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End-to-End Link Reliable Energy Efficient Multipath Routing for Mobile Ad Hoc Networks

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Abstract Among the many multipath routing protocols, the AOMDV is widely used in highly dynamic ad hoc networks because of its generic feature. Since the communicating nodes in AOMDV are prone to link failures and route breaks due to the selection of multiple routes between any source and destination pair based on minimal hop count which does not ensure end-to-end reliable data transmission. To overcome such problems, we propose a novel node disjoint multipath routing protocol called End-to-End Link Reliable Energy Efficient Multipath Routing (E2E-LREEMR) protocol by extending AOMDV. The E2E-LREEMR finds multiple link reliable energy efficient paths between any source and destination pair for data transmission using two metrics such as Path-Link Quality Estimator and Path-Node Energy Estimator. We evaluate the performance of E2E-LREEMR protocol using NS 2.34 with varying network flows under random way-point mobility model and compare it with AOMDV routing protocol in terms of Quality of Service metrics. When there is a hike in network flows, the E2E-LREEMR reduces 30.43 % of average end-to-end delay, 29.44 % of routing overhead, 32.65 % of packet loss ratio, 18.79 % of normalized routing overhead and 12.87 % of energy consumption. It also increases rather 10.26 % of packet delivery ratio and 6.96 % of throughput than AOMDV routing protocol.

Keywords Mobile ad hoc networks · Multipath routing · AOMDV · Link Quality Estimator · Node Energy Estimator · QoS

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1 Introduction

A Mobile Ad hoc Network (MANET) is a group of autonomous mobile device providing multi-hop communications using wireless links and forming dynamic topology. Such networks have no adequate physical infrastructure such as routers, servers, access points or cables or centralized administration. Each mobile node in MANET is acting as a router as well as a node, which makes them highly desirable in war zones, disaster recovery, aircraft and marine communications, industrial, home and other scenarios. The following are the major issues of MANET [1–3]: (i) unpredictable link properties prone to packet collision and signal propagation, (ii) node mobility leading to dynamic topology, (iii) limited battery life of mobile devices, (iv) hidden and exposed terminal problems occur when signals of two nodes are colliding with each other, (v) difficulty in route maintenance due to the change of the behavior of communication medium, and (vi) lacking of security in boundaries of MANET which leads to several attacks such as passive eavesdropping, active interfering, and leakage of secret information, data tampering, message replay, message contamination, and denial-of-service (DoS).

Routing is one of the most important problems to be considered among the many issues to be addressed in MANET. Single path routing protocols usually find an optimal route (single route) between a pair of source and destination. Hence a novel route discovery is required for every route break which leads to high overhead and latency. Nevertheless the multipath routing protocols establish a communication from source to destination by having backup routes. When a primary route fails during end-to-end communication, the backup routes are used to deliver messages efficiently at their destination. Based on the route discovery and maintenance mechanisms of these protocols [4], they are commonly classified into three groups such as (i) proactive, (ii) reactive and (iii) hybrid. With the help of the distance vector-based or link state-based routing strategies, the proactive or table-driven routing protocols find the routes to all destinations at start up and maintain periodic update process. Examples for multipath proactive routing protocols are the multipath destination-sequenced distance-vector (MDSDV) [5] and multipath optimized link state routing (MP-OLSR) [6]. Updating the routing tables frequently leads to the consumption of large amount of memory, bandwidth and power is the only drawback of these algorithms.

However, it is not necessary to maintain the routing information in routing table by each node in the reactive or on-demand routing protocols. During route discovery process, the reactive or on-demand routing protocols determine and maintain the routes only when they are required by the source for data transmission. As a result, the routing overhead is reduced. Examples for such multipath reactive routing protocols are the multipath dynamic source routing (MP-DSR) [7] and the ad hoc on-demand multipath distance vector (AOMDV) [8] protocol is a multipath extension of prominent single path routing protocol, called ad hoc on-demand distance vector (AODV) [9]. The AOMDV provides link-disjoint, loop free and fault tolerance multiple paths in order to improve the network life-time by minimizing packet loss, routing overhead and energy consumption. Optimized minimal maximal residual energy AOMDV (OMMRE-AOMDV) [10] is an improved version of minimal maximal residual energy AOMDV (MMRE-AOMDV) [11]. The OMMRE-AOMDV provides more energy efficient, link-disjoint, loop free and fault tolerance paths in order to improve network lifetime and gives better performance than MMRE-AOMDV and AOMDV. Link reliable energy efficient AOMDV (LR-EE-AOMDV) [12] is an enhanced version of AOMDV [8] which provides multiple link reliable energy efficient shortest paths better than OMMRE-AOMDV and AOMDV. Since the number of paths generated by LR-EE-AOMDV are very limited due to the selection of routes between any source and destination using three metrics integrated approach, the end-to-end delay is very high when the number of connection or network flow increases. The main goal of this work is to design a multipath routing protocol by providing loop free link reliable energy efficient multiple paths from any source to destination with the available resources to meet out the Quality of Service (QoS) requirements of the desired service.

Hybrid multipath routing protocols are new generation of protocols by combining the features of both proactive and reactive protocols together to increase the scalability of nodes. Such protocols reduce the route discovery overheads by allowing the nodes with close proximity to work together to form some sort of a backbone. This can be attained by proactively maintaining routes to nearby nodes and determining routes to far away nodes using reactive route discovery strategy. Example for this category is Zone Routing Protocol (ZRP) [13]. Therefore the reactive (on-demand) routing protocols outperform better than proactive (table-driven) and hybrid routing protocols.

Wireless ad hoc networks are frequently using the broadcast primitives such as bandwidth, energy, delay, load, etc in order to adapt with network changes due to their ad hoc nature and mobile environment. End-to-End reliable data transmission has been an emerging issue in MANET due to the frequent failures of wireless links between nodes. For this reason, we introduce link reliable energy efficient multipath routing protocol by extending the AOMDV protocol in order to select the path with reliable links for data transmission in wireless ad hoc networks, called *End-to-End Link Reliable Energy Efficient Multipath Routing (E2E-LREEMR)* protocol. The AOMDV is selected for enhancement due to its edge over other multipath routing protocols of MANET.

The rest of the paper is organized as follows. Section 2 briefly describes the AOMDV routing protocol. Section 3 presents the proposed protocol. The simulation environment and experimental results are discussed in Sect. 4. Finally, conclusions and future works are given in Sect. 5.

2 Ad Hoc On-demand Multipath Distance Vector routing (AOMDV)

AOMDV routing protocol is an extended version of a prominent on-demand (reactive) single path routing protocol known as AODV routing protocol. AODV does not have efficient fault tolerance capability due to the generation of only one path between any source and destination pair at a time. It fails to provide faster and efficient recovery from route failures in highly dynamic ad hoc networks.

The main objective of AOMDV is to compute loop-free and link-disjoint multiple routes between any source and destination pair in order to eliminate the occurrence of frequent link failures and route breaks with regards to node mobility, node failures, and congestion in traffic, packet collisions, and so on in highly dynamic ad hoc networks. This can be done by adding some extra fields in routing tables and control packets of AODV. The qualities of AOMDV are projected in terms of increased packet delivery ratio, throughput and reduced average end-to-end delay and normalized routing overhead. The loop-free and link-disjoint scheme of AOMDV reduces the end-to-end delay and normalized routing overhead better than AODV.

The AOMDV's routing process has three phases such as (i) route discovery, (ii) route selection, and (iii) route maintenance. In AOMDV, the *RREQ (Route REQuest)*, *RREP (Route REPly)* or *HELLO* packets are transmitted over links of nodes in the intention of establishing, selecting and maintaining routes between any source and destination. These packets are called *Received Signal Strength Indicators (RSSI)* [14]. In AOMDV routing protocol, multiple reverse routes are established by means of propagating RREQs from a source to a destination via intermediate nodes. Similarly the multiple forward routes are established by means of propagating RREPs from a destination to a source via intermediate nodes and the local link connectivity after route establishment [15] is obtained by flooding the HELLO packets between nodes. On receiving HELLO packets, every node locally updates its routing, called *Local Path Update (LPU)*. Routing table of AOMDV routing protocol is updated on-demand periodically upon receiving RREQ/RREP based on the following route update rules as shown in Algorithm 1.

Algorithm 1 *Route Update Rules of AOMDV Protocol [8]*

```
if $(seqnum_i^d < seqnum_j^d)$ then
    $seqnum_i^d := seqnum_j^d$
    if $(i \neq d)$ then
        $advertised\_hopcount_i^d := \infty$
    else
        $advertised\_hopcount_i^d := 0$
    end if
    $route\_list_i^d := NULL$
    insert $(j, advertised\_hopcount_j^d + 1)$ into $route\_list_i^d$
else if $(seqnum_i^d = seqnum_j^d)$
  and $((advertised\_hopcount_i^d, i) > (advertised\_hopcount_j^d, j))$ then
    insert $(j, advertised\_hopcount_j^d + 1)$ into $route\_list_i^d$
end if
```

3 Proposed Protocol

Since the communicating nodes in AOMDV are prone to link failures and route breaks due to the selection of multiple routes between any source and destination pair based on minimal hop count which does not ensure end-to-end reliable data transmission. To overcome this problem, a novel node disjoint multipath routing protocol called *End-to-End Link Reliable Energy Efficient Multipath Routing (E2E-LREEMR)* protocol by extending AOMDV is proposed.

3.1 Routing Metrics

Best routes among multiple routes under certain aspects of the routing process of a protocol are selected by qualitative measures called Routing Metrics [12, 16]. The routing metrics are classified into two categories such as (i) node based routing metrics that are used to select best routes among multiple routes based on the available information of participating nodes such as energy, hop count, etc., and (ii) link based routing metrics that are used to select best routes among multiple routes based on the available information of participating links such as throughput, reliability, etc. End-to-end reliable data transmission has been an issue in multipath routing of MANET, since nodes are prone to failures due to the uncertainty of links between them.

A route with less number of hops among the available routes to the intended destination from the source is selected by a conventional node based routing metric called hop count or path length. In MANET, most of the routing protocols use hop count as their base metric. The suitability of a route is simply evaluated based on path length which neither take packet loss nor link's bandwidth and node's energy into account.

The number of transmissions and retransmissions required to send a data packet over a link are estimated by a qualitative link based routing metric called Expected Transmission Count (ETX)[12, 17] or link ETX [18]. The summation of the ETX of all participating links of the route called path ETX or Path-Link Quality Estimator (P-LQE) or Cumulative Expected Transmission Count (CETX). RREQ or RREP packets are initially used to determine RSSI during route discovery and then HELLO packets are used to determine RSSI during route selection and maintenance. The stability of links between nodes during route discovery is determined by RREQ or RREP packets that are used to calculate both ETX and CETX in this protocol. In this paper, the ETX of a link between nodes along the forward path and the reverse path are computed using RREP and RREQ packets respectively.

The amount of energy required by a node to send a data packet to another node over a link is estimated by a qualitative node based routing metric called Expected Transmission Energy (ETE) [12, 19]. The summation of the ETE value of all participating nodes of the route is called Cumulative Expected Transmission Energy (CETE) or path ETE or Path-Node Energy Estimator (P-NEE). Minimal value of the residual energy of the participating nodes of a route is called Minimal Residual Energy (MRE) [11]. This value is used as threshold for CETE during the selection of routes.

Minimal nodal residual energy and hop count metrics are used for route selection by many researchers. Node failures occur when the minimal nodal residual energy of the path does not meet out the energy required for data transmission. By default, all routing protocols use *Link Expiration Time (LET)* for measuring link stability. A link between nodes has failed to transmit data when it is alive (LET of that link is not expired) but it is not within the transmission range. The scope of our protocol is to measure CETX dynamically for ensuring link reliability in addition to LET and is also to measure CETE for ensuring minimal transmission energy in addition to minimal nodal residual energy for finding link reliable energy efficient paths for data transmission. The E2E-LREEMR protocol uses two metrics integrated approach such as Path-Link Quality Estimator (P-LQE) and Path-Node Energy Estimator (P-NEE) in order to select more link reliable energy efficient paths for data transmission.

For finding multiple routes and selecting a route with a few hop counts among them for data transmission, the AOMDV uses the traditional routing metric hop count. Data loss occurs in AOMDV during data transmission if any link between the nodes of that route fails or energy of any node of that route downs. We propose a novel protocol by modifying AOMDV routing protocol using both *CETX* and *CETE* as path selection metrics to resolve this issue.

3.2 General Procedure

The proposed protocol is an enhanced version of AOMDV which uses the two metrics such as *Path-Link Quality Estimator (P-LQE)* or *Cumulative Expected Transmission Count (CETX)* [20–22] and *Path-Node Energy Estimator (P-NEE)* or *Cumulative Expected Transmission Energy (CETE)* in order to provide more link reliable energy efficient paths for data transmission. It reduces the routing overhead, packet loss ratio, normalized routing overhead, average end-to-end delay and energy consumption. It also improves the packet delivery ratio and throughput. The following is the general procedure of E2E-LREEMR protocol:

1. Determining Residual and Minimal Residual Energy (RE & MRE)
2. Determining Expected Transmission Energy (ETE)
3. Determining Cumulative Expected Transmission Energy (CETE)
4. Determining Expected Transmission Count (ETX)
5. Determining Cumulative Expected Transmission Count (CETX)
6. Route selection based on CETX and CETE

3.2.1 Determining Residual and Minimal Residual Energy (RE & MRE)

In E2E-LREEMR protocol, each RREQ and RREP now carries an additional field called re_energy to hold the residual energy of a node in the path as shown in Table 2. In order to find the minimal nodal residual energy of the route, the routing table has an additional field called mre as shown in Table 1. Line 3 of Algorithm 2 is used to compute the residual energy re_energy. Lines 4–6 of Algorithm 2 are used to keep the mre field of the routing table which considers the lowest one among the residual energy of all participating nodes of the route is illustrated in the equation given below:

$$MRE_{path(S,D)} = \min(RE_i) \quad \forall i \in path(S,D) \tag{1}$$

where $MRE_{path(S,D)}$ represents the minimal residual energy of a route between a source S and a destination D. It is determined by keeping the lowest residual energy among the residual energy RE_i of all participating nodes i of that route during route discovery.

3.2.2 Determining Expected Transmission Energy (ETE)

Energy consumed by a participating node in a node disjoint path for transmitting RREQ/RREP in order to find reverse/forward paths is called *Expected Transmission Energy (ETE)* of that node. The traditional routing metric hop count is not considered as a criterion in our protocol to select the multiple routes between any source and destination pair, instead the two metrics *CETX* and *CETE* combined together to select energy efficient link reliable routes for data transmission. During route discovery phase, the E2E-LREEMR protocol calculates $ETE_{i\in path(S,D)}$ as follows:

$$ETE_{i\in path(S,D)} = EC_{i\in path(S,D)} \tag{2}$$

Table 1 Structure of routing table entries of AOMDV and E2E-LREEMR protocols

AOMDV	E2E-LREEMR
Destination address	Destination address
Sequence number	Sequence number
Advertised hop count	Advertised hop count
route list	**route list**
$\{(nexthop_1, hopcount_1), (nexthop_2, hopcount_2), \ldots\}$	$\{(nexthop_1, \mathbf{cetx_1}, \mathbf{cete_1}, \mathbf{mre_1}), (nexthop_2, \mathbf{cetx_2}, \mathbf{cete_2}, \mathbf{mre_2}), \ldots\}$
Expiration time out	Expiration time out

Table 2 Extended RREQ/RREP message format

SA	DA	Seq.No.	Expire	pHop	CETX	CETE	re_energy

where $ETE_{i \in path(S,D)}$ represents the expected transmission energy of a participating node i of the route. It is calculated by determining the amount of energy consumed $EC_{i \in path(S,D)}$ by that node i during route discovery.

3.2.3 Determining Cumulative Expected Transmission Energy (CETE)

In E2E-LREEMR protocol, each RREQ and RREP of now carries an additional field called *cete* for holding the cumulative expected transmission energy as shown in Table 2. When a source S starts flooding RREQ, it initializes the CETE of its RREQ by 0. Similarly, when a destination D sends back RREP, it initializes the CETE of its RREP by 0. After calculating ETE value of participating nodes along the path from a source node S to a destination node D in a wireless network, the Cumulative ETE value of that path is obtained by calculating the summation of the energy consumed by all participating nodes on that path is shown in Line 2 of Algorithm 2 and is calculated as follows:

$$CETE_{path(S,D)} = \sum_{i=1 \wedge i \in path(S,D)}^{n} ETE_i \tag{3}$$

where $CETE_{path(S,D)}$ represents the cumulative expected transmission energy of a route between a source S and a destination D. It is obtained by the summation of the ETE_i of all participating nodes i during route discovery.

3.2.4 Determining Expected Transmission Count (ETX)

Quality of a link between participating nodes of the path is determined in terms of number of RREQ or RREP packets over a period of time called *Expected Transmission Count (ETX).* The E2E-LREEMR protocol calculates $PRR_{forward(i,j)}$, $PRR_{backward(i,j)}$, and $ETX_{link(i,j)}$ during route discovery phase as follows:

$$PRR_{forward(i,j)} = \frac{Number\ of\ RREQ\ /\ RREP\ packets\ generated\ at\ node\ i}{w\ seconds} \tag{4}$$

Packet Reception Rate (PRR) of uplink quality from the sender to the receiver $PRR_{forward(i,j)}$ is obtained by finding the number of RREQ or RREP packets generated from the sender to the receiver over a period of time, say w seconds.

$$PRR_{backward(i,j)} = \frac{Number\ of\ RREQ\ /\ RREP\ packets\ received\ at\ node\ j}{w\ seconds} \tag{5}$$

Packet Reception Rate (PRR) of downlink quality from the receiver to the sender $PRR_{backward(i,j)}$ is obtained by finding the number of RREQ or RREP packets received by the receiver from the sender over a period of time, say w seconds.

$$ETX_{link(i,j)} = \frac{1}{PRR_{forward(i,j)} \times PRR_{backward(i,j)}} \tag{6}$$

Table 3 Notations and their descriptions

Notation	Description
$ETX_{link(i,j)}$	ETX value of link i and j
$ETX_{path(s,d)}$	Path ETX, called as CETX
$PRR_{forward(i,j)}$	Forward packet reception
	Rate of a link at node i
$PRR_{backward(i,j)}$	Backward packet reception
	Rate of a link at node j
$MRE_{path(s,d)}$	Minimal residual energy of the path
RE_i	Residual energy of node i of the path
ETE_i	ETE value of node i
$CETE_{path(S,D)}$	Path ETE
pHop	Previous node to the
	Current node of the path
i,j	Intermediate nodes
S,s	Source node
D,d	Destination node
SA	Source address
DA	Destination address

The value of $ETX_{link(i,j)}$ is obtained from both uplink quality from the sender to the receiver $PRR_{forward(i,j)}$ and downlink quality from the receiver to the sender $PRR_{backward(i,j)}$. Structure of routing table entries of AOMDV and E2E-LREEMR protocols are illustrated in Table 1 and the notations and their descriptions used in this paper are shown in Table 3.

3.2.5 Determining Cumulative Expected Transmission Count (CETX)

In E2E-LREEMR protocol, each RREQ and RREP of now carries an additional field called cetx for holding the *Cumulative Expected Transmission Count* is shown in Table 2. When a source S starts flooding RREQ, it initializes the CETX of its RREQ by 0. Similarly, when a destination D sends back RREP, it initializes the CETX of its RREP by 0. After calculating ETX value of links between nodes along the path in a wireless network, the Cumulative ETX value of a path from a source node S to a destination node D is obtained by calculating the summation of the ETX value of all participating links of the node disjoint path shown in Line 1 of Algorithm 2 and is calculated as follows:

$$CETX_{path(S,D)} = \sum_{link(i,j)\in path(S,D)} ETX_{link(i,j)} \tag{7}$$

Where path(S, D) is a set of successive links in the path from node S to D such as: path(S, D) = $\{(S, I_1), (I_1, I_2), \ldots, (I_{k-1}, I_k), (I_k, D)\}$.

3.2.6 Route Selection Based on CETX and CETE

In E2E-LREEMR protocol, each RREQ and RREP absolutely carries three additional fields such as (i) CETX is the sum of the ETX value of link over which the RREQ or RREP has traversed, (ii) CETE is the sum of the ETE value of node over which the RREQ or

RREP has traversed and (iii) re_energy is the residual energy of the node are given in Table 2. Similar to AOMDV routing protocol, in E2E-LREEMR, when a node receives a RREQ packet for the first time, it rebroadcasts the RREQ packet immediately.

Algorithm 2 *Route Update Rules of E2E-LREEMR Protocol*

```
$cetx_j^d := cetx_j^d + etx_j^d$
$cete_j^d := cete_j^d + ete_j^d$
$re\_energy_i := initial\_energy_i - consumed\_energy_i$
if $(re\_energy_i < mre_j^d)$ then
    $mre_j^d := re\_energy_i$
end if
if $(seqnum_i^d < seqnum_j^d)$ then
    $seqnum_i^d := seqnum_j^d$
    if $(i \neq d)$ then
        $cetx_i^d := cetx_j^d$
        $cete_i^d := cete_j^d$
        $advertised\_hopcount_i^d := \infty$
    else
        $advertised\_hopcount_i^d := 0$
    end if
    $route\_list_i^d := NULL$
    insert $(j, advertised\_hopcount_j^d + 1, cetx_j^d, cete_j^d, mre_j^d)$ into $route\_list_i^d$
else if $(seqnum_i^d = seqnum_j^d)$ and $((cetx_i^d, i) > (cetx_j^d, j))$
 and $((cete_i^d, i) < mre_j^d)$ then
    insert $(j, advertised\_hopcount_j^d + 1, cetx_j^d, cete_j^d, mre_j^d)$ into $route\_list_i^d$
    //Got a new node disjoint alternate path and insert it into routing table
    if $(num\_paths_i^d = max\_num\_paths)$ and $((cetx_j^d - min(cetx_i^d, i)) \leq 1.0)$
     and $((cete_i^d, i) < mre_j^d)$ then
        insert $(j, advertised\_hopcount_j^d + 1, cetx_j^d, cete_j^d, mre_j^d)$ into $route\_list_i^d$
        $cetx_i^d := cetx_j^d$
        $cete_i^d := cete_j^d$
    end if
end if
```

The E2E-LREEMR protocol invokes its route update rules to setup forward as well as reverse routes whenever a node i receive a route advertisement to a destination d from a neighbour j as shown in Algorithm 2. The variables $seqnum_i^d$, $advertised\_hopcount_i^d$, $route\_list_i^d$, $cetx_j^d$, $cete_j^d$, $re\_energy_j^d$, and mre_j^d are the sequence number, advertised hop count, route list, cumulative expected transmission count, cumulative expected transmission energy, residual energy and minimal residual energy for destination d at node i or node j respectively.

When a source S floods RREQ to a destination D, it initializes the values of CETX and CETE of its RREQ by zero, the pHop *(previous Hop)* of its RREQ by source S, the re_energy of its RREQ by the current energy of that node. Similarly, when a destination D sends back RREP to a source S, it initializes the values of CETX and CETE of its RREP by zero, the pHop *(previous Hop)* of its RREP by destination D, the re_energy of its RREP by the current energy of that node. The mre field of the routing table entry is also initialized by the current energy of the source *(during reverse route set-up)*/destination *(during forward route set-up)* node during route discovery. On receiving the RREQs or RREPs, the intermediate nodes find ETX value in terms of number of RREQ or RREP packets over the ends of the link and ETE value in terms of the energy consumed by a participating node of the path. The CETX and CETE values of our proposed protocol are updated periodically using Algorithm 2 which deals with the following two cases in order to select the paths based on the two metrics such as CETX and CETE:

> **Case 1:** From Lines 7–17 of Algorithm 2, the intermediate node updates its routing table by updating the CETX and CETE values with the CETX and CETE values of RREQ/RREP of this node respectively if the sequence number of just received packet is greater than this node.
>
> **Case 2:** From Lines 18–25 of Algorithm 2, the intermediate node updates its routing table by updating CETX and CETE values with the CETX and CETE values of RREQ/RREP of this node respectively if the sequence number of just received packet is equal to this node and the CETX value of RREQ/RREP is greater than the CETX value of that intermediate node as well as the CETE value of RREQ/RREP is less than the MRE of the path.

Route selection process of E2E-LREEMR protocol is illustrated in Fig. 1. Here the number in each link is the ETX value of that link, the number in each rectangle is the ETE value of that node, the number in each hexagon is the residual energy of that node, and S and D are the source and destination. In E2E-LREEMR protocol, the path with CETX value (CETX < 1 and CETX > 0) and CETE value (CETE $<$ MRE) selected for data transmission. When the ETX value of a link between two nodes is zero, it is considered as a weak link which does not consider for data transmission. For example, node F sends 3 RREQ packets to node H per second, then the $PRR_{forward(F,H)}$ is 3 and the node H receives 1 RREQ packet from node F per second, then the $PRR_{backward(F,H)}$ is 1 and the ETX value of the link between nodes F and H is 0.3. The path S–C–G–D with CETX $= 0.3$, CETE $= 16$ and MRE $= 70$ is selected as a primary route for data transmission and the path S–A–F–H–D with CETX $= 0.6$, CETE $= 21$ and MRE $= 50$ is chosen as alternate route.

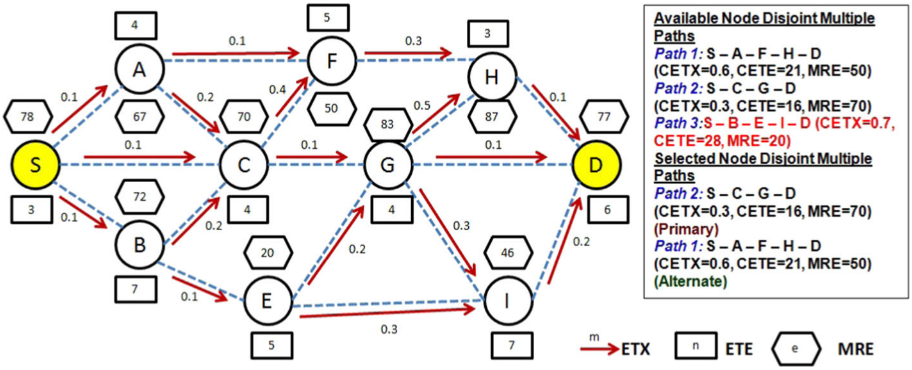


Fig. 1 Route selection process of E2E-LREEMR protocol

4 Simulation Environment and Experimental Results

Simulation [23] is the process of designing a model for a real system and conducting experiments with this model in order to understand the behavior of the system and/or evaluating various strategies for the operation of the system.

4.1 Environmental Setup

The performance of E2E-LREEMR and AOMDV routing protocols are evaluated under Random waypoint mobility model with varying number of connections (Network Flows) using NS 2.34 [24–29] and the simulation parameters are shown in Table 4.

4.2 Performance Metrics

A set of qualitative measures used to evaluate any MANET routing protocol in terms of Quality of Service (QoS) is called as *Performance Metrics*. We have evaluated the following seven different performance metrics:

Table 4 Simulation parameters

Parameter(s)	Value(s)
Simulator	NS-2.34
MAC type	802.11 DCF
Simulation area	1500 m × 1500 m
Simulation time	300 s
Routing protocols	AOMDV & E2E-LREEMR
Traffic Type	CBR(udp)
Data payload	512 bytes/packet
Network loads	4 packets/s
Number of connections	1, 5, 10, 20, 30, 40 (Varying)
Idle power	0.0001 W
Transmission power	1.0 W
Receiving power	1.0 W
Sleep power	0.0001 W
Transition power	0.002 W
Transition time	0.005 s
Initial energy	100 J
Interface queue length	50
Number of nodes	100
Pause time	0 s
Speed	5 m/s
Mobility model	Random Waypoint (RWM)
Frequency	2.4 GHz
Data rate	11.4 Mbps
Carrier sensing range	500 m
Carrier receiving range	250 m

1. *Packet Loss Ratio (%)* is defined as the ratio of data packets which are not delivered to the destination to those generated by the sources. It is calculated as follows:

$$Packet\ Loss = (No.\ of\ Data\ pkts.\ Sent\ -\ No.\ of\ Data\ pkts.\ Received) \tag{8}$$

$$Packet\ Loss\ Ratio = \frac{Packet\ Loss}{No.\ of\ Data\ pkts.\ Sent} \times 100 \tag{9}$$

2. *Normalized Routing overhead (%)* is defined as the number of routing packets transmitted per data packet towards destination during simulation. It is obtained as follows:

$$Normalized\ Routing\ overhead = \frac{No.\ of\ Routing\ pkts.\ Transmitted}{No.\ of\ Data\ pkts.\ Received} \tag{10}$$

3. *Total Energy consumed (in Joules)* is defined as the summation of the energy consumed by all nodes in the simulation environment. The Total energy consumption is calculated as follows:

$$Total\ Energy\ consumed = \sum_{i=1}^{n} (Initial\ Energy_i - Residual\ Energy_i) \tag{11}$$

4. *Throughput (in Kbps)* is defined as the number of bytes received successfully. It is obtained by

$$Throughput = \frac{No.\ of\ Bytes\ Received \times 8}{Simulation\ Time \times 1000} kbps \tag{12}$$

5. *Packet Delivery Ratio (%)* is defined as the ratio of data packets delivered to the destination to those generated by the sources. The Packet Delivery Ratio is calculated as follows:

$$Packet\ Delivery\ Ratio = \frac{No.\ of\ Data\ pkts.\ Received}{No\ of\ Data\ pkts.\ Sent} \times 100 \tag{13}$$

6. *Routing Overhead (Pkts)* is defined as the total number of control or routing packets generated by routing protocol during simulation. It is obtained as follows:

$$Routing\ Overhead = No.\ of\ RTR\ pkts. \tag{14}$$

7. *Average End-to-End delay (in ms)* is defined as the average time of the data packet to be successfully transmitted across a MANET from source to destination. It includes all possible delays such as buffering during the route discovery latency, queuing at the interface queue, retransmission delay at the MAC, the propagation and the transfer time and is calculated as follows:

$$Average\ End\text{-}to\text{-}end\ Delay = \frac{\sum_{i=1}^{n} (R_i - S_i)}{n} \tag{15}$$

where n is the number of data packets successfully transmitted over the MANET, ‘i’ is the unique packet identifier, R_i is the time at which a packet with unique identifier ‘i’ is received and S_i is the time at which a packet with unique identifier ‘i’ is sent. The Average End-to-End Delay should be less for high performance.

Table 5 Packet Loss Ratio (%) and Normalized Routing Overhead (%) of AOMDV & E2E-LREEMR

Network flows	Packet loss ratio (%)		Normalized routing overhead (%)	
	AOMDV	E2E-LREEMR	AOMDV	E2E-LREEMR
1	12.874	3.807	28.867	24.312
5	23.691	10.462	9.805	7.113
10	22.923	14.758	5.301	4.298
20	18.7	15.639	3.067	2.798
30	28.387	22.657	4.23	3.375
40	36.839	29.268	4.66	3.527

Table 6 Total energy consumed (in Joules) and Average End-to-End Delay (in ms) of AOMDV & E2E-LREEMR

Network flows	Total energy consumed (in Joules)		Average End-to-End Delay (in ms)	
	AOMDV	E2E-LREEMR	AOMDV	E2E-LREEMR
1	114.198	50.133	1.478	1.093
5	1307.158	649.548	1.906	1.32
10	3813.791	3054.698	2.148	1.913
20	9782.709	8979.385	3.284	3.096
30	16,272.886	14,631.904	6.769	4.438
40	20,110.853	17,425.555	17.697	11.296

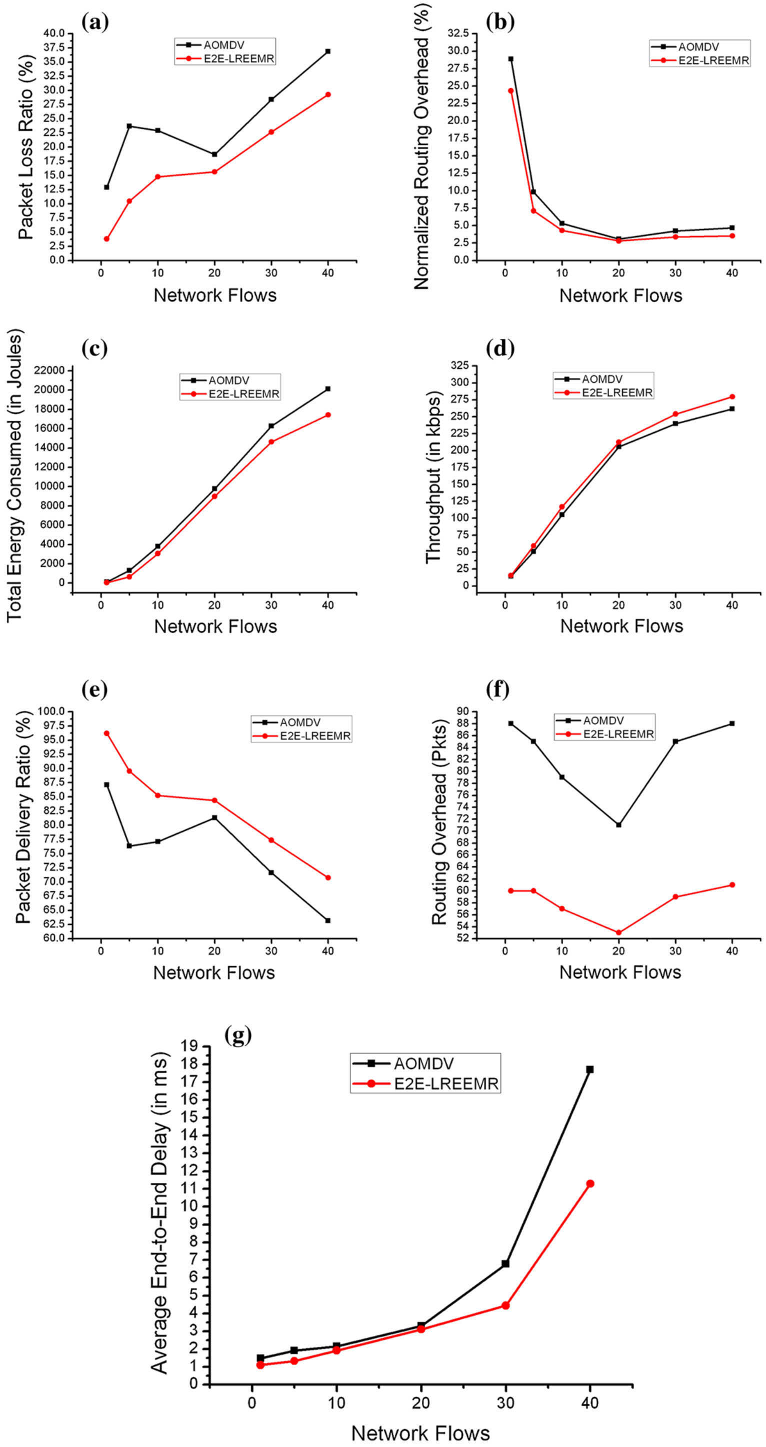
Table 7 Routing Overhead (in Pkts) of AOMDV & E2E-LREEMR

Network flows	Routing overhead (Pkts)	
	AOMDV	E2E-LREEMR
1	88	60
5	85	60
10	79	57
20	71	53
30	85	59
40	88	61

4.3 Experimental Results and Discussion

From Tables 5, 6, 7 and Fig. 2a–c, f, g the E2E-LREEMR reduces the packet loss ratio, normalized routing overhead, total energy consumption, routing overhead and average end-to-end delay better than AOMDV routing protocol respectively because the E2E-LREEMR selects the routes based on CETX value ($\text{CETX} < 1$ and $\text{CETX} > 0$) and CETE value ($\text{CETE} < \text{MRE}$) but in AOMDV routing protocol the routes are selected based on only hop count which does not ensure link reliability.

From Table 8 and Fig. 2d, e the E2E-LREEMR protocol gives high throughput and better packet delivery ratio than AOMDV routing protocol respectively due to the selection


(a)
Packet Loss Ratio (%)
40.0
37.5
35.0
32.5
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(b)
Normalized Routing Overhead (%)
32.5
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(c)
Total Energy Consumed (in Joules)
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(d)
Throughput (in kbps)
325
300
275
250
225
200
175
150
125
100
75
50
25
0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(e)
Packet Delivery Ratio (%)
100.0
97.5
95.0
92.5
90.0
87.5
85.0
82.5
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5
60.0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(f)
Routing Overhead (Pkts)
90
88
86
84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
52
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR
(g)
Average End-to-End Delay (in ms)
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
Network Flows
AOMDV
E2E-LREEMR

◀**Fig. 2** Varying network flows. **a** Packet loss ratio (%). **b** Normalized routing overhead (%). **c** Total energy consumed (in J). **d** Throughput (in kbps). **e** Packet delivery ratio (%). **f** Routing overhead (Pkts). **g** Average end-to-end delay (in ms)

Table 8 Packet Delivery Ratio (%) and Throughput (in kbps) of AOMDV & E2E-LREEMR

Network flows	Packet Delivery Ratio (%)		Throughput (in kbps)	
	AOMDV	E2E-LREEMR	AOMDV	E2E-LREEMR
1	87.126	96.193	14.329	15.606
5	76.309	89.538	50.754	59.248
10	77.077	85.242	105.146	116.959
20	81.3	84.361	205.514	212.499
30	71.613	77.343	239.494	253.974
40	63.161	70.732	261.494	279.399

of link reliable energy efficient paths for data transmission using CETX value (CETX $<$ 1 and CETX $>$ 0) and CETE value (CETE $<$ MRE).

5 Conclusion and Future Work

We have proposed E2E-LREEMR routing protocol by which the selection of multiple link reliable energy efficient paths between any source and destination pair for data transmission can be done using two metrics such as Path-Link Quality Estimator (P-LQE) or Cumulative Expected Transmission Count (CETX) and Path-Node Energy Estimator (P-NEE) or Cumulative Expected Transmission Energy (CETE). It also avoids the occurrence of link failures and route breaks in a highly dynamic ad hoc network. The performance of E2E-LREEMR protocol was compared with AOMDV routing protocol using NS2.34 under random waypoint mobility model in terms of Quality of Service (QoS) metrics. Since the E2E-LREEMR finds multiple link reliable energy efficient paths between any source and destination pair for data transmission using two metrics such as *Path-Link Quality Estimator (P-LQE)* and *Path-Node Energy Estimator (P-NEE)*, when there is a hike in network connection, the E2E-LREEMR reduces 30.43 % of average end-to-end delay, 29.44 % of routing overhead, 32.65 % of packet loss ratio, 18.79 % of normalized routing overhead and 12.87 % of energy consumption better than AOMDV routing protocol. It also increases 10.26 % of packet delivery ratio and 6.96 % of throughput better than AOMDV routing protocol. Simulation results demonstrate that the performance of E2E-LREEMR protocol is better than AOMDV routing protocol. In future we will ensure a great effort to improvise the E2E-LREEMR's overall performance in emerging applications of Delay or Disruption Tolerant Networks (DTN) and Cognitive Radio Ad hoc Networks (CRAN) by considering new metrics in connection with network nodes such as networks life-time, average number of nodes dying in different mobility models by studying and enhancing recent power efficient strategies and routing metrics. In future, the E2E-LREEMR routing protocol will also be modified to cooperate with MAC layer's multi-interface and multi-channel assignment schemes for wireless sensor or vehicular ad hoc networks.

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