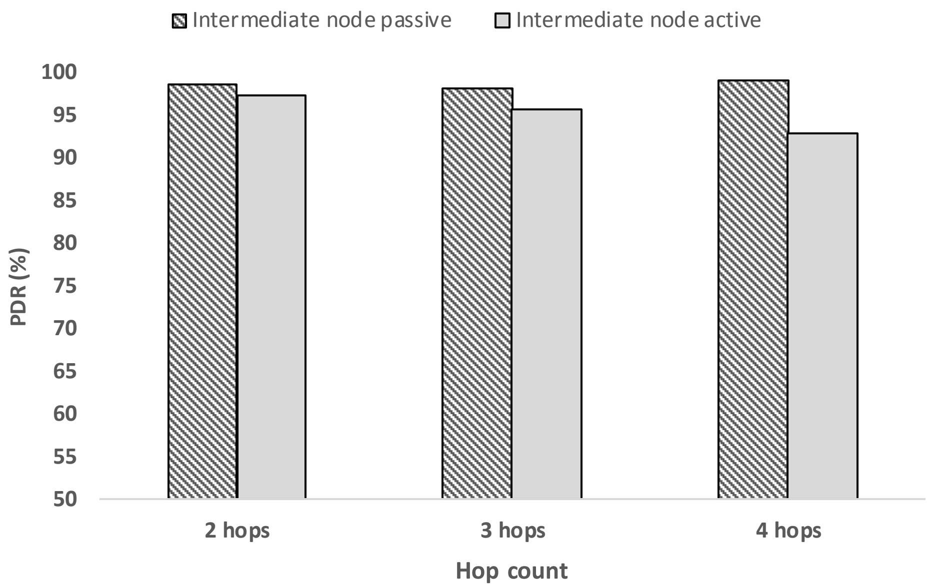


Figure 3-9: AMI data traffic PDR for nodes transmitting to a backhaul node when the intermediate nodes are passive and active. AMI data traffic profile was configured with a packet size of 123 bytes sending 1 packet every 15 seconds.

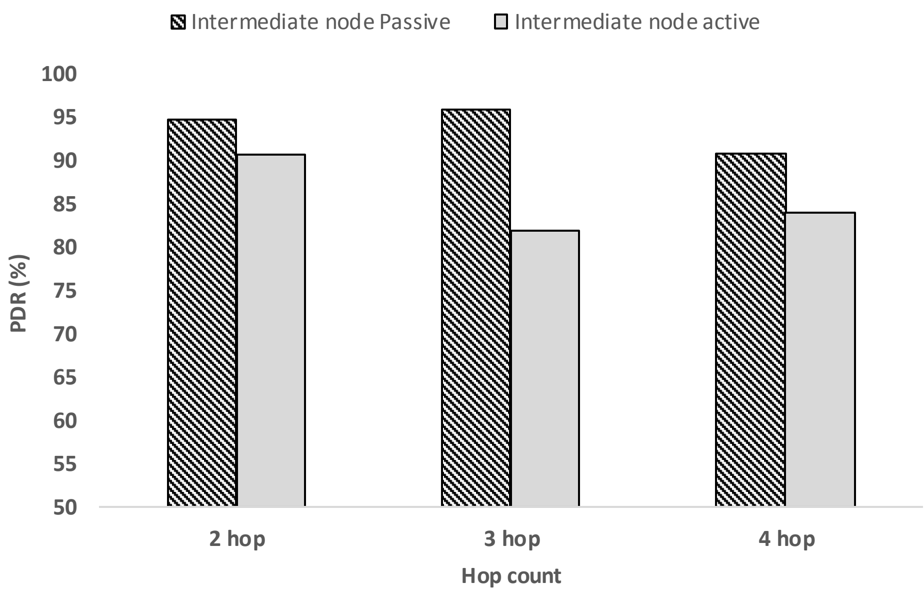


Figure 3-10: PDR for Power quality measurement traffic for nodes transmitting to a backhaul node when the intermediate nodes are passive and active. Power quality measurement traffic profile was configured with a packet size of 512 bytes, sending 2 packets per second.

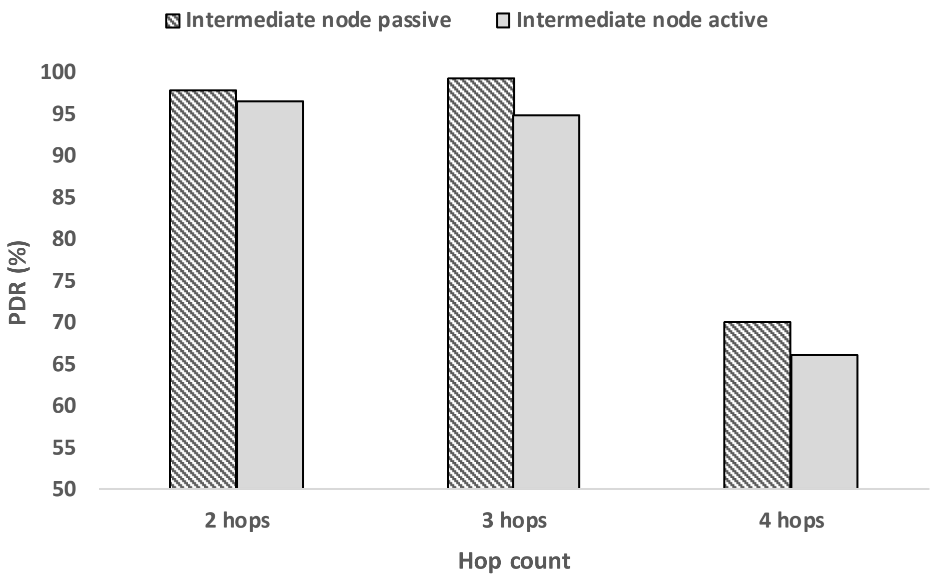


Figure 3-11: PDR for WAM traffic for nodes transmitting to a backhaul node when the intermediate nodes are passive and active. WAM traffic profile was configured with a packet size of 48 bytes, sending 25 packets per second.

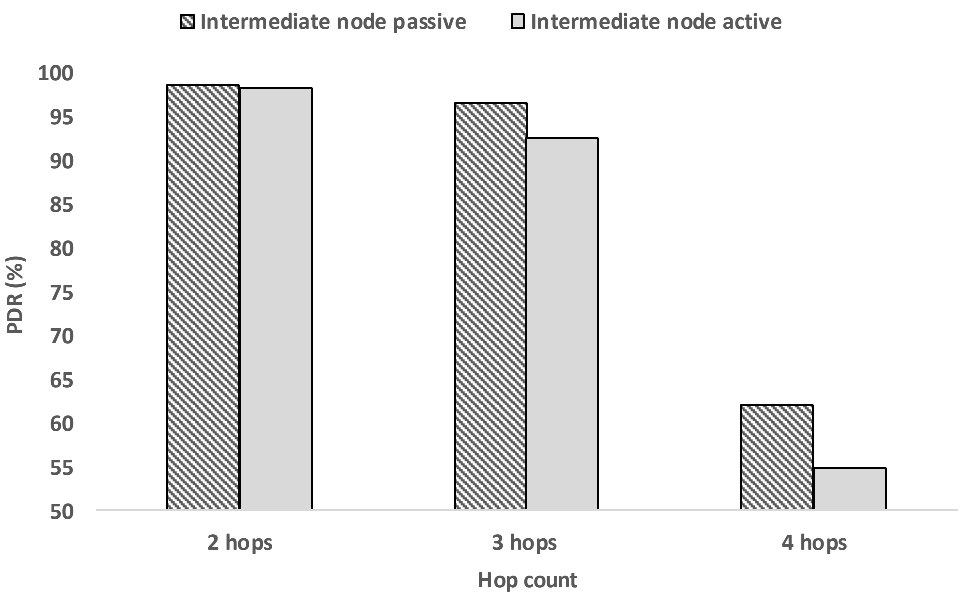


Figure 3-12: PDR for video surveillance update traffic for nodes transmitting to a backhaul node when the intermediate nodes are passive and active. Video surveillance traffic profile was configured with a packet size of 1024 bytes, sending 1 packet per second.

The average PDR for all application traffic when all the nodes are transmitting to the destination is presented in Figure 3-13. For all application traffic, the experimental results give an average PDR of 92% or less for smart meter nodes transmitting to the data concentrator situated a maximum 4 hops away from one of the meters.

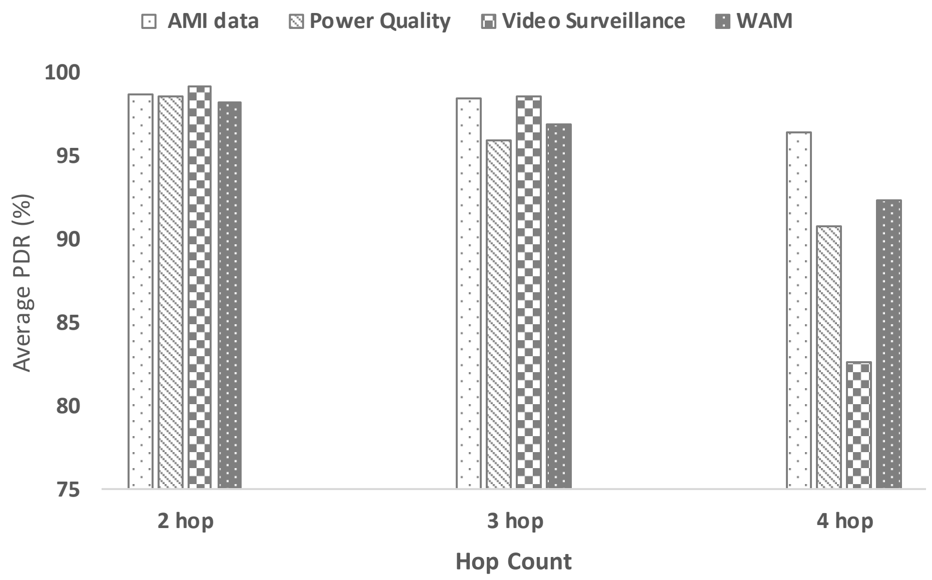


Figure 3-13: Average PDR at different hop count for all applications transmitting to a destination node

Congestion in the ad hoc WMN network can also affect delay and throughput of packets across multi-hops. Apart from reliability which is measured by PDR in this thesis, delay and throughput are other parameters used to evaluate the performance of routing protocols. The average jitter signifies the packets will reach the destination with different delays, The average jitter for all application traffic transmitted to the data concentrator for all the hops considered in the experiment is presented in Figure 3-14.

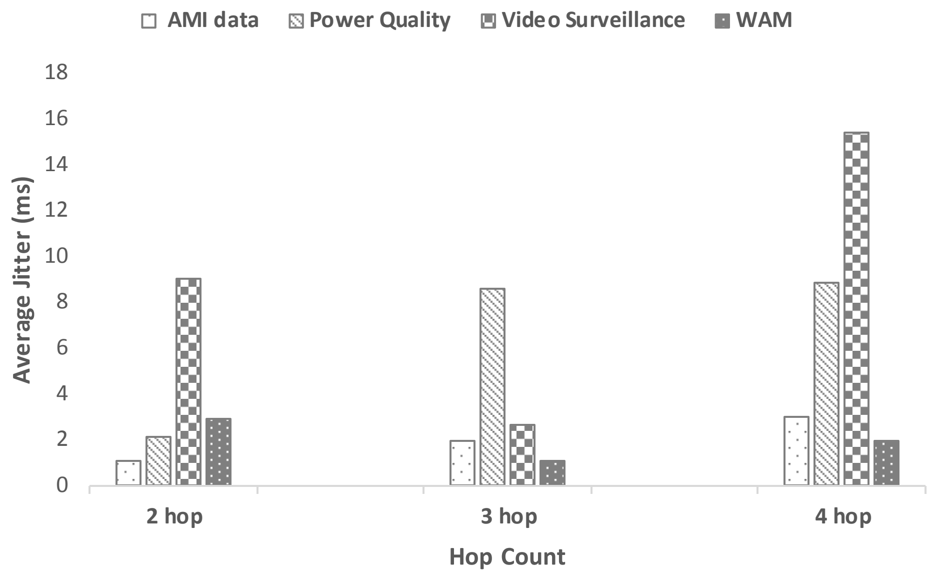


Figure 3-14: Average Jitter at different hop count for all applications transmitting to a backhaul node

The experimental setup is presented to evaluate practical representation of smart meters deployed to transmit Smart Grid application traffic in ad hoc WMN systems. In order to further investigate reliability and delay of Smart Grid application traffic profiles in a NAN environment across multiple hops, a simulation of NAN based ad hoc WMN is carried out using ns-3 network simulator. This is because it is not cost effective acquiring several COTS devices to build a larger network.

3.5. Simulation of NAN based ad hoc WMN.

In this section, an implementation of a NAN based ad hoc WMN using OLSR is presented. The simulation setup is based on a grid topology WMN with smart meters transmitting the Smart Grid traffic profile specified in Table 3-2 to a data concentrator. OLSR routing protocol was implemented in the simulation and its performance was compared with the IEEE 802.11s standard protocol HWMP. The ns-3 environmental parameters and grid topology used for simulating both protocols were set to allow a fair comparison between both protocols in a NAN environment. Performance analysis was carried out for each smart meter transmitting application profiles through the network. Results from the simulation will give a better understanding of the performance of both protocols when transmitting variable traffic profiles on NAN based ad hoc WMN.

3.5.1. Simulation Setup for NAN based ad hoc WMN

In order to study the reliability of Smart Grid traffic over a conventional ad hoc WMN deployed in NAN for AMI, a grid ad hoc WMN topology is used to represent a Smart Grid NAN communication network. While setting up the ad hoc WMN simulation in ns-3 network simulator, the flow monitor module was used to collect a set of performance metric to enable the calculation of metric parameters such as PDR, throughput and delay, which will be used for performance evaluation. A grid topology was used because it is a common topology for mesh network, and can be used to represent distribution of houses in an urban area, for example, the grid plan in Milton Keynes (Davies and Pederson, 2001). Furthermore, the grid topology is more reliable when extracting and comparing results than the randomly distributed nodes in ad hoc WMN. The ns-3 YansWifi channel model was used with the Log distance path loss model, which is designed for buildings, densely populated areas or suburban scenarios. The Log distance path los model assumes an exponential path loss over the distance from sender to receiver. The node environment and routing protocol parameters obtained from the ns-3 manual and used for the simulation are presented in Table 3-3 and Table 3-4.

An N-by-N grid size mesh network with 802.11g PHY layer (and bit rate of 6Mbps) configured on each node was used to represent the Smart Grid NAN for AMI. IEEE 802.11g was used because of its low frequency of 2.4GHz and OFDM modulation scheme, which enables higher transmission range and penetration in built-up areas. One of the mesh nodes on the grid network topology represents the data concentrator, while a number of N-by-N -1 nodes act as smart meters sending data to the data collector. All smart meters on the network send Smart Grid traffic as a periodic UDP Constant Bit Rate (CBR) message. The transmission parameters of all smart meters were set such that their maximum transmission range is 120m and the nodes were placed at a distance of 100 meters apart. This allows each smart meter on the grid to have a minimum of 2 and maximum of 4 smart meter neighbours. The smart meters were arranged as shown in Figure 3-15, while the grid size was varied from 4 x 4 (16 nodes) to 11 x 11 (121 nodes). For each grid size, the data concentrators were situated at the edge, for example, in Figure 3-15, the data concentrator was located at top right corner. All nodes were configured with a single interface. 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.

Table 3-3: Transmission environment parameters

Parameters	**Values**
Path Loss Type	Log distance path loss
Path Loss Exponent	2.7
Reference Loss	46.7 dB
Clear Channel Assessment Threshold	-62 dB
Tx and Rx Gain	1 dB
Min and Max Tx level	18 dBm
Energy Detection Threshold	-89 dBm

Table 3-4: Routing protocol parameters

Parameters	**HWMP**	**OLSR**
Route metric	Air Link Metric (ALM)	Hop count/ETX
Hello interval (s)	--	2
PREQ interval (s)	2	--
Simulation time (s)	86400	86400
Packet size (bytes)	123, 512, 1024, 48	123, 512, 1024, 48
Tx interval (s)	15, 0.5, 1, 0.01	15, 0.5, 1, 0.01
Tx Range (meters)	120	120
Distance btw nodes (m)	100	100

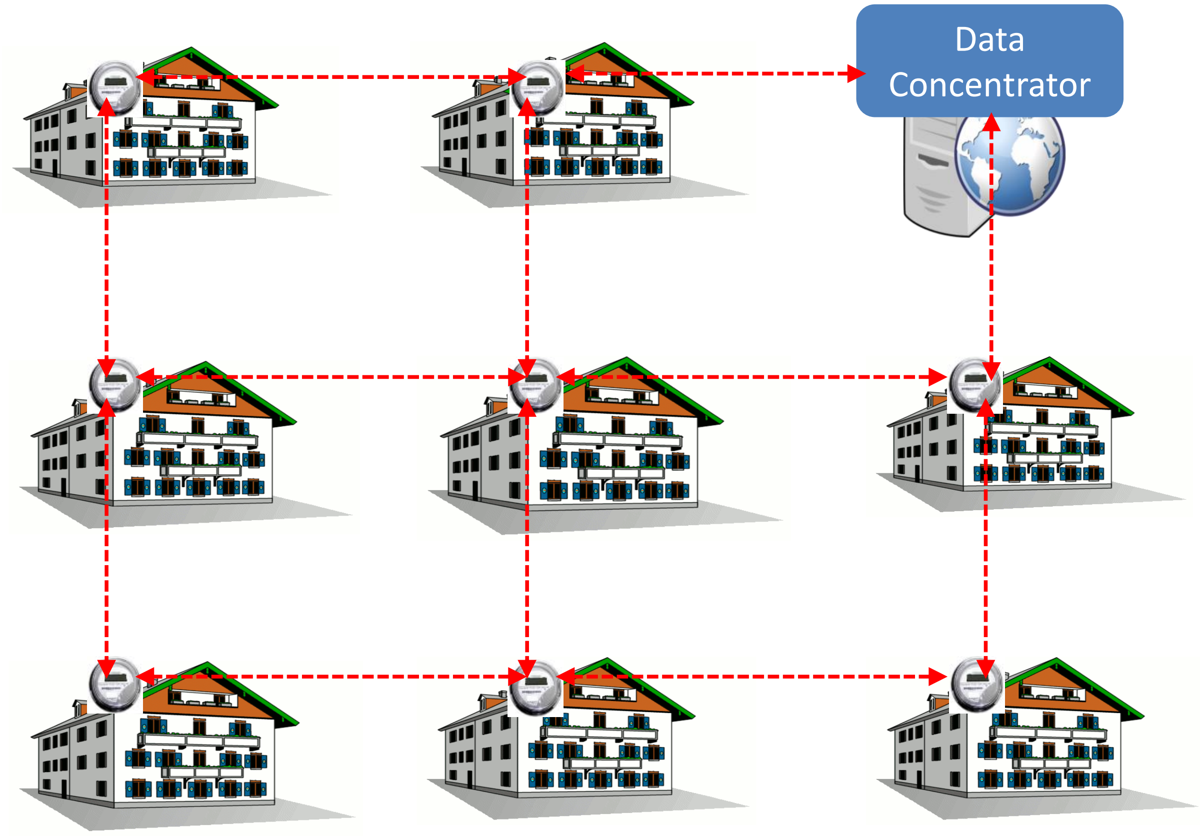


Figure 3-15: A 3 by 3 grid Wireless Mesh network for NAN

3.5.2. Simulation Results and Discussion

The average and median values of PDR and delay of all the smart meters transmitting to the data concentrator was measured for each network grid size. Figure 3-19 depicts the mean and median PDR for smart meter nodes transmitting to a data concentrator for varying grid sizes from 16 to 121 (4x4 to 11x11) nodes. The degradation in PDR as the network scales is as a result of increased packet drops and number of hops traversed by the packet. Figure 3-19a - Figure 3-19d also show PDR performance of OLSR and HWMP for the four Smart Grid traffic profiles. From the PDR results in Figure 3-19a, it is observed that after showing a better performance 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 which transmits a packet size of 123 bytes every 15 seconds. 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 (i.e. root node which is configured as data concentrator) as the network scales. This demonstrates a clear indication of the advantage of OLSR's MPR in achieving better reliability across larger multi-hop networks (Javaid et al., 2010) (Gray et al., 2004). Figure 3-19b, Figure 3-19c and Figure 3-19d represent PDR's for the power quality measurement, video surveillance and WAM applications traffic profile respectively.

The margin in PDR degradation between the two protocols is narrowed down for other applications which have less transmission interval between packets (higher packet generation rate). Reliability in ad hoc WMN is usually 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 high packet generation rate results in higher collision probability and dropped packets in the network. This is evident in Figure 3-19d, where WAM application traffic with a packet size of 48 bytes, generating 25packets/sec, has a lower average PDR at 36 (6x6) grid size on both protocols than video surveillance application traffic which has a packet size of 1024 bytes and generating 1packet/sec. Though a difference of 10% loss rate between WAM and video surveillance traffic profiles is observed in average PDR at a grid size of 36, the difference reduces as the grid size increases. It can be concluded that small sized packets with high generation levels have a higher impact on packet losses than large packet sizes with lower 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 data concentrator. This may be as a result of packet drop at the intermediate nodes as well as increased interference, which causes packet losses at the medium as packets multi-hop through the network.

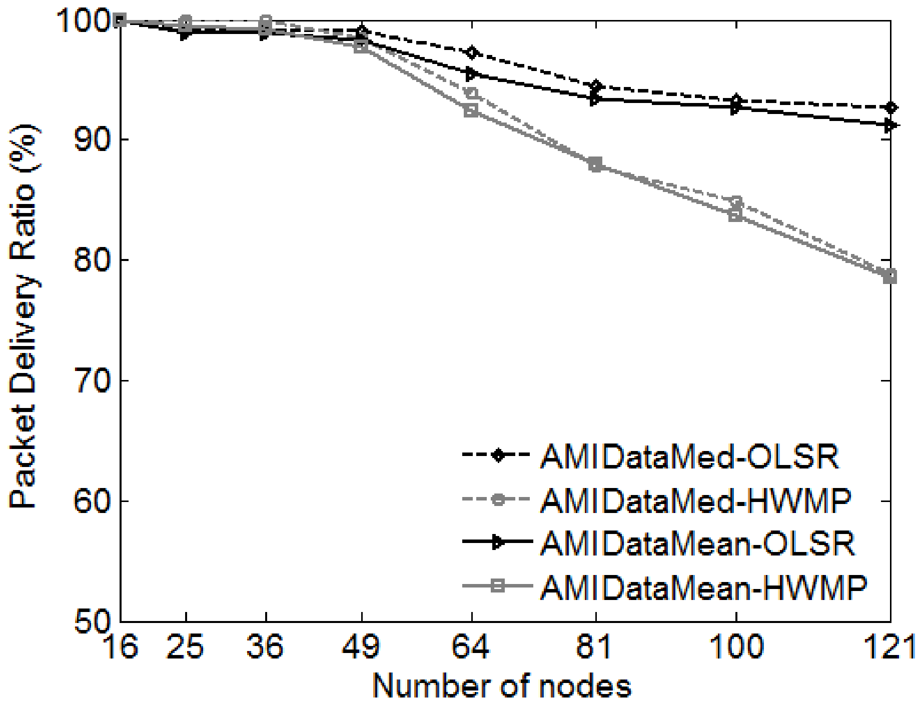


Figure 3-16: Mean and median PDR for AMI data traffic on varying grid sizes using OLSR and HWMP.

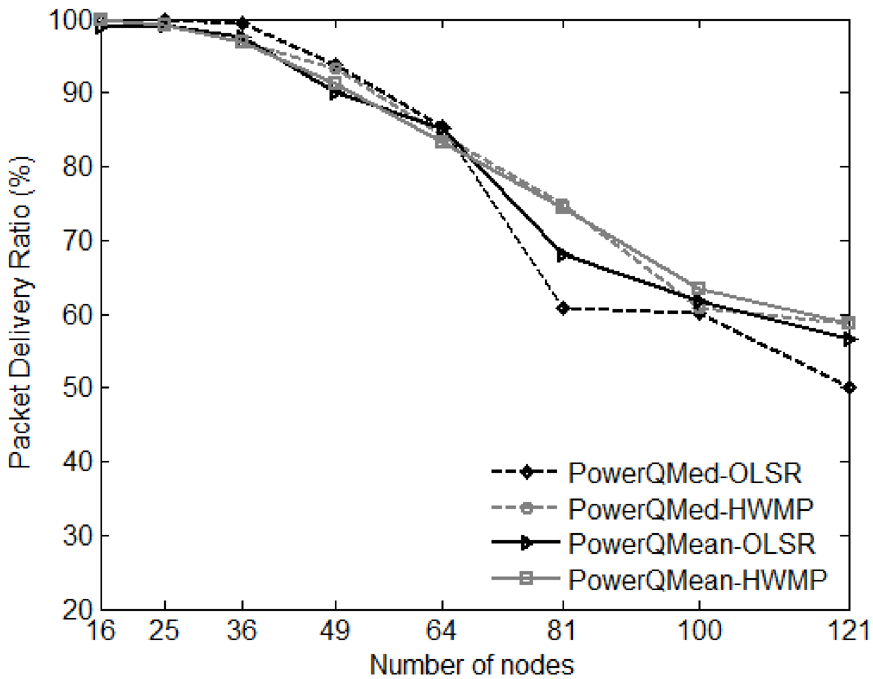


Figure 3-17: Mean and median PDR for power quality measurement traffic on varying grid sizes using OLSR and HWMP.

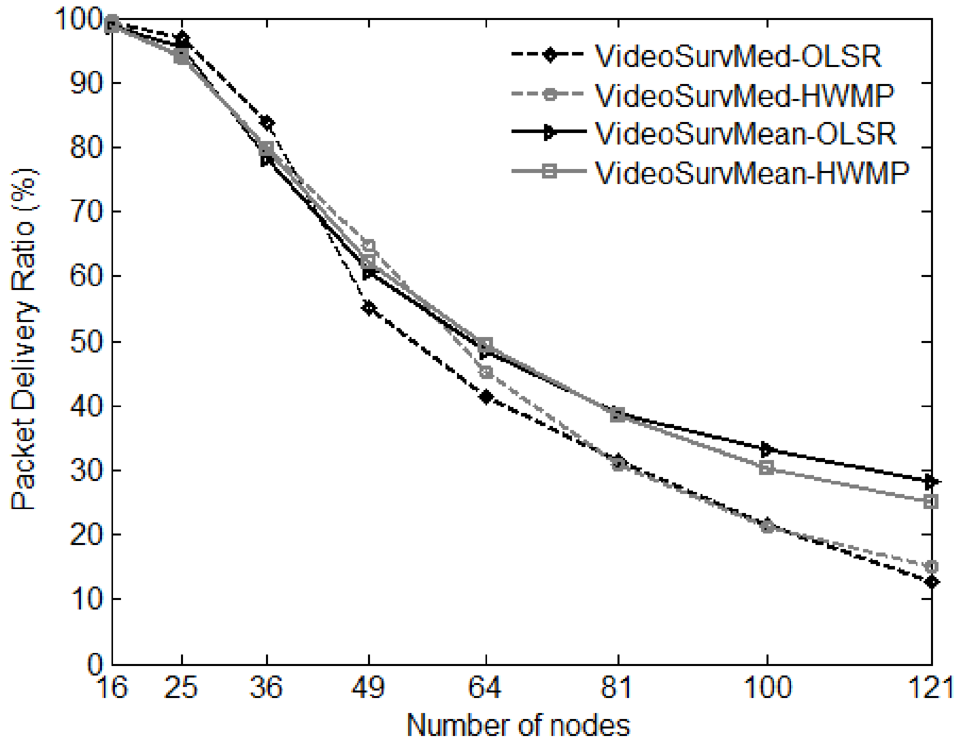


Figure 3-18: Mean and median PDR for video surveillance traffic on varying grid sizes using OLSR and HWMP

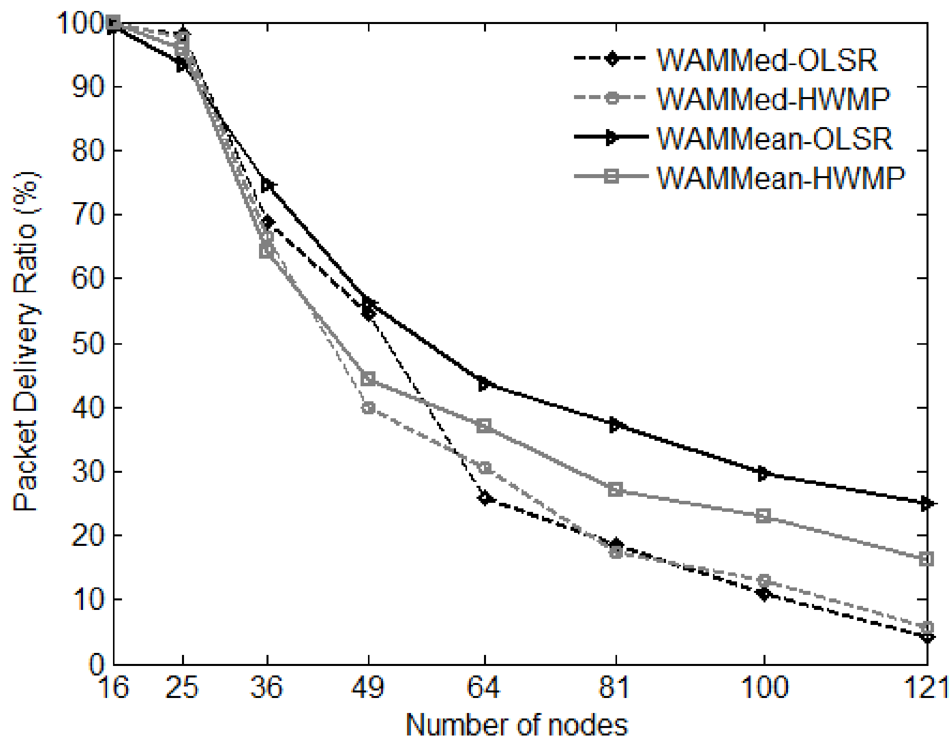


Figure 3-19: Mean and median PDR for WAM traffic on varying grid sizes using OLSR and HWMP

The median and average ETE delay of all smart meters transmitting to the data concentrator for varying grid sizes is presented in Figure 3-20 to Figure 3-23. It is observed that the ETE delay of OLSR is consistently lower than HWMP for AMI data, power quality and video surveillance 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.

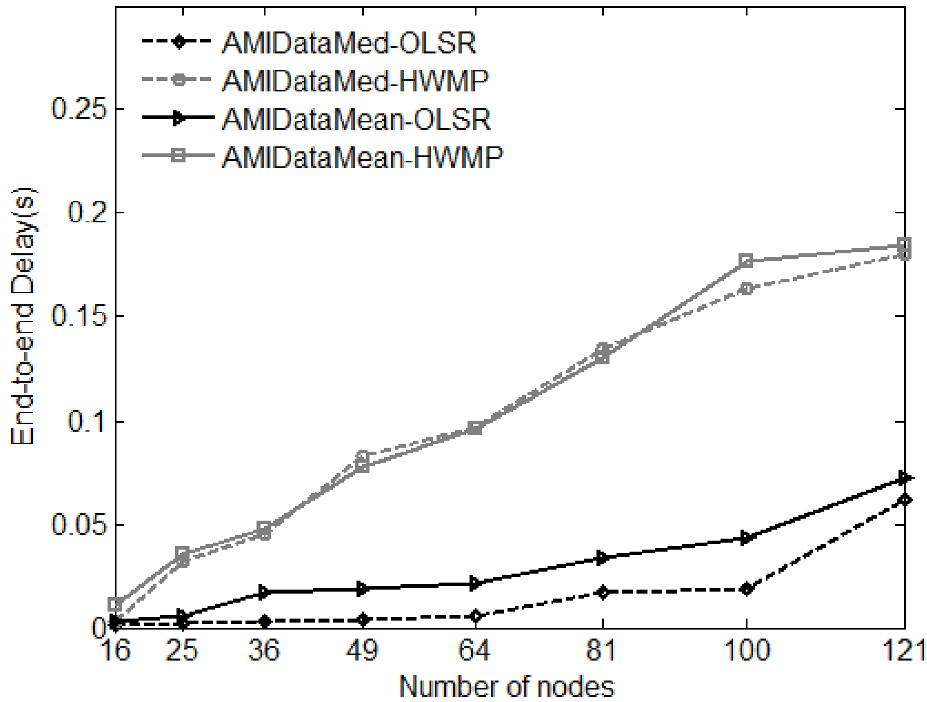


Figure 3-20: Mean and median ETE delay for AMI data traffic on varying grid sizes using OLSR and HWMP.

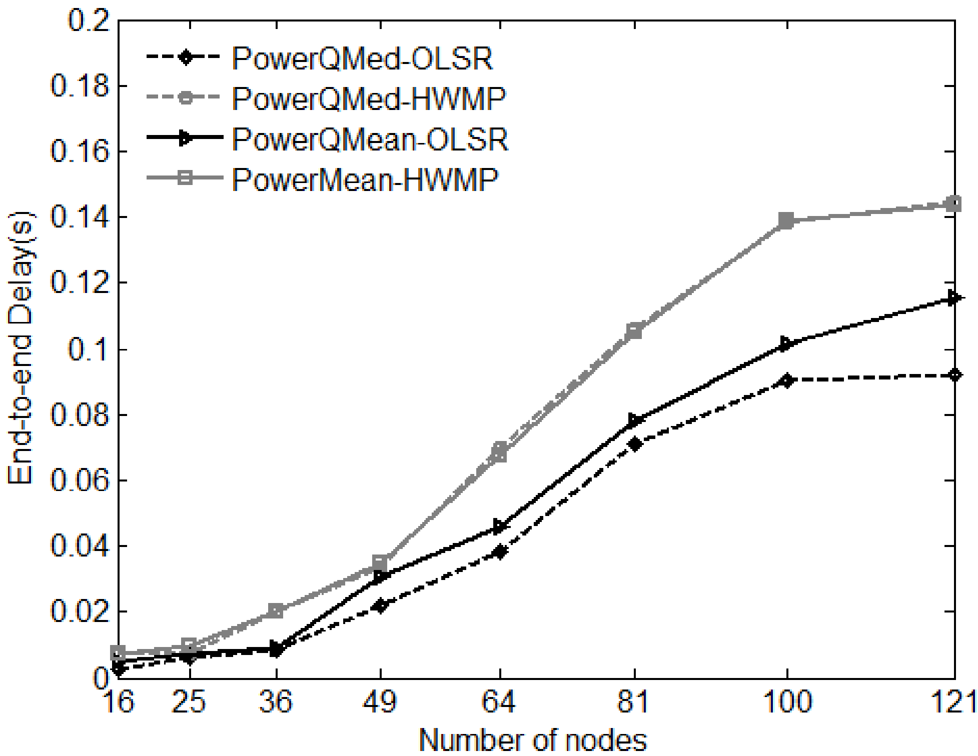


Figure 3-21: Mean and median ETE delay for power quality measurement traffic on varying grid sizes using OLSR and HWMP

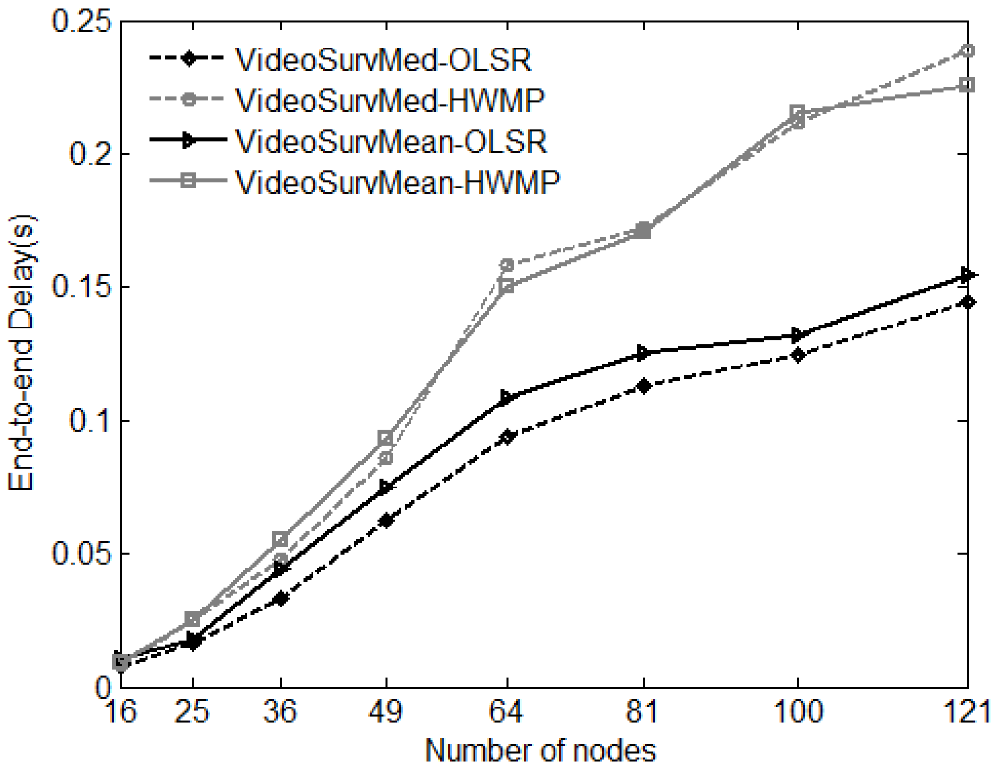


Figure 3-22: Mean and median ETE delay for video surveillance traffic on varying grid sizes using OLSR and HWMP

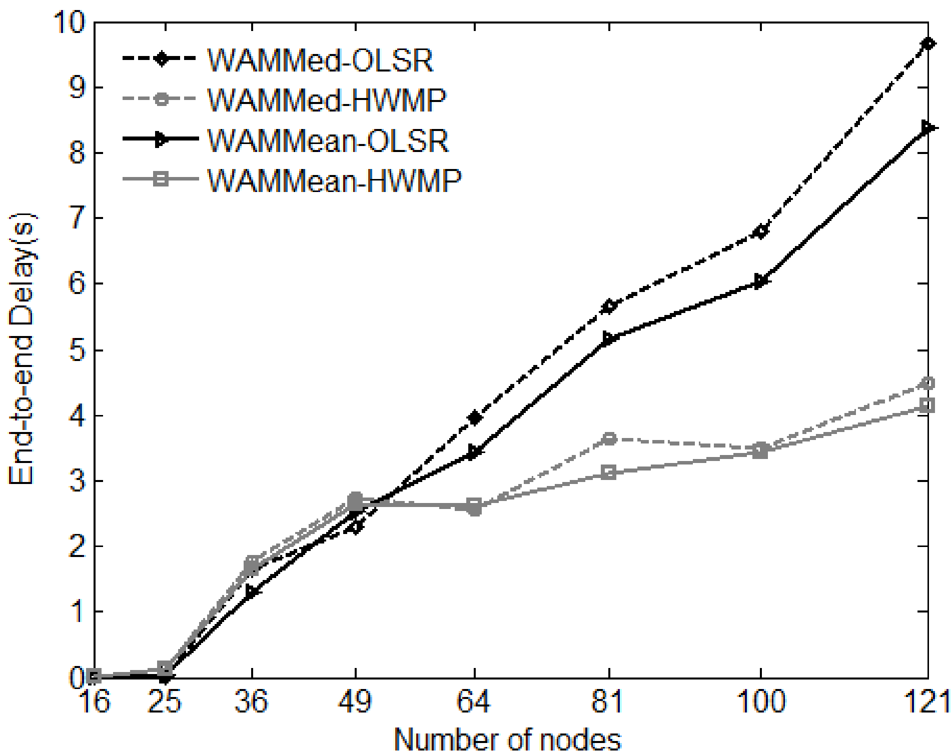


Figure 3-23: Mean and median ETE delay for AMI application traffic on varying grid sizes using OLSR and HWMP.

In Figure 3-24 to Figure 3-27 the average throughput of all smart meters transmitting to the data concentrator for varying grid size is presented. For all Smart Grid traffic profiles, it is observed that average throughput degrades at varying grid sizes for the different application traffic. Average throughput for the application traffic profiles remained approximately the same before it experiences a decline. The average throughput for AMI data traffic profile in Figure 3-24 shows that average throughput decreases rapidly at a grid size of 49. While for other applications, especially video surveillance and WAM in Figure 3-23 and Figure 3-24, a decline in average throughput is observed from 25 grid size on both protocols. This indicates high packet losses and delays on different nodes in the network. A rapid decline of average throughput on power quality traffic profile is observed from 36 grid. These packet losses can also be attributed to route losses as a result of congestion and/or saturation at the intermediate nodes in the network. The performance metric from all the Figures show that the average PDR decline rate of HWMP is steeper than that of OLSR. Nonetheless, reliability performance of both protocols must be improved for all the Smart Grid application traffic profiles across a multi-hop NAN based WMN system.

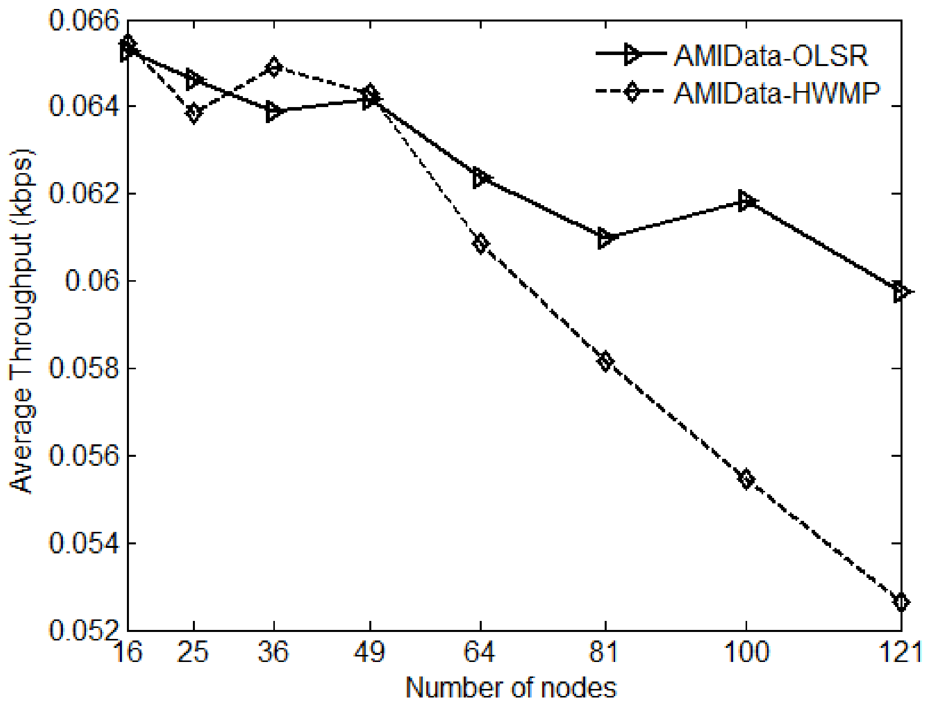


Figure 3-24: Average throughput for AMI data traffic traffic on varying grid sizes using OLSR and HWMP.

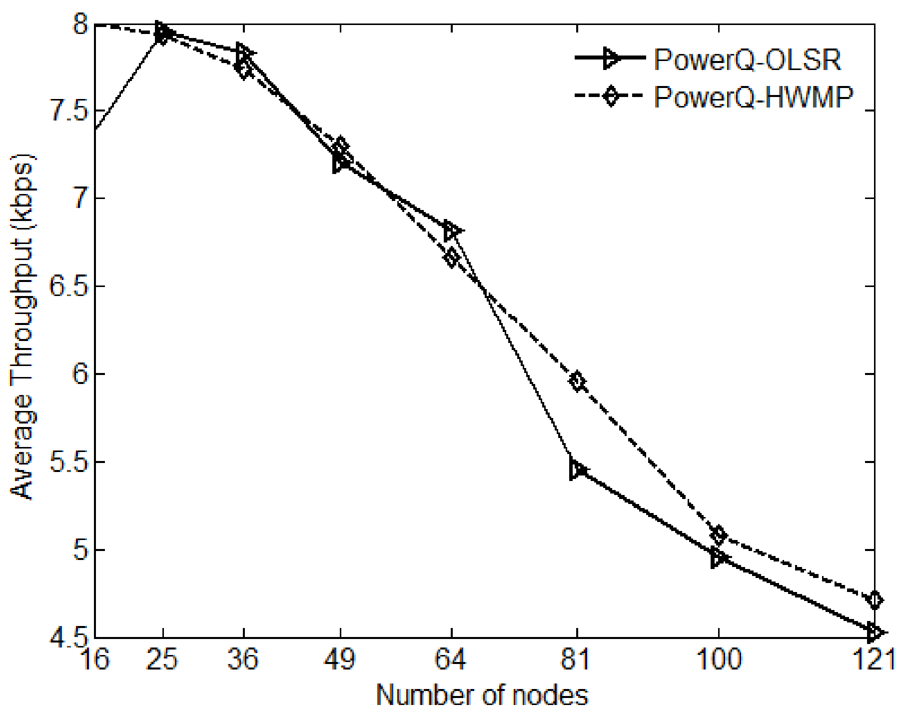


Figure 3-25: Average throughput for power quality measurement traffic on varying grid sizes using OLSR and HWMP.

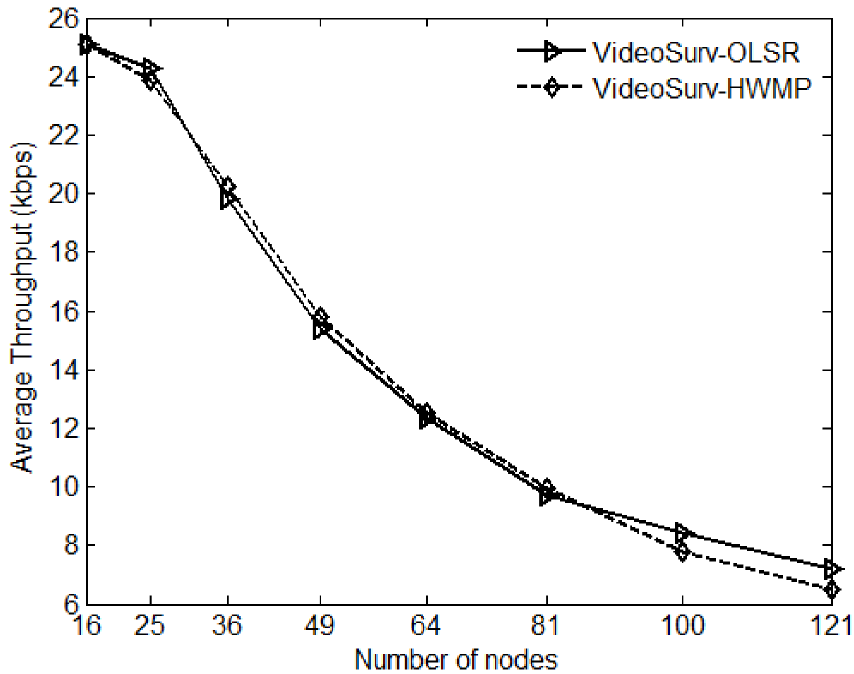


Figure 3-26: Average throughput for video surveillance traffic on varying grid sizes using OLSR and HWMP.

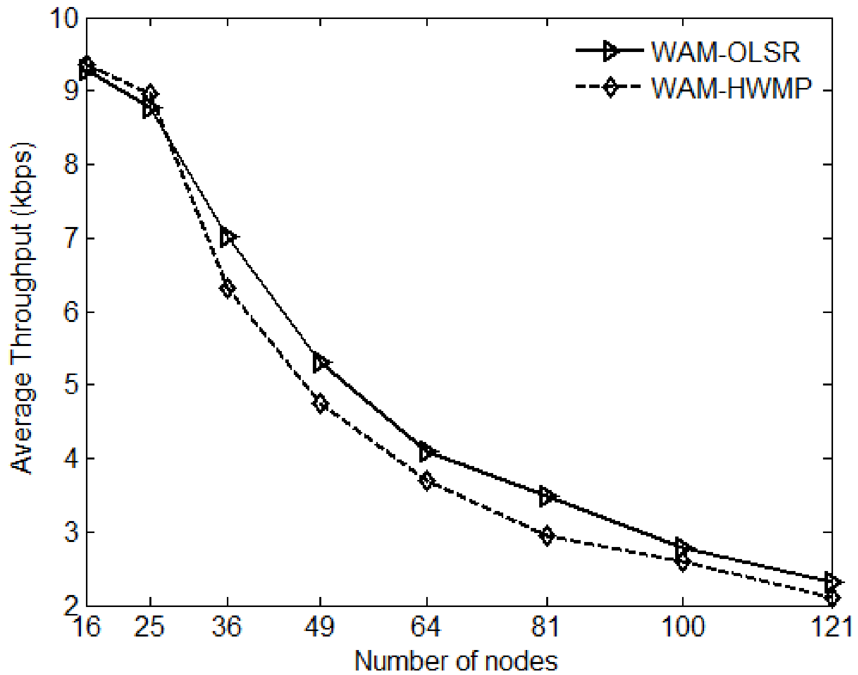


Figure 3-27: Average throughput for WAM traffic on varying grid sizes using OLSR and HWMP.

3.5.3. Key Findings

The results from the experimental implementation of ad hoc WMN and the simulation of NAN based ad hoc WMN presented in this chapter have shown the capabilities of the IEEE 802.11 ad hoc WMN in a Smart Grid's NAN. The studies clearly indicate that when reliability objectives (of over 99.99%) are considered, reliability improvements are needed in the conventional ad hoc WMN to meet the requirements for the Smart Grid applications traffic profiles, especially as the grid size increases (increasing multi-hop). The reliability objectives of Smart Grid application traffic must also be achieved without affecting their delay requirements. The two routing protocols evaluated in this chapter considered the following:

1) Impact of hop count on AMI application traffic: Performance evaluation of routing AMI application traffic using OLSR and HWMP in NAN were studied on different grid network sizes, with the largest having 121 smart meter nodes. The smart meter node is located at the top right corner to enable application traffic to traverse the maximum number of hops on each grid network size.
2) Impact of AMI application load and packet generation rate: Four AMI traffic profiles were assumed: Periodic data transmitted from all nodes with varying packet sizes and packet generation rates.

From the results presented, the key findings include the following:

- Reliability performance varried for different application traffic with increasing number of hops to the data concentrator. Congestion occurred on both protocols for WAM and video surveillance traffic when more than 25 smart meter nodes were deployed in a grid network (i.e. PDR less than 90%), while PDR for power quality on both protocols was less than 90 % when more than 36 smart meter nodes were deployed. The PDR results obtained in our simulation can be compared to that obtained in Saputro et al (Saputro and Akkaya, 2014) using similar traffic load and packet generation rate to evaluate the conventional HWMP. On the other hand, the AMI data traffic recorded an average PDR of over 90% at 64 smart meter nodes.
- Delay for AMI data traffic, power quality measurement and video surveillance were below 250 ms at 121 smart meter nodes. However, the WAM traffic recorded a delay of over 1 second from the 36 smart meter nodes.

The ad hoc WMN is known for its ubiquitous wireless access and extended transmission range, but it incurs higher delays and a general increasing PDR degradation as the grid network size increases. Packets are dropped across a multi-hop WMN for a number of reasons, which include interference, channel errors, contention, collision and the inefficiency of the link metrics in finding the best routing paths. In the experimental implementation, it was also observed that packets can be dropped as a result of intermediate node sending packets.

The requirement of different Smart Grid traffic types in NAN based ad hoc WMN systems can be accomplished by integrating a network management perspective in to the network layer and routing protocols of smart meter nodes. This is to enable the protocols to be aware of the status of each smart meter in the network and the requirement of the targeted application to be transmitted. Performance evaluation of the two conventional ad hoc WMN protocols studied in section 3.5 showed that the IEEE 802.11s standard protocol HWMP does not outperform OLSR while transmitting Smart Grid application traffic profiles from smart meters over multiple hops to the data concentrator in NAN. Therefore OLSR can also be modified to provide a platform for the implementation of cross-layer QoS routing for Smart Grid application traffic to improve reliability. This can be achieved by leveraging the characteristics of delay and loss tolerant application traffic types in order to guarantee the delivery of critical application traffic.

3.6. Chapter Summary

This chapter presents a detailed study of the transmission of Smart Grid application traffic over a conventional ad hoc WMN deployed in NAN. Firstly, a classification of Smart Grid traffic considering specific constraints of the application traffic and network requirements was presented. Different Smart Grid application traffic profiles were generated using UDP/IP protocol to avoid the acknowledgement complexity of connection oriented Transport Control Protocol (TCP) traffic. Furthermore, the performance analysis of two conventional wireless routing protocols; HWMP and OLSR, which use the ALM and ETX link metric respectively were carried out. Since experimental results can differ significantly from simulation results, Section 3.4 contains an experimental implementation of ad hoc WMN, to study the behaviour of Smart Grid application traffic on an experimental ad hoc WMN. Aside from the effect of interference and other channel mediums, it was observed that transmitting Smart Grid traffic profiles over ad hoc WMN could be affected by packet drops at the forwarding intermediate nodes.

The simulation study in section 3.5 evaluated the performance of a NAN based ad hoc WMN in an urban area. The grid network topology was used to represent an urban neighbourhood area and 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 marginally better, in some cases, than the IEEE 802.11s standard default protocol. However, modifications are still required on the OLSR protocol to satisfy the stringent reliability requirements of Smart Grid applications. Thus, cross-layer options for improving the reliability of Smart Grid traffic in ad hoc WMN can be explored using OLSR.

Chapter 4

4.Using OLSR-multiple-metric to improve reliability in NAN based ad hoc WMN

4.1. Introduction

The previous chapter contained a number of simulations and experimental studies, which revealed that using the conventional ad hoc routing protocols in Smart Grid's NAN for AMI raises the need for improvements and QoS-Aware routing, especially with increasing multiple hops in larger NAN based ad hoc WMN networks. This notion has also been acknowledged in (Sabbah et al., 2014) (Ancillotti et al., 2013a); the expanded list of applications will result in the transmission of different types of traffic between NAN devices (i.e smart meters). Thus, the protocols have to be aware of the status of the nodes (e.g., their available capabilities and resources) and the requirements of the application traffic to be transmitted.

Adopting suitable mechanisms to enforce different QoS guarantees to network flows and application traffic profiles depending on Smart Grid application constraints is therefore key to achieving a high level of communication reliability. QoS differentiation in existing communication networks are normally achieved through resource reservation and traffic prioritisation. Various approaches can be employed to prioritise important delay critical data over loss critical data. For instance, many MAC layers (e.g., 802.11e and 802.16) support the specification of different traffic categories and use scheduling algorithms to provide bandwidth differentiation (Wu et al., 2012) (Piro et al., 2012). However, MAC-based solutions are generally limited to providing QoS guarantees on single communication links (i.e. queuing delays). For this reason, there is an increasing awareness that a full-fledged QoS-based architecture and QoS routing with a network management perspective that allows selecting routes with sufficient resources for requested QoS parameters are needed to satisfy the different requirements of AMI applications (Ramírez and Céspedes, 2015).

Although complex, a combination of multiple link metrics with OLSR has been identified as a possible solution for reliable routing in ad hoc WMN. These complexities (i.e. NP[1] complete problem) can be resolved through the use of Analytical Hierarchy Process (AHP) algorithm and pruning techniques. However, the question of this technique can be used to provide reliability for variable Smart Grid application traffic in NAN based ad hoc WMN is yet unproven.

In this chapter, a node architecture to improve the reliability of a smart meter communicating in a NAN based ad hoc WMN is proposed. A case study on the performance of three OLSR link metric versions is carried out using the application traffic profiles presented in Chapter 3 and the ns-2 network simulator. The ns-2 network simulator was used instead of ns-3 because several OLSR link metric versions have been implemented on it. The best two performing metrics were used to show the possibility of

[1] Nondeterministic Polynomial time (NP)-complete problems are problems that are difficult to estimate the number of steps or polynomial time required to solve.

combining multiple metrics with OLSR protocol through the AHP algorithm to select good quality routes and fulfill the requirements of targeted Smart Grid AMI application traffic.

The rest of the chapter is organised as follows: Section 4.2 presents OLSR link metric versions considered in this chapter, Section 4.3 describes the potential reliability improvement in OLSR for NAN. The performance evaluation of the different Link metrics in a NAN based WMN scenario is carried out in Section 4.4 and 4.5, while Section 4.6 presents the combination of multiple metrics through the AHP algorithm. Finally, Section 4.7 highlights the chapter summary.

4.2. ETX variations in OLSR

The ETX link metric used in OLSR is deficient in certain aspects; these include: i) its inability to model the transmission interference and channel errors (Park, 2008); ii) it's inability to model accurately the delivery rate of a network link since it does not consider the forwarding behaviour of nodes that have established such link (Paris et al., 2013); iii) its inability to distinguish between links with different capacities; and iv) the loss probability of small probes differ from that of the data packets (Campista et al., 2008). As a result, different variations of ETX have been developed with the OLSR routing protocol. The following sub-sections give an insight into the ETX variations with OLSR. Much research has been done on link metrics for ad hoc routing protocols. Instead of presenting a survey of the existing literature on routing metric, the focus is mainly on research related to OLSR routing protocol, which, like other protocols, are potential candidates for routing in NAN. The OLSR link metrics versions considered in this chapter are presented as follows:

(1) OLSR-ML (Minimum Loss) (Passos et al., 2006), is also based on probing to calculate delivery ratios. As the name implies, OLSR-ML selects links with the lowest end-to-end loss probability. This is achieved by multiplying the delivery ratios of successful transmission probes in the forward $d_f^{(l)}$ and reverse $d_r^{(l)}$ (acknowledgements). ML reduces route changes and has the advantage of eliminating high loss rate routes; but the disadvantage is that some low quality links may still be considered in choosing a given route. It is depicted in equation (4.1).

$$ML_{p_{e2e}} = \prod_{l \in P_{e2e}} \left(d_f^{(l)} \times d_r^{(l)} \right) \qquad 4.1$$

Where $\left(d_f^{(l)} \times d_r^{(l)} \right)$ is the probability of successful delivery of probes on link l for end-to-end path (P_{e2e}) from source to destination and from destination to source (reverse direction).

(2) OLSR-MD (Minimum Delay) (Cordeiro et al., 2007), MD proposed by Cordeiro et al, selects paths between nodes with the lowest sum of transmission delays to the destination. The transmission delay

measurement comes from the ad hoc probe, which is a great advantage, because it takes into account the differences in clock synchronization.

These link metrics have been implemented with OLSR. However, the metrics trade-off between different performance parameters and the computational burden of other metrics also degrades the performance of the respective protocol. For example, a routing protocol using a particular link metric can achieve high throughput values at the cost of increased end-to-end delay in the case of static networks like Smart Grid (Javaid et al., 2011).

Considering the tradeoff problems with single metrics and the fact that Smart Grid functionality is dependent on the ability of different application traffic to meet certain performance requirements, proposing to implement multiple metrics within the existing routing protocols is explored to assess its performance on guaranteeing QoS for the variety of application traffic in Smart Grid AMI network. Though the selection of a route based on a combination of multiplicative metrics has been proved to be NP-complete (Wang and Crowcroft, 1996), techniques such as the AHP and Pruning proposed in (Moreira et al., 2008), have been used to get around the NP-completeness of multiple metric protocols. The problems of NAN based ad hoc WMN using the OLSR protocols can be classified into two types: Existing problems with OLSR-single metrics that may worsen and new problems that may emerge during the process of using it as the routing protocol in Smart Grid's NAN for AMI.

4.2.1. Existing Problems of OLSR-single metrics

OLSR uses tables to store the topology information and routes based on a selected link metric. Optimisation algorithms such as Dijkstra can then be applied to select best routes to a destination. Due to continuous broadcast updates, routing overhead can cause considerable bandwidth consumption. Other drawbacks include energy inefficiency and routing convergence delay caused by the intensive routes discovery broadcasts at the network start-up. Furthermore, OLSR only gives the best effort path to a destination without considering QoS required by the traffic to be transmitted.

The limitations of a particular link metric used for selecting optimal routing path to a destination also affects the routing protocol used. As a result, proposed solutions to improve effects of single metric routing protocols include the use of heuristics, single compound metric, single mixed metric, composite metric and multiple metrics. For example, authors in (Park, 2008) proposed the EPT for accurately finding high-throughput paths in multi-hop ad hoc wireless networks. The metric is based upon a realistic and practical model that considers both transmission interference and channel-error by (1) determining transmission contention degree of each link as a function of wireless channel-error, (2) quantifying the impact of the wireless channel-error on medium access back off, and (3) considering possible concurrent transmissions when two links do not interfere with each other. In addition, the authors in (Paris et al., 2013) proposed a novel routing metric EFW (Expected Forwarding Counter), a new reliability metric that combines information across the routing and MAC layers to cope with the problem of selfish behavior (i.e., packet dropping) of mesh routers in a WMN.

4.2.2. Problems of OLSR Single metrics in NAN

Problems of single metrics with OLSR in WMN were highlighted in the previous sub-section. In the context of deploying single link metric OLSR in Smart Grid NAN for AMI, a number of new problems can also be anticipated.

The first is the fact that simplified routing parameters considered in a single OLSR link metric are insufficient for the many properties and requirements of various Smart Grid applications. However, a property of each link metric from a number of multiple metrics may play a significant role in providing reliable transmission for one or more Smart Grid application traffic. This can be achieved through more sophisticated link quality estimation methods that consider various Smart Grid application traffic characteristics as well as the available link parameters.

The second problem is the mishandling of latency-tolerant and latency in-tolerant AMI data. Due to the variable requirements and properties of AMI applications, it is necessary to differentiate them in the network layer. However, packets are dropped in the network layer regardless of their importance, simply because the route to the destination from the intermediate node is broken. Thus, measures are needed to mitigate this problem as much as possible to guarantee reliable data transmission in the Smart Grid network. For example, as stated in the previous chapter, general AMI data is time tolerant as long as it is successfully delivered. Data can be differentiated in the network and transmitted successfully to its destination through other routes with higher but tolerable latencies.

4.3. Reliability Improvement in OLSR for NAN

The proposed reliability improvement for OLSR routing protocol in NAN is based on using multiple metrics with the OLSR protocol to provide the best available route for targeted Smart Grid applications. In order to achieve the goal, a node architecture for smart meters in NAN, consisting of a network management perspective at the network layer for routing protocols is presented. This is to enable the protocols to be aware of the node status (e.g., their available capabilities and resources) and the requirements of the targeted applications. Then the process of combining the AHP algorithm and pruning, to perform the multiple-metric routing that will offer the best available routes for targeted

Smart Grid applications based on the considered metrics is presented.

4.3.1. Multiple-metric Node Architecture for NAN devices in AMI

Link state routing protocols such as OLSR update routing paths to a destination based on parameters provided by the link metric being used. The selected routes are then used as the default path for data flow to a destination in the network. When variable AMI application traffic types are considered, a combined link metric of ETX, MD and ML with OLSR can be used to measure QoS parameters such as minimum delay and packet loss rates, in order to provide a reliable path for the variable AMI application requirement in NAN. Figure 4-1 presents a structure of the multiple metric-OLSR protocol for NAN in AMI. The node architecture is a modification of HWMP-RE proposed in (Kim et al., 2012) and the Cross-Layer QoS framework for MANETS (CLQM) architecture proposed by Sarma (Sarma and Nandi, 2008) which defines two interfaces between the application and network layer. This architecture can be utilised to create a platform that will enable evaluation of different link parameters and calculate best paths for targeted applications to their destination in NAN, with the help of a decision making algorithm.

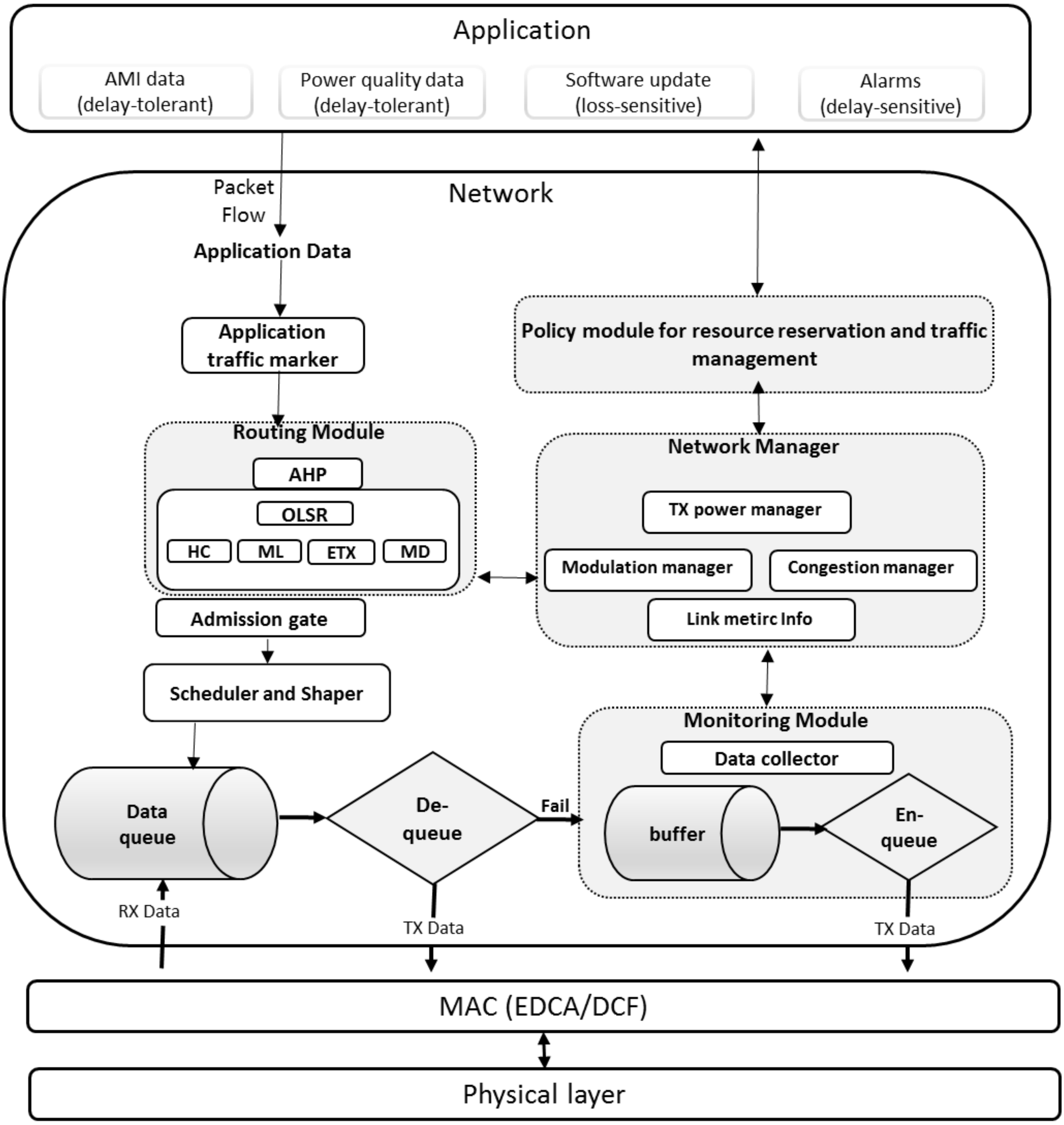


Figure 4-1: Structure of the node architecture for improving OLSR reliability on NAN devices for AMI

4.3.2. Module for multiple-metric path selection in NAN devices

An application of the AHP algorithm for multiple prioritised metrics was proposed for connection-oriented point-to-point communications in (Alkahtani et al., 2006). The use of AHP for multiple metrics with OLSR to improve routing in WMN and deal with high QoS demands was also proposed in (Moreira et al., 2008).

Considering the different applications with special QoS requirements in Smart Grid, changing route priority to meet the special requirements of some traffic is a highly desirable attribute for routing protocols in NAN. For example, when routing application traffic that is delay sensitive as in real time applications, a metric which gives a better end-to-end delay in the network should be considered first priority. In contrast, when routing traffic applications that are sensitive to loss, a metric that has the best delivery reliability performance should be the first priority. As in the previous chapter, loss sensitive Smart Grid traffic was represented by power quality traffic profile transmitting a packet size of 512 bytes every 0.5 seconds. Delay sensitive Smart Grid traffic was represented by wide area measurement traffic transmitting a packet size of 48 bytes every 0.1 s (Kim et al., 2012). There is a presumption that multiple metrics with OLSR through the AHP algorithm will enable the allocation of routing path to each targeted application that is loss or delay sensitive.

4.3.3. Pruning Methods

Pruning methods are applied to many applications to improve their performance. In the context of route link metric values, pruning is a process of eliminating links which have quality values greater than or equal to a given threshold. The threshold can be determined in different ways, such as calculating the median values of all available links to the destination and discarding links with values above or below this threshold. This is done to minimise the number of links to be considered as well as reduce the computational complexity of the AHP algorithm. In this chapter, pruning is done by selecting the best four values of each link metric and applying the decision making algorithm to calculate the best quality route to a destination

4.4. Link Metric Evaluation (Case Study)

In this section, the scenario used in carrying out simulations to measure the performance of each routing metric in terms of reliability and delay is presented. The performance of each metric will also influence the selection of the routing metric that will be used to represent reliability and delay metric for the AHP algorithm.

4.4.1. Simulation Scenario

Simulations were carried out using IPv4/UDP protocol and the shadowing propagation model in ns-2; which assumes that the average received signal power decreases logarithmically with distance. This propagation model can be representative of a large wooded urban area (Moreira et al., 2008). The simulation topology is represented such that packets are sent towards a destination or data concentrator in a grid WMN. The parameters used are presented in Table 4-1. These parameters are similar with the ones used in (Moreira et al., 2008). The major difference is the antenna transmission range and path loss exponent, which was set such that nodes can only communicate with their closest neighbour, to show performance of the routing protocol across more hops to the destination. The aim of the simulation is to study the performance of OLSR routing link metric on delay and loss sensitive smart metering applications. The simulation set up is a representation of smart meters sending data to the data concentrator simultaneously, to demonstrate a worst-case scenario of smart meters communicating with the data concentrator in a NAN.

Table 4-1: Simulation Parameters

Parameters	**Values**
IEEE standard	802.11b
Propagation Model	Shadowing
Antennas	Omnidirectional, 4dB gain
Mesh node carrier sense threshold	-76dBm [IEEE 1999]
Mesh node receiver sensitivity	-80dBm [IEEE 1999]
Path Loss Exponent	2.7

4.4.2. Used Link Metric

Simulations were run to determine the performance of OLSR-ETX, OLSR-ML and OLSR-MD in a NAN which constitute smart meters communicating through an ad hoc WMN network of grid size 2-by-2 to 7-by-7. The simulations were carried out on ns-2.34 using different seeds for the random number generator. Each simulation was run for 50 seconds and repeated five times. As stated in the previous chapter, delay sensitive or time critical applications in Smart Grid are often referred to as small sized packets which need to be delivered to the destination within a stringent latency (tens of milliseconds), while loss sensitive application traffic must be delivered to the destination regardless of time. Two CBR traffic types were considered: 1) CBR flow of 48 bytes transmitting every 0.04 seconds (this could be a WAM traffic, or emergency alarm traffic), and 2) a CBR flow of 512 bytes every 0.5 seconds (power quality data). In the simulation, smart meters were required to simultaneously send data to the data concentrator for each of the CBR traffic using three OLSR link metrics: ETX, MD and ML link metrics in order to choose the best performing metric for each simulation scenario.

4.5. Simulation Results

Performance evaluation was measured by estimating the average end-to-end delay, PDR and throughput on an increasing grid mesh network size. OLSR-ETX had the highest PDR performance as seen in Figure 4-2, but this is not the case with delay. As observed in Figure 4-3, OLSR-ML has the best average delay performance amongst all the other metrics, but the delay still exceeds 200 millisecond from the 5-by-5 grid size for delay sensitive applications. The transmission rate at which the critical data is being sent results in queues and loss packets at the intermediate or forwarding smart meter nodes, which also contributes to high delays. In real smart metering conditions, some delay critical applications may only be event triggered, for example, a fire alarm or security alarm. However, simulating high frequency of delay sensitive application traffic was done to measure the performance of each link metric at worst-case scenario (e.g. a storm day with multiple power outages).

Throughput for both CBR flows on Figure 4-4 show that ETX performs better followed by ML and then MD, though it is observed that there is a decline in the average throughput from the 5-by-5 grid size. The main goal of the simulation is to select the routing metrics with the overall best performance. Results from the simulation scenarios showed that ETX and ML performed better, and thus, they are used with OLSR to improve its routing table computations. Only one CBR flow was considered in each simulation and at 3-by-3 grid network size, the performance of ETX, MD and ML on both loss and delay sensitive simulation scenarios were above 90% for PDR and less than 100 milliseconds delay.

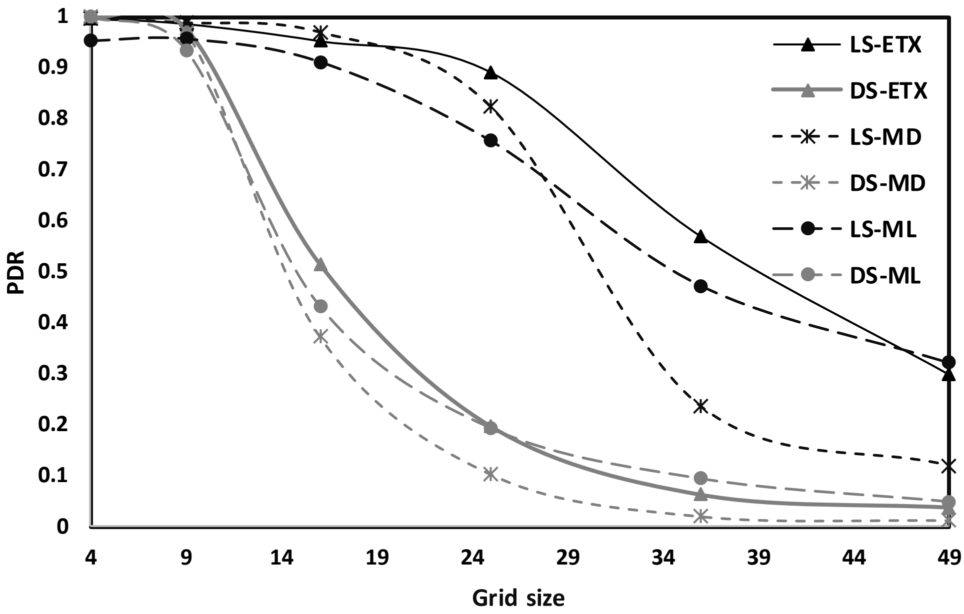


Figure 4-2: PDR for delay and loss sensitive AMI applications

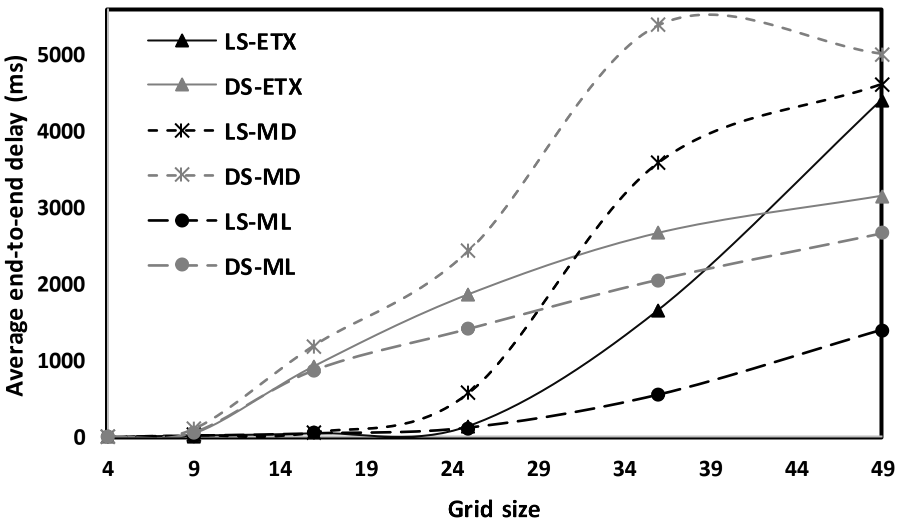


Figure 4-3: End-to-end delay for loss and delay sensitive AMI applications

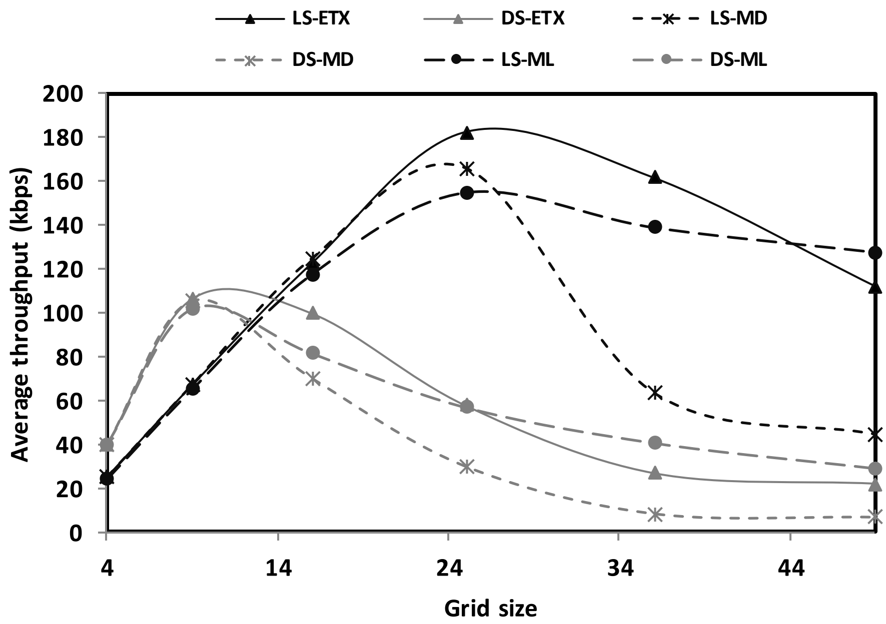


Figure 4-4 Average Throughput for delay and loss sensitive AMI applications

In the next simulation, the number of AMI application traffic sent from each smart meter is incremented from 1 to 4, in order to evaluate performance of each link metric while sending multiple application traffic flow from the smart meters. Other applications considered are from the traffic profiles in Chapter 3, that include: AMI data transmitting 123 bytes of data every 15 seconds and video surveillance traffic (Kim et al., 2012) from the previous chapter. Results in Figure 4-5 and Figure 4-6 show a drop in PDR and an increase in delay on all the link metrics as the number of traffic sent from each meter is increased. ETX and ML still performed better. The losses indicate that the delay and reliability objectives in NAN based ad hoc WMN of certain applications may not be achieved if measures are not considered to guarantee QoS for each application traffic.

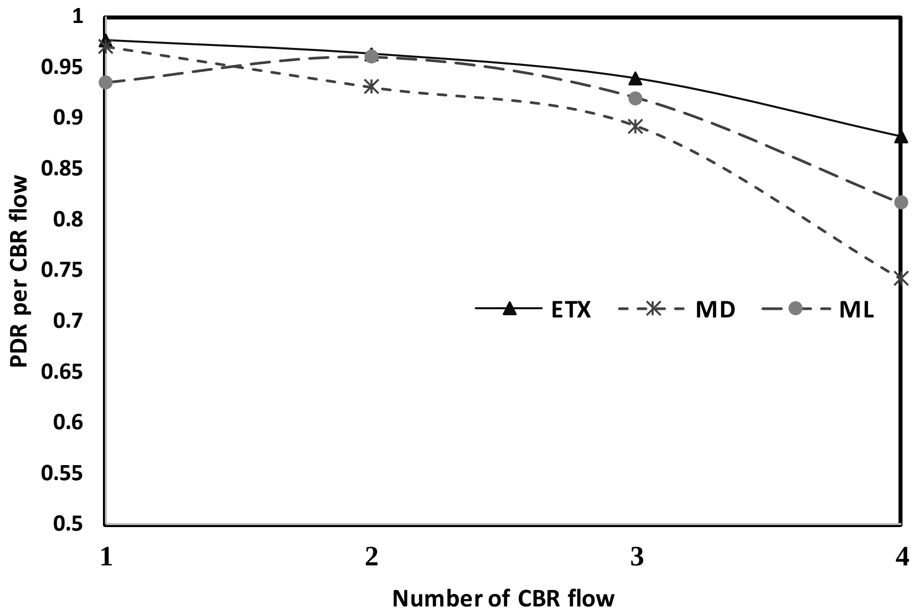


Figure 4-5: PDR obtained from multiple traffic transmitted from Smart meters

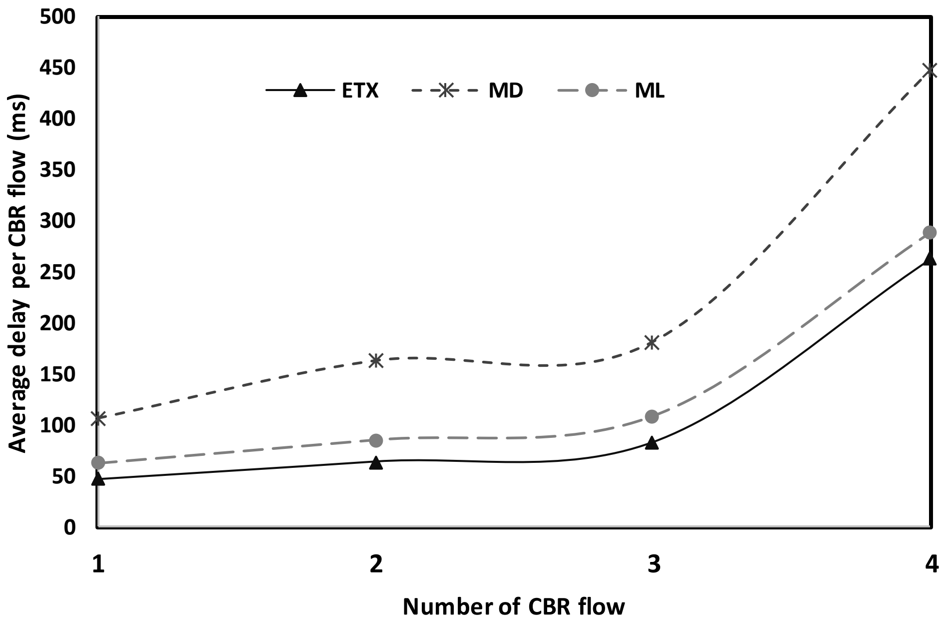


Figure 4-6: Average delay obtained from multiple traffic types transmitted from NAN devices

4.6. Combining multiple link metric with OLSR

AHP is a robust and flexible multi-criteria decision analysis methodology of measurement, developed by (Saaty, 1990), it is widely known in the field of decision-making, when different qualitative and/or quantitative criteria must be applied. This methodology is already being used in a number of applications in the field of telecommunications (Moreira et al., 2008) (Alkahtani et al., 2006), petroleum pipeline network (Dey, 2004), project management (Huang et al., 2008) and health services. By making minor changes to the original AHP methodology, it was used in (Moreira et al., 2008) to decide the best route for multimedia applications to a given destination. This approach is adapted to explore the possibility of providing good quality routes and QoS support for smart meters while sending AMI application traffic characterized by variable requirements.

4.6.1. Applying AHP for routing in NAN based WMN

In order to illustrate the approach of applying AHP with OLSR, the transmission between Node 0 and Node 8 in the 3-by-3 grid mesh network topology shown in Figure 4-7 is considered. Applying AHP will involve three main parts: 1) metric weightings, 2) priority weighting and 3) total score calculations.

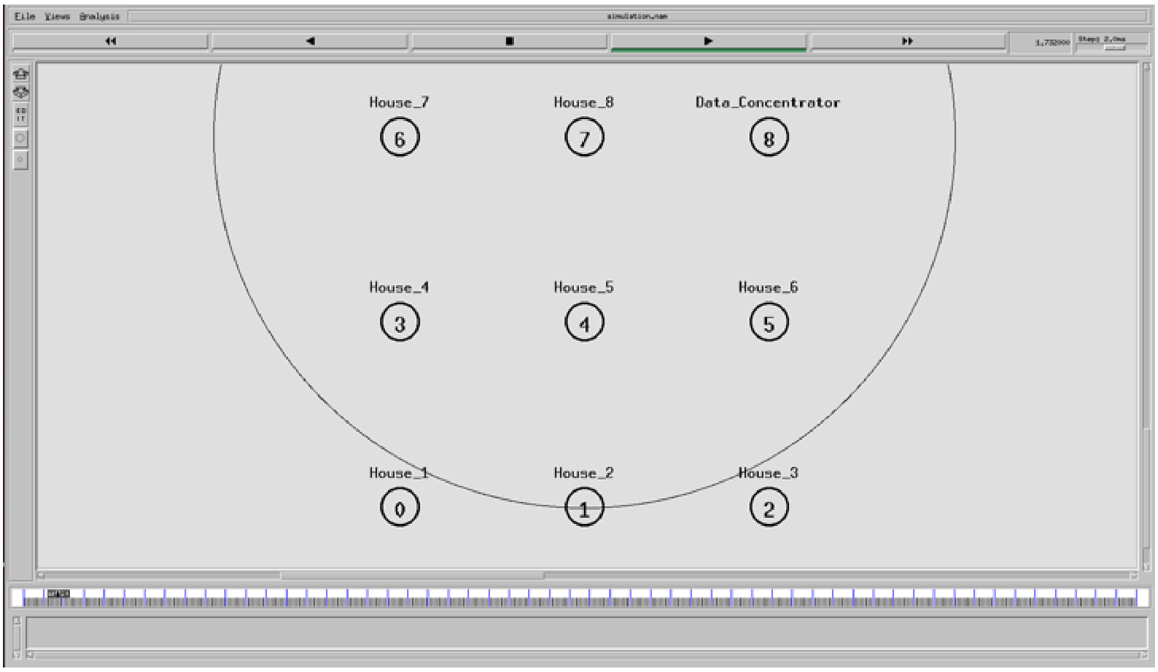


Figure 4-7: 3-by-3 Grid Mesh Network Topology for NAN

4.6.2. Metric Weighting

Step-A: The first step involves finding all possible paths between nodes 0 and 8 on the link metrics to be considered. This is where pruning techniques are applied to reduce the number of paths to be considered. Appendix B shows the routing table of different nodes transmitting to a destination. For ease of computation, instead of considering all possible paths on node 0's (transmitting node) view to node 8 (destination), only four best paths between node 0 and 8 are considered. Metric values for each path were measured by summing up values of all the links in the path. For example, from the routing table in Appendix B, summation of ETX values for link 0478 (1.111 + 1.5873 + 1.5873) is equal to 4.23. The paths considered were only four paths which were selected by pruning other paths greater or equal to the median value of all other possible path between node 0 and node 8. The four paths with the best values were selected to reduce computational complexity and time, which will increase, especially in larger networks when all possible paths are considered. Table 4-2 shows the four paths along with their respective overall values of ETX and ML.

Table 4-2: Metric values for selected Paths from node 0 - 8

Paths	A	B	C	D
Links	0478	048	0378	0158
ETX	4.26	2.69	3.80	4.21
ML	0.52	0.77	0.68	0.44

Step-B: The second step involved the generation of a path-to-path pair-wise comparison matrix (ppcm) for the path values shown in Table 4.2. By using a pair-wise comparison matrix of size $(N \times N)$, where N is the number of paths to the destination. The scores of each metric (ETX and ML) on every path can be determined. The basic idea of the *ppcm* is to compare the quantitative metric of ETX and ML of one path with that of all other paths. The matrix calculations are based on the following equation. Where i and j are paths, and m_j is the overall value of the metric for path j.

- *ppcm (i, i)* = 1, when comparing the same path;
- *ppcm (j, i)* = 1/ *ppcm (i, j)*, for reciprocal paths; and
- *ppcm(i, j)* = m_j/m_i, for min criterion.

Using the metric values presented in Table 4.2 as an example, the *ppcm* for ETX is given by:

$$ppcm\,(ETX) = \begin{bmatrix} 1 & 1.2834 & 0.8920 & 0.9883 \\ 1.5836 & 1 & 1.4126 & 1.5651 \\ 1.1211 & 0.7079 & 1 & 1.1079 \\ 1.0119 & 0.6390 & 0.9026 & 1 \end{bmatrix}$$

Step-C: The normalised path-path pair-wise comparison matrix (*nppcm*) is generated by dividing each entry in column *j* of the *ppcm* by the sum of the entries in that same column. This results in a normalised matrix in which the sum of the entries in each column is 1. The formula for calculation is given as follows:

$$nppcm\,(i, j) = ppcm\,(i, j) / \sum ppcm\_column\,(j)$$

The *nppcm* matrix for ETX is given as:

$$nppcm(ETX) = \begin{bmatrix} 0.2120 & 0.2120 & 0.2120 & 0.2120 \\ 0.3358 & 0.3358 & 0.3358 & 0.3358 \\ 0.2377 & 0.2377 & 0.2377 & 0.2377 \\ 0.2145 & 0.2145 & 0.2145 & 0.2145 \end{bmatrix}$$

Step-D: The average normalised path-path pair-wise comparison matrix (*anppcm*) is calculated for each metric, based on the following equation:

$$anppcm(i) = \frac{\sum nppcm\_row\,(i)}{N}$$

The *anppcm* matrix is $[n \times N]$ where n is the number of metrics used (2 in this case) and N is the number of paths. The *anppcm* for ETX is:

$$anppcm(ETX) = [0.2120 \quad 0.3358 \quad 0.2377 \quad 0.2145]$$

Every metric considered must go through steps B – D in order to obtain its *anppcm*. The complete *anppcm* for ETX and ML is shown below.

$$anppcm = \begin{bmatrix} 0.2120 & 0.3358 & 0.2377 & 0.2145 \\ 0.2761 & 0.1865 & 0.2111 & 0.3263 \end{bmatrix}$$

Each row of this matrix refers to the metrics values of ETX and MD and column refers to the values on each path.

4.6.3. Priority weightings

Step-E: Priority weightings involve the calculation of the average normalised priority pair-wise comparison matrix (*anprpcm*) to determine the relative importance of each metric compared with the other metrics. While performing this process in the original AHP, each metric is normally given absolute numbers that reflect the relative importance of one metric compared to the other, based on the feelings of the decision maker. Then Steps B – D from the weighting metric section are performed to find the *anprpcm*. The modifications proposed by (Alkahtani et al., 2006) were used, which requires the metrics to be assigned weights in the range of [0, 1], where the sum of all the weights equals one, as shown in the matrix below:

$$anprpcm = [0.5, 0.5]$$

The required priority of any of the metrics (ETX/ML) can be set using *anprpcm*. If the priority is set at 0.5 for both ETX and ML metric, it means there was no priority considered for any of the metrics. A priority is set at [0.7, 0.3] for ETX and ML priority is set at [0.3, 0.7] in order to view the path choices for different priorities. High priorities for a particular metric are assigned to ensure that the path of that metric to the destination is given more consideration.

4.6.4. Total score calculations

Step-F: Calculation of the total score for each path can be obtained using the expression below:

$$Total\ Normalised\ score\ of\ path j \sum_{i=1}^{n} (anprpcm[i] \times anppcm[i,j]), \quad j = 1, \ldots, N$$

Table 4-3: Path score for different priorities

Paths	**A**	**B**	**C**	**D**
Links	0478	058	0378	0158
Total path score	0.2441	0.2611	0.2244	**0.2704**
Total score ETX	0.2312	**0.2910**	0.2297	0.2481
Total score ML	0.2569	0.2312	0.2191	**0.2928**

Step-G: The path with the maximum total score in Table 4-3 should be used in the communication between nodes 0 and 8. As observed in Table 4-3, path D has the best link quality when both metrics are given no priority ([0.5, 0.5]). When ETX is given priority (i.e, *anprpcm* = [0.7, 0.3]), path B has the best link quality overall. However, when ML is given priority (i.e, *anprpcm* = [0.3, 0.7]), path D has the best quality.

This shows that this approach can be very interesting in the implementation of multiple metrics on NAN devices for AMI applications. In order to adaptively guarantee the QoS required for each of the application traffic paths, path B can be used for Loss Intolerant traffic, while path D can be used for delay sensitive traffic. This will enable routing of traffic across different paths in the network to a destination, therefore reducing congestion on some intermediate nodes and improving reliability performance.

4.7. Chapter Summary

This chapter explores the possibility of using multiple metrics-OLSR to select good quality links and support QoS routing in NAN based WMN through the use of AHP. Though AHP has been proposed by [6] and [5] for use in selecting good quality links on multimedia applications in wired and wireless networks, it does have the potential to select good quality paths and support QoS routing in NAN for AMI. A case study on the performance of routing metrics while transmitting Smart Grid application traffic profiles in a NAN was presented. Two metrics, ETX and ML were selected and used along with the AHP algorithm to present a case for adaptively supporting QoS for targeted AMI application in a NAN based WMN. Only four best paths out of all possible paths to the destination were considered for each link metric in the AHP algorithm. This is a rather simplistic approach, as there are more possible best routes to the destination and the paths increase as the network scales. Using a large number of possible paths in the AHP algorithm will increase computational complexity and time required to select routes. Therefore, path pruning methods must be developed, especially in large networks, to reduce the matrix computations and complexities for implementing the OLSR multiple-metric algorithm using AHP. The multiple metrics with AHP calculations presented in this chapter showed that it can be used to provide information of the best route an application traffic will traverse to the data concentrator in a NAN.

Chapter 5

5. Implementation of multiple metrics with OLSR using AHP

5.1. Introduction

Some key components to be retrofitted in ad hoc WMN deployed for Smart Grid NAN include the integration of QoS support for Smart Grid applications, improved reliability and reduction of delay across multiple hops. This Chapter implements a multiple metrics approach for improving routing in NAN based ad hoc WMN. The implementation is based on a modification of OLSR protocol in ns-2 that takes in to account different link metric parameters and uses the AHP algorithm to decide a route to transmit packets to the destination (data concentrator). The multiple metrics solution is designed to select good quality links and adaptively provide QoS routing for targeted Smart Grid application traffic. It is designed through a cross-layer approach which supports application level QoS requirements for Smart Grid application traffic types by allowing the use of different types of routing link metrics.

Furthermore, the Chapter critically analyses the multiple metric framework on different Smart Grid NAN topologies and evaluates its performance using the ns-2. A comparative performance evaluation also carried out in ns-2 simulation shows that this solution outperforms classical OLSR link metrics. The novelty of the multiple metrics implementation lies in its ability to select routes for an individual application data type based on its QoS requirements in a single platform.

The Chapter includes the following: - Section 5.2 describes the problems to be tackled by the multiple metrics framework. Section 5.3 presents some previous work related to the implementation of our proposed multiple metrics framework, while an analysis of some well-known Multi-Criteria Decision Making (MCDM) algorithms are discussed in section 5.4. The framework of the multiple metrics implementation is presented in section 5.5. Section 5.6 contains a simulation study and analysis of the routing framework on different topologies. Finally, the chapter summary is highlighted in section 5.7.

5.2. Problem Statement

Improvements are still required on several ad hoc WMN routing protocols classified for NAN to enable them support the reliability of target application traffic. While most routing protocols use a single link metric such as ETX, it is important to reiterate that link metric performance is dependent on the packet size and packet generation rate of the traffic being transmitted. This is evident in the reliability and delay performance of the different Smart Grid application traffic types across multi-hops to a destination, as demonstrated in Chapter 4.

Different link metrics also select paths to the destination using different parameters (i.e. minimum loss rate or delay), which are calculated using different methods. The result is that different paths may be selected to the destination. For example, as demonstrated in Chapter 4, OLSR_ETX and OLSR_ML select paths to a destination by calculating minimum loss. However, unlike ETX which uses a summation of inverse probability of successful transmissions on each link, OLSR_ML uses the product of the probability of successful transmissions on each link. Therefore, ML and ETX could have different paths to the destination which may favour one application requirement over another in terms of delay and reliability.

Transmitting application traffic concurrently using the best path, or different paths provided by a number of considered link metrics can help avoid congestion on intermediate nodes. Consequently, the QoS requirements of varying Smart Grid applications in NAN based WMN may also be better satisfied by forwarding the data along different routes. This means that for a given set of QoS requirements, the routing criteria (i.e. routing/link metric types) have to be determined so that the appropriate routes/paths are selected. Take for example a smart meter which may be a source for many types of application traffic in the Smart Grid system, communicating EV charging information, power quality and AMI application traffic, each with different delay and reliability requirements. As shown in the previous Chapter, the link metric with the shortest delay should be the most appropriate path for delay sensitive traffic, while the one with the best reliability can be used for reliability sensitive traffic.

Existing ad hoc network routing solutions do not consider application traffic requirements when making a routing decision. Such decisions are typically made using only the information acquired at the network layer. For example, both ETX and ML link metric use the Dijkstra algorithm to determine the best route, that is, the one with the least cost. A route selected using any of these metrics does not accommodate the support for different QoS requirements imposed by the diverse Smart Grid application traffic types.

Therefore, we hypothesise that making a routing solution that takes account of Smart Grid application traffic requirements could better satisfy the reliability and performance needs of application traffic types and Smart Grid as a whole. To validate this hypothesis, an implementation of the Multiple-metrics using OLSR and the AHP algorithm is implemented for a NAN based WMN scenario, which can use a cross-layer approach to support QoS by mapping link metric types to targeted application traffic types.

5.3. Related Work

As the name implies, single routing metric types use one routing metric to evaluate and select the route path with the best routing metric value. On the other hand, multiple routing metric types consider and compare two or more routing metric values before selecting the best route. Modifications of both routing metric approaches have been carried out for multimedia applications. The approach related to the proposal in this Chapter involves multiple metrics, which require the use of a decision-making technique.

The Rank Order and Threshhold methods have been the typical techniques used to select the best route in multiple metrics. However, these techniques have a disadvantage of not considering the quality of the routing metric in making decisions. Hence, methods that can consider the quality of all the routing metric types, while satisfying the requirements of the application traffic types are being explored.

A Flexible Route Decision (FRD) framework for MANETs is presented in (Saaty, 1990), which uses a cross-layer approach to support application-level QoS requirements, by allowing its users to rank different types of routing metric through the help of MCDM Techniques. On the other hand, our multiple metric implementation on Smart Grid application traffic profiles use OLSR and the AHP, which is a MCDM technique. A brief description and analysis of most commonly used MCDM techniques is presented and the reason for the choice of AHP is highlighted in the following section.

5.4. Multi-Criteria Decision Making Techniques (MCDM)

In Chapter 3, a discussion and evaluation of two routing protocols for an ad hoc WMN NAN was presented. It was observed that the routing algorithms make routing decisions without considering the requirements of application traffic types. This might not be able to adequately satisfy Smart Grid requirements, especially when variable application traffic types are transmitted concurrently from the smart meter nodes. This section discusses how to make use of a number of MCDM techniques to design a routing decision method that could take both application traffic type requirements and a number of routing metric types into account.

MCDM techniques are considered one of the most well-known techniques in decision-making. The techniques deal with decision situations where the decision maker has several conflicting objectives. In Chapter 4, the AHP algorithm an MCDM technique was proposed for application in decision-making, considering OLSR multiple metric types and the application traffic type requirement in NAN based ad hoc WMN. Apart from the AHP algorithm used in the implementation of the proposed multiple metric, two other MCDM techniques, 'The Weighted Sum Model (WSM) Technique' and 'Weighted Product Model (WPM)' are discussed in this Chapter. For clarity, a number of parameters used in explaining the MCDM techniques are described below:

- RLMT (Route Link Metric Type) refers to link metric considered or assigned by the routing protocol to forward a traffic.
- RLMV (Route Link Metric Values) is the measured values for metric RLMT.
- RLMTW (Route Link Metric Type Weight) is the weight value used to prioritise an RLMT for a particular application.

- Possible Routing Paths (PRP) shows all the available paths from source to destination.

5.4.1. The Weighted Sum Model (WSM) Technique

One of the simplest and most commonly used MCDM techniques in single dimensional problems is the WSM (Osathanunkul, 2013), where all the units of RLMT are the same (e.g. seconds, bytes/sec). WSM approach makes a decision by selecting a route with the highest Weighted Sum Model Score (WSMS). WSMS is calculated from the sum of the performance value of each RLMT. The equation for calculating WSMS is given as:

$$WSMS_i^A = \sum_{j=1}^{n} (RLMV_i^j \times RLMTW_A^j) \qquad 5.1$$

Where $WSMS_i^A$ is the WSMS of all paths (PRP_i) available to forward application traffic type 'A'. While, $RLMV_i^j$ is the value of the link metric type ($RLMT_j$) for all PRP_i. $RLMTW_A^j$ is the weight of the $RLMT_j$ for the Smart Grid application traffic type A. The terms of ($RLMV_i^j \times RLMTW_A^j$) can be called the performance value of PRP_i in terms of $RLMT_j$. This approach is illustrated by applying it to the simple network in Figure 5-1.

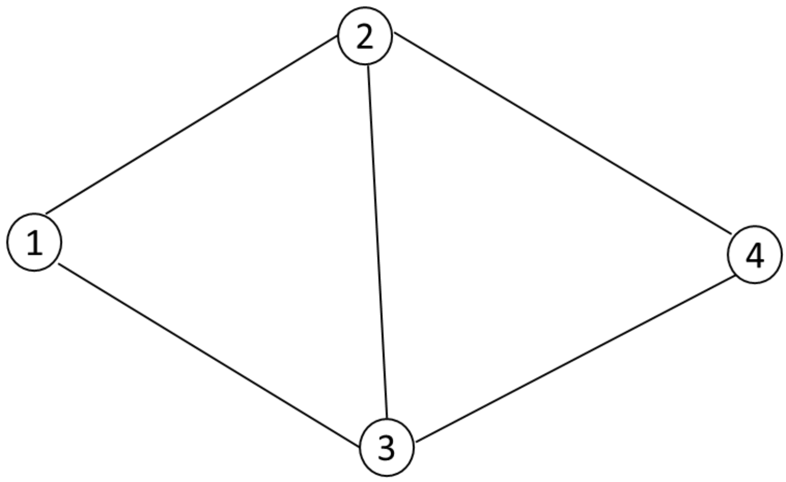


Figure 5-1: Example of a Simple Network

The network shown in Figure 5-1 is a simple network used to illustrate how the WSM technique makes decisions. Suppose that a Smart Grid application traffic type 'A' transmitted from node 1 to node 4 has four PRP's with two RLMT on each PRP. The two RLMT's on each PRP are ETX and MD with RLM values (RLMV) shown in Table 5-1. Where the sum of weights for all the RLMT's is assumed to be 1, the RLMTW of ETX and MD for the Smart Grid application traffic type 'A' are assumed to be [0.5, 0.5].

Table 5-1: Summary the performance value of RLMT

Possible Routing Paths (PRP)	RLMTs (RLMTW$_A$)	
	ETX (0.50)	MD (0.50)
PRP_1 (124)	2.19	1.01
PRP_2 (134)	2.25	0.20
PRP_3 (1234)	3.23	0.51
PRP_4 (1324)	3.45	1.40

The WSMS of the four routing links are:

$$WSMS_1^A = 2.19 \times 0.5 + 1.01 \times 0.5 = 1.6$$

$$WSMS_2^A = 2.25 \times 0.5 + 0.2 \times 0.5 = 1.225$$

$$WSMS_3^A = 3.23 \times 0.5 + 0.51 \times 0.5 = 1.87$$

$$WSMS_4^A = 3.45 \times 0.5 + 1.40 \times 0.5 = 2.43$$

The highest *WSMS* is chosen as the best path to the destination. Based on the performance *WSMS* values presented above, the best link from node 1 to node 4 for the Smart Grid application traffic 'A' is the PRP_2 (1324) link because it has the highest WSMS of 1.40. The difficulty of this method emerges when it is applied to multi-dimensional cases, where the units/scales of RLMTs are different. The scales of RLMTs are often very different in ad hoc WMN, which sometimes makes the WSMS technique unsuitable for ad hoc WMN.

5.4.2. The Weighted Product Model (WPM) Technique

WPM technique is similar to WSM. The main difference is that WPM uses multiplication instead of addition in the model. Each routing candidate is compared with the others by multiplying a number of ratios, one for each RLMT. Each ratio is raised to the power equivalent to the RLMTW of the corresponding RLMT. For example, to compare two routing paths PRP_1 and PRP_2, the ratio between PRP_1 and PRP_2 has to be calculated using the following equation:

$$WPMP^A\left(\frac{PRP_1}{PRP_2}\right) = \prod_{j=1}^{n}(RLMV_1^j \ / \ RLMV_2^j)^{RLMTW_A^j} \qquad 5.2$$

Where $WPMP^A\left(\frac{PRP_1}{PRP_2}\right)$ is a WPM ratio of PRP_1 compared with PRP_2 for Smart Grid application traffic type A. n is the number of RLMTs supported, $RLMV_1^j$ is the metric value of $RLMT_j$ for route PRP_1, and is the weight of $RLMT_j$ for Smart Grid application traffic type A. $RLMV_1^j$ and $RLMV_2^j$ must not be 0. Otherwise the relative value can become an infinity value. In the case that $RLMV_i^j$ is 0, a value of 1 will be used instead (i.e. use 1 to replace 0).

If $WPMP^A\left(\frac{PRP_1}{PRP_2}\right)$ is greater than 1.0, it indicates that PRP_1 is better or more desirable than PRP_2, and vice versa. In the case that $WPMP^A\left(\frac{PRP_1}{PRP_2}\right)$ is higher than 1.0, PRP_2 will be dropped as it is believed to be worse than PRP_1. Then PRP_1 will be compared with the rest of the routing paths. If the value of WPMP is equal to 1.0, then both routes are believed to be equally good. The best route can be selected by dropping the worse ones after comparing all the routing paths against each other.

Recall the simple network in Figure 5-1 and the RLMT performance values in Table 5-1 that were used to illustrate routing decision making for WSM. The same scenario is used to make a routing decision using WPM technique. The ratios between routing candidates are derived in WPM as follows:

$$WPMP^A\left(\frac{PRP_1}{PRP_2}\right) = (2.19 \,/\, 2.25)^{0.5} \times (1.01 \,/\, 0.20)^{0.5} = 2.21 > 1$$

The value of $WPMP^A\left(\frac{PRP_1}{PRP_2}\right)$ is higher than 1 which means PRP_1 is better than PRP_2. PRP_2 is dropped, and PRP_1 is compared against PRP_3:

$$WPMP^A\left(\frac{PRP_1}{PRP_3}\right) = 1.158 > 1$$

This also indicates that PRP_1 is better than PRP_3 because $WPMP^A\left(\frac{PRP_1}{PRP_3}\right)$ is higher than 1. PRP_3 is also discarded and PRP_1 is compared to PRP_4.

$$WPMP^A\left(\frac{PRP_1}{PRP_4}\right) = 0.6767 < 1$$

This indicates that PRP_4 is better than PRP_1 because $WPMP^A\left(\frac{PRP_1}{PRP_4}\right)$ is less than 1. Therefore PRP_1 is discarded and PRP_4 is selected as the best route since it is superior to other routes.

5.4.3. Applying AHP and Further Discussions

The AHP MCDM technique was explained extensively in Chapter 4, where it was used to illustrate its potential for decision-making in ad hoc WMN. The AHP algorithm is also applied to the simple network and its parameters in Figure 5-1 and Table 5-1. The following results were obtained:

$AHP_1^A = 0.2093$

$AHP_2^A = 0.4366$

$AHP_3^A = 0.2163$

$AHP_4^A = 0.1378$

Using the AHP technique for decision-making indicates that PRP_2 has the best link quality for Smart Grid application traffic type 'A' because it has the highest AHP value. Having discussed other MCDM techniques such as WSM and WPM that can be applied for route decision-making in a NAN based ad hoc WMN, the AHP has been selected for the implementation of our multiple-metrics QoS routing approach with OLSR. There are a number of reasons for this:

- WSM requires all RLMTs to be in the same scale (i.e. single dimensional). Otherwise the performance value can be inaccurate when RLMTs have different scales, consequently making the routing decision inaccurate.
- Contrary to WSM, WPM and AHP use relative values, which means multiple RLMTs do not need to be at the same scale.
- AHP is selected because it has support for multi-dimensional criteria and has been used for the OLSR link metric versions considered in this thesis.
- Paths selected by applying the MCDM techniques on the simple network showed that AHP has a better route. It selected PRP_2 which has the lowest delay and one of the lowest ETX values.

The multiple metrics implementation framework allows the AHP MCDM technique to be plugged in, to support multiple metrics routing decision making with OLSR. The next section describes the framework in detail.

5.5. Multiple metric Implementation

The multiple metric using AHP and OLSR is designed to find the best route for an application traffic type. It uses a cross-layer approach, which will bridge the application layer and the network layer and also use the AHP to make a routing decision based on the requirement of the traffic and the information provided by the link metrics at the network layer.

5.5.1. Implementation Overview and Description

The multiple metrics framework is broken down in to five components, which are presented in Figure 5-2. The components in the application traffic types include: the relevant link metrics for the application traffic types (RLMT), the weights assigned to the RLMT for a target application, the decision making technique (AHP) and pruning techniques of RLMTs, and values for the link metrics (RLMT).

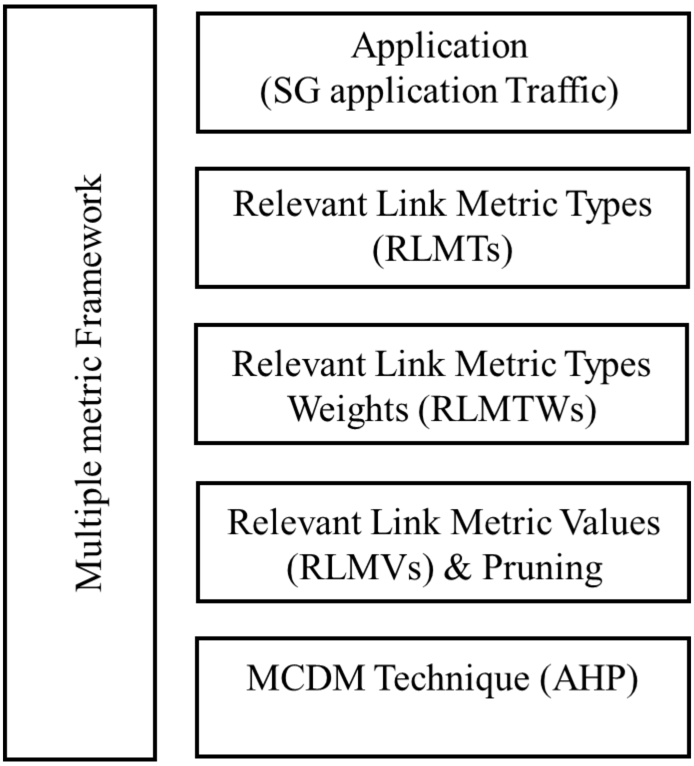


Figure 5-2: Components of the multiple metrics framework

A brief description of the function on each component is given as follows:

Application

The application refers to a Smart Grid application traffic type that will use the function provided by the multiple metrics framework. This is because a Smart Grid application may have different data types, each with unique QoS (reliability or delay) requirements. Examples of this application traffic types are: DR, EV charging, power quality and AMI data (meter reading). Each of these application traffic types can be assigned an RLMT and RLMTW which can be used to find the best route to the destination.

Relevant Link Metric Types

This refers to the link metric types chosen or assigned to a particular application. A link metric is chosen by application traffic, depending on which link metric provides a better PDR or delay. For example, a source node may have two application traffic types running on a device, application type 1 and application type 2. If ETX and MD are the most important metrics that apply to application traffic type 1, they are chosen as the metric types to support its requirements. On the other hand, for application traffic type 2, ETX and ML may be the crucial metric to support its requirements. Therefore, its RLMTs will be ETX and ML.

Relevant Link Metric Type Weights (RLMTWs)

The RLMTs used by application traffic types can be assigned different RLMTWs. These are the weights assigned to each RLMTs that will be used to transmit an application traffic type. The weights are used to indicate the importance of each RLMT. Weights were assigned to RLMTs such that the summation of all weights equals one, and the higher the weight, the more important the RLMT.

Relevant Link Metric Values (RLMVs) and Pruning

RLMVs are link metric values obtained for each path to a destination. The values are derived from OLSR_ETX, OLSR_ML and OLSR_MD link metric algorithms described in Chapter 3 and 4, for different paths to a destination. The number of paths to a destination recorded by routing tables differs, depending on the size of the network. The pruning technique is used to reduce the number of paths to a destination.

Multi-Criteria Decision Making (MCDM) Technique

The AHP is the main component of the multiple metric algorithms, which takes the RLMTWs and RLMVs to make a routing decision. Of all the MCDM techniques discussed in Section 5.4 of this Chapter, the AHP algorithm has demonstrated the ability to locate the best path to the destination when applied to the simple network in Figure 5-1.

Figure 5-3 shows a multiple metric implementation of three application traffic types running on a device, along with their chosen metric types and weights.

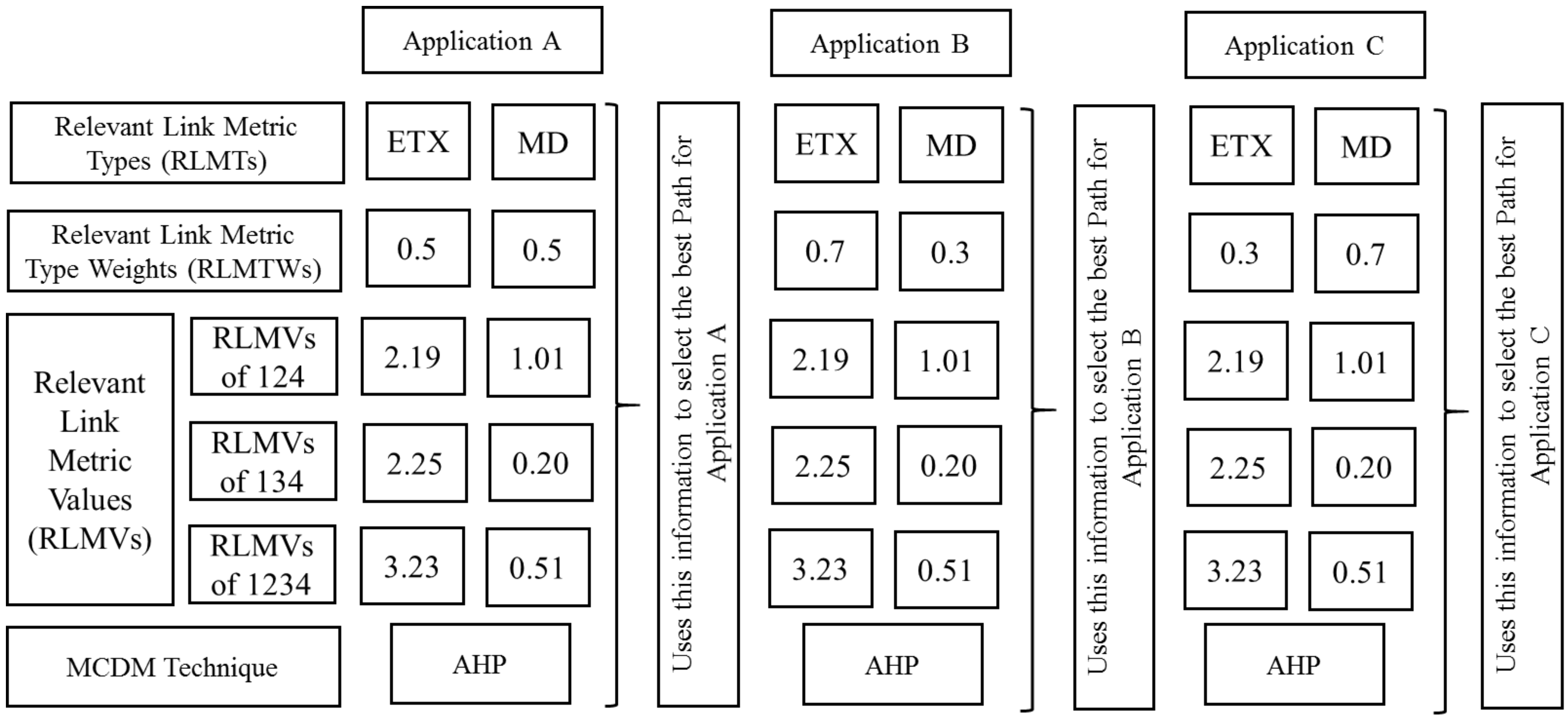


Figure 5-3: Example of using the multiple metrics framework for three different application traffic types

5.5.2. Implementation Description

A procedure of the multiple metrics for deciding a good quality link involves the following: (1) selecting the RLMTs to use for each application traffic type, (2) link metric weighting and assigning priority weights RLMTWs, and (3) making a route decision to select a path to the destination.

Selecting the RLMTs to use for each application traffic type

In order to map application traffic type to a specific path, the RLMT that will run on the node for a particular application data type must be decided. This is because it is required that the link metric domain of OLSR on each node contains a set of RLMTs that will be selected based on the QoS requirements of the application traffic type. The process of selecting an RLMT candidate to satisfy a QoS required by an application traffic is achieved by using the case study presented in Section 4.4.

Link metric Weighting and Assigning weights to all RLMTs used on each application traffic type

The link metric domain of OLSR on each node contains a set of RLMTs that will be selected based on the QoS requirements of the application traffic type. In order to map application traffic type to a specific path, the RLMT that will run on smart meter nodes to send a particular application data type must be decided. When the RLMTs are chosen for different application traffic types and the the link metric weighting is carried out, assigning weights on each RLMT are used to determine the importance of the RLMT in forwarding an application. As discussed in Chapter four, the higher the weight of the RLMT, the greater the importance or priority. Table 5-2 shows that different applications may have different sets of RLMTW values. For application traffic type A, the weight for ETX ($RLMTW_A^{ETX}$) is set as 0.5 and ML ($RLMTW_A^{MD}$) is set as 0.5. While the weights of ETX and ML for application traffic type B, which considers ETX as the most important RLMT are set as ($RLMTW_B^{ETX}$ as 0.7) and ($RLMTW_B^{MD}$ as 0.3). For application data C where ML is given more priority, the weights of ETX and ML are set ($RLMTW_B^{ETX}$ as 0.3) and ($RLMTW_B^{MD}$ as 0.7).

Making route decisions to select a path to destination

Following the selection of the RLMTs and the application of link metric weighting and the RLMTWs (AHP) to set priorities for different application traffic types. Each application traffic type is then transmitted using the best link calculated by AHP. This is achieved by modifying existing procedures in ns-2 run-time to map each link calculated by the AHP to an application traffic type, on all the smart meter nodes in the network to the data concentrator.

5.5.3. Multiple metrics Framework Discussion

The multiple metrics framework is designed to better satisfy the QoS requirements of an application traffic type in Smart Grid, by choosing the most appropriate path provided by the link metric to route the application traffic type. In addition to supporting different requirements of an application traffic type, the multiple metric path selection capability offered by this framework can also help to improve the overall routing performance in a NAN based ad hoc WMN. In the simple network example provided in Figure 5-1, it has been observed that different link metrics can have different best paths to a destination, depending on the parameters used to calculate the link metric values. If only a single link metric routing algorithm is supported, a route that has the best metric value (e.g. least hop count) will always be chosen, regardless of the application data type being transmitted. Consequently, the chosen route will be used more often to transmit all data types to the destination.

This can lead to one of two problems in NAN based ad hoc WMN. The first problem is the "bottleneck" problem, which causes congestion and impairs the flow of data because a certain part of the network is busier than other parts. The other is the network partition problem. This refers to broken connection that will occur as a result of the bottleneck problems. For example, in NAN based WMNs, the smart meters along the congested path of the network will experience more data losses, which will affect the routing performance. However, using the multiple metrics framework for routing decision enables per application traffic type routing that can support targeted application traffic and also provide better distribution of traffic across different routes. This is expected to reduce the chances of the aforementioned problems.

The process of assigning a route to designated traffic is achieved by deciding which RLMTs will be used by the application traffic. After the RLMT is decided, the path to the destination for each traffic flow is decided by the AHP. All packets with the same packet size and flow rate are routed through the intermediate nodes specified by the AHP. This technique is only considered because smart meters in a NAN based ad hoc WMN are static and do not require movement of nodes, which makes it a very predictable topology.

The next section discusses the simulation studies carried out and analyses the results from the study.

5.6. Simulation Study

In this section, the scenario and setup used in implementing the multiple metric OLSR with AHP is presented. Although the use of other network simulator tools such as ns-3, OMNeT++ or OPNET are possible, all the implementation and simulation is done using ns-2 (the same simulation package used in Chapter 4). The routing protocol used is the OLSR protocol, which is modified to consider three link metrics versions, namely, OLSR-ETX, OLSR-ML and OLSR-MD during its route discovery process for transmitting different AMI application traffic in Smart Grid.

5.6.1. Simulation Scenario

The characteristics and performance of different AMI application traffic types as they traverse multiple hops to a destination have been discussed and evaluated in this thesis. In this simulation scenario, a typical evaluation of the functions of smart meter nodes in a real AMI scenario, where variable application traffic types are transmitted upwards towards the data concentrator and downward to the smart meters is presented. Figure 5-4 is a representation of the simulation scenario, which outlines home users transmitting their periodic billing data (AMI data) as well as sending their EV charging information simultaneously. At the same time the utility company is measuring power quality for all households and transmitting DR information to the customers for peak pricing. Given that, in reality this might not occur simultaneously for long periods on all houses in an area, this simulation assumes it occurs simultaneously on all smart meters in the neighbourhood area for a period of 50 seconds, five times a day.

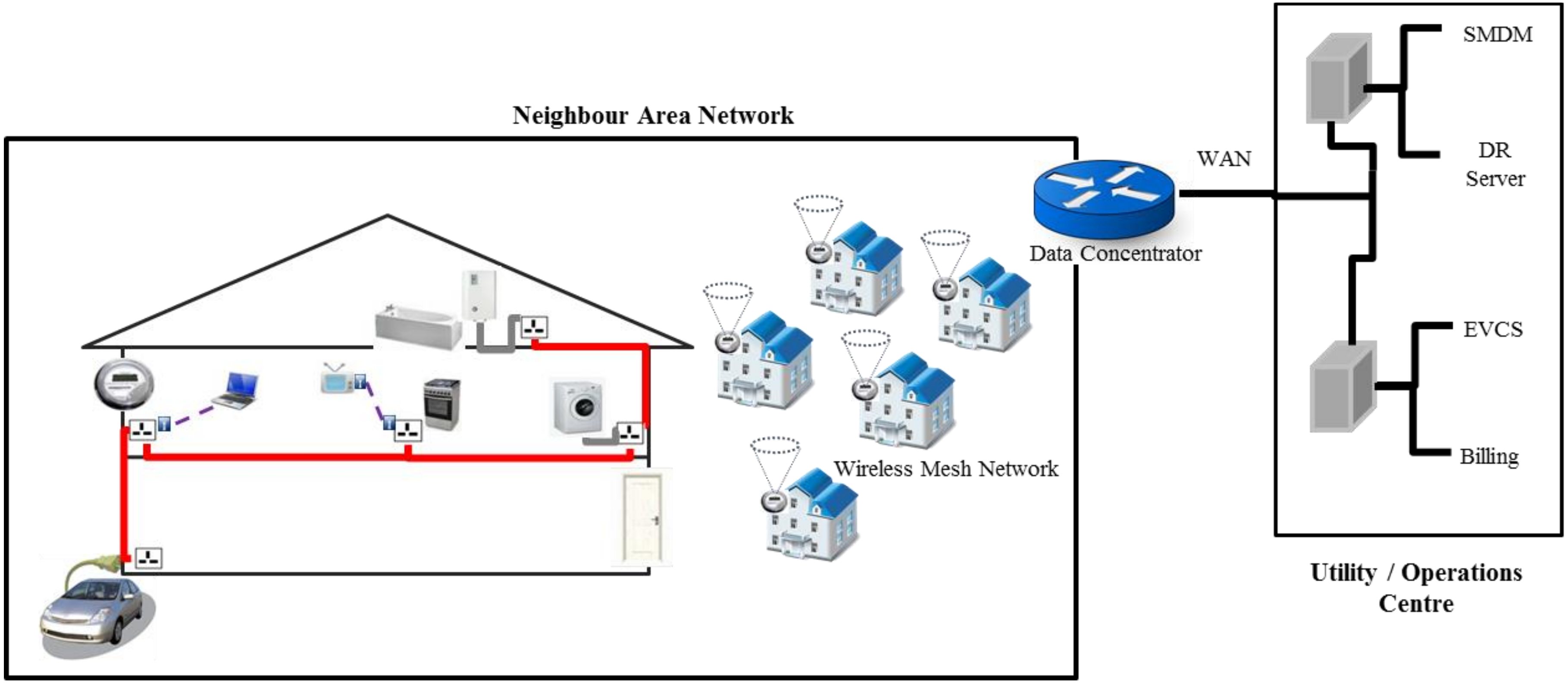


Figure 5-4: Simulation Scenario of an AMI in NAN

5.6.2. Simulation Setup

Each of the link metrics calculates paths to the destination using forwarded and acknowledged OLSR probes (control messages). The parameters used are the same as those used in Table 4-1 in Chapter 4. The dimension of space in the NAN network is set as 500 x 500 m^2 and a grid size of 25 smart meters, separated 100m apart are simulated in an ad hoc WMN, sending their metering application traffic to a data concentrator. The UDP CBR traffic was used to represent AMI application traffic types and traffic was generated from each smart meter node in the network to the destination node (data concentrator). Smart meters are mainly the designated traffic sources at the home premises and are required to send or receive information to or from the data concentrator. The simulation setup attempts to replicate the trend of bi-directional flow of information between smart meters and the data concentrator, while using the ad hoc WMN as the communication medium.

Four application traffic models (EV charging data, AMI data, Power Quality and DR) were transmitted simultaneously from the smart meters towards (upward) and from (downward) the data concentrator. Based on the application traffic transmitted the network is assessed for successful upload/download traffic in terms of latency and reliability. The packet size and data rate used for a particular traffic type is dependent on the AMI application types. For example, a near real time traffic similar to VOIP traffic is used to represent the EV charging traffic, which requires strict delays (delay sensitive application traffic type). Therefore, a packet size of 40 bytes and data rate of 8 kbps, similar to VOIP traffic is used to model the EV charging application traffic. In the case of DR, since peak price advertisement is a multicast traffic that does not elicit acknowledgement, it is simply modelled as UDP-based traffic, in which the data concentrator sends price signals to the UDP server installed on smart meter nodes. AMI data traffic and power quality measurement data traffic is also modelled using UDP and all the nodes are connected to the data concentrator through the ad hoc WMN. The AHP multiple metrics implementation with OLSR is carried out only in the upward direction (i.e. from smart meters to data concentrator) and compared with other OLSR link metric versions. This is because only single traffic is transmitted in the downward direction.

The topology was varied by increasing the cluster size of smart meter nodes in the area and changing the position of the data concentrator, to measure and compare performance at different instance. Performance indices such as packet loss, PDR, throughput and average delay, which were used to assess the network in Chapter 3 and 4 were also used to evaluate performance.

5.6.3. Results and Discussions

In this section, the simulation results of the NAN based WMN system under consideration is discussed and presented. In order to evaluate the performance of the proposed multiple metrics, it is compared to the other OLSR link metric types: ETX, ML and MD.

5.6.3.1. Dropped Packets

Whilst all application traffic types transmitted simultaneously, Figure 5-5 to Figure 5-8 show the packets transmitted and dropped for each application traffic type: EV charging data, AMI data, Power Quality and DR. As observed in the Figures, OLSR multiple metrics (OLSR_M-M) managed to keep the number of dropped packets low when compared to other OLSR versions. This improvement is very important when dealing with application traffic in Smart Grid because OLSR_M-M does not only reduce dropped packets, but also increases the reliability and enables transmission of a target application traffic type that requires certain network parameters provided by a particular link metric through the path.

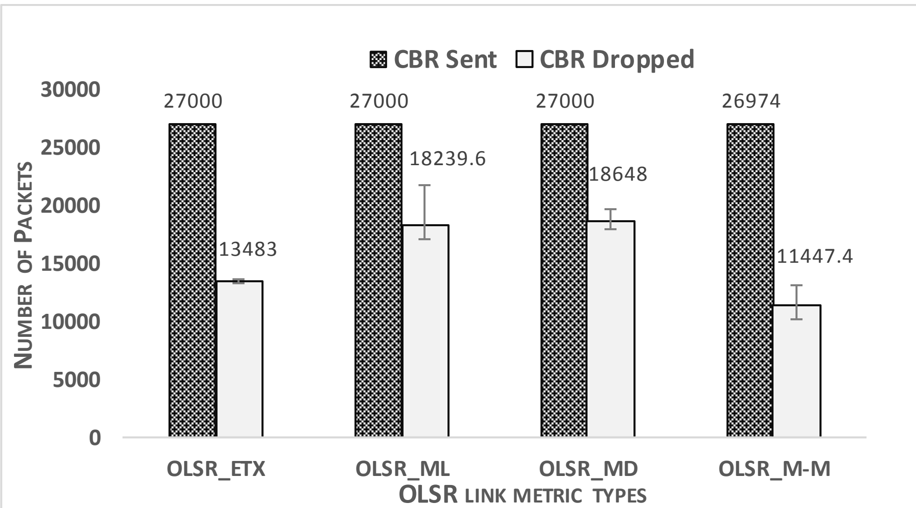


Figure 5-5: CBR packets Transmitted/Dropped for EV charging application traffic

Figure 5-5 shows the EV charging application traffic, which has the highest number of transmitted CBR traffic (about 25 packets per second) of all traffic considered in the simulation. Though a high number of packets have been dropped, it did not replicate the number of losses incurred on other OLSR versions. This can be attributed to better path selection by the multiple metrics algorithm and the alternative paths it provides to other application traffic types to reduce congestion and bottle neck problems on specific intermediate nodes.

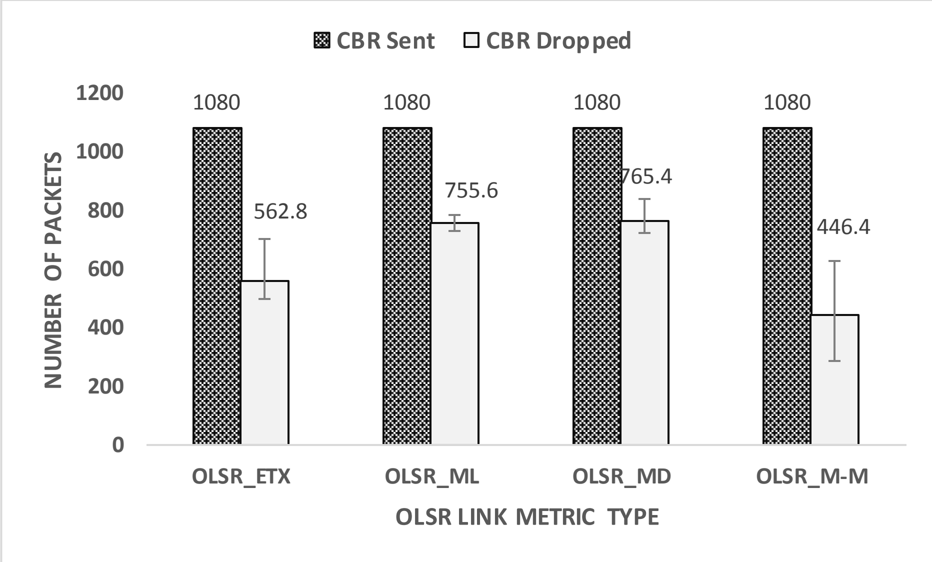


Figure 5-6: CBR Transmitted/Dropped for AMI data application traffic

In Figure 5-6, the transmitted and dropped CBR packets for AMI data is presented with the OLSR_M-M recording the lowest number of packet losses.

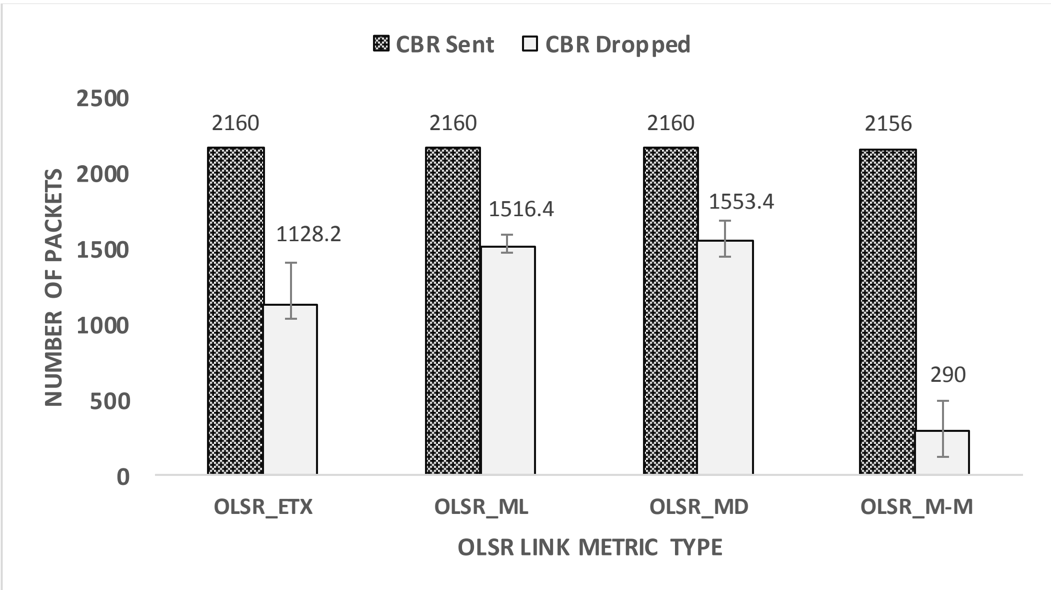


Figure 5-7: CBR Transmitted/Dropped for Power Quality application traffic

Figure 5-7 shows the CBR packets transmitted and dropped for the Power Quality measurement data. The packet losses recorded for this application are also lower than that of other OLSR versions. It shows that an improvement of around 74% of dropped packets is achieved by using OLSR_M-M, compared to other versions of OLSR.

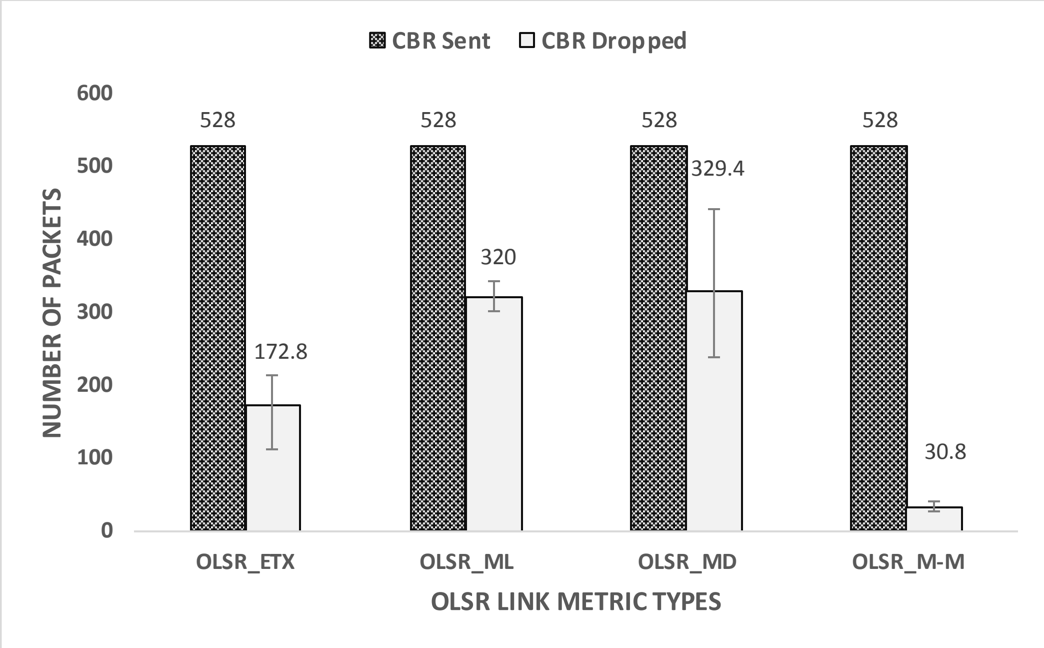


Figure 5-8: DR CBR packets Transmitted/Dropped for peak pricing

Contrary to the other application traffic types transmitted upward towards a data concentrator, the DR traffic is broadcast downwards to the smart meter nodes. While using the OLSR_M-M to simultaneously transmit application traffic to the destination, in Figure 5-8, the OLSR_M-M also showed lower losses on the DR multicast when compared to other OLSR versions.

5.6.3.2. Network Reliability

The reliability of the network is measured by computing average PDRs of successful transmission for all application traffic on all OLSR versions. It is also important to reiterate that a successful upload of an application traffic type is considered as one in which 100% of transmitted packets are received and acknowledged at the destination (data concentrator). The average PDR for simultaneously transmitting all AMI application traffic across the NAN based ad hoc WMN on each OLSR version is presented in Figure 5-9.

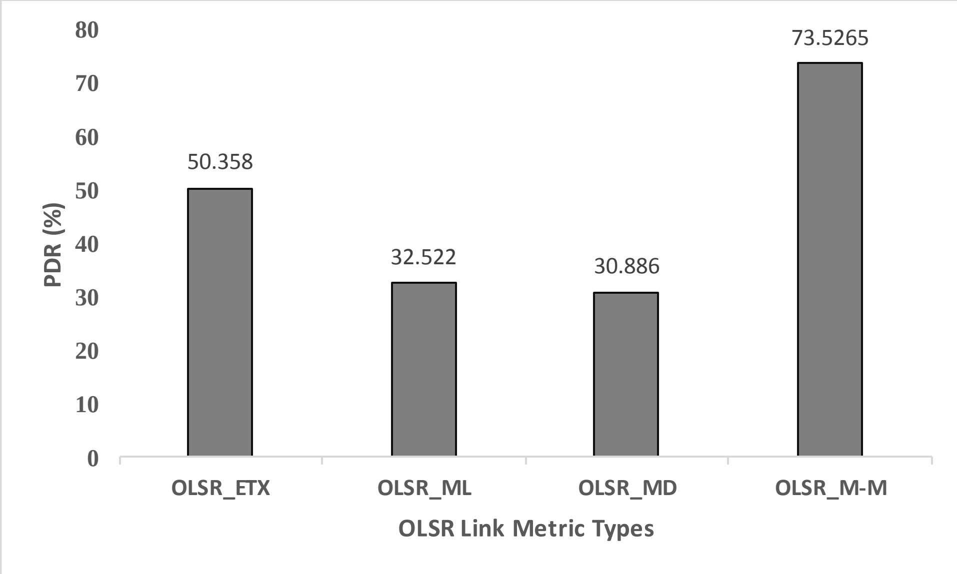


Figure 5-9: Average PDR for all application traffic

Another means of evaluating the reliability of the network is the Loss probability per application traffic flow. In this context, Loss probability is the probability of losses for a group of identical traffic. It is calculated by dividing the dropped packets by the number of transmitted packets. Figure 5-10 shows the Loss probability of each application traffic type, where the OLSR_M-M shows the lowest Loss probability on all application traffic types.

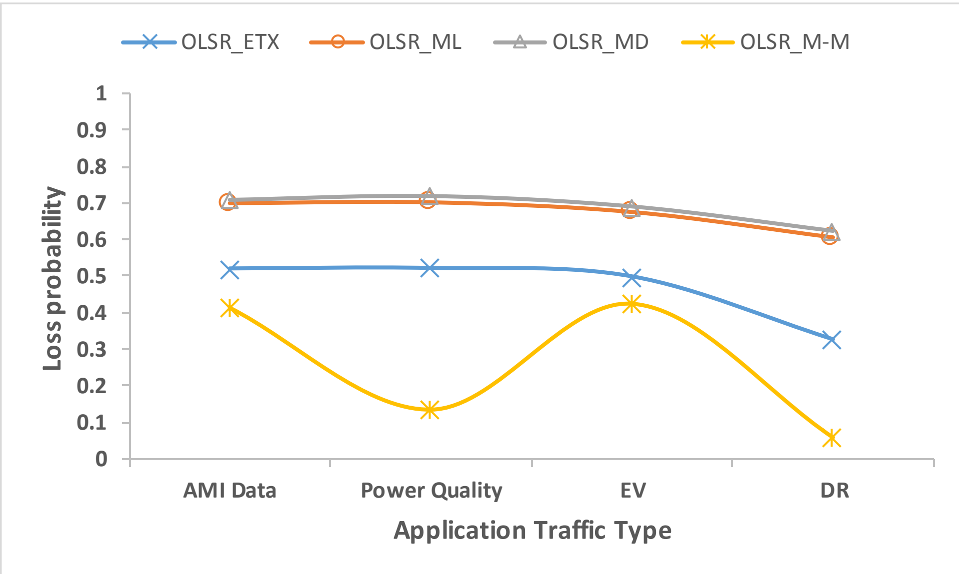


Figure 5-10: Loss probability for all application traffic type

5.6.3.3. Average Delay

An evaluation of the average ETE delay is carried out for all application traffic from the smart meter nodes to the data concentrator, as well as the DR traffic traversing from the data concentrator to the smart meters. As mentioned earlier, the IEEE 802.11b standard with a maximum data rate of 11 Mbps is employed for this study. Other standards with higher bandwidth and data rates may provide higher throughput. The average ETE delay for all application traffic on the different OLSR versions is presented in Figure 5-11.

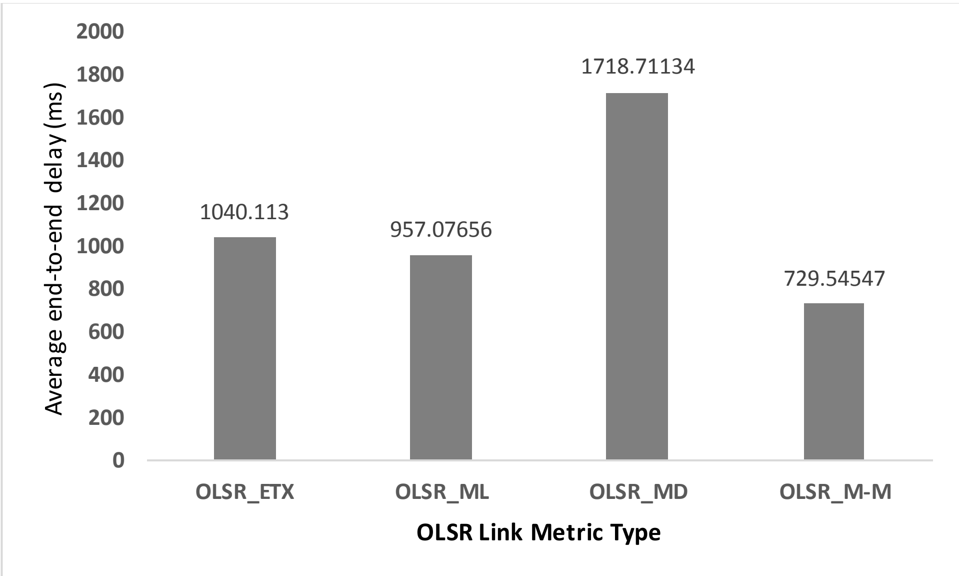


Figure 5-11: Average end-to-end delay for all applications.

OLSR_ETX has the lowest average ETE delay of all the existing OLSR versions. The OLSR_M-M results showed that average ETE delay can be further reduced by 29%.

5.6.4. Performance Evaluation on different Grid cluster sizes

Performance of the network of ad hoc WMN responds differently to traffic characteristics such as packet generation rate and packet size. Similarly, the WMN responds differently to the number of nodes in the network topology and position of the destination node. An evaluation of the performance of OLSR_MM while increasing the number of smart meter nodes within the 500 x 500 m^2 area was carried out. The proposed OLSR_M-M is compared to the other OLSR versions. The network scenarios considered are as follows:

- A grid topology with smart meter nodes increased from 25 to 36, 49 and 64 grid clusters. This results in the distance between each smart meter node reduced from 100 m to 80 m, 66 m and 57 m for each grid cluster respectively.

- The grid topology network was also evaluated for the position of the data concentrator, which was positioned at the top right corner and the centre of the grid.

The average PDR on grid clusters of 25, 36, 49 and 64 smart meter nodes with the data concentrator placed at the centre and at the top corner is presented in Figure 5-12 and Figure 5-13. When the data concentrator is placed in the centre of the grid, the number of hops to the destination is reduced. However, the amount of data transmitted between the smart meter node and the data concentrator is not affected. It is observed in Figure 5-12 that OLSR_M-M and ETX have comparable PDR performances on all grid sizes and in Figure 5-13 OLSR_M-M performs better than other OLSR versions on all grid sizes. The results shows that the multiple metrics solution improves the overall PDR of the application traffic in both the central and top corner placement of the data concentrator. The reliability improvement of OLSR_M-M when the data concentrator is placed at the top corner is higher than that of central placement. It can be further concluded that sending traffic across multiple paths from source to destination using OLSR_M-M is more effective in reducing packet drops and congestion over higher number hops to a destination.

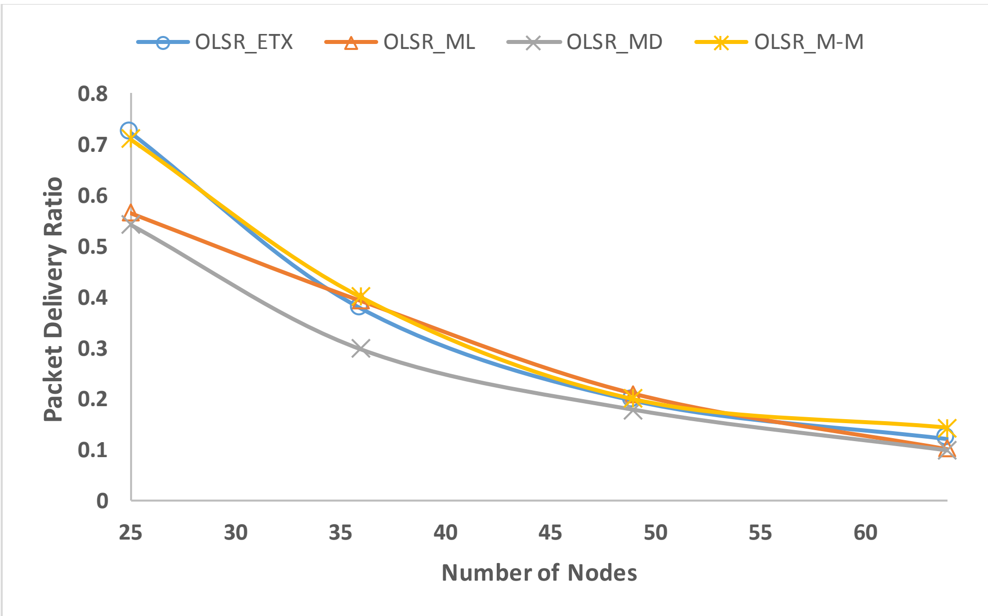


Figure 5-12: PDR for Smart Grid application on Grid clusters with a central placement of the data concentrator.

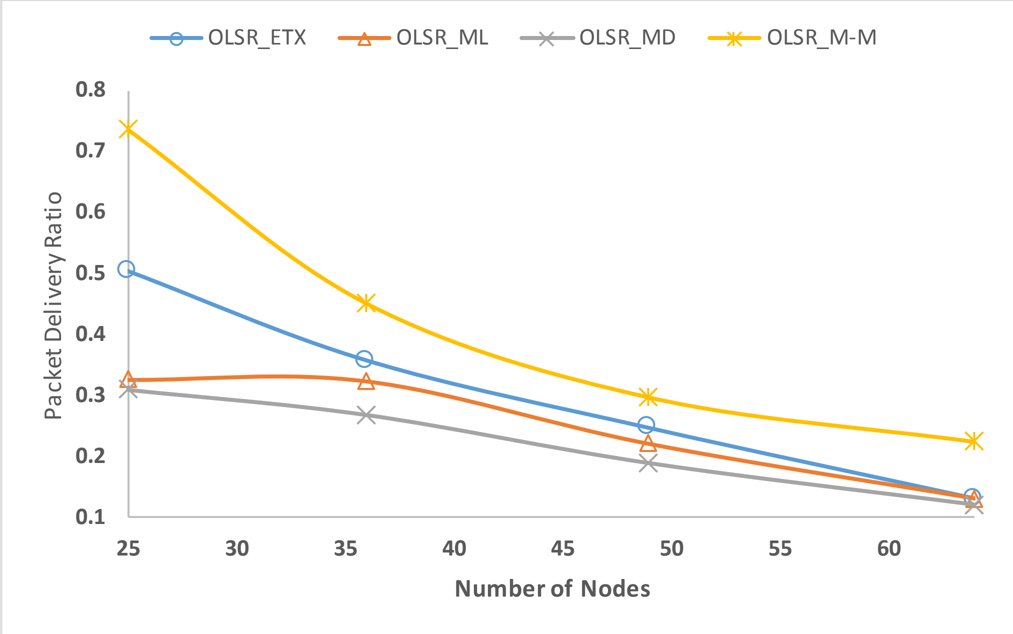


Figure 5-13: PDR for Smart Grid application on grid clusters with the data concentrator placed at the top corner.

Overall, the grid clusters with data concentrator placement at the centre of the grid obtained higher reliability percentage than when the data concentrator is placed at the top corner. In respect to smart meter deployment in NAN, the placement of data concentrators closer to the smart meter nodes can improve reliability.

Figure 5-14 and Figure 5-15 show the average ETE delay for both node placement scenarios. The OLSR_M-M managed to keep the delays within 4500 ms at 64 grid cluster when the data concentrator is placed at the centre, and 4700 ms when the data concentrator is placed at the top corner. The average ETE delay for grid clusters with data concentrator placed at the top corner recorded higher delay than the grid clusters with data concentrator placed at the centre. This is because of the distance to the data concentrator. The main advantage of our routing protocol approach is that it has a better reliability performance, even than ETX which has the best performance of all OLSR versions in terms of PDR. The OLSR_M-M also recorded an average end-to-end delay which is as low as that of OLSR_ML, which has the best average end to end delay of all OLSR versions.

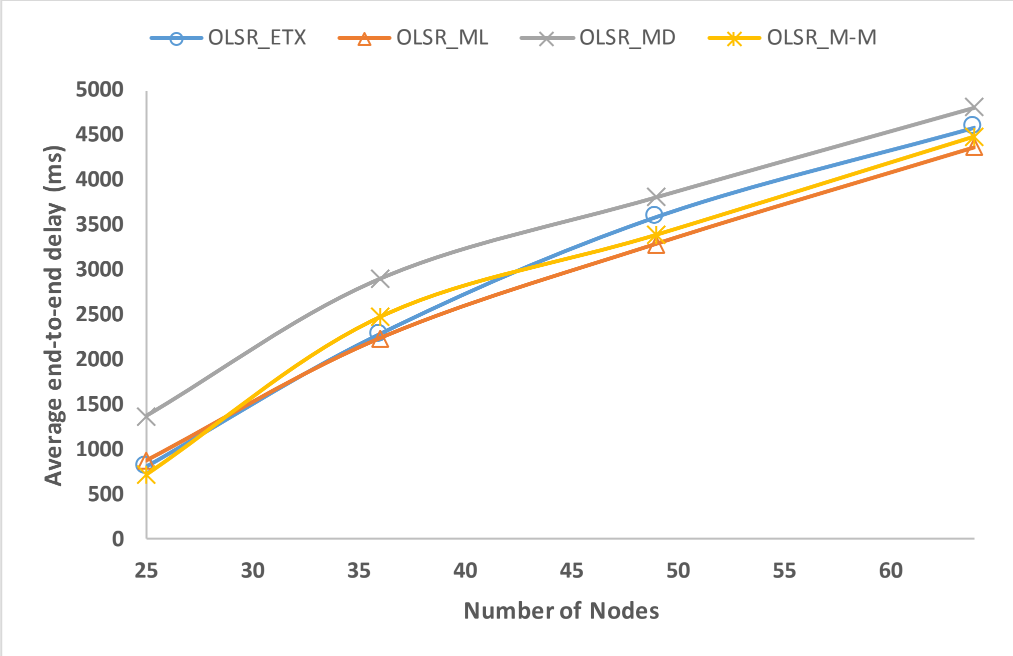


Figure 5-14: Average end to end delay for Smart Grid application on grid clusters with a central placement of the data concentrator.

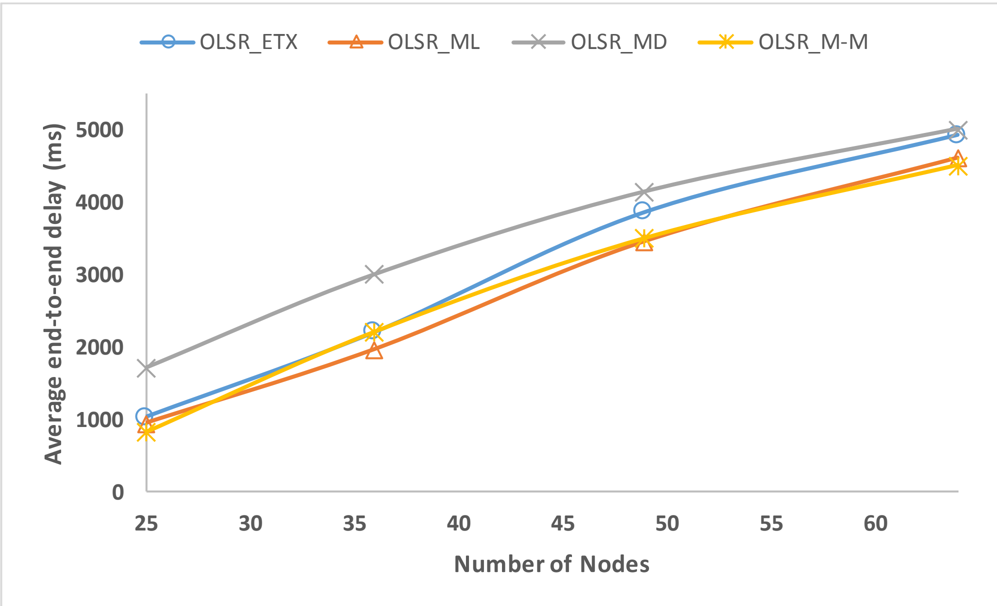


Figure 5-15: Average end to end delay Smart Grid application on grid clusters with the data concentrator placed at the top corner.

5.7. Key Findings

The simulation results presented in Section 5.6.3 are summarised in Table 5-2. For each application traffic type, the table shows the reliability and delay performance for each link metric version. The first set of results obtained are from a 25 grid cluster NAN topology which analyses the PDR of each application traffic type. The average PDR and average ETE delay of all applications in the 25 grid cluster scenario is then presented.

Table 5-2: Summary of simulation results

Application Traffic Type	**Route Link Metric Types**				**Best Performance**
EV	**OLSR_ETX**	**OLSR_ML**	**OLSR_MD**	**OLSR_M-M**	
PDR (%)	50.06 %	32.5%	30.1%	57.5%	OLSR_M-M
AMI Data	**OLSR_ETX**	**OLSR_ML**	**OLSR_MD**	**OLSR_M-M**	
PDR (%)	47.8%	30.04%	29.13%	58.67%	OLSR_M-M
Power Quality Data	**OLSR_ETX**	**OLSR_ML**	**OLSR_MD**	**OLSR_M-M**	
PDR (%)	47.8%	29.8%	27.94%	86.65	OLSR_M-M
DR	**OLSR_ETX**	**OLSR_ML**	**OLSR_MD**	**OLSR_M-M**	
PDR (%)	67.3%	39.4%	37.7%	91.4%	OLSR_M-M
Total Average	**OLSR_ETX**	**OLSR_ML**	**OLSR_MD**	**OLSR_M-M**	
PDR (%)	50.358	32.522	30.886	73.5265	OLSR_M-M
Average ETE Delay (ms)	1040.113	957.07	1718.71134	729.54347	

The following observations can be drawn from Table 5-2:

- The routing decision made by OLSR_M-M provided the highest PDR for reliability and delay sensitive application traffic such as EV and DR.
- Similarly, for Power quality and periodic AMI data application traffic types, the PDR for OLSR_M-M was highest.
- The average end-to-end delay was also improved on OLSR_M-M, compared to other OLSR_M-M versions.

Other NAN based ad hoc WMN scenarios were explored by using other network topologies to evaluate the performance of the proposed OLSR_M-M implementation. The topologies evaluated are:

- Different grid cluster topologies with 25, 36, 49 and 64 smart meter nodes.
- Data concentrator placement, at the centre of the grid and at the top right corner of the grid.

The results show that data concentrator placement at the centre performed better on all grid clusters than data concentrator placement at the top right corner. This is an indication that placing the data concentrator for future ad hoc WMN deployment for NAN closer to the smart meter nodes will improve the network reliability and delay. However, there was no significant difference in the performance of OLSR_M-M in both scenarios.

From the results presented in this Chapter, the OLSR_M-M outperformed the other OLSR versions. The proposed protocol can find a route that best improves the reliability of all the application traffic types transmitted to the data concentrator simultaneously. The multipath routing provided by OLSR_M-M using multiple metrics and AHP has increased the PDR and reduced the delay of all the application traffic types, compared to any of the OLSR single metric versions. Consequently, the multiple metric routing approach can be used to provide QoS routing for target Smart grid application traffic types. All the application traffic types transmitted in the simulation used a required parameter provided from the link metrics to make decisions on their path to the data concentrator. The simulation results have shown that with the use of multiple metrics, an application traffic type QoS requirement can be better satisfied. It is also important to indicate that the use of multiple metric is not only limited to the routing protocol and link metric types used in our simulations.

5.8. Chapter Summary

Variable application data types must be supported when an ad hoc WMN is deployed as the communication network in Smart Grid NAN. The traffic of these different applications will impose strict QoS requirements in terms of performance, reliability and delay. This Chapter presented an implementation of multiple metrics routing, firstly, to improve routing of Smart Grid application traffic in NAN and Secondly, to demonstrate that application level QoS requirements can be better supported using measured parameters by different metrics to select the best possible route to best satisfy a given requirement of specific application traffic. The multiple metric implementation supported route decision-making, using AHP with different OLSR link metric versions. In order to accommodate the requirements of different Smart Grid application traffic, the multiple OLSR routing metric versions identified in Chapter 4 were interpreted in to the routing implementation. The implementation uses the AHP decision-making algorithm to prioritise the selection of a desirable route for target application traffic.

This implementation has shown that the weakness exhibited by some existing single metric routing algorithms when deployed in a NAN based ad hoc WMN can be reduced. The simulation results for OLSR_M-M on all the topologies evaluated in this Chapter shows an improvement in reliability for all application traffic with minimal effect on delay.

Chapter 6

6. Conclusions and Future Work

6.1. Conclusions

It has been recognised within the electricity industry and the research community that a reliable and resilient communication system is one of the principal foundations of Smart Grid. Nonetheless, there is still constant deliberation on the most appropriate technology for Smart Grid deployment and the necessary adjustments to meet specifications of different applications and traffic sources (devices/nodes). In spite of the fact that wireless communication technologies have predominance over other communication technologies in this field, there exists some challenges and uncertainties. These include the network performance of the communication technologies in a M2M environment, where a vast number of emerging application traffic types with different requirements are transferred between different devices. Another important challenge is adaptability to current and future communications needs. The enormous size of the electrical grid has led to the recommendation of a hierarchical deployment of communication technologies referred to as network components of the Smart Grid by the research community.

This thesis has been particularly centred on the communication of NAN component of Smart Grid. As a potential communication technology for NAN, the IEEE 802.11 ad hoc WMN is also subjected to vulnerabilities and challenges, including selecting the most appropriate routing protocol.

The goal of this research was to identify these challenges and suggest appropriate measures that will enable improved network reliability on a NAN based IEEE 802.11 ad hoc WMN and guarantee maximum benefit for the utility operator. In particular, the thesis has validated the bottleneck and congestion issue across multi-hops in ad hoc WMN deployed in NAN, and proposed a number of solutions to this problem. Most important, it should be realised that the ad hoc WMN has no QoS support for target Smart Grid applications across multi-hops to the destination, or data concentrator in the case of NAN. In recognition of this, the thesis explored a cross-layer approach using multiple link metric routing with OLSR to enhance the reliability of routing and provide QoS support for application specific requirements across multiple hops in NAN based ad hoc WMN. The cross-layer routing approach is used because it enables protocols to make decisions that demonstrate cognisance of the resources and capabilities of intermediate nodes as well as enhance routing decision based on the type of application to be transmitted. Cross-layer routing approach is also a key requirement for the implementation of network management capabilities and QoS support for target application traffic types on routing protocols.

This chapter summarises the work presented in this thesis; it highlights the main contributions as well as associated results and conclusions from research findings. In addition, it presents a discussion on the prospective research directions and recommends future work.

It is important to state that this research was done in collaboration with a local small and medium enterprise (SME) company. The SME sought to collaborate with utility companies to adapt novel communication techniques as well as integrate both IP and QoS into pre-existing non-IP communication systems for Smart Grid communication. The benefit of this study includes modifying the ad hoc WMN for reliable communication in the NAN segment of Smart Grid.

This study provided a background to Smart Grid communication in Chapter 2, which gave an overview of Smart Grid communication systems and key Smart Grid applications, as well as their traffic requirements and characteristics. The adaptation of ITU's USN architecture and review of available communication technologies for Smart Grid is presented. The USN architecture was recommended to provide a seamless ubiquitous coverage and interaction with all the Smart Grid traffic sources on the hierarchical communication network. The chapter also discussed Smart Grid applications and network components and suggested layers of the USN architecture to be deployed. It highlighted that a seamless heterogeneous communication for Smart Grid could only be achieved through a secure and QoS aware USN middleware system to minimise the vulnerabilities and challenges of a heterogeneous Smart grid communication network. Given that the characteristics of different existing communication technologies for Smart Grid vary; it was recommended that the choice of communication technology must depend on technical and economic factors as well as their capability to guarantee security, reliability and resilience. For this reason, a review of existing communication technologies was carried out with emphasis on technologies that can combine to form a reliable heterogeneous network for Smart Grid.

The emphasis of the study was shifted to routing in Smart Grid’s NAN, specifically the ad hoc WMN and OLSR protocol, which is the research path of the thesis. The NAN is a Smart Grid segment that will involve routing. Though other routing protocols have been proposed for this Smart Grid segment, the OLSR protocol was selected because it has good performance in large networks and it is also implemented on existing CoTs devices that will speed up experimental evaluation and research.

Chapter 3 presented a classification of Smart Grid application traffic according to their packet sizes and delay objectives. Four traffic class categories were identified representing the importance of Smart Grid traffic, namely, delay tolerant - loss tolerant class, delay tolerant - loss intolerant class, delay sensitive - loss tolerant class and delay sensitive – loss intolerant class. A performance analysis of routing capabilities of the ad hoc WMN in a NAN for AMI using traffic profiles that represent each Smart Grid application traffic class was carried out on an experimental setup and ns-3 simulation. During the simulation study, two routing protocols, IEEE 802.11s HWMP and the OLSR routing protocols were evaluated. The OLSR was compared against HWMP because it is the protocol specified for ad hoc WMN (IEEE 802.11s) standard to validate its performance. Based on the topology and parameters used in the simulation, results showed that the performance of OLSR protocol in terms of delay, PDR and throughput, is the same or, in some cases, marginally better than the IEEE 802.11s standard default protocol. Based on the results, a recommendation was reached to study cross-layer network management options and QoS routing in NAN for AMI using OLSR.

Based on the recommendations in Chapter 3, the possibility of using multiple metrics OLSR to support QoS routing in NAN based WMN for AMI through the use of AHP was studied in Chapter 4. During the study, two metrics - OLSR_ETX and OLSR_ML - were selected as the best performing link metrics on reliability and delay respectively. They were used along with the AHP algorithm to present a case for adaptively supporting QoS (delay and reliability) for targeted AMI application in a NAN based WMN.

Chapter 5 presented the implementation process to improve the performance of OLSR by using multiple metrics, guaranteeing best route selection for application traffic types in NAN. Results from the implementation on ns-2 showed an improvement in the reliability and delay performance of application traffic types with high QoS demands in Smart Grid NAN. The improvements were based on the AHP an MCDM technique and multiple OLSR link metrics to select routes to the data concentrator that best suits an application traffic type. This process has provided a novel method of overcoming the weaknesses of single metrics, introducing QoS routing, and supporting variable application traffic types in a NAN based ad hoc WMN.

6.2. Summary of Contributions

The thesis has made the following contributions and discoveries:

Review and Background

Utility companies have been sceptical about what a Smart Grid entails and how to go about integrating conventional communication technologies into their systems. One significant contribution of this thesis is the background, which presented the legacy of the electrical grid, and the in-depth review on the application characteristics, network components and traffic requirements of major Smart Grid applications. In addition, it recommends an architecture that will allow better management of the QoS and facilitate interoperability with other technologies. The review had five key sections.

1. First, it defines four fundamental building blocks of Smart Grid namely: Distributed Energy and Automation, Utility applications, data management and end ETE communication networks.
2. Secondly, it presents a detailed architecture of the communication network, highlighting the different network components and utility application traffic types that must be supported by the communication network.

3. Thirdly, it demonstrates that the advancement of a hierarchical network for the Smart Grid requires a heterogeneous communication network that can only operate seamlessly through communication network architecture. This led to the recommendation of a USN architecture that incorporates a QoS aware middleware system to support all application traffic types and enable quick processing of data.
4. Fourthly, a review of the available wired and wireless communication technologies is presented, highlighting their characteristics as well as their pros and cons.
5. Lastly, the thesis discusses factors that affect the choice of communication technologies in different network components. The considerations of the technical and economic factors shifted the research in the direction of ad hoc WMN in Smart Grid's NAN communication segment, which is the focus of the research.

The information and recommendations contained in the background are valuable to the Utility companies and Smart Grid research community in studying and implementing reliable communication for Smart Grid.

Evaluation of OLSR and HWMP in the context of Smart Grid application traffic types

There has been no consensus by utility companies and the research community on which routing protocol to be deployed in NAN for AMI. This thesis contributed to this discussion by evaluating OLSR and HWMP to understand their performance in a NAN based ad hoc WMN for Smart Grid. The following was carried out:

1. Based on the review of Smart Grid applications that incorporate different traffic types with variable delay objectives and packet sizes, some traffic profiles were generated and a performance evaluation of the ad hoc WMN using OLSR was carried out and compared with the HWMP routing protocol.
2. From experimental and simulation results and analysis, the original HWMP (which is the standard WMN routing protocol) and OLSR implementation in ns-3 had comparable performances in terms of PDR, ETE delay and throughput. It was also observed that PDR and throughput for all application traffic types dropped significantly across multiple hops in the incremental grid topology sizes. Particularly, PDR, which is the measure of reliability in this thesis, dropped below 90% from the 5 by 5 grid size on most application traffic types. Similarly, the average ETE delay for application increased, especially on the delay-sensitive, loss-sensitive application traffic profile that involves traffic of small sized packets, transmitting at an interval of milliseconds. Apart from the existing problems with ad hoc WMN such as interference, which affects reliability in a multi-hop network, the losses were attributed to

congestion at the intermediate nodes and poor path selection by the single link metric used in the routing protocols.

The fact that NAN involves simultaneously sending multiple application traffic types with different reliability and delay objectives from smart meters to a data concentrator led to the recommendation of OLSR as a potential routing protocol to investigate cross-layer and QoS routing implementation to support target application traffic types in NAN based ad hoc WMN. The traffic profiles used in this investigation can also be used for evaluating performance in other routing protocols and communication technologies discussed in Chapter 2.

Reliability improvement for Smart Grid application traffic types

Integrating QoS across multiple hops and ensuring the selection of good quality link by smart meter nodes has been a challenging issue in most routing protocols. The following were carried out to advance the performance of conventional OLSR in a NAN based ad hoc WMN:

1. The thesis studied multiple metrics routing approach combined with the proactive OLSR protocol. Although any combination of additive and multiplicative metrics is an NP-complete problem, the use of AHP and Pruning techniques have been proven to get around any difficulties.
2. The implementation and performance evaluation in ns-2 showed that it could be used to provide QoS routing as well as improve reliability and delay for application traffic types in NAN based ad hoc WMN.

Though multihop capability of WMN extends network coverage in NAN, it is observed that at three hops, PDR degrades to less than 90 % when transmitting all application traffic types to destinations. Therefore, achieving a reliability of over 99 % as suggested by UTC and Verizon for some Smart Grid application traffic across a higher number of hops will require more development in other areas of WMN. This includes channel error, collision and the development of interference aware link metric.

Most current Smart Grid pilot projects focus on network enhancement efforts such as local balancing, DSM and Distributed generation that require high reliability of ICT techniques. As existing pilot projects expand to larger scale, Smart Grid network enhancement efforts are expected to increase and the challenge of network reliability is also likely to increase. This brings a greater dependence on communication systems and data management systems. The OLSR multiple metrics technique developed in this thesis has a lot of potential applicability in improving reliability for different application data in Smart Grid, especially in small grid area where the nodes are connected within two to three hops to the destination.

The results and recommendations in this thesis can be used to influence the research community and utility companies to consider the use of ad hoc WMN and OLSR for communication in NAN (especially areas within three hops). It will also help to speed up the development of Smart Grid and enable the utility as a whole to realise the level of reliability required for the transmission of application traffic types. This will enhance the functionality of applications that can enable efficient power distribution, better load estimations, and integration of renewable energies for more environmentally friendly power generation.

6.3. Future Research Direction

The multiple metrics was researched for NAN because it can improve reliability by selecting good quality links and while at the same time supporting QoS routing for variable application traffic types. Given that this research is one of the first investigations involving the applicability of an IEEE 802.11 ad hoc WMN and OLSR within NAN, a number of potential areas for future study could emerge. The results obtained from this research were based on ns-3 and ns-2 simulation software that require the simplification of real-world properties such as radio and channel characteristics. This may lead to results and conclusions, which do not reflect the behaviour of ad hoc WMN networks in a real world scenario. Hence, more research and experimental analysis are required. The other areas suggested for investigation, and future research are discussed as follows:

1. The link metrics utilised for the implementation of multiple metrics OLSR with AHP are those implemented in ns-2. While these metrics measure important QoS parameters that include delay and packet loss rate, there are several other link metrics that have been implemented with OLSR and measure different QoS parameters such as power consumption and bandwidth. Studying the addition of such link metrics to the proposal in this thesis is essential to evaluate their impact on selecting good routing links and support more requirements of different application traffic. This is possible because AHP supports multi-dimensional criteria that can accommodate different link metric parameters.
2. It is also necessary to assess the impact of OLSR probes or control messages used to determine the link metric values for ETX, ML, and MD. The process by which each metric uses the messages can also influence the performance of the multiple metrics proposal.
3. Weights were assigned in this thesis manually, based on case studies carried out on different application traffic types. This performance of each of the metric in providing certain QoS can change depending on channel conditions. Determining weights to prioritise a link metric to be used by an application traffic type should be assigned dynamically. This will ensure improved

reliability even when a link metric reduces performance as a result of the network conditions. Therefore, the method of assigning weights dynamically must be researched.

4. The unfeasible possible paths to the destination were eliminated, by first deleting paths above the mean threshold, then selecting the best four paths for all the link metrics being considered. This pruning process is very simplistic because only four paths to the destination are considered on each link metric. Hence to consider more paths, more effective pruning processes must be developed to reduce computational complexities of the AHP algorithm on each node in the network.
5. More detailed experimental studies are also required to speed up the implementation of the multiple metrics proposal. This thesis showed that the optimisation of OLSR using multiple metrics is advantageous. Research can also be carried out into other proactive and reactive routing protocols since they all use a single metric to select paths to destinations.
6. Finally, QoS integration is essential in communication technologies deployed for Smart Grid. For example, the IEC61850 defines a standard for the design of electrical substation operation which incorporates priorities for time-critical-messages. The standard applies to single hop and Ethernet communication technologies. However, in wireless communication technologies, multi-hopping has become a desirable quality to extend reliable communication network across long distances to remote locations. This proposal can be researched to retrofit QoS in other communication standards that require routing across multiple hops. This refers to other low-cost communication technologies for NAN such as PLC, which involves routing.

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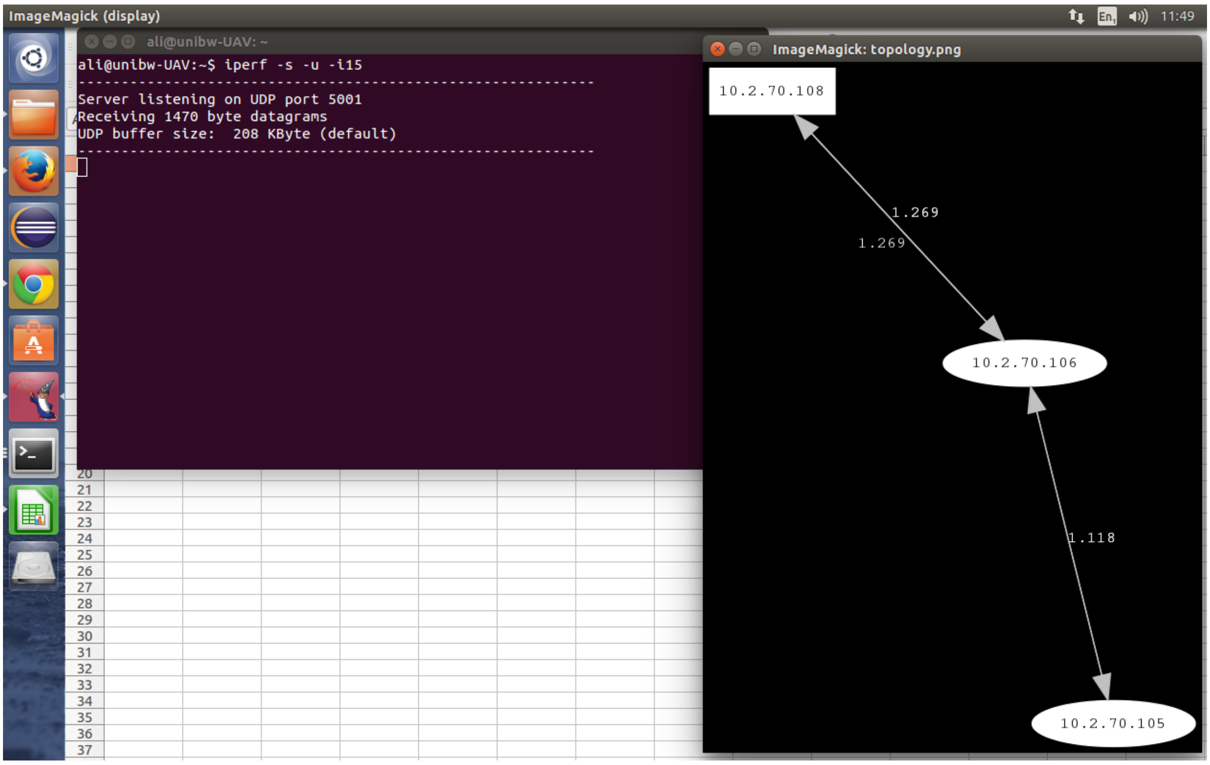
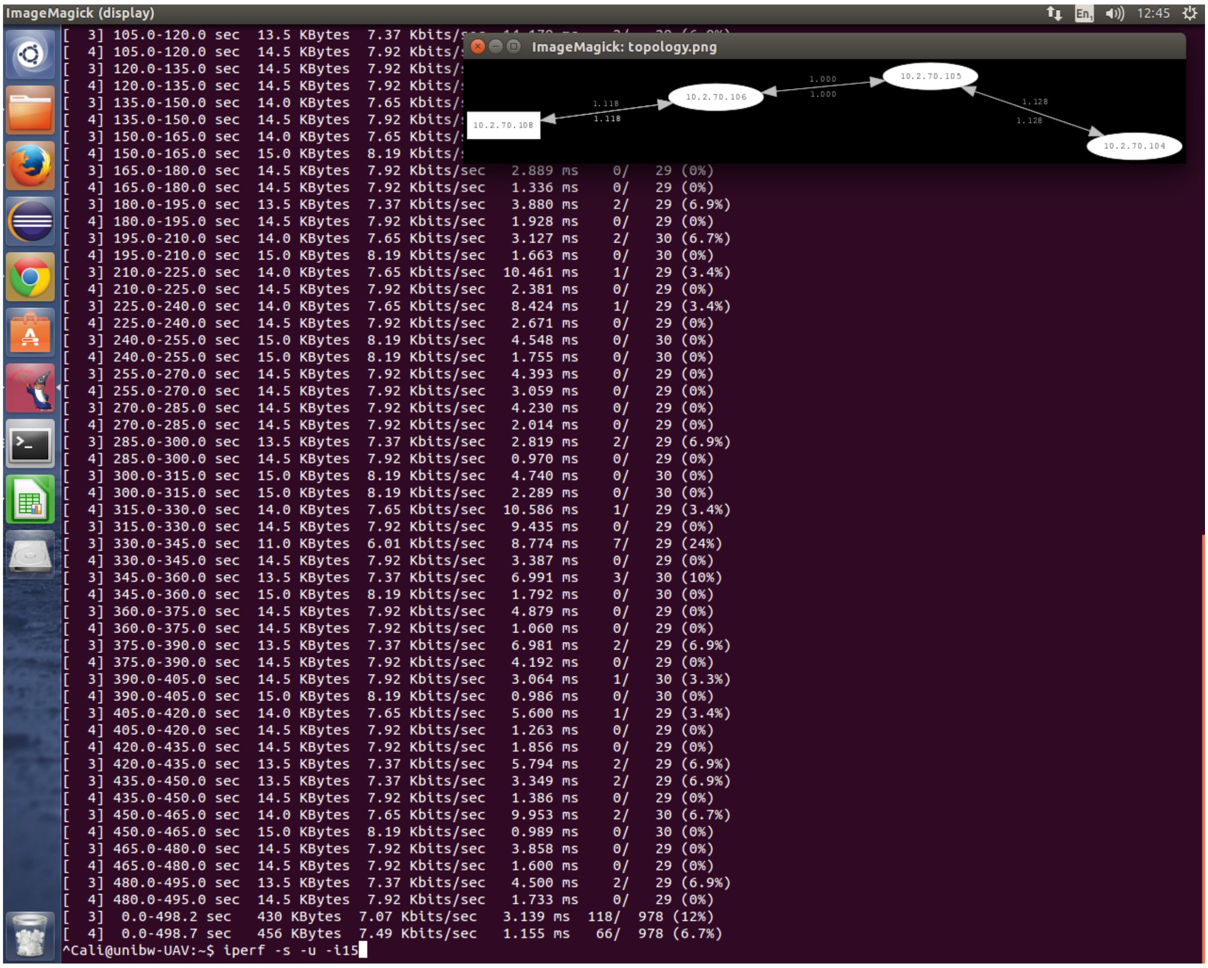
Appendix A

Screenshots from experimental setup of smart meter nodes

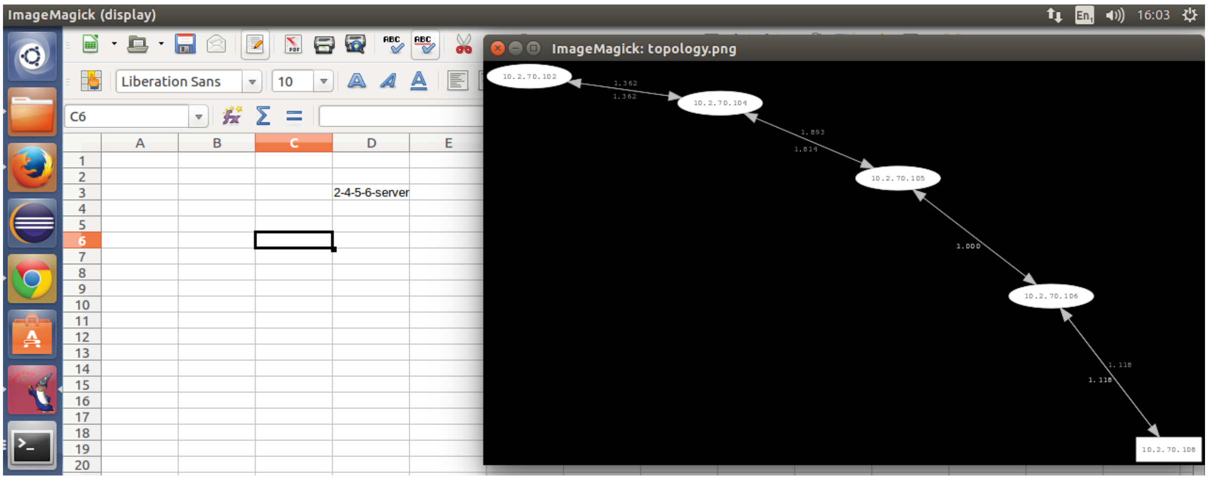
As described in section 3.4, the experiment implementation of smart meter nodes in ad hoc WMN was carried out using nexus 7. More screenshots of the communication between smart meter nodes on 2 hops to 4 hops obtained from Linux ImageMagick are presented.



ImageMagick view of 2 hop experimental ad hoc connection of smart meter nodes



ImageMagick view of 3 hop experimental ad hoc connection of smart meter nodes



ImageMagick view of 4 hop experimental ad hoc connection of smart meter nodes

Appendix B

Example of routing table generated on a transmitting node

Routing table showing the OLSR_ML and OLSR_ETX values for Node 1 transmitting to Node 9.

	Node 0			Node 1			Node 2	
Dest	ETX	ML	Dest	ETX	ML	Dest	ETX	ML
1	1.11111	0.81	0	1.11111	0.56	0	1.25	0.63
2	1.11111	0.81	2	1.25	0.63	1	1.25	0.63
3	1.11111	0.48	3	2.08333	0.56	3	1.25	0.63
4	1.11111	0.81	4	2.38095	0.49	4	2.0408	0.9
5	8.33333	0.81	5	1.25	0.63	5	1.5873	0.9
6	1.11111	0.48	6	2.08333	0.12	6	2.0408	0.25
7	1.11111	0.35	7	2.38095	0.3	7	2.0408	0.9
8	**4.76191**	0.02	8	4.16667	0.3	8	1.5873	0.9

	Node 3			Node 4			Node 5	
Dest	ETX	ML	Dest	ETX	ML	Dest	ETX	ML
0	1.111111	0.32	0	1.42857	0.49	0	6.25	0.3
1	1.851852	0.32	1	2.38095	0.49	1	1.851852	0.9
2	1.851852	0.1	2	2.38095	0.49	2	1.851852	0.9
4	1.428571	0.42	3	1.42857	0.48	3	2.380952	0.49
5	1.428571	0.35	5	2.38095	0.49	4	2.380952	0.49
6	1.111111	0.42	6	2.38095	0.35	6	4.761905	0.63
7	1.111111	0.35	7	1.5873	0.48	7	1.851852	0.63
8	2.777778	0.35	8	**1.5873**	0.49	8	1.851852	0.81

	Node 6			Node 7			Node 8	
Dest	ETX	ML	Dest	ETX	ML	Dest	ETX	ML
0	1.111111	0.21	0	3.703704	0.25	0	8.33333	0.09
1	1.111111	0.06	1	1.785714	0.3	1	3.33333	0.04
2	25	0.03	2	1.785714	0.63	2	1.5873	0.81
3	1.111111	0.21	3	1.785714	0.63	3	11.1111	0.12
4	2.040816	0.35	4	1.785714	0.48	4	1.5873	0.81
5	1.5625	0.63	5	1.587302	0.63	5	1.5873	0.81
7	1.5625	0.63	6	1.785714	0.63	6	1.5873	0.64
8	1.5625	0.63	8	1.587302	0.64	7	1.5873	0.64