Performance Evaluation of Energy Efficient Ad Hoc Routing Protocols

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***Abstract*— Energy aware routing protocols are consistently cited as efficient solutions for ad hoc and sensor networks routing and data management. However, there is not a consistent approach to define the energy related cost metrics that are used to guide the routing protocol performance. This paper provides a survey and analysis of energy related metrics used for ad hoc routing. First, the most common energy efficient routing protocols are classified into four categories based on the energy cost metrics employed. Then, the results of our simulation-based analysis are presented. We conducted a complete set of simulations to compare and contrast the performance of various energy-related metrics. Our analysis provides a comparison of the performance of energy cost metrics used within AODV-based ad hoc routing protocols.**

I. Introduction

Mobile ad hoc network (MANET) is composed of a collection of mobile nodes which can move freely. Therefore, dynamic topology, unstable links, limited energy capacity and absence of fixed infrastructure are special features for MANET when compared to wired networks. MANET does not have centralized controllers, which makes it different from traditional wireless networks (cellular networks and wireless LAN). Due to these special features, the design of routing protocols for MANET becomes a challenge.

Classical ad hoc routing protocols, such as AODV [1] and DSR [2], aim to find the shortest path route during the route discovery phase. Shortest-path based routing has good performance for wired networks. However, this is not true for MANET, since shortest path routing causes power depletion by overusing nodes along the shortest path. Sometimes, power depletion at specified nodes can cause network partitioning. In order to solve this problem, energy efficient routing protocols [3]–[17] have been heavily studied in recent years. Most of them consider energy related cost metrics instead of the hop count or distance metrics.

In this paper, we survey the recent research in energy efficient routing protocols for ad hoc networks. We classify the power efficient routing protocols into four categories based on their path selection scheme. The first set of protocols use the energy cost for transmission as the cost metric and aim to save energy consumption per packet. However, such protocols do not take the nodes' energy capacity into account. Thus, the energy consumption is not fair among nodes in the network. *Minimum Total Transmission Power Routing* (MTPR) [4] is an example protocol for this category. The second set of protocols use the remaining energy capacity as the cost metric, which means that the fairness of energy consumption becomes the main focus. But, these protocols can not guarantee the energy consumption is minimized. The third set of protocols are similar to the second set, but use estimated node lifetime instead of node energy capacity as the route selection criteria. Therefore, these protocols still aim to fairly distribute energy consumption. In order to both conserve energy consumption and achieve consumption fairness, *Conditional Max-Min Battery Capacity Routing* (CMMBCR) [3] has been proposed to combine these two metrics. CMMBCR is an example of the fourth category of protocols, which use combined metrics to represent energy cost.

Although most of the papers which propose these power efficient routing protocols discuss simulation-based performance evaluation, understandably, the vast majority of these papers narrowly focus on comparing their power efficient routing protocol with a classical ad hoc routing protocol (such as AODV and DSR). Unfortunately, these papers largely ignore the results of other papers and often rely on specific simulation settings or simplified models. To fully and fairly study the performance of these different energy-related routing metrics or routing protocols, we implement all of them in the most popular network simulator (NS-2), using the same underlying ad hoc routing protocol (AODV). We conduct a complete set of simulations to evaluate these protocols. The most similar works in the literature are [18] and [19]. However, [18] compared three different energy efficient routing protocols with minimum-hop routing protocol using their own simulators, while [19] also did performance evaluations for three energy efficient routing protocols by implementing them based on DSR in NS-2. In this paper, we implement a greater number of energy efficient protocols than [18], [19]; we use AODV as the base protocol; we use NS-2; and we evaluate protocol performance considering models both with and without overhearing. The result is a thorough, informative study.

The rest of this paper is organized as follows. In Section II, we survey and classify different energy efficient routing protocols for MANET. Then, simulations and performance analysis are given in Section III. Finally, SectionIV concludes the paper.

II. Energy Efficient Routing Protocols

One of the key challenges in the deployment of mobile ad hoc networks is how to prolong the lifetime of the networks. The lifetime of ad hoc network is limited by the battery energy in wireless devices. Energy depletion of nodes can interrupt communication and, even worse, cause network partitioning. Thus, energy efficiency is critical for the design of network protocols. Recently, different energy-related routing metrics and energy aware routing protocols have been proposed in order to achieve energy conservation and increase the lifetime of the network.

Energy-related metrics used by these energy aware routing protocols can be broadly classified into four categories: transmission power, remaining energy capacity, estimated node lifetime, and combined energy metrics.

Here, for each metric used by certain routing protocols, we always consider a k-hop route $R = v_0, v_1, \cdots, v_k$ from the source v_0 to destination v_k. We also use the following notations in the rest of this paper.

TABLE I
Explanations of the notations

Notations	Meaning
C_R	cost of route R
$P_T(i)$	transmission power of node v_i
$P_R(i)$	receiving power of node v_i
$E_r^i(t)$	remaining energy capacity of node v_i at time t
E_o^i	initial energy capacity of node v_i
$T_r^i(t)$	estimated remaining lifetime of node v_i at t
$DR_i(t)$	drain rate of node v_i at time t

A. Transmission Power

According to the propagation model in [20], the received signal power attenuates as d^{-n} where d is the transmission distance, and usually, $n = 2$ for short distance and $n = 4$ for longer distance. In order to conserve energy, senders dynamically adjust the transmission power proportional to the transmission distance. The MTPR proposed in [4] uses the transmission power as the cost metric. The cost function is defined as:

$$C_R = \sum_{i=0}^{k-1} P_T(i) \tag{1}$$

The MTPR scheme selects the route with the minimum cost value. Thus, it can ensure that energy consumption per packet is the minimum. $P_T(i)$ is proportional to $||v_i, v_{i+1}||^n$, while $||v_i, v_{i+1}||$ is the distance between node v_i and v_{i+1}. Thus, MTPR tends to select routes with more hops, which results in more nodes along the route and longer end-to-end delay. To more accurately represent the energy cost and constrain hop count, the power cost $P_R(i+1)$, for the transceiver at node v_{i+1} to receive a packet, is also added to the above cost function:

$$C_R = \sum_{i=0}^{k-1} (P_T(i) + P_R(i+1)) \tag{2}$$

Here, $P_R(i+1)$ can help reduce hop count compared to the original MTPR. Notice that if the wireless sender can not adjust the transmission power, the MTPR will be the same as the minimum hop routing. [5] and [6] use a similar metric as MTPR to select routes with the minimum total transmission power. In [6], the authors propose the Minimum Power Routing protocol (MPR) and show a detailed model for calculating transmission power; formally:

$$P_T(i) = \frac{\varepsilon ||v_i, v_{i+1}||^n}{S_{i,i+1}} \tag{3}$$

Here, ε is a constant, and $S_{i,i+1}$ characterizes the current channel conditions and interference on link (v_i, v_{i+1}). $S_{i,i+1}$ is a dynamic factor and is estimated based on the historical data. Compared with MTPR, MPR can more accurately estimate the transmission power during the route discovery phase.

B. Remaining Energy Capacity

The network lifetime is defined as the duration from the beginning of the network setup to the first depletion of a node in the network. MTPR can minimize the energy consumption per packet, but it might cause node depletion. If some node works on multiple minimum cost paths, it can get depleted fast. Therefore, the network lifetime is not ensured. To maximize the network lifetime, a number of power aware routing protocols have been proposed which use the remaining energy capacity as the cost metric. Different cost functions are used in different solutions. In [3], the authors proposed the Minimum Battery Cost Routing (MBCR) which used the remaining energy capacity as a cost metric, and the cost function is defined as follows:

$$C_R = \sum_{i=1}^{k-1} f(E_r^i(t)) \tag{4}$$

where

$$f(E_r^i(t)) = \frac{1}{E_r^i(t)} \tag{5}$$

MBCR selects routes with a minimum cost value to ensure the route with the maximum remaining energy capacity will be chosen. However, MBCR only considers the summation of the remaining energy capacity. Thus, routes containing nodes with little energy capacity can still be chosen. To overcome this problem, [3] improved MBCR with the following cost function:

$$C_R = \max_{i=1}^{k-1} f(E_r^i(t)) \tag{6}$$

This new approach is called Min-Max Battery Cost Routing (MMBCR), which always chooses the route with the maximum bottleneck remaining battery capacity. Therefore, MMBCR can maximize the lifetime of the network. Max-Min Routing Protocol (MMRP) and Max-Min Energy DSR (MME-DSR) proposed in [7] and [8], respectively, both use the same metric and cost function as MMBCR.

Both MBCR and MMBCR use the remaining energy capacity as the cost metric, and there are some other approaches which transform this metric into other metrics, for example, delay. The approach proposed in [9] classified nodes into the following three energy zones based on their remaining energy capacity:

Normal Zone: The remaining energy capacity of a node is above 20% of its initial value.
Warning Zone: The remaining energy capacity of a node is between 10% and 20% of its initial value.
Danger Zone: The remaining energy capacity of a node is below 10% of its initial value.
The cost function is defined as:

$$C_R = \sum_{i=1}^{k-1} C(i) \tag{7}$$

where $C(i)$ represents the cost of node v_i and $C(i) = C_{normal}, C_{warning}$ or C_{danger}, which is determined by the energy zones defined above. $C_{normal}, C_{warning}$ and C_{danger} are predefined costs such that $C_{normal} < C_{warning} < C_{danger}$. In [9], the authors also improved this approach by increasing the cost for nodes which lie in the Warning or Danger Zone but have sufficiently large number of neighbors. Thus, $C(i) = C_{normal}, k_i C_{warning}$ or $k_i C_{danger}$, where k_i is proportional to the number of neighbors of node v_i. In this way, even though a node is in the Warning or Danger Zone, it can still be chosen on a route only if it has sufficient neighbors. Thus, the depletion of this node can not result in a network partition.

Local Energy-Aware Routing based on AODV (LEAR-AODV) in [10] used a threshold approach during the route discovery phase. When node v_i received a RREQ message at time t, it compared its current remaining energy capacity with the predefined threshold value θ. If $E_r^i(t) \leq \theta$, the message is dropped. Otherwise, the message is processed and forwarded. In [15], authors used a similar but more complicated approach compared to LEAR-AODV. The proposed Energy-Aware Probability Routing (EAPR) mechanism used the following probability model to determine whether to forward or drop the RREQ message.

$$p_i = \begin{cases} 1 & E_r^i(t) \geq \theta \\ \alpha * (E_r^i(t)/\theta) & E_r^i(t) < \theta \end{cases} \tag{8}$$

where p_i is the probability for node v_i to forward the Route Request message, θ is predefined energy threshold value, which is the same for all nodes, and α is a coefficient. Both LEAR-ADOV and EAPR use a predefined threshold value to determine whether a node participates in the route discovery or not. If the node has enough remaining energy capacity, both schemes allow it to forward the RREQ message. Otherwise, for LEAR-AODV, the node drops the message, while for EAPR, the node forwards the message with a probability which is determined by the remaining energy capacity. The lower the energy capacity, the smaller the probability for the node to participate in the route discovery.

Time Delay On-demand Routing (TDOD) in [16] transfers the remaining energy capacity into waiting delay. Thus, for the TDOD mechanism, route request messages are delayed for some time before they are forwarded. The delay function is as follow:

$$D_i(t) = \frac{1}{E_r^i(t)} \tag{9}$$

where $D_i(t)$ is the delay before node v_i forwards the message. Therefore, TDOD allocates higher delay to nodes with lower energy capacity (since each node only forwards the first arrived RREQ message, but drops all later duplicated messages). Messages from nodes with lower capacity are likely to be dropped. The destination node selects the first arrived route request message, which has the lowest delay. Thus, this delay mechanism selects routes with high remaining energy capacity. In [7], the authors also use this delay mechanism to design their Request-Delay Routing Protocol(RDRP). Besides using the delay function in TDOD, RDRP also applied other delay functions to show how they influence the performance.

C. Estimated Node Lifetime

As we can see, numerous power aware routing protocols use the remaining energy capacity as the cost metric. However, some researchers claim that it is not enough to guarantee the lifetime of a node because a node with high energy capacity can also get depleted if there is high traffic passing through it. In [11], the authors proposed a new metric, drain rate, which is defined as the rate at which energy is consumed at a given node. The corresponding cost function is defined as:

$$C_R = \min T_r^i(t) \tag{10}$$

where

$$T_r^i(t) = \frac{E_r^i(t)}{DR_i(t)} \tag{11}$$

where $DR_i(t)$ is the drain rate of node v_i at time t. Thus, the lifetime of path R is determined by the minimum T_r^i along the path. And the Minimum Drain Rate (MDR) mechanism will select the route with the maximum lifetime. In this approach, each node monitors its energy consumption during the given past interval τ and maintains the drain rate value using an exponential weighted moving average method; formally:

$$DR_i(t) = \alpha \times DR_i(t-\tau) + (1-\alpha) \times DR_i^{sample} \tag{12}$$

where $DR_i(t-\tau)$ and DR_i^{sample} represents the previous and the newly monitored drain rate values, respectively.

In [12], the authors propose Lifetime Prediction Routing (LPR), which is also based on battery lifetime prediction. LPR also favors routes with longer lifetime. The lifetime of a route is determined as follow:

$$C_R = Min\ T_r^i(t) \tag{13}$$

LPR uses a Simple Moving Average (SMA) predictor which keeps track of the last N values of the residual energy and the corresponding time instances for the last N packets received/relayed by each node to estimate the node battery lifetime. The lifetime of a node is computed as follows:

$$T_r^i(t) = \frac{E_{r,j}^i(t)}{\frac{1}{N-1}\sum_{l=j-N+1}^{j} DR_{i,l}(t)} \tag{14}$$

where: $E_{r,j}^i(t)$ is the remaining battery capacity at the time t when the jth packet is being sent or relayed through the current node v_i; $DR_{i,l}(t)$ is the drain rate of the current node v_i at time t when the lth packet was sent and is calculated as the ratio of the difference between residual energy capacities of the nodes for packet $l-1$ and l and the difference between arrival times of these two packets; and N is the length of the history used for calculating the SMA.

TABLE II

ENERGY RELATED COST METRICS

Metric Classifications	Prorotols	Objective	Drawback
Total transmission power	[4] (MTPR), [5], [6] (MPR)	Minimize energy consumption	May cause node depletion
Remaining energy capacity	[3] (MBCR), [3] (MMBCR), [9], [10] (LEAR-AODV), [15] (EAPR), [16] (TDOD)	Evenly distribute energy depletion	Does not ensure least energy cost path
Remaining node lifetime	[11] (MDR), [12] (LPR)	Evenly distribute energy depletion	Does not ensure least energy cost path
Combination	[3] (CMMBCR), [13], [14] (PSR), [17] (PAOD)	Tradeoff between power consumption and fairness	Hard to find perfect tradeoff

D. Combined Energy Metrics

In order to both minimize the energy consumption per packet and maximize the network lifetime, several protocols are proposed in recent research. [3] proposed the Conditional Max-Min Battery Capacity Routing (CMMBCR). In CMMBCR, the battery capacity for route R is defined as the minimum remaining battery capacity of nodes along the route, and the route selection is divided into two steps. First, CMMBCR discovers all possible paths during the route discovery phase and adds them to set A. Second, for each route in set A, if the minimum battery capacity of nodes along the route is larger than a predefined value γ, it is added to set Q. The route selection decision is made according to the following conditions: (1) if $Q \neq \emptyset$, apply MTPR scheme, i.e., choose the route with the minimum total transmission power; (2) if $Q = \emptyset$, apply MMBCR scheme, i.e., choose the route with the maximum battery capacity. Here, γ can be treated as the energy percentage of the full energy capacity which ranges from 0 to 100.

$$\begin{cases} \gamma = 0 & same\ as\ MTPR \\ 0 < \gamma < 100 & apply\ MTPR\ to\ routes\ of \\ & battery\ capacity\ larger\ than\ \gamma \\ \gamma = 100 & same\ as\ MMBCR \end{cases} \tag{15}$$

Therefore, CMMBCR can protect nodes with low energy capacity from being depleted by setting the threshold γ.

[13] compared three different cost functions: the first one is the same as MTPR. The second and the third ones both use metrics which combine transmission power and remaining energy capacity. The second cost function is defined as follows:

$$C_R = \sum_{i=0}^{k-1} \frac{P_T(i)}{min(E_r^i(t), E_r^{i+1}(t))} \tag{16}$$

Compared with MTPR, cost function 2 favors nodes that are not heavily utilized since the remaining energy capacity is used in the function. The third cost function uses the weighted function to combine the two metrics; formally:

$$C_R = \sum_{i=0}^{k-1} (w_1 \frac{P_T(i)}{P_{max}} + w_2 \frac{E_o^{i+1}}{E_r^{i+1}(t)}) \tag{17}$$

where P_{max} is the maximum transmission power, w_1 and w_2 are two weight values that can be adjusted to favor either of the two items. At the beginning, the second item should be one. This function has the same effect as MTPR. However, with the energy capacity decreasing, the second item increases, which makes the cost of the route increase too. Thus, it also attempts to avoid nodes with little energy resource, while minimizing the energy consumption.

In [14], Power-aware Source Routing (PSR) is proposed, which also combines the transmission power and remaining energy capacity as the cost metric. The cost function is defined as follow:

$$C_R = \sum_{i=0}^{k-1} P_T(i) (\frac{E_o^i}{E_r^i(t)})^\alpha \tag{18}$$

where α is a positive weighting factor.

In [17], Power-Aware On-Demand (PAOD) protocol is proposed which combines hop count and remaining battery capacity. When node v_i receives a RREQ message, it computes a threshold value with The following equation:

$$\theta_i(t) = \frac{E_o^i}{(t/\eta)^\kappa + 1} \tag{19}$$

where η and κ are predefined positive constants. If $E_r^i(t)$ is larger than $\theta_i(t)$, the RREQ message will be processed and forwarded. Otherwise, node v_i will drop the message. The cost function of the route is as follow:

$$C_R = A \times k - B \times min\{E_r^i(t) | i = 1, ..., k\} \tag{20}$$

where k is the hop count, A and B are both predefined positive constants. PAOD selects the route with the minimum cost value, which represents a route with smaller hop count and larger battery lifetime.

We conclude and compare the advantages, and drawbacks of all these protocols in table II.

III. PERFORMANCE EVALUATION

We analyze the following protocols: MTPR, MBCR, MMBCR, TDOD, MDR and CMMBCR by implementing and testing them in NS-2 [21], a discrete event-driven network simulator. All of the implementation are modified from the AODV protocol in NS-2.

A. Energy Model

NS2 uses the wireless interface which works like the 914MHZ Lucent WaveLAN DSSS radio interface [22]. Nodes use omni-directional antenna, and the transmission range is 250 meters.

Fixed transmission and receiving power: Energy consumption only counts receiving and transmission. Thus, idle nodes do not consume energy. The power for transmission and receiving are *fixed* values, 0.66 Watt and 0.365 Watt, respectively. Assume a packet p with time length $t(p)$; when

a node transmits p, its energy capacity will be decreased by $E_{tx}(p)$, where $E_{tx}(p) = 0.66 \times t(p)$; when a node receives p, its energy capacity will be decreased by $E_{rx}(p)$, where $E_{rx}(p) = 0.395 \times t(p)$. Thus, under this model, MTPR is the same as the minimum hop routing. It is possible to modify this model to adjustable transmission power based on the transmission distance, as we described in Section II. We did simulations with adjustable transmission power, but can not include the results in this paper due to the space limit.

With or without overhearing: NS-2 counts the energy consumption of overhearing wireless channels. I.e., a node will consume receiving power for all packets it hears. We modified the energy consumption model in NS-2 so that it can turn on/off the overhearing. In order to measure the effect of the overhearing, we conducted two sets of simulations, one with overhearing and one without overhearing.

B. Network Setting

We simulate a network with 50 mobile nodes randomly distributed in a $600m \times 600m$ region. The simulation time is 900 seconds each run. The mobility model uses the random waypoint model, and node speed is randomly distributed between $(0 - 20)$ meters per second. We did two sets of simulations for mobile and static scenarios respectively. For mobile scenarios, we set the pause time as 0. For the traffic models, we use CBR sources, but the source-destination pairs are randomly chosen over the network. There are 10, 20 and 30 connections to represent different degrees of traffic load in different sets of simulations. In addition, the waiting time for the destination to reply to the RREQ message is set as $50ms$. We set the threshold γ in CMMBCR as 15% for the simulation.

C. Performance

We evaluate the performance of six routing protocols via simulations under various scenarios. All results are summarized by Tables III-XIV. In each table, the columns are the name of the protocol, the average delivery ratio (DR), the average end-to-end delay (Delay), the average overhead (Overhead), the average energy consumption (E-Con) and the standard deviation of the remaining energy (E-Dev) among all the nodes. We use **bold font** to identify the *best* result in each column.

1) Results Without Overhearing: We first study the performance under the model without overhearing.

Static Scenarios: Tables III, IV and V show the simulation results of static setting with 10, 20 and 30 connections, respectively. First, for all routing protocols, it is clear that the routing performance (DR, Delay and Overhead) decreases while the traffic load increases. Similarly, the network consumes more energy with higher traffic loads. Figures 1(a) and 1(b) show the energy-related performances. In term of energy consumption, MTPR is the one that performs well in most scenarios. But it is interesting that MTPR does not always have the least energy consumption in static scenarios. One reason may be that since MTPR always takes the shortest path it could lead to more collisions, which cost energy. The results in the deviation of remaining energy also indicate this. MTPR has almost the worst deviation in all three cases, because all other protocols consider the remaining energy in the route metric. Notice that TDOD has the best performance when traffic load is high (30 connections). Remember that TDOD adds delay based on the remaining energy which could avoid collisions with neighbors during route discovery. The high traffic load case has more route discovery packets and may lead to more collisions. Thus, TDOD may achieve better performance under high traffic.

TABLE III

STATIC NETWORK WITH 10 CONNECTIONS (WITHOUT OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.999881	0.015060	0.011771	23.907269	9.156139
MBCR	0.999614	0.014476	0.023462	**22.944956**	**7.630641**
MMBCR	0.999822	0.015992	0.013495	24.376727	7.646056
TDOD	0.999822	0.016355	0.016324	24.883062	9.134326
MDR	0.999494	0.019153	0.030354	27.929781	7.739330
CMMBCR	0.999494	0.015123	0.030696	23.638377	8.226625

TABLE IV

STATIC NETWORK WITH 20 CONNECTIONS (WITHOUT OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.995364	0.022099	0.102004	**40.687572**	9.592310
MBCR	0.995377	0.024209	0.160060	42.407922	8.756987
MMBCR	0.994104	0.026457	0.223449	44.064109	**7.939207**
TDOD	0.992255	0.029459	0.273526	45.306257	9.415896
MDR	0.995707	0.024870	0.169197	42.910999	8.803344
CMMBCR	0.979010	0.023414	0.110010	41.087063	8.196747

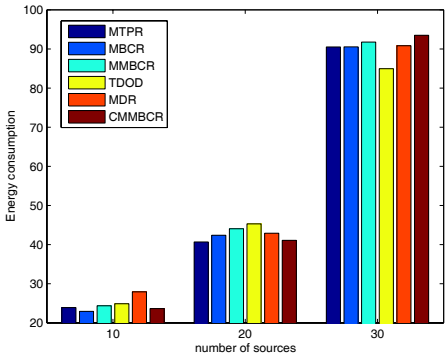
TABLE V

STATIC NETWORK WITH 30 CONNECTIONS (WITHOUT OVERHEARING)

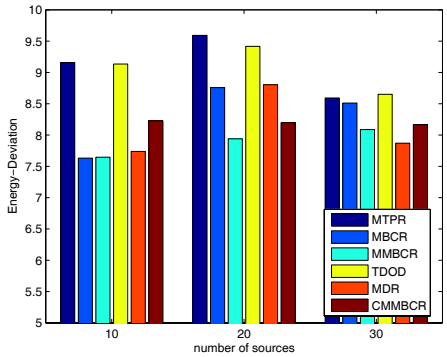
Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.499851	4.302653	4.996282	90.50776	8.592205
MBCR	0.505409	4.247943	4.938367	90.526014	8.511804
MMBCR	0.493040	4.554065	5.255407	91.763786	8.086865
TDOD	0.502339	4.103599	4.503983	**84.940890**	8.649906
MDR	0.490201	4.468021	5.172181	90.812939	**7.870351**
CMMBCR	0.491387	4.619596	5.196660	93.486140	8.165447

Mobile Scenarios: Tables VI, VII and VIII show the simulation results of mobile settings with 10, 20 and 30 connections, respectively. Figures 1(c) and 1(d) illustrate the energy-related performances. For light traffic, (Table VI and VII), the results of mobile scenarios are worse than those of static scenarios. However, for high traffic, the result of the mobile case is much better than that of the static case. E.g., the delivery ratio improves over 30%. This shows that mobility can help routing performance under high traffic load. For the results here, it is much clearer than in the static cases that MTPR almost consumes less energy and has worse standard deviation than the others. For high traffic load, TDOD also spends least energy among all methods due to the same reason we explained in the static scenarios.

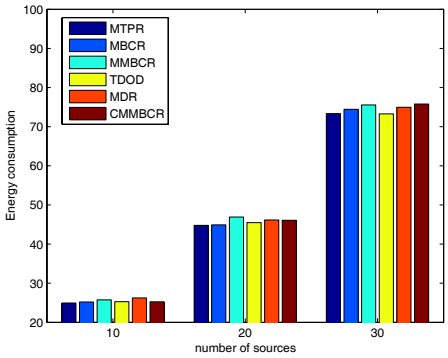
2) Results With Overhearing: We now turn on the overhearing when we compute the energy consumption. Notice that for MTPR, this will only affect the last two metrics in our results: energy consumption and standard deviation of the remaining energy. But for others, since they consider the



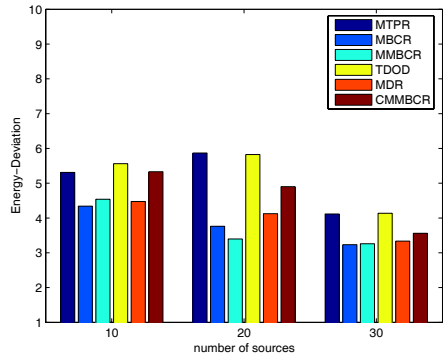
(a) Average Energy Consumption (Static Network without Overhearing)



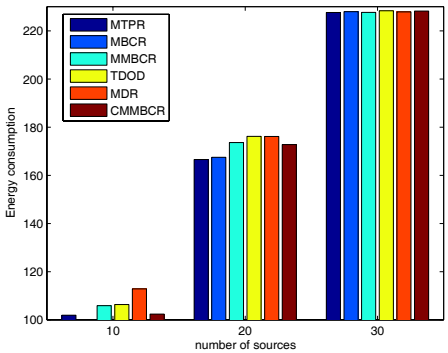
(b) Standard Deviation of Remaining Energy (Static Network without Overhearing)



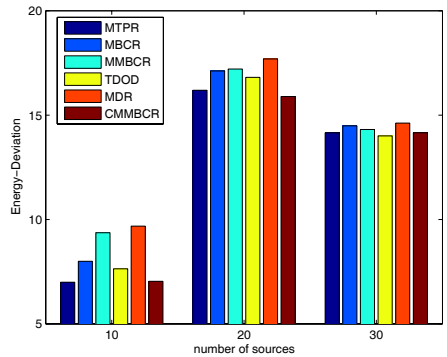
(c) Average Energy Consumption (Mobile Network without Overhearing)



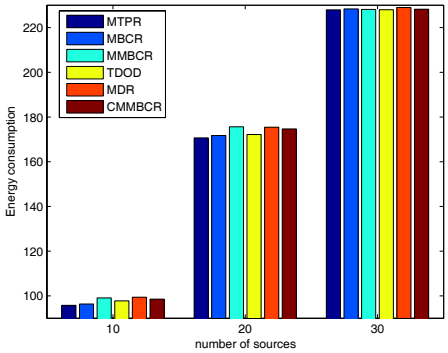
(d) Standard Deviation of Remaining Energy (Mobile Network without Overhearing)



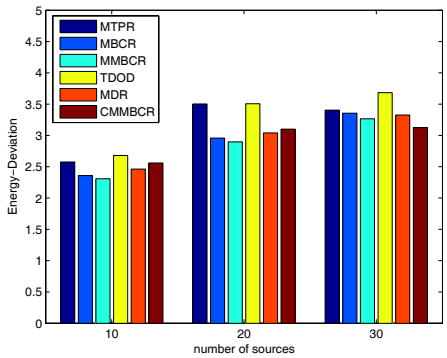
(e) Average Energy Consumption (Static Network with Overhearing)



(f) Standard Deviation of Remaining Energy (Static Network with Overhearing)



(g) Average Energy Consumption (Mobile Network with Overhearing)



(h) Standard Deviation of Remaining Energy (Mobile Network with Overhearing)

Fig. 1. Energy-related performance of different routing methods for both static networks and mobile networks (with or without overhearing).

TABLE VI

MOBILE NETWORK WITH 10 CONNECTIONS (WITHOUT OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.985958	0.014085	0.481639	**24.947783**	5.310532
MBCR	0.990084	0.014338	0.523058	25.194687	**4.340262**
MMBCR	0.990660	0.014812	0.486639	25.747310	4.539410
TDOD	0.985804	0.015298	0.489026	25.285385	5.560103
MDR	0.989462	0.015208	0.538269	26.236164	4.475483
CMMBCR	0.991179	0.014557	0.446186	25.248989	5.330392

TABLE VII

MOBILE NETWORK WITH 20 CONNECTIONS (WITHOUT OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.987068	0.024401	0.477711	**44.794892**	5.867938
MBCR	0.983603	0.024238	0.482640	44.917987	3.761897
MMBCR	0.982382	0.029008	0.535719	46.909521	**3.396535**
TDOD	0.986632	0.026625	0.506814	45.472629	5.823668
MDR	0.979683	0.026002	0.523143	46.161898	4.122967
CMMBCR	0.986476	0.028511	0.482597	46.085889	4.900898

remaining energy capacity, overhearing will affect the route selection.

Static Scenarios: Tables IX, X and XI show the simulation results of static settings with 10, 20 and 30 connections, respectively. Figures 1(e) and 1(f) illustrate the energy-related performances. Notice that when comparing with results without overhearing, the energy consumption is much higher when we consider the overhearing. Again the MTPR in most cases spends the least energy. It is a surprise that the deviation of the MTPR is not worse when comparing with those of the others. This may be due to the following two reasons: (1) when considering the overhearing, the energy consumption is also spread to all neighbors along the routes; and (2) our traffic loads are also randomly generated in the network. In summary, MTPR performs well with overhearing.

Mobile Scenarios: Tables XII, XIII and XIV show the simulation results of mobile setting with 10, 20 and 30 connections, respectively. Figures 1(g) and 1(h) illustrate the energy-related performances in the simulations. In all three cases, MTPR uses the least energy while has the worse deviation.

3) Summary: Summarizing all cases in our simulation, we can conclude the follows:

- MTPR usually conserves more energy than other methods (e.g., it takes the leading position in most cases), however, it does not evenly distribute the energy consumption in the network;
- The other methods consider the remaining energy capacity or node remaining life time. Thus they can diversify the traffic in the network and distribute the energy consumption more evenly than MTPR; however, from our simulation there is no golden solution for all cases (i.e., no clear winner in these groups);
- The energy consumed by overhearing is significant. None of the routing methods considered adequately address this issue. We can modify the routing protocols by considering the overhearing during the route discovery phase. However, with node mobility, it is hard to estimate the overhearing cost. Thus, an energy efficient MAC protocol may be a more feasible solution.

TABLE VIII

MOBILE NETWORK WITH 30 CONNECTIONS (WITHOUT OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.811254	0.757120	1.450301	73.358092	4.115321
MBCR	0.802019	0.732784	1.541298	74.441506	**3.234536**
MMBCR	0.787394	0.915314	1.647589	75.563952	3.260226
TDOD	0.801417	0.750204	1.526809	**73.268255**	4.135444
MDR	0.793228	0.753898	1.577745	74.954412	3.336158
CMMBCR	0.786381	0.970880	1.550689	75.794514	3.559285

TABLE IX

STATIC NETWORK WITH 10 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.999881	0.015060	0.011771	101.920115	**6.994391**
MBCR	0.999881	0.013996	0.012485	**95.9956290**	7.995769
MMBCR	0.999584	0.016985	0.025499	105.887825	9.363319
TDOD	0.999495	0.016476	0.033994	106.331749	7.636412
MDR	0.999436	0.018780	0.029798	112.856820	9.682343
CMMBCR	0.999553	0.015616	0.026425	102.384508	7.039649

TABLE X

STATIC NETWORK WITH 20 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.995364	0.022099	0.102004	**166.576348**	16.190266
MBCR	0.995713	0.023384	0.158720	167.477804	17.114866
MMBCR	0.995458	0.026327	0.167199	173.626690	17.206448
TDOD	0.990191	0.026128	0.180789	176.162660	16.808626
MDR	0.993707	0.027936	0.221034	176.122343	17.688297
CMMBCR	0.995288	0.025104	0.166338	172.774483	**15.890305**

TABLE XI

STATIC NETWORK WITH 30 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.499851	4.302653	4.996282	**227.634865**	14.148140
MBCR	0.514139	4.416469	4.835277	227.962797	14.485435
MMBCR	0.474760	4.301828	5.478373	227.646616	14.311254
TDOD	0.520261	3.946859	4.298207	228.348041	**14.004957**
MDR	0.488583	4.344182	5.109337	227.865371	14.620082
CMMBCR	0.493885	4.530852	5.138701	228.209146	14.154546

TABLE XII

MOBILE NETWORK WITH 10 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.985958	0.014085	0.481639	**95.814971**	2.576626
MBCR	0.989832	0.014281	0.530937	96.399828	2.359506
MMBCR	0.989889	0.014988	0.532056	99.110597	**2.308858**
TDOD	0.990606	0.015249	0.514540	97.782156	2.680260
MDR	0.990709	0.015202	0.500902	99.444179	2.463082
CMMBCR	0.989907	0.015256	0.515595	98.573403	2.559586

TABLE XIII

MOBILE NETWORK WITH 20 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.987068	0.024401	0.477711	**170.658444**	3.503287
MBCR	0.985024	0.024462	0.483920	171.717557	2.958192
MMBCR	0.984077	0.030921	0.510146	175.627012	**2.897864**
TDOD	0.985562	0.026335	0.476373	172.167776	3.505665
MDR	0.987222	0.026444	0.496909	175.456722	3.039602
CMMBCR	0.985591	0.027994	0.500031	174.667202	3.100583

TABLE XIV

MOBILE NETWORK WITH 30 CONNECTIONS (WITH OVERHEARING)

Protocols	DR	Delay	Overhead	E-Con	E-Dev
MTPR	0.811254	0.757120	1.450301	**227.921642**	3.404381
MBCR	0.800409	0.815237	1.572144	228.327839	3.355097
MMBCR	0.806422	0.652521	1.504925	228.092578	3.265912
TDOD	0.800720	0.718735	1.503582	227.972860	3.682320
MDR	0.794708	0.926736	1.615565	228.997488	3.326285
CMMBCR	0.770366	1.056322	1.842011	228.220850	**3.125605**

IV. CONCLUSION

We surveyed energy efficient routing protocols for ad hoc networks and classified them into four categories. Extensive simulations with different scenarios showed that protocols in the first category (i.e. MTPR) can find the minimum energy cost path and conserve energy when compared to protocols in the other three categories, most of time. However, protocols in the second and third categories can more evenly distribute energy consumption among nodes in the network, which means they can extend the network lifetime. Because protocols in the fourth category use combined energy metrics (e.g. CMMBCR), their performance is between the first and the second or the third categories. The CMMBCR can easily combine the two metrics, however, it is difficult to find the optimal tradeoff to achieve the best performance.

The simulation results also showed that, overhearing consumes a large amount of energy, which obviously will decrease the network lifetime. Researchers also proposed solutions to reduce the effect of overhearing in recent works. For example, [23] proposed a new interface idling mechanism, which can extend the network lifetime by up to 86% by reducing overhearing expenditure.

ACKNOWLEDGMENT

The work of Yu Wang was supported, in part, by funds provided by Oak Ridge Associated Universities and the University of North Carolina at Charlotte.

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