Chapter 4

Energy Efficient AODV Routing Protocols Based On Adaptive Fuzzy Threshold Energy

4.1. Introduction

As seen in the previous chapter, energy efficiency plays a major role in the design of routing protocols for MANETs. There are different processes of power consumption in a mobile node. Communication is one of the main processes of energy consumption. In the Chapter 3, the main goal of the load distribution method is to balance the energy usage among the nodes and to maximize the network lifetime by avoiding over-utilized nodes when selecting a routing path. Hence, a routing algorithm based on load distribution approach is proposed wherein, the intermediate node, whose residual energy is less than the threshold energy, will not take part in the process of routing. It conserves its energy to last as longer as possible. The threshold value is adaptive and it depends upon the average residual energies of all the neighboring nodes at each hop.

Several energy efficient routing protocols have been proposed based on load distribution approach. An AODV-based node caching routing protocol with adaptive workload balancing (AODV-NC-WLB) has been developed in [Sunsook Jung et al., 2005]. In [S M Lambor et al., 2011], it has been shown that as the network lifetime increases, the percentage energy consumption decreases with increase in the number of hops and attains a minimum at critical hops. After the critical hops, the energy consumption gradually increases due to increase in cumulative energy consumption of the intermediate nodes. A Local Energy-Aware Routing protocol which achieves a trade-off between balanced energy consumption and shortest routing delay and at the same time avoids the blocking and route cache problems is proposed in [Kyungtae Woo et al., 2001].

A part of this chapter is published in the
In this chapter, the method proposed in the Chapter 3 is extended by using fuzzy logic to determine the value of adaptive threshold energy.

**4.2. Adaptive fuzzy threshold energy**

It is expected that a MANET lasts for a longer duration. To achieve this, we need to ensure that no node is overused during routing process. Hence, the routing load needs to be equally distributed among all the neighboring nodes. Otherwise, it results in early network partitioning. In this section, a fuzzy based adaptive threshold energy policy is proposed, in which only the nodes with energy above the fuzzy threshold energy value can take part in the route discovery process. This method ensures that no node is overused and hence the life time of the MANET gets enhanced. In our proposed protocol, we have different threshold level at different hops. This is because at each hop we have different set of neighbors having different residual energies. The fundamental idea behind the proposed protocol is to apply the remaining battery capacity of each node as a prime metric in the route selection process.

The cost of a node to forward a packet keeps increasing as its residual energy continues to decrease. The residual energy defines the reluctance or willingness of intermediate nodes to respond to route requests and forward data traffic. When energy \( R_{E_i} \) in a node \( i \) is lower than a predefined threshold level \( R_{E_{ith}} \), i.e., \( R_{E_i} \leq R_{E_{ith}} \), the node does not forward the route request control message, but simply drops it. Thus, it does not participate in the route selection and forwarding phase.

The proposed methodology is based on adaptive fuzzy thresholding of residual energy of nodes participating in the route discovery from source to destination.

Let \( R_{E_i}, i = 1, 2, \ldots, n \), be the residual energies of the \( n \) neighboring nodes of a transmitter node. Let \( \text{min} R_{E} = \min \{ R_{E_i} \} \), \( \text{max} R_{E} = \max \{ R_{E_i} \} \) and \( \text{mid} R_{E} = (\text{min} R_{E} + \text{max} R_{E}) / 2 \). We define the three fuzzy subsets of these nodes with low, medium and high residual energy whose membership functions \( \mu_{\text{low}} \), \( \mu_{\text{medium}} \) and \( \mu_{\text{high}} \), respectively, are given below (Figure 4.1).
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\[
\mu_{\text{low}}(RE_i) = \begin{cases} 
\frac{RE_i - \text{mid}RE}{\text{min} RE - \text{mid}RE}, & \text{min} RE \leq RE_i \leq \text{max} RE \\
0, & \text{mid}RE \leq RE_i \leq \text{max} RE 
\end{cases}
\]

\[
\mu_{\text{medium}}(RE_i) = \begin{cases} 
\frac{RE_i - \text{mid}RE}{\text{min} RE - \text{mid}RE}, & \text{min} RE \leq RE_i \leq \text{mid}RE \\
\frac{RE_i - \text{max} RE}{\text{mid}RE - \text{max} RE}, & \text{mid}RE \leq RE_i \leq \text{max} RE 
\end{cases}
\]

\[
\mu_{\text{high}}(RE_i) = \begin{cases} 
0, & \text{min} RE \leq RE_i \leq \text{mid}RE \\
\frac{RE_i - \text{mid}RE}{\text{max} RE - \text{mid}RE}, & \text{mid}RE \leq RE_i \leq \text{max} RE 
\end{cases}
\]

Then, the membership value \( \mu \) of \( RE_i \) for the \( i^{th} \) node is given by:

\[
\mu_i(RE_i) = \max\left\{ \mu_{\text{low}}(RE_i), \mu_{\text{medium}}(RE_i), \mu_{\text{high}}(RE_i) \right\}
\]

Let \( RE_{th} \) be the value of \( RE_i \) for which the membership value is minimum among neighboring nodes, i.e.,

\[
\mu_{th}(RE_{th}) = \min_{1 \leq i \leq n} \left\{ \mu_i(RE_i) \right\}
\]

If there is a tie, it is broken by selecting the node with \( \text{min} \) \( RE \) among the nodes with the same minimum membership value. Then, \( RE_{th} \) obtained by this defuzzification process, is used as the threshold energy value, which is transmitted in RREQ packet to the neighboring nodes.
4.3. Delay sensitivity

Two new energy aware and delay sensitive routing protocols are proposed, one based on average residual energy and queue length, the other based on adaptive fuzzy threshold energy and queue length at each hop.

4.3.1. Energy efficient delay sensitivity based on average residual energy and queue length

The specific goal of the load distribution approach is to balance the energy usage of all mobile nodes by selecting a route with underutilized nodes rather than the shortest route. The residual energy of a node represents the reluctance or willingness of intermediate nodes to respond to route requests and forward data traffic. When energy $RE_i$ in a node $i$ is lower than a predefined threshold level $RE_{th}$, i.e., $RE_i \leq RE_{th}$, where $RE_{th}$ is the average residual energy of all the neighboring nodes at each hop, then node $i$ does not forward the route request control message, but simply drops it. Thus, it does not participate in the route selection and forwarding phase. Otherwise, at each hop, we determine $Q_{th}$, which is the average queue length of all the neighboring nodes. If the queue size of a neighbor $Q_i > Q_{th}$, i.e. queue size is more than threshold queue size, then the node simply ignores the route request. If $RE_i > RE_{th}$ and $Q_i < Q_{th}$, the node will forward the route request to its next hop. This process starts at source and continues till the destination receives the route request.

Figure 4.1. Membership functions for nodes with fuzzy RE levels.
4.3.2. Energy efficient delay sensitivity based on adaptive fuzzy threshold energy and queue length.

In this method, for the calculation of threshold energy $RE_{th}$, we use fuzzy mathematical approach as described in section 4.2. The $RE_{th}$ obtained by this defuzzification process, is used as the threshold energy value, which is transmitted in RREQ packet to the neighboring nodes. The similar fuzzy approach is used to calculate threshold queue size $Q_{th}$. Instead of using residual energies of neighboring nodes, we use their respective queue lengths, and thus obtain $Q_{th}$. If, for a neighboring node $i$, $RE_i > RE_{th}$ and $Q_i < Q_{th}$, where $RE_i$ and $Q_i$ are residual energy and queue length of node $i$, then the node will forward the route request to its next hop. Otherwise, the node simply drops the route request packet. This process starts at source and continues till the destination receives the route request packet.

4.4. Proposed methodology

The proposed methodology is based on the computation of adaptive fuzzy threshold energy (as in the Section 4.2). Further, it is modified to account for delay sensitivity by considering the queue length of packets.

The proposed routing algorithm is, thus, the modified AODV routing protocol incorporating the fuzzy based adaptive energy thresholding during route discovery stage which is given below.

Protocol based on adaptive fuzzy threshold energy (AFTE)

Algorithm: Energy efficient routing protocol with adaptive fuzzy threshold energy (AFTE)

Step 1. Let $S$ be the source node having $n$ neighbors with residual energy levels $RE_i$, $i = 1,..,n$. Initialize hopcount = 0.

Step 2. For node $S$, compute initial threshold energy $RE_{th}$ using the fuzzy mathematical procedure described in Section 4.2.
Step 3. The node S floods request packet RREQ to all its neighbors after embedding the value $RE_{\text{TH}}$ into RREQ, for establishment of path connection to destination node D.

Step 4. Each intermediate node, which receives RREQ, checks whether its residual energy is greater than $RE_{\text{TH}}$. If ‘yes’, go to step 5 else simply drop the RREQ packet.

Step 5. Intermediate node responds by sending reply packet RREP if it has a path to destination. Go to step 7.

Step 6. Intermediate node forwards RREQ after replacing the embedded $RE_{\text{TH}}$ value by the modified threshold value calculated using the procedure given in Section 4.2.

Step 7. Increment the hopcount by 1.

Step 8. Repeat Steps 4 to 7 until packet sent by node S reaches the destination node D. Output the value of the hopcount.

*Delay sensitivity*

The above routing algorithm is modified suitably in the Step 4 to implement delay sensitivity based on average residual energy and queue size as discussed in the Section 4.3. Accordingly, the following two methods are designed for implementation:

(i) Energy efficient delay sensitive routing protocol based on average residual energy and queue size (EEDS-1).

(ii) Energy efficient delay sensitive routing protocol based on adaptive fuzzy threshold energy and queue size (EEDS-2).

**4.5. Results and discussions**

The simulation experiments are carried out for the following algorithms:

(i) Proposed method based on adaptive fuzzy threshold energy (AFTE)

(ii) Proposed methods based on delay sensitivity EEDS-1 and EEDS-2.

The experimental results and analysis of the results are given below.
4.5.1. Adaptive fuzzy threshold energy

The proposed protocol is implemented using NS2 simulator, for different simulation times (50,100,...,500) and for different number of nodes (50,100,...,300) in steps of 50. The other parameters used for simulation are given below in the Table 4.1.

**TABLE 4.1. Simulation parameters used for LAEE and AFTE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>500sec, 100sec.</td>
</tr>
<tr>
<td>Terrain Area</td>
<td>500 X 500 sq. mts</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>50,100,150,200,250,300</td>
</tr>
<tr>
<td>Node placement</td>
<td>Random</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>RWP</td>
</tr>
<tr>
<td>Channel Frequency</td>
<td>2.4 G.Hz.</td>
</tr>
<tr>
<td>Routing Protocol</td>
<td>LAEE, AFTE</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>250 mts</td>
</tr>
<tr>
<td>Initial Energy for each node</td>
<td>100 Joules</td>
</tr>
</tbody>
</table>

The simulation results for different node densities ranging from 50-300 in steps of 50 are shown in the Figures 4.2 and 4.3. The complete summary of the simulation results is given in the Table 4.2. The results are compared with the performance of the Load Aware Energy Efficient Routing Protocol (LAEE). In the Figure 4.2, it is observed that as the simulation time increases, the average energy consumed by the mobile nodes keeps on increasing. The proposed routing algorithm AFTE consumes lesser energy as compared to LAEE routing algorithm. All the nodes drain off their residual energy by 450 sec. for LAEE protocol, for 50 and 150 nodes and at 400 sec. for 250 nodes, whereas for the proposed AFTE algorithm it occurs at 500 sec. for 50 nodes, at 600 sec. for 150 nodes and at 550 sec. for 250 nodes.
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(a)

(b)

(c)
Figure 4.2. The average energy consumed vs. simulation time for LAEE and AFTE.
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(a)

(b)

(c)
Figure 4.3. The percentage of dead nodes vs. simulation time for LAEE and AFTE
The Figure 4.3 shows the percentage of dead nodes as the simulation time varies from 50 to 500 sec. in steps of 50 sec. When the nodes lose all their residual energy, they can be declared as dead nodes. The network lifetime depends on the lifetime of the nodes. Network partitioning is usually defined [Marco Fotino et al., 2011] according to the following criteria:

- The time until the first node burns out its entire battery budget.
- The time until a certain portion of the nodes fails.
- The time until the network partitioning occurs.

Considering the first node failure, it can be seen that in case of LAEE protocol, the network partitioning occurs between 300 to 350 sec. for 50 and 250 nodes and between 350 to 400 sec. for 200 nodes. For the proposed AFTE protocol, it occurs between 350 to 400 sec. for 50 and 150 nodes and between 400 to 450 sec. for 250 nodes. It can also be seen that the residual energy of all the nodes becomes zero at simulation time $t=500$ sec., at $t=450$ sec. and at $t=400$ sec. correspondingly for $n=50$, $n=150$ and $n=250$ for the LAEE protocol. For AFTE protocol it occurs at $t=500$ sec., at $t=600$ sec. and at $t=550$ sec. Further the nodes lose all their residual energy (thus become dead) rapidly in case of LAEE protocol as compared to the gradual decrease of energy in case of AFTE protocol. Hence, the AFTE protocol is able to provide more lifetime for the network. The results of simulation for all nodes ranging from 50 to 300 in steps of 50, is given in the Table 4.2. From the Table 4.2, we observe that, for a smaller number of nodes (50), considering the network partitioning due to a single node failure, AFTE protocol is more efficient as it provides 10.6% more lifetime as compared to LAEE. For medium density of nodes (100-150 nodes), considering network partitioning due to 50% node failure, AFTE is more advantageous as it achieves 12 to 14% more lifetime as compared to LAEE. When 100% node failure is considered, AFTE achieves 20 to 33% extra lifetime than LAEE. For more denser networks (200-300 nodes), AFTE is advantageous under all circumstances. Considering network partitioning due to single nodes failure, AFTE achieves 13 to 31% more lifetime as compared to LAEE. Similarly, considering network partitioning due to failure of 50% node failure, it provides 13 to 26% more lifetime. Finally, considering 100% nodes failure, AFTE performs well as it gives an additional life time of 22 to 37% as compared to LAEE protocol.
Table 4.2. Performance comparison of LAEE and AFTE routing protocols for different node densities.

<table>
<thead>
<tr>
<th>No. of Nodes</th>
<th>Time when first node’s residual energy becomes zero</th>
<th>Time when 50% of nodes’ residual energy becomes zero</th>
<th>Time when 100% of nodes’ residual energy becomes zero</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LAEE</td>
<td>AFTE</td>
<td>LAEE</td>
</tr>
<tr>
<td>50</td>
<td>320</td>
<td>354</td>
<td>423</td>
</tr>
<tr>
<td>100</td>
<td>362</td>
<td>364</td>
<td>425</td>
</tr>
<tr>
<td>150</td>
<td>360</td>
<td>364</td>
<td>422</td>
</tr>
<tr>
<td>200</td>
<td>362</td>
<td>410</td>
<td>392</td>
</tr>
<tr>
<td>250</td>
<td>308</td>
<td>405</td>
<td>383</td>
</tr>
<tr>
<td>300</td>
<td>260</td>
<td>308</td>
<td>372</td>
</tr>
</tbody>
</table>

4.5.2. Delay sensitivity

The proposed protocols, namely, EEDS-1 and EEDS-2, are implemented using NS2 simulator, for different simulation times (50, 100, ..., 500) and for different number of nodes (50, 100, ..., 300). The other parameters used for simulation are given below in the Table 4.3. The simulation results for protocols EEDS-1 and EEDS-2 are compared with the commonly used routing protocol AODV.

Table 4.3. Simulation parameters used for EEDS-1, EEDS-2, AODV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>50, 100, ..., 500 secs.</td>
</tr>
<tr>
<td>Terrain Area</td>
<td>500 X 500 sq. mts</td>
</tr>
<tr>
<td>Number of Nodes</td>
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</tr>
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<td>Node placement</td>
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<tr>
<td>Channel Frequency</td>
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</tr>
<tr>
<td>Routing Protocol</td>
<td>EEDS-1, EEDS-2, AODV</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>250 mts</td>
</tr>
<tr>
<td>Initial Energy for each Node</td>
<td>100 Joules</td>
</tr>
</tbody>
</table>
Figure 4.4. The average energy consumed vs. simulation time for (a) 50 nodes, (b) 100 nodes, (c) 150 nodes, (d) 200 nodes, (e) 250 nodes, and (f) 300 nodes for EEDS-1 and EEDS-2.
The simulation experiments are conducted for different node densities ranging from 50 to 300 in steps of 50 and for different simulation times ranging from 50 to 500 sec., in steps of 50 sec. The simulation results are shown in the Figures 4.4 and 4.5. In the Figure 4.4, it is observed that as the simulation time increases, the average energy consumed by the mobile nodes keeps on increasing. The proposed routing protocols EEDS-1 and EEDS-2 consume lesser energy as compared to AODV routing algorithm. On an average, EEDS-1 protocol consumes 14 to 29% less energy as compared to AODV, whereas EEDS-2 consumes 23 to 51% less energy as compared to AODV. Hence, the results show that EEDS-2 is more energy efficient than EEDS-1. From the results it is also observed that, for smaller simulation times (50-100sec.), the energy conservation is less, whereas for simulation times between 150 to 300 sec., the energy conservation is more. For simulation beyond 350 sec., the energy conservation is again less.

From the Figure 4.5, it can be seen that EEDS-1 and EEDS-2 result in lesser end-to-end delay as compared to AODV for all node densities and for all simulation times. On an average EEDS-1 achieves 10 to 26% lesser end-to-end delay, whereas EEDS-2 achieves 23 to 34% lesser end-t-end delay as compared to AODV. In this case also EEDS-2 outperforms EEDS-1.
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(a) Simulation time (50 nodes)

(b) Simulation time (100 nodes)

(c) Simulation time (n=150)
Figure 4.5. The average end-to-end delay vs. simulation time for (a) 50 nodes, (b) 100 nodes, (c) 150 nodes, (d) 200 nodes, (e) 250 nodes, and (f) 300 nodes for AODV, EEDS-1 and EEDS-2.
4.6. Conclusion

In this Chapter, a novel routing algorithm based on adaptive fuzzy threshold energy is proposed. In the proposed protocol, the energy of a mobile node is conserved by employing fuzzy threshold energy at each hop which is always a function of the residual energy of neighbors of that node. The average network lifetime is enhanced by 13% considering first node failure, 15% considering 50% node failure and 23% considering 100% node failure. The simulation experiments have been conducted using NS2 simulator. The experimental results show that the proposed algorithm AFTE performs better as compared to the LAEE protocol.

Further, two energy efficient and delay sensitive protocols, one (EEDS-1) based on average threshold energy and queue size, and the other (EEDS-2) based on fuzzy threshold energy and queue size are proposed. On an average, EEDS-1 protocol consumes 14 to 29% less energy as compared to AODV, whereas EEDS-2 consumes 23 to 51% less energy as compared to AODV. It is also observed that EEDS-1 achieves 10 to 26% lesser end-to-end delay, whereas EEDS-2 achieves 23 to 34% lesser end-to-end delay as compared to AODV. Thus, EEDS-2 is found to outperform AODV and EEDS-1 in terms of energy awareness and delay sensitivity.