2013

Study of the Scalability of Modified AODV-UU Routing Protocol for the Smart Grid Application

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By

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A Thesis
Submitted to the Faculty of Graduate Studies through
the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

2012

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ABSTRACT

Smart grid (SG) is said to be the grid of the 21st century. In SG, networking and communication facilities are included with the conventional grid system, and it allows the flexibilities of distributed control, power generation and load management. All of these issues can suitably be controlled by the efficient design of SG. The success of SG depends on the success of efficient networking of connected nodes and loads. In this thesis, wireless sensors has been considered as SG sensing nodes, and adhoc on demand distance vector (AODV) routing has been considered as the networking protocol for SG. The scalability of AODV has been studied in the simulation environment. We have proposed a modified AODV protocol for the SG application which is based on the concept of making some nodes more intelligent than others. The obtained simulation result shows a significant reduction of delays in the proposed system.

To my parents, my wife Ireen Rani and daughter Fatima

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor Dr. Kemal E. Tepe for his supervision, counselling, and assistance during my research work. It was a great opportunity for me to work with him, and I highly appreciate his great personality, plentiful patience and motivating advice for me to do the research and writing the thesis. I would also like to express thanks to my thesis committee members, Dr. Khalid and Dr. Zamani for their valuable contributions and suggestions.

I would also like to thank Khaja Mohammad Shazzad, Kazi Atiqur Rahman for their useful contribution and discussion on AODV and OMNeT++. I would like to thank all the staff members of the Department of Electrical and Computer Engineering. I would also like to thank Andria for her gentle and supportive attitude throughout my study period at the university. I would like to acknowledge the valuable support by the Ministry of Colleges and Universities, Ontario, Canada for my research. Especially, I am grateful to my affectionate parents for their encouragement, and motivation. I am forever grateful to them for my upbringing. I am also appreciative to my wife Ireen for her compassionate and caring attitude and moral support.

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Abbreviations

ABR	Associativity based routing
AMI	Advanced metering infrastructure
AODV	Adhoc on demand distance vector
AODV-UU	Adhoc on demand distance vector – Uppsala University
ART	Active route timeout
BLR	Beacon-less routing
BVR	Beacon-vector routing
CGSR	Clustered gateway switch routing
CIM	Common information model
DG	Distributed generation
DSDV	Destination sequenced distance vector routing
DSDV	Destination sequenced distance vector
DSR	Dynamic source routing
EG	Electric grid
EV	Electric vehicles
GPS	Global positioning system
GPL	General Public License
GPSR	Greedy perimeter stateless routing
HEV	Hybrid electric vehicle
HWMP	Hybrid wireless mesh protocol
ICT	Information and communication technologies

IEC	International electromechanical commission
IEDs	Intelligent electronic devices
IGF	Implicit geographic forwarding
IPAODV	Improved on demand distance vector
LMR	Light weight mobile routing
LLN	Low power lossy network
MANET	Mobile Ad hoc network
MAODV-UU	Modified Adhoc on demand distance vector – Uppsala University
M2P	Multipoint to point
NIST	National Institute of standard and technology
PMU	Phasor measurement unit
PLC	Power line communication
PMR	Power line multipath routing
P2P	Point to point
P2M	Point to multipoint
RREP	Route reply
RREQ	Route request
RPL	Routing protocol for low power and lossy networks
SEP	Smart energy profile
SERM	Secure energy routing mechanism
SG	Smart grid
SMR	Split multipath routing
SSA	Signal stability adaptive routing
TORA	Temporarily ordered routing algorithm

WAMR	Wireless automatic meter reading system
WMN	Wireless mesh network
WSN	Wireless sensor networks

1 Introduction

Electric power is one of the most important commodities of modern society. The electrical power distribution system design has not been changed since its inception and significant amount of energy is lost during distribution and delivery. The development of information and communication technologies (ICT) has opened a new era of modernizing the power delivery systems, hence, the concept of smart grid (SG) arises from the idea of adding communication and control facilities with the present grid. SG can be considered as a large network and it needs two-way efficient communication. Another notable point is that the efficient use of energy will reduce the CO_2emissions caused by the power generating units. When the renewable energy resources, like wind turbines and solar cells are generating power, and the operators at bulk power generation facilities such as nuclear or fossil fuel burning plants have little control over the smaller generating units. Consequently, it is quite evident that the grid needs to integrate a large amount of variable power with bulk generation systems and there is also a need for addressing management of these resources. Incorporation of the SG can save billions of dollars by increasing efficiency and controlling power disruption. In this thesis, we have simulated the test-bed implementation of AODV-UU using simulation with OMNeT++ for the smart grid application and we also have compared the test-bed AODV-UU implementation with the simulation and it strongly supports the test-bed implementation. We have observed the scalabilities of AODV protocols for the SG application and have also observed the throughput for the increasing number of nodes. The obtained result shows that the throughput of linear topology of nodes is better than the grid topology. In this thesis, we have proposed a way of reducing the delay of routing by the modified AODV-UU protocol. In the regular AODV-UU, all the nodes are equal, with routes being made when needed. In modified AODV-UU (MAODV-UU), we have made some nodes more intelligent than the others, also the result of the simulation environment shows a decrease of delay, this is why it can be said that the MAODV-UU can reduce the delay for the real world applications and will be useful for the realization of SG for increasing the energy efficiency.

1.1 Motivation

The national academy of engineering science has declared electric grid (EG) as the supreme engineering achievements of twentieth century [1]. The grid has gained a little change from the original grid designed by Thomas Edison and Nicola Tesla back in 1880’s and to the point of functionalities, this is mainly one way flow of power from the generation to the loads. The benefits of modernizing the grid can be summarized as follows

1. To economize the production and delivery of power,
2. To increase the consumer awareness for better energy consumption and control,
3. To use renewable resources in order to reduce CO_2 emission,
4. To increase the service reliability, and
5. To accommodate the grid with the increasing demand of electric vehicle (EV) for reducing the oil dependency of automobiles. [2]

The power generation and transmission system is designed in such a way that it can meet the peak demand at all the time, however, in reality, it happens infrequently and not for a long time. By using the communication facilities of SG, the load can be redistributed, as a result the power supply system does not depend on any major generating units and small generating units can also contribute to the grid. Seamless integration of power from small generating units like solar energy and wind turbines can also be done by using SG. At present, the electricity is being used by the conventional flat metering system, and consumers are less concerned about the unit price of electricity. For better control of the operation, smart appliances will have controller units which will let the user know about the price of using the electricity at that specific time. For example, a refrigerator could run the defrost cycle to save power when there is a peak demand of electricity. Eventually, power consumed by many refrigeration units will be reduced at this peak time, saving energy that can be used for another much needed load.

Now, with the invention of electric vehicle (EV) the future demands of electricity will raise while also providing an increase in distributed power storage because of their batteries. The electric car loads are variable and the system has to be capable of meeting the needs. If, most of the cars, start charging during peak hours, the generating stations have to add more units to meet the demand. Off peak time charging provides the flexibilities of better power distribution, and the SG is envisioned to control these kinds of load management i.e. addition of sudden load changing scenarios.

In SG, sensors will be installed along the grid systems which are able to forecast any anomalies in the grid, for example, malfunction or a deteriorating transformer can be forecasted before it breaks down. The necessary precautionary measures can be taken beforehand and it will increase the power supply reliability. The modern communication and information technologies will play an important role for the functionality of SG. SG will be a vast networking of sensors, advanced metering infrastructure (AMI) and devices at home, and also a central data center is required for managing this vast amount of real time data. Technical committee's of IEC, IEEE, ISO etc. are working for the standardisation of SG. The invention of microprocessor, networking and control has opened the opportunities of grid modernization, thus, it can be said that the full capabilities of smart grid will take decades to achieve.

In some parts of the SG, ad hoc networks are considered suitable for communication. As SG is a large communication network, it requires highly scalable and delay efficient routing protocols for efficient routing. Literature review shows that ad hoc on demand distance vector (AODV) is a better choice for ad hoc routing in SG. But the scalability of AODV in SG is not tested till now, moreover, testing scalability requires large number of nodes in a scenario. It is not feasible to have a real-time test-bed with hundreds of nodes, and for this reason we calibrated a small simulation scenario considering a small real-time test-bed scenario. We have a real-time test-bed which has the implementation of AODV Uppsala University (AODV-UU) with six nodes in a small SG scenario. We used it for calibrating our simulation scenario, then we have evaluated the same AODV-UU in OMNeT++ in larger scale (i.e. with 10, 20, 30, etc. nodes) to justify its scalability. The average throughput follows the similar trends as in the real-time implementation. Then we proposed modified AODV-UU (MAODV-UU) to make it more delay efficient, and the simulation result shows that MAODV-UU reduces average packet latency.

Moreover, Canada ranks second among the electricity exporting countries [3]. In 2009, USA has imported 51,108,502 Megawatthours electricity from Canada and has exported 17,490,264 Megawatthours to Canada [3]. In USA half of the electric power is generated by using coal and half of these generating units are above 40 years old [2].

One of the major causes of green house effect is CO_2 emission. In USA, 41% of the CO_2 emission is caused by the power generating units [4]. Brattle group has estimated that by the year 2030, the electric utility industries of USA require an infrastructure investment of $1.5 trillion to 2.0 trillion [5]. If the power grid is made 5% more efficient, the saved energy will be equivalent to eliminating the fuel and emission reduction from 53 million cars [6].

From these reports, it is quite evident that improvement of transmission and distribution of power and integration of renewable energy can increase efficiency and save billions of dollars. This will also help in reducing CO_2 emission by increasing renewable energy resources which is going to mitigate the green house effect.

1.2 Significant Contribution

SG is a large network of distributed nodes and subsequently the efficiency of SG depends on the successful communication among these nodes. The grid should be capable of integrating small power units and distribution of the power to the loads efficiently, thus it requires quick response from the control point of view. The data transfer among the nodes of any network requires efficient routing with minimum delay. In this thesis, we have compared the test-bed AODV-UU implementation with the simulation and it strongly supports the test-bed implementation. We have observed the scalabilities of AODV-UU protocols for the SG application using simulation with OMNeT++, and have also observed the throughput for the increasing number of nodes. The obtained simulation result strongly supports that the throughput of the string topology of nodes is better than the grid topology. We have also modified the AODV-UU protocol. In the regular AODV-UU, all the nodes are equally intelligent, and it makes the routes when needed. In modified AODV-UU (MAODV-UU), we have made some nodes more intelligent than the others. The intelligent nodes can retain the routing information of the previously made routes, thus, when an application requires making route the intelligent nodes helps to reduce the route set up time. The simulation result shows a significant decrease of delay which is a very useful contribution for the application of MAODV-UU for the SG.

1.3 Thesis organization

Chapter 2 discusses about the SG, measurements and metering of SG, power system communication development history, SG communication requirement, various communication technologies of SG, standards of SG, routing, adhoc routing and SG routing protocol overview. Chapter 3 discusses about the simulation setup, scalability test of AODV-UU, proposed work of modified AODV-UU and the simulation environment. Chapter 4 discusses about the result analysis in string and grid scenario. Chapter 5 discusses about the conclusion and future work.

2 Smart Grid

2.1 What is Smart Grid?

The conventional grid is made by interconnecting distributed power plants. SG is the addition of bidirectional flows of information and power to the grid system, thus it provides a better control of the power system by incorporating digital system, automation and self healing capabilities. SG also enhances the efficiency, security and reliability of the power system by the application of better communication technologies. The authors in [7] presented a comparison of the conventional grid and SG as in Table 2.1.

Existing Grid	**Smart Grid**
Electromechanical	Digital
One way communication	Two Way communication
Centralized generation	Distributed generation
Few sensors	Sensors are integrated
Manual monitoring	Self monitoring
Manual restoration	Self – healing
Failures and blackout	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

Table 2.1 Comparison between the present grid and the smart grid [7].

SG is called by many names i.e. intelligent grid, future grid, intergrid or intragrid and an improvement of twentieth century power grid [10]. National institute of standard and technology (NIST) has created a conceptual model of SG as shown with modification in Figure 2.1 [8].

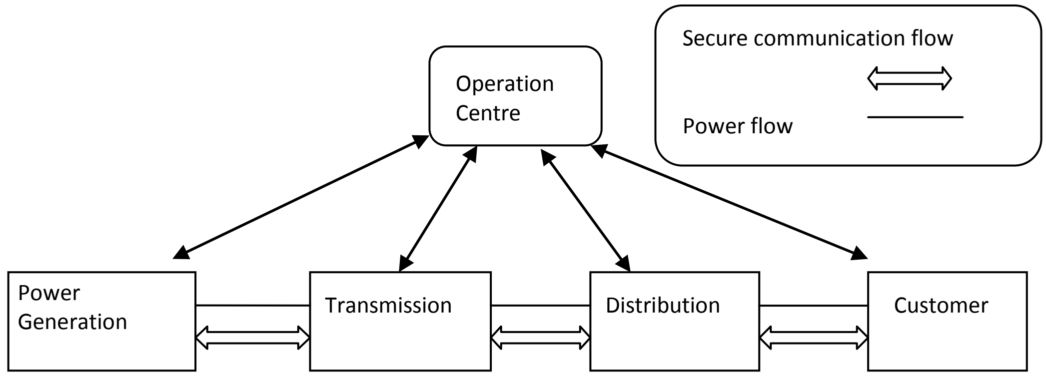

Figure 2.1 Smart grid conceptual models.

In the traditional grid, power is transmitted from the generating unit to the load, whereas in smart grid, any amount of power, small or large, generated by the household or other units including from solar cell or wind turbine is added to the grid. This distributed generation (DG) of power has to be accommodated in SG. Though, at present, the numbers of DGs are small, it is going to be larger and decentralized in the future SG. The future SG has been predicted to

1. Accommodate DGs in present grid,
2. Introduce a decentralised DG system that work with centralized generation system, and
3. DGs will supply most of the power than the centralized generation [9].

Largely deployed sensors in SG will play a vital role for the information monitoring and measurement, moreover, these sensors need to be connected with the other units with networking and communication technologies. The communication technologies for the SG can be classified as follows.

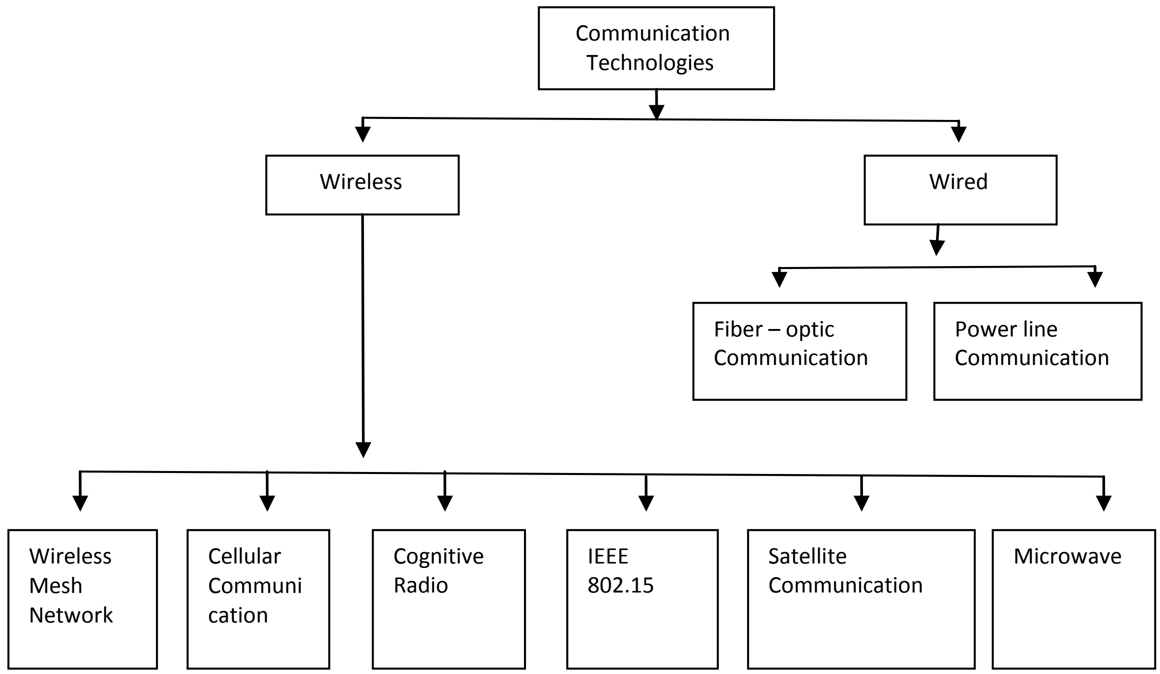

Table 2.2 Communication technologies of smart grid [10].

2.2 Measurements and Metering of SG

Information monitoring and measurement can be divided into two sub categories e.g. metering by smart meter and monitoring by advanced technologies.

2.2.1 Smart Meters for Metering

These meters function as two way communication between the meter and the central subsystems. Smart meters collect the real time data of household appliances and send it to an access point, as well as this real time data consisting of voltage, current and consumed power can also be routed to the distribution center. Smart meters can connect or disconnect and control the appliances remotely, in addition the consumers can differentiate each appliance's consumed power, and take the right decision for operating the appliances at the right time (off peak hour) for reducing bills. Smart meters can inform the user to use the appliances at off peak hour for reducing bills [10].

2.2.2 Monitoring and Measurement

SG needs a continuous real time information of the grid status. Leon et al [11] has proposed that the grid should be embedded with the sensor networks and it should help to determine the real time electrical and mechanical status of the grid. The collapse of towers, disconnected conductors, line faults or other mechanical failures can be detected by the sensor networks and also can help to determine the real time control measures for ensuring uninterrupted power supply. The sensor networks of SG should fulfill the following requirements [12, 13, 14]:

- **Quality of service**

  The sensor networks will generate a lot of information, thus the connectivity of the network should support the high reliability, low latency and high throughput. The controller at the control center should receive the data in a timely manner.

- **Remote access**

  The sensor networks must be accessed remotely and should have remote configuration facility.

- **Environment withstanding**

  The SG environment is mostly outdoor type. The sensors must be able to withstand the rain and shine, dirt and dust and other signal interferences.

2.3 Power System Communication Development History

The research on communication technologies of SG has passed through a considerable development in the course of time. Table 2.3 shows the communication system development summary [12].

Phase	Years	System Characteristics	Network Architecture	Communication Media	Communication Protocols and Standards
Non Standardiz ed	Up – to 1985	Many proprietary systems. Single vendor per system. Basic data collection	Hierarchical tree, Single master, Isolated substations	RS232 and RS485 Dial Up, Trunk Radio, Power line carrier, Less than 1200 bps.	Modbus, SEL, WISP, Conitel 2020
Standard Developm ent Begins	1985 - 1995	Multi vendor systems, Protocol conversion	Hierarchical Tree, Multiple masters, Redundant links	Leased lines, Packet Radio 9600 to 1200	DNP3 Serial, IEC 60870, TASE 2
Local Area Networks (LANs) and Wide Area Networks (WANs)	1995 - 2000	Introduction of LANs in substations. Merging protection and SCADA Networks	Peer to Peer Communicatio n in Substation. Joining substation via WAN.	Ethernet Spread Spectrum Radio, Frame Relay, Megabit data rates.	TCP-IP, FTP, Telnet, HTTP, DNP3, WAN/LAN, UCA 2.0
Integratio n into Business	2000 to Present	Merging automation and Business	Linking of utility WAN to corporate	Digital Cellular IP Radios Wireless	TCP-IP, IEC 61850

Table 2.3 Communication system development summary for the power system.

SG will encompass various small renewable energy resources i.e. solar cells, wind turbines, tidal waves, small hydro power generating units, geothermal heat and the energy from the wastes. Basically, these are small power generating units that can be used for meeting the local needs or can be added to the grid for organized distribution. These small units manifold the complexities of power management, furthermore, the communication and control of smart grid must be capable enough to address all these needs.

2.4 Communication Requirements for the Smart Grid

Communicating among systems of various functionalities is the foundation of smart grid. Poor communication will disrupt the essence of smart grid, and it may also disrupt the grid system. The communication needs to maintain the following factors for the efficient operation of an SG [15, 18].

2.4.1 Network Latency

The latency of a network is defined as the maximum time required for a message to reach from the source to the destination. The latency requirements among the various types of functionalities are different. For example, the message exchange between intelligent electronic devices (IEDs) requires less time compared to the supervisory control and data acquisition (SCADA) message exchange between the electrical sensors and the control centre. The data rate of the network and number of hops required for sending the data also affects the latency.

2.4.2 The Criticality of Data Delivery

The protocols used for the smart grid applications should provide the criticality of different data delivery depending on the applications. This can be taken into account at the time of designing an application. The criticality of data delivery may be classified into three categories as follows:

i) Highly critical: If the system needs a confirmation of the end to end delivery of any sensitive data (i.e. switchgear position changing information), the criticality level of the communication is considered very high. As this kind data is very sensitive in SG, this is required for ensuring a successful delivery.

ii) Medium critical: When there is no need for the end to end delivery confirmation of data, it can be considered as medium critical. For example, measurement data of voltages and currents.

iii) Non critical: When the loss of data is acceptable to the receiver, it can be considered as non-critical. The message repetition can improve the data reliability in these cases. For example, the loss of some monitoring data of certain interval can be considered as this type.

2.4.3 The Data Reliability

In the SG, the functional devices rely on the communication backbone network for the reliable data delivery, and the backbone network should be capable to meet all the needs. The communication network or the resources can affect because of improper data delivery. If the time of detecting, assembling and monitoring of a control message exceeds the time limit, it can be treated as a timeout failure. The failure of any layer of the "protocol suites" will be treated as network failure.

2.4.4 Security

The SG is a large network stretching hundreds of miles. If the wireless communication system is used for communication media, then the data security becomes very important. Spoofing of data may affect the SG systems, and consequently, for the secured delivery of data, access should be limited to the authorised personnel and encryption of data may be adopted.

2.4.5 Time Synchronization

There are some devices of SG which requires time synchronization. For example, the phasor measurement unit (PMU) needs the time synchronized data for providing the real time electrical measurements. This data is used for the controlling, analysis and measurements of the power system.

2.4.6 Multicast Support

Sometimes, the system needs to send the same information to various resources. Instead of sending the message individually, the message is sent to a switch and it is retransmitted to all the outgoing ports [15, 18].

2.5 Wireless Technologies for the Smart Grid

Wireless technologies has the advantages of rapid installation, lower cabling cost, increased mobility than over wired ones and it also supports remote end applications [16]. The following wireless technologies can be applied for the SG communication.

2.5.1 **Wireless Networks**

a) Wireless Mesh Networks

Wireless mesh network (WMN) is one of the promising technologies for the next generation wireless networking [17]. It can offer the networking requirements and the benefits of WMN are described below [10].

- **Reliability of communication and connectivity**

  In WMN redundant path offer greater flexibility for communication, also the key feature is that WMNs are self organized and self configured and useful for the electric power system automation.

- **Larger coverage and high data rates**

  The smart meters, sensors and other SG equipments will generate a high volume of data which has to be transferred all the way down to the control center for monitoring and other applications. WMN has the capabilities of addressing this requirement [10].

b) Cellular Communication for the SG Applications

Cellular communication is a terrestrial radio communication and it performs the networking services from the Cell/Base station. Researchers have studied on the applicability of this technology for the SG. The study of Hung et al. [18] proposes that the communication of the sensor nodes with the backend nodes by cellular networks.

c) Cognitive Radio

Ghassemi et al. [19] has proposed that cognitive radio's can be used for the SG applications and this is based on IEEE 802.22 protocol. The communication by the cognitive radio between the SG control center and the consumer has been proposed by Ma. et al. [20].

d) 802.15.4 Standard Based Wireless Communication for SG

This standard is used in three component technologies as described in [21]. Those are WirelessHART, ZigBee and ISA100.11a. ZigBee is suitable for the low data rate, low energy consumption and secured communication. U.S. national institute of standard technology (NIST) [8] has selected ZigBee smart energy profile (SEP) as communication standard for the SG customer premise network. Many companies selected ZigBee as smart metering devices communication technology [7]. The ZigBee smart energy profile (SEP) supports the features like pricing at the real time, response according to demand, enhanced support of metering and the control of load [23]. Self organised and time synchronised mesh architecture is used by the WirelessHART system. It operates on 2.4 GHz band and uses the 802.15.4 based standard radios. International society of automation has developed ISA100.11a standard and this is an open standard for the wireless networking. For the power generation plant and substation WSN applications, the WirelessHART or ISA100.11a is recommended [10].

e) Satellite Communication for the SG

The lack of communication structure has made it difficult to communicate with the remote power generating units and substations. Satellite communication can be used for this type of communication. The wind energy based remote deployment units can be communicated by the global coverage of satellite communication system as stated by Deep et al. [24] and this can also be cost effective. The terrestrial system of communication may be disrupted by natural disasters, hence, for valuable and necessary data transfer satellite communication may be used as the backup system. There are two short comings of satellite communications, first is large delay and second vulnerability to fading due to the weather condition which can profoundly degrade the total performance of satellite communication [22, 10].

f) Microwave or Free Space Optical Communication for the Smart Grid

Microwaves systems work with the line of sight communication systems. Microwaves are field proven technologies for the telecommunication, and have been in use for decades. Microwaves are suitable for the rural communication where the infrastructure is not available or it is difficult to install. The disadvantage of the microwave communication is that the signal is heavily attenuated by any obstruction on the path of communication. Another way of communication, called free space optical communication uses the propagation of light through free space, and is a point-to-point communication with a very narrow beam. This is a directional and secure communication [10].

2.6 Wired Technologies for SG

2.6.1 Optical Fibre

Optical fibre communication has been in use for the communication between the power generation and network control centre for a long time [10]. Optical fibers are immune to interference and this property has made it suitable for the uses in high voltage environment [25]. Optical fibre's can carry a high volume of data, so it can be used as the communication medium for automation application [12].

2.6.2 Power Line Communication (PLC)

The electric power transmission cables are used for the transfer of data in PLC technology. PLC has the minimum cost due to the use of established power lines. PLC is subjected to noisy medium, interference, emission and change of impedances. The data security is also low in PLC [10].

2.7 Wireless Sensor Networks for the Smart Grid Automation

Wireless sensor networks (WSN) can be used for SG networking nodes. This WSN may be thought of as low power, low cost functional nodes. The nodes are small in size and communicate with each other over short distances [12]. These small nodes can read the various forms of physical information such as temperature, vibration, noise radiation. It can also transform these measured parameters into electrical signals [12]. Tiny nodes of WSN can route or relay the data packets to the sink in multi hop, infra structure less architecture [26]. WSN offers better quality and coverage than the traditional stand alone sensors with the sensor network using wireless adhoc networking for its application [29]. WSN may be used as reliable system for electric system automation. It has various uses i.e. WSN can be used in wireless automatic meter reading (WAMR) system for the real time energy consumption reading. In WSN the network topology depends on application requirements [12].

A sample network is shown in Figure 2.3. This tiny sensor's can collect data and route to the sink node [26].

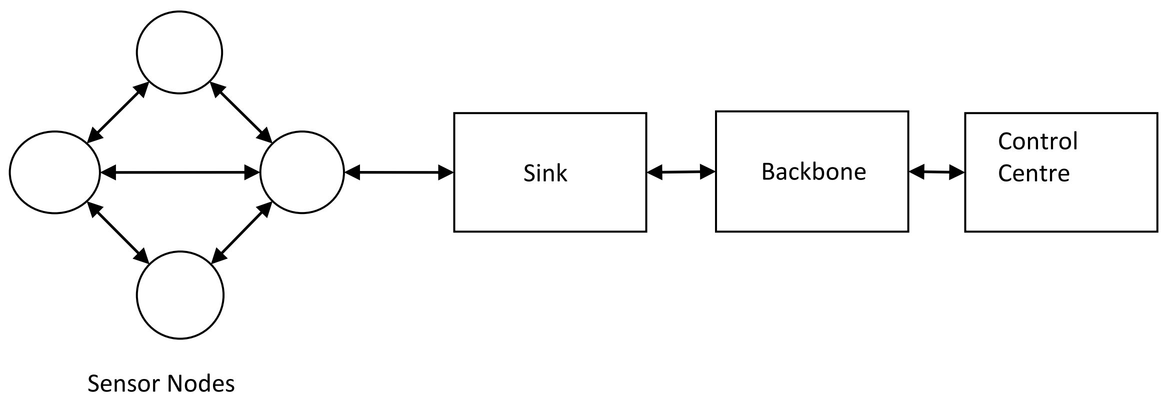

Figure 2.2 Smart grid sensor based network architecture.

The measured data is then transferred by the backbone nodes to the control centre.

2.7.1 Wireless Sensor Networks Benefits in SG

WSN offers a real time and trusted network monitoring for the electric systems. The major benefits are described below. A monitoring system integrated with the sensors can reduce the fault detection time and recommencement of power supply service [12].

Large area coverage

A large number of sensor nodes cover a large area of monitoring, and after the installation of WSN the human intervention is almost negligible [12].

More fault tolerant capacity

In WSN, the nodes are densely deployed and the correlation of data is high. The WSN is a large distributed network with redundant routes. It allows the monitoring and maintenance information to be transported in case of route or sensor node failure [12].

Accuracy of data measurement

The different physical phenomena of the electric system are sensed by the multiple sensors [12], and it can be said that a sensor based network is more accurate because of multiple sensors.

Necessary data processing

Sensor nodes can filter data according to the application. This reduces the unnecessary processing and only the required information is transmitted to the data centre. It helps to reduce the communication overhead [12].

Self maintenance

The sensor nodes have self configuration capabilities, and it offers very rapid deployment. The sensor nodes can make ad hoc networks which does not have the conventional topological architecture of the nodes. Faulty sensors can be removed or new sensors can be added easily without compromising the fundamental objective of electric power system monitoring [12].

Low cost

WSN is a low cost device and it consumes low power, thus, it provides a cost effective way of networking than the other sensors [12].

2.7.2 Design Factors for Wireless Sensor Networks

WSN can be used for system automation of the SG. For the cost effective solution of SG, supporting the existing structure and fulfilling the application need, designers need to consider the following factors [12].

a) Topology and network architecture

The topology of WSN has notable effects on the routing protocols, lifetime and the network ranges. The architecture includes the physical and logical organization of the sensor nodes and its density. The WSN nodes need to effectively cover the networking area. Network organization impacts the energy consumption of the nodes and protocol of communication [12].

b) The application program

The sensor nodes transmit and relay lots of data. These data needs to be quantified and classified [27]. It can be achieved by analyzing applications used for electric system automation [12].

c) Limitation of resources

The design and implementation of wireless sensor networks is limited by the – energy, processing and memory resources. The battery lifetime of the sensor nodes limits the lifetime of sensor networks [28]. This is why, the communication protocol for the sensor nodes should provide high energy efficiency [12].

d) Timing requirements

This is very important that the control centre should receive data at the right time for the requested operation of the SG. The delay of data communication mainly composed of processing and transmission delay. If the data takes a long time for the processing and transmission, it becomes outdated and may results in a wrong decision. Hence, the communication protocol used in WSN should be able to support the efficient communication system [12].

e) Fault tolerance

Interference of another signal, lack of power or damage may trigger the failure of the sensor nodes. The design should be such that failure of some nodes does not affect the network parameters. Reliability is very important for sensor networks [26]. Fault tolerant capacity of the sensor networks is being considered now and the fault tolerance of the sensor networks has been modelled in [30]. The probability of not failing within the time interval $(0, t)$, can be expressed by the Poisson distribution

$$R_k(t) = e^{-\lambda_k t} \quad \text{..(1)}$$

Failure rate of the sensor node k is λ_k and the fault tolerance or reliability is denoted by $R_k(t)$ and the time period by t [26].

f) Scalability

A large number of sensor nodes may be deployed in an area. The density of the sensor nodes may vary from a few hundred to several thousands in a region. The density, μ of the sensor nodes can be calculated by [31].

$$\mu(R) = (N.\pi R^2)/\mathrm{A} \quad \text{..(2)}$$

Where N is the number of sensor nodes in a specific region A and R is the Radio transmission ranges [31].

2.7.3 Wireless Sensor Networks for the Electric System Monitoring

Natural disasters, equipment malfunction or failure, or accidents may results electric power outages. That is why, this is very crucial that the electric systems should be controlled and monitored and the power supply authority should get the monitoring information at the right time for taking necessary precaution [11]. Wind turbines and photovoltaic cells are distributed resources which can potentially compensate the power supply shortage. But, the integration of large number of these types of resources with the existing power system is a challenging task. These integrations can be solved by sensing, metering, communication and IT services [32].

A well designed sensor based network with the appropriate protocol can be used for the fault detection and other monitoring purposes. WSN provides the opportunities of real time and reliable monitoring of power supply system [12].

2.8 IEEE Standards for the Smart Grid (SG)

IEEE has released a group of standards for the power system communications. These are briefly described below [15].

a) IEEE C37.1

IEEE C37.1 standard [33] is about the functional requirements relating to the SCADA (Supervisory Control and Data Acquisition) and system automation. It tells about the specification, definition and SCADA application for electric substations. The electric substation system architecture and function is discussed in this standard.

b) IEEE 1379

IEEE 1379 [34] is the recommendation of implementation guideline and communication of intelligent electronic devices (IED) and remote terminal unit (RTU) of the electric substation. Existing protocols has been used for the communication support.

c) IEEE 1547

IEEE 1547 proposes about the electric power system which connects the distributed resources. This protocol consists of three sections.

i) Power system [35]
ii) Exchange of information [36]
iii) Test compliance [37]

The power system standard discusses about the power conversion technology requirement and their inter-connection for providing quality services. The information exchange standard discusses about the power system monitoring and control through the data communication networks. The test compliance tells about the procedure for verifying the compliance of an interconnection system with the standards [15].

d) IEEE 1646, IEEE Standard for the Delay in the Smart Grid

IEEE 1646 [36] specifies about the standards of communication delivery time for the exchanged information of internal and external electric substation protection, control and data acquisition systems. This standard categorizes the substation communication and also defines the requirement of communication delay for those categories. Timing is one of the most important factors for SG communication. The IEEE and International electrotechanical commission (IEC) has guidelines for the communication delay requirements for the different information exchange. The end to end delay is the sum of processing and transmission delay of each traversed node. The source generates delay due to message format and transmission. The intermediate nodes add delay by processing and retransmission of the message. The destination adds delay by decoding and presenting to the application.

Information types	Internal to substation	External to substation
Protection information, High speed	1/4 cycle	8 to 12 ms
Monitoring and control Information, medium speed	16 ms	1 s
Operations and maintenance information, low-speed	1 s	10 s
Text strings	2 s	10 s
Processed data files	10 s	30 s
Program files	1 min	10 min
Image files	10 s	1 min
Audio and Video data streams	1 s	1 s

Table 2.4 IEEE 1646 standard: communication timing requirements for electric substation automation [36].

e) IEEE P1901

IEEE P1901 is a standard for high speed power line communication for the utility, in home multimedia and SG application requirements [38]. This standard integrates the power line communication into the wireless networks [39]

f) IEEE P2030

IEEE P2030 proposes the interoperability's of the SG. This protocol ensures the seamless data transfer of a two way communication for the electric power generation, power delivery and customer side application [39].

2.9 IEC Standards

For the control and communication of electric power systems the International Electrotechnical Commission (IEC) has submitted a number of standards. Standard 61850 defines communication between the transmission, distribution and substation system automation [39]. Standard 61870-6 defines data exchange between utility control centre and utilities, power pools and regional control centers [39]. IEC 61970 and IEC 61969 define the common information model (CIM). This is necessary for data communication between devices and networks. IEC 61970 is a transmission domain and IEC 61969 is a distribution domain standard [39]. For the smart grid application, CIM standards are integral and it connects many devices to a single network [39].

2.10 Routing in Smart Grid

SG is considered as a blend of interconnecting communication technologies with various devices. This is a large network of routers, switches, computers, smart meters, house appliances, sensors, renewable energy resources and electrical vehicles. Each of these devices has different CPU capacity, memory usage and storage ability, and, the routing protocol has to consider all these factors. In order to cope with various communication environments the nodes in the smart grid need to be equipped with multiple interfaces rather than a single interface. Hence, the nodes can operate with multiple radios and channels. These types of flexibilities will enhance the opportunities of alternate routes. The same functional devices can be grouped in a network, and may be used with different protocols. Therefore, the interoperability of the nodes is highly desirable [40].

2.11 Smart Grid Routing Factors to be Considered

2.11.1 Interoperability between Smart Grid Nodes

SG is a complex system of interconnected devices. Different equipments need to use the information efficiently and securely. The network and nodes needs to be managed with high efficiency to prevent blackout and network failure. The different networks which have been grouped according to their functionality can communicate with other network by the gateway services. These gateway nodes can support t interoperability by adapting different protocols. Deployment of such gateways on every part of the network may not be cost effective, and there is a need for new protocols to support home area network (HAN), neighborhood area network (NAN) and wide area network (WAN) environments [40].

2.11.2 Placement of Smart Grid Nodes

SG will have various network topologies. Hundreds of gateways, sensors and smart meters are fixed and deployed in the network as needed. The transmission range and density will be varying and requires a variety of network topologies needs to be addressed. Collision may be higher at the data collector and there will be a need for additional relay nodes. The nodes placement needs careful planning for reducing the bottlenecks and packet loss [40].

2.11.3 Smart Grid Node Mobility

Most smart grid nodes of NAN, HAN and WAN's are static. The maintenance vehicle, electric vehicles can be considered as mobile nodes. Mobility of these nodes adds new challenges to the routing protocol. Sensors are a part of the smart grid network and should be able to communicate with the mobile maintenance work force. The efficient routing with low latency and reliability is highly desirable. The disturbing factors like interference and node failure also needs to be considered [40].

2.11.4 Scalability of Smart Grid

Supporting the scalability is one of the key factors for the SG application. Thousands of smart meters will send real time data to the utility companies. The electric power user density will decide the no. of nodes used. The user densities of electric power of the city will be more than the rural areas. The factors like discovery of new route(s), and efficient distribution of packets will grow with the increasing network. The routing protocol needs to support the scalability of the nodes as per requirements [40].

2.12 Ad hoc Routing Protocols for the Smart Grid

2.12.1 Mobile Ad hoc Network Background

Mobile ad hoc network (MANET) is formed by a group of mobile nodes. This is a multihop network having the capabilities of self-organizing and self-configuring. The word ad hoc is derived from the Latin origin and it means ‘for this’ or ‘for this only’. MANET is very suitable for military application and it seems to be very appropriate for this because at the military environment, where infrastructure based network is difficult to install and maintain. In MANET each node can serve as both a node and a router. MANET is very helpful where there is need to make a network without any established infrastructure. It can make a network at any time at any place into reality. MANET permits the dynamic topology and any node is free to join or exit the network, meaning the network topology can change in unpredictable manners. Information is transferred in a peer to peer mode and it uses the multihop routing, also maintaining the route in dynamic topology requires a lot of challenges. MANET also has the civil application like smart grid, process control, disaster management and peer communications etc [41].

The discussion in Section 2.7 reveals that WSN is very effective for SG, and this WSN can be effectively implemented using ad hoc communication.

2.12.2 Ad hoc Routing Protocols

- **Ad hoc routing protocol classification**

Ad hoc routing protocols can be divided into following categories.

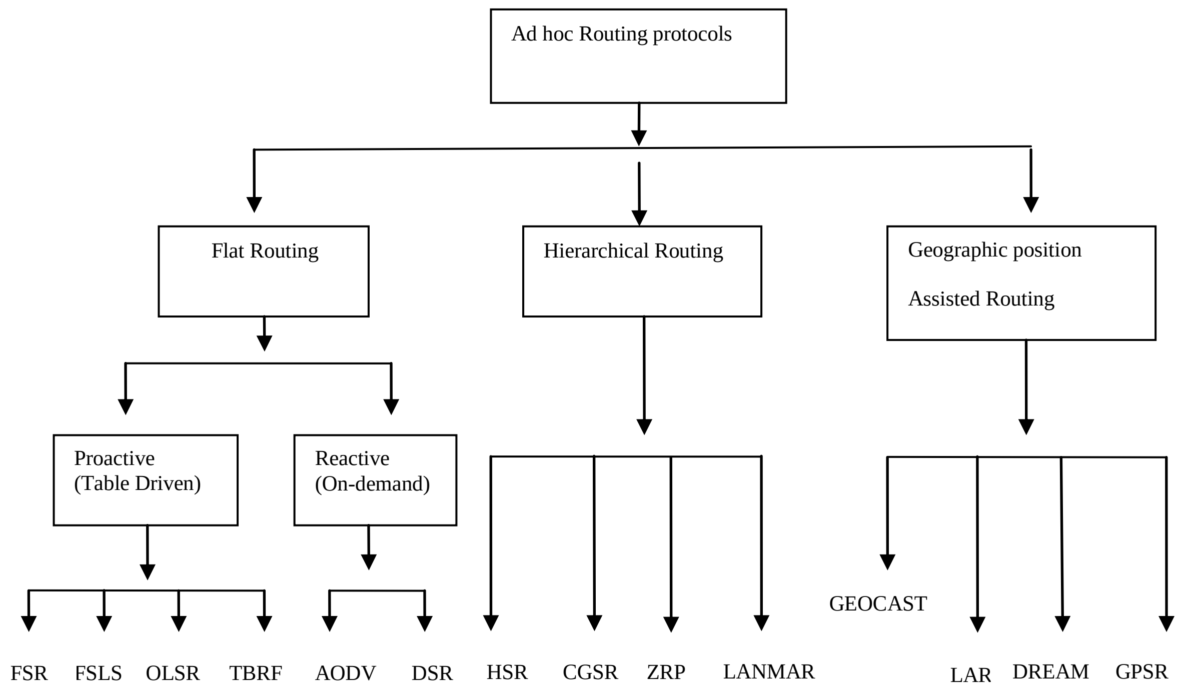

Table 2.5 Ad hoc routing protocol classification [41].

Some of the routing protocol categories related to SG are briefly described below.

- **Hierarchical routing**

The nodes of the networks have the different roles in hierarchical routing. Wireless hierarchical routing organizes nodes in groups and assigns the nodes with different function inside and outside of the group [41].

- **Geographical position assisted routing**

In this routing each node is integrated with the Global positioning system (GPS). The reduction of GPS price has opened the opportunity of using the GPS with the nodes and it provides excellent precision [41].

Dynamic source routing (DSR) maintains information on multiple routes in route cache and does not work well with the large network. Thus, the source node can check the route cache for routing information before initiating the routing request. The DSR protocol does not maintain the routine connectivity message with the neighbourhood nodes. The major difference between the DSR and AODV is that in DSR each packet contains the complete routing information and in AODV each packet carries only destination address.

AODV has less routing overhead than the DSR and AODV is also adaptable to dynamic networks. In the Light weight mobile routing (LMR) protocol routes are determined by the flooding techniques. LMR nodes maintain multipath routes to each destination. LMR has the limitation of producing invalid routes and caused extra delays. Temporarily ordered routing algorithm (TORA) is derived from the LMR protocol and it supports multicasting. TORA also has the probabilities of making the invalid routes. Associativity based routing (ABR) is a source initiated routing protocol where a route is selected principally on the basis of stability using query-reply technique for route determination. Signal stability adaptive routing (SSA) is derived from ABR and it determines a route on the basis of signal strength and the stability of the location. In SSA the intermediate nodes cannot reply to the route request, and it creates long delays [42].

- **Flat routing**

Flat routing functions with a flat addressing scheme, where each node of the network has the equal role [41].

As my research is related to the reactive routing protocols, proactive and reactive protocols are briefly described below.

- **Proactive routing protocol**

In the proactive routing protocol each node maintains the routing information of all other nodes of the network. This routing information is stored in a number of tables which are updated with the change of topology or in a regular basis. For example, Destination sequenced distance vector routing (DSDV) and Clustered gateway switch routing (CGSR) etc. are proactive protocols [42].

- **Reactive routing protocols**

Reactive routing protocols maintain the information of only the active routes of the network. It reduces the overhead of the proactive routing protocol. Routes are determined and maintained for the nodes that want to send data to a particular destination. The example of reactive routing protocols is AODV and DSR [42]. Most of the protocols of this type perform their operations broadly in two phases e.g. route discovery and route maintenance. Our proposed mechanism is also based on this category. The routing mechanism of this type of protocol is described in more detail in the next sub-sections.

2.13 Overview of Some Smart Grid Routing Protocols

There are lot of proposed protocols designed for multihop communication in different applications. Some of these previously proposed protocols are investigated for smart grid, and some are modified to fit with smart grid. This section contains a brief discussion on some of these protocols.

An improved routing protocol based on AODV for power line communication has been proposed in [43]. The improved on demand distance vector (IPAODV) routing cope with the topology changes of power line communication networks. Two changes have been proposed from the conventional AODV

a) Stable neighbours are selected during the route discovery

b) Over head is reduced by improving the route maintenance.

IPAODV determines the link quality by the received Hello messages. If the number of received Hello message is less than a threshold, then the link quality is assumed to be low i.e. a threshold value is used for the link quality assessment. If the link quality goes below the threshold than the neighbourhood entry is deleted. When the link quality is higher than the threshold, the neighbourhood is considered valid. Accordingly, in IPAODV regular Hello messages is not sent like conventional AODV. These unused Hello message slots are used for data packets in IPAODV [43].

The geographic Routing Protocol has been proposed in [44]. It has considered the static nature of SG and the WSN. Two other methods i.e. beacon-less routing (BLR) uses the location information for the reduction of routing overhead [45] and beacon-vector routing (BVR) [46] and implicit geographic forwarding (IGF) [47] has been considered. Greedy perimeter stateless routing (GPSR) techniques can be used in wireless networks [48].

In [49] Power line multipath routing (PMR) is used as source routing protocol which builds multiple routes by the use of request/reply cycles. PMR reduces the broadcasting overhead. Split multipath routing (SMR) [50] is suitable for finding the disjoint routes. In

[51] the routing protocol for low power lossy network (LLN) has been proposed by the Internet engineering task force (IETF). Routing protocol for low power and lossy networks (RPL) is based on IPV6. It can support point-to-point (P2P), point-to-multipoint (P2M) and multipoint-to-point (M2P) communication. This protocol supports message confidentiality and integrity.

Performance comparison of RPL and geographical routing protocol [52] has been conducted. Both can be used for smart utility networks. Hydro is another routing protocol [53] which supports the point-to-point (P2P) communication. This is a hybrid protocol and it supports the centralized control.

The secure energy routing mechanism (SERM) was proposed in [54]. SERM provides security by using secure key management. For the smart metering application wireless mesh based networks are being used in North America and other parts of the world [55]. For the neighbourhood area networks (NAN) energy management RF mesh based network is being used in [55]. For the smart grid back bone networks IEEE 802.11s is proposed in [56]. This protocol supports hybrid wireless mesh protocol (HWMP). HWMP is useful for static mesh networks.

In this sub-section, we discussed some routing protocols proposed for SG applications. Our research in this thesis is mostly related to AODV and AODV-UU. So, we briefly described AODV and AODV-UU in the next sub-sections.

2.13.1 An Overview of Ad hoc On-demand Distance Vector (AODV)

We proposed the modified AODV (MAODV) routing protocol, which is based on some changes of the mechanism of AODV, for the SG application. The mechanism of AODV is briefly discussed in this sub-section. AODV protocol is derived from the DSDV algorithm. AODV is an on-demand routing protocols in which the nodes maintain routing information which lie on an active path. The main phases of AODV are discussed below.

AODV creates route when needed and this is a reactive routing protocol. It has been shown in Figure2.3. Connection with the neighboring nodes is detected and maintained by the use of hello messages. Each active node broadcasts the hello message; hence, failure to hear the hello message from the neighbor link indicates a link break. In order to transmitting data to an unknown destination a source node broadcasts a route request (RREQ) for the destination. Every intermediate node receiving the RREQ makes a route to the source. If the receiving node receives the RREQ for the first time and is not intended destination, the node will rebroadcast the RREQ.

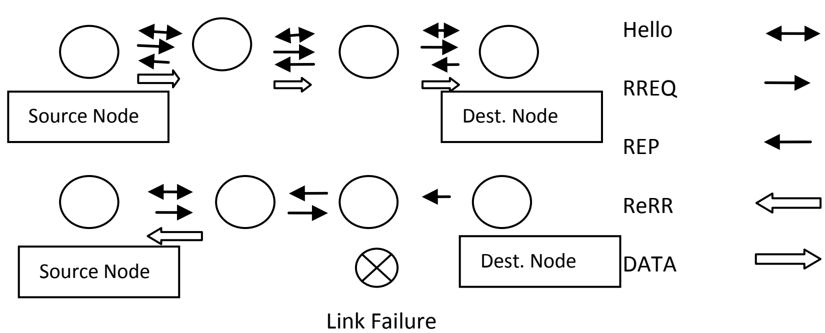

Figure 2.3 AODV routing protocol.

Again, if the receiving node contains the current route to the destination or itself is the destination, it will generate route reply (RREP). The RREP is unicasted in hop by hop to the source. The route to the destination is created through the propagation of RREP. After receiving the RREP, the source stores the destination route to the destination and starts data transmission. If the source receives the multiple RREP, it chooses the route with the shortest hop count. While the data transfer continues from the source to the destination, the node across the established route update the timers related to the routes and maintains the route in the routing table. For the unused route, the node cannot decide whether the route is still valid or not and detects the route from its routing table. If a link break is detected during data transfer a route error (RERR) message is sent to the source in a hop-by-hop manner and the intermediate nodes invalidate the route to the unreachable destination. When the source receives the RERR, it marks the route as invalid and the route discovery process is reinitiated [57].

2.14 An Overview of AODV Uppsala University (AODV-UU)

AODV-UU implements the AODV protocol [58], and it is compliant with IETF RFC 3561. AODV-UU was developed by the Uppsala University, Sweden and released under the GNU general public license (GPL). The suffix UU is added for the word Uppsala University. AODV-UU was initially written in C for running with Linux. It is popular among the academician and researcher’s [66]. Uppsala University’s AODV implementation has been imported to the INET framework. This is integrated with INETMANET too.

The mobile ad hoc network (MANET) supports the multi-hop communication by using IP routing. In this thesis, we are using modified AODV-UU for the SG communication.

In this section, we discussed about routing in SG. We have given overviews of some related routing protocols along with AODV and AODV-UU. We have tested AODV-UU in a real-time test-bed scenario and compared those outcomes with the simulation results. We used INETMANET with OMNET ++ to simulate different SG related metrics of AODV-UU. The next chapter contains an overview of our simulation platform, OMNeT++.

3 Proposed Works

The existing grid lacks the communication facilities needed for the information exchange. In SG, the system components and the sensor nodes are linked by the communication paths among them. This communication path provides the control and management abilities of the power transmission and distribution of the commercial and residential substations. A reliable and real-time information transfer is very crucial for the power delivery from the generation to the consumer through the SG system. The outage and disturbance of the power system can largely be reduced by the on line system monitoring, diagnosis and protection [59]. To meet these requirements, SG networking application needs the wireless ad hoc networking techniques for data communication. In SG, the sensor nodes will be installed across the grid system for data communication in multihop. But, multihop data dissemination requires very efficient and scalable routing algorithm especially for a large network like SG. A lot of SG researchers are considering AODV as a smart grid WSN routing protocol. From literature review we find that AODV is a throughput and delay efficient routing protocol, and most of the existing evaluations of AODV are done in comparatively small networks (i.e. smaller compared to SG). In this thesis, we worked on the justification of AODV-UU in a larger network like SG. For scalability testing we need larger scenario, and it is difficult to make real-time large scenario (i.e. more odes in one route), hence we have taken help of simulation to form large scenario scalability testing. Prior to large scale scalability testing, we calibrated our simulation setup with small scale real-time test-bed. We also proposed some modifications to AODV-UU to make it more delay efficient. The proposed work is divided into three parts.

a) Calibration of the simulation setup: Comparison of AODV-UU in the test-bed and simulation environment (OMNeT++) for small scale scenario.

b) Scalability test of AODV UU in large scale string and grid scenario using OMNET++.

c) Modification of AODV-UU for making it efficient for the SG application, and evaluation in string and grid scenario.

3.1 Calibration of the Simulation Setup: Comparison of AODV-UU in the Test-bed and Simulation Environment (OMNeT++) for Small Scale Scenario

We have a test-bed implementation of ad hoc networks for the SG application with several laptops are using as sensor nodes in the test-bed. The nodes run on Linux, and the necessary software for the AODV-UU has been installed, which helps to create any small scenario for any evaluation. This part of the thesis is about calibrating our simulation setup with real-time test-bed, as well as discussing how we created a scenario using AODV-UU in the test-bed and collected the required results. The same scenario has been created at the simulation environment of INETMANET based on OMNET++, and AODV-UU is used in the simulation the same as in the test-bed. The obtained data is expected to be the mimic of the real application scenario, and this simulation is just another way of obtaining the desired result. It is worth to say that if any system works well in the simulation, it may or may not work in the real world application. But, if the system does not work at the simulation, it can be predicted that the system is not going to work for the real world application. The obtained result is analyzed in Section 4.1.

3.2 Scalability Test of AODV UU in Large Scale String and Grid SG Scenario Using OMNeT++

The test-bed experiments were done with six nodes due to hardware constraints, cost and interference, and because of this we developed simulation environment for scalability testing of AODV-UU in large scale scenario. Two types of topologies, namely linear and grid topologies, the results are presented in Section 4.2.1 and 4.2.2.

3.3 Proposed Modified AODV-UU for SG Application

The functionality and success of SG depends on the real-time monitoring, measurement and control of power systems. In every sensor node, there is delay due to processing and transmission of data packets across the smart grid. In this thesis, we tried to reduce delay in the network layer by adapting a new method to reduce the route setup time. We are calling it modified AODV-UU.

In the regular AODV protocol [58], an active route is defined as a route towards a destination that has a routing table entry and that is marked as valid. Only active routes can be used to forward data packets. Moreover, each node keeps its routing table as long as the active route timeout (ART) allows it to retain the route. When the ART is expired, the routing table entry of the node is deleted.

In SG, the sensor nodes are one of the key components of the large network, and if all the nodes retain the routing table, it becomes a static and continuous process, and if any node leaves or joins the network it is time consuming to reorganize the route. The continuous retention of the routing table by any node consumes more power, and so the battery life is quickly exhausted. In order to improve this phenomenon, we proposed a modification of the AUDV-UU in this thesis work.

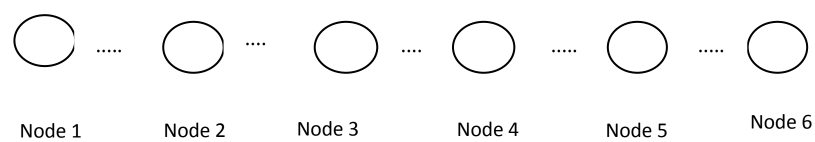

Figure 3.1 Regular AODV-UU with all nodes is equal.

Figure 3.2 Modified AODV-UU with every fifth node is more intelligent than other nodes after source node.

In the regular AODV-UU, each node having the same capability of retaining the routing table. The routing table of each node is deleted after a certain user defined time, but, if the routing table can be retained for a certain time the route set up time can be reduced. As SG scenario is semi static, retaining the route for a short span of time may reduce delay and increase the network throughput. In the proposed modified AODV-UU system, every fifth node in a string like topology network will be able to retain the previous route for a comparatively longer time. Moreover, when a source node is asking for a route to the destination node, the route request packet does not need to go all the way down to the destination for the route set up. The sending node will get the route information much ahead of the regular route set up time and it will reduce the end-to-end delay of the data transfer.

3.3.1 **Grid Scenario**

We have considered a mesh like structure of 12 nodes as shown in the Figure 3.3 for evaluating MAODV-UU.

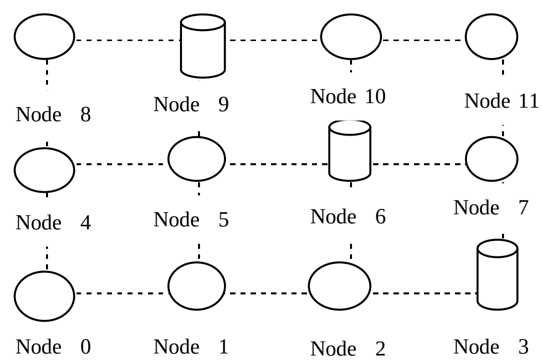

Figure 3.3 Grid networks of 12 nodes.

The nodes are placed at equal distance from each other. Only the neighbouring nodes are in the transmission range and the simulation parameters are same as Table 4.5.

We have operated a ping application between node 0 and 12 for creating route among the nodes. The PING application is operated for 20 seconds and according to the default AODV-UU settings, the route is supposed to expire after 20 seconds. A UDP application is started after 50 seconds for measuring the delay between node 2 and 10. The lately started UDP application ensures that the previous routes have been expired. This UDP application makes new routes. At this scenario, the measured value of the delay is

0.0444168s. Now, for this specific scenario, we have made nodes 3, 6 and 9 intelligent. Hence, these nodes will store the routing information created by the PING application. After applying the intelligence, the delay is measured again between nodes 2 and 10 which show an improvement of the delay characteristic. It is analyzed in more detail in Section 4.3.

3.4 Overview of the Simulation Environment: OMNeT++

OMNeT++ is an extensible, modular component based C++ simulation library and framework [60, 61, 62, 63]. This simulator incorporates an objective and modular network test-bed. Academic research users can use it free, and this is open-source software. It is an objective oriented modular discrete event network simulation framework. It has a generic architecture, and can be used to simulate various models. This is a very useful tool for the traffic and complex network modeling, queuing system modeling and validation of hardware architecture, modeling of multiprocessors and distributed systems. In general any system which can be represented by the discrete events can be modeled and simulated by the OMNeT++.

Both the Linux and Windows platforms are supported by OMNeT++. The components of OMNeT++ can be described as

a) Simulation kernel library.
b) NED topology description language (nedc) compiler.
c) NED files graphical Network editor.
d) GUI environment for the simulation execution (TKenv).
e) Command line interface (Cmdenv).
f) Graphical vector plotting tool (plove).

g) Make file creation and random number seed generation (RNG) tools.

The very basic feature of OMNeT++ is that it is modular, and modules can be composed of sub modules. Models contain nested modules and these models communicate through gates and the gates are linked through connections. A connection can be assigned with data rate, error rate and propagation delay. Network models are a collection of nodes which are connected by links. Interconnected nodes in a network make the topology. Model structure is described by the network description (NED) language. NED language has a human readable textual topology. NED files can also be created by other languages (perl, awk etc). NED language provides the modular descriptions of a network.

Network description may contain simple and compound module declaration, channel definition and network definition. The compound and simple module of one network can be used for other network description. The program compilation process transfers the message definition into C++ classes.

3.4.1 **OMNeT++ User Interface**

OMNeT++ design permits the user to have access to the internal structures of the code. Users can initiate or terminate a simulation or change the variables within the simulation. These distinct features add flexibility to the simulator. Simulation kernel and the user interfaces interaction is achieved by the various well defined interfaces. A user can use several interfaces without changing the kernel. Simulation model can use different interfaces. The user has the flexibility to test and debug the user defined graphical interfaces.

OMNeT++ can be used with two different interfaces. Those are

a) Tkenv - Graphical user interface and
b) Cmdenv - Command line user interface.

The Tkenv can be used for debugging of simulation execution. User can have a view of the simulation, and the Tkenv provides a visualization of the whole simulation. Tkenv also provides the flexibility of showing results during the simulation execution.

Tkenv contains the following features.

a) Each module text output can have separate window.
b) Execution of the program by user defined events.
c) Insertion of break point.
d) Animated flow of messages.
e) Model, object report can be found.
f) Objectives and variables can be examined.
g) Simulation results graphical display.
h) Flexibility of stopping and restarting a simulation.

Cmdenv works like any other command like interfaces and it is fast. This is very suitable for the batch file execution, and that can also run and compile on different platforms. Cmdenv runs the simulation according to the configuration files, which can be run in two modes.

a) **Normal mode** Textual format of debugging can be done in this mode.
Event banners and module output is written to the standard output or a designated file.

b) **Express mode** When the simulation takes a long time to run, it can be made faster by running at the Express mode, and this is useful for long simulation run. Periodical status updates are displayed in this simulation mode [60, 61, 62, 63].

3.4.2 **INET Framework**

INET framework contains the protocol implementations of IPV4, IPV6, TCP, SCTP, UDP and many other application models. The link layer models include PPP, Ethernet, 802.11 etc. By using network auto configurations, static routing can be set up, and routing protocol implementation can also be used. INET frame work supports both the wireless and the mobile simulation [64].

3.4.3 **INETMANET**

INETMANET works with the INET framework. This software is on continuous development by the research community, and its functionality is same as INET framework which has some additional modules that are very useful for wireless communication modeling. Any routing or MAC protocols can be also modeled by INETMANET [65].

4 Result analysis

4.1 Calibration of the Simulation Setup: Comparison of AODV-UU in the Test-bed and Simulation Environment (OMNeT++) for Small Scale Scenario

In the simulation environment, the nodes are placed at a reasonable distance apart from each other and this is done for making a suitable scenario for the ad hoc networks. The distances between the nodes are set in such a way that the transmitted signal is only received by the neighbouring nodes. Therefore, it can be predicted that the ad hoc characteristics of the network has been created. The test-bed scenario has been created with a small number of nodes same as in the simulation. In both cases, a string topology as shown in Figure 4.1 has been chosen for the calibration.

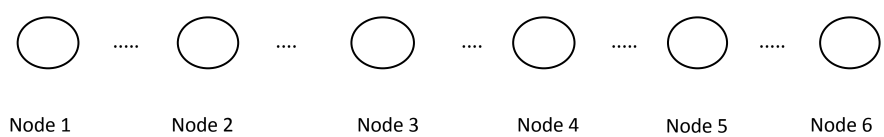

Figure 4.1 String topology of six nodes.

A string topology of six nodes with all the nodes having equal intelligence is chosen. We send data from node 1 to node 6. According to the principle of AODV-UU, first route is made by Node 1, and then data is transferred from node 1 to 6.

AODV-UU is integrated with the INETMANET in the OMNET++ simulation environment. We have established the network with the following parameters (See Table 4.1).

Simulator	OMNET++
Protocol	AODV-UU
Simulation Duration	5000 second
Number of Nodes	6
Model	String Topology
MAC Layer Protocol	IEEE 802.11 a/b/g

Table 4.1 Simulation Parameters AODV-UU.

In both cases (i.e. simulation and test-bed), the throughput is recorded on hop-by-hop basis. At first data was sent from Node 1 to Node 3. It creates a 2-hop and the throughput is measured, then the number of hops is increased, and the same experiment was done for 3, 4 and 5 hops. As the number of hops increases the throughput decreases due to the routing overheads.

No. of Hops	Simulation Time	Throughput Simulation	Throughput Test-bed	No. of nodes
2	5000 second	4.285 Mb/s	6.42 Mb/s	3
3	5000 second	2.068 Mb/s	4.03 Mb/s	4
4	5000 second	1.51 Mb/s	3.6 Mb/s	5
5	5000 second	1.2 Mb/s	1.95 Mb/s	6

Table 4.2 Simulation and experimental data for the six nodes.

The obtained data has been compared with the test-bed data. The comparative graph of the two results is shown below.

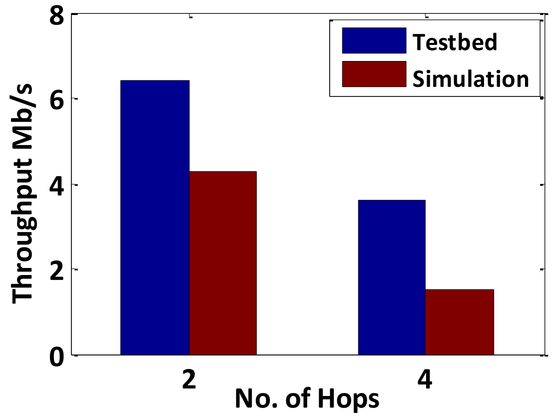

Figure 4.2 Comparison of test-bed and simulation results.

The obtained results of the simulation are shown in Table 4.2. It shows a gradual decrease of the throughput with the increasing number of hops. This is quite obvious due to overhead increment for the increased number of hops. The test-bed result is comparatively higher than the simulation results for every setup. This may be due to the assumptions made during simulations. For example, the channel model in the simulation is not as perfect as the real world. There is also a difference in MAC protocol. The test-bed is using IEEE 802.11 a/b/g/n as a MAC Layer protocol where as the simulator is using IEEE 802.11 a/b/g, and due to this we are getting little less throughput. The key point is that we are concerned about the trend of the graphs. The decreasing trend of the throughput in simulation strongly supports the test-bed implementation of AODV-UU. As this research is done for making a real world application of AODV-UU at the sensor nodes for the SG application, it can be said that the obtained data and the trend of the graphs strongly supports the AODV-UU for real world application. Moreover, this simulator is suitable for the scalability testing of AODV-UU for large scale scenario.

4.2 Scalability Test of AODV-UU in Large Scale SG Scenario Using OMNET++

4.2.1 String Scenario

In this part of the thesis we have tested the scalabilities of the nodes by using the same parameters as the six nodes and the obtained data is shown below. The simulation is conducted with the AODV-UU in OMNeT ++.

Figure 4.3 Scalability of nodes in the string scenario.

The obtained data is shown in table 6.1 in appendices 1 and the plotted graph of the throughput (i.e. Mb/s) is shown in Figure 4.4.

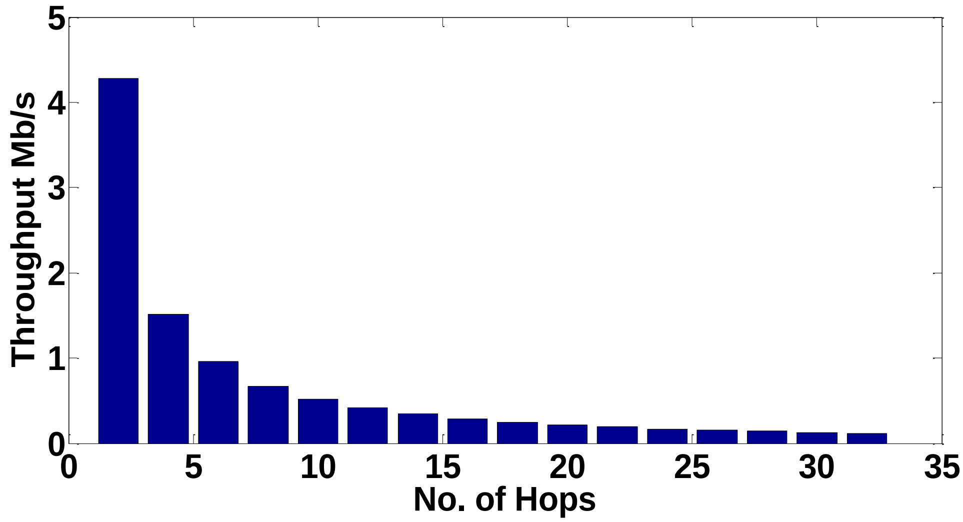

Figure 4.4 Variation of throughput with network size.

The result shows a decreasing trend of throughputs as the number of hops between source and destination increases. We used maximum 33 nodes for this test. In the simulation environment, the distances between the nodes are set in such a way that the transmitted signal is only received by the neighbouring nodes. As the number of hops increases the overhead increases, and the throughput starts decreasing. In this simulation, IPV4 is integrated with the system, and it has a hop limitation of thirty two (32), thus, practically this is not feasible to send data at a distance more than 32 hops. We need to make another routing request after thirty two hops, if we want to test AODV-UU for more than 32 hops.

4.2.2 **Grid Scenario**

In this part of the thesis, we have tested the scalability of the AODV-UU in grid scenario. We used several grid set up. These are 10 nodes (i.e. 5 x 2 nodes), 20 nodes (5 x 4), 30 nodes (5x 6), 40 nodes (5 x 8), and 50 nodes (5 x 10) grid.

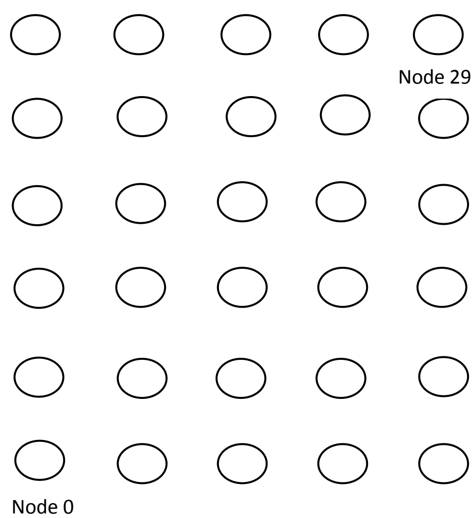

Figure 4.5 A Grid scenario of 5 x 6 (30) nodes.

The grid setup of nodes is shown in Figure 4.5. We are sending data from node 0 to node 29, and measuring the throughput between them. The simulation parameters are the same as in the string scenario. The measured throughput for various set ups with the grid scenario is shown in Table 4.3 below.

No. of Nodes	**Throughput Mb/s**
10	0.5863
20	0.136
30	0.0364
40	0.00979
50	0.004977

Table 4.3 Throughput with various numbers of nodes in grid scenario.

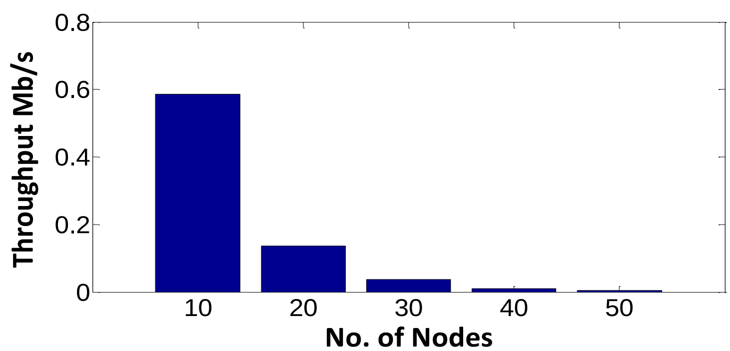

Figure 4.6 Throughput with various numbers of nodes in grid scenario.

The noticeable point in Figure 4.6 is that there is an abrupt decrease of the throughput as the number of nodes increases. In the string scenario the decrement slope of the throughput is less than the grid scenario, and it can be said that performance of AODV is better in string topology compared to grid topology.

4.3 Modified AODV-UU for SG Application

In this section we investigated AODV-UU and modified AODV-UU for both string and grid topologies

4.3.1 String Scenario

A string scenario of thirty three nodes has been used for AODV-UU and modified AODV-UU. The simulation parameters for this network are chosen as shown in Table 4.4

Simulator	OMNET++
Protocol	AODV-UU
Simulation Duration	5000 second
Number of Nodes	33
Model	String Topology
MAC Layer Protocol	IEEE 802.11 b/g

Table 4.4 Simulation parameters of modified AODV-UU.

In case of modified AODV-UU, we added extra intelligence (i.e. they will have long time route caching ability) to every fifth node of the string.

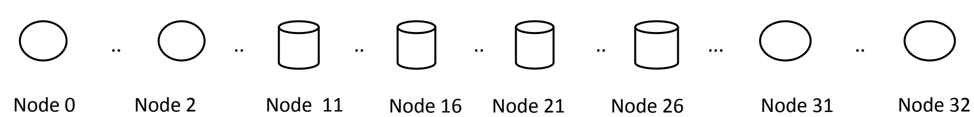

Figure 4.7 String scenarios of thirty three nodes (thirty two hops).

At first, we started the PING application between Node 0 and Node 32. This application will make a route from source to destination. This PING application is operated for 20 seconds, and delay is measured between Node 6 and Node 31. A UDP application is started at 50s in order to ensure that the route has expired in all the nodes. The default active route time (ART) of AODV-UU is 20s. We need to make the node intelligent for retaining the route. Every fifth node is made to retain the route, so that we can save route setup time. After running the PING application, we have retained the route information of the Node 11, 16, 21 and 26 for comparatively longer period. This has been done by keeping the route table entry for these nodes and the route information of all the other nodes expires with the default ART. Now, the delay is measured between node six and node thirty one.

The test is conducted by running two applications one after another. The first one, PING application is operated to make the route, and the second one is conducted to set up the route within a short time, and to measure the delay. Without intelligence, the average delay between Node 6 and 31 is 1.3739 seconds. After applying intelligence, the average value of the delay is 1.2341 seconds. This is a significant decrease of delay for the twenty five hop (26 nodes) string network. After introducing the intelligence, the average delay is decreased by 10.17%.

No. of nodes	**Delay without Intelligence**	**Delay with Intelligence**	**Percentage Decrease of delay**
26	1.3739s	1.2341s	10.17

Table 4.5 Delay in string scenario.

4.3.2 **Grid Scenario**

This simulation is conducted for measuring delay in a grid scenario with and without intelligent nodes. The obtained delay between Node 2 and 12 without intelligence is 0.0444168 seconds and with intelligence is 0.0400365 seconds. This shows a clear 9.86% decrease in delay with the adaption of intelligence to some nodes.

No. of nodes	**Delay without Intelligence**	**Delay with Intelligence**	**Percentage Decrease of delay**
11	0.0444168s	0.0400365s	9.86

Table 4.6 Delay in grid scenario.

5 Conclusion and Future Work

The smart grid is expected to provide the opportunities of better control, configuration and management of the power system. As an SG is a network of a large number of nodes the bidirectional information flow among the wireless nodes is a prime need to get maximum output. Therefore, an effective routing protocol is needed to maintain an efficient information flow in SG. In this thesis, we analyzed different aspects of AODV-UU routing protocol for SG. For a small scale scenario, we have compared the throughput of AODV-UU in a real-time test-bed set up with the throughput obtained from the simulation environment in OMNet++. The simulation result shows a close trend of throughput with the test-bed result. The scalability of AODV-UU has been tested in a large scale string scenario, and it shows that the throughput of the network is decreasing exponentially with the increment of the number of nodes in the effective route. The result also reveals that AODV-UU is scalable up to thirty two hops. We have also tested the throughput of AODV-UU in a grid scenario. In grid scenario, the throughput decreases more rapidly than the string scenario. It is evident that AODV-UU performs better in the string scenario compared to the grid scenario. This thesis also contains a modification of AODV-UU where some nodes are provided more intelligence than the rest of the nodes. This modified AODV-UU shows a lower latency than the regular AODV-UU, and it can be a useful strategy for any SG practical application.

Future works can be done by implementation of the modified AODV-UU on the test-bed scenario or in industrial application. SG is considered as a large network with the interconnected nodes. It needs delay efficient routing protocols for the better performance and the modified AODV-UU is one of the ways to decrease the latency. Moreover, AODV protocol exchanges regular HELLO messages with the neighboring nodes, and as the SG topology is semi static this regular exchange of HELLO messages can be reduced. This reduced HELLO message slots can also be used for data transfer thus increasing throughput.

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Appendix

1.

No. of Hops	**Throughput(Mb/s)**	**No. of nodes**
2	4.28	3
3	2.06	4
4	1.51	5
5	1.2	6
6	0.96	7
7	0.8	8
8	0.674	9
9	0.5911	10
10	0.524	11
11	0.468	12
12	0.421	13
13	0.38	14
14	0.35	15
15	0.32	16
16	0.29	17
17	0.276	18
18	0.256	19

19	0.239	20
20	0.225	21
21	0.212	22
22	0.20	23
23	0.189	24
24	0.178	25
25	0.170	26
26	0.163	27
27	0.157	28
28	0.150	29
29	0.144	30
30	0.139	31
31	0.133	32
32	0.128	33

Table 6.1 Simulation data for the thirty three nodes 32 hops.

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