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Research Article

Energy, Traffic Load, and Link Quality Aware Ad Hoc Routing Protocol for Wireless Sensor Network Based Smart Metering Infrastructure

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Electricity industry is in the midst of revolutionary transition from outdated ageing power infrastructure to an intelligent sophisticated smart grid network utilizing modern communication technologies to enhance power generation, transmission, distribution, and consumption. Smart metering infrastructure is an integral part of the smart power grid revolution. Smart meters, in addition to their primary billing functions, serve as distributed Wireless Sensor Network (WSN) nodes for enhancing grid reliability. Existing ad hoc routing protocols are based on single routing criterion such as hop count. This single routing metric approach can overload and deplete resource constrained smart meters along preferred paths. A protocol is needed which is aware of energy level and traffic congestion of smart metering nodes. In addition, protocol should select route based on link quality for optimal routing. In this paper, a novel WSN ad hoc routing protocol ETL-AODV is proposed for reliable and energy efficient communication of smart metering nodes. Three simulation based case studies are conducted to analyze the performance of the proposed protocol, and relative comparison is provided based on four metrics: (i) packet delivery ratio (PDR), (ii) normalized routing load (NRL) (iii) average energy consumption and (iv) average end-to-end delay.

1. Introduction

This century has witnessed exponential increase in electricity consumption, and its unchecked use has brought us to the verge of a power crisis. Developed nations of the world are working on solutions for energy conservation. Smart grid is a revolutionary concept aimed at reducing energy wastages and making ageing electric infrastructure more efficient, reliable, and intelligent. The core component of smart grid is smart metering infrastructure which upgrades electric meters into smart communicating nodes relaying power consumption statistics and event reports to the power grid control centre in real time manner [1]. This has opened new horizons of research areas emphasizing on communication and networking of smart meters.

Smart metering infrastructure, also known as "neighbourhood area network," enables two-way communications between consumers and electricity supplying companies. Smart meters communicate with home appliances and transmit their power usage statistics to grid control centre in regular intervals. 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 all stages of its operation. Both wired and wireless communication mediums are being utilized for smart metering deployment. Wired medium uses existing power lines as means of communication. However, it suffers from low data rate issues, frequent harmonics disturbances, and unavailability during powering failures. Wireless communication is being considered a key enabler technology for smart metering communications. One of the most attractive characteristics of wireless medium is absence of physical connection between nodes thus requiring minimal deployment cost and management. This ensures continued connectivity even in case of power failures.

Recently, wireless sensor network (WSN) is being rapidly utilized for interconnectivity of smart meters [2]. WSN is a class of ad hoc network which organizes the smart meters in an infrastructure less distributed reconfigurable topology. Smart meters with their wireless capability transmit their own and relay other meter readings to the power grid control centre. Many WSN ad hoc routing protocols have been proposed which consider the limited battery life and computational capability of sensor nodes. Data centric protocols reduce redundancy in data transmissions for prolonging nodes lifetime. They utilize Query method which is not suitable for time driven monitoring applications. Hierarchical routing protocols improve energy consumption by locally grouping the nodes into clusters. However, they require frequent exchange of control messages for cluster formation. Location aided protocols, although energy efficient, require the use of expensive localization hardware for their working. Most of the WSN routing protocols work on flooding mechanism for event reporting to the sink. However, smart metering infrastructure represents a specific kind of network deployment due to large number of static metering nodes communicating in outdoor environment in time driven periodic fashion. Most of the time smart meter reading collection exhibits a many-to-one scenario with all metering nodes communicating with the sink and overloading the nodes close to it. Furthermore, smart meters running on power lines use rechargeable batteries for wireless communication module and back up requirements in case of power failure scenarios so energy consumption of protocols should also be considered.

Ad hoc on demand distance vector (AODV) [3] routing protocol is utilized by the Zigbee standard for deployment of WSN of home sensors and appliances. 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 next hop entry for each destination. Sequence number ensures loop free routing. It is a good choice especially for event driven or periodic data driven WSN applications like smart metering. In this paper, a new ad hoc routing protocol (ETL-AODV) is proposed to achieve reliability, energy efficiency, and self-healing requirements of WSN based smart metering deployment. We have proposed modified routing criterion of AODV by utilizing multiple routing metrics approach and have presented simulation studies for performance analysis of our protocol.

The organization of the paper is as follows. In Section 2, we present background study on ad hoc routing protocols for smart metering application. Issues associated with deploying ad hoc routing protocol for WSN based smart metering infrastructure are highlighted, and current work on improving routing criterion of AODV is discussed. The proposed ad hoc routing protocol is presented in Section 3, and its performance, under different case studies, is presented in Section 4.

2. Background

Smart meters are provided with wireless interfaces to form mesh network. Due to inherent features such as the distributed nature of the network hosts along with redundancy and lack of single point of failure, the ad hoc networks exhibit robustness which is highly desirable for low cost commercial application. ad hoc networking represents a peer-to-peer multihop communication architecture. For each sink, there is a mesh network of metering nodes communicating with it in self-organized autonomous fashion.

Ad hoc routing algorithms dynamically determine the best path towards the destination based on the network status and in case of node failure, routing tables of nodes are updated to route the packet along alternative routes. Ad hoc routing protocols are classified into three types depending upon their route formation techniques as explained below.

(i) *Proactive* (table driven): every node maintains a table of routes to every other node in the network and requires frequent exchange of topology messages. Examples: *destination sequence distance vector* (DSDV) [4], *optimized link state routing* (OLSR) *protocol* [5].

(ii) *Reactive* (on demand): routes are formed only when required. Examples: *ad hoc on-demand distance vector* (AODV), *dynamic source routing* (DSR) [6].

(iii) *Hybrid*: it combines characteristics of reactive and proactive protocols. Example: *zone routing protocol* (ZRP) [7].

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 the expense of bandwidth and power consumption while reactive protocols are bandwidth and energy efficient at the expense of route discovery delays. Smart metering devices are small in size and are cost effective due to the enormous deployment volume. Since smart metering deployment could consist of large number of nodes, the routing table that each node would have to keep could be huge, and therefore proactive protocols are not suitable for these kinds of networks.

2.1. Current Research on Wireless Mesh Routing Protocols for Smart Metering Infrastructure.

Geelen et al. [8] proposed wireless mesh communication protocol for smart metering based on time synchronization. Metering nodes initiate communication with the concentrator nodes in predefined allotted slots. Nodes try to directly communicate with the target nodes, and, in case of communication failure, controlled flooding search is utilized in AODV style.

Distributed autonomous depth first routing (DADR) [9] is proactive distance vector routing protocol concerned with minimizing control overhead due to changing link conditions and provides at the most K possible paths for each destination. This protocol comes with increase in CPU and memory overheads of intermediate nodes due to additional state in data forwarding phase.

A hybrid routing protocol (Hydro) [10] is a link state routing protocol for low-power and lossy networks. It utilizes directed acyclic graph to build multiple routes to border routers. Nodes periodically piggyback topology reports on frequent data traffic to border router which in turn have global view of the network. This source routing can be a large overhead for networks with large number of nodes such as in case of smart metering network which may require many hops to reach the destination.

RPL [11] is distance vector routing protocol, currently under development, aimed for low-power and lossy networks such as home automation and industrial applications. It establishes directed acyclic graph based topology for supporting multiple sinks. A modified RPL based on ETX link metric was proposed for meeting reliability and latency requirements in AMI networks.

Gharavi and Hu [12] modified Hybrid Wireless mesh routing protocol (HWMP) for IEEE 802.11s based wireless mesh network (WMN) which establishes multiple paths to multiple gateways using proactive routing while on demand routing is initiated on path failures. Backup buffer stores their packets which are forwarded through backup routes in case of link failures. Jung et al. [13] proposed link error metric for IEEE 802.11s based WMN for accommodating varying packet size in smart grid scenario and route fluctuation prevention algorithm to improve overall reliability of the mesh network.

Li and Zhang [14] presented multiconstrained QoS routing for smart grid. It is based on simple greedy algorithm based on two QoS requirements of delay and outage probability. Lichtensteiger et al. [15] proposed geographic routing based mesh system for smart metering infrastructure and concluded that improved performance is achieved given that coverage gaps are filled. Ullo et al. [16] evaluated Zigbee based wireless sensor network for smart metering infrastructure and observed that congestion and delay increase with number of nodes.

2.2. Motivation. The routing protocols previously mentioned are aimed at increasing reliability of the network [17]. These protocols are focused on utilizing single routing criteria and are not designed with multiple routing metrics. In addition, they do not consider energy consumption of the nodes. This behaviour may become harmful for battery powered smart meters specifically those that are close to the sink as they will be involved in most of the multihop transmissions leading to fast energy depletion and congestion. In addition to this, link quality should be considered as well since frequent route breaks occur in wireless sensor networks due to fading effects and signal interference. Routing protocol should be aware of residual energy, traffic load, and link quality between the nodes to overcome the aforementioned issues. Taking this into mind, a new ad hoc routing protocol is proposed with route formation improved in such a way that nodes embed their residual energy, traffic load, and link quality information in the route request packets, and destination is able to select the best available path to the source.

2.3. AODV Based Routing Algorithm. Our protocol is based on the AODV routing protocol since its features are very much suitable for the smart metering infrastructure. Due to its reactive nature, no topology messages exchange is required for communication along the links which reduces bandwidth utilization particularly for large number of metering node network. AODV is favourable for resource constrained nodes such as battery powered smart meters due to its small routing table size wherein only next hop neighbour entry is maintained for each destination. The most important advantage of AODV is its ability to heal itself in case of nodes or routes failures. These are some of the advantages that make AODV a suitable candidate for smart metering infrastructure. AODV creates considerable routing overhead with relatively higher delay in route discovery phase as compared to other routing techniques. As our network is composed of static nodes with relaxed latency requirements so this issue may be overlooked for the advantages we gain. As suggested by research work in [18], AODV needs modification for use in smart metering infrastructure. AODV is based on minimum hop counting algorithm. However, minimum hop count routing does not always yield the best path. These shortest path routing protocols degrade network performance due to traffic congestion, unstable links, and power depletion on nodes along minimum hop path.

2.4. Prior Work on Routing Criterion Optimization of AODV. Originally proposed AODV algorithm selects routes based on minimum hop count. Many variants of AODV have been studied and proposed by the researchers utilizing various routing metrics for enhancing AODV performance. Most of the authors improved AODV performance using a single routing criterion. For instance, research works in [19–22] consider the energy level parameter of the nodes (residual or drain rate) as routing criterion for prolonging network lifetime. Similarly, the works in [23–26] consider the traffic load (buffer occupancy levels) of the nodes during route formation phase for reducing congestion. The works in [27–31] utilize the strongest link paths (based on received signal strength or SNR) for establishing stable routes.

The limitation of single routing metric for path selection has a side effect of overloading and depleting the resources along the selected path. Our work is concerned with utilizing multiple metrics for enhanced performance. Few variants of AODV consider multiple routing criterions. ETR-AODV [32] considers nodes residual energy and traffic load during route selection. R-AODV [33] proposed the idea of higher and lower level thresholds of battery level and signal strength. The thresholds decide when backup route should be searched and utilized. EM-AODV [34] is composed of composite metric of signal strength, battery power, and bandwidth. MMRP and its two variants (MMRP-I, MMRP-A) [35] are based on AODV and consider weighted contribution of hop count, traffic load, and residual energy of nodes for route selection.

3. Protocol Description

Our proposed protocol (ETL-AODV) is described as follows.

3.1. Routing Metrics. AODV was basically designed for mobile ad hoc networks (MANETs) and as such it only considers hop count during route discovery for finding shortest paths to the destination. This criterion needs to be modified for smart metering infrastructure since smart meter nodes are resource deficient and we need to consider energy consumptions of the nodes, traffic loads, and link quality during route selection for improving the performance.

3.1.1. Energy Level. Energy is a valuable resource for battery powered smart meters since their life directly depends upon how much energy is available to them. The energy level of the nodes involved in most of multihop transmission (like the ones closer to the sink) will be depleted quickly, and so the protocol should consider energy states of the nodes during route formation for forming the routes with highest energy nodes. Our protocol keeps track of the energy state of the nodes on the basis of residual energy of the node. Energy of the node is scaled on (0-1) scale using

$$E = \frac{E_r}{E_{\max}}, \quad (1)$$

where E_r is the remaining energy and $E_{\max}$ is the maximum energy available to the node. The energy value will vary from 1 to 0 with 1 corresponding to full energy level and 0 for all energy depleted (dead node).

3.1.2. Traffic Load. Traffic congestion is experienced by the nodes when incoming traffic is much higher than outgoing traffic. Smart metering nodes buffer the incoming packets in finite size queue and start dropping any new incoming packets when queue is full. Nodes which serve maximum number of nodes in multihop transmission (like the ones close to sink) are likely to experience maximum traffic load leading to traffic congestion. Traffic load of the nodes should be counted in during route selection for minimizing the congestion.

Our protocol measures traffic load of the node by measuring the interval between two received data packets and is normalized on (0-1) scale with 1 denoting minimum traffic load. Interval is updated using exponential smoothing function to avoid abrupt traffic jitters as shown in the following equation:

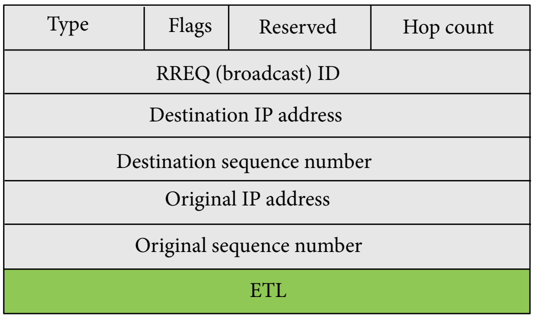
$$T_F = (1 - \beta) \times \text{intvl}_{\text{old}} + \beta \times \text{intvl}_{\text{new}}, \quad (2)$$

where $\text{intvl}_{\text{old}}$ and $\text{intvl}_{\text{new}}$ are old and new intervals, respectively and β is adjustable parameter between 0 and 1. The larger the β value, the more sensitive to the new value. We have chosen β as 0.2 in our simulations.

3.1.3. Link Quality. Smart metering nodes communicate in outdoor environment, and active route breaks occur even on stationary nodes due to the effect of shadowing and consequently cause the network degradation. Shortest available path is not always the best path available since routing over short path with weak RF link quality leads to increased packet loss and retransmissions. Consequently, our protocol measures signal strength of the nodes while choosing candidates for route formation. Link quality (L_Q) is scaled on (0-1) scale using the following equation:

$$L_Q = \frac{S_P}{S_{\max}}, \quad (3)$$

where S_P is the signal strength of the packets received and $S_{\max}$ is the maximum signal strength available. In this way, Link Quality parameter varies from 1 to 0 with 1 denoting best link available.



Type	Flags	Reserved	Hop count
RREQ (broadcast) ID			
Destination IP address			
Destination sequence number			
Original IP address			
Original sequence number			
ETL			

Figure 1: RREQ packet format of ETL-AODV with ETL field appended.

3.1.4. Multimetric Combination. Routing based on multiple criteria is a classification problem, and it complies to the additive combination rule [36], and we can combine multiple criteria (energy level, traffic load, link quality, and hop count) into a single criterion to get improved performance. Most of the multimetric routing protocols use the weighted sum approach to combine multiple metrics over an available path. In our protocol, ETL value is assigned to each node using the following general linear equation:

$$\text{ETL}_{\text{node}} = \sum_{i=1}^{n} \alpha_i m_i, \quad (4)$$

where ETL is the value assigned to the node. "i" runs for all "n" number of metrics, and α is the weight assigned to metric "m". Here in our protocol, we combine three metrics (energy level, traffic load, and link quality) with equal weights to get ETL value of a node as

$$\text{ETL}_{\text{node}} = W_E * E + W_T * T_F + W_L * L_Q. \quad (5)$$

Here, we can assign priorities to different metrics depending upon application. Note that cumulative sum of the weights (W_E, W_T, W_L) should always be equal to 1 so that ETL value obtained will be in range of (0-1). In this way, by selecting nodes with maximum ETL values for route formation, we can maximize the network performance.

3.2. Route Request Procedure. In AODV, whenever the source needs to find a route to new destination, it broadcasts a special route discovery packet (route Request packet—RREQ). Each node on receiving RREQ packet further propagates it until it reaches the destination. Nodes only reply back to RREQ packet if they know a route to destination or they are the destination. We have appended a new ETL field in RREQ packet to carry ETL information as shown in Figure 1.

Source node broadcasts RREQ packet with ETL value initialized to 1. Each intermediate node on receiving the RREQ packet appends their ETL value inside RREQ's ETL

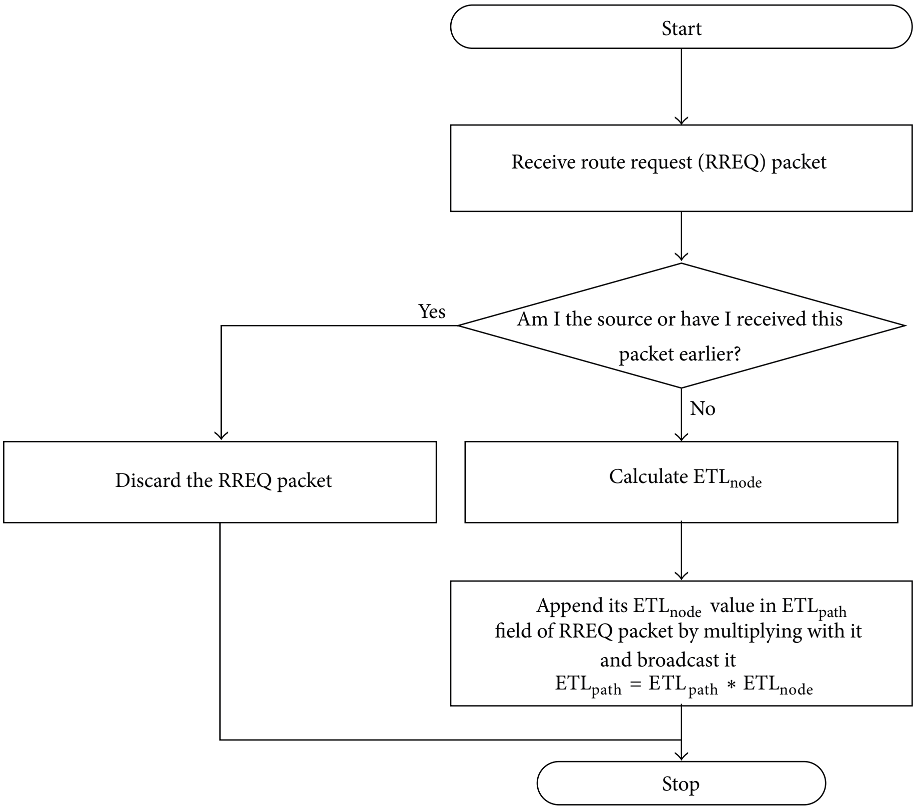


Figure 2: RREQ reception at intermediate node.

field by multiplying with the value contained in the packet. As a result, ETL_{node} value of all the nodes along the path is multiplied to obtain the ETL_{path} value for the path as follows:

$$\text{ETL}_{\text{path}} = \prod_{i=1}^{k} \text{ETL}_{\text{node}}; \quad (6)$$

here "i" runs for all "k" number of nodes in a specific path, and by taking the product we get values in range (0, 1). This is shown in Figure 2.

3.3. Route Selection by the Destination Node. In AODV, destination node on receiving the first route request replies back and discards any further route requests because of its shortest path formation behaviour. In our protocol, destination node on receiving first route request (RREQ) waits for a small amount of time Δt and then replies back for a path with maximum $\text{ETL}_{\text{final}}$ value as shown in Figures 3 and 4. $\text{ETL}_{\text{final}}$ is evaluated to cater for the hop count in route selection and is evaluated using the following relation:

$$\text{ETL}_{\text{final}} = k_1 * \text{ETL}_{\text{path}} + k_2 * \text{HF}, \quad (7)$$

where k_1 and k_2 are weights with condition ($k_1 + k_2 = 1$) and HF is the hop factor calculated as

$$\text{HF} = \frac{H_{\max} - H_{\text{count}}}{H_{\max}}, \quad (8)$$

where H_{count} is the present hop count and $H_{\max}$ is the maximum hop count permissible by the protocol. Hop factor will have the value in range (0, 1) with direct links having HF as 1 and will keep on decreasing with the increase in the number of intermediate nodes. These weights can be varied to change importance of ETL_{path} and the hop count during route selection. Here, we have initialized values of each one of them to 0.5. It is important to note that any other alternative function can also be used without impacting generality of the proposed solution.

3.4. Low Energy Alert. Energy is the most important commodity for battery operated wireless networks, and therefore protocol design should be energy efficient. AODV has a drawback that a route once formed is continued to be used until transmission is completed or route breaks. Neglecting energy level of nodes in active routes may result in usage of all of their available energy. Our protocol tackles this problem by incorporating alert behaviour in the nodes. Our protocol keeps an eye on energy level of the node and sends an alert to the source node in case the battery level drops below a threshold value (Figure 5). Source node will discover some other route (if available) and saving the low battery node from becoming dead. Once the energy level of the node is improved, it can be included in future route formations.

3.5. MAC Level Acknowledgement. AODV utilizes periodic exchange of HELLO packets between neighbouring nodes for

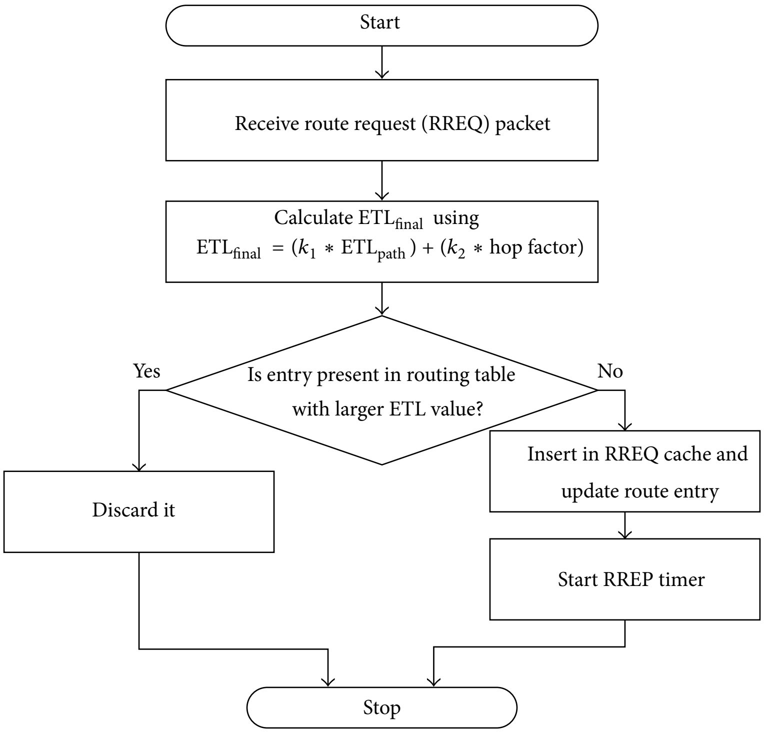


Figure 3: RREQ selection by destination node.

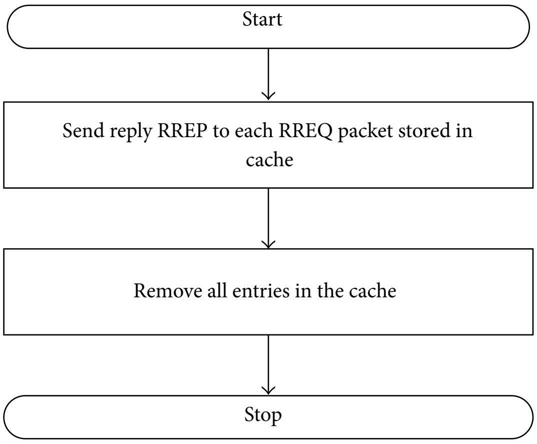


Figure 4: Route reply generation by the destination node.

reliability purposes at the cost of increased routing overhead. Our protocol, instead of using HELLO packets, utilizes MAC level acknowledgement which leads to improved reliability as well as reduced routing overhead.

3.6. Route Reply by Destination Node Only. In our protocol, intermediate nodes are not allowed to reply back to RREQs even if they have route to destination, and they continue to propagate RREQ packet along the path until it reaches the destination node. This is to ensure that the highest performance route is selected by the destination node since it has the global view of all the nodes to make a wise decision.

Table 1: Network simulation parameters.

Simulation parameters	
Routing protocol	ETL-AODV, AODV
MAC layer/PHY layer	802.11
Channel type	Wireless channel
Propagation model	Two ray ground, shadowing
Traffic type	Constant bit rate (CBR)
CBR packet size	100 Bytes
CBR packet interval	1 sec, 60 sec
Route reply timer	0.1 sec
Low battery threshold	0.5
Antenna model	Omni Antenna

4. Simulation Results

We have implemented our protocol in network simulator (NS-2). The smart meter nodes were configured with parameters derived from the specifications of a real smart meter [37]. Network simulation parameters are given in Table 1.

The performance metrics used are as follows.

(i) *Packet Delivery Ratio (PDR)*. It is calculated as the ratio of number of received data packets to the number of sent data packets. It measures how much of the sent data made up to the receiver thus representing reliability of the protocol. It is desirable to have maximum packet delivery ratio.

(ii) *Normalized Routing Load (NRL)*. It represents number of routing control packets exchanged in the

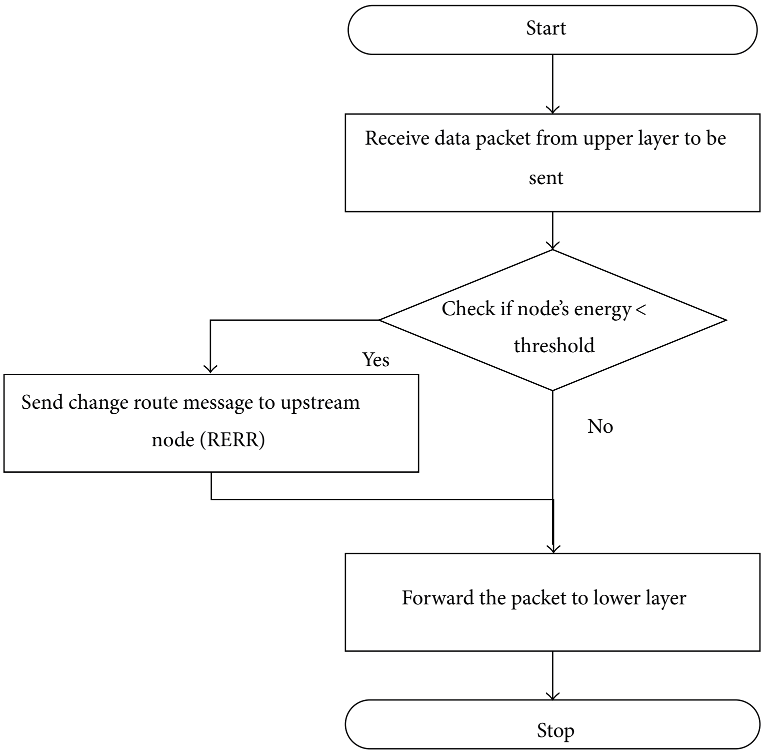


FIGURE 5: Route change request at low energy.

network. It is calculated as ratio of number of received routing packets to the number of received data packets. It is desirable to have minimum routing overhead for the efficient operation of the network.

(iii) *Average Energy Consumption*. This metric indicates energy consumed in the nodes of the network. Battery powered smart meters require energy efficient protocol operation for prolonging network lifetime.

(iv) *Average End-to-End Delay*. This metric indicates latency in the communication network. It is calculated as the ratio of total time taken by all the packets to reach the destination to the total number of packets. Protocol should have minimum average delay for prompt data transfer. Although metering application is less sensitive to delays, however, outages notifications require to be transmitted without any delay.

We conducted three simulation based case studies for analyzing the performance of our proposed protocol. First simulation experiment was designed to mark performance based on individual metrics by setting desired metric's coefficient to 1 and others to 0. The second and third considered equal contribution of all metrics.

4.1. Case Study I. Three scenarios were simulated to analyze the effect of individual metrics (energy, traffic load, and link quality).

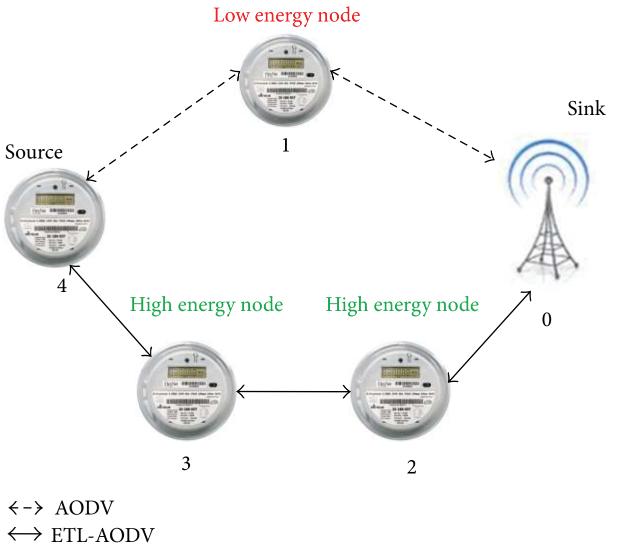


FIGURE 6: Scenario I.

4.1.1. Scenario I. In Scenario I (Figure 6), we measured performance of the protocol based on energy criterion by setting ETL coefficients in (5) as (1, 0, 0). Initial energy of all the nodes is set to 10 joules except node 1 with 6 joules. When Node 4 wants to communicate with node 0, two routes can be formed (4-1-0) and (4-3-2-0). The AODV chose the shortest path thus draining energy deficient node 1 and consequently

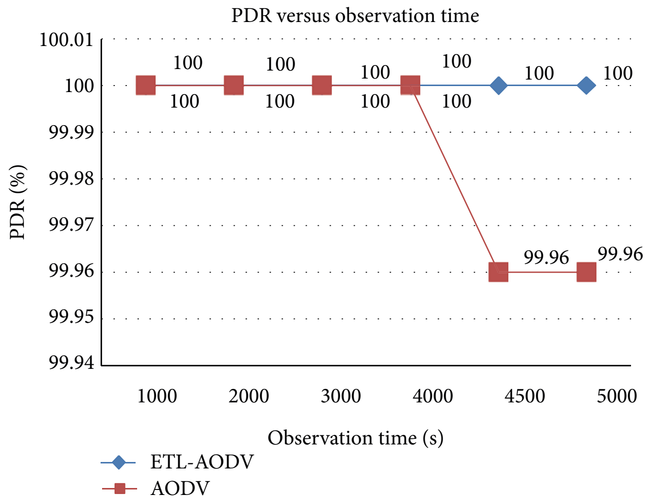


FIGURE 7: PDR in Scenario I.

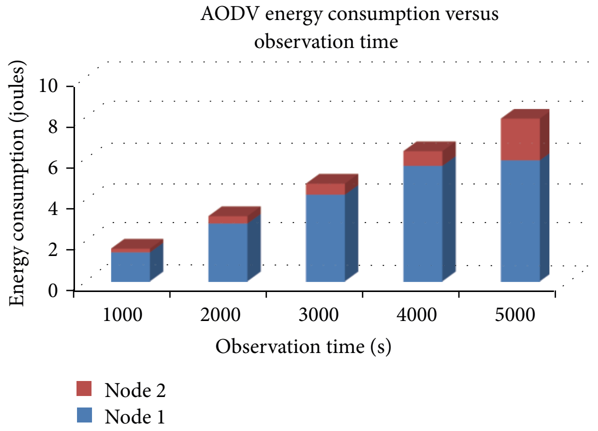


FIGURE 8: AODV energy consumption in Scenario I.

limiting network lifetime to 4500 sec and dropping PDR below 100%. In ETL-AODV, node 0 received two RREQs one via node 1 with ETL$_{\text{Final}}$ = 0.73 and the other via node 2 with ETL$_{\text{Final}}$ = 0.95. Consequently, ETL-AODV chose high residual energy path (4-3-2-0) thus keeping PDR 100% and extending network lifetime (time interval from beginning till the death of first node) to 5500 sec. At time 2546.0028, energy of node 3 fell below 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. Results for PDR and energy consumption of nodes 1 and 2 are given in Figures 7, 8, and 9.

4.1.2. Scenario II. In Scenario II (Figure 10), we set the ETL coefficients in (5) as (0, 1, 0) for considering the effect of only the traffic load in routing decisions. Node 1 and node 4 are source meters with node 0 as sink node. Node 1 starts sending Data to sink at the start of simulation with 0.1 sec packet intervals depicting heavy load. We switch on node 4 a bit later at time 80 sec to study which route will be chosen by the protocols. Node 4 has two disjoint paths towards node

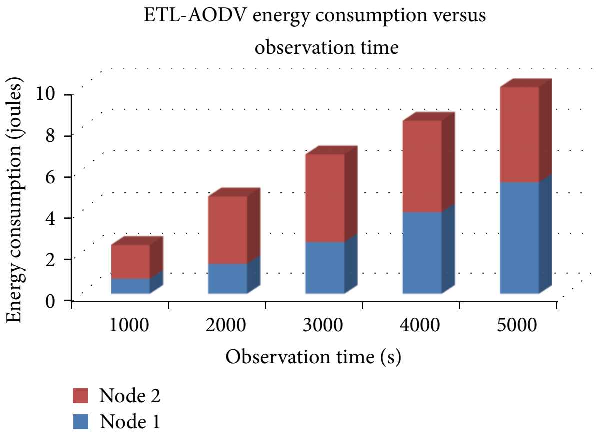


FIGURE 9: ETL-AODV energy consumption in Scenario I.

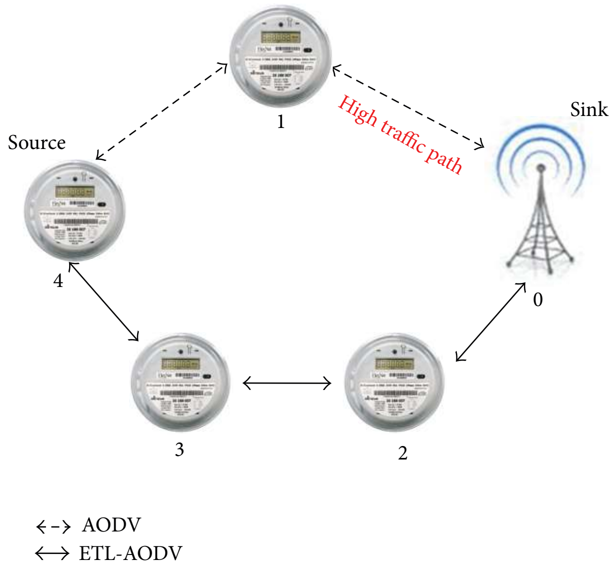


FIGURE 10: Scenario II.

0 (4-1-0 and 4-3-2-0). The former path although the shortest path will increase loading on node 1 as it is also forwarding data to the sink leading to traffic congestion, fast energy depletions, and packet drops. AODV chose this path and consequently PDR dropped to 98.87%. In case of ETL-AODV, node 0 received two RREQs of node 4, one via node 1 with ETL$_{\text{Final}}$ = 0.47 and the other via node 2 with ETL$_{\text{Final}}$ = 0.95. Consequently, ETL-AODV chose low traffic path (4-3-2-0) thus retaining PDR to 100%. The result of PDR is depicted in Figure 11. Similarly, ETL-AODV exhibited lower NRL and average end-to-end delay as compared to AODV (Figures 12 and 13).

4.1.3. Scenario III. In Scenario III (Figure 14), we studied effect of choosing link quality in routing decision by setting ETL coefficients in (5) as $(0, 0, 1)$. Furthermore, we chose shadowing propagation model to simulate an outdoor “shadowed urban area” with the parameters set as

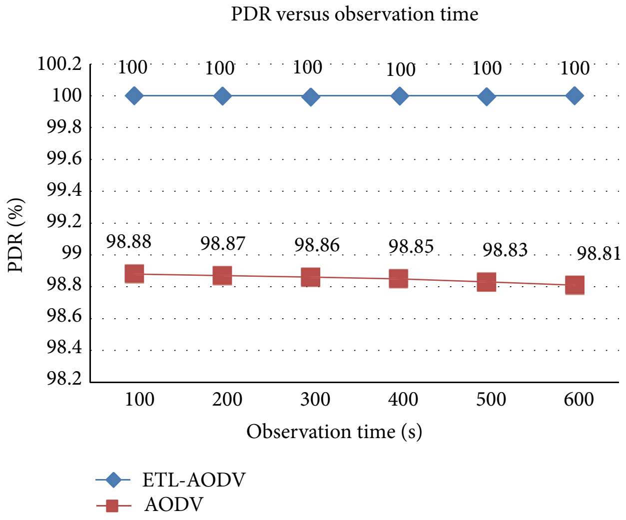


Figure 11: PDR in Scenario II.

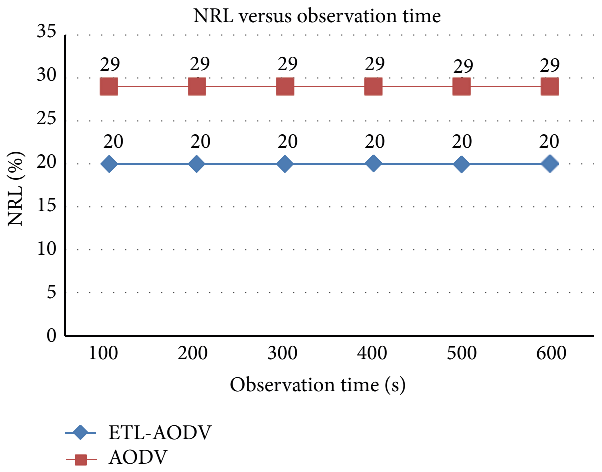


Figure 12: NRL in Scenario II.

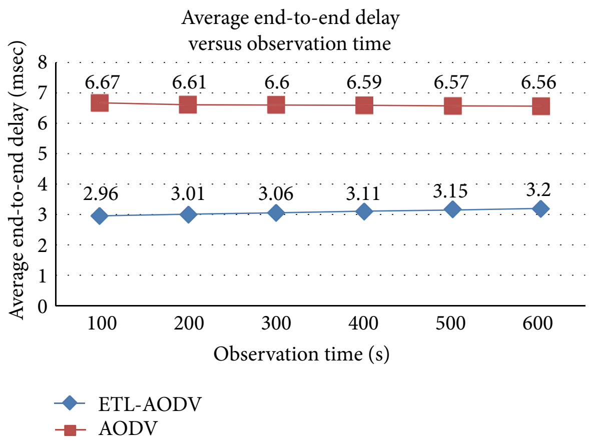


Figure 13: Average end-to-end delay in Scenario II.

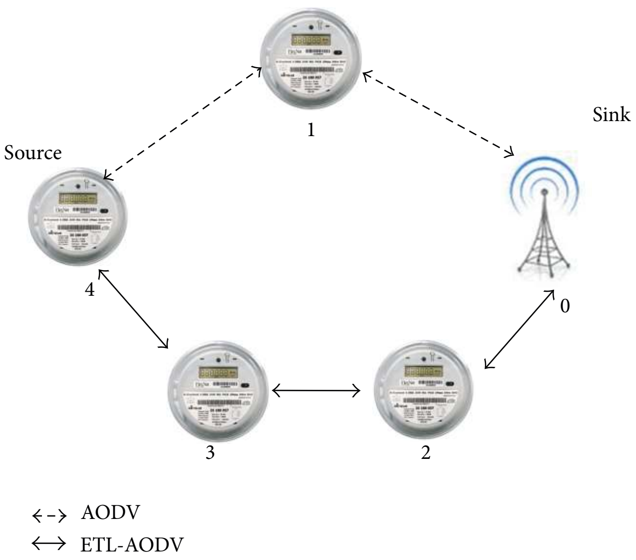


Figure 14: Scenario III.

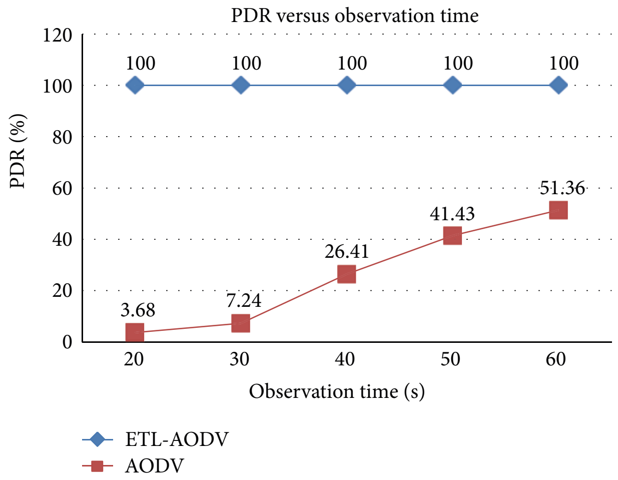


Figure 15: PDR in Scenario III.

path loss exponent = 2.7 and *standard deviation* = 4. Node 4 is the source meter communicating with the sink node 0. There are two disjoint paths from node 2 to node 0 (4-1-0 and 4-3-2-0). The former one is the shortest but node 1 is deliberately placed further away to degrade Link Quality. As expected, AODV chose the weak link quality path. In case of ETL-ADOV, node 0 received two RREQs of node 4, one via node 1 with $\mathrm{ETL}_{\mathrm{Final}} = 0.47$ and the other via node 2 with $\mathrm{ETL}_{\mathrm{Final}} = 0.50$. Consequently, ETL-AODV chose high link quality path (4-3-2-0) thus retaining PDR to 100%. Average end-to-end delay and normalized routing load were very small as compared to that of AODV. The results for PDR, NRL and average end-to-end delay are shown in Figures 15, 16 and 17.

4.2. Case Study II.

In Case Study II, we considered all the three parameters of ETL metric with equal contribution by setting ETL coefficients in (5) as (1/3, 1/3, 1/3). We simulated

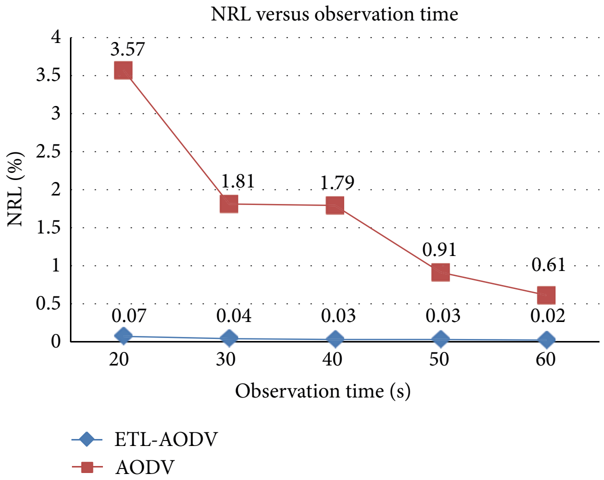


FIGURE 16: NRL in Scenario III.

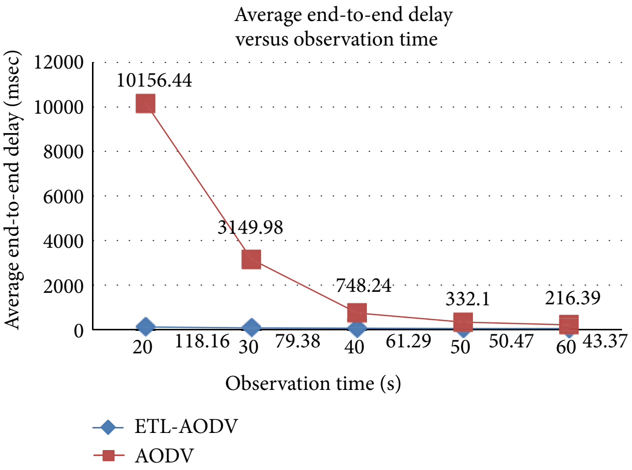


FIGURE 17: Average end-to-end delay in Scenario III.

topologies based on real geographic suburban region with location of houses as wireless metering nodes as shown in Figure 18 and star denoting location of sink node.

We increased the number of houses from 25 to 125 in regular grid structure and evaluated the performance of our proposed protocol. The sending interval was set as 60 seconds, and all of the metering nodes were configured to start sending data to sink at time chosen from uniform random distribution (0–60) sec. We chose shadowing propagation model to simulate an outdoor "shadowed urban area" with the parameters set as path loss exponent = 2.7 and standard deviation = 4. All the simulations were run for 1 hour. We simulated each topology 10 times with different seed value and averaged the result. The results for PDR, NRL, average energy consumption and average end-to-end delay are given below.

4.2.1. Packet Delivery Ratio (PDR). The results of PDR for two protocols simulated are shown in Figure 19.

FIGURE 18: Geographical area with houses as nodes position.

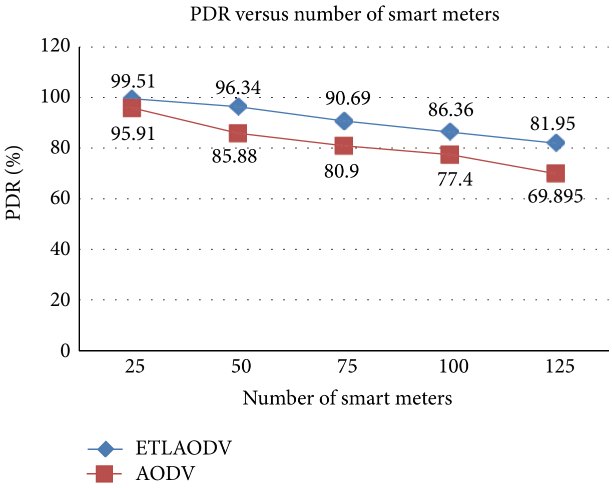


FIGURE 19: PDR versus number of smart meters.

A general decreasing trend is observed for both protocols with 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 enhancing PDR. On the other hand, AODV forms only the shortest route which can have negative impact on PDR. ETL-AODV maintained 80% PDR for 125 number of homes in shadowed region as compared to AODV whose PDR declined to 69.8%.

4.2.2. Normalized Routing Load (NRL). The results for NRL are shown in Figure 20. 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 submetrics leading to reduced exchange of control packets.

4.2.3. Average Energy Consumption. The results for average energy consumption of nodes are shown in Figure 21. 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 waters and gas meters for prolonging network and node lifetime.

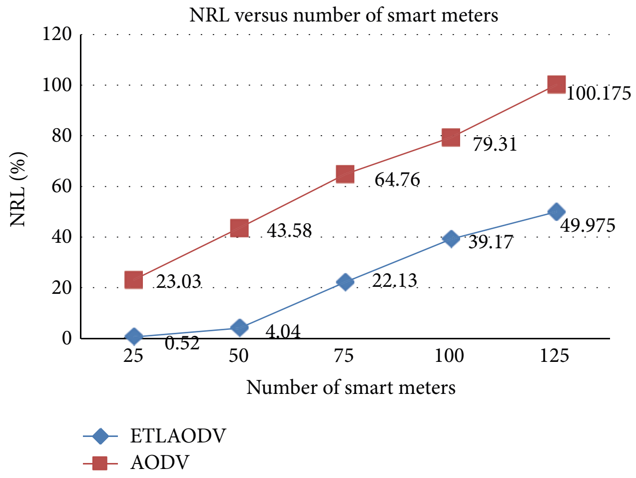


Figure 20: NRL versus number of smart meters.

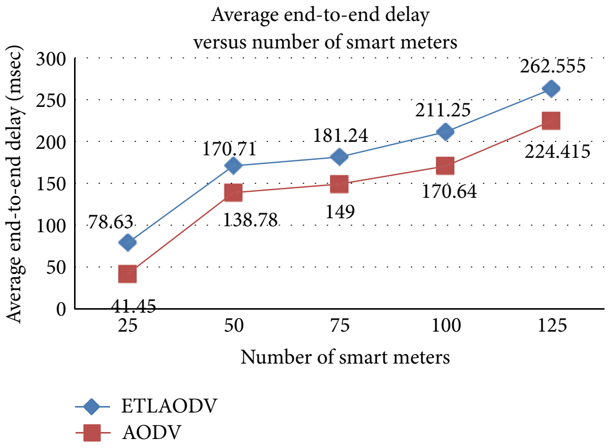


Figure 22: Average end-to-end delay versus number of smart meters.

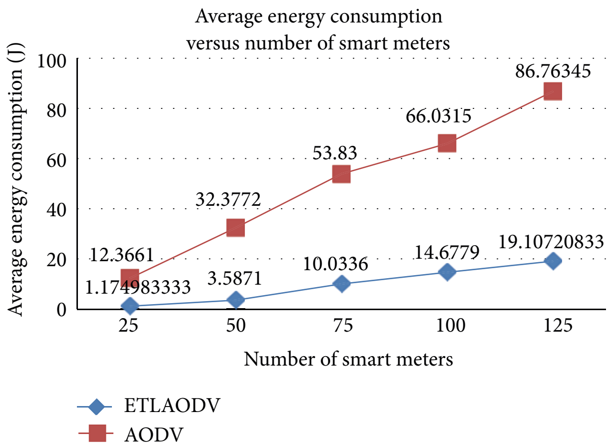


Figure 21: Average energy consumption versus number of smart meters.

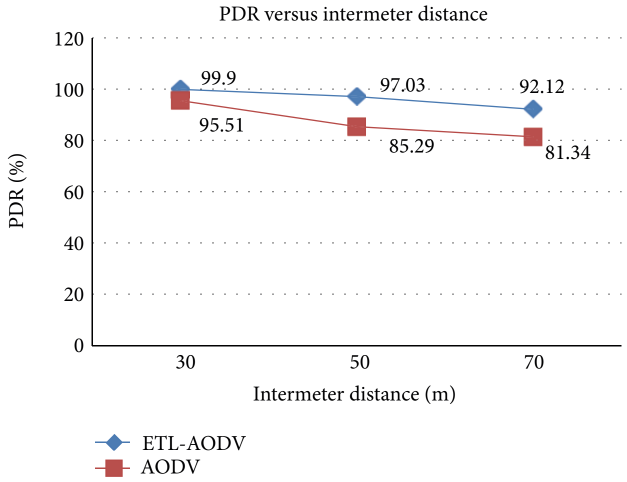


Figure 23: PDR versus intermeter distance.

4.2.4. Average End-to-End Delay. The results for average end-to-end delay are shown in Figure 22. 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 an issue in smart metering applications so this can be compromised for improved PDR, NRL, and energy consumption of nodes.

4.3. Case Study III. In Case Study III, we analyzed the effect of intermeter distances on performance metrics for both protocols. We chose 50 homes topology and simulated the network for one hour with same simulation parameters as of case study II. The results for PDR, NRL, average energy consumption and average end-to-end delay are given below.

4.3.1. Packet Delivery Ratio (PDR). The results for PDR are shown in Figure 23. Both protocols follow declining trend with the increase in intermeter 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 interdistance between nodes starts to increase, PDR is severely affected due to shadowing effects. ETL-AODV outperforms AODV for all three intermeter distances due to formation of stable paths.

4.3.2. Normalized Routing Load (NRL). The results for NRL for ETL-AODV and AODV are plotted in Figure 24. NRL gradually increases with the increase in intermeter distances. However, significant improvement is observed in case of ETL-AODV due to improved route discovery leading to less control overhead. Formation of stable optimum paths leads to less route breakages and ultimately low NRL.

4.3.3. Average Energy Consumption. The results for average energy consumption for both protocols are plotted in Figure 25. As observed, ETL-AODV has much lower average energy consumption as compared to AODV which increases with increasing intermeter distances. Unstable routes are prone to frequent breakages due to shadowing effects leading

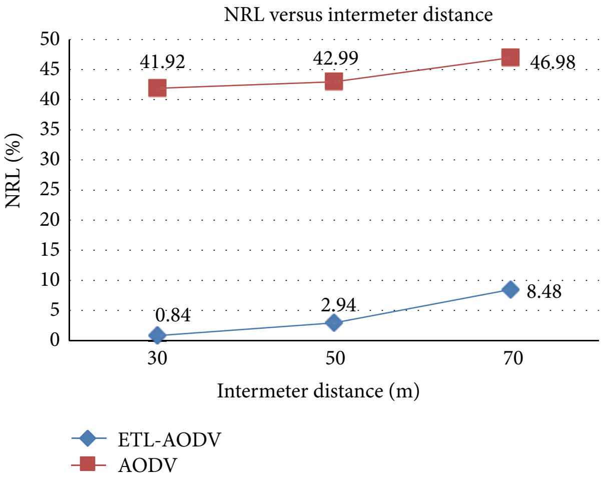


Figure 24: NRL versus intermeter Distance.

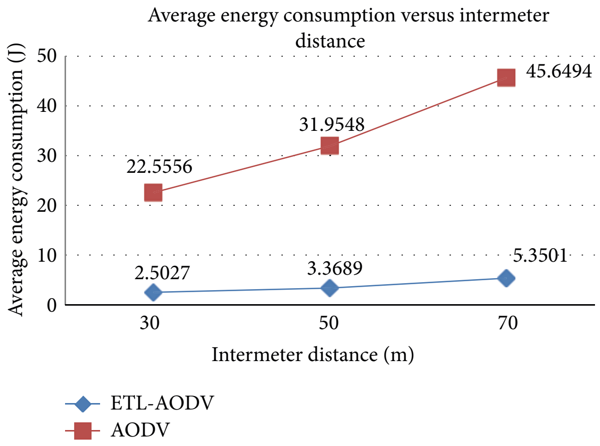


Figure 25: Average energy consumption versus intermeter distance.

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.

4.3.4. Average End-to-End Delay. The results for average end-to-end delay are plotted in Figure 26. ETL-AODV has higher average end-to-end delay as compared to AODV for 30 m intermeter spacing due to additional route selection waiting time at sink node. However, latency in AODV is higher as compared to ETL-AODV at 50 m and 70 m intermeter 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 degrades AODV performance.

5. Conclusion and Future Work

In this paper, we have proposed a reliable WSN ad hoc routing protocol (ETL-AODV) for smart metering infrastructure. The proposed protocol is based on AODV designed for low cost and resource constrained smart metering sensor nodes. Enhanced reliability is achieved by considering energy level, traffic load, and link quality of the nodes to establish appropriate route from smart meter to the sink. Our simulations studies indicate that the use of the aforementioned parameters for route selection results in improved packet delivery ratio and reduced energy consumption of metering sensor nodes.

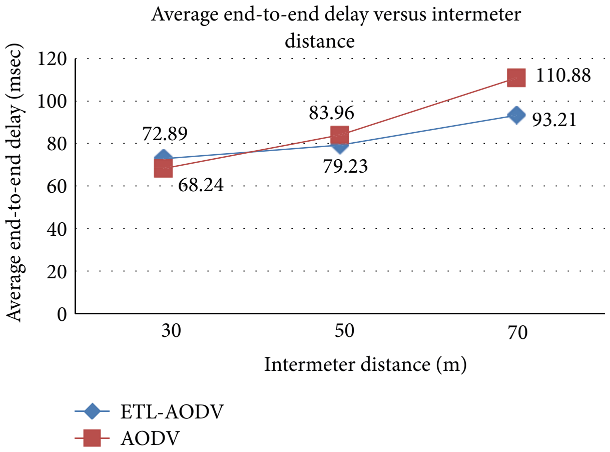


Figure 26: Average end-to-end delay versus intermeter distance.

For future work, we wish to implement our proposed protocol on hardware testbed to consolidate simulation results.

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