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Date : 11th Nov 2013

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UNIVERSITI TEKNOLOGI PETRONAS

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DECLARATION OF THESIS

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Date : 11th NOV. 2013

Date : 11-11-2013

DEDICATION

I dedicate this work to my beloved **parents** along with my four loving **sisters.**

ACKNOWLEDGEMENTS

First and foremost, I am greatly thankful to Allah the Almighty for bestowing His countless blessings on me and giving me strength and courage for successful completion of this research work.

I would like to express my deepest gratitude and appreciation to my Supervisor Dr. Low Tang Jung who gave me opportunity to carry out this research work. He was always there whenever I needed him. He gave me complete freedom to try out new ideas and continuously supported me throughout this research. The following quote describing best leader always reminds me of him "A leader is best when people barely know he exists, not so good when people obey and acclaim him, worse when they despise him....But of a good leader who talks little when his work is done, his aim fulfilled, they will say: We did it ourselves ". I particularly appreciate his great patience for deeply reviewing my research papers and Thesis.

I am also grateful to members of my symposiums evaluation panel, Dr. Halabi Bin Hasbullah and Dr. Baharum Bin Baharudin, for their useful comments. They gave me instructive suggestions for improving this research work throughout the two years.

I am greatly thankful to Internet Society for granting me Fellowship to attend IETF 86th meeting (USA, March'13) which gave me opportunity of lifetime to discuss my research findings with inventors of ad-hoc routing protocols. Special thanks to Mr. Charles E. Perkins (author of AODV routing protocol) and Mr. Fred Baker (Former IETF Chair) for sharing their valuable knowledge and giving me handful directions for this research work.

I am grateful to Universiti Teknologi PETRONAS (UTP) Malaysia for financially supporting me through their Graduate Assistantship program and also to COMSATS Institute of Information & Technology (CIIT) Pakistan for providing me this opportunity of study at UTP.

I wish to thank my friends and colleagues especially my housemates Arslan and Irfan for their valuable support and great friendship. I am equally thankful to my close friend and colleague, Omer Chughtai, for reviewing my Thesis and helping me whenever I got stuck in work.

Last but not least, I am thankful to all anonymous reviewers especially those of International Journal of Distributed Sensor Network for reviewing this work and giving me valuable suggestions and expert opinion for improving quality of this research work.

Thank you everyone!

ABSTRACT

Smart grid is a modern version of power grid which utilizes integrated communication network for enhanced power generation, transmission, distribution and consumption. Smart metering infrastructure is one of the core components of smart grid paradigm in which smart meters in addition to their primary billing functions serve as distributed sensor nodes for enhanced grid's reliability. Smart metering communication network makes available the power usage related measurements of the customers to electricity companies in real time for greatly enhancing the planning, operation and outage response of the grid.

Recently, there has been great interest from research community on multi-hop wireless ad-hoc network based implementation of smart metering communication network. Routing protocol design of ad-hoc networks is challenging field as each ad-hoc network deployment has specific requirements depending upon the network resources and concerned application. Based on literature survey consolidated with preliminary simulations, it was concluded that among the two types of ad-hoc routing protocols, reactive protocols perform better then proactive ones with AODV recommended for resource constrained smart metering infrastructure. However AODV protocol design, like many other ad-hoc routing protocols, has limitation of single routing metric (minimum hop count) for route selection which could overload or deplete network resources along selected paths.

To overcome this, multiple metrics based ad-hoc routing protocol “ETL-AODV” is proposed in this thesis which considers residual energy, traffic load and link quality of the nodes during route discovery phase. The associated route discovery and route management phases of the proposed ad-hoc routing protocol are designed for reliable, energy efficient and light weight routing in smart metering communication network. The proposed protocol is implemented in Network Simulator (NS-2) and its performance is compared with AODV routing protocol. Simulations are grouped into three studies for observing the effect of individual metric, node's density and inter meter distances. Based on simulation results analysis, it is concluded that proposed protocol achieves increased packet delivery ratio, reduced energy consumption and minimal routing overhead for ad-hoc network deployment of resource constrained smart meters.

ABSTRAK

Grid pintar ialah suatu grid tenaga versi moden yang menggunakan rangkaian komunikasi yang disepadukan untuk penjanaan, transmisi, pengagihan dan penggunaan kuasa. Infrastruktur meter pintar ialah salah satu komponen utama paradigma grid pintar di mana meter pintar dengan fungsi pengebilan primernya merupakan nod sensor agihan untuk kebolehpercayaan lanjutan grid. Rangkaian komunikasi meter pintar membuat pengukuran penggunaan tenaga elektrik pelanggan kepada syarikat bekalan elektrik tersedia dalam masa sebenar, serta meningkatkan perancangan, operasi dan tindak balas gangguan tenaga grid tersebut.

Kebelakangan ini, komuniti penyelidikan memberi perhatian tinggi kepada rangkaian ad-hoc wayarles multi-hop yang melaksanakan rangkaian komunikasi meter pintar. Reka bentuk protokol penghalaan rangkaian ad-hoc merupakan bidang yang mencabar kerana setiap kerahan rangkaian ad-hoc mempunyai keperluan khusus yang bergantung kepada sumber rangkaian dan aplikasi yang berkaitan. Berdasarkan penyelidikan sorotan kajian yang digabungkan dengan simulasi awalan, ia boleh disimpulkan bahawa di kalangan dua jenis protokol penghalaan ad-hoc, protokol reaktif beroperasi dengan lebih baik daripada protokol proaktif dengan AODV yang disyorkan untuk infrastruktur meter pintar dengan sumber terkekang. Akan tetapi, reka bentuk protokol AODV, seperti kebanyakan protokol penghalaan ad-hoc yang lain, mempunyai pengehadan metrik tunggal penghalaan (kiraan minimum hop) untuk pilihan penghalaan yang boleh membebankan atau menyusutkan sumber rangkaian di sepanjang laluan terpilih.

Untuk mengatasi keadaan ini, metrik pelbagai berdasarkan protokol penghalaan ad-hoc "ETL-AODV" dicadangkan dalam tesis ini, dan protokol ini mengambil kira sisa tenaga, beban trafik dan kualiti rangkaian nod, semasa peringkat penemuan laluan. Peringkat penemuan dan pengurusan laluan berkaitan protokol penghalaan ad-hoc yang dicadangkan telah direka untuk penghalaan yang ringan dan penggunaan kuasa yang efisien serta boleh dipercayai untuk rangkaian komunikasi meter pintar. Protokol yang dicadangkan dilaksanakan dalam Simulator Rangkaian (NS-2) dan prestasinya dibandingkan dengan protokol penghalaan AODV. Simulasi dikategorikan kepada tiga kajian untuk menyelidik kesan metrik individu, kepadatan nod dan jarak antara meter. Oleh itu, berdasarkan analisis hasil simulasi, protokol yang dicadangkan mencapai peningkatan nisbah penghantaran paket, pengurangan penggunaan tenaga dan overhed penghalaan yang minimum untuk kerahan rangkaian ad-hoc dengan sumber terkekang meter pintar.

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LIST OF ABBREVIATIONS

NETL	National Energy Technology Laboratory
NAN	Neighborhood Area Network
CPU	Central Processing Unit
AODV	Ad-hoc on Demand Distance Vector routing protocol
NIST	National Institute of Standard and Technology
SCADA	Supervisory Control And Data Acquisition
RTU	Remote Terminal Unit
HAN	Home Area Network
WAN	Wide Area Network
AMI	Advanced Metering Infrastructure
PLC	Power Line Communication
IEEE	Institute of Electrical and Electronics Engineers
RF	Radio Frequency
NS-2	Network Simulator version 2
IETF	Internet Engineering Task Force
DSDV	Destination-Sequenced Distance Vector routing protocol
OLSR	Optimized Link State Routing Protocol
DSR	Dynamic Source Routing Protocol
RREQ	Route Request packet
ZRP	Zone Routing Protocol
DADR	Distributed Autonomous Depth-first Routing
ID	Identification number
RPL	Routing Protocol for Low-Power and Lossy Networks
TORA	Temporally-Ordered Routing Algorithm
MANET	Mobile Ad-hoc Network
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
RFC	Request For Comments

RREP	Route Reply packet
RERR	Route Error packet
IP	Internet Protocol
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TCL	Tool Command Language
SNRT	Signal to Noise Ratio Threshold
WLAN	Wireless Local Area Network
IR	Infrared
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Ppectrum
PHY	Physical Layer
MAC	Media Access Control layer
CBR	Constant Bit Rate
PDR	Packet Delivery Ratio
NRL	Normalized Routing Load
ETL	Energy, Traffic Load and Link Quality factors
GIS	Geographic Information System

CHAPTER 1

INTRODUCTION

This chapter starts with Introduction and later leads to the background on smart metering infrastructure. Then motivation is discussed for developing an Ad-hoc routing protocol for smart metering infrastructure. Problem statement and Objectives to be accomplished for this research are also presented here. Finally this chapter concludes with the research approach and organization of the thesis.

1.1 Introduction

Electricity consumption is expected to be an ever increasing issue. Electricity demand is increasing twice as fast as overall energy used and is likely to rise at least 73% by 2035 [1], [2], [3]. Our increasing dependence on electricity is stressing the power grid [4] and, as a result, power outages have grown from being infrequent interruptions to becoming a serious liabilities to the economy. According to National Energy Technology Laboratory (NETL) report, US loose $100 billion per year due to power outages which accounted to approximately 1% of national economy output [5]. Prevalent aging electric infrastructure designed decades ago needs to be upgraded so that it is more resilient and efficient. Smart grid is the modern version of power grid which incorporates communication among constituent entities of power grid for enhanced power generation, transmission and distribution. Smart grid transforms the traditional power grid into an intelligent network of interconnected devices with inter-communication ability for improving services. Many countries have started deploying smart grid networks on experimental basis and have achieved tremendous results [6].

One of the important issues in smart grid paradigm is the design of communication network for providing energy efficiently and for a reliable communication in smart meters with their data collectors. This vital component, also referred to as Neighborhood Area Network (NAN- Figure 1.1), consists of large number of low cost metering nodes communicating with single data collector in outdoor environment. In addition to electricity meters, gas and water smart meters may also utilize this network for propagating their readings. The nodes of this network may have limitations in terms of CPU processing power, memory and battery life. A data routing protocol is thus essential for efficiently forwarding collected energy usage statistics of consumers to the data collector. Wireless ad-hoc network is being rapidly deployed for intercommunication of smart meters. Smart meters in the form of radio nodes are organized in mesh topology wherein metering data is relayed to backend control grid by multiple hops. Each ad-hoc network deployment requires specific routing protocol depending upon constituent network nodes, topologies, environmental factors and target goals. Thus, a design of dedicated ad-hoc routing protocol to be fully aware of the peculiar characteristics of smart metering network is imperative to the success of smart grid.

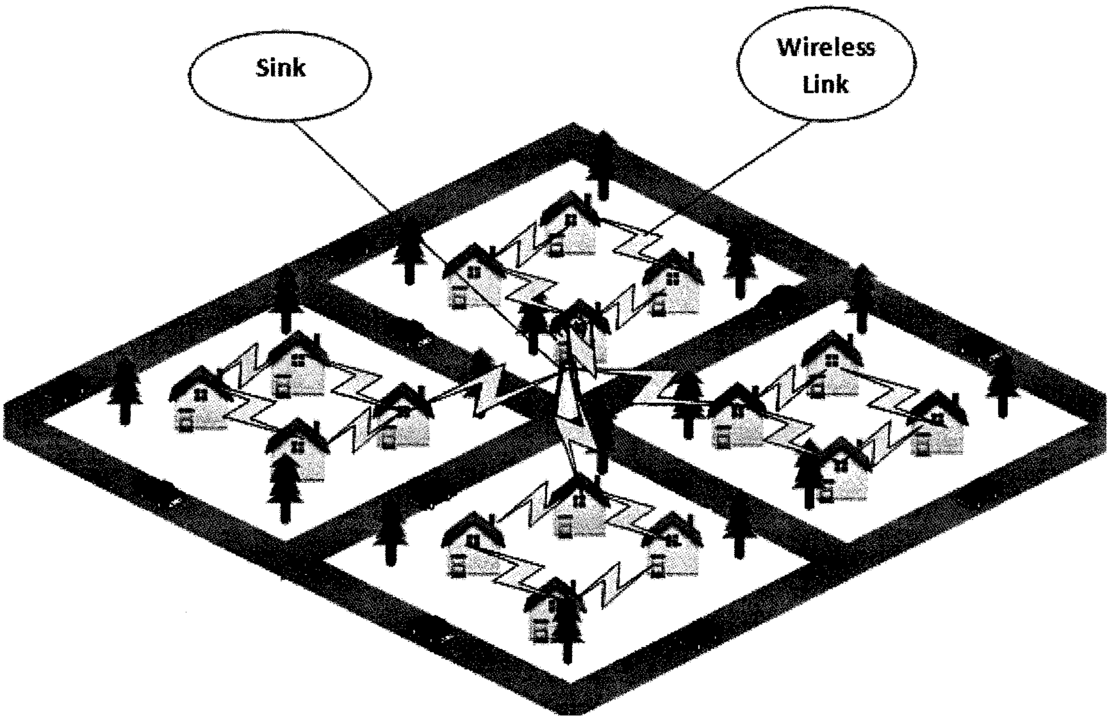


Figure 1.1: Neighborhood Area Network (NAN)

In this thesis, an ad-hoc routing protocol called Energy, Traffic load and Link quality aware ad-hoc routing protocol (ETL-AODV) is proposed by keeping in mind the low energy consumption and limited storage capacity of the metering node as well as deteriorating effects of fading in outdoor communications. Literature survey and preliminary simulation results have indicated that Ad-hoc On-demand distance vector routing protocol (AODV) is most suitable for resource constrained nodes. However, minimum hop count routing criterion, which is the spirit of most existing ad-hoc routing protocols, can overload and deplete network resources in the selected routes of the smart metering network. To overcome this, a technique for considering energy, traffic load and link quality along with the hop count during routing decision is thus been proposed and implemented. The proposed protocol is aware of energy consumption, traffic load, and the link quality of the nodes. Moreover, it offers flexibility to accommodate the heterogeneity of the nodes (battery powered / non-battery powered) during route selection process. Simulation results showed that improved performance is achieved in terms of packet delivery ratio, routing overhead and energy consumption of the smart metering nodes.

1.2 Smart Grid

The revolutionary concept employed in smart grid is the two way communication between electricity suppliers and consumers at appliances/meter level. It enables the suppliers to monitor power usage among the consumers to make smart decisions related to power saving. Home appliances can also communicate with the smart grid to optimize power consumption. Smart grid is capable to turn appliances off during peak hours and turn them on when the load is low. In addition, many new services such as time of usage based billing can be utilized [7]. Such a modernized interconnected electricity network is considered necessary for addressing the ever increasing electricity load demand.

The entire electric grid comprises of three main subsystems namely generation, transmission and distribution. Conceptual model of smart grid, created by National institute of standard and technology (NIST) [8], is shown with modification in Figure 1.2 wherein secure communication exists among smart grid entities along with the electrical power flow. In contrast, the existing electric grid is monitored by a very outdated communication system consisting of computer assisted SCADA system. It is composed of Remote Terminal Units (RTU) to collect data at transmission and distribution level linked with the SCADA system [9]. This system is not fully autonomous and required human assistance. This network was designed decades ago and is inefficient to meet current load requirements. Load fluctuations during peak hours adversely affect this ageing grid. Today, a much more intelligent and autonomous electric grid is required to utilize integrated communications for high efficiency and uninterrupted power supply to the consumers.

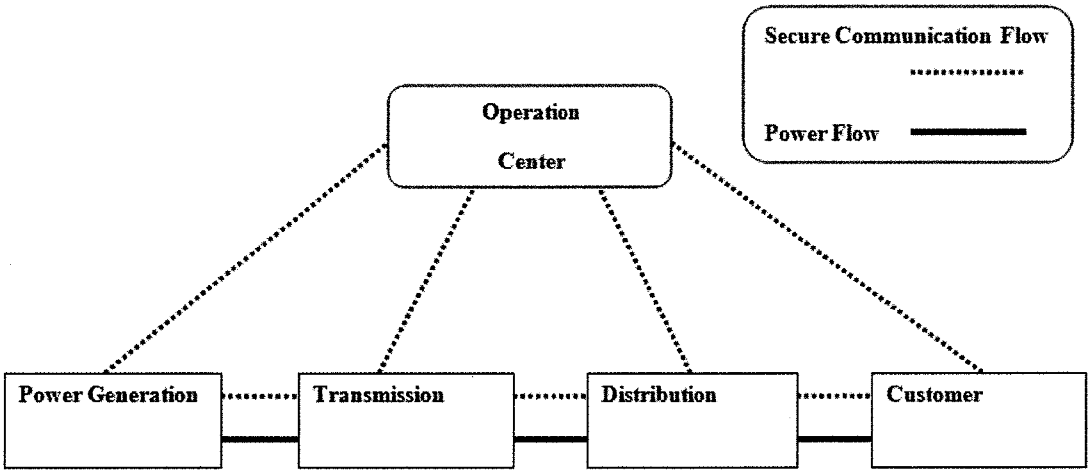


Figure 1.2: Smart Grid Conceptual Model

1.2.1 Smart Grid Communication Network

It is envisaged that design of communication network will be a fundamental challenge for the smart grid deployment. Hierarchically, smart grid communication network is composed of three parts [10]:

1.2.1.1 Home Area Network (HAN)

The Home Area Network belongs to the customer domain and comprises of home appliances and sensors. These devices report their power usage information to the smart meter which in turn forwards it to the central grid. The preferred medium of communication for HANs is wireless communication (such as ZigBee [11], [12]) since it offers flexibility in terms of plug and play and, moreover, a large number of home appliances will be uneconomical for in house wiring. The Home Area Networks can span for area of thousands of square feet and has small data rate requirements in the order of 1-10 Kbps.

1.2.1.2 Neighborhood Area Network (NAN)

The main role of Neighborhood Area Networks is to make possible the communications of smart meters with backend control center. The NANs are deployed in outdoor environment and may consist of hundreds of smart meters. NANs connect the smart meters with gateways (collector) to relay the metering data. The coverage area of NANs is in order of 1-10 square miles and has relatively higher bandwidth requirements of around 10 - 1000 Kbps. Both the wired (Power Line Communications) and Wireless (Cellular, Ad-hoc Mesh Network, WiMax) communication mediums are considered for NANs. However there is no specific smart grid specification in this respect.

1.2.1.3 Wide Area Network (WAN)

The Wide Area Networks connect several NANs with the backhaul network. Gateways or Collection points are located on poles to collect Data from metering nodes of NANs and forward them to the grid control center. The coverage area is much higher in terms of thousands of square miles. Likewise, Date rate requirements are in the order of 10 - 100 Mbps. Communication technologies such as 3G Cellular, WiMAX and Optical Fibers are chosen for deploying WANs.

Having described these three types of ANs above, the focus of this thesis is on Ad-hoc routing in Neighborhood Area Networks (NANs) only.

1.3 Smart Metering Infrastructure

Smart Metering Infrastructure, also known as Advanced Metering Infrastructure (AMI), is the core component of smart grid paradigm which makes possible two way communication between consumers and electricity suppliers at meter level. Smart meters, in addition to their traditional billing operations, serve as communication nodes monitoring and updating power usage statistics to the grid control center. This information is very critical for electricity suppliers as it is used for efficient power generation and distribution. Electricity supplying companies can have real time view of load/demand and can preemptively bolster the grid against interruptions leading to improved reliability in its operation.

1.3.1 Smart Metering Advantages

Although smart metering has numerous advantages, the important ones include:

- Accurate metering data is available in real time by which losses can be timely detected and addressed.
- Efficient load balancing to increase utilization of the grid for better investment in power generation, transmission and distribution.
- Availability of Power Quality Information leads to improvement of performance of the grid.
- Efficient energy consumption for reducing carbon emissions footprint.

1.3.2 Smart Metering Infrastructure Communication Methods

Wired and Wireless are two prevalent communication technologies for Smart Metering Infrastructure [13].

1.3.2.1 Wired based metering communications

Power Line Communication (PLC) is commonly used in wired mode of communication for inter communication of smart meters. Its main advantage is the use of existing power lines as means for communication leading to less deployment cost. However, PLC suffers from low data rates issue which becomes prominent in case of large number of metering nodes. Increase in data rates require expenditure on associated equipment. Power Lines are frequently disrupted from harmonics and transients which disturbs the communication medium. This communication medium becomes unavailable during power failures.

1.3.2.2 Wireless based metering communications

Wireless communication is considered to be a key enabler technology for smart metering communications. It refers to several options such as IEEE 802.11, IEEE 802.15.4, RF Mesh, IEEE 802.16 and 3G/4G. One of the most attractive characteristics of wireless medium is the absence of physical connection between nodes thus requiring minimal deployment cost and management. This ensures continued connectivity even in the case of power failures. Another advantage is availability of high data rates for metering applications.

1.3.3 Ad-hoc Network Deployment of Smart Meters

Ad-hoc (Infrastructure less) networks have been considered a promising candidate for smart metering deployment. Smart meters, with their wireless, capability can transmit their own data as well as can forward other meters readings to the collector in multi-hop manner. This leads to less transmission requirements and a more self configuring network. Routing in ad-hoc networks has attracted attention of numerous researchers, however not many works have been done in specific to smart metering deployment. AODV (Ad-Hoc On Demand Distance Vector) routing protocol is a well researched Ad-hoc routing protocol and is considered very suitable for Mobile Ad-hoc Networks and Wireless Sensor Networks. AODV is also utilized by Zigbee protocol stack in HAN communications.

In fact, Smart Metering Infrastructure represents a specific kind Ad-hoc network deployment with large number of nodes in static topology. Smart meters are usually low power, low cost devices operating in harsh outdoor environments. Furthermore, smart meters utilize batteries for various functions and backup scenarios. Smart meter deployment in ad-hoc model is currently an exciting new research area. This thesis is focusing on improving ad-hoc routing for smart meter network in terms of reliability and energy efficiency.

1.4 Motivation

Belonging to a developing country, Pakistan is currently facing serious electricity crisis of all times [14]. This has naturally intrigued this researcher to do research in the emerging field of smart grids. Load shedding of over 18 hours is being observed [15] which has severely affected the economy of the country and causing chaos to the daily lives of its people. The operation of the current power grid is inefficient where demand fluctuation can strain the power grid during peak hours posing reliability, quality and availability issues. The current grid mostly relies on non-renewable resources leading to environmental and resource scarcity issues. The existing communication network for the smart grids is inadequate and covers only generation and transmission segments. Lack of real time monitoring at Distribution segment has brought the country to a point where demand has largely exceeded the supply. The speed and capacity of the installed communication network is not able to cope with the future growth of smart grid applications.

Smart metering, under the umbrella of smart grid concept, is a low cost self manageable emerging technology designed for improving power grid in terms of reliability, economics, efficiency, environment, security, and safety [16]. Ad-hoc network is a low cost, scalable and self configuring type of network which is being considered a potential candidate for deployment of wireless smart metering applications. Ad-hoc networks require specific attention to routing domain due to their peculiar characteristics. Ad-hoc network for smart meters is a new concept and many issues related to data routing needs to be addressed. Classical ad-hoc routing protocols need to be explored for smart metering applications and this is the key motivation of this research project.

1.5 Problem Statement

Minimum-hop count routing is the spirit of most existing ad-hoc routing protocols. But minimum-hop count routing is not always the best available solution which may result in an unstable, power waste, low packet delivery path [17].

Energy is considered to be the most valuable asset for resource constrained Ad-hoc networks such as Wireless Sensor Networks. This factor limits the overall lifetime of the network. Electricity smart meters are usually powered by mains lines. However, Gas and Water smart meters run on batteries for their operation [18],[19]. Batteries are also responsible for backup purposes such as during the line cut. In multi-hop networks, energy of a node can be depleted quickly if it gets involved in many transmissions, such as the one closed to the sink and the source. Thus node's energy status needs to be taken into consideration during route selection operation.

Ad-hoc networks have a special characteristic that nodes are not only sender and receiver but they are also involved in forwarding the data of their neighboring nodes. This feature can overload some metering nodes such as the ones closed to the sink as they will be selected in most of the multi-hop routes. The overloading of nodes is a source of traffic congestion that can severely degrade smart metering network's performance.

Smart metering nodes deployed in ad-hoc model are inexpensive devices with low cost radios for communication. These nodes when deployed in outdoor environment are often susceptible to route breaks due to link quality fluctuations and shadowing effects. Furthermore, routing over short path with a weak link quality is more harmful as compared to relatively longer path with a strong link quality. This is due to large number of retransmissions thus degrading the performance. Stability of a route depends on the quality of the link that can be determined from the received signal strength. It is desirable to choose route with high quality for ensuring maximum packet delivery ratio.

Neglecting aforementioned parameters during route formation has a deteriorating effect on smart metering (Ad-hoc) nodes particularly those that are closer to the sink (readings collector) as they are involved in most of the multi hop transmissions leading to fast energy depletion and traffic congestion. All of these concerns call for an efficient and reliable ad-hoc routing protocol for smart metering network which considers these constraints in routing decision. Most of prior work on multi-hop networks relied largely on single routing metric e.g. either the hop count, energy level or the link quality metric. The limitation of single routing metric for guiding path selection has a side-effect of overloading and depleting the resources along the selected path.

Therefore, a new on-demand ad-hoc routing protocol is needed with multiple routing metrics in such a way that residual energy, traffic load, link quality and hop count metrics are considered altogether during route formation for enhancing smart metering network's performance.

1.6 Research Objectives

Based on the above mentioned problems, the aim of this thesis is to design an ad-hoc routing protocol for smart metering network to provide reliable, lightweight and energy efficient routing. In this context, the objectives can be outlined as follow:

1. To study existing well known Ad-hoc routing schemes (Reactive and Proactive) in finding the best applicable scheme for ad-hoc network with smart meters.

2. To analyze the issues and problems associated with the selected Ad-hoc routing scheme with respect to Ad-hoc network comprises of smart meters.

3. To propose a new ad-hoc routing protocol for reliable, light weight and energy efficient routing in smart meter ad-hoc network.

4. To evaluate the performance of the proposed protocol through rigorous simulations.

1.7 Research Approach

This research starts off with literature review of the existing well known ad-hoc routing protocols to find out which ones can be best applicable to ad-hoc network of smart meters. Open Source Network Simulator (NS-2) is chosen as simulation platform and detailed understanding of simulator syntax and functions is developed. The protocols are then simulated in NS-2 to consolidate findings from literature survey.

The literature review has led to the finding of AODV as the most suitable approach for smart meters deployed in ad-hoc network model. After which, issues associated with AODV when used as routing protocol for smart metering infrastructure are analyzed critically.

Route discovery and selection procedure of AODV are modified such that a route is established with nodes having maximum energy level, minimum traffic load and highest signal strengths. The modified ad-hoc routing protocol is implemented in Network Simulator NS-2 and simulations are conducted using the real world housing topologies to assess its performance. The overall research approach can be expressed as in Figure 1.3:

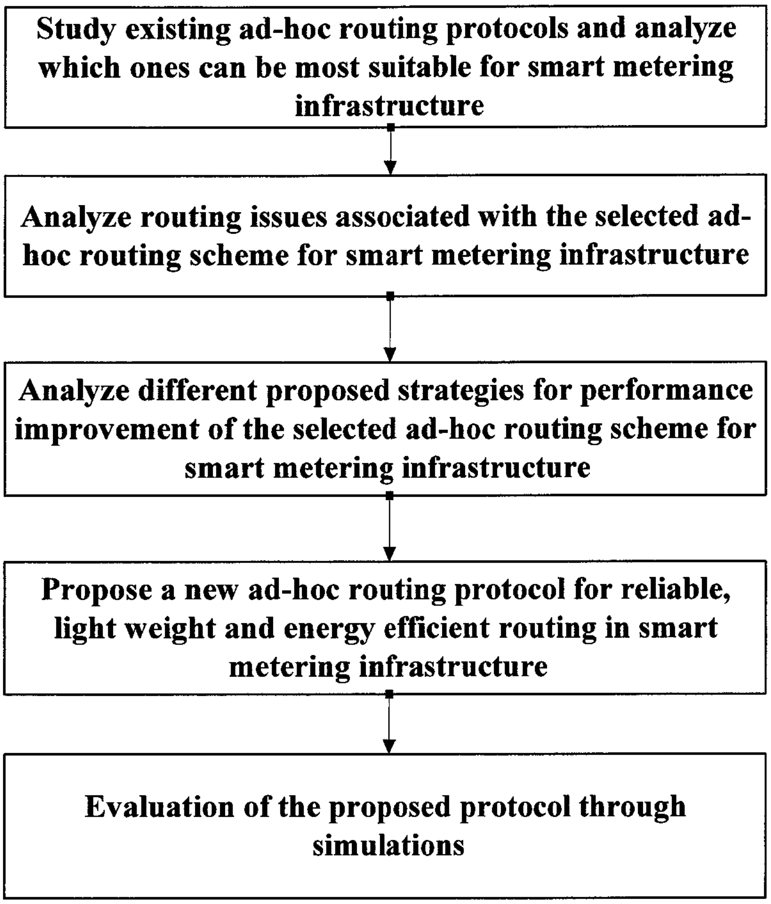


Figure 1.3: Research Approach

1.8 Thesis Organization

This thesis is organized into five chapters arranged as thus: Chapter 2 presents overall background of smart metering deployment in ad-hoc network model. Detailed review of existing well known ad-hoc routing protocols is presented and their performance is analyzed in the scope of smart metering scenario. Issues associated with routing are also discussed and literature survey of existing works on performance improvement of ad-hoc routing is presented.

Chapter 3 presents the complete methodology of the proposed ad-hoc routing protocol. The proposed protocol is presented and explained in detail with help of flowcharts, examples and pseudocode.

Chapter 4 presents the simulation results. It starts with description of simulator used and simulation settings. Simulation results for the performance of the proposed protocol are presented in the form of three simulation studies and critically analyzed in detail.

Chapter 5 presents the conclusion of the research work in conjunction with the key contributions of the research and the future research directions.

List of our publications for this research work is also attached at the end of this dissertation.

1.9 Summary

This chapter presents basic overview of this thesis covering the fundamentals like general introduction, motivation, problem statement, objectives, research approach and thesis organization.

CHAPTER 2

BACKGROUND KNOWLEDGE AND LITERATURE REVIEW

This chapter presents background knowledge and discusses the related works relevant to this research. The chapter starts with basics of ad-hoc networks focusing on routing domain. Literature survey findings and comparative analysis of ad-hoc routing schemes in the scope of smart metering infrastructure is also discussed. After which, AODV protocol and routing issues relevant to smart metering deployment are highlighted. Finally, related works in making AODV be aware of Energy consumption, Traffic Load and Link Quality are described.

2.1 Ad-hoc Networks

Ad-hoc networks are a class of communication networks operating without any infrastructure or centralized control. The nodes of such network function as routers by forwarding packets of their own and of neighboring nodes. The nodes organize themselves in distributed reconfigurable topologies.

The main advantage of ad-hoc networks is cost effectiveness. Ad-hoc networks work without any support of infrastructure and eliminate the need for base stations. This effectively reduces the deployment cost since the costs of installation, operation and maintenance of network equipment is eliminated. Additional investment is not required in the event of network expansion. The ad-hoc network provides ease in network deployment and management. The ad-hoc network nodes can adapt to topology changes and effectively re-route messages in case of node failures. Ad-hoc networks exhibit robustness due to redundancy and lack of single point of failure which is highly desirable for low cost applications [20].

2.1.1 Properties of Ad-hoc Networks

Ad-hoc networks have the properties of conventional wireless networks but also possess some unique properties. These distinct properties of ad-hoc networks need to be considered when designing, deploying and analyzing the performance of the stationary or mobile ad-hoc networks ([21], pg 204-220). These distinct properties are:

a) Multi hopping

Instead of direct communication links, the packets in ad-hoc networks traverse several nodes (hops) from source to destination. This multi-hop characteristic is beneficial for energy conservation, spectrum reuse and obstacle negotiation.

b) Self-organization

The nodes in ad-hoc networks self-organize themselves depending on network requirements. The nodes independently determine their own configuration parameters like routing, addressing, position identification, power control and re-routing in case of node failures.

c) Resource constrained nodes

Most of the ad-hoc networks consist of resource constrained nodes i.e. limited computational capability, low memory capacities and limited power supply. Resource efficient protocol design is thus necessary for optimum performance of the ad-hoc networks.

d) Scalability

In some applications, ad-hoc network can grow in size into several hundred of nodes. Routing in such a large node networks is often a critical challenge in ad-hoc network design.

2.1.2 Ad-hoc Networks Applications

Due to inherent characteristics of re-configurability, low deployment cost and easy network management, ad-hoc networks find themselves in numerous applications such as:

a) Wireless Sensor Network

It is a class of wireless ad-hoc network with nodes as sensors deployed in a specific application domain. Some of the challenges observed in such networks include limited power supply, large number of nodes and harsh deploying environments.

b) Wireless Mesh Network

Ad-hoc networks can be connected with infrastructure networks for increasing communication range. This arrangement leads to cost effective data transfer capability as well as freedom of mobility

c) Vehicular Ad-hoc Network

Ad-hoc networks are being used for intercommunication between vehicles for providing safety and comfort to road users. Vehicles communicate with one another and the infrastructure for averting critical conditions like road accidents and traffic jams.

d) Military Applications

Ad-hoc networks are used for establishing communication among soldiers in battlefields. Ad-hoc networks can be quickly deployed in inhospitable and hostile terrains for assisting military operations.

e) Emergency Operation / Disaster Relief Scenarios

Ad-hoc Networks are very effective in emergency operations such as search and rescue, disaster management and crowd control. The characteristics of self-organization with minimum overhead and quick deployment make ad-hoc networks ideal choice for such scenarios.

2.2 Routing in Ad-hoc Networks

Characteristics such as decentralized control, dynamic network topology, and power and bandwidth limitations make ad-hoc networks very different from conventional infrastructure networks. Hence, routing protocol design becomes extremely challenging for ad-hoc networks. Routing techniques employed in conventional wireless networks are found to be not effective in ad-hoc networks due to variation in radio propagation characteristics, routing overheads and scalability issues etc. A few specialized ad-hoc routing protocols have been developed by the Wireless Group of IETF ([22], pg 642) . On the basis of route formation, ad-hoc routing protocols can be broadly classified as reactive (on-demand), proactive (table driven) and hybrid.

2.2.1 Proactive (Table Driven) Routing Protocols

These class of ad-hoc routing protocols are considered to be extension of wired networks routing protocols wherein each node keeps a table of routes to every other node in the network. These routing tables contain entries such as distance to other nodes as well as the next hop entry for each destination node. These routing tables need to be updated periodically to maintain accurate and consistent routing information. Any topology change is propagated throughout the network.

The advantages of proactive protocols include availability of routing information for all the nodes at any given time which leads to less delay in route set up phase. The disadvantages include heavy control overhead due to frequent exchange of topology messages. The bandwidth utilization becomes severe in case of large networks with low mobility or small networks with high mobility. Furthermore, size of routing tables becomes larger for large networks. The issue of stale routing information becomes prominent if routing updates are received with delay ([21], pg 308-310).

Generally, proactive protocols differ from one another based on method of propagation of route changes and number of routing tables used. Common examples include Destination-Sequenced Distance Vector (DSDV) [23] protocol and Optimized Link State Routing Protocol (OLSR) [24].

a) Destination-Sequenced Distance Vector (DSDV) protocol

It is based on Bellman Ford routing algorithm in which each node maintains list of shortest paths and first node in the path to all the nodes of the network. It utilizes sequence numbers to distinguish stale routes from new ones and also to eliminate routing loops.

b) Optimized Link State Routing Protocol (OLSR)

This class of proactive routing protocol utilizes multipoint relaying technique in which only selected nodes broadcast topology information during flooding process. In this way, flooding process is optimized. Route discovery delay is absent as routes are already available due to topology message exchanges.

2.2.2 Reactive (On-Demand) Routing Protocols

On-demand routing protocols set up routes only when source needs to communicate with another node. This is different from proactive protocols where routing information is available at all times. The working of these protocols depend on two steps, namely route discovery and route maintenance phases. The duty of route discovery procedure is to discover route from source to destination. The route maintenance phase is used for validating the routes. In case of stale entries, new route discoveries are initiated.

The advantages of reactive protocols include reduced bandwidth utilization due to absence of periodic exchange of topology messages. However, route discovery procedure suffers from high routing overhead and delay in route set up. Common examples include Ad-hoc On-demand Distance Vector (AODV) [25] and Dynamic Source Routing (DSR) [26] Protocols.

a) Ad-hoc On-demand Distance Vector (AODV)

In AODV protocol, nodes broadcasts route requests packets (RREQs) which are replied back by the destination node or intermediate node if have recently used a route to destination. Nodes keep minimal routing table size with next hop entry for destination. Sequence numbers are employed to ensure loop free routing.

b) Dynamic Source Routing (DSR) Protocols

DSR protocol is a type of source routing protocol in which each packet contains complete path information. Every node updates its route cache with path information contained in the packet when it passes through it. Due to source routing, routing overhead is proportional to path length ([21], pg 320).

2.2.3 Hybrid Routing Protocol

Hybrid protocol combine features of both table driven and on-demand routing protocols. Common example includes Zone Routing Protocol (ZRP) [27]. In ZRP, nodes define routing zone around each node which utilizes proactive routing while routing between zones is done using on-demand method. As a result, control overhead is reduced along with the latency due to route discovery procedure.

2.3 Literature Survey on Ad-hoc Routing in Smart Metering Infrastructure

As ad-hoc smart metering deployment is relatively a new technology so not much research works have been done in this area. Geleen et al. [28] proposed wireless mesh routing protocol for smart metering infrastructure. The protocol uses proprietary format optimized for limited number of communication nodes. The protocol works in on-demand mode where source nodes communicate with the concentrator nodes (sink) when required. The node first tries to send packet directly to destination node and waits for acknowledgement. If it failed then route search is initiated in flooding manner as in the case of On-demand routing protocols. Each intermediate node on receiving search packet updates its ID in packet's route list. The destination node on receiving search packet waits for a small time and sends back acknowledgement packet. This protocol has limitation in terms of supporting limited number of nodes due to packet route list field as in case of source based routing protocols.

Another work is the DADR (Distributed Autonomous Depth-first Routing) [29] which is a proactive distributed distance vector routing protocol for coping with changing link conditions and implemented for Advanced Metering Infrastructure (AMI) applications. The protocol utilizes periodic exchange of HELLO packets (containing routing table information) between neighboring nodes. In case of link failures, protocol reroutes the packets through alternate paths (at the most K possible paths for each destination) using modified depth first search algorithm guided by routing tables. Each data packet contains unique frame ID (FID) and each data forwarding node keeps a separate FID table (data structure) for each packet to avoid loops. The protocol increases CPU and memory overheads of intermediate nodes due to additional state in data forwarding phase. Loops might occur when acknowledgement packets are lost or when FID table is deleted too early.

RF mesh based communication system is proposed and simulated in [30] for outdoor smart metering infrastructure where metering nodes transmit their data in predefined allotted slots on different frequency channel according to frequency hopping sequence. Routing between the nodes is done using geographical routing. Simulation results utilizing geographical maps indicate the protocol performs reasonably well for large number of nodes deployment. However, it requires the providing of geographical coordinates of collector to each metering node during commissioning.

A Hybrid Routing Protocol (Hydro) [31] is a link state routing protocol proposed for low-power and lossy networks such as in wall plug meters. Directed Acyclic graph is utilized to build multiple routes to border routers. Nodes uses default route to send packets to border router and maintain link statistics. Nodes periodically piggyback top ranked entries of default table in the form of topology reports on frequent data traffic to border router which in turn have global view of the network. After this, triangle routing occurs with source node forwarding data to the border router which in turn sends it to the destination using source routing. By using link state database, border router then uses route install message to optimize point-point routing between nodes. This source routing can be a large overhead for networks with large number of nodes such as in the case of smart metering network which may require many hops to reach the destination.

The work in [32] has compared performance of upcoming RPL (Routing Protocol for Low power and Lossy networks) and Geographic routing protocol for wireless sensor network based smart metering infrastructure. According to simulated results, both protocols perform reasonably well for this smart metering scenario. However RPL is still in development stage and its field experience is not available and unreliable links can cause storm of trickle timer resets. On the other hand, geographic routing protocol requires additional network configuration stage to program nodes' coordinates in their memories.

Proactive protocols optimize routing delays at the expense of bandwidth and power consumption while On-demand routing protocols are considered to perform better in situations where power and bandwidth limitations are a concern ([22], pg 647). Many research publications are available for comparative analysis of ad-hoc routing protocols such as in [33] where authors compared performance analysis of proactive (DSDV, OLSR), reactive (AODV, DSR) and hybrid (TORA) ad-hoc routing protocols for wireless sensor networks and concluded AODV always performed better with single or multiple sources. Similarly, in [34] authors concluded AODV is more energy efficient than OLSR but has higher average end-to-end delay for large number of hops. AODV outperformed OLSR in terms of mobility support. Similarly in [35] authors found AODV has better packet delivery ratio but consumes more energy than DSR. Table 2.1 and 2.2 summarize findings of the research works discussed so far.

Table 2.1: Existing ad-hoc routing protocols for smart metering infrastructure

Existing Research Work	**Issues**
Wireless Mesh Communication Protocol for Smart Metering [28]	The protocol is designed for minimum number of communication nodes due to packet route list field as in source based routing protocols
DADR Protocol [29]	Utilize periodic exchange of HELLO messages (containing Routing Table) between neighboring nodes. The protocol increases CPU and memory overheads of intermediate nodes due to additional state in data forwarding phase. Protocol suffers from routing loops in some scenarios.
RF Mesh System [30]	Requires providing geographical coordinates of collector to each metering node during commissioning
HYDRO Protocol [31]	Source routing can be a large overhead for networks with large number of nodes such as in case of smart metering network
RPL and Geographic Routing for Smart Metering Application [32]	Still in development stage and field experience is not available and unreliable links can cause storm of trickle timer resets. Geographic routing protocol requires additional network configuration stage to program node's coordinates in nodes memory

Table 2.2: Performance analysis of AODV in MANETS

Research Work	Protocols for Comparison	Result
[33]	AODV, DSR, DSDV, OLSR, TORA	AODV always performs better with single or multiple sources
[34]	AODV, OLSR	AODV is more energy efficient but has higher average end-to-end delay
[35]	AODV, DSR	AODV has better packet delivery ratio but consumes more energy than DSR.

In literature, these protocols have been compared in mobile ad-hoc networks (MANETS). Very few studies did performance analysis of ad-hoc routing protocols in the context of smart metering deployment where the nodes are static. One author of [36] did a very detailed comparative analysis of ad-hoc routing protocols in smart metering deployment. Three protocols AODV, DSR and DSDV were chosen to provide comparison between reactive and proactive protocols for smart metering. Auckland city's Mt Eden suburb was chosen as the basis for generating the topologies. The performance comparison was based on sixteen individual combinations of four propagation models (namely Friis, Two Ray Ground, Rayleigh fading and Shadowing), two transport layer protocols (TCP and UDP) and two operating frequencies (900 MHz and 2.4 GHZ). Moreover, the effects of variation in meters density, inter meter distances, data rate and data packet size and self healing were also analyzed. It was concluded that AODV and DSR (On-demand) ad-hoc routing protocols outperforms the DSDV (table-driven) protocol. Hence AODV and DSR protocols are recommended for implementing smart meter networks based on the IEEE 802.11 standards with AODV being the better choice of the two.

As a preliminary study and to consolidate literature findings, this research did comparative analysis of proactive, reactive and hybrid ad-hoc routing protocols for smart metering scenario [37]. Five common ad-hoc routing protocols AODV, DSR, DSDV, OLSR and ZRP were simulated in NS-2 for smart metering scenario. Three different flat grid topologies (number of nodes 25, 50 and 75) were simulated with the objective to determine which kind of ad-hoc routing protocol (reactive, proactive and hybrid) will be most suitable for smart metering deployment. All of the metering nodes were configured to send data packet to the sink node in periodic interval of 1 minute and the simulations were run for one hour. From simulation results and after quantifying the performance of the protocols based on metrics of data delivery ratio, energy consumption, delay and routing overhead, it was found that AODV and DSR (Reactive Protocols) showed satisfactory performance as compared to DSDV, OLSR (Proactive) and ZRP (Hybrid) for smart metering deployment with AODV best suited for resource constrained smart meters. Please refer to Appendix A for details on this preliminary study. Table 2.3 summarizes these research works.

Based on above findings, AODV was chosen as base routing algorithm for this research work.

Table 2.3: Comparative studies of ad-hoc routing protocols in scope of smart metering deployment

Research Work	**Protocols for Comparison**			**Recommended Protocol**
	Proactive	Reactive	Hybrid	
[36]	DSDV	AODV, DSR	-	AODV
[37]	DSDV, OLSR	AODV, DSR	ZRP	AODV

The following features explain why AODV is suitable for smart metering ad-hoc deployment:

- Due to its reactive nature, periodic exchange of topology message is eliminated leading to reduced bandwidth utilization which becomes prominent with large metering nodes in the network.
- Routes to destination are determined on demand where routing paths are discovered depending on the usage of those paths.

- Small routing table size with only next hop entry is maintained for destination. This feature is beneficial for memory constrained smart meters such as gas and water smart meters.
- Self-healing characteristics in the event of routes or nodes failures.

These features of AODV offer great potential for it to be chosen for our network structure. However, AODV has a limitation in terms of higher delay in route discovery phase. Fortunately, smart metering network is composed of static nodes with relaxed latency requirements so this limitation can be compromised for the advantages gained.

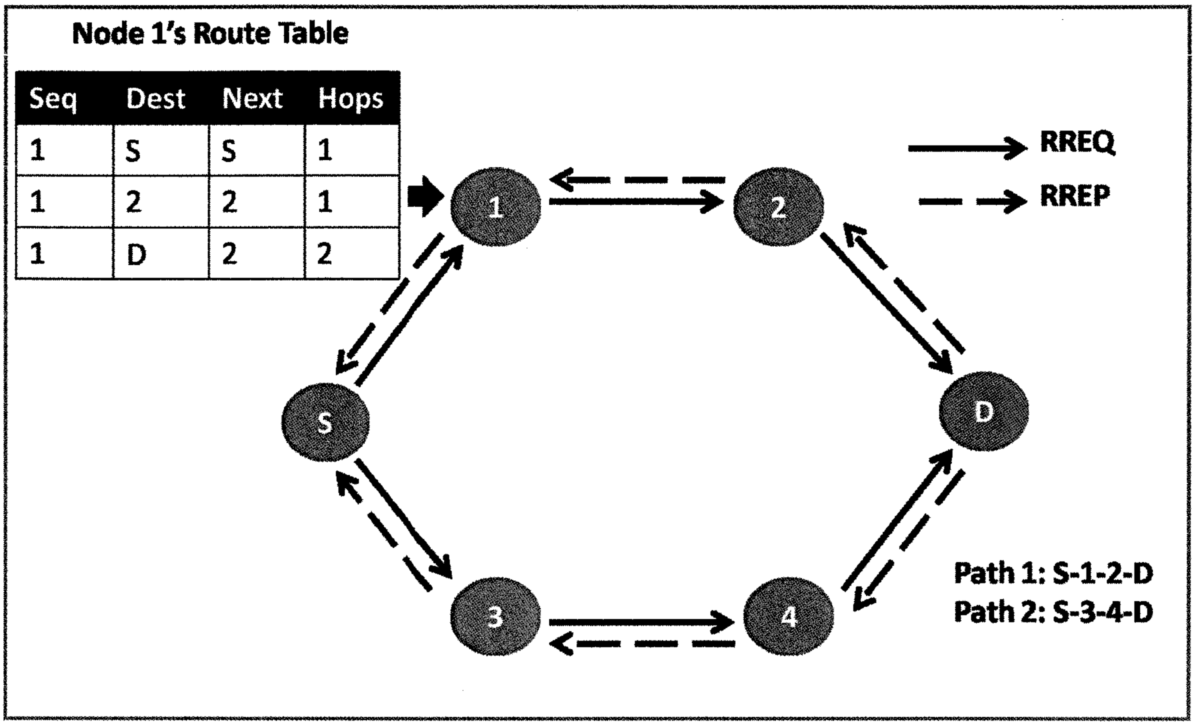
2.4 Ad-hoc On-demand Distance Vector (AODV) Routing Protocol

AODV has the following main control packets as defined in RFC 3561:

- Route Request (RREQ): This control packet is broadcasted by the node when it needs to find a route to destination. All neighboring nodes within its communication range receive this RREQ packet. On reception, neighboring node set up reverse route entry to the source from which RREQ originated.
- Route Reply (RREP): This control packet is sent by destination node or intermediate nodes if they have valid route to destination.
- Route Error (RERR): This control packet is sent by the node to its neighboring nodes indicating loss of link.

When a node needs to send a packet to destination, it refers to its routing table. If route is already present then source node simple forwards the packet along the recorded route. On the other hand if no route is present then route discovery procedure is initiated in which source node broadcasts RREQ packets to its neighboring nodes. Nodes receiving RREQ packets set up backward pointer to source node in routing tables. In addition to source node's sequence number, IP address and Broadcast ID, RREQ packets contain the most recent sequence number for the destination. Those intermediate nodes having route to destination with sequence number greater than or equal to that enclosed in RREQ packet, respond back to the originator of RREQ packet by replying with RREP packet. Otherwise, intermediate nodes rebroadcast RREQ packets. Moreover, nodes keep track of RREQ's IP addresses and Broadcast IDs and discard duplicate RREQ packets. In this way RREQ packet continue to propagate until it reaches the destination. The destination node replies back to the first received RREQ packet with RREP packet. As the RREP packet propagates back to source node, intermediate nodes forwarding RREP set up forward pointers to destination node in routing tables. On reception of RREP packet by the source node, route is set up. Later if source node receive RREP with greater sequence number or with same sequence number but with smaller hop count then it updates its routing table and use fresh route.

In AODV, a route is considered active and is used as long as data packets travel through it periodically from source to destination. Once source node stop sending data through an active route, the link will time out and eventually route is deleted from intermediate node's routing tables. If a link breaks for an active route then node upstream of the link-break propagates RERR packet back to source node to notify it about unreachable destination. Source node then initiates new route discovery. AODV is simple minimal routing protocol which maintains information for next hop for each destination in routing table instead of complete path.


Node 1's Route Table

Seq	Dest	Next	Hops
1	S	S	1
1	2	2	1
1	D	2	2

Figure 2.1: Route Discovery in AODV

Figure 2.1 represents typical AODV route discovery procedure. In this scenario, node 'S' needs to send data to node 'D'. It broadcasts route request packet (RREQ) for the node 'D'. When node 'D' receives RREQ, it replies back with route reply (RREP) packet. As a result of route discovery, node 1 caches routes to nodes 'S' , '2' and 'D' in its routing table.

2.5 Need for Improvement in AODV for smart metering deployment

AODV was designed for mobile ad-hoc networks (MANETS) where nodes are mobile and objective of routing algorithm is to form shortest routes on demand. Wireless ad-hoc network is application oriented so different applications determine different network topologies and routing design practices. Most of the classical ad-hoc routing protocols such as AODV are based on hop count routing criterion. However, shortest path does not always yields optimal path.

Douglas S. J. De Couto et al. [17], utilized two experimental wireless networks, one indoor and one outdoor, to access the performance of minimum hop count routing algorithms in multi-hop networks. DSDV was chosen as routing protocol and it was concluded that usually multiple minimum hop count paths, available in the network, have poor throughput. Consequently, minimum hop count routing often chooses paths that have less capacity than the best paths that exist in the network. Route with minimum hop count route has least number of hops from source to destination and is considered shortest. However, such long links may be unreliable and prone to link failures. In such cases, sufficient channel capacity is consumed in retransmissions. It was concluded that *shortest path routing metric is not sufficient and inconclusive for multi-hop networks performance analysis/measurements*.

Batteries play an important role in determining the lifetime of a battery powered smart metering ad-hoc network (water and gas smart meters as well as sensor nodes attached to smart meters [18], [19]) so energy state of the nodes should be considered during a route formation. Utilizing the shortest path all the time can cause congestion in that path thus lowering packet delivery ratio. Furthermore, frequent route breaks may occur due to low signal strength paths.

Hence, it is needed to improve routing criterion of AODV in scope of smart metering deployment. The next section reviews related works on modifying routing metric of AODV.

2.6 Prior Works on Improvement of AODV Routing Metric

Prior works on improvement of AODV routing metric relies largely on single routing metric. This section describes the review on metrics related to energy, traffic load and link quality as follow:

2.6.1 Based on Energy Metric

M. Veerayya et al. [38] proposed energy aware ad-hoc routing protocol (SQ-AODV) based on AODV algorithm. As per the authors, a key to enable Quality of service (QoS) in ad-hoc networks is to find routes that have high probability to live for the duration of the session. The routing criterion used in SQ-AODV is Average Energy Drain Rate (AEDR) which is computed by averaging the Energy Drain Rate (EDR) of nodes using exponential averaging function. The EDR is computed as difference between energy of nodes at periodic intervals divided by the length of the interval. During Route Discovery phase, intermediate node on receiving RREQ checks whether its residual energy based on current AEDR can sustain the duration of the application session. The session is only granted if that is the case. If session duration is unknown then session is granted if residual energy is greater than threshold. Bottleneck lifetime field of RREQ is updated. Destination node selects route with maximum life-time of bottleneck node. The second modification proposed is *make-before-break* approach that is when current energy of the node falls below threshold value then it sends route change request to source node which begins a new route discovery procedure. Simulation results indicated improved packet delivery ratio, packet delay, routing overhead and node expiration time as compared to AODV protocol.

Yonghui Chen et al. in [39] stated AODV does not consider energy of nodes during route discovery process leading to network partition. The authors proposed EEAODV protocol that selects a route which has nodes with highest residual energies and a large number of neighboring nodes. Each node stores its neighboring nodes in a set according to their residual energies and calculates its neighbor changing rate based on energy consumption and mobility of its neighboring nodes. The probability of link failure is increased if such an intermediate node is chosen in route which has higher value of neighbor changing rate. During route discovery phase, intermediate node only forwards RREQ packet if its neighboring changing rate is less than a threshold. Otherwise it discards RREQ packet. Simulation results showed EEAODV has higher packet delivery ratio, increased network lifetime and reduced average end-to-end delay as compared to AODV protocol.

Tie Hieng Tie et al. in [40] proposed Maximum Energy Level Ad Hoc Distance Vector (MEL-AODV) routing protocol which considers overall energy level of nodes during route selection with the fact that the path with highest combined energy will be better to ensure maximum path availability. Each intermediate node on receiving RREQ packet adds its current energy level to accumulative energy field of RREQ packet. The destination node on receiving first RREQ waits for additional 2 to 3 route requests and replies back along path with having the highest energy nodes. Simulation results indicated improved network lifetime and increased packet delivery ratio with MEL-AODV as compared to AODV routing protocol.

2.6.2 Based on Traffic Metric

Li Xia et al. [41] proposed an improved AODV protocol (AODV-I) with congestion control and route repair mechanism of RREQ messages added. The proposed protocol considers traffic load of the intermediate nodes during route discovery based on their buffer occupancy level. On receiving RREQ packet, intermediate node judges its busy level based on this buffer occupancy level. If the node is idle then RREQ will be broadcasted immediately. Otherwise it is broadcasted with some delay time. This is to ensure that RREQ reaches the destination via less loaded nodes. On the other hand if intermediate node has fresh route to destination then it only replies back with RREP if it is idle. During forwarding of RREP messages, if the next hop node becomes unavailable then intermediate node caches RREP packet and broadcasts 1- hop RREQ packet to neighboring nodes. If anyone of the neighboring nodes is idle and has route back to source then it is utilized in the new route formed. Simulation results indicated increased packet delivery ratio and lower latency with the proposed routing protocol as compared to AODV.

YuHua Yan et al. [42] proposed an adaptive load balancing approach for on-demand ad-hoc routing protocols. The authors applied their technique to AODV routing protocol and named it as AODV- LB in which a threshold value is used to determine whether an intermediate node is loaded. The threshold is a variable and is adaptive to network conditions. Each node maintains an average queue occupancy level which is based on its own queue level and also of its neighboring nodes that becomes available through exchange of queue information in HELLO packets. There is a specific field in RREQ packets in which the sum of the average queue occupancy level of nodes along the route is recorded in a cumulative manner. On receiving RREQ packet, each intermediate node calculates its threshold value based on its average queue occupancy level and cumulative average queue value of RREQ packet. If current queue occupancy level of the node is less than threshold then the intermediate node responds to RREQ packets as normal. Otherwise, it drops the packet. Simulation results comparing performance AODV–LB and AODV were presented that showed when traffic load is high then AODV–LB can improve the packet delivery ratios with lower delay. Moreover, traffic load is distributed evenly among the nodes in the network.

The work in [43] proposed a traffic and mobility aware AODV routing protocol called AODVLM. An additional field is appended in RREQ packets in which each intermediate node adds its current vacant queue size into it. The destination node, on receiving multiples RREQs, selects that RREQ which has lowest cumulative vacant queue size. In this way, lower traffic load nodes are utilized in the formation of routes. Instead of transmitting the data through a single path, routes are made to expire after a predetermined period. As a result new efficient routes are determined from time to time which is prominent especially in mobile ad-hoc networks. Comparative analysis of AODVLM with AODV shows improvement in throughput and packet delivery ratio.

2.6.3 Based on Link Quality Metric

San Yuan Wang et al. [44] proposed a signal-strength-base on-demand routing protocol SSOD similar to AODV protocol. The proposed scheme establishes shortest path first and later switches to strongest link paths for longer transmissions. Two fields have been added to RREQ packet i.e. minimum signal strength level and sum of signal strength level across the route. During Route discovery phase, each intermediate node on receiving a RREQ packet shall embeds its signal strength level in the minimum signal strength level field of RREQ if its signal strength is less than the minimum value contained in the packet. Similarly, it adds its signal strength value to the cumulative signal strength level field of RREQ. In this way, the minimum signal strength level fields denotes bottleneck link in the route and the cumulative fields indicate all links present in the route. The destination node, on receiving first route request, replies back and keeps on receiving RREQ packets. On timer expiry, it replies back a path with strongest links path. Simulation results, considering nodes density, mobility and traffic load indicate signal-strength-base route formation outperforms AODV routing scheme in terms of delivery ratio, throughput and delay.

Ruay-Shiung Chang et al. [45] presented a received signal-strength-base AODV routing protocol AODV-RSS which utilizes received signal strength and received signal strength changing rate to predict link available time (LAT), and construct routes based on minimum hop count and link available time. The received signal strength is larger when nodes are closer. Difference of received signal strength between pair of nodes at two different time instants can indicate relative speed between two nodes. Based on relative speed and distance calculated from received signal strength, the total time for link availability is calculated to denote how long two nodes remain connected. The protocol then chooses routes based on minimum hop count and satisfactory link available time. Simulation results utilizing different LAT constraints suggest AODV-RSS has higher route connection time and lower route re-establishment frequency as compared to AODV.

Jiwan Park et. al. [46] proposed a link quality aware AODV protocol (CM-AODV) which select the routes based on signal-to-interference plus noise ratio (SINR). Eight reserved bits of AODV RREQ packet are utilized to store minimum SINR value of the links. Each intermediate node, on receiving RREQ packet, calculates its SINR value and compares it with the minimum SINR field of RREQ packet. The value is updated if SINR of the receiving node is less then minimum SINR value of RREQ field. In this way, RREQ carries information about the weakest link in the path. Intermediate nodes also forward duplicate copies of RREQ with highest link quality to find multiple robust paths. Destination node sorts the receiving RREQs in descending order of link quality and replies back to all RREQs in a sorted order. Source node on receiving the first RREP establishes primary path and store remaining RREPs as backup paths which shall be utilized when needed. Simulation results indicate CM-AODV outperforms AODV and AOMDV in terms of packet delivery ratio, average end-to-end delay and routing overhead.

2.6.4 Based on Multiple Metrics

Prior work on routing metric of AODV routing protocol relies mostly on single routing criterion. As stated earlier, this approach has the drawback of overloading and depletion of resources along the selected path. To overcome this issue, routing design based on multiple metrics has been proposed recently.

Kapil Kumar et al. [47] proposed an energy and traffic aware routing approach as an extension of AODV. Two additional fields, one for traffic congestion and other for energy consumption were added to RREQ packet. Similarly these two fields were added in routing tables. Nodes calculate their traffic load based on interface queue size and energy level based on residual energy. Nodes embed the above two parameters in RREQ packets along with hop count information and broadcast them. Destination node waits for small time interval and then replies back along a path having nodes with maximum energy, lowest traffic load and minimum hop count. In this work only algorithm is presented and no simulations are provided to assess the performance of the proposed algorithm.

N Thantry et al. [48] proposed an enhanced metric for AODV routing protocol (EM-AODV) which takes into account the signal strength (affinity), bandwidth and energy consumption of nodes during route selection. Three additional fields are added in RREP packet in corresponding to affinity, bandwidth and energy level of the nodes. These three fields along with the source next hop field are added into the routing table of nodes. On top of this, two additional tables 'SNR Average Table' and 'Bandwidth Table' are utilized for storing information about link quality and available bandwidths with neighboring nodes. The destination node replies to multiple RREQs having node-disjoint paths. Each intermediate node, on receiving the RREP, updates the affinity, bandwidth and residual battery fields of RREP packet. Source node, on receiving multiple RREPs, constructs multiple paths to destination and splits the data according to affinity, bandwidth and residual energy of nodes. Furthermore, a route is discarded if residual battery capacity along the path is less than the threshold. Simulations in comparing the performance of EM-AODV with original AODV suggest that improvement is achieved in terms of throughput, route discovery frequency and packet drops. However, simulations show no significant improvement in terms of control overhead, average end-to-end delay and average energy consumption of nodes.

Lijuan Cao et al. [49] proposed a set of protocols based on the multiple metric routing protocol MMRP which combines traffic load, energy consumption and hop count into a single path cost metric. MMRP is based on AODV in which the path cost metric is a linear sum of hop count, traffic load and energy cost. The goal of the routing protocol is to find a route having minim path cost. The priority of individual metric can be set using weight coefficients. Traffic load is determined using exponentially smoothened interval between two received data packets and energy cost is computed using transmission power. Only the destination node is allowed to send RREP. Destination node on receiving the first RREQ waits for a period of time for additional RREQs and replies back along a path with minimum path cost. The authors then proposed extension of MMRP protocol named as MMRP-I wherein intermediate nodes can process the later received RREQs if they have better path cost values. However, there is a tradeoff between overhead and performance that can be balanced in such a way that only those later received RREQs are processed by intermediate nodes whose cost value is greater than previous ones by factor of some pre-determined threshold. Finally MMRP-A is proposed to accommodate heterogeneous devices in the network which assigns coefficients in the composite metric based on device classification. Simulations comparing performance of MMRP-I ,MMRP , load aware routing, energy efficient routing and shortest path routing indicate MMRP-I exhibit better delivery ratio and delay at added cost of overhead and energy consumption. Simulation results for MMRP-A, AODV and energy efficient routing indicate that MMRP-A has higher deliver ratio, lower delay and overhead, with higher remaining energy when at low mobility levels. It is concluded by the authors that the use of multiple metrics for calculating path costs results in improved performance and lower overall resource consumption.

The summary of these works on routing criterion optimization of AODV is given in Table 2.4

Table 2.4: Summary of past work related to routing metric of AODV protocol

Research Work	**Routing Metric Considered**		
	Energy	**Traffic Load**	**Link Quality**
SQ-AODV [38]	Yes	No	No
EEAODV [39]	Yes	No	No
MEL-AODV [40]	Yes	No	No
AODV – I [41]	No	Yes	No
AODV – LB [42]	No	Yes	No
AODVLM [43]	No	Yes	No
SSOD [44]	No	No	Yes
AODV-RSS [45]	No	No	Yes
CM-AODV [46]	No	No	Yes
ETR-AODV [47]	Yes	Yes	No
EM-AODV [48]	Yes	No	Yes
MMRP, MMRP-I, MMRP-A [49]	Yes	Yes	No

2.7 Need for Multiple Metrics Based Routing in Smart Metering Infrastructure

As per literature survey of related work, it is found that most of the work on routing metrics of ad-hoc routing protocols is focused on single metric like either the energy level, the traffic load or the link quality metric. These are aimed at improving the single concerned performance metric at the cost of compromising rest of the metrics. For instance, energy efficient routing design improves energy consumption of the network but is oblivious of routing failures resulting from link breakages and traffic congestion.

Moreover, very few have studied the possibility of considering multiple routing metrics and these too are focused on generic ad-hoc networks. As indicated earlier, each specific ad-hoc network implementation requires dedicated routing protocol design which varies from one scenario to another. What needed is to explore the possibility of using multiple metrics based routing in smart metering infrastructure and analyze its performance.

To best of this literature review, no other research has studied the possibility of utilizing multiple metrics based routing design (specifically considering energy level, traffic load, link quality along with the standard hop count) for performance enhancement of ad-hoc routing protocol in smart metering communication network. Therefore in this thesis, all of the aforementioned parameters have been utilized in routing decision of the proposed protocol for enhanced performance in scope of smart metering deployment.

2.8 Summary

This chapter presented a critical literature review of ad-hoc routing protocols in relation to smart metering deployment. This chapter highlights the background of ad-hoc routing with review on their respective properties and applications. Literature review on comparative performance analysis of existing ad-hoc routing protocols is presented and it is concluded that AODV is the most suitable protocol for resource constrained smart metering deployment. Issues associated with 'hop count' metric are highlighted and existing works on optimization of routing metric of AODV are discussed. It was found that most of the past research works considered only single routing criterion and very few have considered the possibility of using multiple routing metrics in routing decisions. This leads to the proposal of this research to work on considering all three parameters i.e. energy, traffic load and link quality along with hop count for enhancing the routing performance.

CHAPTER 3

ON DEMAND AD-HOC ROUTING PROTOCOL FOR SMART METERING INFRASTRUCTURE

In this chapter, the complete design and working of the proposed ETL-AODV protocol is presented and discussed. The chapter starts with description of network model assumptions and progresses with the description of routing metrics used and the proposed method of combining the metrics into a composite multi routing metric. After that, route discovery and route management phases are discussed in detail and explained with the help of flowcharts and an example. Finally the pseudo code of the complete protocol is presented.

3.1 Network Model and Assumptions

The smart metering infrastructure considered in this research consists of ad-hoc deployment of smart meters. Smart meters can either have built-in wireless transceivers for communication with the data collector or wireless sensor nodes can be attached to ordinary meters. All smart metering nodes send their data to a single data collector of their region. Geographic regions can be divided in the form of 'areas' (i.e. $area_0$, $area_1$....$area_n$) where in each area it consists of group of smart metering nodes associated with distinct data collector of its area (see Figure 3.1). The proposed ETL-AODV protocol runs in each area and the current research work assess the protocol performance in a specific area. In the proposed protocol, the following assumptions are considered:

a) All smart metering nodes in an area have pre-programmed node ID or IP address of the data collector of that area which will be utilized in route discoveries.

b) The data collector is located in the center of the area. All the metering nodes and data collector are static.

c) The battery (energy), communication capabilities, computation, memory and sensing range of all metering nodes is the same i.e. homogeneous node. All smart metering nodes have limited energy source (battery powered) with equal initial energy capacity. The data collector is provided with comparatively higher energy and memory storage resources. Each metering node consumes same amount of power to transmit and receive one bit of data.

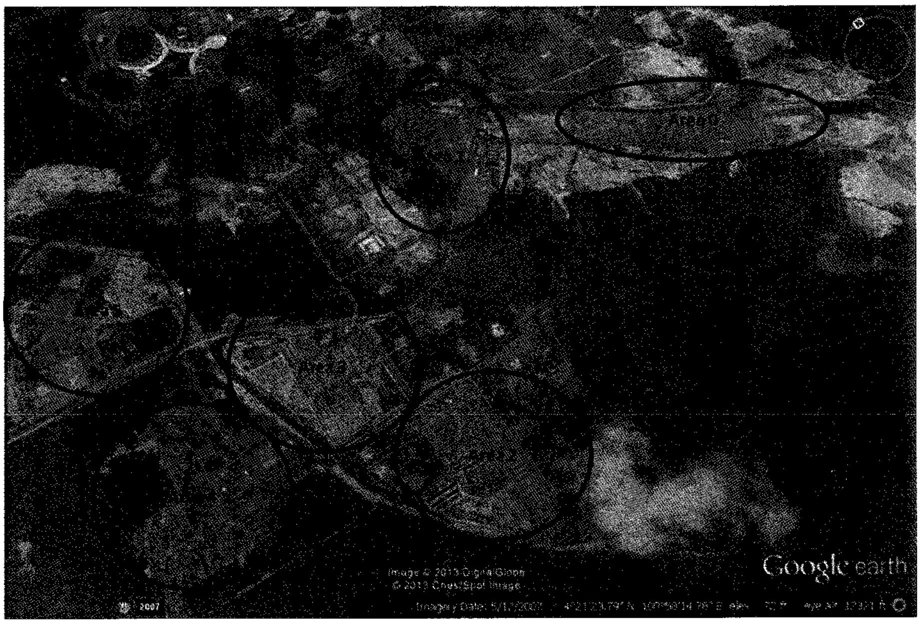


Figure 3.1: Google earth snapshot of Bandar Seri Iskandar (Malaysia) region with conceptual Smart Metering Areas

It is important to note that in our network model, no assumption is made about size of the area and distribution of homes in a specific area. A housing society can be considered as a single area or combination of small areas. The geographic partitioning of a region into different areas is beyond the scope of this research work and may vary with different network vendors. This thesis will assume the network as composed of single area with all metering nodes communicating via a single data collector.

3.2 Routing Metrics

As mentioned in Chapter 2, most of multi-hop routing protocols consider a single routing criterion usually in the form of either the hop count, the energy level, the traffic load or the link quality. Limiting the route selection based on a single criterion can lead to congestion, energy depletion and unstable routes. This research proposed a composite multi metric routing criterion by integrating three parameters as defined in below sections:

3.2.1 Energy Factor

The proposed protocol considers the residual energy of the nodes participating in route discovery procedure with the objective of selecting those nodes which have highest residual energies. This energy factor '*E*' is normalized to [0, 1] scale using Eq. 3.1:

$$E = \frac{E_r}{E_{max}} \tag{3.1}$$

Where 'E_r' is the residual energy of the node determined by the battery of the smart meter and 'E_{max}' is the maximum energy available to the node. Hence, the Energy factor '*E*' will vary in the range of 0 to 1 with 1 indicating full battery level and 0 for dead battery. The aim of the routing protocol is to include all those nodes which have maximum '*E*' factor. E_r, E_{max} and E factors are depicted in Figure 3.2.

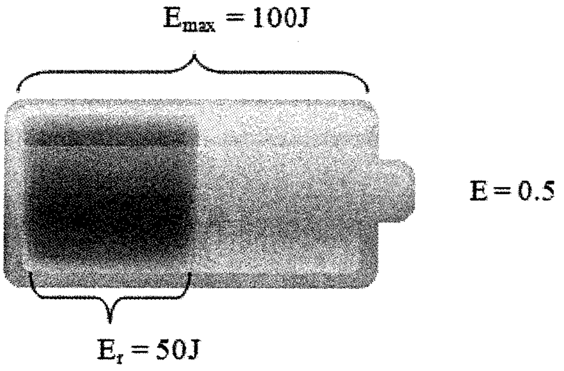


Figure 3.2: Battery model illustrating E_r, E_{max} and E factors

3.2.2 Traffic Load

The Traffic load factor 'T_F' of the nodes is estimated based on the interval between two received data packets. This interval is scaled to the range of [0, 1] with 1 indicating no traffic load and 0 meaning fully loaded node. The objective is to select those nodes for route formation which have lowest traffic load or highest T_F values. Furthermore, this interval is updated using exponential smoothing function (Eq. 3.2) for removing abrupt traffic jitters:

$$T_F = (1 - \beta)\ x\ intvl_{old} + \beta\ x\ intvl_{new} \tag{3.2}$$

where $intvl_{old}$ and $intvl_{new}$ are old and new time intervals respectively and β is smoothing constant in the range of 0 to 1. Value of β close to one has less smoothing effect and more receptive to recent fluctuations while values close to 0 have large smoothing effect with less receptive to recent changes. We have used β as 0.2 in our simulations. This Traffic Load estimation is depicted in Figure 3.3.

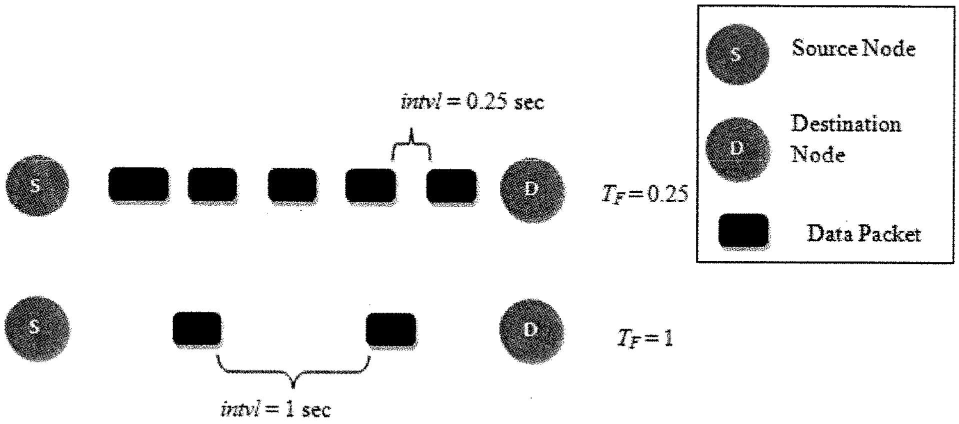


Figure 3.3: Traffic Load estimation

3.2.3 Link Quality

The proposed protocol estimates the link quality based on received signal strength with the objective of selecting highest quality links in the route formation phase. This Link Quality factor 'L_Q' is normalized on [0, 1] scale using Eq. 3.3 as:

$$L_Q = \frac{S_P}{S_{max}} \tag{3.3}$$

where 'S_p' is the signal strength of the packet received and 'S_{max}' is the maximum signal strength possible. In this way, Link Quality factor 'L_Q' will vary in [0, 1] range with 1 denoting strongest link. S_P and S_{max} are illustrated in Figure 3.4.

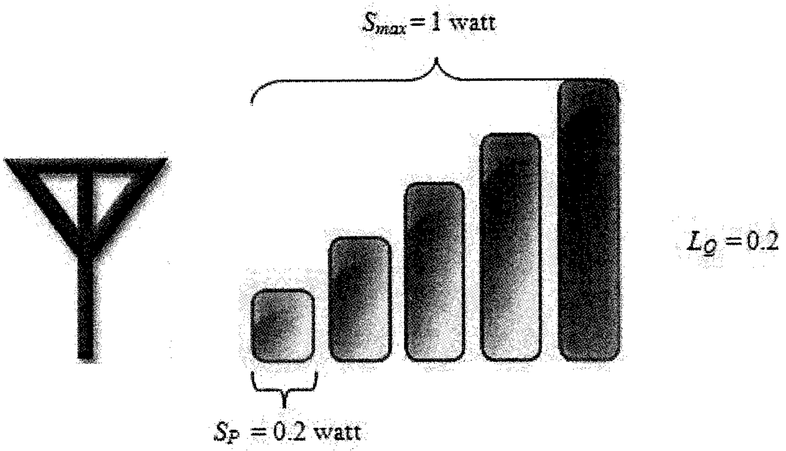


Figure 3.4: S_{max}, S_p and L_Q factors computed for received signal strength

3.2.4 Multiple Metrics Combination

The above mentioned normalized factors i.e. energy, traffic load and link quality are combined into a composite routing metric using linear addition rule. Most of the research regarding multi metric combination follows weighted sum approach (as in case of [48] and [49]) using general linear Eq. 3.4:

$$\sum_{i=1}^{n} \alpha_i \, m_i \tag{3.4}$$

where 'α' is the weight assigned to i^{th} metric 'm' and 'i' runs for all number 'n' number of metrics. In this research, there are three scaled factors (E, T_F, L_Q) which are combined using Eq. 3.5:

$$ETL_{node} = W_E * E + W_T * T_F + W_L * L_Q \tag{3.5}$$

where (W_E, W_T, W_L) are weighted factors for calculating multiple metric value 'ETL_{node}'. Here the priority of three sub metrics can be changed using weighted coefficients. The cumulative sum of the weights (W_E, W_T, W_L) should always be equal to 1 so that ETL_{node} value obtained will be in the range of [0 – 1]. As a result, nodes selected in the route formation phase should exhibit maximum ETL_{node} values.

3.3 Route Discovery Phase

In on demand routing protocols, when source needs to communicate with a node for which it does not have a route, it initiates route discovery phase by broadcasting Route Request Packet (RREQ). One additional field for ETL_{path} is appended in standard AODV RREQ packet (see Figure 3.5). Source node prepares RREQ packet with required entries and broadcast it with ETL_{path} field initialized to 1.

<table>
<tr><td>Type</td><td>Flags</td><td>Reserved</td><td>Hop Count</td></tr>
<tr><td colspan="4">RREQ (Broadcast ID)</td></tr>
<tr><td colspan="4">Destination IP Address</td></tr>
<tr><td colspan="4">Destination Sequence Number</td></tr>
<tr><td colspan="4">Original IP Address</td></tr>
<tr><td colspan="4">Original Sequence Number</td></tr>
<tr><td colspan="4">ETLpath</td></tr>
</table>

Figure 3.5: ETL field appended at bottom of RREQ packet

Each Intermediate node on receiving RREQ packet first checks whether it has already received this RREQ packet before. If yes, it discards the packet, otherwise, it creates reverse route entry to the source node with the last hop as next hop entry in its routing table. After that, it calculates its ETL_{node} value from Eq. 3.5, multiplies it with the accumulated ETL_{path} value carried by RREQ packet and stores it in ETL_{path} field of RREQ packet using Eq. 3.6 as

$$ETL_{path} = ETL'_{path} * ETL_{node} \tag{3.6}$$

where ETL'_{path} is the accumulated values of the previous nodes in the path. As a result, ETL_{node} values of all the nodes in a path get multiplied as follow:

$$ETL_{path} = \prod_{i=1}^{k} ETL_{node} \tag{3.7}$$

here 'i' run for all 'k' number of nodes in a specific path. The product varies in the range of [0, 1]. After this, intermediate node broadcasts RREQ packet. This route discovery phase is illustrated in Figure 3.6.

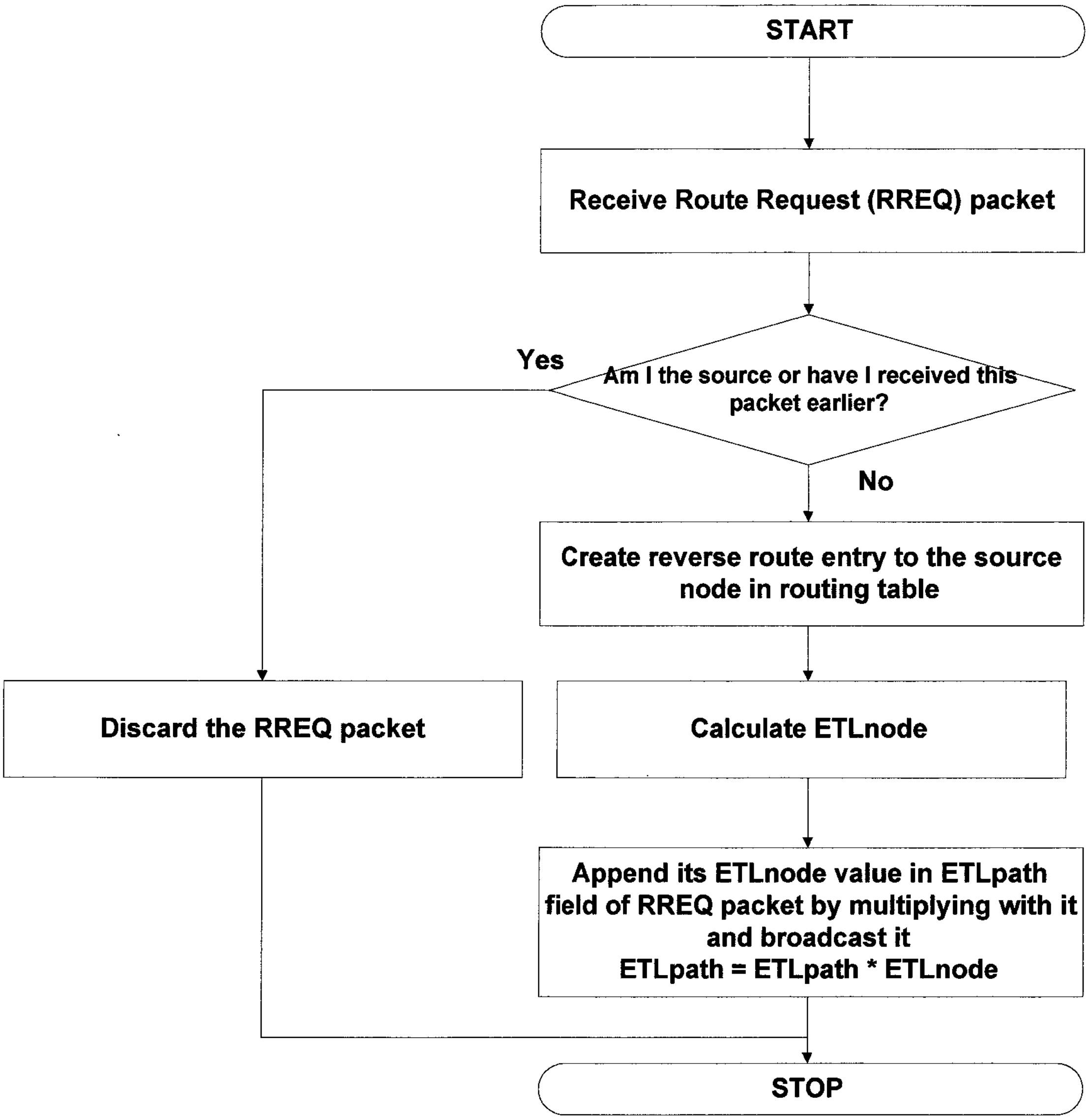


Figure 3.6: Flowchart of route discovery phase for intermediate node

To illustrate this ETL_{path} calculation phase of the protocol, consider a six node Ad-hoc network as shown in Figure 3.7:

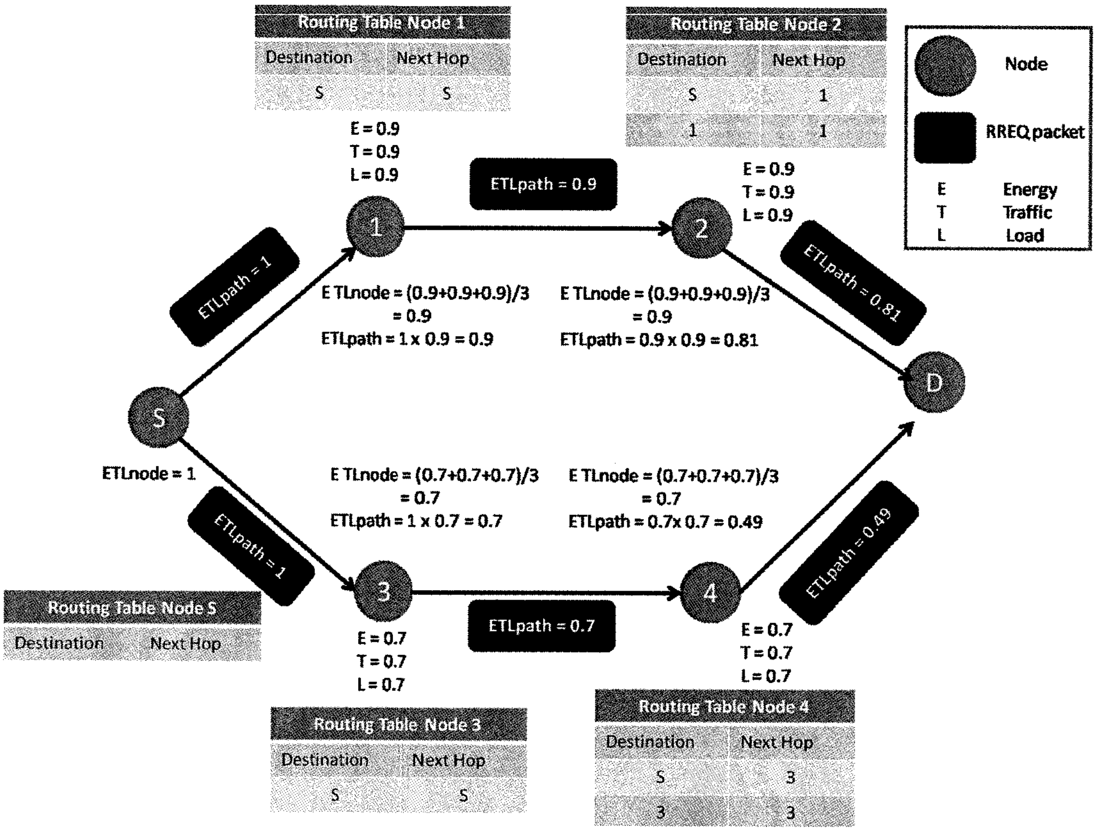


Figure 3.7: Example of six node ad-hoc network in route discovery phase

Node 'S' needs to send data to Destination node 'D' and two paths are available. One via path S-1-2-D and the other via path S-3-4-D. Supposed values for the Energy, Traffic Load and Link quality factors (*E, T, L*) are shown in the figure with nodes in path (S-1-2-D) having relatively better *E, T, L* values. The source node broadcasts Route Request Packet RREQ with ETL_{path} field set to 1. When RREQ packet reaches node 1, ETL_{node} value is calculated using Eq. 3.5 as:

$$ETL_{node} = \frac{0.9 + 0.9 + 0.9}{3} = 0.9$$

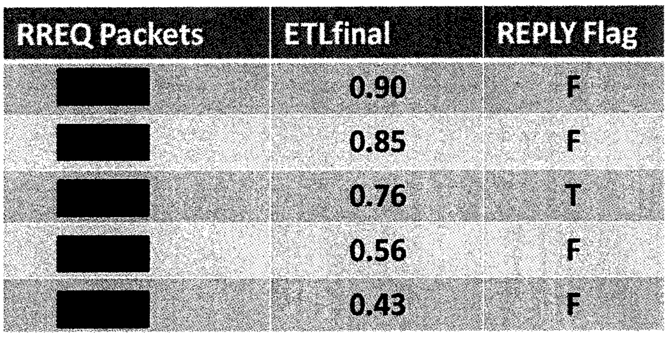
This value is stored in ETL_{path} field of RREQ packet using Eq. 3.6 as:

$$ETL_{path} = 1 * 0.9 = 0.9$$

This RREQ packet is broadcasted again and consequently reaches node 2 where ETL_{node} is calculated and appended in RREQ packet and then broadcasted again. Ultimately, it reaches the destination node 'D'. Similarly, for the RREQ packet traversing the path 'S-3-4-D', these steps are performed at each node and finally the RREQ packet reaches the destination node. Now destination node receives two RREQs packets; one via path (S-1-2-D) with ETL_{path} = 0.81 and the other via path (S-3-4-D) with ETL_{path} = 0.49. Obviously the route S-1-2-D is selected.

3.3.1 Route selection by the Destination node

The main objective of the original AODV routing protocol is to form the shortest path and as such the destination node on receiving first RREQ packet replies back and discards other RREQs which are received later. In the proposed route selection procedure, destination node on receiving first RREQ packet does not reply back instantly (which is most likely to be received via shortest path). Instead, the destination node is to wait for a small amount of time Δt for possible getting routes with better ETL_{path} values. To accommodate the reception of the additional RREQs, the destination node keeps a RREQ cache (see Figure 3.8) in which received RREQs are stored and ultimately flushed down after every *RREQ_PURGE* time interval (set as 6 seconds in our simulations). The REPLY flag is used to keep track which of the RREQ packets currently in RREQ cache have been replied back.



RREQ Packets	ETLfinal	REPLY Flag
■	0.90	F
■	0.85	F
■	0.76	T
■	0.56	F
■	0.43	F

Figure 3.8: Example of RREQ cache

For the destination node, its ETL_{node} value is equal to its Link quality factor. The reason being destination node (sink) is super node and its energy and traffic load are not considered as constraints. Therefore destination node calculates its ETL_{node} value (which is same as its Link Quality factor) and multiplies it with the ETL_{path} value of the RREQ packet to get newer ETL_{path} value using Eq. 3.6.

If the hop count is not used then a case might appear when nodes have unlimited energy supply like electric meters, highest link quality and no traffic load such that *E, T, L* values are all equal to one. In such network conditions, packets traversing long and short routes will have equal ETL_{path} values. Obviously in such a case, shorter routes should be selected to minimize the delays. To accommodate this, destination node evaluates final ETL_{final} values for the route using Eq. 3.7 as:

$$ETL_{final} = w_1 * ETL_{path} + w_2 * HF \tag{3.8}$$

where 'w_1' and 'w_2' are weight coefficients with condition ($w_1+w_2 = 1$) and *HF* is Hop Factor defined in Eq. 3.8 as:

$$HF = \frac{H_{max} - H_{count}}{H_{max}} \tag{3.9}$$

Where H_{count} is the present hop count and H_{max} is the maximum hop count permissible by the protocol. As a result, *HF* will vary in range of [0, 1] with higher values indicating shorter paths. We have chosen w_1 and w_2 as 0.5 so equal weightage is assigned to cumulative *ETL* values and Path length.

The destination node then consults its RREQ cache to check if it has received any RREQ earlier with same source and *Broadcast ID* and larger ETL_{final} value. If that is the case then it just discards the current RREQ packet. Otherwise it starts *RREQ_REPLY* timer, if not started already, and stores RREQ packet in its RREQ cache with *REPLY* Flag as false. It also creates or updates reverse route entry to the source node with last hop as next hop entry in its routing table. In this way, out of all received RREQs for a particular source, only that RREQ is stored in RREQ cache which has maximum ETL_{final} value. This phase is illustrated in figure 3.9.

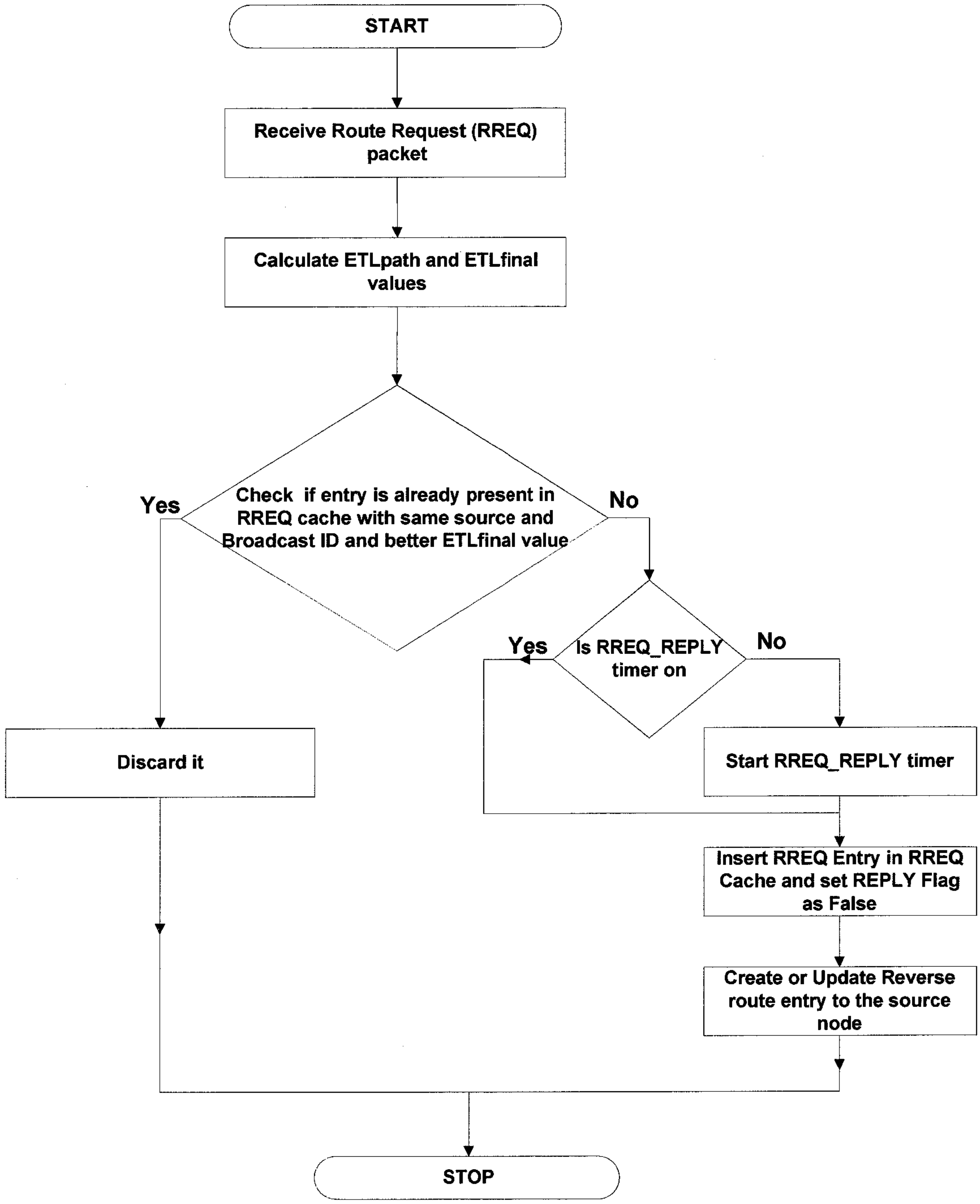


Figure 3.9: Flowchart of route selection phase at destination node

On *RREQ_REPLY* timer expiry (set as 0.1 seconds in our simulations), destination node replies back with RREP packet to all those RREQs stored in the RREQ cache which are yet to be replied (i.e. with *REPLY* Flag as false) and change their *REPLY* flags to true as shown in Figure 3.10.

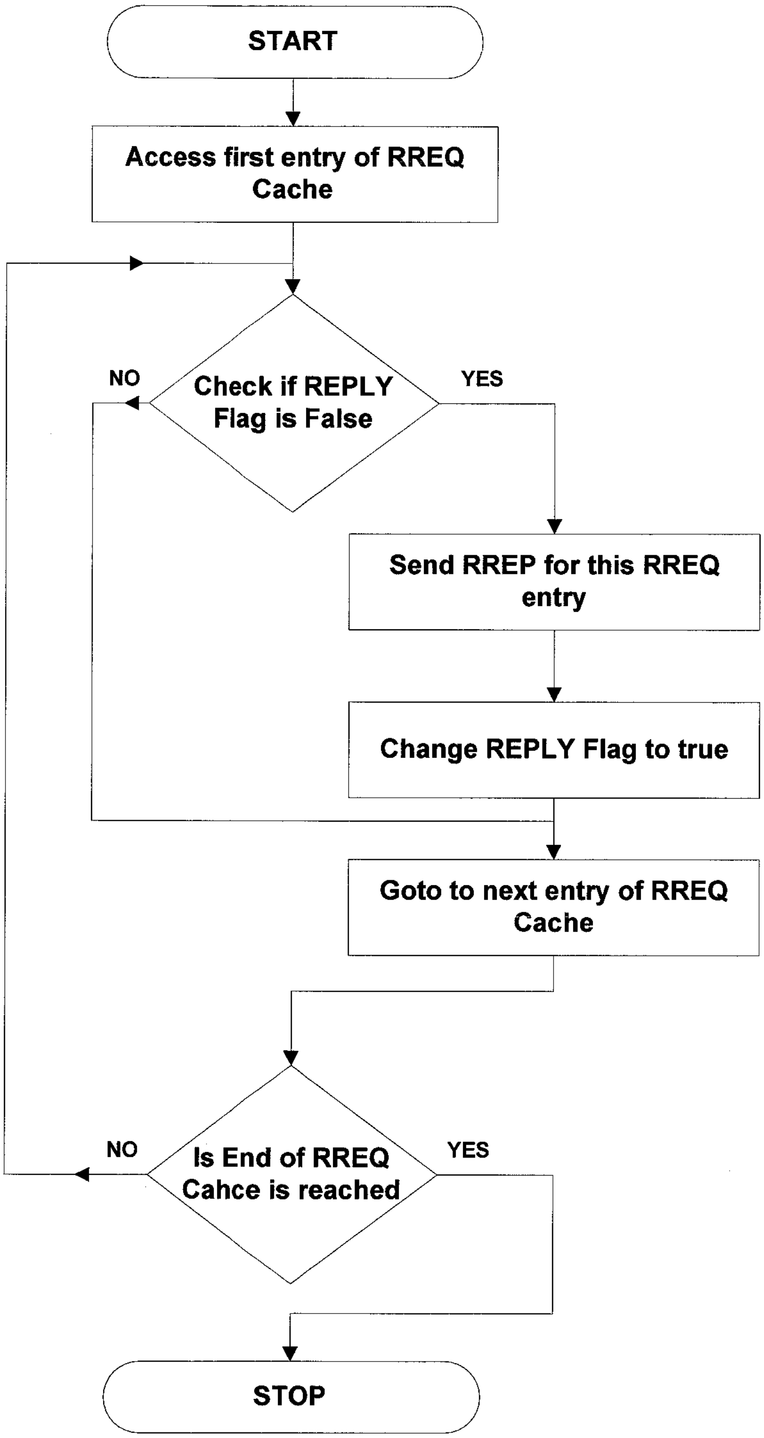


Figure 3.10: Flowchart of operations on RREQ cache during route selection in destination node

RREQ cache is emptied after every *RREQ_PURGE* time interval. The RREP propagates through intermediate node back to source node. On receiving RREP packet each intermediate node sets up forward route entry to the destination node.

Then on receiving RREP packet the source node creates entry in routing table and starts to send data packets along the setup route.

Let's examine this route selection procedure with an example of a six node Ad-hoc network developed in section 3.2. Suppose the destination node first received RREQ packet at time '*t1*' via path S-1-2-D with $ETL_{path} = 0.81$. Let the Link quality value be 0.9 for both routes which will be equal to ETL_{node} of the destination node. The destination node computes ETL_{path} using Eq. 3.6 as:

$$ETL_{path} = 0.81 * 0.9 = 0.73$$

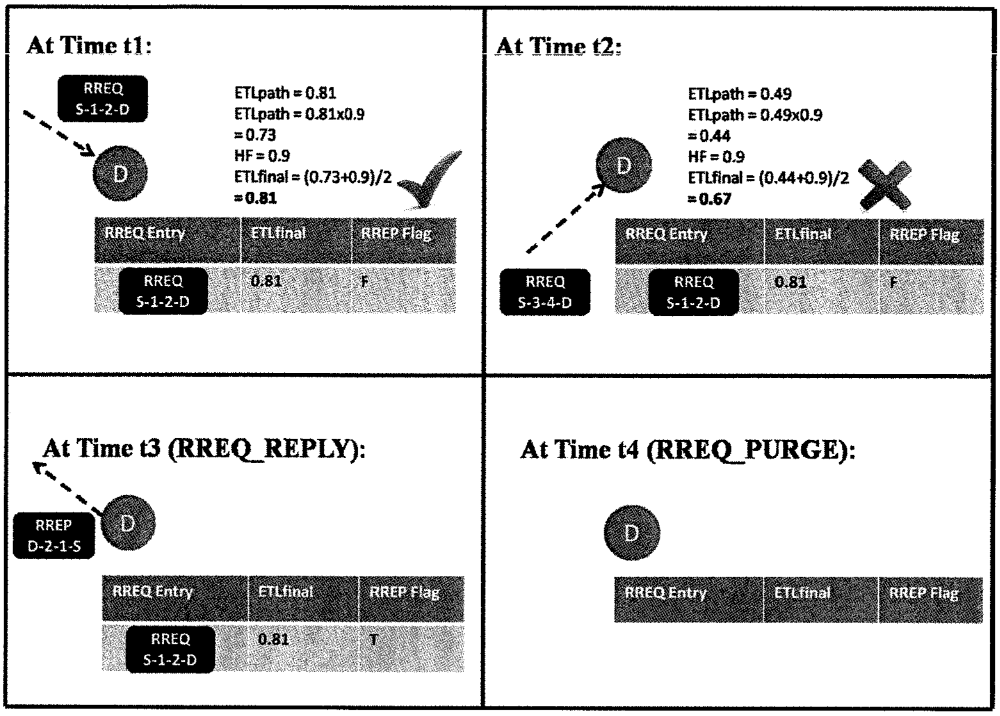
The destination node calculates Hop Factor '*HF*' for this three hops path using equation 3.8 with maximum hop count limit set to 30 as:

$$HF = \frac{30 - 3}{30} = 0.90$$

and ETL_{final} using equation 3.7 as

$$ETL_{final} = \frac{0.73 + 0.90}{2} = 0.81$$

After checking with RREQ cache, the destination node stores this RREQ packet in the RREQ cache (since there is no RREQ of source node 'S' currently in the RREQ cache yet). It sets the *REPLY* flag of the stored RREQ packet as false and starts the *RREQ_REPLY* timer. It also creates reverse route entry to the source node 'S' with next hop as node '2' in its routing table. Let the other RREQ packet reaches the destination node at some later time '*t2*' via path S-3-4-D. Its ETL_{final} would then be computed to be 0.675. As its ETL_{final} value is smaller than the ETL_{final} value of the already stored RREQ packet of source node 'S' so this ETL_{final} is discarded. When *RREQ_REPLY* timer expires at time '*t3*', the destination nodes sends RREP packet to source S via path D-2-1-S and changes *REPLY* flag to true. Upon *RREQ_PURGE* timer expiry at time '*t4*', destination node empties out the RREQ cache. These set of events are illustrated graphically in Figures 3.10 and 3.11 with working of route cache of destination node 'D' at four different time intervals (t1 < t2 < t3 < t4) in Figure 3.10 and RREP propagation path in Figure 3.11.



At Time t1:

RREQ Entry	ETLfinal	RREP Flag
RREQ S-1-2-D	0.81	F

At Time t2:

RREQ Entry	ETLfinal	RREP Flag
RREQ S-1-2-D	0.81	F

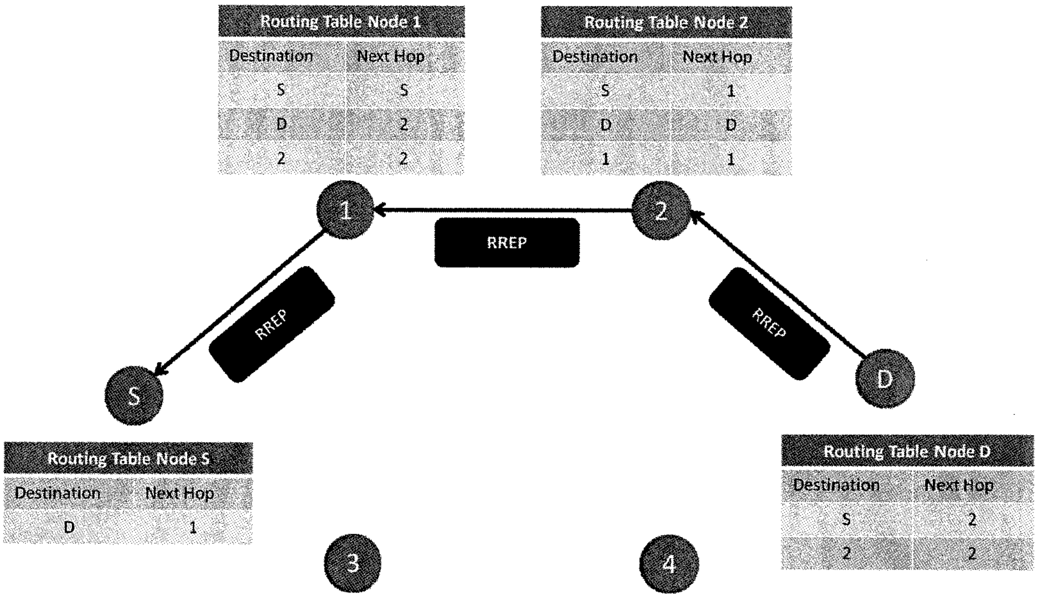
At Time t3 (RREQ_REPLY):

RREQ Entry	ETLfinal	RREP Flag
RREQ S-1-2-D	0.81	T

At Time t4 (RREQ_PURGE):

RREQ Entry	ETLfinal	RREP Flag

Figure 3.11: Route cache of destination node at time intervals t1, t2, t3 and t4



Routing Table Node 1

Destination	Next Hop
S	S
D	2
2	2

Routing Table Node 2

Destination	Next Hop
S	1
D	D
1	1

Routing Table Node S

Destination	Next Hop
D	1

Routing Table Node D

Destination	Next Hop
S	2
2	2

Figure 3.12: RREP propagation in the network

On receiving RREP packet, source node ‘S’ starts sending data to destination node ‘D’ via S-1-2-D path. One important thing to note is that unlike AODV, intermediate nodes are refrained from sending RREPs even if they have route to destination and consequently RREQ packet is made to propagate in the network until it reaches the destination node. This is to ensure that the most optimal path gets selected by the destination node since it has global view of the end-to-end of the whole network.

3.4 Route Management for Low Energy Nodes

Energy is considered to be one of the most important entities for resource constrained wireless ad-hoc networks since network lifetime is solely determined by it. In case of smart metering network, battery powered nodes such as gas and water smart meters as well as wireless sensor nodes attached to smart metering network needs an energy consumption aware routing protocol for prolonging network lifetime. Although during route formation, routes are chosen with maximum residual energy nodes. However, once the route is formed it continues to be used till transmission is completed or the route breaks. This scheme has a major drawback that nodes used in the route may deplete their energy quickly.

To overcome this, ETL-AODV keeps track of energy level of the intermediate nodes and alerts the source node if the battery level of any of the nodes in the currently used routes falls below a threshold value '*LOW_ENERGY_THRESHOLD*' (used as 0.5 in our simulations). On receiving low energy alert, source node then searches for a new route with possibility of having nodes with comparatively higher residual energies.

When an intermediate node has to forward data packet of some other nodes, it checks if its energy level is above the *LOW_ENERGY_THRESHOLD* value. If that is the case then it continues to forward the packets as in a normal routine. Contrary if its energy level is below *LOW_ENERGY_THRESHOLD* value and its *LOW_ENERGY_NOTIFY* flag is false then it sends Low Energy error packet back to source node, change *LOW_ENERGY_NOTIFY* to true and continue to forward the packets as usual. Consequently this scheme follows make-before-break approach such that the low energy nodes, instead of dropping the packets, continue to forward the packets of other nodes and alerts the source node as well. The flag is utilized here to notify the source node for only once instead of sending low energy error packets again and again.

After propagating through the route, once low energy error packet reaches the source node, it can start the route discovery phase with the objective of finding possibly better routes. The routing protocol changes the *LOW_ENERGY_NOTIFY* flag back to false once its energy level exceeds *LOW_ENERGY_THRESHOLD* value possibly through charging. This low energy scheme is illustrated in the figure 3.13.

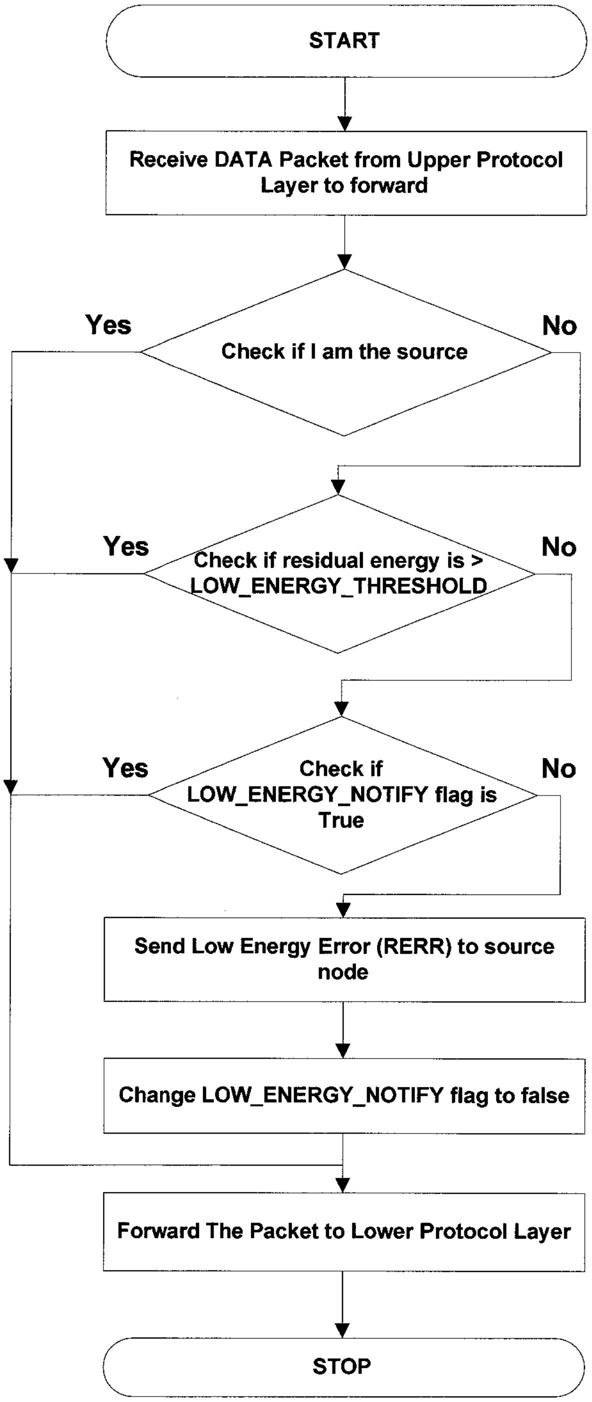


Figure 3.13: Flowchart of Low energy error (RERR) generation

Considering the example of six nodes ad-hoc network in section 3.2, the route S-1-2-D being utilized for longer time, a time will come when the energy level of nodes 1 and 2 depleted below threshold value. Once this happens, intermediate node whose energy depletes earlier (i.e. falls below LOW_ENERGY_THRESHOLD) will send Low energy alert RERR back to the source notifying it. The source node will then start Route discovery procedure in search of more appropriate routes (see Figure 3.14).

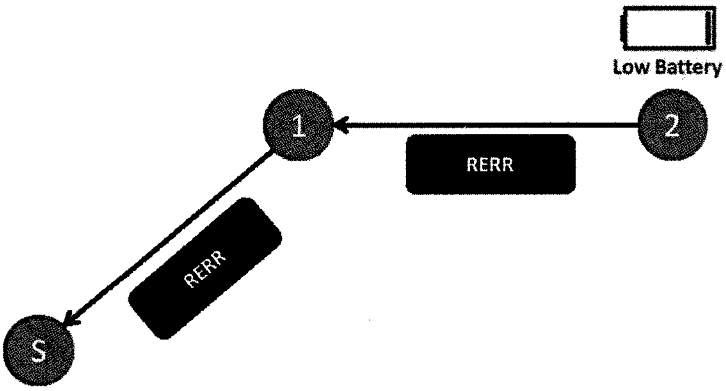


Figure 3.14: RERR propagation in the example of ad-hoc network

3.5 No exchange of HELLO packets

Classical on-demand routing protocol AODV utilizes periodic exchange of HELLO (control) packets between neighboring nodes to keep updating which of the neighboring nodes are still alive. This is to ensure high reliability at the expense of high bandwidth utilized. This approach was designed for mobile ad-hoc networks where frequency of route breakup is much higher as compared to static networks. Furthermore, in case of smart metering deployment, number of nodes can be quite large and so HELLO control packets traffic can create routing overhead problems. To keep protocol operation simple, our protocol ETL-AODV uses MAC level acknowledgement instead of HELLO packets for enhanced reliability to avoid any additional overhead incurred by use of HELLO packets in routing layer. Link Layer Feedback is prominent feature of 802.11 and 802.15.4 MAC protocol families which enables the link layer to detect if the link in the next hop has failed and notifies it to the upper protocol layers. This process speeds up the link failure detection as it takes place in data link layer instead of routing layer. On receiving link failure feedback from the MAC layer, ETL-AODV can start a new route discovery.

3.6 Pseudo code

The Pseudo code of the proposed protocol is given below:

At Source Meter Node:

```
1.   If    route is present in routing table Then
2.         Transmit data packet through the selected route
3.   Else
4.         Set value of $ETL_{path}$ field in RREQ packet to 1.0 and broadcast it
5.         If    source receives RREP within timeout interval Then
6.               source updates its routing table
7.               source transmits data through selected path
8.         Else
9.               GOTO step 4
10.        End If
11.  End If
```

Intermediate Meter Node receives Route Request (RREQ) packet:

```
12.  If    intermediate node is the source node OR duplicate RREQ is received
     Then
13.        Discard RREQ packet
14.  Else
15.        Create reverse route entry to the source node
16.        Calculate $ETL_{node}$      // equation 3.5
17.        Append $ETL_{node}$ value in $ETL_{path}$ field of RREQ packet // equation 3.6
18.        Broadcast RREQ packet
19.  End If
```

Route Selection at Destination Meter Node:

```
20. Calculate $ETL_{path}$ value    // equation 3.6
21. Calculate $ETL_{final}$ value    // equation 3.8
22. If  RREQ cache already contains RREQ packet with same source ID AND
        same broadcast ID  AND larger $ETL_{final}$ value  Then
23.     Discard RREQ packet
24. Else
25.     If  RREQ_REPLY timer is off  Then
26.         Turn on RREQ_REPLY timer
27.     End If
28.     Insert RREQ entry in RREQ cache and set RREQ_FLAG as False
29.     Create or update route entry to the source node
30. End If
31. If  RREQ_REPLY timer expires  Then
32.     Access first entry of RREQ cache
33.     If  RREP flag is false  Then
34.         Send Route Reply RREP packet for current RREQ entry
35.         Set REPLY Flag as True
36.     End If
37.     GOTO next entry of RREQ cache
38.     If  End of RREQ cache is not reached  Then
39.         GOTO step 33
40.     End If
41. End If
42. If  RREQ_PURGE timer expires  Then
43.     Empty RREQ Cache
44. End If
```

Low Energy Error (RRER) Alert by Intermediate Meter Node:

```
45. If  data packet is received from upper layer to be forwarded  Then
46.     If  intermediate node is source of the data packet  Then
```

```
47.                 GOTO step 52
48.             Else If     current energy < LOW_ENERGY_THRESHOLD AND
                    LOW_ENERGY_NOTIFY Flag is False     Then
49.                 Send Low Energy Error RERR packet to source node
50.                 Set LOW_ENERGY_NOTIFY Flag as True
51.             End If
52.             Forward the data packet to lower layer
53.     End If
```

3.7 Summary

In this chapter, the proposed protocol ETL-AODV for ad-hoc deployment of smart metering infrastructure is presented. The proposed protocol utilizes concept of multiple metrics approach for considering energy consumption, traffic load, Link quality and path length during route formation phase. This chapter starts with description of network model assumptions and multiple metrics description. The associated route discovery phases consisting of RREQ propagation and Route selection are explicitly explained in detail with the help of flowcharts and an easy to understand example of an ad-hoc network. Route management phase consisting of Low energy alert is illustrated at the end followed by the pseudo code of the proposed protocol.

CHAPTER 4

SIMULATION RESULTS AND ANALYSIS

This Chapter presents the simulation results and analysis of the results for the proposed 'ETL-AODV' protocol. The chapter starts with introduction of network simulator NS-2 and progresses with building the basics of network simulation. Next to follow are simulations results presented in the form of three simulation studies along with detailed analysis of the results.

4.1 Network Simulator Version 2 (NS-2)

In this research work, Network Simulator (NS-2) was chosen as the simulation tool. According to survey conducted in [50], 75.5% of the research conducted on Ad-hoc networks utilize simulation as research tool to present their findings. The percentage use of different simulators is shown in Figure 4.1. It can be seen that NS-2 is the most popular simulation tool used by the researchers.

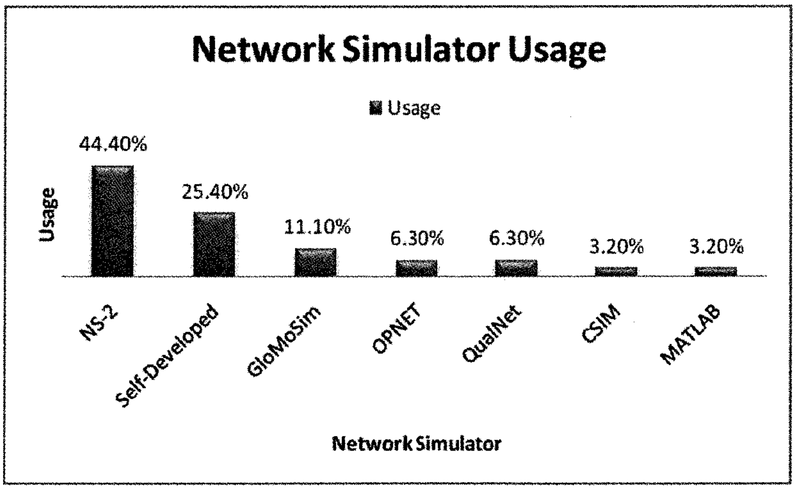


Figure 4.1: Network Simulators Usage [50]

NS-2 is an open source network simulation software and is reported to be the most preferred simulation tool. For this reason, NS-2 was chosen for this research work. NS-2 is a discrete event object oriented simulator developed by University of California at Berkeley and the VINT project [51]. Later on, Monarch project wireless extension [52] was added for simulating wireless scenarios.

NS-2 utilizes two programming languages C++ and OTCL (Object oriented Tool Command Languages). TCL and C++ are used as front end and back end respectively where changes in C++ scripts are compiled while those in TCL are interpreted. C++ is faster than TCL in terms of execution time. However it is slower in terms of compilation time. Therefore, C++ is more suitable for protocol implementations while TCL scripts are utilized for simulation parameters such as topology, traffic pattern and protocols configurations. Physical activities are converted into events and are processed when they are scheduled to occur. Simulation output results are written in text based format to a trace file with "*.tr*' extension. These trace files can be analyzed with help of AWK scripts. Figure 4.2 describes the overall components of NS-2 simulator.

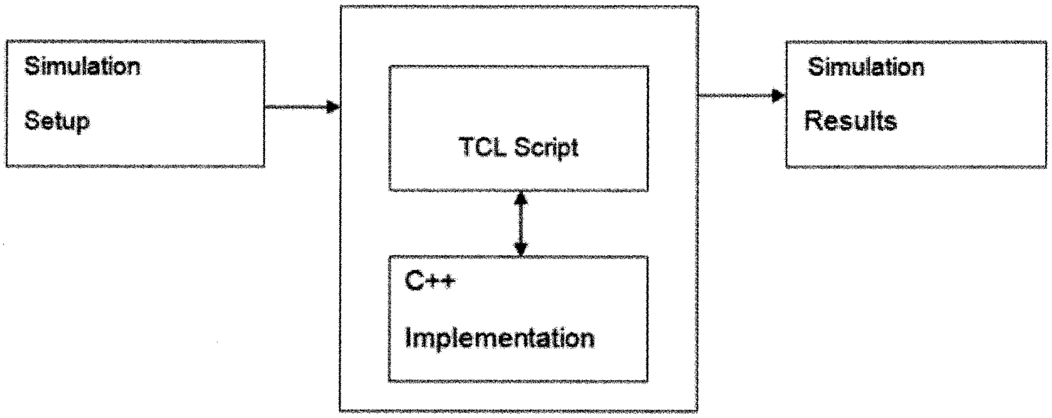


Figure 4.2: Conceptual components of NS-2

4.2 Simulation Design

In this section, the overall architecture of ad-hoc smart meter network in NS-2 is presented.

4.2.1 NS-2 Setup

NS-2 simulator version 2.34 is employed in this research. The NS-2 is designed to run on UNIX systems. Therefore NS-2 was built and run on Ubuntu 10.04.

The proposed ETL-AODV protocol was implemented in C++ in NS-2 (see screenshot in Figure 4.3). *etlaodv.h* is header file with protocol configuration parameters such as ETL coefficients values, energy threshold and route selection timer values. The code for protocol functions such as route discovery procedure and route selection are implemented in *etlaodv.cc* file. Control packets such as RREQ are defined in *etlaodv_packet.h* file. The rest of the files are utilized for routing queues and route tables. These files were incorporated into NS-2 so that ETL-AODV can be utilized as standalone routing protocol with any TCL file.

The simulation scenario was implemented using TCL script language for setting up simulation parameters such as parameters for physical layer, position of nodes, radio propagation model, MAC type and routing protocol.

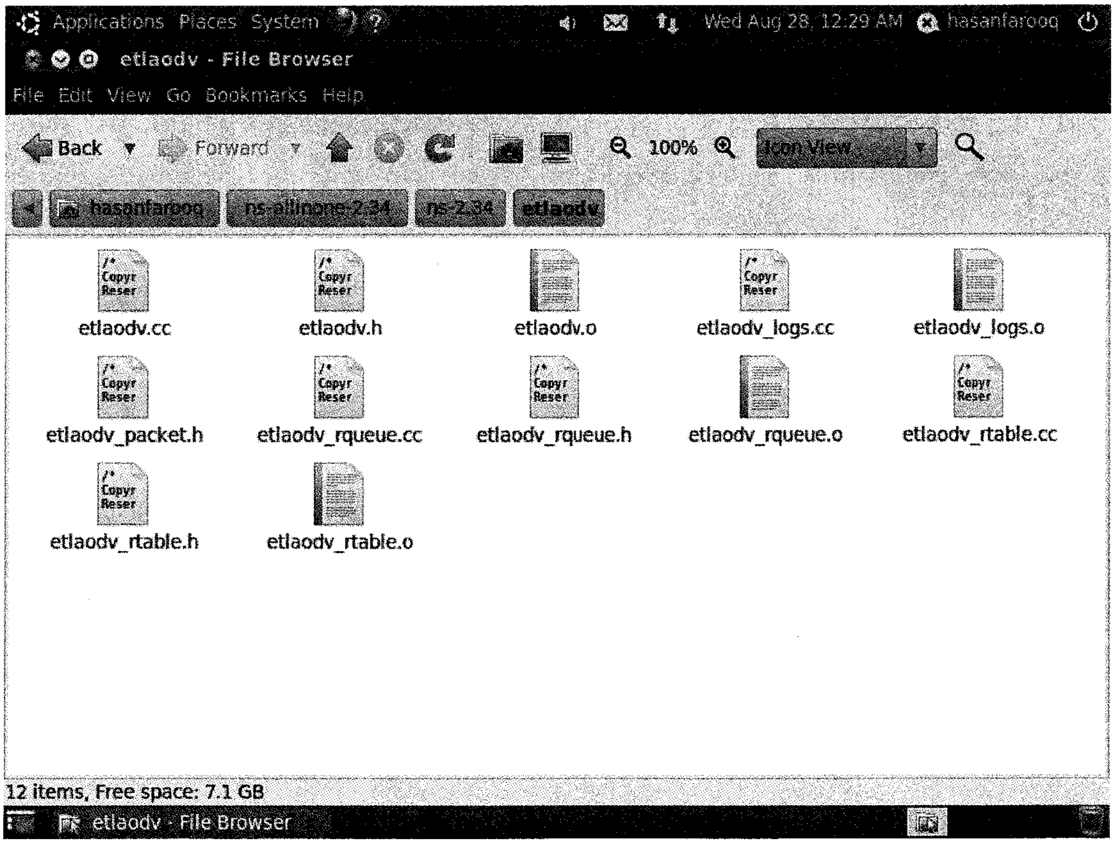
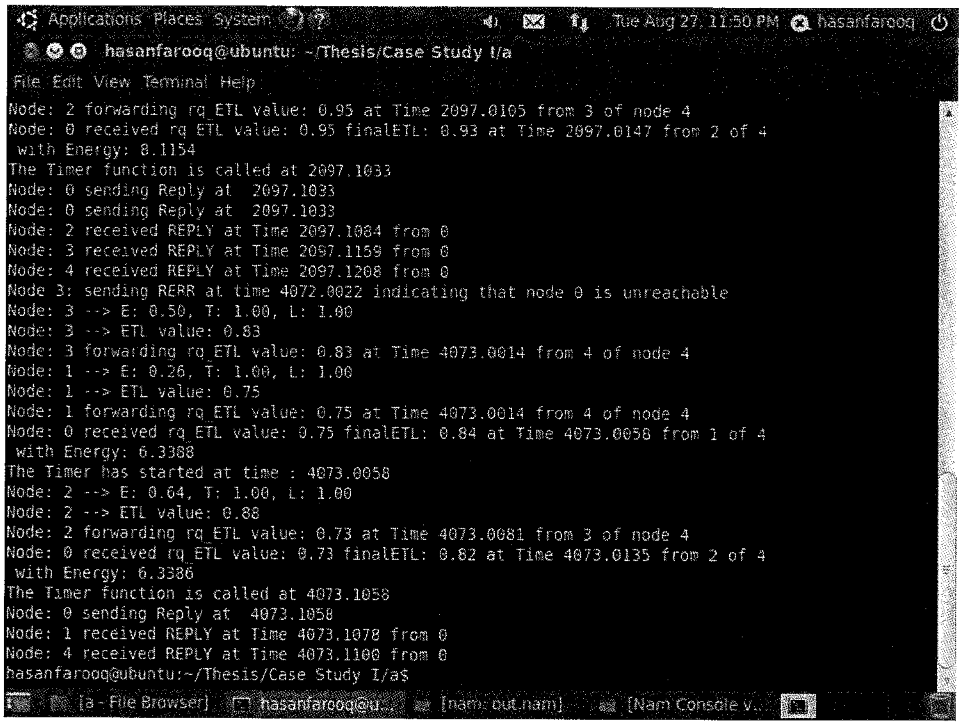


Figure 4.3: ETL-AODV files in NS-2

A snapshot of Terminal screen with ETL-AODV running in NS-2 is shown in Figure 4.4 while Figure 4.5 gives snapshot of one of the network Animator tool used in one of the network simulations.



```
Node: 2 forwarding rq_ETL value: 0.95 at Time 2097.0105 from 3 of node 4
Node: 0 received rq ETL value: 0.95 finalETL: 0.93 at Time 2097.0147 from 2 of 4
 with Energy: 8.1154
The Timer function is called at 2097.1033
Node: 0 sending Reply at  2097.1033
Node: 0 sending Reply at  2097.1033
Node: 2 received REPLY at Time 2097.1084 from 0
Node: 3 received REPLY at Time 2097.1159 from 0
Node: 4 received REPLY at Time 2097.1208 from 0
Node 3: sending RERR at time 4072.0022 indicating that node 0 is unreachable
Node: 3 --> E: 0.50, T: 1.00, L: 1.00
Node: 3 --> ETL value: 0.83
Node: 3 forwarding rq_ETL value: 0.83 at Time 4073.0014 from 4 of node 4
Node: 1 --> E: 0.26, T: 1.00, L: 1.00
Node: 1 --> ETL value: 0.75
Node: 1 forwarding rq_ETL value: 0.75 at Time 4073.0014 from 4 of node 4
Node: 0 received rq_ETL value: 0.75 finalETL: 0.84 at Time 4073.0058 from 1 of 4
 with Energy: 6.3388
The Timer has started at time : 4073.0058
Node: 2 --> E: 0.64, T: 1.00, L: 1.00
Node: 2 --> ETL value: 0.88
Node: 2 forwarding rq_ETL value: 0.73 at Time 4073.0081 from 3 of node 4
Node: 0 received rq_ETL value: 0.73 finalETL: 0.82 at Time 4073.0135 from 2 of 4
 with Energy: 6.3386
The Timer function is called at 4073.1058
Node: 0 sending Reply at  4073.1058
Node: 1 received REPLY at Time 4073.1078 from 0
Node: 4 received REPLY at Time 4073.1100 from 0
hasanfarooq@ubuntu:~/Thesis/Case Study I/a$
```

Figure 4.4: Screenshot of Terminal screen with ETL-AODV running

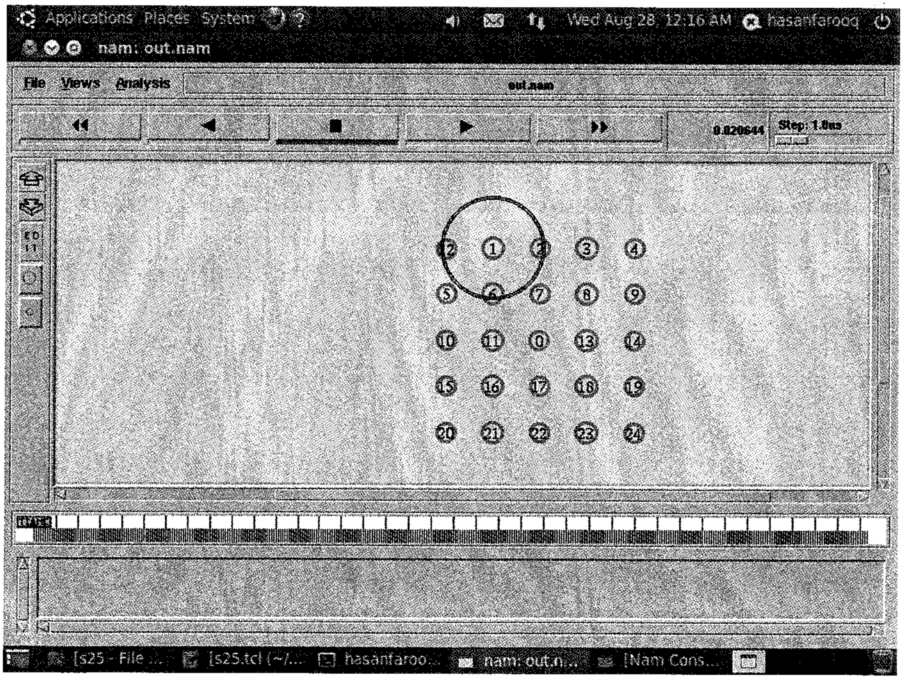
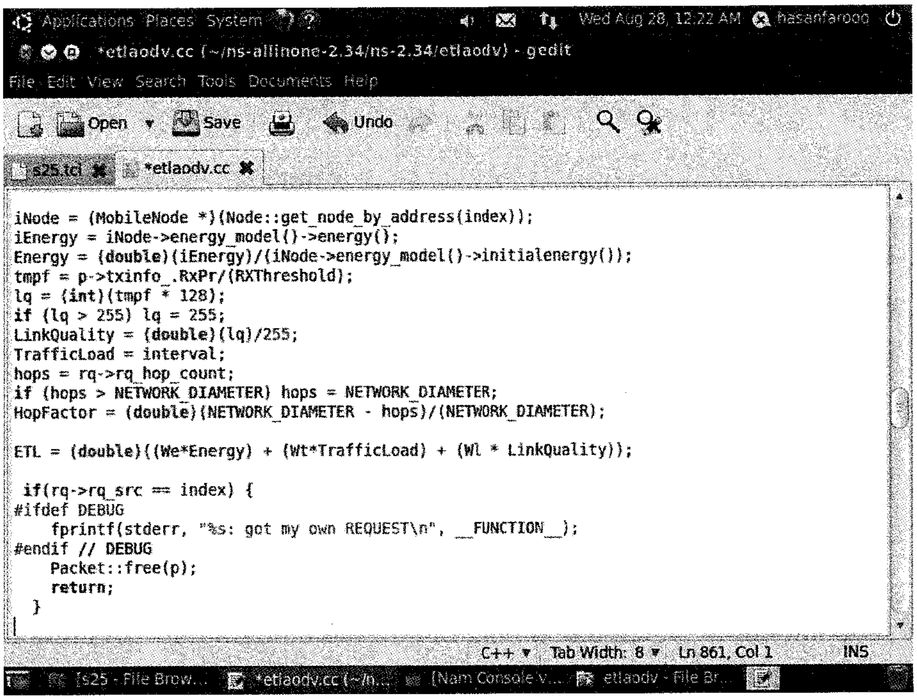


Figure 4.5: Screenshot of Network Animator tool

A screenshot of a portion of etlaodv.cc file is given in Figures 4.6 and 4.7. Please refer to Appendix B for simulation codes.

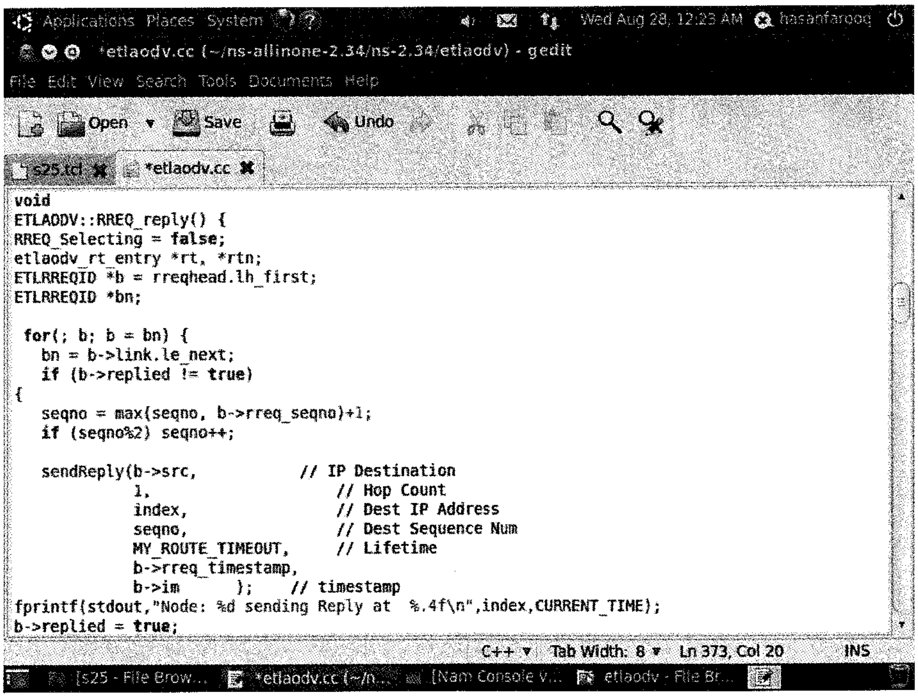


```
iNode = (MobileNode *)(Node::get_node_by_address(index));
iEnergy = iNode->energy_model()->energy();
Energy = (double)(iEnergy)/(iNode->energy_model()->initialenergy());
tmpf = p->txinfo_.RxPr/(RXThreshold);
lq = (int)(tmpf * 128);
if (lq > 255) lq = 255;
LinkQuality = (double)(lq)/255;
TrafficLoad = interval;
hops = rq->rq_hop_count;
if (hops > NETWORK_DIAMETER) hops = NETWORK_DIAMETER;
HopFactor = (double)(NETWORK_DIAMETER - hops)/(NETWORK_DIAMETER);

ETL = (double)((We*Energy) + (Wt*TrafficLoad) + (Wl * LinkQuality));

 if(rq->rq_src == index) {
#ifdef DEBUG
    fprintf(stderr, "%s: got my own REQUEST\n", __FUNCTION__);
#endif // DEBUG
    Packet::free(p);
    return;
  }
```

Figure 4.6: Screenshot of a portion of etlaodv.cc file with function for calculating ETL values



```
void
ETLAODV::RREQ_reply() {
RREQ_Selecting = false;
etlaodv_rt_entry *rt, *rtn;
ETLRREQID *b = rreqhead.lh_first;
ETLRREQID *bn;

 for(; b; b = bn) {
   bn = b->link.le_next;
   if (b->replied != true)
{
   seqno = max(seqno, b->rreq_seqno)+1;
   if (seqno%2) seqno++;

   sendReply(b->src,           // IP Destination
             1,                   // Hop Count
             index,               // Dest IP Address
             seqno,               // Dest Sequence Num
             MY_ROUTE_TIMEOUT,    // Lifetime
             b->rreq_timestamp,
             b->im      );    // timestamp
fprintf(stdout,"Node: %d sending Reply at  %.4f\n",index,CURRENT_TIME);
b->replied = true;
```

Figure 4.7: Screenshot of a portion of etlaodv.cc file with function for sending RREP packet by destination node

4.2.2 Simulation Topology

Most of the research on Ad-hoc Networks such as MANETS utilizes random node topology in their simulations. However, Smart meter Ad-hoc network is designed to be a network with static nodes deployed in more or less relatively planned regular grid structure (see Figure 4.8). The homes position can be considered as nodes position for smart grid simulation purposes such as those done in [53]. The topologies were constructed using NS2 Scenarios Generator 2 (NSG2) utility [54] and imported into NS-2.

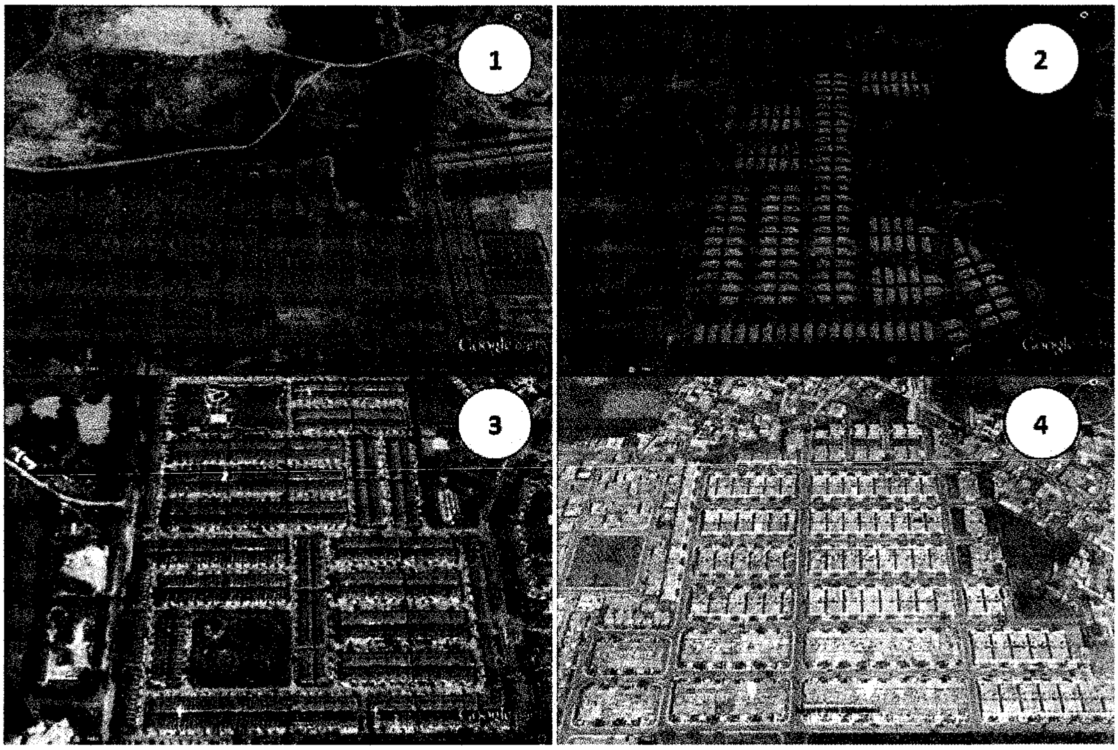


Figure 4.8: Google Earth snapshots of (1) Bandar U Seri Iskandar, Malaysia (2) Desa Tronoh, Malaysia (3) Kuala Lumpur, Malaysia (4) Lahore, Pakistan indicating regular grid structure

4.2.3 Traffic Pattern

Random traffic connections can be setup in NS-2 between any numbers of nodes by using default traffic generator program cbrgen.tcl [51]. This random nature of traffic generation is very useful for Mobile Ad-hoc networks. However, Smart meter ad-hoc network operates in more deterministic fashion with all metering nodes sending their readings to same sink node (collector) in pre-defined interval.

Therefore, this cbrgen.tcl file was modified in such a way that it accepts number of smart meters, seed value and sending interval as input parameters and returns traffic file with all metering nodes sending data to same sink node (designated as 0 in our simulations). In addition, all smart meters start to send data at a time T chosen from uniform random distribution ((T ~ **U** (**0**, **I**)) where I is interval (set as 60 seconds in the simulations). The modified cbrgen.tcl file and output Traffic file are provided in Appendix B.

4.2.4 Radio Propagation Model

Radio propagation models are used to determine the received signal power of each packet. By default three models are provided by NS-2. These are Free Space Model, Two Ray Ground Model, and Shadowing Model.

4.2.4.1 Free Space Model

It assumes ideal propagation conditions with only one clear line-of-sight path between transmitter and receiver. The received signal power in free space at distance'd' is calculated using Eq. 4.1[55]:

$$P_r = \frac{(P_t * G_t * G_r * \lambda^2)}{(4\pi^2 * d^2 * L)} \qquad (4.1)$$

where P_t and P_r are power of signal transmitted and received respectively, G_t and G_r are transmitter and receiver gains respectively, L is system loss and λ is wavelength. The Free Space Model represents communication range as a circle around a transmitter. If receiver is inside this circle, it will receive all packets otherwise it loses all packets.

4.2.4.2 Two Ray Ground Model

It considers direct path as well as ground reflection communication path and has more accurate calculation than the free space model. Eq. 4.2[55] is used to calculate the received signal power in the two ray ground reflection model at distance d as:

$$P_r = \frac{(P_t * G_t * G_r * h_t^2 * h_r^2)}{(d^4 * L)} \tag{4.2}$$

where h_t and h_r are the heights of the transmitter antennas and the receiver antennae respectively.

4.2.4.3 Shadowing Model

Free Space Model and Two Ray Ground model assumed communication range as an ideal circle. In reality, the received power at a certain distance is a random variable due to multipath propagation effects (also known as fading effects) due to obstructions such as trees and buildings. A more general and widely used model is Shadowing [55]. The shadowing model is represented by Eq. 4.3[51] as:

$$\left[\frac{P_r(d)}{P_r(d_o)}\right]_{dB} = -10\beta \log(d/d_0) + X_{dB} \tag{4.3}$$

where $P_r(d)$ is mean received power at distance d, d_o is reference distance, β is path loss exponent usually empirically determined from field experiments, X_{dB} is Gaussian random variable with zero mean and standard deviation σ_{dB} which is also obtained by measurements. Some typical values of β and σ_{dB} are given in Table 4.1 and 4.2. This shadowing model extends ideal circle model as richer statistical model wherein nodes can only probabilistically communicate when near edge of communication range.

Qin and Kunz [56] observed that active route breaks occur even on stationary nodes due to the effect of shadowing and consequently cause network degradation. They suggested that physical layer models which include the shadowing propagation model can provide realistic results. Stepanov et al. [57] also concluded that shadowing causes serious degradation in the network performance.

Consequently Shadowing Model is used in these research simulations for more realistic results. Manufactures of wireless cards normally use $\beta = 2.7$ to specify the maximum transmission range for a typical outdoor environment [57]. The research works in [36] and [53] employing shadowing model for ad-hoc deployment of smart meters used $\beta = 2.7$ and $\sigma_{dB} = 4$ in their simulations and therefore these values were chosen to be in this research simulations as well.

Table 4.1: Some Typical values of Path Loss Exponent β

Environment		**β**
Outdoor	Free Space	2
	Shadowed Urban Area	2.7 - 5
In building	Line-of-Sight	1.6 - 1.8
	Obstructed	4 - 6

Table 4.2: Some Typical values of standard deviation σ_{dB}

Environment	**σ_{dB}**
Outdoor	4 - 12
Office, hard partition	7
Office, soft partition	9.6
Factory, line-of-sight	3 - 6
Factory, obstructed	6.8

4.2.5 Signal Reception Model

The signal reception model used in the simulations is Signal-to-Noise Ratio Threshold (SNRT) model which is the default reception model in NS-2. It utilizes three fixed thresholds i.e., carrier sense threshold (*CSThresh* – the lower limit), receive threshold

(*RxThresh* – the upper limit) and capture threshold (*CPThresh*). If the signal strength of the received signal is greater than or equal to the *RXthresh*, the signal (packet) is received correctly and handed to the upper protocol layers. The packet is received with errors if the received signal strength falls between the upper limit *RXThresh* and the lower limit *CSThresh*. Any packet with signal strength below the *CSThresh* limit is discarded by the receiver as noise. Moreover, another signal received by the node while receiving the desired signal can cause collision if sum of powers of both received signals is not less than *CPThresh* (in dB) which is usually accepted as 10dB [57]. The value for *RXThresh* for a given communication range (used as 100m in this simulations) and propagation model utilized is determined from separate utility provided with NS-2 at *~ns/indep-utils/propagation/threshold.cc*. The value of *CSThresh* is generally set as 2.2 times the value of *RXThresh*.

4.2.6 Energy Model

In NS-2, energy is a node attribute which represents energy level of a node. Every node has some initial energy at the beginning of simulation which is gradually decremented for each packet received and transmitted by an amount *DecrRcvEnergy* and *DecrTxEnergy* respectively as shown in following Eq. 4.4[51] and Eq. 4.5[51]:

$$DcerRcvEnergy = P_{rx} * rcvtime \qquad (4.4)$$

where P_{rx} is receiving power of node and *rcvtime* is the amount of time taken to receive packets.

$$DcerTxEnergy = P_{tx} * txtime \qquad (4.5)$$

where P_{tx} is transmitting power of node and *txtime* is the amount of time taken to transmit packets.

4.2.7 IEEE 802.11 Standard

IEEE 802.11 is a standard published by IEEE in 1997 for defining Physical and MAC layers for wireless local area network (WLAN). Since then, many amendments in the form of versions (a/b/g/n) have emerged utilizing different frequency bands and modulation schemes. 802.11 devices operate in 2.4, 3.6, 5 and 60 GHz frequency bands depending upon the version of 802.11 used. The standards dictate rules such as adhering to the frequency, modulation scheme guidelines, radiated power and restrictions. The IEEE 802.11 standard allows three modes of data transmission (i) Infrared (IR), (ii) direct sequence spread spectrum (DSSS) and (iii) frequency hopping spread spectrum (FHSS). 802.11 can work in both infrastructure as well as infrastructure less modes (ad-hoc network). The default 802.11 model implemented in NS-2 utilizes 2.4 GHz frequency band operating at 2Mbps data rate with approximate outdoor range of 100m.

IEEE 802.11 is being deployed widely for smart metering AMI networks and applications such as in [58] and [59] and therefore likewise IEEE 802.11 is utilized for PHY and MAC Layers in infrastructure less ad-hoc mode for this research simulations.

4.2.8 Protocol Stack

One of the requirements of NS-2 is that all protocol layers need to be initialized (i.e., PHY, MAC, Network, Transport, and Application) for each node with appropriate protocol. As indicated in previous section, IEEE 802.11 is utilized for PHY and MAC Layers in infrastructure less ad-hoc mode. ETL-AODV and AODV are used as Layer 3 routing protocols for comparative analysis. For simulating smart meters sending meter readings to the collector, UDP has been used at Transport layer with Constant Bit Rate (CBR) traffic source at Application layer.

4.2.9 Performance Metrics

Different performance metrics are chosen for simulations by keeping in mind network and application requirements. The following metrics were chosen for protocols evaluation:

4.2.9.1 Packet Delivery Ratio (PDR)

This metric represents reliability of the protocol by measuring how much of the transmitted packets made up to the receiver. It is measured as:

$$\frac{Number\ of\ Received\ Data\ Packets}{Number\ of\ Transmitted\ Data\ Packets} \tag{4.6}$$

It is desirable to have maximum packet delivery ratio. Considering smart metering application, this metric will be most important in assessing protocols performances.

4.2.9.2 Normalized Routing Load (NRL)

This metric indicates the routing control overhead. It is measured as

$$\frac{Number\ of\ Received\ Routing\ Packets}{Number\ of\ Received\ Data\ Packets} \tag{4.7}$$

It is desirable to have minimum routing overhead for the efficient operation of the network. For resource constrained smart meters, routing protocol should have minimal NRL for efficient usage of network resources.

4.2.9.3 Average Energy Consumption

This metric measures the average energy consumption of nodes present in the network. It is measured as:

$$\frac{Sum\ of\ Residual\ Energy\ of\ all\ Nodes}{Total\ number\ of\ Nodes} \tag{4.8}$$

It is desirable to have minimum average energy consumption of nodes in particular for battery powered smart meters (Water and Gas smart meters). Energy efficient protocol operation is needed for prolonging network lifetime.

4.2.9.4 Average End-to-End Delay

The difference between sending time of a packet at source and receiving time at destination is known as end-to-end delay and it includes all possible delays. This metric indicates latency in the communication network. Average End-to-End Delay is measured as:

$$\frac{Total\ Time\ taken\ by\ all\ Packets\ to\ reach\ destination}{Total\ number\ of\ Packets} \tag{4.9}$$

It is desirable to have minimum value for this metric and is considered important for real time applications. Considering delay tolerant application like smart metering scenario, this metric can be flexible in design. However serious degradation in its value is equally harmful.

4.3 Results and Analysis

Three simulation studies were conducted for analyzing the performance of the proposed ETL-AODV protocol. The baseline settings employed in NS-2 for all three studies are given in Table 4.3

Table 4.3: Baseline settings for NS-2 simulations

Simulation Parameters	
Traffic Type	Constant Bit Rate (CBR)
CBR Packet Size	100 Bytes
Routing Protocol	ETL-AODV, AODV
RREQ_REPLY Timer	0.1 sec
RREQ_PURGE Timer	6 seconds
LOW_ENERGY_THRESHOLD	0.5
Queue Size	50 packets
MAC layer/ PHY layer	802.11
Channel type	Wireless Channel
Tx Power	0.3 w
Rx Power	0.3 w
Antenna Model	Omni Antenna
Transmission Range	100m

4.3.1 Simulation Study I: Effect of Individual Routing Metrics (E, T, L)

In the first simulation study, the effect of individual metrics of the three coefficients (E, T, and L) was studied by setting desired ETL's Coefficient to 1 and the rest of others to 0. Three scenarios were simulated with each utilizing only one of the ETL coefficients (Energy, Traffic Load, and Link Quality).

4.3.1.1 Scenario I: Energy Metric

This simulated scenario (see Figure 4.9) used simulation parameters given in Table 4.4, to analyze the performance of the protocol based on Energy metric by setting ETL coefficients in equation (3.5) as (1, 0, 0). Two Ray Ground model was used to neglect drops due to link quality issues and analyze packet drops due to low energies only.

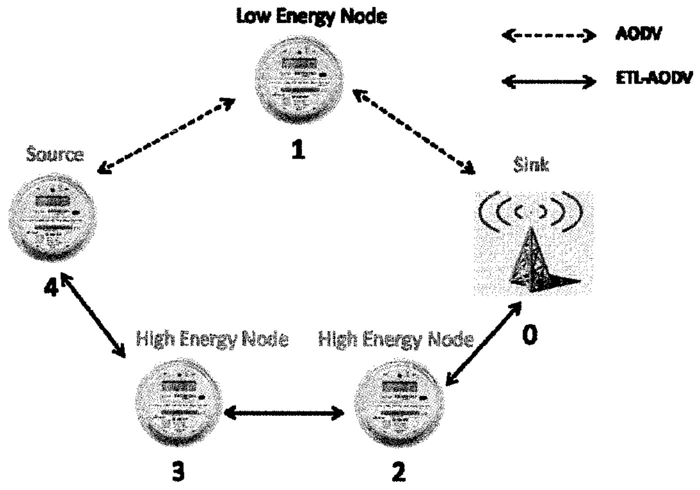


Figure 4.9: Scenario I: Basic Energy Simulation

Table 4.4: Simulation Parameters for Scenario I

Simulation Parameters	
CBR Packet Interval	1 sec
Radio Propagation Model	Two Ray Ground , Shadowing
Initial Energy	Node 4,2,3 → 10 J Node 1 → 6 J Node 0 → 100 J
Simulation Time	6000 sec

Source node '4' needs to send meter readings to sink node '0'. Initial energy of all nodes is set to 10 Joules except node '1' with energy 6 Joules. As a result of route discovery, two routes can be formed (4-1-0) and (4-3-2-0). Route (4-1-0) is shortest one but with low energy node in the path while route (4-3-2-0) is relatively longer path but with higher energy nodes. When simulated, AODV as by its characteristics chose shortest path (4-1-0) and continued to drain energy of node '1' thereby limiting network lifetime to 4500 seconds (time interval from start of simulation till death of first node) with attained PDR below 100%. In the case of ETL-AODV, sink received two route requests, one via node '1' with ETL_{Final} of 0.73 and the other via node '2' with ETL_{Final} of 0.95. Consequently ETL-AODV chose (4-3-2-0) route retaining PDR at 100% and extending network lifetime to 5500 sec. At time 2546.0028 seconds, energy of node '3' fell below *LOW_ENERGY_THRESHOLD* (0.50) and so it sent Route Error to upstream node without breaking the connection and consequently on second route discovery, path (4-1-0) was formed.

The results for PDR are shown in Figure 4.10. A sharp decline in PDR of AODV is observed at 4500 seconds when node '1' dies out.

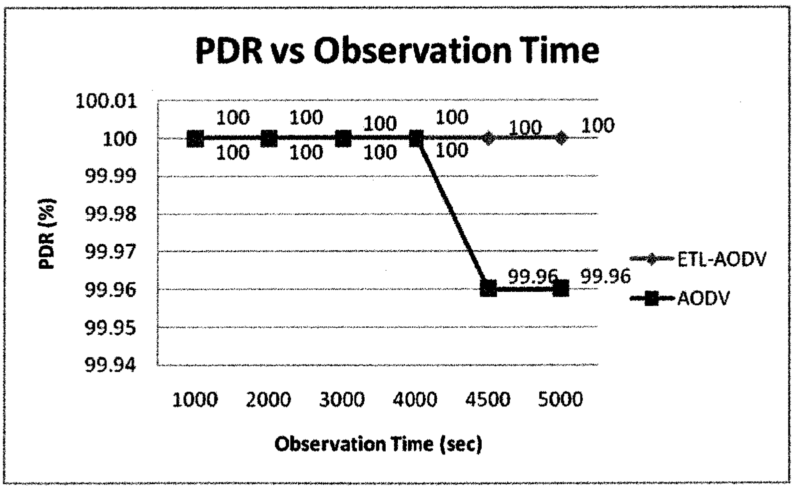


Figure 4.10: Packet Delivery Ratio (PDR) in Scenario I

The energy consumption of nodes '1' and '2' is shown in Figures (4.11 and 4.12). It can be seen that relatively balanced energy consumption is observed in case of ETL-AODV as compared to AODV where node '1' is more utilized thus declining network lifetime.

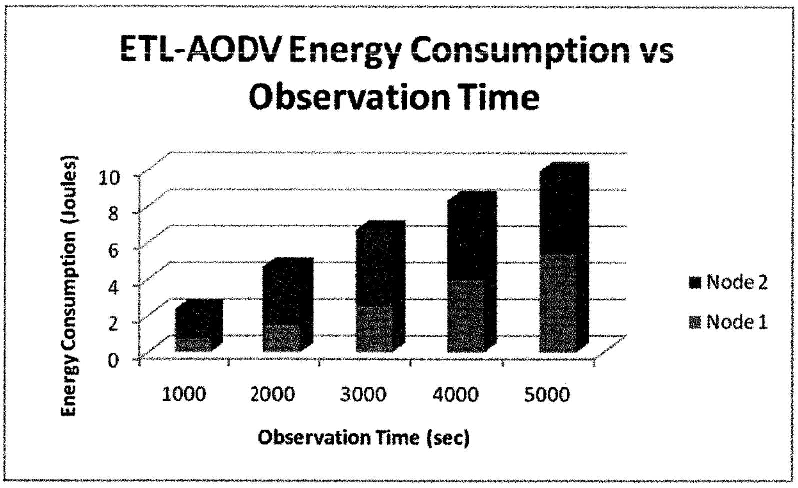


Figure 4.11: ETL-AODV Energy consumption in Scenario I

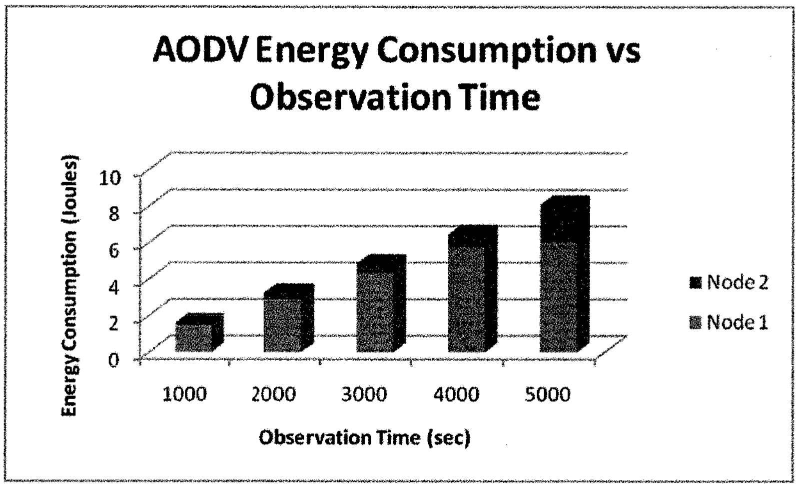


Figure 4.12: AODV Energy consumption in Scenario I

The graph given in Figure 4.13 indicates number of routing control packets for both of the protocols. A slightly higher overhead is observed in ETL-AODV at time 3000 seconds when node '1' informs source node of its low energy status and new route discovery is performed.

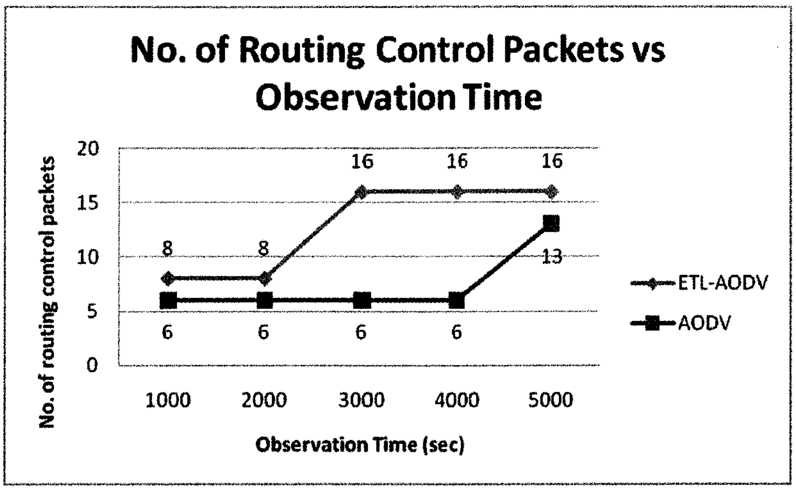


Figure 4.13: No. of routing control packets in Scenario I

The results for average end-to-end delay are shown in Figure 4.14 A general trend of decreasing average end-to-end delay is observed in both of the protocols as more data packets gets transferred from source to sink node. AODV shows slightly less avg. end-to-end delay as compared to ETL-AODV. This is due to additional time taken by route selection phase at sink node.

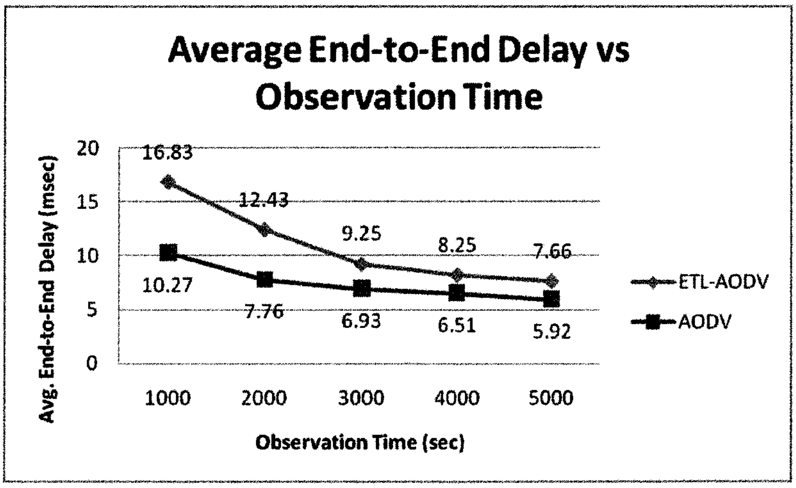


Figure 4.14: Average End-to-End Delay in Scenario I

4.3.1.2 Scenario II: Traffic Load Metric

Scenario II (see Figure 4.15) is simulated with simulation parameters given in Table 4.5, for considering the effect of Traffic Load factor by setting ETL coefficients in

Eq. 3.5 as (0, 1, 0). Two Ray Ground Model was chosen to observe the packet drops due to Traffic Congestion only.

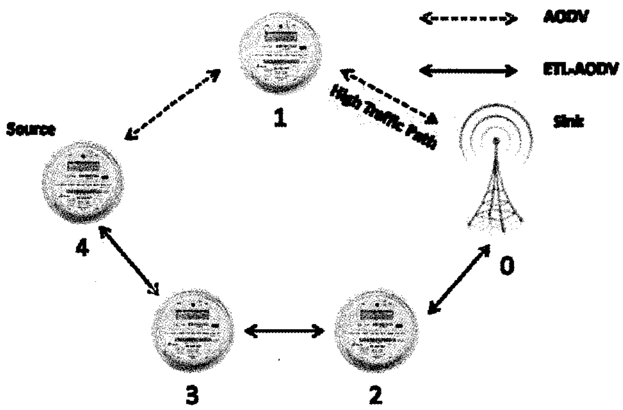


Figure 4.15: Scenario II: Basic Traffic load Simulation

Table 4.5: Simulation Parameters for Scenario II

Simulation Parameters	
CBR Packet Interval	Node 4 → 1 sec Node 1 → 0.1 sec
Radio Propagation Model	Two Ray Ground
Initial Energy	Node 4,3,2,1 → 10 J Node 0 → 100 J
Simulation Time	600 sec

Nodes '4' and '1' are source meters with node 0 as sink node. At start of simulation, node '1' is configured to start sending data to sink with 0.1 sec packet intervals depicting heavy load on this route. Node '4' was switched a bit later at time 80 sec to study which route would be chosen by the protocols. As indicated by route discovery phase, node '4' had two disjoint paths towards node '0' (4-1-0 and 4-3-2-0). The former path, although the shortest path, would increase loading on node '1' as it was also forwarding data to the sink leading to traffic congestion, fast energy depletions and packet drops. When simulated, AODV chose shortest path (4-1-0) and consequently PDR dropped to 98.87% due to traffic congestion. On the other hand when ETL-AODV was simulated, node '0' received two RREQs of node '4', one via node '1' with ETL_{Final} of value 0.47 and the other via node '2' with ETL_{Final} of value 0.95. Consequently, ETL-AODV chose Low Traffic Path (4-3-2-0) thus avoiding congestion and retained PDR of 100%.

The PDR for both protocols is shown in Figure 4.16. As can be seen, AODV has lower PDR as compared to ETL-AODV due to traffic congestion in node 1 and it continues to decline with the increase in time.

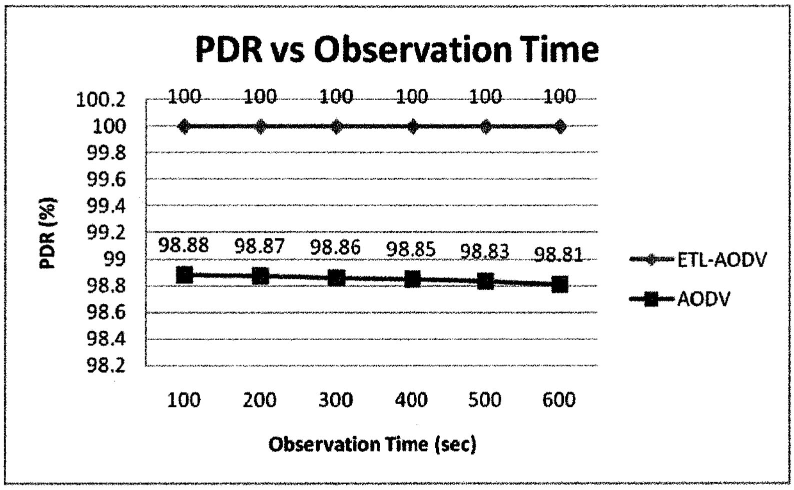


Figure 4.16: PDR in Scenario II

Similarly, AODV showed relatively higher NRL (see Figure 4.17) as compared to ETL-AODV. This is due to additional route discoveries in AODV resulting from packet drops.

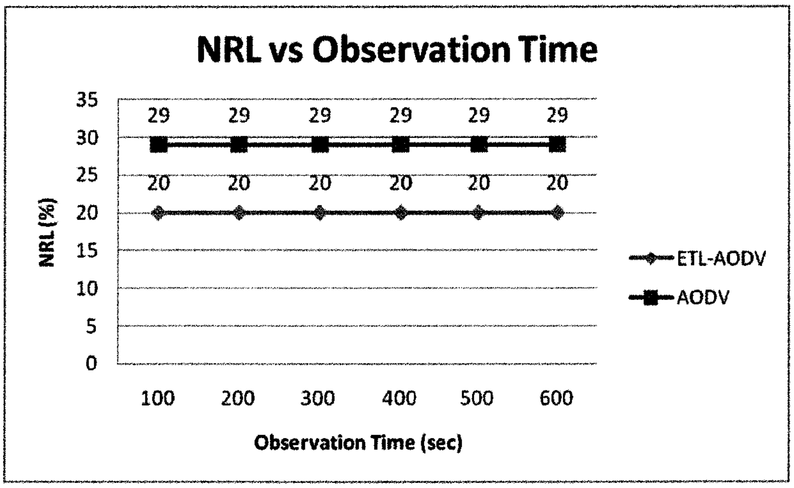


Figure 4.17: NRL in Scenario II

The result for energy consumption of node '1' is given in Table 4.6 for both of the protocols. Node '1' comparatively has higher energy consumption in case of AODV since it transmitted its own readings as well as forwarded readings of node '4'. The results for avg. end-to-end delay (see Figure 4.18) shows AODV has much higher latency than ETL-AODV due to traffic congestion experienced in route (4-1-0).

Table 4.6: Energy consumption in Node '1'

Routing Protocol	Energy Consumption of Node 1
ETL-AODV	7.2 J
AODV	9.1 J

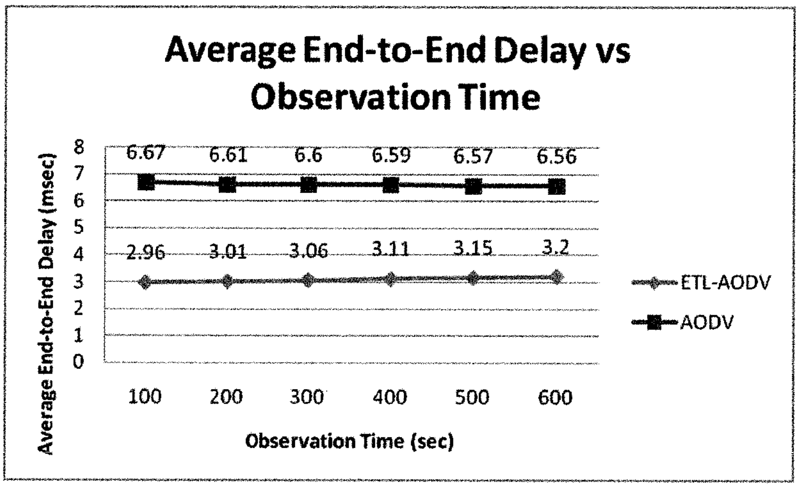


Figure 4.18: Average End-to-End Delay in Scenario II

4.3.1.3 Scenario III: Link Quality Metric

Scenario III (see Figure 4.19) was simulated with network simulation parameters given in Table 4.7 to study the effect of Link Quality factor on PDR.

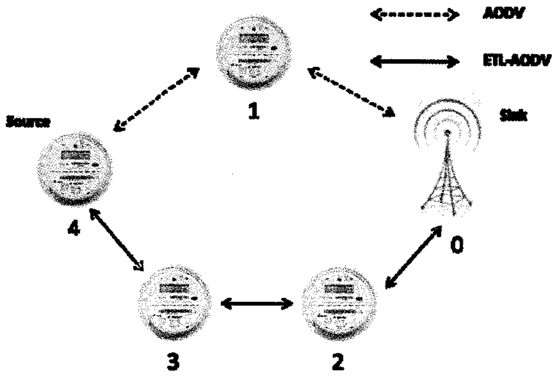


Figure 4.19: Scenario III: basic Link Quality Simulation

Table 4.7: Simulation Parameters for Scenario III

Simulation Parameters	
CBR Packet Interval	Node 4 → 1 sec
Radio Propagation Model	Shadowing
Initial Energy	Node 4,3,2,1 → 10 J Node 0 → 100 J
Simulation Time	60 sec

Node '4' is source meter starting to send data to sink node '0' via two available disjoint paths (4-1-0) and (4-3-2-0). The former path, although shortest, has larger spacing between nodes thus affecting received signal strength. Initially, the network was simulated with Two-Ray Ground radio propagation model. PDR for both protocols came to be 100%. This was because Two Ray Ground model does not consider shadowing and fading effects which can cause link breaks even for static nodes. Thus, a more realistic Shadowing radio propagation model was chosen and simulated in the scenario III. AODV chose weaker link quality path (4-1-0) due to larger spacing. ETL-AODV, on other hand, had two paths available one via node '1' with ETL_{Final}= 0.47 and the other via node '2' with ETL_{Final}=0.50. Consequently, ETL-AODV chose higher Link Quality path (4-3-2-0) thus retaining PDR at 100%. The PDR for both protocols is shown in Figure 4.20.

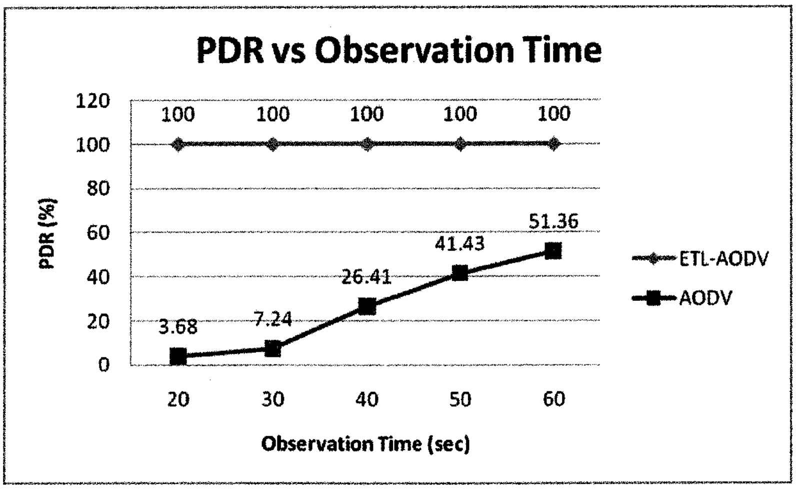


Figure 4.20: PDR in Scenario III

Normalized routing load and average end-to-end delay were very small for ETL-AODV as compared to AODV as shown in Figures 4.21 and 4.22 respectively. The end-to-end delay experienced in case of AODV is considerably higher (i.e. around 10 seconds) at start of simulation due to routing failures resulting from frequent breakage of low link quality paths.

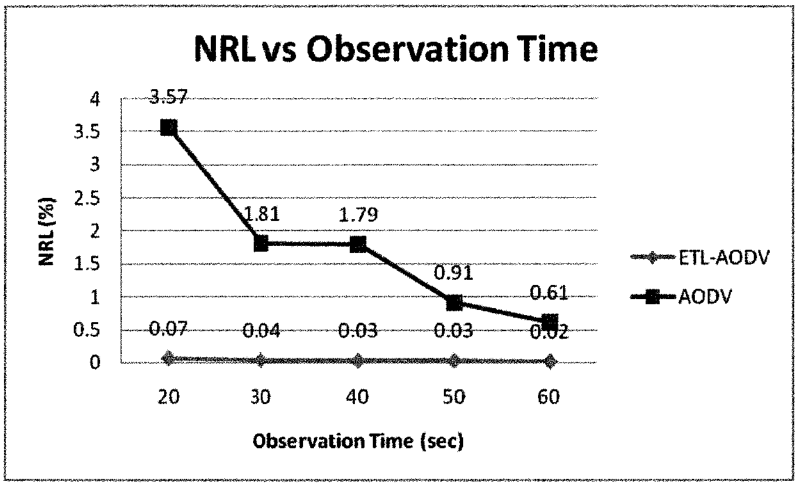


Figure 4.21: NRL in Scenario III

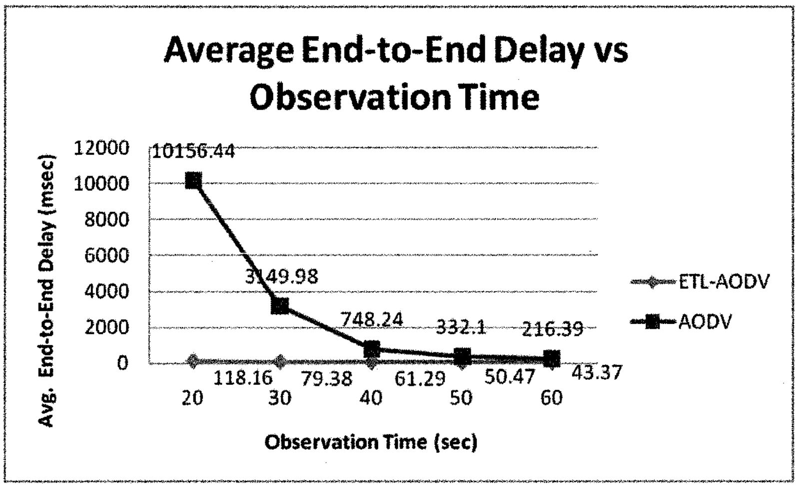


Figure 4.22: Average End-to-End Delay in Scenario III

4.3.1.4 Conclusions Drawn from Simulation Study I Results

From the simulation study I, it is concluded that:

- Considering energy metric during route formation can lead to improved packet delivery ratio, balanced energy consumption of nodes close to sink and improved network lifetime.

- Traffic Load of the nodes, when considered during route formation, leads to improvement in packet delivery ratio, low energy consumption of bottleneck nodes, reduced routing overhead and network delays.
- Link quality consideration during route formation phase leads to formation of more stable routes leading to improved packet delivery ratio, reduced routing overhead and reduced network latency.
- Shadowing Model is a more realistic model as compared to Two Ray Ground model as it simulates fading channel characteristics.

4.3.2 Simulation Study II: Effect of utilizing multiple routing metrics (E, T, L)

In this case study, all the three parameters of ETL metrics were taken into consideration with equal contribution by setting ETL coefficients in Eq. 3.5 as (1/3, 1/3, 1/3). Regular grid based topologies were simulated in similarity to real geographic sub-urban region with location of houses as wireless metering nodes and star denoting location of sink node (see Figure 4.23). The inter meter spacing was set to 50 meters. The number of houses were varied from 25 to 125 for evaluating the performance of the proposed protocol.

Figure 4.23: Geographical area with houses as nodes position

4.3.2.1 Network Simulation Settings

All of the metering nodes were configured to start sending data to sink at a time chosen from uniform random distribution (0 - 60) seconds with interval chosen as 1 packet per minute. Shadowing Propagation model was chosen to simulate an outdoor "shadowed urban area" with the parameters set as *path loss exponent* = 2.7 and *standard deviation* = 4. All simulations were run for 1 hour.

4.3.2.2 Results and Analysis

a) Packet Delivery Ratio (PDR)

The results of PDR for the two protocols simulated are shown in Figure 4.24.

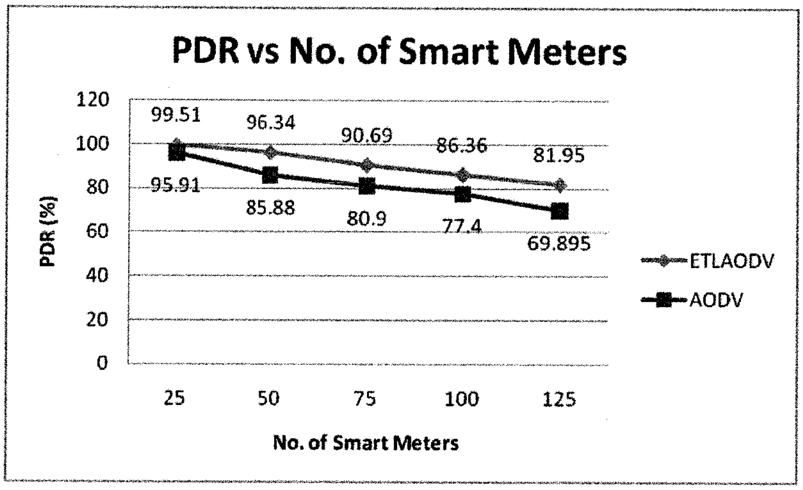


Figure 4.24: PDR vs No. of Smart Meters

A general decreasing trend is observed for both protocols with an increase in number of metering nodes. However, for each set of nodes, ETL-AODV outperforms AODV protocol. This is due to the fact that ETL-AODV considers Energy, Traffic Load and Link Quality during route formation so more stable routes are formed thus able to enhancing the PDR. On the other hand, AODV forms shortest route only thus can have negative impact on PDR as observed in the graph. ETL-AODV maintained PDR above 80% for 125 numbers of homes in shadowed region as compared to AODV whose PDR declined below 70%.

b) *Normalized Routing Load (NRL)*

The results for NRL are shown in Figure 4.25. As predicted, ETL-AODV has much lower routing overhead as compared to AODV. This is due to formation of stable routes by considering all three sub metrics leading to reduced exchange of control packets. NRL, in case of AODV, exceeds 100% as number of routing packets become greater then number of data packets in the network.

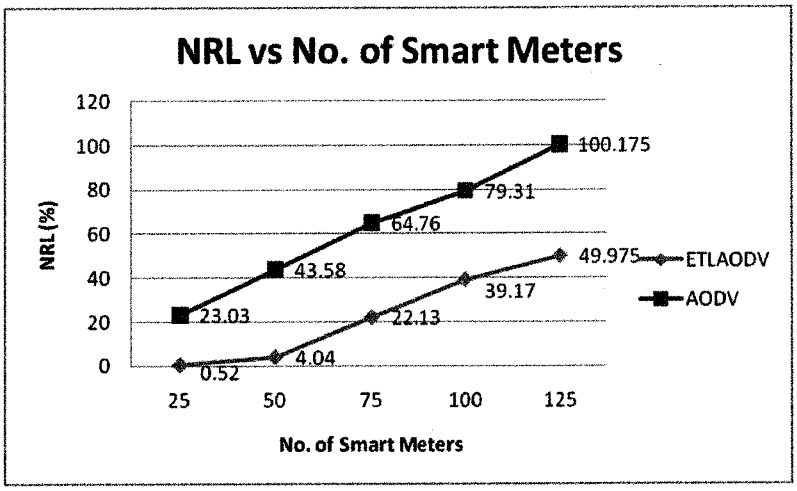


Figure 4.25: NRL vs No. of Smart Meters

c) *Average Energy Consumption*

The results for average energy consumption of nodes are shown in Figure 4.26.

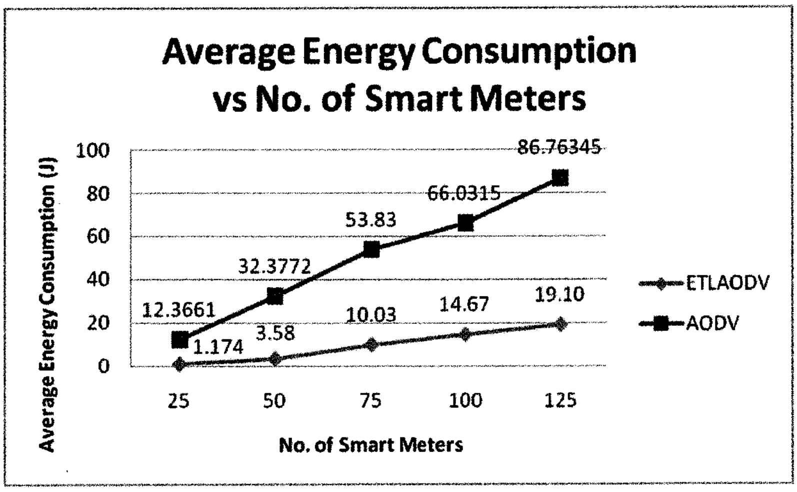


Figure 4.26: Average Energy Consumption vs No. of Smart Meters

ETL-AODV has much better energy consumption as compared to AODV due to inclusion of energy metric in routing decisions. This metric is much useful for battery powered smart meters such as water and gas meters for prolonging network and node lifetime.

d) *Average End-to-End Delay*

The results for average end-to-end delay are shown in Figure 4.27. Both protocols show increasing trend with increase in number of houses. ETL-AODV exhibits a bit higher delay due to additional route selection phase in destination node. However, as time constraint is not issue in smart metering applications so this can be compromised for improved PDR, NRL and energy consumption of nodes.

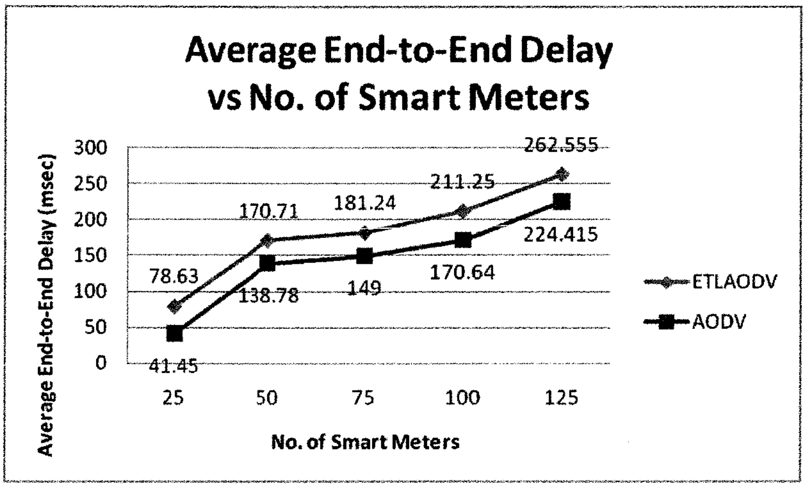


Figure 4.27: Average End-to-End Delay vs No. of Smart Meters

4.3.2.3 Conclusions Drawn from Simulation Study II

From simulation study II, it is inferred that:

- Performance of the network decreases with increase in number of communication nodes.

- Energy, Traffic Load and Link quality should all be considered for improved packet delivery ratios, reduced energy consumption and routing control overheads.
- Although ETL-AODV exhibits relatively larger delay, however, it can be relaxed when compared with huge improvements obtained in other performance metrics.
- For retaining delivery ratios above 90% with ETL-AODV, each individual 'Area' should have a maximum of 75 smart metering nodes (homes).

4.3.3 Simulation Study III: Effect of Inter Meter Spacing

In this simulation study, the effect of inter meter distances is analyzed on the performance metrics for both AODV and ETL-AODV protocols.

4.3.3.1 Network Simulation Settings

50 homes topology was chosen with three inter-meter distances (30m, 50m and 70 m). All of the metering nodes were configured to start sending data to sink at a time chosen from uniform random distribution (0 - 60) seconds with interval chosen as 1 packet per minute. Shadowing Propagation model was chosen to simulate an outdoor "shadowed urban area" with the parameters set as *path loss exponent* = 2.7 and *standard deviation* = 4. All simulations were run for 1 hour.

4.3.3.2 Results and Analysis

a) *Packet Delivery Ratio (PDR)*

The results for PDR are shown in Figure 4.28. Both of the protocols follow declining trend with an increase in inter meter distances. This is due to the fact that when nodes are close to one another in ad-hoc network, variety of routes are available thus enhancing PDR. As inter distance between nodes starts to increase, PDR is severely affected due to shadowing effects. ETL-AODV outperforms AODV for all three inter meter distances due to formation of optimum paths.

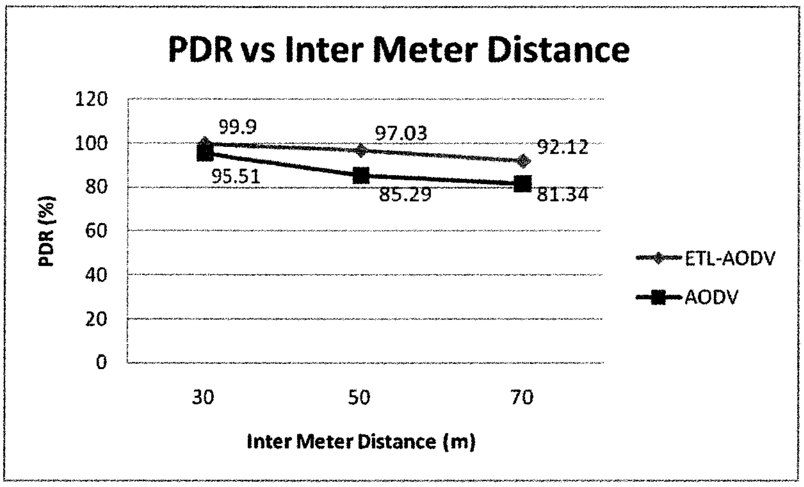


Figure 4.28: PDR vs Inter Meter Distance

b) *Normalized Routing Load (NRL)*

The results for NRL for ETL-AODV and AODV are plotted in Figure 4.29. NRL gradually increases with an increase in inter meter distances. However, significant improvement is observed in case of ETL-AODV due to optimized route discovery leading to less control overhead. Formations of stable optimum paths leads to less route breakages and ultimately lower NRL.

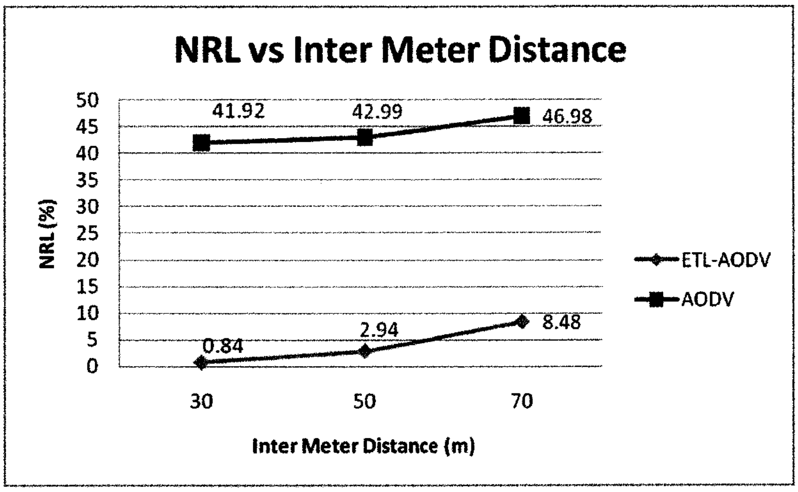


Figure 4.29: NRL vs Inter Meter Distance

c) *Average Energy Consumption*

The results for Average Energy Consumption for both protocols are plotted in Figure 4.30. As observed, ETL-AODV exhibits much lower average energy consumption as compared to AODV which increases with increasing inter meter distances. Unstable routes are prone to frequent breakages due to shadowing effects leading to high overhead route discoveries which increase energy consumption of nodes. This is harmful for battery operated smart meters such as gas and water smart meters.

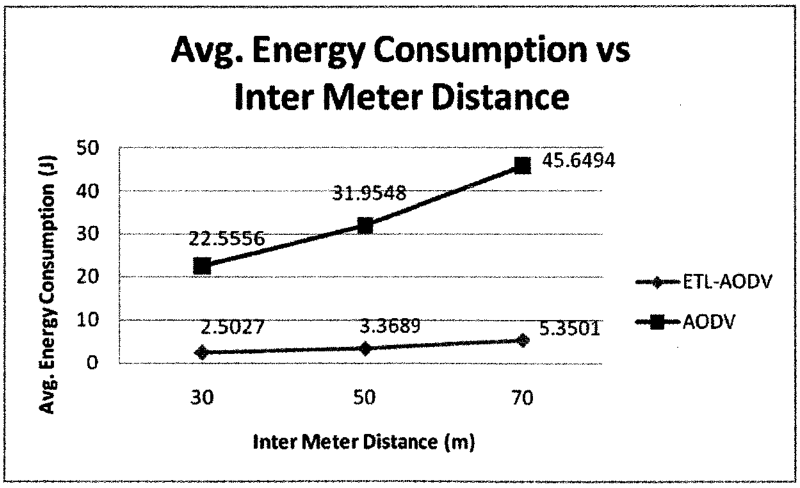


Figure 4.30: Average Energy Consumption vs Inter Meter Distance

d) *Average End-To-End Delay*

The results for average end-to-end delay are shown in Figure 4.31. ETL-AODV has higher average end-to-end delay as compared to AODV for 30m inter meter spacing due to additional route selection waiting time at sink node. However, latency in AODV is higher as compared to ETL-AODV at 50m and 70m inter meter spacing. This is due to the fact that at large distance, links are prone to more breakages due to link fluctuations results from shadowing effects which severely effects AODV performance.

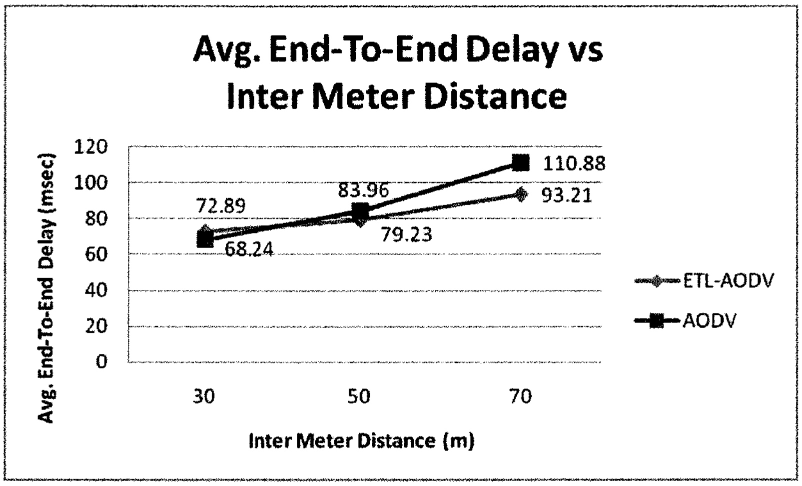


Figure 4.31: Average End-to-End Delay vs Inter Meter Distance

4.3.3.3 Conclusions Drawn from Simulation Study III

From the analysis of results of simulation study III, it can be concluded that:

- Performance of the network decreases with increase in inter-meter distances.
- ETL-AODV outperforms AODV for all set of inter meter distances (30m, 50m and 75m)

4.4 Summary

This chapter presents simulation results and analysis of the proposed ETL-AODV routing protocol and its performance is accessed against AODV routing protocol. The chapter starts with introduction of network simulator (NS-2) along with the description of simulation design and performance metrics. The simulations are grouped in the form of three studies analyzing effect of individual metrics, metering nodes density and inter-meter distances respectively. It is found that in all simulations, ETL-AODV outperforms AODV routing protocol and, therefore, it can be a good choice for resource constrained smart metering infrastructure (Neighborhood Area Networks).

CHAPTER 5

CONCLUSION AND FUTURE DIRECTION

This chapter concludes the thesis with summary of the overall research work and highlighting the achievement of research objectives, research contributions and recommendations for future work.

5.1 Research Summary

Ad-hoc network is an infrastructure less self-organizing class of wireless network which is a promising candidate for establishing smart metering communication infrastructure. Smart meters (Electric, Water and Gas) are resource constrained nodes, which can either have a built-in wireless transceiver or have a wireless sensor attached to them to form multi hop ad-hoc network for uploading real time power usage statistics to some collector sinks. The protocol stack for ad-hoc networks vary widely depending upon the applications. Routing in Ad-hoc networks is a challenging issue and it requires protocols specifically designed by keeping in mind the network and the nodes' unique characteristics as well as the application concerned.

The aim of this research is to develop an ad-hoc routing protocol for smart metering infrastructure that possesses high delivery ratio, low energy consumption and reduced routing overhead to support a reliable, energy efficient and light weight routing. The protocol is designed by keeping in mind the hardware restrictions of metering nodes that they are of limited processing capability, storage and energy supply. Electric meters are mostly powered by mains lines, however, gas and water smart meters are battery powered. Due to large number of communicating nodes, those that are closed to the collector nodes become involved in lots of multi-hop transmissions thus experiencing traffic bottleneck congestion. Obstacles such as trees form shadowing effects and degrade link qualities. The proposed protocol is designed to address all of these constraints.

Most of the literature available in area of ad-hoc networks is related to mobile ad-hoc networks (MANETs) and very few research works have been done in the field of ad-hoc deployment of smart meters. Therefore, the literature available on MANETS was studied to identify routing design tactics, methodologies and limitations. Literature survey on comparative analysis of routing protocols indicated On-demand routing (AODV) is more suitable for resource constrained nodes. The preliminary simulations in comparing reactive, proactive and hybrid ad-hoc routing protocols complemented initial survey findings that AODV is best suited for resource constrained smart metering topology. Therefore, AODV protocol was chosen as base routing algorithm (Route discovery and Maintenance phase) and was analyzed further in detail. It was found that like many others, this protocol is designed based on single routing metric approach (hop count). This single routing criterion has limitations in terms of overloading and depleting node's resources along a chosen route.

To overcome this, multiple metrics technique was developed such that during route discovery phase, each intermediate node embeds its residual energy, traffic load and link quality (E, T, L) in route requests packets and finally the destination node can select the most suitable route keeping in mind the multiple metrics parameters (E, T, L) along with the hop count. Weighted coefficients are utilized for accommodating heterogeneity among mainlines powered and battery powered nodes. To keep protocol design light weight and simple, Route Cache is kept only at the destination node with having only one RREQ entry per source node. Moreover, low energy alert has been implemented for reducing packet drops resulting from low energy issues.

The proposed protocol was implemented in network simulator NS-2 using C++ language and simulation scenarios were created using TCL scripting language. The performance of the protocol was assessed against AODV protocol using performance metrics of packet delivery ratio, normalized routing load, average energy consumption of the network and average end-to-end delay. The simulation studies were grouped into three groups. The first simulation was further sub-divided into three scenarios each considered only one of the three (E, T, L) metrics for highlighting their importance. It was found that the proposed protocol outperformed AODV in each scenario. The second simulation study considered the effect of the number of metering nodes on the protocols performances. Simulation topologies consisted of regular grid structure as observed in most of the real world housing topologies. IEEE 802.11 was utilized at PHY and MAC layers while Shadowing radio propagation model was utilized for more realistic results. It was found that for each set of nodes, ETL-AODV performed reasonably better than AODV protocol. It was concluded that to attain more than 90% PDR using ETL-AODV routing protocol with one packet per minute as metering interval, geographical regional should be divided into areas such that each area should have a maximum of 75 metering nodes associated with the corresponding area's data collector. The third simulation study was concerned with the effect of inter meter distances on protocols performances. It was found that performance decreases with increase in inter meter distances, however, for each distance ETL-AODV again performed better than AODV routing protocol.

As a conclusion based on the results obtained by using Network Simulator (NS-2), the proposed protocol is energy, traffic load and link quality aware ad-hoc routing protocol that is able for providing reliable, energy efficient and light weight routing in ad-hoc network of resource constrained smart meters.

5.2 Achievement of Research Objectives

The objectives of this research work are outlined below along with their respective achievements:

1. To study existing well known Ad-hoc routing schemes (Reactive and Proactive) and find out which can be best applicable in an ad-hoc network of smart meters.

   To achieve this objective, detailed literature survey complemented with initial simulation was done and it was found Reactive (On-demand) ad-hoc routing is more suitable for smart metering infrastructure with AODV best suited for resource constrained smart meters.

2. To analyze the issues and problems associated with the selected Ad-hoc routing scheme when applied in an Ad-hoc network of smart meters.

   To achieve this objective, literature survey was done along with the simulation findings and it was found that single routing metric (hop count) can overload and deplete network resources along the preferred paths. Moreover, a route once selected is continued to be utilized oblivious of energy level of the nodes.

3. To propose a new ad-hoc routing protocol for reliable, light weight and energy efficient routing in smart meter network that can be deployed in ad-hoc network model.

   To achieve this objective, a new application specific routing protocol (ETL-AODV) was designed, based on features of original AODV routing algorithm. It considers energy level of the nodes, traffic load and link qualities during route formation for reliable, energy efficient and light weight routing in ad-hoc network of smart meters.

4. To evaluate the performance of the proposed protocol through rigorous simulations.

   To achieve this objective, proposed protocol was implemented as a standalone routing protocol in Network Simulator (NS-2) and extensive simulations in the form of three simulation studies were carried out and its performances was compared against AODV protocol using performance metrics of packet delivery ratio, normalized routing load, average energy consumption of the nodes and average end-to-end delay.

5.3 Research Contributions

This research work makes the following main research contributions:

1. Comparative analysis of ad-hoc routing schemes (Proactive Vs Reactive) for ad-hoc deployment of smart meters. This thesis proposes reactive over

proactive ad-hoc routing schemes for resource constrained smart metering nodes based on the claims bolstered by literature survey findings and consolidated by preliminary simulation results. Furthermore, among reactive ad-hoc routing class, AODV is proposed and its shortcomings are highlighted.

2. Propose and develop reliable, energy efficient and light weight routing scheme for ad-hoc network using smart meters. In this thesis, energy, traffic load and link quality aware ad-hoc routing protocol is proposed for routing in smart metering infrastructure. Multiple metrics routing criterion is proposed and associated route discovery, selection and management phases are carefully designed.

3. Implementation and evaluation of the proposed protocol. The proposed protocol has been implemented as a standalone routing layer in network simulator NS-2. The performance of the protocol is compared with the original AODV routing protocol. In terms of performance metrics, the proposed protocol achieves higher packet delivery ratios, lower energy consumption and routing overheads as compared to AODV protocol. The proposed protocol can be utilized with any set of protocol stack.

4. Open up a new research path for multiple-metric aware routing protocol for smart metering application.

5.4 Future Directions

Some of the few interesting future directions based on extension of the research work presented in this thesis are as follows:

1. The weight coefficients of Energy, Traffic load and Link quality parameters in Eq. 3.6 i.e. W_E, W_T, W_L can be optimized for best solution using various techniques such as first constructing 'Pareto-optimal Front' and then picking up a non-dominated solution. This is a multi-criteria decision making

(MCDM) problem and there can be methods like TOPSIS, PROMETHEE, ELECTRE, and AHP [60].

2. This multiple metrics scheme can be utilized in other on-demand ad-hoc routing protocols such as DSR and DYMO [61] with little or no modifications.
3. In smart metering application, data packets are continually sent out at regular intervals to the sink node. The routing table information or ETL values can be piggybacked on data packets payload so destination can have routing related information about nodes without exchange of additional control messages.
4. Simulation topologies can be created using Geographical Information Systems (GIS) data corresponding to the realistic network topologies of actual smart meter network deployments worldwide.
5. In the simulations, many-to-one scenario was simulated. One-to-many scenarios, where collector communicates with set of meters for control or data retransmission requirements, shall be simulated and investigated. Moreover, self-healing behavior of the proposed protocol can also be investigated by switching off some nodes randomly.
6. The protocol can be implemented physically using Laptops running UNIX operating systems or wireless sensor nodes to provide important comparison between simulation and real hardware results.

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LIST OF PUBLICATIONS

Journal Publications

1. H. Farooq and L. T. Jung, "Energy, Traffic Load and Link Quality Aware Ad-hoc Routing Protocol for Wireless Sensor Network based Smart Metering Infrastructure," International Journal of Distributed Sensor Networks, vol. 2013, pp. 13, 2013.
   (ISI Indexed Impact Factor: 0.727, 2013).

Conference Publications

1. H. Farooq and L. T. Jung, "Multi Metric On-Demand Ad-hoc Routing Protocol for Wireless Smart Metering Deployment," IEEE 11th Malaysia International Conference on Communication (MICC), Kuala Lumpur, 2013.

2. H. Farooq and L. T. Jung, "Performance Analysis of Ad-hoc Routing Protocols In Smart Metering Infrastructure," Science and Information Conference (SAI), London, UK, 2013.

3. H. Farooq and L. T. Jung, "Performance Analysis of AODV Routing Protocol for Wireless Sensor Network based Smart Metering," IOP Conference Series: Earth and Environmental Science, vol. 16, p. 012003, 2013.

4. H. Farooq and L. T. Jung, "Health, link quality and reputation aware routing protocol (HLR-AODV) for Wireless Sensor Network in Smart Power Grid," International Conference on Computer & Information Science (ICCIS), pp. 664-669, 2012.

Fellowships

1. IETF 86th Fellowship (USA, March'13) for work on AODV for Smart Metering Infrastructure.

- Discussed proposed ETL-AODV protocol with developers of AODV Routing Protocol (IETF MANET Working Group).

APPENDIX A

PERFORMANCE ANALYSIS OF AD-HOC ROUTING PROTOCOLS IN SMART METERING INFRASTRUCTURE

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Abstract— **Smart Metering Infrastructure is an integral part of the Smart Power Grid Revolution. Wireless Ad-hoc Network is considered a promising candidate for enabling smart metering communications. This paper investigates which kind of Ad-hoc routing scheme (proactive, reactive and hybrid) will be most suitable for Smart Metering Infrastructure. Simulation studies utilizing three different topologies are conducted to analyze the performance of the protocols and relative comparison is provided based on four metrics of (i) Packet Delivery Ratio, (ii) Average Energy Consumption of Nodes (iii) Average End-End Delay and (iv) Normalized Routing Load.**

Keywords— Smart Grid; Ad-hoc Network ; Smart Metering; Routing Protocol; OLSR; DSDV; AODV; DSR; ZRP

I. INTRODUCTION

Smart Metering is the core component of the Smart Grid concept wherein modern communication technologies are utilized for enhancing power generation, transmission and distribution [1]. Smart Metering Network also referred to as Neighborhood Area Network (NAN) consists of Smart meters communicating with one another and local access point forming mesh network. Smart meters in addition to performing traditional metering function, also serve as widely deployed sensors across the whole power network. Smart Metering infrastructure enable electric companies to measure voltage, current, power factor and send outage notifications, for improving reliability in all stages of its operations. This helps electric companies in accurate load forecasting and better load management to preemptively bolster the power grid against service outages [2].

It is envisaged that wireless ad-hoc network will be the key technology in smart metering infrastructure. Smart meters with wireless capability could transmit their own and forward other meter readings to the collector. Self-configuring nature leads to ease in network deployment and management. Smart metering network, although static network, pose some complexities due to all the nodes communicating with single collector. This ad-hoc network deployment of smart meters is greatly influenced by the nature of ad-hoc routing protocol used. Proactive protocols optimize routing delays at expense of bandwidth and power consumption while reactive protocols are bandwidth and energy efficient at expense of route discovery delays. Although power is not issue for electric meters since they are powered by main lines however water and gas smart meters are battery powered. Batteries are used as a power source for various functions in the meters such as for collecting and transmitting data. Moreover during line breaks, all smart meters run on internal batteries. So energy consumption of ad-hoc routing protocol needs to be taken into account for battery-powered wireless metering applications [3]. As such, it is necessary to determine what kind of ad-hoc routing protocol (Proactive, Reactive, Hybrid) will perform best in smart metering ad-hoc network based on metrics of Packet Delivery Ratio, Average Energy Consumption, Average End-End Delay and Normalized Routing Load.

The objective of this paper is to analyze the performance of (Reactive, Proactive and Hybrid) ad-hoc routing protocols for smart metering scenario and determine which one of them will be most suitable for this kind of deployment. The rest of this paper is organized as follows: Section II provides glimpse of related protocols for smart metering infrastructure. Section III provides an overview of ad-hoc routing protocols. Methodology is described in Section IV. Simulation results and comparative analysis is given in Section V. Finally section VI draws conclusion and provide directions for future work.

II. RELATED WORK

Although researchers have done performance evaluation studies of routing protocols for ad-hoc networks but most of them are concerned with mobile ad-hoc networks (MANETS) such as in [4] where nodes are free to move. Smart Meters deployment differs from traditional ad-hoc deployment in sense that nodes are static and all nodes transmit their readings simultaneously to a single readings collector (sink). Large scale deployment of smart meters also affects the performance of ad-hoc network. S. Ullo et al. [5] simulated AODV for smart metering infrastructure for measuring end to end delay, traffic congestion and worm-hole security attack and concluded end-end delay and PDR is affected with increase in number of nodes.

Some dedicated ad-hoc routing protocols have designed for smart metering applications such as in [6], [7], [8] and [9]. They have been designed for enhancing reliability of smart metering communication. However in this paper we restrict ourselves to testing smart metering topology using only classical ad-hoc routing protocols (AODV [10], DSR [11], DSDV [12], OLSR [13] and ZRP [14]) as the scope of this paper is to find out which kind of ad-hoc routing protocol (Reactive, Proactive and Hybrid) performs better in smart metering scenario. Furthermore the aforementioned protocols are building blocks of all ad-hoc routing protocols existing today. The main contribution of this paper is comparative analysis of Ad-hoc routing protocols in the scope of smart metering infrastructure.

III. AD-HOC ROUTING PROTOCOLS

In this section we review the most commonly used Ad -hoc routing protocols. Ad-hoc routing protocols are classified as:

A. Reactive (On Demand):

In these protocols, routes are formed only when required. Example: Ad hoc on-demand Distance Vector (AODV), Dynamic Source Routing (DSR).

1) AODV

In AODV, nodes broadcast route requests for new route discoveries which are replied back by the destination or intermediate nodes if they have recently used a route to the destination. Nodes keep minimal routing table size with one node per destination. Sequence number ensures loop free routing.

2) DSR

DSR is based on source routing in which complete path is specified in the packet header to eliminate periodic table-update messages. However this approach results in high overhead for long paths.

B. Proactive (Table driven):

In Proactive protocols, every node maintains a table of routes for all the network nodes and requires the frequent exchange of control messages for routing purposes. Examples: Destination-Sequence Distance-Vector (DSDV), Optimized Link State Routing Protocol (OLSR).

1) DSDV

DSDV is based on Bellman Ford routing algorithm in which each node maintains a table of routes to all available destinations, and nodes frequently exchange topology messages to update routing information. It utilizes sequence number to eliminate routing loops.

2) OLSR

OLSR route discovery delay is absent since route are already available due to topology message exchanges. OLSR optimizes flooding process through Multipoint Relaying Technique (MPR) such that only selected nodes broadcast topology information during flooding process.

C. Hybrid:

Hybrid Protocols combines characteristics of Proactive and Reactive protocols. Example: Zone Routing Protocol (ZRP).

1) ZRP

ZRP defines routing zone around a node which uses proactive routing while communication between zones is done through reactive routing. As a result, control overhead is reduced along with the latency associated with route discovery procedures.

IV. METHODOLOGY

We simulated five ad-hoc routing protocols (OLSR, DSDV, AODV, DSR, ZRP) using the well researched Network Simulator NS-2[15]. We used regular grid pattern of node deployment for our simulations similar to real geographic residential topology such as shown in Figure 1. Most of the simulation studies on Smart Grid, such as in [16], use regular pattern of node deployment since modern housing deployments utilizing smart metering infrastructure follow this pattern. Three flat regular grid topologies with number of nodes 25, 50 and 75 were used in the simulations to analyze and compare the protocols performance.

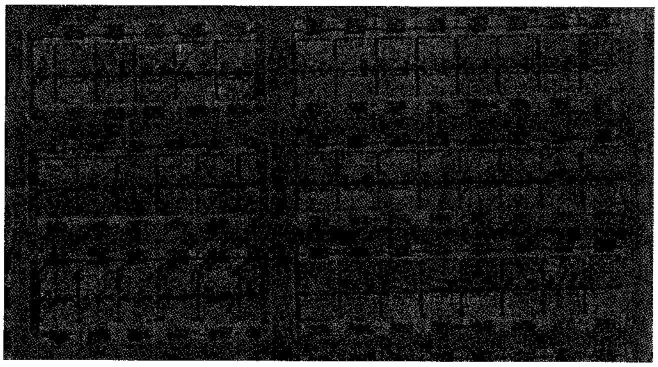

Fig. 1. Real World Housing Topology

Simulation settings are given in Table I. All smart meters sent constant bit rate traffic (CBR) of 100 bytes packet size to the sink node. The traffic interval was chosen to be 1 packet per minute. All metering traffic started at time interval chosen randomly from [0-60] seconds interval.

TABLE I. PROTOCOLS SIMULATION PARAMETERS

Simulation Parameters	
Routing Protocol	OLSR,DSDV,AODV,DSR,ZRP
MAC layer/ PHY layer	802.11
Channel type	Wireless Channel
Propagation model	Two Ray Ground
Traffic Type	CBR
CBR Packet Size	100 Bytes
Interface Queue Type	Queue/DropTail/PriQueue
Antenna Model	Omni Antenna
Simulation Time	3600 Sec

We simulated the selected five ad-hoc routing protocols to benchmark their performance in scope of smart metering scenarios.

V. SIMULATION RESULTS

The simulation results attained for five ad-hoc routing protocols are described below:

A. Packet Delivery Ratio

This metric represents the reliability of the protocol by measuring how much of the transmitted packets made up to the receiver. It is measured as:

$$\frac{\sum \textbf{Number of Received Data Packets}}{\sum \textbf{Number of Sent Data Packets}} \quad (1)$$

It is desirable to have maximum packet delivery ratio.
The simulation results for Packet Delivery Ratio are shown in Fig. 2. The results indicate DSR outperforms all others with 100% packet delivery ratio for 25 and 50 nodes and minimal packet loss for 75 nodes. Then comes the ZRP protocol with packet delivery ratio around 99.9%. AODV, DSDV and OLSR exhibit reasonable packet delivery ratio of above 99.70%. In all cases, packet delivery ratio continues to decrease with increase in number of nodes.

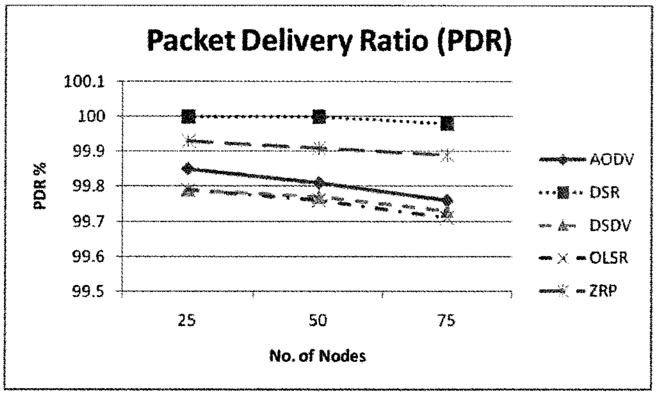

Fig. 2. Packet Delivery Ratio vs No.of Nodes

B. Average Energy Consumption

This metric measures average energy consumption of the nodes in the network with respect to the protocol used. It is measured as:

$$\frac{\textbf{Sum of Residual Enrgy of all the Nodes}}{\textbf{Total number of Nodes}} \quad (2)$$

Battery powered smart meters (Water and Gas Smart meters) requires energy efficient protocol operation for prolonging network lifetime. The results given in Fig. 3 indicate highest energy consumption in ZRP routing protocol due to exchange of large number of routing messages exchange. OLSR shows higher energy consumption as compared to the rest of the protocols. Lowest energy consumption is observed in AODV protocol.

C. Average End-to-End Delay

This metric indicates latency in the communication network. It is defined as:

$$\frac{\textbf{Total time taken by all the Packets to reach Destination}}{\textbf{Total number of Packets}} \quad (3)$$

Protocol should have minimum average delay for prompt data transfer. Although metering application are less sensitive to delays however outages notifications require to be transmitted without any delay. The results for Average end-to-end delays are shown in the Fig. 4. Highest delay is observed in AODV due to initial route discovery procedure. ZRP shows slight higher end-end delay as compared to DSDV. The minimum delay is observed in DSR and OLSR routing protocols.

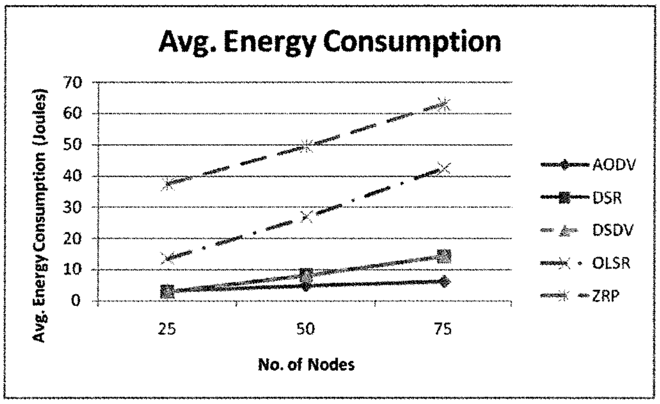

Fig. 3. Avg. Energy Consumption vs No. of Nodes

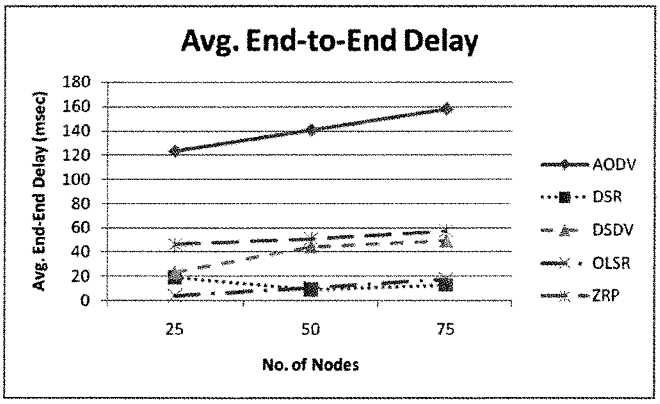

Fig. 4. Avg. End-to-End Delay vs No. of Nodes

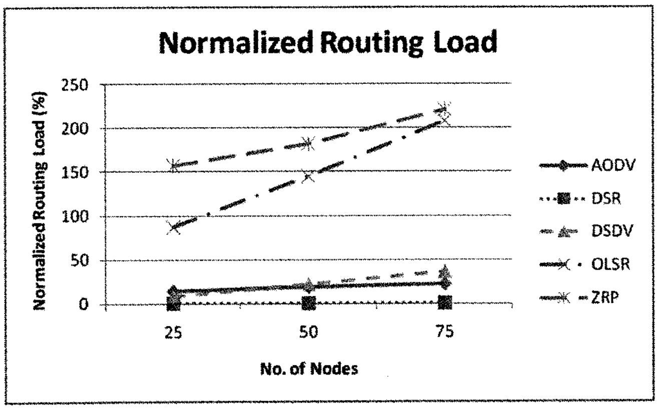

Fig. 5. Normalized Routing Load vs No. of Nodes

D. Normalized Routing Load

It represents number of routing control packets exchanged in the network. It is defined as:

$$\frac{\sum \textbf{Number of Received Routing Packets}}{\sum \textbf{Number of Received Data Packets}} \qquad (4)$$

It is desirable to have minimum routing overhead for the efficient operation of the network. Fig. 5 shows normalized routing load of the protocols. ZRP is the most expensive in terms of routing overhead. OLSR shows a slight higher control packet exchange as compared to the rest of the protocols. AODV and DSR have lower routing overheads then other three protocols with DSR having the least.

VI. CONCLUSION & FUTURE WORK

In this paper, we presented the simulated performance of the most common Ad-hoc routing protocols (OLSR, DSDV, ZODV, DSR, ZRP) for smart metering scenario. The results for all the performance metrics indicate OLSR and ZRP have poor performance for this specific network. Although DSR outperforms all the protocols however it suffers from large routing packet header size for large number of nodes since it carries the complete path in its header structure. This is not suitable for large number of resource constrained nodes deployment. It is the same case for DSDV since it enlists all available destinations in its routing table with routes which may never be used and topology message exchange even in the absence of traffic. This leaves us with AODV routing protocol which in spite of large end-end delay, shows comparable performance with DSR and DSDV. An important feature of AODV is small routing table size with only frequently used routes.

In light of these simulation results, it can be concluded that reactive ad-hoc routing protocols AODV and DSR show satisfactory performance for smart metering deployment. However, AODV will be best suited for resource constrained static nodes as in the case of wireless sensor network. In future work, we want to test these protocols on hardware platform to consolidate our simulation results.

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APPENDIX B

SAMPLE CODE

```
============================================================================
//Sample etlaodv.cc file code

#include <etlaodv/etlaodv.h>
#include <etlaodv/etlaodv_packet.h>
#include <random.h>
#include <cmu-trace.h>
#define max(a,b)        ( (a) > (b) ? (a) : (b) )
#define min(a,b)        ( (a) < (b) ? (a) : (b) )
#define CURRENT_TIME    Scheduler::instance().clock()
/*
   Constructor
*/
ETLAODV::ETLAODV(nsaddr_t id) : Agent(PT_ETLAODV),btimer(this), htimer(this),
ntimer(this), rtimer(this), lrtimer(this), rqueue(), rqtimer(this),
rreqpurgetimer(this)
{
      index = id;
      seqno = 2;
      bid = 1;
      MobileNode *iNode;
      iEnergy = 0.0;
      ETL = 0.0;
      RREQ_Selecting = false;
      change_route_notify = false;
      time_old = 0.0;
      time_new = 0.0;
      interval_old = 0.0;
      interval_new =0.0;
      interval = 1.0;
      LIST_INIT(&nbhead);
      LIST_INIT(&bihead);
      LIST_INIT(&rreqhead);
      logtarget = 0;
      ifqueue = 0;
}
/*
   Timers
*/
void ETLRreqPurgeTimer::handle(Event*)
{
      agent->RREQ_purge();
      Scheduler::instance().schedule(this, &intr, RREQ_Purge);
}
void ETLRREQReplyTimer::handle(Event*)
{
      fprintf(stderr, "The Timer function is called at %.4f\n",CURRENT_TIME);
      agent->RREQ_reply();
}
void ETLBroadcastTimer::handle(Event*)
{
      agent->id_purge();
```

```
        Scheduler::instance().schedule(this, &intr, BCAST_ID_SAVE);
}
/*
   Broadcast ID Functions
*/
void ETLAODV::id_insert(nsaddr_t id, u_int32_t bid)
{
        ETLBroadcastID *b = new ETLBroadcastID(id, bid);
        assert(b);
        b->expire = CURRENT_TIME + BCAST_ID_SAVE;
        LIST_INSERT_HEAD(&bihead, b, link);
}
bool ETLAODV::id_lookup(nsaddr_t id, u_int32_t bid)
{
        ETLBroadcastID *b = bihead.lh_first;
        for( ; b; b = b->link.le_next)
        {
                if ((b->src == id) && (b->id == bid))
                return true;
        }
        return false;
}
void ETLAODV::id_purge()
{       ETLBroadcastID *b = bihead.lh_first;
        ETLBroadcastID *bn;
        double now = CURRENT_TIME;
        for(; b; b = bn)
        {
                bn = b->link.le_next;
                if(b->expire <= now)
                {
                        LIST_REMOVE(b,link);
                        delete b;
                }
        }
}
/*
   RREQ Cache Functions
*/
void ETLAODV::RREQ_insert(nsaddr_t id, u_int32_t bid,double rqETL,double
rqtimestamp,
u_int32_t rqseqno, nsaddr_t im)
{
        ETLRREQID *b = new ETLRREQID(id, bid,rqETL,rqtimestamp,rqseqno,im);
        ETLRREQID *ba = rreqhead.lh_first;
        ETLRREQID *bn;
        assert(b);
        b->replied = false;
        LIST_INSERT_HEAD(&rreqhead, b, link);
}
bool ETLAODV::RREQ_lookup(nsaddr_t id, u_int32_t bid,double rqETL)
{
        ETLRREQID *b = rreqhead.lh_first;
        for( ; b; b = b->link.le_next)
        {
                if ((b->src == id) && (b->id == bid) &&(b->rreq_ETL >= rqETL))
                return true;
```

```
      }
      return false;
}
void ETLAODV::RREQ_purge()
{
      ETLRREQID *b = rreqhead.lh_first;
      ETLRREQID *bn;
      for(; b; b = bn)
      {
            bn = b->link.le_next;
            LIST_REMOVE(b,link);
            delete b;
      }
}
void ETLAODV::RREQ_reply()
{
      RREQ_Selecting = false;
      etlaodv_rt_entry *rt, *rtn;
      ETLRREQID *b = rreqhead.lh_first;
      ETLRREQID *bn;
      for(; b; b = bn)
      {
      bn = b->link.le_next;
      if (b->replied != true)
      {
            seqno = max(seqno, b->rreq_seqno)+1;
            if (seqno%2) seqno++;
            sendReply(b->src,1,index,seqno,MY_ROUTE_TIMEOUT,b-
            >rreq_timestamp, b->im);
            fprintf(stdout,"Node: %d sending Reply at
            %.4f\n",index,CURRENT_TIME);
            b->replied = true;
      }
}
/*
   LOW ENERGY NOTIFY Function
*/
void ETLAODV::Energy_Low_Notify()
{
      double Node_Energy;
      iNode = (MobileNode *)(Node::get_node_by_address(index));
      iEnergy = iNode->energy_model()->energy();
      Node_Energy = (double)(iEnergy)/(iNode->energy_model()-
      >initialenergy());
      if(Node_Energy > ROUTE_ERROR_THRESHOLD)
      {
      change_route_notify = false;
      }
}
/*
   RREQ Receive Function
*/
void ETLAODV::recvRequest(Packet *p)
{
      struct hdr_cmn *ch = HDR_CMN(p);
      struct hdr_ip *ih = HDR_IP(p);
      struct hdr_aodv_request *rq = HDR_AODV_REQUEST(p);
```

```
etlaodv_rt_entry *rt;
int lq;
double tmpf;
double TrafficLoad;
double LinkQuality;
double HopFactor;
int hops;
double Energy;
double finalETL;
iNode = (MobileNode *)(Node::get_node_by_address(index));
iEnergy = iNode->energy_model()->energy();
Energy = (double)(iEnergy)/(iNode->energy_model()->initialenergy());
tmpf = p->txinfo_.RxPr/(RXThreshold);
lq = (int)(tmpf * 128);
if (lq > 255) lq = 255;
LinkQuality = (double)(lq)/255;
TrafficLoad = interval;
hops = rq->rq_hop_count;
if (hops > NETWORK_DIAMETER) hops = NETWORK_DIAMETER;
HopFactor = (double)(NETWORK_DIAMETER - hops)/(NETWORK_DIAMETER);
ETL = (double) ( Energy + TrafficLoad + LinkQuality)/3;
      if(rq->rq_src == index)
{
      Packet::free(p);
      return;
}
if(rq->rq_dst != index)
{
      if (id_lookup(rq->rq_src, rq->rq_bcast_id))
      {
            Packet::free(p);
            return;
      }
}
id_insert(rq->rq_src, rq->rq_bcast_id);
etlaodv_rt_entry *rt0; // rt0 is the reverse route
rt0 = rtable.rt_lookup(rq->rq_src);
if(rt0 == 0)
{
      rt0 = rtable.rt_add(rq->rq_src);
}
rt0->rt_expire = max(rt0->rt_expire, (CURRENT_TIME + REV_ROUTE_LIFE));
if (rq->rq_dst != index)
{
      if ( (rq->rq_src_seqno > rt0->rt_seqno ) ||
      ((rq->rq_src_seqno == rt0->rt_seqno) &&
      (rq->rq_hop_count < rt0->rt_hops)) )
      {
            rt_update(rt0, rq->rq_src_seqno, rq->rq_hop_count, ih-
            >saddr(),max(rt0->rt_expire, (CURRENT_TIME +
            REV_ROUTE_LIFE)) );
            if (rt0->rt_req_timeout > 0.0)
            {
                        rt0->rt_req_cnt = 0;
                        rt0->rt_req_timeout = 0.0;
                        rt0->rt_req_last_ttl = rq->rq_hop_count;
```

```
                        rt0->rt_expire = CURRENT_TIME +
                        ACTIVE_ROUTE_TIMEOUT;
                }
                assert (rt0->rt_flags == RTF_UP);
                Packet *buffered_pkt;
                while ((buffered_pkt = rqueue.deque(rt0->rt_dst)))
                {
                        if (rt0 && (rt0->rt_flags == RTF_UP))
                    {
                        assert(rt0->rt_hops != INFINITY2);
                        forward(rt0, buffered_pkt, NO_DELAY);
                        }
                }
        }
}
rt = rtable.rt_lookup(rq->rq_dst);
if(rq->rq_dst == index)
{
        rq->rq_ETL = (rq->rq_ETL) * (LinkQuality);
        finalETL = (0.5 * rq->rq_ETL)+(0.5 * HopFactor);
        fprintf(stdout,"Node: %d received rq_ETL value: %.2f finalETL:
        %.2f at Time %.4f from %d of %d with Energy: %.4f\n",index,
        rq->rq_ETL,finalETL,CURRENT_TIME,ih->saddr(),rq->rq_src,iEnergy);
        if (RREQ_lookup(rq->rq_src, rq->rq_bcast_id,finalETL))
        {
                Packet::free(p);
                return;
        }
        else
        {
                if(!RREQ_Selecting)
                {
                        RREQ_Selecting = true;
                        Scheduler::instance().schedule(&rqtimer, p->copy() ,
                        RREQ_Reply);
                        fprintf(stderr, "The Timer has started at time : %.4f
                        \n",CURRENT_TIME);
                }
                RREQ_insert(rq->rq_src, rq->rq_bcast_id,finalETL,
                rq->rq_timestamp,rq->rq_dst_seqno,ih->saddr());
                rt_update(rt0, rq->rq_src_seqno, rq->rq_hop_count, ih-
                >saddr(),
                max(rt0->rt_expire, (CURRENT_TIME + REV_ROUTE_LIFE)) );
                rt0->rt_ETL = finalETL;
                if (rt0->rt_req_timeout > 0.0)
                {
                        rt0->rt_req_cnt = 0;
                            rt0->rt_req_timeout = 0.0;
                            rt0->rt_req_last_ttl = rq->rq_hop_count;
                            rt0->rt_expire = CURRENT_TIME +
                            ACTIVE_ROUTE_TIMEOUT;
                }
                Packet::free(p);
        }
}
else
{
```

```
            fprintf(stdout,"Node: %d --> E: %0.2f, T: %0.2f,
            L: %0.2f\n",index,Energy,TrafficLoad,LinkQuality);
            fprintf(stdout,"Node: %d --> ETL value: %.2f\n",index,ETL);
            rq->rq_ETL = (rq->rq_ETL)* (ETL); // Modification 4
            fprintf(stdout,"Node: %d forwarding rq_ETL value: %.2f at Time
            %.4f from %d of node %d\n",index,
            rq->rq_ETL,CURRENT_TIME,ih->saddr(),rq->rq_src);
            ih->saddr() = index;
            ih->daddr() = IP_BROADCAST;
            rq->rq_hop_count += 1;
            // Maximum sequence number seen en route
            if (rt) rq->rq_dst_seqno = max(rt->rt_seqno, rq->rq_dst_seqno);
            forward((etlaodv_rt_entry*) 0, p, DELAY);
      }
}

/*
Packet Forward Funtion
*/
void ETLAODV::forward(etlaodv_rt_entry *rt, Packet *p, double delay)
{
      struct hdr_cmn *ch = HDR_CMN(p);
      struct hdr_ip *ih = HDR_IP(p);
      double Node_Energy;
      iNode = (MobileNode *)(Node::get_node_by_address(index));
      if(ih->ttl_ == 0)
      {
            drop(p, DROP_RTR_TTL);
            return;
      }
      if (ch->ptype() != PT_ETLAODV && ch->direction() == hdr_cmn::UP &&
      ((u_int32_t)ih->daddr() == IP_BROADCAST) || (ih->daddr() ==
      here_.addr_))
      {
            dmux_->recv(p,0);
            return;
      }
      if (rt) {
                  time_new = CURRENT_TIME;
                  interval_new = time_new - time_old;
                  interval = (((1 - Traffic_Beta) * interval_old) +
                  (Traffic_Beta * interval_new));
                  if (interval > 1.0)
                  {
                        interval = 1.0;
                  }
                  time_old = time_new;
                  interval_old = interval_new;
                  iEnergy = iNode->energy_model()->energy();
                  Node_Energy = (double)(iEnergy)/(iNode->energy_model()->
                  initialenergy());
                  if((ih->saddr() != index) && (Node_Energy <
                  ROUTE_ERROR_THRESHOLD) && ! change_route_notify )
                  {
                        Packet *rerr = Packet::alloc();
                        struct hdr_aodv_error *re = HDR_AODV_ERROR(rerr);
                        re->DestCount = 0;
```

```
                re->unreachable_dst[ re->DestCount] = rt->rt_dst;
                re->unreachable_dst_seqno[ re->DestCount] = rt-
                >rt_seqno;
                re->DestCount += 1;
                fprintf(stdout, "Node %d: sending RERR at time %.4f
                indicating that node %d is unreachable\n",
                index,CURRENT_TIME,rt->rt_dst);
                sendError(rerr, false);
                change_route_notify = true;
            }
            assert(rt->rt_flags == RTF_UP);
            rt->rt_expire = CURRENT_TIME + ACTIVE_ROUTE_TIMEOUT;
            ch->next_hop_ = rt->rt_nexthop;
                ch->addr_type() = NS_AF_INET;
            ch->direction() = hdr_cmn::DOWN;
        }
        else
        {
            assert(ih->daddr() == (nsaddr_t) IP_BROADCAST);
            ch->addr_type() = NS_AF_NONE;
            ch->direction() = hdr_cmn::DOWN;
        }

        if (ih->daddr() == (nsaddr_t) IP_BROADCAST)
        {
            assert(rt == 0);
            if (ch->ptype() == PT_ETLAODV)
            {
                Scheduler::instance().schedule(target_, p,
                0.01 * Random::uniform());
            }
            else
            {
                Scheduler::instance().schedule(target_, p, 0.);  //
                No jitter
            }
        }
        else
        {
            if(delay > 0.0)
            {
                Scheduler::instance().schedule(target_, p, delay);
            }
        else
        {
            Scheduler::instance().schedule(target_, p, 0.);
        }
    }

}
```

```
//=========================================================================
//Sample etlaodv.h code

class ETLAODV;

#define alpha     0
#define beta      0
#define gamma     1
#define Traffic_Beta    0.2
#define ETL_threshold   0.50
#define RXThreshold     1.42681e-08
#define BCAST_ID_SAVE         6
#define RREQ_Reply            0.1
#define RREQ_Purge            6
#define FREQUENCY             60
#define ROUTE_ERROR_THRESHOLD 0.50

class ETLBroadcastTimer : public Handler
{
      public:
        ETLBroadcastTimer(ETLAODV* a) : agent(a) {}
        void      handle(Event*);
      private:
        ETLAODV    *agent;
      Event intr;
};

class ETLRreqPurgeTimer : public Handler
{
      public:
      ETLRreqPurgeTimer(ETLAODV* a) : agent(a) {}
      void    handle(Event*);
      private:
      ETLAODV    *agent;
      Event   intr;
};

class ETLRREQReplyTimer : public Handler
{
      public:
      ETLRREQReplyTimer(ETLAODV* a) : agent(a) {}
      void    handle(Event*);
      private:
      ETLAODV    *agent;
      Event   intr;
};

class ETLBroadcastID
{
      friend class ETLAODV;
      public:
        ETLBroadcastID(nsaddr_t i, u_int32_t b) { src = i; id = b;  }
      protected:
        LIST_ENTRY(ETLBroadcastID) link;
        nsaddr_t        src;
        u_int32_t       id;
        double          expire;         // now + BCAST_ID_SAVE s
```

```
};

LIST_HEAD(aodv_bcache, ETLBroadcastID);

class ETLRREQID
{
      friend class ETLAODV;
      public:
      ETLRREQID(nsaddr_t i, u_int32_t b,double x,double y,u_int32_t
      z,nsaddr_t interm) { src = i; id = b; rreq_ETL = x;
      rreq_timestamp = y;rreq_seqno = z;im = interm; }
      protected:
      LIST_ENTRY(ETLRREQID) link;
      nsaddr_t        src;
      u_int32_t       id;
      double            rreq_ETL;
      double            rreq_timestamp;
      u_int32_t   rreq_seqno;
      nsaddr_t        im;
      bool        replied;
};

LIST_HEAD(aodv_rreqcache, ETLRREQID);

//=============================================================================
// Sample etlaodv_packet.h

/*
RREQ Packet Structure
*/
struct hdr_aodv_request
{
      u_int8_t        rq_type;
      u_int8_t        reserved[2];
      u_int8_t        rq_hop_count;
      u_int32_t       rq_bcast_id;
      nsaddr_t        rq_dst;
      u_int32_t       rq_dst_seqno;
      nsaddr_t        rq_src;
      u_int32_t       rq_src_seqno;
      double            rq_ETL;
      double          rq_timestamp;
      inline int size()
      {
            int sz = 0;
            sz = 8*sizeof(u_int32_t);
            assert (sz >= 0);
            return sz;
      }
};
```

```
//============================================================================
// Sample Tcl File

set val(chan)    Channel/WirelessChannel    ;# channel type
set val(prop)    Propagation/Shadowing      ;# radio-propagation model
set val(netif)   Phy/WirelessPhy            ;# network interface type
set val(mac)     Mac/802_11                 ;# MAC type
set val(ifq)     Queue/DropTail/PriQueue    ;# interface queue type
set val(ll)      LL                         ;# link layer type
set val(ant)     Antenna/OmniAntenna        ;# antenna model
set val(ifqlen)  50                         ;# max packet in ifq
set val(nn)      25                       ;# number of mobilenodes
set val(rp)      ETLAODV                  ;# routing protocol
set val(x)       801                      ;# X dimension of topography
set val(y)       501                      ;# Y dimension of topography
set val(stop)    4000.0                   ;# time of simulation end
set val(cp)        "cbr-1" ;
set val(cbrstop) 3600.0 ;
set ns [ new Simulator]
Phy/WirelessPhy set CSThresh_ 3.13898e-08
Phy/WirelessPhy set RXThresh_ 1.42681e-08
Phy/WirelessPhy set Pt_ 0.281838
Propagation/Shadowing set pathlossExp_ 2.7
Propagation/Shadowing set std_db_ 4.0
Propagation/Shadowing set dist0_ 1.0
Propagation/Shadowing set seed_ 0
set topo       [ new Topography]
$topo load_flatgrid $val(x) $val(y)
create-god $val(nn)
set tracefile [ open out.tr w]
$ns use-newtrace
$ns trace-all $tracefile
set namfile [ open out.nam w]
$ns namtrace-all $namfile
$ns namtrace-all-wireless $namfile $val(x) $val(y)
set chan [ new $val(chan)] ;#Create wireless channel
$ns node-config -adhocRouting  $val(rp) \
                -llType        $val(ll) \
                -macType       $val(mac) \
                -ifqType       $val(ifq) \
                -ifqLen        $val(ifqlen) \
                -antType       $val(ant) \
                -propType      $val(prop) \
                -phyType       $val(netif) \
                -channel       $chan \
                -topoInstance  $topo \
                -agentTrace    ON \
                -routerTrace   ON \
                -macTrace      ON \
                -movementTrace ON \
                -energyModel "EnergyModel" \
                -initialEnergy 500 \
                -rxPower 0.3 \
                -txPower 0.3
$ns node-config -initialEnergy 500.0
set n0 [ $ns node]
$n0 set X_ 600
```

```
$n0 set Y_ 301
$n0 set Z_ 0.0
$ns initial_node_pos $n0 20
$ns node-config -initialEnergy 50.0
set n1 [ $ns node]
$n1 set X_ 551
$n1 set Y_ 401
$n1 set Z_ 0.0
$ns initial_node_pos $n1 20
set n2 [ $ns node]
$n2 set X_ 601
$n2 set Y_ 401
$n2 set Z_ 0.0
$ns initial_node_pos $n2 20
set n3 [ $ns node]
$n3 set X_ 651
$n3 set Y_ 401
$n3 set Z_ 0.0
$ns initial_node_pos $n3 20
set n4 [ $ns node]
$n4 set X_ 701
$n4 set Y_ 401
$n4 set Z_ 0.0
$ns initial_node_pos $n4 20
set n5 [ $ns node]
$n5 set X_ 501
$n5 set Y_ 351
$n5 set Z_ 0.0
$ns initial_node_pos $n5 20
set n6 [ $ns node]
$n6 set X_ 551
$n6 set Y_ 351
$n6 set Z_ 0.0
$ns initial_node_pos $n6 20
set n7 [ $ns node]
$n7 set X_ 601
$n7 set Y_ 351
$n7 set Z_ 0.0
$ns initial_node_pos $n7 20
set n8 [ $ns node]
$n8 set X_ 651
$n8 set Y_ 351
$n8 set Z_ 0.0
$ns initial_node_pos $n8 20
set n9 [ $ns node]
$n9 set X_ 701
$n9 set Y_ 351
$n9 set Z_ 0.0
$ns initial_node_pos $n9 20
set n10 [ $ns node]
$n10 set X_ 501
$n10 set Y_ 301
$n10 set Z_ 0.0
$ns initial_node_pos $n10 20
set n11 [ $ns node]
$n11 set X_ 551
$n11 set Y_ 301
```

```
$n11 set Z_ 0.0
$ns initial_node_pos $n11 20
set n12 [ $ns node]
$n12 set X_ 501
$n12 set Y_ 399
$n12 set Z_ 0.0
$ns initial_node_pos $n12 20
set n13 [ $ns node]
$n13 set X_ 651
$n13 set Y_ 301
$n13 set Z_ 0.0
$ns initial_node_pos $n13 20
set n14 [ $ns node]
$n14 set X_ 701
$n14 set Y_ 301
$n14 set Z_ 0.0
$ns initial_node_pos $n14 20
set n15 [ $ns node]
$n15 set X_ 501
$n15 set Y_ 251
$n15 set Z_ 0.0
$ns initial_node_pos $n15 20
set n16 [ $ns node]
$n16 set X_ 551
$n16 set Y_ 251
$n16 set Z_ 0.0
$ns initial_node_pos $n16 20
set n17 [ $ns node]
$n17 set X_ 601
$n17 set Y_ 251
$n17 set Z_ 0.0
$ns initial_node_pos $n17 20
set n18 [ $ns node]
$n18 set X_ 651
$n18 set Y_ 251
$n18 set Z_ 0.0
$ns initial_node_pos $n18 20
set n19 [ $ns node]
$n19 set X_ 701
$n19 set Y_ 251
$n19 set Z_ 0.0
$ns initial_node_pos $n19 20
set n20 [ $ns node]
$n20 set X_ 501
$n20 set Y_ 201
$n20 set Z_ 0.0
$ns initial_node_pos $n20 20
set n21 [ $ns node]
$n21 set X_ 551
$n21 set Y_ 201
$n21 set Z_ 0.0
$ns initial_node_pos $n21 20
set n22 [ $ns node]
$n22 set X_ 601
$n22 set Y_ 201
$n22 set Z_ 0.0
$ns initial_node_pos $n22 20
```

```
set n23 [ $ns node]
$n23 set X_ 651
$n23 set Y_ 201
$n23 set Z_ 0.0
$ns initial_node_pos $n23 20
set n24 [ $ns node]
$n24 set X_ 701
$n24 set Y_ 201
$n24 set Z_ 0.0
$ns initial_node_pos $n24 20
if {  $val(cp) == ""}
{
      puts "*** Note: no connection pattern specified."
      set val(cp) "none"
}
else
{
      puts "Loading connection pattern..."
      source $val(cp)
}
for {set i 1} {$i < $val(nn) } {  incr i }
{
      $ns at $val(cbrstop) "\$cbr$i stop"
}
proc finish {}
{
      global ns tracefile namfile
      $ns flush-trace
      close $tracefile
      close $namfile
      exec nam out.nam &
      exit 0
}
for {set i 0} {$i < $val(nn) } {  incr i }
{
      $ns at $val(stop) "\$n$i reset"
}
$ns at $val(stop) "$ns nam-end-wireless $val(stop)"
$ns at $val(stop) "finish"
$ns at $val(stop) "puts \"done\" ; $ns halt"
$ns run
```

//===

// Sample Traffic Pattern Input File

```
set opt(nn)        0
set opt(seed)      0.0
set opt(mc)        0
set opt(pktsize)   100
set opt(rate)      0
set opt(interval)  0.0
set opt(type)      ""
proc usage {}
{
      global argv0
```

```
        puts "\nusage: $argv0 \[ -type cbr|tcp\] \[ -nn nodes\] \[ -seed seed\]
\[ -mc connections\] \[ -interval interval\]\n"
}
proc getopt { argc argv}
{
        global opt
        lappend optlist nn seed mc interval type
        for { set i 0} { $i < $argc} { incr i}
        {
                set arg [ lindex $argv $i]
                if {[ string range $arg 0 0] != "-"} continue
                set name [ string range $arg 1 end]
                set opt($name) [ lindex $argv [ expr $i+1]]
        }
}
proc create-cbr-connection {  src dst }
{
        global rng cbr_cnt opt
        set stime [ $rng uniform 0.0 60.0]
        puts "#\n# $src connecting to $dst at time $stime\n#"
        puts "set udp$src \[ new Agent/UDP\] "
        puts "\$ns attach-agent \$n$src \$udp$src"
        puts "set cbr$src \[ new Application/Traffic/CBR\] "
        puts "\$cbr$src set packetSize_ $opt(pktsize)"
        puts "\$cbr$src set interval_ $opt(interval)"
        puts "\$cbr$src set random_ 1"
        puts "\$cbr$src set maxpkts_ 10000"
        puts "\$cbr$src attach-agent \$udp$src"
        puts "\$ns connect \$udp$src \$null"
        puts "\$ns at $stime \"\$cbr$src start\""
}
getopt $argc $argv
if {  $opt(type) == "" }
{
        usage
        exit
}
elseif {  $opt(type) == "cbr" }
{
        if {  $opt(nn) == 0 || $opt(seed) == 0.0 || $opt(mc) == 0 ||
$opt(interval) == 0 }
        {
                usage
                exit
        }
}
puts "#\n# nodes: $opt(nn), max conn: $opt(mc), send rate: $opt(interval),
seed: $opt(seed)\n#"
set rng [ new RNG]
$rng seed $opt(seed)
set u [ new RandomVariable/Uniform]
$u set min_ 0
$u set max_ 100
$u use-rng $rng
set cbr_cnt 0
set src_cnt 0
set dst 0
```

```
puts "set null \[ new Agent/Null\] "
puts "\$ns attach-agent \$n0 \$null"
for { set i 1} { $i < $opt(nn)+1 } { incr i}
{
      create-cbr-connection $i $dst
}

//==============================================================================
// Sample Traffic Pattern Output File

#
# nodes: 48, max conn: 48, send rate: 60, seed: 1.0
#
set null [ new Agent/Null]
$ns attach-agent $n0 $null
#
# 1 connecting to 0 at time 0.020374618480156464
#
set udp1 [ new Agent/UDP]
$ns attach-agent $n1 $udp1
set cbr1 [ new Application/Traffic/CBR]
$cbr1 set packetSize_ 100
$cbr1 set interval_ 60
$cbr1 set random_ 1
$cbr1 set maxpkts_ 10000
$cbr1 attach-agent $udp1
$ns connect $udp1 $null
$ns at 0.020374618480156464 "$cbr1 start"
#
# 2 connecting to 0 at time 33.352842951823419
#
set udp2 [ new Agent/UDP]
$ns attach-agent $n2 $udp2
set cbr2 [ new Application/Traffic/CBR]
$cbr2 set packetSize_ 100
$cbr2 set interval_ 60
$cbr2 set random_ 1
$cbr2 set maxpkts_ 10000
$cbr2 attach-agent $udp2
$ns connect $udp2 $null
$ns at 33.352842951823419 "$cbr2 start"
#
# 3 connecting to 0 at time 0.85227962622990816
#
set udp3 [ new Agent/UDP]
$ns attach-agent $n3 $udp3
set cbr3 [ new Application/Traffic/CBR]
$cbr3 set packetSize_ 100
$cbr3 set interval_ 60
$cbr3 set random_ 1
$cbr3 set maxpkts_ 10000
$cbr3 attach-agent $udp3
$ns connect $udp3 $null
$ns at 0.85227962622990816 "$cbr3 start"
#
# 4 connecting to 0 at time 5.2873602627252039
#
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set udp4 [ new Agent/UDP]
$ns attach-agent $n4 $udp4
set cbr4 [ new Application/Traffic/CBR]
$cbr4 set packetSize_ 100
$cbr4 set interval_ 60
$cbr4 set random_ 1
$cbr4 set maxpkts_ 10000
$cbr4 attach-agent $udp4
$ns connect $udp4 $null
$ns at 5.2873602627252039 "$cbr4 start"
#
# 5 connecting to 0 at time 26.470402910593155
#
set udp5 [ new Agent/UDP]
$ns attach-agent $n5 $udp5
set cbr5 [ new Application/Traffic/CBR]
$cbr5 set packetSize_ 100
$cbr5 set interval_ 60
$cbr5 set random_ 1
$cbr5 set maxpkts_ 10000
$cbr5 attach-agent $udp5
$ns connect $udp5 $null
$ns at 26.470402910593155 "$cbr5 start"
#

===============================================================================
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