Energy Efficient Route Selection Mechanisms for Mobile Ad Hoc Networks

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I. INTRODUCTION

Mobile ad-hoc networks (MANET) [1] are wireless networks with no fixed infrastructure. Nodes belonging to a MANET can either be end-points of a data interchange or can act as routers when the two end-points are not directly within their radio range. A critical issue for MANETs is that the activity of nodes is energy-constrained. Developing routing protocols for MANETs has been an extensive research area during the past few years, and various proactive and reactive routing protocols have been proposed [2]. However, the majority of the routing proposals have not focused on the energy constraints of untethered nodes. Only recently many protocols have appeared that consider energy-aware optimizations [3], [4], [5].

Only a few proposals have especially focused on the design of route selection protocols that provide efficient energy utilization when performing route discovery [6], [7], [8]. The Minimum Total Transmission Power Routing (MTPR) [6] attempts to minimize the total transmission energy consumption of nodes participating in an acquired route. However, because the transmission energy required is proportional to \( d^\alpha \), where \( d \) is the distance between two nodes and \( 2 \leq \alpha \leq 4 \) [9], MTPR tends to select routes with more hops than the min-hop path, which involves more nodes and increases end-to-end delays. Moreover, since MTPR does not consider the remaining energy of nodes, it may not succeed in extending the lifetime of each node. Singh et al. [7] proposed the Min-Max Battery Cost Routing (MMBCR), which considers the residual battery energy capacity of nodes as the operative metric. MMBCR allows the nodes with high residual capacity to participate in the routing process more often than the nodes with low residual capacity. In every possible path, there exists a weakest node which has the minimum residual battery capacity. The MMBCR approach tries to choose a path whose weakest node has the maximum remaining energy among the weakest nodes in other possible routes to the same destination. MMBCR extends the lifetime of nodes but it does not guarantee that the total transmission energy is minimized over a chosen route. Finally, the Conditional Max-Min Battery Capacity Routing (CMMBBCR) [8] is a hybrid approach that considers both the total transmission energy consumption of routes and the remaining energy of nodes. However, it does not guarantee that the nodes with high remaining energy will survive without energy breakage even when heavy traffic is passing through the node.

The main contribution of this paper is the introduction of a new metric, the drain rate, to be used with the residual battery capacity of a node to predict the lifetime of nodes according to current traffic conditions. Section II describes the Minimum Drain Rate (MDR) mechanism, which incorporates the drain rate metric into the routing process. This new metric was required because energy saving mechanisms based only on metrics related to the remaining energy cannot be used to establish the best route between source and destination nodes, for example when a heavy flow of data packets crosses a given path. This mechanism is basically a energy-aware route selection algorithm that can be applied to the route discovery component of any MANET routing protocol. Because MDR does not guarantee that the total transmission energy is minimized over a chosen route, the Conditional Minimum Drain Rate (CMDR) mechanism is also introduced. CMDR attempts to prolong the lifetime of both nodes and connections, while minimizing the total transmission energy consumed per packet.

Section IV compares the performance of MDR against the MTPR and MMBCR proposals using the ns-2 simulator with the CMU wireless extension [13]. In this analysis, MDR, MTPR, MMBCR, CMDR and CMMBBCR run as part of DSR [14]. We also take into consideration the energy consumed by overhearing the packet transmitted by neighboring nodes. The receiving process in a node includes two different situations: receiving actual data and receiving neighbor’s data (i.e., overhearing). In an MANET, when a peer-to-peer packet is sent, it is overheard by all the neighbors of the transmitting node, thus all the nodes inside the transmitter’s radio area consume energy even though the packet is not sent to them. The overhearing process depends on the radio range, as all nodes inside the transmitter’s radio compass share the same radio channel.
II. THE MINIMUM DRAIN RATE MECHANISM

Energy saving mechanisms based only on metrics related to the remaining energy cannot be used to establish the best route between source and destination nodes. If a node is willing to accept all route requests only because it currently has enough residual battery capacity, much traffic load will be injected through that node. In this sense, the actual drain rate of energy consumption of the node will tend to be high, resulting in a sharp reduction of battery energy. As a consequence, it could exhaust the node’s energy supply very quickly, causing the node to halt soon. To mitigate this problem, other metrics, based on the traffic load characteristics, could be employed. To this end, techniques to accurately measure traffic load at nodes should be devised. Even though the number of packets buffered in the node’s queue can be used to measure the traffic load, it is not trivial to devise an efficient cost function that combines the buffer information with the remaining battery energy.

We propose the drain rate as the metric that measures the energy dissipation rate in a given node. Each node monitors its energy consumption caused by the transmission, reception, and overhearing activities and computes the energy drain rate, denoted by $DR_i$, for every $T$ seconds sampling interval by averaging the amount of energy dissipation rate for every $T$ seconds. The corresponding cost function can be calculated by utilizing the well-known exponential weighted moving average method (see Eq. 1) applied to the drain rate values $DR_{old}$ and $DR_{sample}$, which represent the previous and the newly calculated values.

$$DR_i = \alpha \times DR_{old} + (1 - \alpha) \times DR_{sample} \quad (1)$$

To better reflect the current condition of energy expenditure of nodes, we give higher priority to the current sample drain rate by setting $\alpha = 0.3$. The ratio $\frac{RBP_i}{DR_i}$, where $RBP_i$ denotes the residual battery energy at node $n_i$, indicates when the remaining battery of node $n_i$ is exhausted, i.e., how long node $n_i$ can keep up with routing operations with current traffic conditions based on the residual energy. The corresponding cost function can be defined as:

$$C_i = \frac{RBP_i}{DR_i} \quad (2)$$

The maximum lifetime of a given path $r_p$ is determined by the minimum value of $C_i$ over the path, that is $L_p = \min_{\forall r_p \in \mathcal{R}} C_i$. The Minimum Drain Rate (MDR) mechanism is based on selecting the route $r_M$, contained in the set of all possible routes $r_s$ between the source and the destination nodes, that presents the highest maximum lifetime value, that is $r_M = r_p = \max_{\forall r_s \in \mathcal{R}} L_i$.

Because the status of the selected path can change over time due to variations in the energy drain rate at nodes, the activation of a new path selection depends only on the underlying routing protocol. In order to apply those energy-aware mechanisms to MANET routing protocols, all source nodes should periodically obtain new routes that take into account the continuously changing energy states of network nodes in proactive or reactive manner. When applied to proactive routing protocols, all the nodes are required to maintain the route and update energy information of nodes regardless of their demand for routes. In contrast, when applying to on-demand reactive routing protocols, they require all source nodes to perform periodic route recovery in order to find a new energy-aware route even when there is no route breakage.

A. The Conditional Minimum Drain Rate Mechanism

MDR does not guarantee that the total transmission energy is minimized over a chosen route, as in MMBCR. We therefore propose a modified version called Conditional Minimum Drain Rate (CMDR). The CMDR mechanism is based on choosing a path with minimum total transmission energy among all the possible paths constituted by nodes with a lifetime higher than a given threshold, i.e., $\frac{RBP_i}{DR_i} \geq \delta$ as in the MTPR approach. In case no route verifies this condition, CMDR switches to the basic MDR mechanism.

Formally, given $r_s$ as the set of all possible routes between a given source and a destination, and $\pi \subset r_s$ a subset where $\forall r_s \in \pi$. $L_i \geq \delta$, if $\pi \neq \emptyset$, then the chosen route $(r_M)$ is the one that minimizes the total transmission energy with the MTPR protocol applied. Otherwise, $r_M = r_p = \max \forall r_s \in \pi$, as in the MDR mechanism.

To overcome the ambiguity of selecting the value for the threshold $\gamma$, we take advantage of a threshold $\delta$, an absolute time value, which takes into account the current traffic condition. This threshold represents how long each node can sustain its current traffic with its remaining battery energy (RBP) and drain rate (DR), without energy breakage. Actually we should consider that not all the RBP is available for the wireless interface. In [15] the authors describe how the RBP is shared among the different parts of a mobile node. Around the 18-20% of the RBP is used for the wireless interface.

III. IMPLEMENTATION METHODOLOGY

Proper energy management is not possible without accurate and reliable information about the condition of the battery and its remaining capacity. A simple reading of terminal voltage yields little information about the present state of charge and lacks the required accuracy for the proposed algorithms. We require the availability of precise monitoring technologies to obtain a correct estimation of the residual battery energy. The most common technology used today for high-end portable devices, such as notebook computers, is the one described by the Smart Battery System Implementers Forum (SBS-IF) [10], an industry consortium for smart-battery systems. Battery-capacity monitoring devices that conform to the SBS-IF requirements, may report a multitude of critical information. Parameters reported include cell...
voltage, average and instantaneous current, temperature, remaining battery capacity, remaining time to empty, relative and absolute battery state-of-charge. Smaller handheld devices such as cellular phones and PDAs may provide the same level of accuracy and repeatability from the capacity-monitoring device. To provide a cost-effective solution, most battery-capacity-monitoring devices act as an analog front-end, capturing accurate charge, discharge, temperature, and voltage activities of the battery. This information is then passed on to the system processor. We can therefore assume that the mobile device can provide the algorithms with the current value for the RBP, represented in mWh.

Based on the work by Laura Feeney and Martin Nilsson [5], we defined a specific energy expenditure model. The energy consumed by the network interface when a host sends, receives or discards a packet can be described using a linear equation: \( E = m \cdot p + n \), where \( p \) is the packet size in bytes and \( m \) and \( n \) are constants that must be experimentally derived and that vary depending on the type of operation. Factor \( n \) represents a fixed cost for each operation.

The energy used by the wireless NIC during an interval \( \Delta t \) is calculated as:

\[
E(n_i) = (m_{pp} \cdot b_{pp} + n_{pp} \cdot p_{pp}) + (m_b \cdot b_b + n_b \cdot p_b) + (m_s \cdot b_s + n_s \cdot p_s) + (m_r \cdot b_r + n_r \cdot p_r)
\]

where \( p_{pp} \) indicates the number of packets sent point-to-point, \( b_b \) the number of packets broadcasted, \( p_{pp} \) the number of packets received point-to-point, \( b_b \) the number of packets received by a broadcast, and \( p_{pp} \) the number of packets received by overhearing. Variables \( b_{pp}, b_b, b_s, \) \( b_r \), and \( p_{pp} \) represent the number of bits sent point-to-point, broadcasted, received point-to-point, received by broadcast, and received by overhearing, respectively.

We simplified the above formula and used the following approximation:

\[
DR_{sample} = m^s \cdot b^s + m^r \cdot b^r + n^s_{pp} \cdot p^s_{pp} + n^r_{pp} \cdot p^r_{pp}
\]

where \( p^s_{pp}, p^r_{pp} \), and \( b^r, b^s \), and \( p^r, p^s \) are the number of hops, the packet end-to-end delay and the throughput; the end-to-end delay includes the time spent in the queue at all nodes. Each simulation had a duration of 800 seconds. During each simulation we generated 12 constant bit rate (CBR) connections producing 3 packets/seconds with a packet size of 512 bytes.

When a node receives a Route Request packet and the Target Address field matches this node’s own IP address, then the node returns a Route Reply to the initiator of this Route Request as described in Section 6.2.4. of [14] after coping the value hold in the \( C_i \) field. If none of the error situations described in Section 6.2.2. of [14] are verified and therefore the current node is simply a node that belongs to the path, the node should calculate the value of \( C_i \) and compare it with the value hold in the packet. Only if the calculated \( C_i \) is less that this value, the corresponding packet field should be changed.

When the Route Reply packet reaches the initiator node, the value hold in the \( C_i \) field should be stored in the cache with the other possible paths.

Finally, when a node has to send a data packet, it has to apply the desired algorithm, i.e., either the MDR or the CMDR, to chose among all the possible routes stored in the cache, as stated in Section 4.1. [14].

IV. PERFORMANCE STUDY

In this section, we compare the performance of the MDR mechanism against the MTTPR and the MMBCR mechanisms using the ns-2 simulator with the CMU wireless extension [13]. The DSR protocol was used as the underlying route discovery and maintenance protocol.

We have shown [12] that CMMBCR performs similarly to MTTPR when small values of \( \gamma \) are used, while it performs similarly to MMBCR with large values of \( \gamma \).

We concentrate our study on estimating the expiration time, or halt-time, of nodes. The halt-time expresses how long a node has been active before it halts due to lack of battery capacity. The halt-time of nodes directly affects the lifetime of an active route and possibly of a connection, we therefore also evaluate the connection’s expiration time (cet). We also measured the average values for: the number of hops, the packet end-to-end delay and the throughput; the end-to-end delay includes the time spent in the queue at all nodes. Each simulation had a duration of 800 seconds. During each simulation we generated 12 constant bit rate (CBR) connections producing 3 packets/seconds with a packet size of 512 bytes.

We used a fixed transmission range of 250 meters, given that only a few wireless cards can be configured to use multiple energy levels. Hence, MTTPR behaves exactly like the protocol using minimum-hop paths, because the shortest path minimizes the total transmission energy consumed per packet. In theory, MTTPR can reduce the total transmission energy consumed per packet only when all nodes are capable of adjusting their transmission ranges according to the distance between nodes.

We used the "random waypoint" model to simulate nodes movement. The motion is characterized by two factors: the maximum speed and the pause time. Each node starts moving from its initial position to a random target position selected inside the simulation area. The node speed is uniformly distributed between 0 and the maximum speed. When a node reaches the target position, it waits for the pause time, then selects another random target location and moves again.

We adopted the energy consumption model described in Section III. We assumed all mobile nodes to be
equipped with 2 Mbps IEEE 802.11 network interface cards. All nodes have their initial energy values randomly selected. Because some nodes with very low energy level might not attempt to start the communication, we assign more initial energy to the source and the destination nodes. We modified the ns-2 energy model to allow the measuring of the battery energy to be consumed by overhearing the wireless channel. According to [5] we used the following values for the energy constants: $m^{s} = 0.019$, $m^{p} = 0.0005$, and $n^{pp} = 0.420$.

A. Dense Network Scenario

We first evaluate the various mechanisms in a dense network scenario. The network consists of 49 mobile nodes equally distributed over a 540 meters x 540 meters area (see Figure 1). We concentrate on two different situations: a completely static environment and a dynamic environment.

![Fig. 1. The dense network scenario: 49 nodes equally distributed over a 540 m x 540 m area.](image)

A.1 Static Environment

We evaluate the behavior of the MTPR, MMBCR and MDR mechanisms when all nodes maintain their initial position throughout the duration of the simulations. Figure 2 illustrates the expiration time of nodes and of connections. In Figure 2a, the expiration times are sorted in ascending order; there is therefore no direct relation between the connection numbers of this figure and those of Figure 1.

The MTPR approach attempts to minimize the total transmission energy consumed per packet, regardless of the lifetime of each node; there is therefore no guarantee to extend the lifetime of nodes. MTPR exhibits longer lifetime of connections despite shorter lifetime of nodes because it is able to easily acquire many other alternative routes with enough battery, whereas the other mechanisms force more nodes to consume energy by using much longer routes.

The MMBCR approach tries to evenly distribute the energy consumption among nodes by using their residual battery capacity. However, because it allows nodes to accept all connection requests if they temporarily have enough battery regardless of current traffic condition, nodes will eventually experience lack of battery and halt. The absence of some particular nodes due to the traffic overload, forces the current connection to attempt to establish a new route. Therefore, as Figure 2b shows, MMBCR suffers from the short lifetime of connections.

The MDR approach can properly extend the lifetime of nodes and of connections by evenly distributing the energy expenditure among nodes. It avoids the over-dissipation of specific nodes by taking into account the current traffic condition and by utilizing the drain rate of the residual battery capacity.

Table I summarizes the numeric results. Because MTPR utilizes the paths with minimum hops, it shows the best values for end-to-end delay, hop counts and throughput. Also, note that in MTPR, the time when the first connection is disconnected occurs much earlier than that of the last connection. This is because it uses shortest paths rather than balancing the burden of packet forwarding based on the remaining energy at nodes.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DENSE NETWORK SCENARIO, STATIC ENVIRONMENT: 12 CONNECTIONS. CET IS THE CONNECTION’S EXPIRATION TIME.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MTPR</td>
</tr>
<tr>
<td>End-to-end Delay</td>
<td>0.0361</td>
</tr>
<tr>
<td>Hop Count</td>
<td>4.7</td>
</tr>
<tr>
<td>Throughput</td>
<td>9118</td>
</tr>
<tr>
<td>Mean cet</td>
<td>257.06</td>
</tr>
</tbody>
</table>

When we consider the overhearing activities, all approaches behave similarly, because the nodes that are close to a transmitting node consume their energy even though the approaches attempt to balance energy consumption by using more stable routes in terms of residual capacity and drain rate.

A.2 Dynamic Environment

We evaluate the behavior of the three mechanisms when all nodes keep on moving throughout the duration
of the simulation. We use a pause time value of 30 seconds and a maximum speed value of 10 meter/second.

We can observe that, when considering overhearing, we obtain the same results as in the static environment (see Figure 3). However, when we ignore the overhearing effect, the MTPR mechanism presents the worst performance in terms of the expiration time of nodes, because MTPR makes many nodes over the shortest paths continue to participate in forwarding packets regardless of their remaining battery energy, until they run out of their battery energy. However, the MTPR mechanism is better than the others with respect to the other performance metrics, because it can easily utilize alternative routes due to the high density of network (see Table II). MMBCR has some periods with better performance than MDR in terms of node’s lifetime. The main goal of MDR is not only to extend the lifetime of nodes, but also to avoid the over-dissipation of energy at critical nodes in order to extend the lifetime of connections. Table II and Figure 3.b show that MDR outperforms MMBCR with respect to lifetime of connections. In particular, Figure 3.b indicates that MTPR has the highest variation among the expiration times of connections. This implies that MTPR does not distribute the energy consumption evenly among nodes, while the other protocols can efficiently balance the usage of residual capacity of energy among nodes.

When compared to the static environment, we can observe that the average end-to-end delay increased because all packets in the queue had spent much time in waiting for the existence of new paths possible until nodes moved and the network partitions were resolved after the network partitions occurred.

B. Sparse Network Scenario

We now evaluate the various mechanisms considering a sparse network consisting of 50 nodes placed in an area of 1 km x 1 km. Each node is initially placed at a randomly selected position.

B.1 Static Environment

In a static environment and when considering the overhearing activity, all proposals behave similarly. When overhearing is not considered some connections could not progress any more simultaneously at around 100 seconds. Some nodes halt before we reach 100 seconds. The halt of these nodes could make the sparse network partitioned. It seemed that these connections relied on the critical nodes as their intermediate nodes without which the six connections cannot acquire any other alternative routes. Thereafter, the source and destination nodes of the remaining connections were together in each partitioned network and could continue their communications. Therefore, starting from 100 seconds we obtain a behavior similar to the scenario of a dense network. Furthermore, because the sparse network limits the number of routes available, all protocols show similar performance results (see Table III). Specifically, while the dense network allows many paths with the same number of minimum hops to appear in the network, the sparse network can expect almost one or two shortest paths with the same hops. Therefore, while MMBCR and MDR can balance traffic by alternating the usage of existing routes with different hops, MTPR concentrates the traffic on the shortest path, resulting in the increase of the average end-to-end delay per packet.

![Graph](image1)

**Fig. 3.** Dense network scenario, dynamic environment (10 meter/second): 12 connections.

![Graph](image2)

**Fig. 3.** Dense network scenario, dynamic environment (10 meter/second): 12 connections.

**TABLE II**

<table>
<thead>
<tr>
<th></th>
<th>MTPR</th>
<th>MMBCR</th>
<th>MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-end Delay</td>
<td>0.022</td>
<td>0.0247</td>
<td>0.028</td>
</tr>
<tr>
<td>Hop Count</td>
<td>2.12</td>
<td>2.33</td>
<td>2.24</td>
</tr>
<tr>
<td>Throughput</td>
<td>20709</td>
<td>18510</td>
<td>19781</td>
</tr>
<tr>
<td>Mean cet</td>
<td>578.68</td>
<td>519.15</td>
<td>550.65</td>
</tr>
</tbody>
</table>

**TABLE III**

<table>
<thead>
<tr>
<th></th>
<th>MTPR</th>
<th>MMBCR</th>
<th>MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-end Delay</td>
<td>0.082</td>
<td>0.040</td>
<td>0.053</td>
</tr>
<tr>
<td>Hop Count</td>
<td>2.68</td>
<td>2.73</td>
<td>2.70</td>
</tr>
<tr>
<td>Throughput</td>
<td>11702</td>
<td>11297</td>
<td>11357</td>
</tr>
<tr>
<td>Mean cet</td>
<td>324.57</td>
<td>314.51</td>
<td>316.57</td>
</tr>
</tbody>
</table>

B.2 Dynamic Environment

When introducing the node mobility, the MTPR mechanism allows some particular nodes to halt earlier than in the other protocols because MTPR agrees to use the shortest paths. On the other hand, MMBCR and MDR distribute the energy spending by alternating the usage of
existing paths, if any. MDR seems to use longer routes among a few paths even in the sparse network to balance energy consumption among nodes. As some nodes die over time, the total number of possible routes between the source and destination nodes decreases. Moreover, the nodes movement allows new routes to appear. In MTPR, it is more likely that the nodes over a given path have enough remaining capacity of battery than in the other protocols, because the other protocols enabled most of nodes in the network to consume their energy. To think collectively for sparse networks, the performance totally depends on the node mobility. Eventually, as Table IV shows, all protocols show similar performance, particularly because of the limitation of routes available.

However, although the protocols show the similar behavior with respect to most of performance, MDR achieves longer average lifetime of connections (see Table IV).

| TABLE IV |
| SPARSE NETWORK SCENARIO, DYNAMIC ENVIRONMENT (10 METER/SECOND): 50 NODES, 12 CONNECTIONS. CET IS THE CONNECTION’S EXPIRATION TIME. |
| | MTPR | MMBCR | MDR |
| End-to-end Delay | 0.66 | 0.48 | 0.56 |
| Hop Count | 2.97 | 3.03 | 2.99 |
| Throughput | 14674 | 14674 | 14614 |
| Mean cet | 458.66 | 439.38 | 467.49 |

V. CONCLUSIONS

In this paper we proposed a new metric, the drain rate, to be used to predict the lifetime of nodes according to current traffic conditions. Combined with the value of the remaining battery capacity, this metric is used to establish whether or not a node can be part of an active route. We described a mechanism, called the Minimum Drain Rate (MDR) that can be used in any of the existing MANET routing protocols as a route establishment criterion. This metric is good at reflecting the current dissipation of energy without considering other traffic measurements, like queue length and the number of connections passing through the nodes. The main goal of MDR is to extend the lifetime of each node, while prolonging the lifetime of each connection.

Using the ns-2 simulator, we compared MDR against the Minimum Total Transmission Energy Routing (MTPR) and the Min-Max Battery Cost Routing (MMBCR) mechanisms. The results show that MDR avoids over-dissipation, because it can avoid situations in which a few nodes allow too much traffic to pass through themselves, simply because their remaining battery capacity is temporarily high.

In addition, we showed how the overhearing activity can affect the performance of the various mechanisms. When we consider the overhearing activity, all protocols behave similarly because the nearby nodes to a transmitting node also consume their energy. Because network interface cards in the near future could allow nodes to switch themselves into the sleep mode with low cost in terms of energy consumption and transition time, MDR can be utilized efficiently to extend the lifetime of both nodes and connections.

ACKNOWLEDGMENTS

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