Power-Aware Routing Based on The Energy Drain Rate for Mobile Ad Hoc Networks

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***Abstract*—Mobile ad hoc networks' (MANETs) inherent power limitation makes power-awareness a critical requirement for MANET protocols. In this paper, we propose a new routing metric, the *drain rate*, which predicts the lifetime of a node as a function of current traffic conditions. We describe the Minimum Drain Rate (MDR) mechanism which uses a combination of the drain rate with remaining battery capacity to establish routes. MDR can be employed by any existing MANET routing protocol to achieve a dual goal: extend both nodal battery life and connection lifetime. Using the ns-2 simulator and the Dynamic Source Routing (DSR) protocol, we compared MDR to the Minimum Total Transmission Power Routing (MTPR) scheme and the Min-Max Battery Cost Routing (MMBCR) scheme and proved that MDR is the best approach to achieve the dual goal.**

***Index Terms*—Mobile Ad Hoc Network, Power-aware, Route Selection, Drain Rate.**

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 of untethered nodes is that nodes are normally power-constrained. Developing routing protocols for MANETs has been an extensive research area during the past few years and many proactive and reactive routing protocols have been proposed [2].

However, the majority of the routing proposals to date have not focused on the power constraints of untethered nodes. Work on power-aware protocols have appeared only recently [4], [5], [6], [7].

A few proposals especially focused on the design of routing protocols providing efficient power utilization. The *Minimum Total Transmission Power Routing* (MTPR) scheme [8] tries to minimize the total transmission power consumption of nodes participating in an acquired route. If we consider a generic route $r_d = n_0, n_1, ..., n_d$, where n_0 is the source node and n_d is the destination node and a function T(n_i,n_j) which denotes the energy consumed in transmitting over the hop (n_i, n_j), the total transmission power for the route is calculated as: $P(r_d) = \sum_{i=0}^{d-1} T(n_i, n_{i+1})$. The optimal route r_O is the one which verifies the following condition: $P(r_O) = \min_{r_j \in r_*} P(r_j)$, where r_* is the set of all possible routes. Since the transmission power required is proportional to d^α, where d is the distance between two nodes and α between 2 and 4 [3], MTPR selects the routes with more hops. It inherently accepts the possibility that the participation of more nodes in forwarding packets will increase the end-to-end delay. Moreover, because MTPR fails to consider the remaining power of nodes, it might not succeed in extending the lifetime of each host.

S. Singh et al. [9] proposed the *Min-Max Battery Cost Routing* (MMBCR) scheme, which considers the residual battery power capacity of nodes as the metric in order to extend the lifetime of nodes. Let $c_i(t)$ be the battery capacity of host n_i at time t. We define $f_i(t)$ as a battery cost function of host n_i. The less capacity it has, the more reluctant it is to forward packets; the proposed value is: $f_i(t) = 1/c_i(t)$. If only the summation of the values of battery cost function is considered, a route containing nodes with little remaining battery capacity may still be selected. MMBCR defines the route cost as: $R(r_j) = \max_{\forall n_i \in r_j} f_i(t)$. The desired route r_O is obtained so that $R(r_O) = \min_{r_j \in r_*} R(r_j)$, where r_* is the set of all possible routes. 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. Hence, MMBCR tries to choose a path whose weakest node has the maximum remaining power among the weakest nodes in other possible routes to the same destination. However, MMBCR does not guarantee that the total transmission power is minimized over a chosen route.

Finally, a hybrid approach was devised by C.K Toh [10] that relies on the residual battery capacity of nodes. The *Conditional Max-Min Battery Capacity Routing* (CMMBCR) mechanism considers both the total transmission energy consumption of routes and the remaining power of nodes. When all nodes in some possible routes have sufficient remaining battery capacity (i.e., above a threshold γ), a route with minimum total transmission power among these routes is chosen. Since less total power is required to forward packets for each connection, the relaying load for most nodes must be reduced, and their lifetime will be extended. However, if all routes have nodes with low battery capacity (i.e., below the threshold), a route including nodes with the lowest battery capacity must be avoided to extend the lifetime of these nodes with MMBCR applied. We define the battery capacity for route r_j at time t as: $R_j(t) = \min_{\forall n_i \in r_j} c_i(t)$.

Given two nodes, n_a and n_b, this mechanism considers two sets Q and A, where Q is the set of all possible routes between n_a and n_b at time t, and A is the set of all possible routes between any two nodes at time t for which the condition $R_j(t) \geq \gamma$ holds. The route selection scheme operates as follows: if all nodes in a given paths have remaining battery capacity higher than γ, choose a path in A $\cap$ Q $\neq \emptyset$ by applying MTPR scheme; otherwise select a route r_i with the maximum battery capacity (i.e., MMBCR is applied).

However, this scheme does not guarantee that the nodes with high remaining power will survive without power breakage, even when heavy traffic is passing through the node because CMMBCR also relies on residual battery capacity as in MMBCR. Especially, the performance totally depends on selected γ threshold value.

This paper proposes a new metric, the *drain rate*, to be used in conjunction with residual battery capacity to predict the lifetime of nodes according to the current traffic conditions. Section II describes the *Minimum Drain Rate* (MDR) mechanism, which incorporates the drain rate metric into the routing process. This mechanism is basically a power-aware route selection algorithm that could be applied to any MANET routing protocol when performing route discovery. Section III compares the performance of MDR against the MTPR and MMBCR proposals by using the *ns-2* simulator with the CMU wireless extension [11]. In this analysis, MDR, MTPR and MMBCR run as part of DSR [12], and we also take into consideration the energy consumption caused by overhearing the packet transmitted by neighboring nodes. Section IV presents our concluding remarks.

II. The Minimum Drain Rate mechanism

When the remaining power is the only metric used to establish the best route between the source and the destination, we cannot guarantee

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that a node on the route, even with a high value of remaining battery power, will survive if used to route a heavy traffic load.

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 rates of power consumption of the node will tend to be high, resulting in a sharp reduction of battery power. As a consequence, it could exhaust the node's power supply fast causing the node to die soon.

To mitigate this problem, traffic load information, besides residual battery power, could be employed. To this end, techniques to accurately measure traffic load at nodes should be devised. Even though "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 power.

We propose the *drain rate* as a way to account for the rate at which energy gets dissipated at a given node. Each node monitors its energy consumption and maintains its battery power drain rate value DR_i by averaging the amount of energy consumption and estimating the energy dissipation per second during the given past interval. DR_i indicates how much average energy is consumed by node n_i per second during the interval.

We monitor all energy dissipation caused by transmission, reception, and overhearing when estimating the energy consumption.

The ratio $\frac{RBP_i}{DR_i}$, where RBP_i denotes the *residual battery power* at node n_i, tells us when the remaining battery of node n_i is exhausted. In other words, this ratio represents how long the remaining energy can keep up the connections with current traffic condition. The corresponding cost function can be defined as:

$$C_i \quad = \quad \frac{RBP_i}{DR_i} \tag{1}$$

The maximum lifetime of a given path r_p is determined by the minimum value of C_i over the path, that is:

$$L_p = \min_{\forall n_i \in r_p} C_i, \tag{2}$$

The MDR mechanism is therefore based on selecting the route r_M, contained in the set of all possible routes r_* between the source and the destination node, that presents the highest maximum lifetime value, that is:

$$r_M \doteq r_p = \max_{\forall r_i \in r_*} L_i, \tag{3}$$

Note that, since the status of the selected path can change over time due to variation in the power drain rate at nodes, the activation of a new path selection depends only on the underlying routing protocol. In order to apply those power-aware mechanisms to MANET routing protocols, all source nodes should periodically obtain new routes that take into account the continuously changing power 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 power 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 power-aware route even when there is no route breakage.

In this work, each node n_i computes its energy drain rate, denoted by DR_i, by utilizing the well-known exponential weighted moving average method (see Eq. 4). Based on two values, DR_{old} and DR_{sample}, representing the previous and the newly calculated values, a new drain rate is calculated every T seconds.

$$DR_i \quad = \quad \alpha \times DR_{old} + (1-\alpha) \times DR_{sample} \tag{4}$$

We are currently using $T = 6$ seconds and $\alpha = 0.3$ thus giving higher priority to the current sample drain rate to better reflect the current condition of energy expenditure of nodes. The value for T is a critical value that should be carefully chose to avoid the overhead of continuously keeping track of the energy consumption while still reflecting the past history properly.

Finally, MDR still does not guarantee that the total transmission power is minimized over a chosen route, as in MMBCR. However, based on a γ threshold, CMMBCR can apply MDR instead of MMBCR when all routes have nodes with low battery capacity (i.e., below the threshold) in order to prolong the lifetime of both nodes and connections as well as to minimize the total transmission power consumed per packet.

III. Performance Study

We investigate the performance of MDR mechanism compared against MTPR and MMBCR by using the *ns-2* simulator with the CMU wireless extension. We used DSR as our underlying route discovery and maintenance protocol. However, we modified DSR to force the source node to periodically refresh its cache and to trigger a new route recovery every 10 seconds for better reflecting power condition of all nodes.

Furthermore, during route discovery, the source node was made to select the best route, adopting the power-aware route selection mechanisms described earlier, while collecting all the route replies transmitted by the destination node. We had to avoid to use some route cache optimization techniques performed by the intermediate nodes, because the cached routes stored would not represent the current power consumption state.

For our simulations, we use a fixed transmission range of 250 meters which is supported by most of practical and current network interface cards. Actually, only a few network interface cards can be configured to use different power levels. Hence, since the minimum-hop path minimizes the total transmission power consumed per packet, MTPR selects the shortest path among possible routes, thus behaves exactly like the protocol using minimum-hop paths. In theory, only when all nodes are capable of adjusting their transmission ranges according to the distance between nodes, MTPR can reduce the total transmission power consumed per packet by utilizing the routes with more hops having short transmission ranges.

We use the "random waypoint" model to generate node movement. In this model, the motion is characterized by two factors: (a) maximum speed and (b) pause time. Each node starts moving from its initial position to a random target position selected inside the simulation area. The speed of nodes is uniformly distributed between 0 and the maximum speed of 10 m/s. When a node reaches the target position, it waits for the pause time, then selects another random target location and moves again. Finally, sources generate data traffic using a leaky bucket shaping technique. We generate 12 constant bit rate (CBR) connections of 3 packets/seconds with a packet size of 512 bytes.

We mainly investigate the *halt-time* of nodes, i.e., the time it takes for a node to halt due to lack of battery capacity. The halt-time directly affects the lifetime of connections. We therefore also evaluate the expiration time of connections. Finally, we measure the average values for the hops number, the packet end-to-end delay and the actual throughput. The end-to-end delay includes the time spent in the queue at all nodes.

A. Energy Consumption Model

We assume all mobile nodes to be equipped with IEEE 802.11 network interface card with data rates of 2 Mbps. The energy expenditure needed to transmit a packet p is: $E(p) = i * v * t_p$ Joules, where i is the current value, v the voltage, and t_p the time taken to transmit the packet p. In our simulation, the voltage, v is chosen as 5 V and we assume the packet transmission time t_p is calculated by $(p_h/2 * 10^6 + p_d/2 * 10^6)sec$, where p_h is the packet header size in bits and p_d the payload size. The currents required to transmit and receive the packet used in the simulations are 280mA and 240mA, respectively. Moreover, we account for energy spent by nodes overhearing packets. As shown in [7], we assume the energy consumption caused by overhearing data transmission is the same as that consumed by actually receiving the packet.

For the purpose of evaluating the effect of overhearing, we modified the ns-2 energy model to allow the battery power to be consumed by overhearing the wireless channel. The total amount of energy, $E(n_i)$, consumed at a node n_i is determined as:

$$E(n_i) \quad = \quad E_{tx}(n_i) + E_{rx}(n_i) + (N-1) * E_o(n_i) \qquad (5)$$

, where E_{tx}, E_{rx}, and E_o denote the amount of energy expenditure by transmission, reception, and overhearing of a packet, respectively. N represents the average number of neighboring nodes affected by a transmission from node n_i. Eq.(5) implies that when the network is more dense, the packet overhearing causes more energy consumption.

Moreover, in our simulation, all nodes have their initial energy values randomly selected. In addition, since some node with low energy might not attempt to start the communication, we assigned more initial energy to the source and destination nodes than the others.

B. Results with a Dense Network Scenario

We first compared the routing mechanisms in a dense network scenario. The network consisted of 49 mobile nodes equally distributed over a 540 m x 540 m area (see Figure 1).

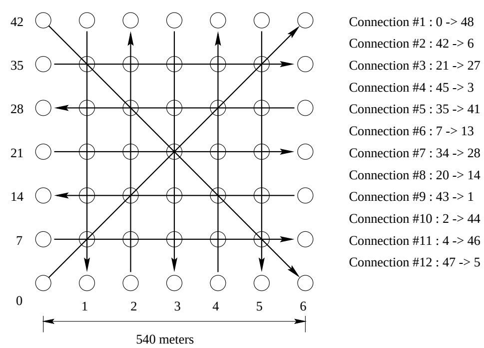


Fig. 1. The dense network scenario: 49 nodes equally distributed over a 540 m x 540 m area.

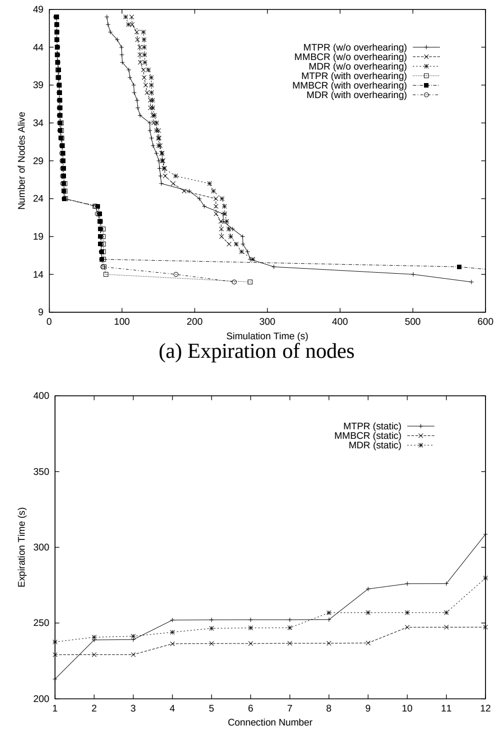
1) Static Environment: Figure 2 compares the expiration time of nodes and connections; The connection number in Figure 2.b does not correspond to the connection number of Figure 1. The expiration times are sorted in ascending order.

The MTPR approach attempts to minimize the total transmission power 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, since it allows nodes to accept all connection requests if they temporarily have enough battery regardless of current traffic condition, nodes 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 2.b shows, MMBCR suffers from the short lifetime of connections.

The MDR approach can properly satisfy the two goals, namely to extend the lifetime of nodes and 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, because it uses shortest paths rather than balancing the burden of packet forwarding based on the remaining energy at nodes.



(a) Expiration of nodes

(b) Expiration of connections

Fig. 2. Dense network scenario, static environment, 12 connections.

	MTPR	MMBCR	MDR
End-to-end Delay	0.0361	0.047	0.042
Hop Count	4.7	4.95	4.74
Throughput	9118	8403	9019
Mean cet	257.06	237.37	250.88

TABLE I

DENSE NETWORK SCENARIO, STATIC ENVIRONMENT, 12 CONNECTIONS. CET IS THE CONNECTION'S EXPIRATION TIME.

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.

Figure 3 shows the comparison of the amount of energy consumed by the participating nodes according to the network card activity. When overhearing is considered, we can observe that most of energy consumption is caused by the overhearing activity. We see that some techniques are required to reduce this energy expenditure by, for example, switching the network interface cards to the sleep mode.

2) Dynamic Environment: We used a pause time value of 30 seconds and a maximum speed value of 10 m/s. When considering overhearing, we still obtain the same results showing that all protocols behave similarly (see Figure **??**). When the overhearing effect is ignored, MTPR presents the worst performance in terms of lifetime of nodes due to the concentration of traffic. However, MTPR is better than the other protocols with respect to other performance metrics, because it can easily utilize alternative routes due to the high density of the network (see Table II). MMBCR has some periods with better performance than MDR in terms of node lifetime.

The main goal of MDR is not just to extend the lifetime of each node more than in MMBCR, but to avoid the over-dissipation of energy at critical nodes to extend the lifetime of both connections and nodes. Table II and Figure **??**.b show that MDR outperforms MM-

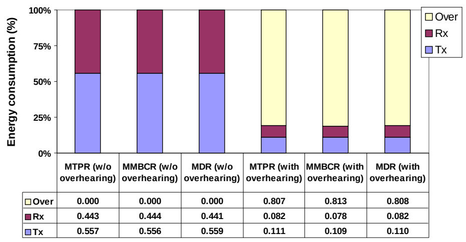
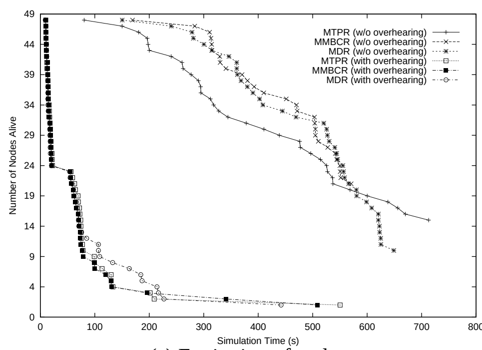


Fig. 3. Static environment scenario: energy consumption.

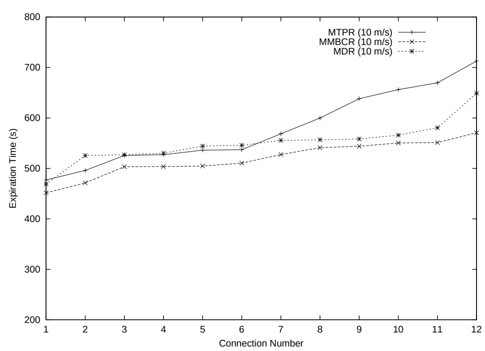
	MTPR	MMBCR	MDR
End-to-end Delay	0.022	0.0247	0.028
Hop Count	2.12	2.33	2.24
Throughput	20709	18510	19781
Mean cet	578.68	519.15	550.65

TABLE II
DENSE NETWORK SCENARIO, DYNAMIC ENVIRONMENT (10 M/S), 12 CONNECTIONS. CET IS THE CONNECTION'S EXPIRATION TIME.

BCR with respect to lifetime of connections. In particular, Figure **??**.b indicates that MTPR has the highest variation among the connection expiration times. It 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.



(a) Expiration of nodes



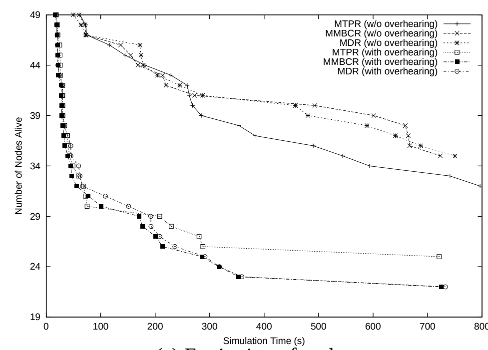
(b) Expiration of connections

Fig. 4. Dense network scenario, dynamic environment (10 m/s), 12 connections.

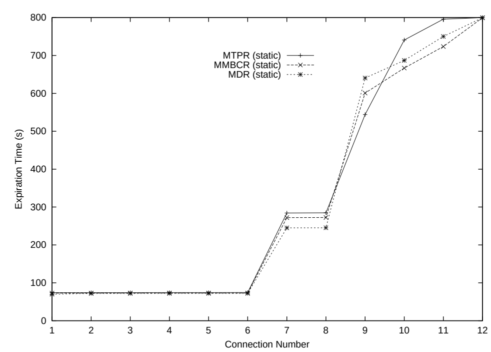
C. Results with a Sparse Network Scenario

In this section, we present the simulation results when considering a sparse network consisting of 50 nodes placed in an area of 1 km x 1 km and starting from a random initial position.

1) Static Environment: In a static environment and when considering the overhearing activity, all proposals behave similarly (see Figure 5.a). When overhearing is not considered, we can see that six connections could not progress any more simultaneously at around 100 seconds (see Figure 5.b). When looking at Figure 5.a, it can be observed that three nodes halt before we reach 100 seconds. The halt of three nodes could make the sparse network partitioned. It seemed that the six 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, Figure 5.a shows similar behaviour compared to the scenario of dense network. Besides, 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 sticks to concentrating the traffic on the shortest path, resulting in the increase of the average end-to-end delay per packet.



(a) Expiration of nodes



(b) Expiration of connections

Fig. 5. Sparse network scenario, static environment, 50 nodes, 12 connections.

2) Dynamic Environment: Finally, we consider node mobility. MTPR 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 routes possible between the source and destination nodes decreases. Moreover, the node 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 the sparse network, the performance totally depends on the node mobility. Eventually, as Figure 6 and Table

	MTPR	MMBCR	MDR
End-to-end Delay	0.082	0.040	0.053
Hop Count	2.68	2.73	2.70
Throughput	11702	11297	11357
Mean cet	324.57	314.51	316.57

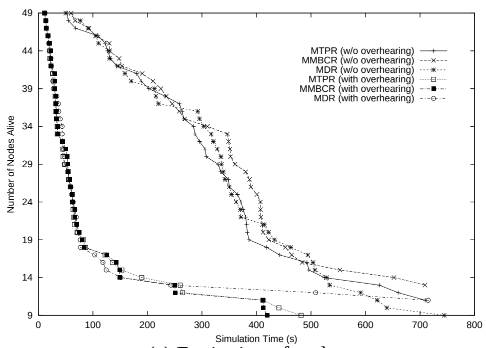
TABLE III
SPARSE NETWORK SCENARIO, STATIC ENVIRONMENT, 50 NODES, 12 CONNECTIONS. CET IS THE CONNECTION'S EXPIRATION TIME.

	MTPR	MMBCR	MDR
End-to-end Delay	0.66	0.48	0.56
Hop Count	2.97	3.03	2.99
Throughput	14674	14467	14614
Mean cet	458.66	439.38	467.49

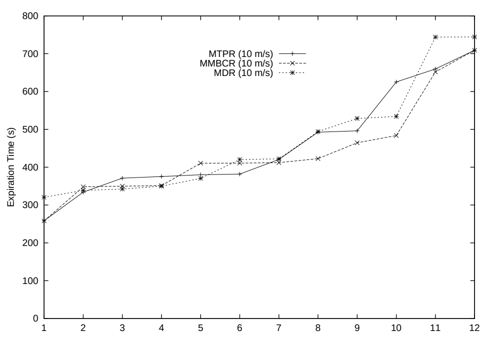
TABLE IV
SPARSE NETWORK SCENARIO, DYNAMIC ENVIRONMENT (10 M/S), 50 NODES, 12 CON NECTIONS. CET IS THE CONNECTION'S EXPIRATION TIME.

IV show, all protocols show similar performance, particularly because of the limitation of routes available.

In addition, when compared to the static environment, we can observe that the average end-to-end delay increased because all packets in the queue spent much time in waiting for the existence of new paths possible due to node movement after the network partition occurred. However, although the protocols show similar behaviour, Table IV shows that MDR can achieve longer average lifetime of connections.



(a) Expiration of nodes



(b) Expiration of connections

Fig. 6. Sparse network scenario, dynamic environment (10 m/s), 50 nodes, 12 connections.

IV. CONCLUSION

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 MANETs 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 not only to extend the lifetime of each node, but also to prolong the lifetime of each connection.

Using the ns-2 simulator, we compared MDR against the Minimum Total Transmission Power Routing (MTPR) and the Min-Max Battery Cost Routing (MMBCR) mechanisms. The results showed 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. This happens even if the energy consumption is balanced by using more stable route in terms of remaining capacity and drain rate. Given this result, it appears that new techniques should be devised to reduce this energy consumption by switching the network interface cards into off state (*sleep state*). 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.

Finally, it should be pointed out that MDR does not guarantee that the total transmission power is minimized over a chosen route, as in MMBCR. However, based on a γ threshold, CMMBCR can apply MDR instead of MMBCR when all routes have nodes with low battery capacity (i.e., below the threshold) in order to prolong the lifetime of both nodes and connections as well as to minimize the total transmission power consumed per packet. Such a conditional version of MDR is a promising avenue for future studies.

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