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무선 Ad Hoc 통신망에서 에너지 소모율(Energy Drain Rate)에 기반한 경로선택 프로토콜

김 동 균

Route Selection Protocol based on Energy Drain Rates in Mobile Ad Hoc Networks

Dong-Kyun Kim*

ABSTRACT

Untethered nodes in mobile ad-hoc networks strongly depend on the efficient use of their batteries. In this paper, we propose a new metric, the drain rate, to forecast the lifetime of nodes according to current traffic conditions. This metric is combined with the value of the remaining battery capacity to determine which nodes can be part of an active route. We describe new route selection mechanisms for MANET routing protocols, which we call the Minimum Drain Rate (MDR) and the Conditional Minimum Drain Rate (CMDR). MDR extends nodal battery life and the duration of paths, while CMDR also minimizes the total transmission power consumed per packet. Using the ns-2 simulator and the dynamic source routing (DSR) protocol, we compare MDR and CMDR against prior proposals for power-aware routing and show that using the drain rate for power-aware route selection offers superior performance results.

Key Words : Mobile Ad Hoc Network; Routing; 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 is that the activity of nodes is power-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 power constraints of untethered nodes, although many protocols that are power-aware have appeared only recently [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14]. Only a few proposals have especially focused on the design of route selection protocols that provide efficient power utilization when performing route discovery [12], [13], [14].

The Minimum Total Transmission Power Routing (MTPR) [12] attempts to minimize the total transmission power consumption of nodes participating in an acquired route. However, because the transmission power

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* 경북대학교 컴퓨터공학과 이동통신망연구실(dongkyun@knu.ac.kr)
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required is proportional to d^{α}, where is the distance between two nodes and $2 \leqq \alpha \leqq 4$ [3], 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 power of nodes, it may not succeed in extending the lifetime of each node. Singh et al. [13] proposed the Min-Max Battery Cost Routing (MMBCR), which considers the residual battery power 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 power 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 power is minimized over a chosen route. Finally, the Conditional Max-Min Battery Capacity Routing (CMMBCR) [14] is a hybrid approach that considers both the total transmission energy consumption of routes and the remaining power of nodes. However, it does not guarantee that the nodes with high remaining power will survive without power breakage even when heavy traffic is passing through the node. Section II provides more details on the above prior work. 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 III 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 can be applied to the route discovery component of any MANET routing protocol. Because MDR does not guarantee that the total transmission power 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 power consumed per packet.

Section IV compares the performance of MDR against the MTPR and MMBCR proposals, and the performance of CMDR against CMMBCR, using the ns-2 simulator with the CMU wireless extension [16]. In this analysis, MDR, MTPR, MMBCR, CMDR and CMMBCR run as part of DSR [17], and we also take into consideration the energy consumed by overhearing the packet transmitted by neighboring nodes. Finally, the concluding remark is given in Section V.

II. Related Works

In this section, we present a brief description of the three relevant power-aware routing algorithms proposed recently.

1. The Minimum Total Transmission Power Routing

The Minimum Total Transmission Power Routing (MTPR) [12] mechanism makes use of a simple energy metric representing the total energy consumed along the route. If we consider a generic route $r_d = n_0, n_1, \ldots, n_d$, where n_0 is the source node and n_d is the destination node and a function $T(n_i, n_j)$ denoting 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 satisfies the following condition:

$$P(r_O) = \min_{r_j \in r_*} P(r_j)$$

, where is the set of all possible routes.

2. The Min-Max Battery Cost Routing

Although MTPR can reduce the total transmission power consumed per packet, it does not reflect directly on the lifetime of each node. In other words, the remaining battery capacity of each node is a more accurate metric to describe the lifetime of each node. Let $c_i(t)$ be the battery capacity of node n_i at time t. We define $f_i(t)$ as a battery cost function of node n_i. The less capacity a node 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 battery cost is considered, a route containing nodes with little remaining battery capacity may still be selected. The Min-Max Battery Cost Routing (MMBCR) [13], defines the route

$$R(r_j) = \max_{\forall n_i \in r_j} f_i(t)$$

cost as:

The desired route r_O is obtained so that

$$R(r_O) = \min_{r_j \in r_*} R(r_j)$$

, where is the set of all possible routes.

Because MMBCR considers the weakest and crucial node over the path, a route with the best condition among paths impacted by each crucial node over each path is selected.

3. The Conditional Max-Min Battery Capacity Routing

Prolonging the lifetime of each node while minimizing the total transmission power consumed per packet is not trivial. The MMBCR mechanism, for example, does not guarantee that the total transmission power consumed per packet over a chosen path is minimized. The Conditional Max-Min Battery Capacity Routing (CMMBCR) [14] attempts to perform a hybrid approach between MTPR and MMBCR. CMMBCR 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 is chosen among these routes. The relaying load for most nodes must be reduced, because less total power is required to forward packets for each connection, and their lifetime is 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. We define the

$$R_j(t) = \min_{\forall n_i \in r_j} c_i(t)$$

battery capacity for route r_j at time t as

.

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 $R_j(t) \geqq \gamma$ 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 $A \cap Q \neq 0$ by applying the MTPR scheme; otherwise, select a route r_i with the maximum battery capacity. However, in

CMMBCR, we face the dilemma of choosing the threshold γ, and the specification of CMMBCR [14] does not state how to select the threshold value.

CMMBCR simply makes use of the relative percentage of the currently remaining energy of each node. Unfortunately, it is not possible to efficiently determine γ. CMMBCR either needs a centralized server to keep track of the energy status of all the mobile nodes, or nodes must inform one another about the remaining power at each node. If γ is taken as an absolute value, there is no easy way to decide the threshold value without considering the current network status, e.g., the network traffic.

Ⅲ. THE MINIMUM DRAIN RATE MECHANISM

1. The Basic Minimum Drain Rate Mechanism

Power saving mechanisms based only on metrics related to the remaining power 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 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 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 power.

We propose the *drain rate* as the metric that measures the *energy dissipation rate* in a given node. Each node n_i 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 consumption and estimating the energy dissipation per second during the past T seconds. In this work, T is set to 6 seconds.

The actual value of DR_i is calculated by utilizing the well-known exponential weighted moving average method

(see Eq. 1) applied to the drain rate DR_{old} values and DR_{sample}, which represent the previous and the newly calculated values.

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

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 RBP_i/DR_i , where RBP_i denotes the residual battery power 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: $C_i = \frac{RBP_i}{DR_i}$.

The maximum lifetime of a given path r_p is determined by the minimum value of C_i

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

over the path, that is:

The Minimum Drain Rate (MDR) mechanism is based on selecting the route r_M, contained in the set of all possible routes r_* between the source and the destination nodes, that presents the highest maximum lifetime value,

that is:

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

Because the status of the selected path can change over time due to variations 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. The performance of the proposed scheme for different values of is the subject of future studies.

2. The Conditional Minimum Drain Rate Mechanism

MDR does not guarantee that the total transmission power 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 power among all the possible paths constituted by nodes with a lifetime higher than a given threshold, i.e., $\dfrac{RBP_i}{DR_i} \geqq \delta$ as in the MTPR approach.

In case no route verifies this condition, CMDR switches to the basic MDR mechanism. Formally, given r_* as the set of all possible routes between a given source and a destination, and $r_*^{@} \subset r_*$ a subset where $\forall r_i \in r_*^{@}, L_i \geqq \delta$, if $r_*^{@} \neq 0$, then the chosen route (r_M) is the one that minimizes the total transmission power with the MTPR protocol applied. Otherwise,

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

as in the MDR mechanism.

To overcome the ambiguity of selecting the value for the threshold γ, we take advantage of a threshold δ, 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 power (RBP) and drain rate (DR), without power breakage. Because the values assigned to δ can influence the performance of the CMDR mechanism, Section Ⅳ-5 describes how to properly assign a value to δ.

Ⅳ PERFORMANCE STUDY

In this section, we compare the performance of the MDR mechanism against the MTPR and the MMBCR mechanisms, and the performance of CMDR against CMMBCR using the ns-2 simulator with the CMU wireless extension [16].

We have shown [15] that CMMBCR performs similarly to MTPR when small values of γ are used, while it performs similarly to MMBCR with large values of γ. 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 constant bit rate (CBR) connections producing packets/seconds with a packet size of bytes.

The DSR protocol was used as the underlying route discovery and maintenance protocol. We modified DSR to force the source node to periodically refresh its cache and to trigger a new route recovery process every 10 seconds to better reflect the power condition of all nodes. During route discovery, the source node was made to select the best route using the mechanism under analysis, while collecting all the route replies transmitted by the destination node. We had to avoid using some route cache optimization techniques performed by the intermediate nodes, because the cached routes would not represent the current power consumption state. We used a fixed transmission range of 250 meters, given that only a few wireless cards can be configured to use multiple power levels. Hence, MTPR behaves exactly like the protocol using minimum-hop paths, because the shortest path minimizes the total transmission power consumed per packet. In theory, MTPR can reduce the total transmission power consumed per packet only when all nodes are capable of adjusting their transmission ranges according to the distance between nodes.

We use 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.

1. Energy Consumption Model

We assume that all mobile nodes are 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. The energy expenditure needed to transmit a packet is: $E(p) = i \times v \times t_p$ Joules, where i is the current value, v the voltage, and t_p the time taken to transmit the packet . In our simulation, the voltage, v is chosen as 5 V and we assume that the packet transmission time t_p is $(p_h/2 \times 10^6 + p_d/2 \times 10^6)$ 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.

We assume that the energy consumption caused by overhearing data transmission is the same as the energy consumed by actually receiving the packet [11]. 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 by:

$$E(n_i) = E_{tx}(n_i) + E_{rx}(n_i) + (N-1) \times E_o(n_i)$$

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. The equation implies that the packet overhearing causes more energy consumption when the network is more dense.

2. 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 m x 540 m area (see Figure 1). We concentrate on two different situations: a completely static environment and a dynamic environment.

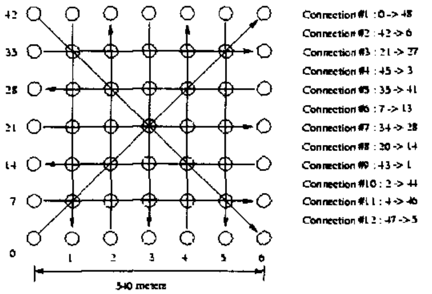


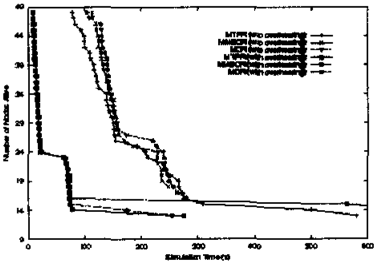
Fig. 1. The dense network scenario: 49 nodes equally distributed over a 540 m x 540 m area.

2.1 Static Environment

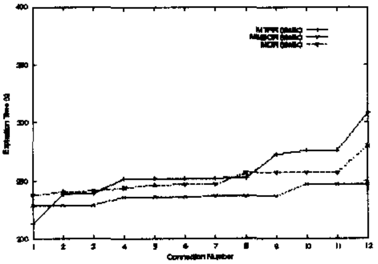
We evaluate the behavior of the MTPR, MMBCR and MDR mechanisms when all nodes maintain their initial position throughout the duration of the simulations. Figure 2 illustrates the expiration time of nodes and of connections. In Figure 2.b, the expiration times are sorted in ascending order; there is therefore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

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 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.

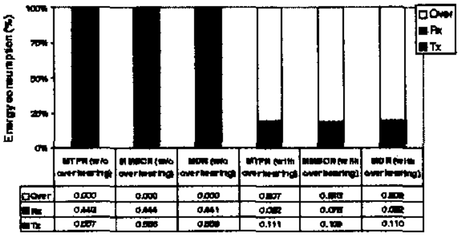


Fig. 3. Static environment scenario: energy consumption.

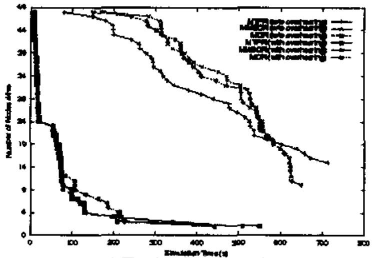
2.2 Dynamic Environment

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 m/s. We can observe that, when considering overhearing, we obtain the same results as in the static environment (see Figure 4).

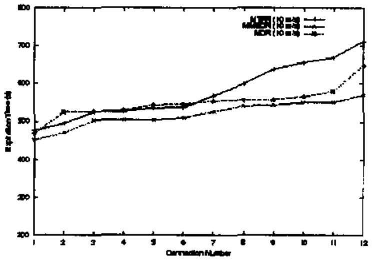
However, when we ignore the overhearing effect, the MTPR mechanism presents the worst performance in terms of the expiration time of nodes, because MTPR makes many nodes over the shortest paths continue to participate in forwarding packets regardless of their remaining battery power, until they run out of their battery power.

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 4.b show that MDR outperforms MMBCR with respect to lifetime of connections. In particular, Figure 4.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.



(a) Expiration of nodes



(b) Expiration of connections

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

	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.

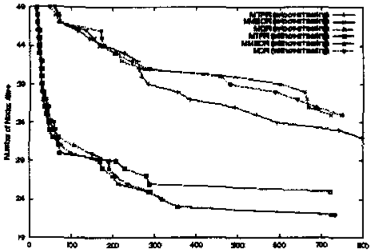
3. Sparse Network Scenario

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.

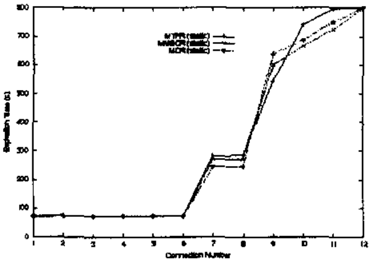
3.1 Static Environment

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). Figure 5.a shows 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 behavior compared 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.

3.2 Dynamic Environment



(a) Expiration of nodes



(b) Expiration of connections

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

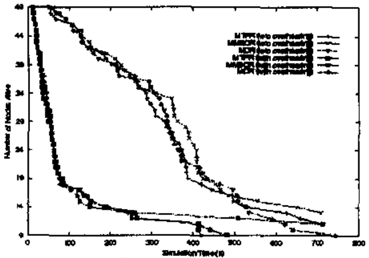
When introducing the node mobility, the MTPR mechanism allows some particular nodes to halt earlier than in the other protocols because MTPR agrees to use the shortest paths. On the other hand, MMBCR and MDR distribute the energy spending by alternating the usage of existing paths, if any. MDR seems 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 routes possible between the source and destination nodes decreases.

	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

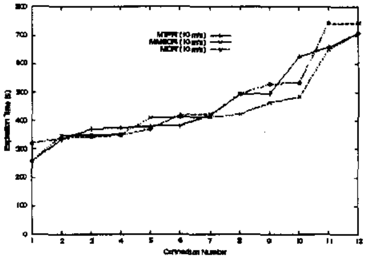
TABLE III

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

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 Figure 6 and Table IV show, 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).



(a) Expiration of nodes



(b) Expiration of connections

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

	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 CONNECTIONS. CET IS THE CONNECTION'S EXPIRATION TIME.

4. Comparison of CMDR and CMMBCR: using γ as the threshold

In this section, we compare the CMDR

mechanism against the CMMBCR one by using γ as the threshold value. The γ value is used as a boundary to decide when to adopt the conditional or the basic version of the MDR and the MMBCR mechanisms. In other words, instead of using δ, CMDR can be modified to choose a path with minimum total transmission power among all the possible paths constituted by nodes with a residual battery power higher than a given threshold, i.e., $RBP_i \geq \gamma$, as in the MTPR approach. In case no route verifies this condition, CMDR switches to the MDR mechanism. This threshold is expressed as a percentage of the initial battery power of a node. We used three values for γ : 25 %, 50 % and 75 %.

We first consider the performance in the dense network as shown in Figure 1 with and without node mobility. As expected, when there exist available routes satisfying the threshold γ, the two protocols apply MTPR to select the best route. Otherwise, MDR is able to show better performance than MMBCR in terms of expiration time of both nodes and connections, regardless of node mobility (see Figure 7 and Figure 8) because of the same reasons pointed out earlier in the performance study section of MDR. In addition, CMDR outperforms CMMBCR in terms of throughput and mean connection's expiration time (see Table V and Table VI). CMDR obtained increased throughput because it allowed connections to survive longer than CMMBCR did.

	$\gamma = 25$ %		$\gamma = 50$ %		$\gamma = 75$ %	
	CMMBCR	CMDR	CMMBCR	CMDR	CMMBCR	CMDR
E2E Delay	0.039	0.034	0.039	0.041	0.041	0.038
Hop Count	4.73	4.71	4.77	4.74	4.77	4.75
Throughput	8955	9327	8952	9079	8808	9093
Mean cet	252.43	262.09	251.29	255.41	245.88	254.58

TABLE V

STATIC ENVIRONMENT SCENARIO, NO MOBILITY; E2E IS END-TO-END. CET IS THE CONNECTION EXPIRATION TIME.

	$\gamma = 25$ %		$\gamma = 50$ %		$\gamma = 75$ %	
	CMMBCR	CMDR	CMMBCR	CMDR	CMMBCR	CMDR
E2E Delay	0.022	0.022	0.024	0.023	0.022	0.022
Hop Count	2.19	2.17	2.20	2.18	2.24	2.19
Throughput	19911	20166	19609	19638	19418	19524
Mean cet	558.43	565.77	550.74	563.10	540.25	547.64

TABLE VI

DYNAMIC ENVIRONMENT SCENARIO, MOBILITY (10 M/S); E2E IS END-TO-END. CET IS THE CONNECTION EXPIRATION TIME.

Unlike the case of a dense network, a sparse network limits the number of routes available between source and destination nodes, resulting in the fact that the two approaches select similar paths whenever they find them. Therefore, CMDR and CMMBCR have similar performance results, regardless of node mobility. However, CMDR still shows a little better performance than CMMBCR (see Figure 9, Figure 10, Table VII and Table VIII).

	$\gamma = 25$ %		$\gamma = 50$ %		$\gamma = 75$ %	
	CMMBCR	CMDR	CMMBCR	CMDR	CMMBCR	CMDR
E2E Delay	0.063	0.043	0.047	0.042	0.058	0.042
Hop Count	3.06	2.96	3.08	3.04	3.06	3.00
Throughput	14317	14632	14298	14466	14162	14377
Mean cet	434.50	449.40	446.69	455.36	445.43	472.13

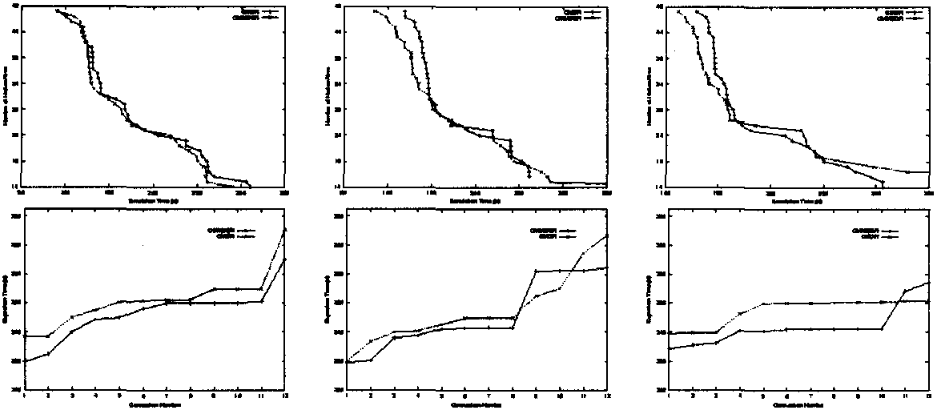
TABLE VIII

SPARSE NETWORK SCENARIO, MOBILITY (10 M/S); E2E IS END-TO-END. CET IS THE CONNECTION EXPIRATION TIME.

5. Performance of CMDR according to the threshold δ

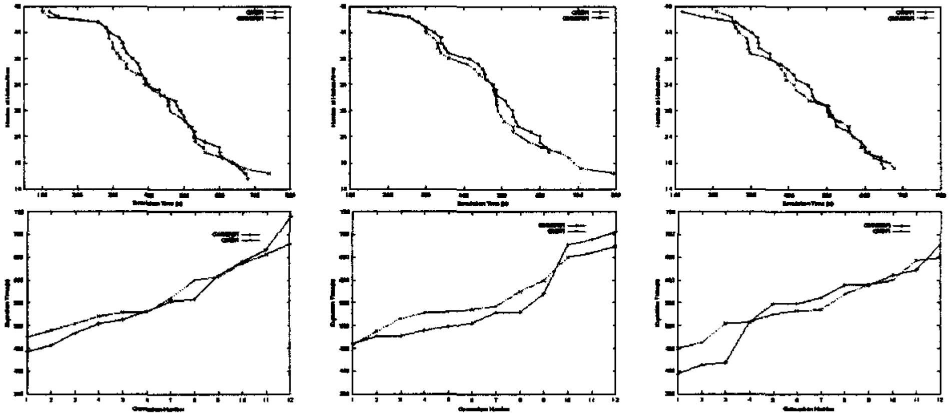
The results from the previous simulations show that CMDR outperforms CMMBCR even when we used the same threshold selection scheme, i.e., remaining battery power despite the ambiguity of the threshold. In this section, we investigate the performance according to absolute time values of δ.

In a dense network environment, regardless of node mobility, CMDR with lower δ values approaches the performance of MTPR, while CMDR with higher δ values approaches the performance of MDR (see



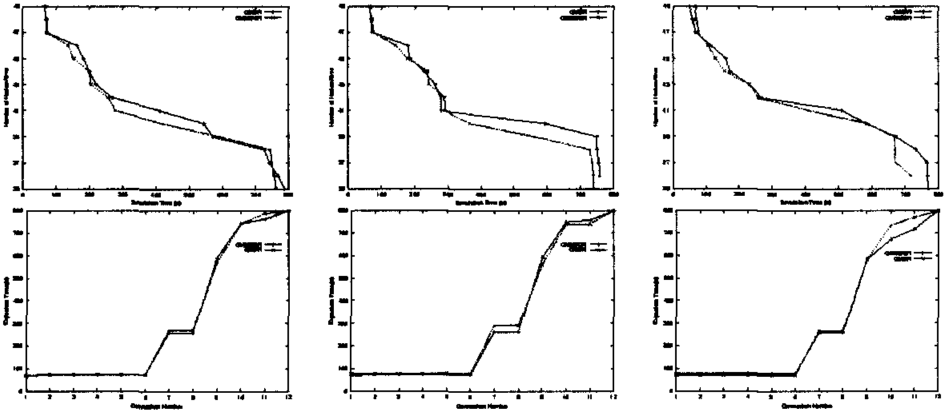
(a) $\gamma = 25$ %　(b) $\gamma = 50$ %　(c) $\gamma = 75$ %

Fig. 7. Static environment scenario, No mobility, Expiration time of nodes and connections.



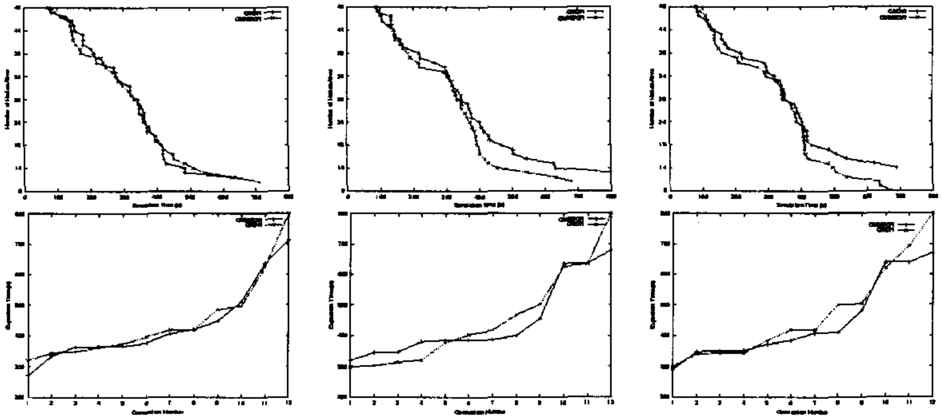
(a) $\gamma = 25$ %　(b) $\gamma = 50$ %　(c) $\gamma = 75$ %

Fig. 8. Dynamic environment scenario, Mobility (10 m/s), Expiration time of nodes and connections.



(a) $\gamma = 25$ %　(b) $\gamma = 50$ %　(c) $\gamma = 75$ %

Fig. 9. Sparse network scenario, No Mobility, Expiration time of nodes and connections.



(a) $\gamma = 25\ \%$ (b) $\gamma = 50\ \%$ (c) $\gamma = 75\ \%$

Fig. 10. Sparce network scenario, Mobility (10 m/s), Expiration time of nodes and connections.

Figure 11.a and Figure 11.b). In particular, CMDR with a higher threshold shows better performance in terms of mean expiration time of nodes, but worse performance in terms of mean expiration time of connections, because the different rate of the MDR participation alters the performance. In addition, a lower threshold derives high deviation of mean expiration time of nodes and connections than a higher threshold does. Therefore, the threshold δ can be used as a performance protection threshold. In other words, if all nodes are equally important and should not be overused, a higher value of δ is expected. In the static network, some connections cannot progress because network partitions easily occur. However, in a dynamic network, the node mobility allows new paths to appear and network partitions are resolved.

Therefore, the lifetime of connections in the dynamic network, when compared to the static network, significantly increases. Moreover, due to the same reason, we used δ values of different scale, specially large values, when we consider node mobility. Since we obtained very similar results with MDR when we simulated the performance with δ greater than 200 seconds and 400 seconds in the static and dynamic networks, respectively, we do not show the results for other values of δ. In addition, because the static network makes nodes participate in forwarding more frequently than the dynamic network does, the lifetime of nodes in the static network is also smaller than that in the dynamic network.

In a sparse static network, CMDR exhibits similar performance to the case of a dense network. This is because the network is prone to network partitions and there can exist some groups of nodes that can be dense (see Figure 12.a).

However, when we include node mobility, we did not obtain very different results for different values of δ due to the limited number of routes available. Furthermore, different thresholds did not produce highly different values of deviation from the mean expiration time of nodes and connections. Therefore, δ does not play a crucial role in the sparse network with node movement (see Figure 12.b). However, although we obtain similar behavior, CMDR with a higher threshold still shows a little better performance in terms of mean expiration time of nodes, but a little worse performance in terms of mean expiration time of connections.

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 Power 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. 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, we also presented the Conditional MDR (CMDR), which also tries to minimize the total transmission power consumed per packet. In contrast to CMMBCR with the ambiguity of threshold selection, CMDR makes use of an absolute time threshold, which is much easier to establish. CMDR was shown to be better than CMMBCR in terms of performance and threshold selection.

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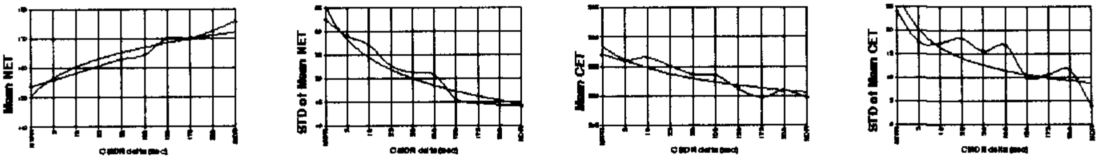
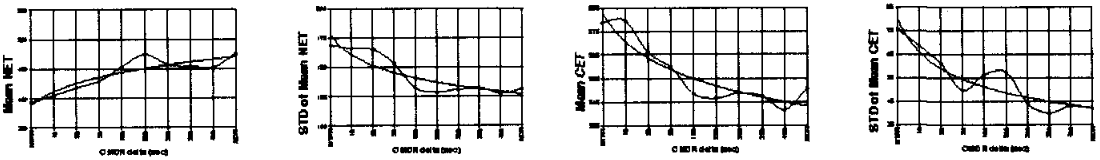
김 동 규(Dong-Kyun Kim)

1994년 2월 : 경북대학교 컴퓨터공학과 학사
1996년 2월 : 서울대학교 컴퓨터공학과 석사
1999 년 6 월 : 미국 조지아 공대 방문 연구원
2001년 8월 : 서울대학교 전기.컴퓨터공학부 박사
2002년 12월 : 미국 캘리포니아 산타크루즈 대학교 Post-Doc. 연구원
2003년 3월~현재 : 경북대학교 컴퓨터공학과 전임강사

<주관심분야> 이동통신망 프로토콜, 무선 Ad Hoc 통신망, 이동 인터넷

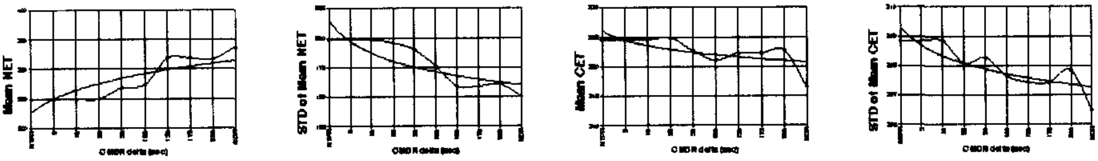


(a) Static environment scenario, No Mobility.

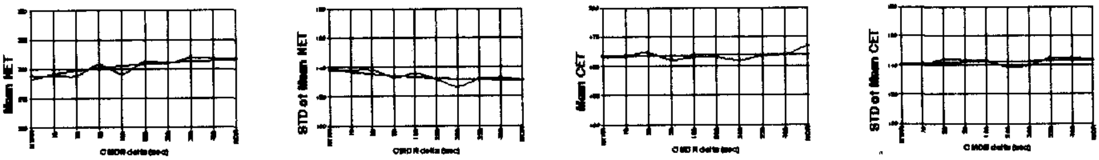


(b) Dynamic environment scenario, Mobility (10 m/s)

Fig. 11. Dense network scenario. CET and NET is connection and node expiration time, respectively. STD is standard deviation.



(a) Static environment scenario, No Mobility.



(b) Dynamic environment scenario, Mobility (10 m/s)

Fig. 12. Sparse network scenario. CET and NET is connection and node expiration time, respectively. STD is standard deviation.