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Energy-aware routing algorithms for wireless ad hoc networks with heterogeneous power supplies

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ABSTRACT

Although many energy-aware routing schemes have been proposed for wireless ad hoc networks, they are not optimized for networks with heterogeneous power supplies, where nodes may run on battery or be connected to the mains (grid network). In this paper, we propose several energy-aware routing algorithms for such ad hoc networks. The proposed algorithms feature directing the traffic load dynamically towards mains-powered devices keeping the hop count of selected routes minimal. We unify these algorithms into a framework in which the route selection is formulated as a bi-criteria decision making problem. Minimizing the energy cost for end-to-end packet transfer and minimizing the hop count are the two criteria in this framework. Various algorithms that we propose differ in the way they define the energy cost for end-to-end packet traversal or the way they solve the bi-criteria decision making problem. Some of them consider the energy consumed to transmit and receive packets, while others also consider the residual battery energy of battery-enabled nodes. The proposed algorithms use either the weighted sum approach or the lexicographic method to solve the bi-criteria decision making problem. We evaluate the performance of our algorithms in static and mobile ad hoc networks, and in networks with and without transmission power control. Through extensive simulations we show that our algorithms can significantly enhance the lifetime of battery-powered nodes while the hop count is kept close to its optimal value. We also discuss the scenarios and conditions in which each algorithm could be suitably deployed.

1. Introduction

Energy-aware routing is an effective scheme to prolong the lifetime of energy-constrained nodes in wireless ad hoc networks [1–13]. Routes are discovered considering the energy cost to transmit packets from source nodes to destination nodes, or considering the remaining battery energy of nodes. This could result in finding routes in which nodes consume less amount of energy for packet forwarding, or routes in which nodes are likely to have more remaining battery energy.

The existing energy-aware routing schemes, however, are not optimized for networks with heterogeneous power supplies. In some applications of ad hoc networking, there might be devices in the network which are connected to the mains (grid network). A simple example is a meeting scenario, where laptops of participants form an ad hoc network to exchange information during the meeting. Some laptops might be connected to the mains, while others use their batteries (see Fig. 1). Another scenario is home networking, where devices at home form an ad hoc network to exchange context [14]. In a home network, most devices are connected to the mains (e.g., appliances), while some handheld devices may run on a battery (e.g., a smart phone). In these scenarios and other similar scenarios of ad hoc networking, energy-aware routing schemes could be

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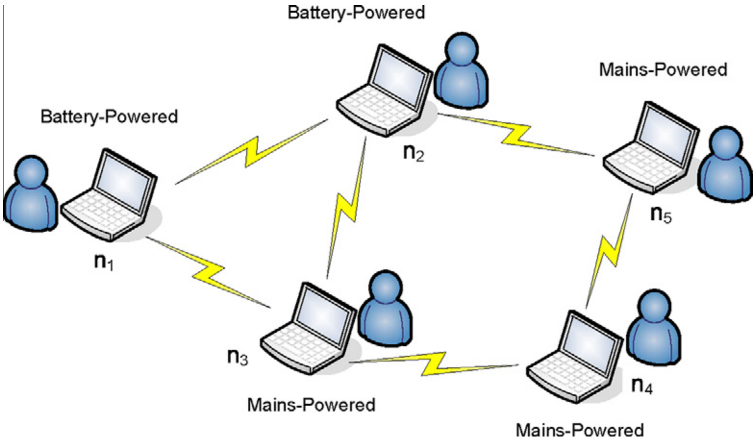

Fig. 1. Schematic of a wireless ad hoc network comprised of mains and battery powered devices.

devised considering the heterogeneity of power supply of nodes to avoid relaying over battery-powered (BP) devices. We can benefit from the advantage of having mains-powered (MP) nodes in the network to reduce the energy consumption of BP nodes for packet forwarding. This can extend the lifetime of BP nodes in such networks.

Although we can deploy the existing energy-aware routing schemes in networks with MP nodes, for instance, by considering no energy cost for packet forwarding by such nodes, such solutions may not be optimal. One problem is the increased hop count. Considering no energy cost for MP nodes may increase the number of hops of the selected routes, because longer routes consisting of MP nodes will be preferred to shorter routes consisting of BP nodes. Apart from this, the existing schemes are not designed on the basis of a realistic energy consumption model for packet exchange over wireless links. Many energy-aware routing schemes such as those proposed in [15,16,1,11,12,17,18] do not consider the energy consumed by processing elements of transceivers during packet transmission and reception. Measurements presented in [19] show that these sources of energy consumption might be in the same order as the transmission power of nodes which is considered in the design of energy-aware routing schemes in [15,16,1,11,12,17,18].

The novelty in this paper is the proposal of novel energy-aware routing algorithms for ad hoc networks which consist of both MP and BP nodes. To this end, we use a realistic energy consumption model for packet transmission and reception over wireless links, where the energy consumed by processing elements of nodes are also taken into account. We provide a detailed explanation for energy consumption of nodes by bringing into the picture the effect of transmission power control [20,21] on the consumed energy. The energy consumption model that we present can also provide a substrate for further investigations on energy-aware routing in multi-rate wireless ad hoc networks. Nevertheless, in this paper, we only consider single-rate networks, and leave multi-rate networks for future studies.

On the basis of the developed energy consumption model, we propose Least Battery-powered Nodes Routing (LBNR) and Minimum battery cost with Least battery-powered Nodes Routing (MLNR) algorithms. LBNR and MLNR algorithms minimize the energy cost of end-to-end packet traversal in ad hoc networks keeping the hop count of the selected routes minimal. They differ with each other in the way they define the energy cost of packet forwarding. LBNR considers the power supply of nodes and their consumed energy for packet transmission and reception, while MLNR considers the residual battery power of BP nodes as well.

We unify LBNR and MLNR algorithms into a generic framework for energy-aware routing in ad hoc networks. The route selection in this framework is formulated as a bi-criteria decision making problem. Minimizing the energy cost of end-to-end packet traversal and minimizing the hop count of selected routes are the two criteria that we consider in this paper. Nevertheless, other criteria such as maximizing end-to-end reliability of routes could also be easily added to the proposed framework. By using different methods to solve the bi-criteria decision making problem, we then propose LBNR–LM and MLNR–LM algorithms, which use the lexicographic method [22], and LBNR–WSA and MLNR–WSA, which use the weighted sum approach [22]. We use extensive simulations to evaluate the performance of the proposed algorithms in static and mobile ad hoc networks and in networks with and without transmission power control.

An important characteristic of our proposed algorithms is that (as we will show in the paper) they can generalize some of the well-known energy-aware routing algorithms such as MBCR (minimum battery cost routing) and MTPR (minimum total transmission power routing) [1,2]. Furthermore, while the proposed algorithms in this paper have been designed for ad hoc networks with both MP and BP nodes, they can also be deployed in networks with only BP nodes. This makes, our proposed algorithms generalized schemes which are applicable not only to the networks with only BP nodes but also to the networks with both BP and MP nodes. Moreover, our proposed algorithms have the advantage of being designed on the basis of a more realistic energy consumption model compared to the existing schemes.

The rest of the paper is organized as follows: we explain preliminaries including the energy consumption model in Section 2. In Section 3, we present the unified routing framework that provides a generalized formulation for route selection in LBNR and MLNR algorithms. We present LBNR and MLNR algorithms in Sections 4 and 5, respectively. In Section 6, we explain how the proposed routing algorithms could be deployed in practice. We evaluate the performance of the proposed algorithms in Section 7. We conclude in Section 8.

2. Preliminaries

In this section, we define the network model as well as the mathematical model for computing the energy consumed during transmission and reception of packets over wireless links.

2.1. Network model

Consider the topology of a wireless ad hoc network represented by a graph $G(\mathbb{V},\mathbb{E})$, where $\mathbb{V}$ and $\mathbb{E}$ are the set of nodes and links, respectively. We assume that $\mathbb{V} = \mathbb{V}_b \cup \mathbb{V}_m$, where $\mathbb{V}_b$ is the set of BP nodes, and $\mathbb{V}_m$ is the set of MP nodes. The fraction of MP nodes in the network is denoted by $\sigma = \frac{N_m}{N}$, in which $N = |\mathbb{V}|$ is the total number of nodes in the network (both BP and MP) and $N_m = |\mathbb{V}_m|$ is the number of MP nodes in the network. The remaining battery energy of node i is denoted by C_i (Joule), and the maximum battery energy of a BP node is denoted by C. Without loss of generality, we assume the maximum battery energy for all BP nodes is the same. If the battery energy of a BP node falls bellow the threshold C_{th}, the node is considered to be dead. The Euclidean distance between nodes i and j in the network is denoted by $d_{i,j}$ (meter). We represent a path $\mathcal{P}$ with $h(\mathcal{P})$ hops in the network by $\mathcal{P} = \langle n_1, n_2, \ldots, n_{h(\mathcal{P})}, n_{h(\mathcal{P})+1}\rangle$, where $n_k \in \mathbb{V}$ is the kth node of $\mathcal{P}$, $k = 1, \ldots, h(\mathcal{P}) + 1$, and its remaining battery energy is denoted by C_{n_k}. Here, n_1 is the source node, $n_{h(\mathcal{P})+1}$ is the destination node, and the rest are relays.

2.2. Energy consumption model

In this work, we assume nodes use the same wireless interface with similar power consumption profile. The power required to run the processing elements of the wireless interface when a packet is transmitted and received are denoted by P_t and P_r [W], respectively. Let $P_{i,j}$ [W] be the transmission power from node i to node j, and $\kappa \leqslant 1$ be the power efficiency of the power amplifier of the transmitter. Therefore, the power that node i requires to run its power amplifier to transmit data to node j is $P_{i,j}/\kappa$. Let $R_{i,j}$ be the rate [bit/s] at which i transmits data to j. As a practical assumption, we consider the same transmission rate for all nodes. That is, $R_{i,j} = R\ \forall (i,j) \in \mathbb{E}$. This rate is basically determined by the modulation and channel coding scheme deployed by the wireless interface which are the same for all nodes.

Given the notations and the assumptions, the energy consumed by node i to transmit a packet of size L bits to node j is

$$\varepsilon_{i,j} = \left(P_t + \frac{P_{i,j}}{\kappa}\right)T = \left(P_t + \frac{P_{i,j}}{\kappa}\right)\frac{L}{R}\ [\mathrm{J}], \tag{1}$$

where T is the time required to transmit L bits with the rate R bits/s. Similarly the energy consumed by node j to receive the packet is

$$\omega = P_r T = P_r \frac{L}{R}\ [\mathrm{J}]. \tag{2}$$

2.3. Transmission power control

Transmission power control (TPC) is a well-accepted technique in wireless ad hoc networks to save energy [20,21,23–26]. Nodes reduce their transmission power to consume less energy for packet transmission to their neighboring nodes. Reducing the transmission power of nodes can also increase the network capacity [27,26]. In the design and evaluation of the proposed energy-aware routing algorithms in this paper, we assume nodes deploy TPC as defined bellow:

Definition 1 (*TPC*). Given a data transmission rate R, a transmitting node i keeps its transmission power for data transmission to a receiving node j as low as required to satisfy a target bit error rate δ at the receiving node.

The target bit error rate (BER) δ is a design parameter. It has close relation with the maximum transmission power and the maximum transmission range of the wireless technology. The maximum transmission power is usually the minimum power required to satisfy the target BER when the receiver is located on the border of the transmission range. Due to path loss experienced by electromagnetic waves, the received signal strength increases as the distance between the transmitter and the receiver decreases. This, in turn, reduces the BER. With TPC, a node adjusts its transmission power to a value just enough to satisfy the target BER δ. To this aim, the received signal to noise and interference ratio (SINR) must be above a threshold. This threshold depends on the modulation and channel coding schemes employed by the wireless interface.

Let γ_{min} be the required SINR for having the target BER δ, $d_{i,j}$ be the distance between i and j, η be the pass-loss exponent of the environment ($2 \leqslant \eta \leqslant 4$), and $\mathcal{N}$ be the noise and interference power. When TPC is deployed, we need to have

$$\frac{g_1 P_{i,j}}{\mathcal{N} d_{i,j}^{\eta}} \geqslant \gamma_{min}, \tag{3}$$

where g_1 is a constant which depends on the gain of transmitting and receiving antennas. The minimum transmission power of node i required to satisfy the target BER δ at node j is

$$P_{i,j} = g_2 d_{i,j}^{\eta}, \tag{4}$$

where g_2 is defined as $g_2 = \frac{\mathcal{N}\gamma_{min}}{g_1}$.

For the sake of completeness, we also consider a case in which nodes are not able to adjust their transmission power according to the distance to the receiver. In such a case, all nodes transmit packets with the same transmission power. Since we assumed nodes deploy the same wireless interface, this common transmission power could to be the maximum transmission power of nodes. That is, $P_{i,j} = P_{max}\ \forall(i,j) \in \mathbb{E}$, where P_{max} is the maximum transmission power of nodes which results in a common transmission range d_{max}. We refer to this scheme as packet transmission without TPC.

To achieve the target BER δ when a node transmits with maximum power P_{max} and the receiver is at the transmission range d_{max}, we need to have[1]

$$P_{max} = g_2 d_{max}^{\eta}. \tag{5}$$

From (4) and (5), the adjusted transmission power $P_{i,j}$ when TPC is deployed by nodes could be calculated as

$$P_{i,j} = P_{max}\left(\frac{d_{i,j}}{d_{max}}\right)^{\eta}. \tag{6}$$

If we replace $P_{i,j}$ from (6) into (1), the energy consumed to transmit a packet of size L bits from node i to node j when TPC is supported by nodes is obtained as follows:

$$\varepsilon_{i,j} = (\beta_1 + \beta_2 d_{i,j}^{\eta})L, \tag{7}$$

where $\beta_1 = \frac{P_t}{R}$ and $\beta_2 = \frac{P_{max}}{\kappa R d_{max}^{\eta}}$. Similarly by defining $\beta_3 = \frac{P_r}{R}$, (2) is written as

$$\omega = \beta_3 L, \quad \forall(i,j) \in \mathbb{E}. \tag{8}$$

If TPC is not supported (i.e., $P_{i,j} = P_{max}$), then from (1) the energy consumed to transmit a packet over a link is achieved as follows:

$$\varepsilon_{max} = \beta_4 L, \tag{9}$$

in which $\beta_4 = \beta_1 + \frac{P_{max}}{\kappa L}$.

Note that adjusting the transmission power by nodes is subjected to keeping the data transmission rate over wireless channels constant. In other words, by increasing the transmission power from the minimum required value for reliable signal detection $P_{i,j}$ to its maximum value P_{max}, only the received signal strength increases while the transmission rate remains unchanged. Considering the same transmission rate for all nodes means that we implicitly assumed the wireless interface is single rate. Therefore, β_i, $i = 1,\ldots,4$, is fixed for all nodes. If the wireless interface is multi rate, depending on the received signal strength, the transmission rate over a link changes. Therefore, different links may have different transmission rates. This can result in different values for β_i, $i = 1,\ldots,4$, for different links. How multi rate communications could be deployed in wireless ad hoc networks and how we can design efficient energy-aware routing algorithms for such networks are beyond the scope of this paper.

In this paper, we develop several energy-aware routing algorithms for single rate wireless ad hoc networks with MP and BP nodes on the basis of the explained energy consumption model for packet transmission and reception over wireless links. In the next section, we present a generalized formulation for route selection by all the algorithms that we propose in this paper. Then, we describe each algorithm separately. For each algorithm, two cases of packet transmission with and without TPC will be discussed. Table 1 summarizes the definitions of various parameters introduced in this section and those which will be introduced later.

3. The energy-aware routing framework

The key idea that we use in the design of energy-aware routing algorithms for ad hoc networks with heterogeneous power supplies is to avoid using BP nodes of the network as relaying nodes and direct the relay traffic to MP nodes of the network. The challenge is to design routing algorithms which are able to consider not only the heterogeneity of power supply of nodes in route selection but also the energy cost of packet transmission and reception over wireless link and the remaining battery energy of BP nodes. To this end, we assign an energy-related cost function $\mathcal{X}(\mathcal{P})$ to each path $\mathcal{P}$ which is the energy cost of using that path for end-to-end packet transmitter from the source to the destination. We define $\mathcal{X}(\mathcal{P})$ as

$$\mathcal{X}(\mathcal{P}) = \sum_{k=1}^{h(\mathcal{P})} \phi(n_k, n_{k+1}), \tag{10}$$

where $\phi(n_k, n_{k+1})$ is the energy cost of forwarding a packet over link $(n_k, n_{k+1}) \in \mathcal{P}$. To direct the relay traffic to MP nodes, no energy cost is considered for packet forwarding by MP nodes, because they do not lose their battery energy when they forward a packet. In other words, $\phi(n_k, n_{k+1})$ is zero if both n_k and n_{k+1} are MP. However, if n_k and n_{k+1} are BP, $\phi(n_k, n_{k+1})$ includes the energy cost of packet transmission by n_k as well as the energy cost of packet reception by n_{k+1}. Infact, $\mathcal{X}(\mathcal{P})$ is the energy cost of BP nodes of a path for end-to-end packet transmission which must be minimized.

Minimizing $\mathcal{X}(\mathcal{P})$ without considering any energy cost for MP nodes may increase the number of hops of the selected routes, because longer routes consisting of MP nodes will be preferred to shorter routes consisting of BP nodes. As a design goal, we try to find a path which has the minimum energy cost and the minimum number of hops. Let $\mathbb{A} = \{\mathcal{P}_q\}_{q=1}^{Q}$ be the set of available paths between a pair of source–destination nodes. We define the *optimal path* as a path that its energy cost and its hop count is smaller than the energy cost and hop count of other paths, respectively. In other words, the optimal path is $\mathcal{P}_m \in \mathbb{A}$ such that

$$\begin{cases} \mathcal{X}(\mathcal{P}_m) \leqslant \mathcal{X}(\mathcal{P}_q), \\ h(\mathcal{P}_m) \leqslant h(\mathcal{P}_q), \end{cases} \tag{11}$$

$\forall \mathcal{P}_q \in \mathbb{A}$, where $\mathcal{X}(\mathcal{P}_q)$ and $h(\mathcal{P}_q)$ are the energy cost and the hop count of $\mathcal{P}_q \in \mathbb{A}$, respectively. As (11) suggests, the route selection is a bi-criteria decision making

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[1] Here, we assumed that the inference power is (approximately) the same at different points of the network.

Table 1
Nomenclature.

Parameter	Description
$\mathbb{V}$	Set of nodes of the network
$\mathbb{V}_b$	Set of BP nodes of the network
$\mathbb{V}_m$	Set of MP nodes of the network
$\mathbb{E}$	Set of links of the network
$\mathbb{A}$	Set of paths between a source and a destination node
N	The number of nodes of the network
N_m	The number of MP nodes of the network
$\sigma = N_m/N$	Fraction of MP nodes in the network
C_i	Battery energy of node i
C	Maximum battery energy of BP nodes
C_{th}	Battery death threshold of BP nodes
(i,j)	A link from node i to node j
$\mathcal{P}$	A path in the network
$\varepsilon_{i,j}$	Consumed energy for packet transmission from i to j
ω	Consumed energy for packet reception by a node
$P_{i,j}$	Transmission power from node i to node j
P_t	Power consumed by processing elements of the transmitter circuit
P_r	Power consumed by processing elements of the receiving circuit
P_{max}	Maximum transmission power of nodes
κ	Power efficiency of transmitter amplifier
d_{max}	Transmission range of nodes
R	Data rate of the wireless interface
L	Packet length
$d_{i,j}$	Distance between node i and node j
δ	Target bit error rate of the wireless interface
β_i,	$i = 1,\ldots,4$
Energy	consumption parameters
η	Path-loss component
$h(\mathcal{P})$	Hop count of path $\mathcal{P}$
$\mathcal{X}(\mathcal{P})$	The energy cost of path $\mathcal{P}$
$\phi(i,j)$	The energy cost of link (i,j)
$\phi_{wsa}(i,j)$	The WSA energy cost of link (i,j)
$\phi_{lbnr}(i,j)$	The energy cost of link (i,j) in LBNR–LM
$\phi_{mlnr}(i,j)$	The energy cost of link (i,j) in MLNR–LM
$\phi_{wlbnr}(i,j)$	The WSA energy cost of link (i,j) in LBNR–WSA
$\phi_{wmlnr}(i,j)$	The WSA energy cost of link (i,j) in MLNR–WSA
a	Weighing coefficient in the WSA algorithms
b	Normalization coefficient in the WSA algorithms

problem. Minimizing the energy cost and the hop count are the two criteria. In other words, the energy cost and the hop-count of routes are the objectives which must be minimized simultaneously. Nevertheless, a bi-criteria (generally a multi-criteria) decision making problem may not have a solution optimizing both (all) criteria. There might be a solution that optimizes one of the criteria, but there may not be a solution optimizing both (all) criteria simultaneously. The *lexicographic method* and the *weighted sum approach* are two methods that we can use to solve multi-criteria decision making problems [22].

Lexicographic method: the lexicographic method (LM) considers the priority of different criteria in the decision making process to find an optimal solution. According to LM, if minimizing the energy cost of routes has a priority higher than minimizing their hop count, then the optimal path is a path with the minimum energy cost. However, if there are several paths between a source and a destination which have the minimum energy cost, the path with the minimum number of hops is selected amongst them. In other words, let $\mathbb{B} \subset \mathbb{A}$ be as follows:

$$\mathbb{B} = \left\{\mathcal{P}_n \in \mathbb{A} : \mathcal{X}(\mathcal{P}_n) \leqslant \mathcal{X}(\mathcal{P}_q)\ \forall \mathcal{P}_q \in \mathbb{A}\right\}.$$

If $|\mathbb{B}| = 1$, the only element of $\mathbb{B}$ is the optimal path. If $|\mathbb{B}| > 1$, the optimal path is $\mathcal{P}_m \in \mathbb{B}$, where

$$h(\mathcal{P}_m) \leqslant h(\mathcal{P}_n), \quad \forall \mathcal{P}_n \in \mathbb{B}.$$

The weighted sum approach: the weighted sum approach (WSA), considers the relative weight of different criteria with respect to each other. In WSA, a single objective is defined for decision making, which is a weighted sum of all the objectives. The optimal solution of the multi-criteria decision making problem is a solution which optimizes the resulting single objective.

According to WSA, we define a single cost function for each path $\mathcal{P}$ as

$$\mathcal{Y}(\mathcal{P}) = a\frac{\mathcal{X}(\mathcal{P})}{b} + (1-a)h(\mathcal{P}). \tag{12}$$

The path which minimizes $\mathcal{Y}(\mathcal{P})$ is then selected as the optimal path. Here, $0 \leqslant a \leqslant 1$ is the relative weight of minimizing the energy cost of routes to minimizing their hop count in the decision making process. Parameter b is a normalizing coefficient to match unit of the energy cost of a route and its variation range to that of the hop count of the route such that these two values could be added to each other. Since energy cost and hop count have different units, they can not be added without normalization.

By replacing $\mathcal{X}(\mathcal{P})$ in (12) with its definition given in (10), $\mathcal{Y}(\mathcal{P})$ becomes

$$\mathcal{Y}(\mathcal{P}) = \sum_{k=1}^{h(\mathcal{P})} \left(\frac{a}{b}\phi(n_k, n_{k+1}) + 1 - a\right). \tag{13}$$

Eq. (13) suggests that in WSA a new energy cost function is defined for each link as

$$\phi_{wsa}(n_k, n_{k+1}) = \frac{a}{b}\phi(n_k, n_{k+1}) + 1 - a. \tag{14}$$

Therefore, the optimal path when WSA is used is $\mathcal{P}_m \in \mathbb{A}$ such that

$$\begin{cases} \mathcal{Y}(\mathcal{P}_m) \leqslant \mathcal{Y}(\mathcal{P}_q)\ \forall \mathcal{P}_q \in \mathbb{A} \\ \mathcal{Y}(\mathcal{P}_q) = \sum\limits_{k=1}^{h(\mathcal{P}_q)} \phi_{wsa}(n_k, n_{k+1}). \end{cases}$$

We refer to $\phi_{wsa}(n_k,n_{k+1})$ as the *WSA energy cost* of link $(n_k, n_{k+1}) \in \mathcal{P}$ to distinguish it from the *actual energy cost* of the link (i.e., $\phi(n_k,n_{k+1})$).

Choice of normalizing coefficient b and weighing coefficient a in WSA: as mentioned before, b is a normalizing coefficient to match the unit of the energy cost of a route and its variation range to that of the hop count of the route such that these two values could be added to each other to form a new objective for route selection. For example, if the unit of the energy cost $\mathcal{X}(\mathcal{P})$ is Joule, b must be in Joule as well, because the hop count has no unit. Furthermore, in order to bring the energy cost of a path to the same order of its hop count, we define b as the maximum energy cost that the path could have. For instance, if the energy cost of a path with 3 hops is 0.05 [J] and the maximum energy cost for packet forwarding at each hop is 0.02 [J], then we choose $b = 3 \times 0.02 = 0.06$ [J]. With this choice the normalized energy cost of the path will be 0.05/0.06 = 5/6. Note that although the normalized energy cost of a path might be smaller than its hop count, it does not necessarily mean that WSA favours the hop count to the energy cost. The tunable parameter a has the critical role here which controls the priority of energy cost to hop count in route selection.

If $a = 0$, we have $\phi_{wsa}(n_k, n_{k+1})|_{a=0} = 1$. This means the optimal path in WSA will be the path which minimizes the number of hops. In other words, if $a = 0$, any energy-aware routing algorithm devised on the basis of WSA turns to be the shortest-path routing (SHR) algorithm. For $a = 1$, the WSA energy cost of a link changes to

$$\phi_{wsa}(n_k, n_{k+1})|_{a=1} = \frac{1}{b}\phi(n_k, n_{k+1}).$$

Since b is a constant term, it has no influence in selecting the optimal path. Therefore, we can simplify the WSA energy cost of links as

$$\phi_{wsa}(n_k, n_{k+1})|_{a=1} = \phi(n_k, n_{k+1}), \tag{15}$$

without changing the optimal path. Eq. (15) implies that when $a = 1$, the WSA energy cost of a link is the actual energy cost of the link. In other words, if $a = 1$, any energy-aware routing algorithm devised on the basis of WSA only considers the energy cost as the routing metric and finds a path with the minimum energy cost as the optimal path. However, for any value of a between its two limits 0 and 1, the energy cost might be favored to the hop count in route selection or vice versa. We will further discuss the effect of coefficient a on the performance of WSA-based routing algorithms in Section 7.

As we remember, LM considers minimizing the actual energy cost of paths as the primary criterion for route selection. Therefore, the optimal path in WSA with $a = 1$ and in LM could be the same. Note that this may not be always true. LM considers minimizing the hop count as the second criterion. When there are several paths which have the minimum energy cost, LM chooses a path with the minimum number of hops among them. On the other hand, in WSA with $a = 1$, minimizing the actual energy cost is the only criterion for route selection. Hence, when there are several paths with the minimum energy cost, one of them will be chosen randomly (tie breaking). However, if by chance the path with the minimum number of hops among those with the minimum energy cost is selected, or there is only one path which has the minimum energy cost, the optimal path in WSA with $a = 1$ will be the same as the optimal path in LM.

In the next two sections, we introduce different formulations for computing the actual energy cost of links to devise several energy-aware routing algorithms based on the routing framework introduced in this section.

4. Least Battery-powered Nodes Routing (LBNR) algorithms

LBNR defines a suit of energy-aware routing algorithms which consider type of power supply of nodes and their consumed energy for transmission and reception of packets over wireless links to compute the energy cost of routes. In the sequel, we introduce LBNR–LM and LBNR–WSA algorithms.

4.1. LBNR–LM

LBNR–LM uses the lexicographic method to find optimal routes. It considers a higher priority for minimizing the energy cost of routes rather than minimizing their number of hops. In LBNR–LM, the actual energy cost of a link is defined as follows:

$$\phi_{lbnr}(n_k, n_{k+1}) = \varepsilon_{n_k,n_{k+1}} f(n_k) + \omega f(n_{k+1}), \tag{16}$$

where $\varepsilon_{n_k,n_{k+1}}$ is the consumed energy to transmit a packet over the link, as defined in (7), and ω is the energy consumed for receiving the packet as defined in (8). Here, we define $f(n_k)$ as

$$f(n_k) = \begin{cases} 1, & n_k \in \mathbb{V}_b, \\ 0, & n_k \in \mathbb{V}_m. \end{cases} \tag{17}$$

The definition of $f(n_k)$ implies that the energy cost for packet transmission and reception is considered to be zero for an MP node.

If TPC is supported, we can find an alternative expression for the energy cost of a link in LBNR–LM. To this end, we need to replace $\varepsilon_{n_k,n_{k+1}}$ and ω in (16) from their definitions given in (7) and (8), respectively. The alternative expression is as follows:

$$\phi_{lbnr}(n_k, n_{k+1}) = L\Big((\beta_1 + \beta_2 d^{\eta}_{n_k,n_{k+1}})f(n_k) + \beta_3 f(n_{k+1})\Big).$$

Since the packet size L is a constant term in all link costs, we can use the normalized energy cost of links with respect to the packet size L without changing the ranking of routes in terms of their energy cost. Therefore, $\phi_{lbnr}(n_k, n_{k+1})$ could be computed as

$$\phi_{lbnr}(n_k, n_{k+1}) = (\beta_1 + \beta_2 d^{\eta}_{n_k,n_{k+1}})f(n_k) + \beta_3 f(n_{k+1}). \tag{18}$$

When nodes are able to adjust their transmission power according to the distance, LBNR–LM finds a path with the minimum number of hops amongst those which minimize the total energy consumed by BP nodes for packet transfer from the source to the destination.

Special case: if all nodes in the network are BP (i.e., $f(n_k) = 1\ \forall n_k \in \mathbb{V}$), and we neglect the power consumed by processing elements of the wireless interface (i.e., $\beta_1 = \beta_3 = 0$), then $\phi_{lbnr}(n_k, n_{k+1}) = \beta_2 d^{\eta}_{n_k,n_{k+1}}$. In such a case, the energy cost of a link as defined by LBNR–LM is the same as the energy cost of a link as defined by MTPR [1,2] algorithm.

Theorem 1. *If TPC is not supported, LBNR–LM finds a path with the minimum number of hops amongst those which have the minimum number of BP nodes.*

Proof. When nodes do not support TPC, the energy consumed by nodes to transmit a packet over a link is the same for all nodes, i.e., $\varepsilon_{n_k,n_{k+1}} = \varepsilon_{max}$. Therefore, the energy cost associated to a link by LBNR–LM is

$$\phi_{lbnr}(n_k, n_{k+1}) = \varepsilon_{max} f(n_k) + \omega f(n_{k+1}). \tag{19}$$

Accordingly, the energy cost of a path $\mathcal{P}$ is

$$\mathcal{X}_{lbnr}(\mathcal{P}) = \sum_{k=1}^{h(\mathcal{P})} (\varepsilon_{max} f(n_k) + \omega f(n_{k+1})),$$

which could be alternatively represented as

$$\mathcal{X}_{lbnr}(\mathcal{P}) = \varepsilon_{max} f(n_1) + \omega f(n_{h(\mathcal{P})+1}) + (\varepsilon_{max} + \omega) \times \sum_{k=2}^{h(\mathcal{P})} f(n_k). \tag{20}$$

Since all available paths between the source node n_1 and the destination node $n_{h(\mathcal{P})+1}$ have the common term $\varepsilon_{max} f(n_1) + \omega f(n_{h(\mathcal{P})+1})$ in their energy cost, we can remove this common term in (20) without changing the ranking of available paths between the source and the destination with regard to the energy cost. Furthermore, we can remove the constant term $\varepsilon_{max} + \omega$ from the remaining expression, and add $f(n_1)$, while the ranking of available routes remains the same. After these linear operations, the energy cost of a path in LBNR–LM without TPC is simplified as follows:

$$\mathcal{X}_{lbnr}(\mathcal{P}) = \sum_{k=1}^{h(\mathcal{P})} f(n_k), \tag{21}$$

which means the energy cost of a link is simply

$$\phi_{lbnr}(n_k, n_{k+1}) = f(n_k). \tag{22}$$

Remember that $f(n_k) = 1$ for BP nodes and $f(n_k) = 0$ for MP nodes. Therefore, the path with the minimum energy cost when (22) defines the link cost is the path with the minimum number of BP nodes. In other words, LBNR–LM without TPC selects a path with the minimum number of hops amongst those paths which have the minimum number of BP nodes. □

Theorem 1 implies that if TPC is not supported, we can simplify selection of energy-efficient routes in LBNR–LM. Since the energy-efficient path between two nodes is the path with the minimum number of BP nodes, we can consider a two-level weight for links and find the shortest path. That is, the link weight could be 0 if the link is originating from an MP node, and could be 1 if the link is originating from a BP node.

4.2. LBNR–WSA

LBNR–WSA uses the weighted sum approach to find optimal routes. It defines the WSA energy cost of a link as follows:

$$\phi_{wlbnr}(n_k, n_{k+1}) = \frac{a}{b} \phi_{lbnr}(n_k, n_{k+1}) + 1 - a, \tag{23}$$

where $\phi_{lbnr}(n_k, n_{k+1})$ is the actual energy cost of a link as defined by (16). If we replace $\phi_{lbnr}(n_k, n_{k+1})$ in (23) from (16), the general expression for WSA energy cost in LBNR–WSA will be as follows:

$$\phi_{wlbnr}(n_k, n_{k+1}) = \frac{a}{b} (\varepsilon_{n_k,n_{k+1}} f(n_k) + \omega f(n_{k+1})) + 1 - a. \tag{24}$$

For LBNR–WSA, we define the normalizing coefficient b as the maximum energy consumed for transmission and reception of a packet over a wireless link. That is,

$$b = \varepsilon_{max} + \omega = (\beta_4 + \beta_3)L.$$

If TPC is supported, we can find an alternative expression for WSA energy cost of a link in LBNR–WSA by replacing $\varepsilon_{n_k,n_{k+1}}$ and ω in (24) from their definitions given in (7) and (8), respectively. This alternative expression is as follows:

$$\phi_{wlbnr}(n_k, n_{k+1}) = \frac{a}{(\beta_4 + \beta_3)} \left[\left(\beta_1 + \beta_2 d^{\eta}_{n_k,n_{k+1}} \right) f(n_k) + \beta_3 f(n_{k+1}) \right] + 1 - a. \tag{25}$$

As (25) suggests, LBNR–WSA with TPC defines a tunable energy cost for links, where the energy cost of using a link is proportional to the energy consumed for transmission and reception of a packet over that link. By tuning the coefficient a, the link weights in (25) will change. This, in turn, can change the performance of the LBNR–WSA algorithm as we will show in Section 7.

Theorem 2. *If TPC is not supported, WSA energy cost of a link in LBNR–WSA reduces to* $\phi_{wlbnr}(n_k, n_{k+1}) = af(n_k) + 1 - a$.

Proof. When nodes do not support TPC, the consumed energy for transmission of a packet over a wireless link will be same for all nodes. Therefore, (24) changes to

$$\phi_{wlbnr}(n_k, n_{k+1}) = \frac{a}{\varepsilon_{max} + \omega} (\varepsilon_{max} f(n_k) + \omega f(n_{k+1})) + 1 - a. \tag{26}$$

If we use the same linear operations that we used to arrive at (22), we can simplify (26) as

$$\phi_{wlbnr}(n_k, n_{k+1}) = af(n_k) + 1 - a \tag{27}$$

without changing the ranking of routes with regard to their energy cost. □

Theorem 2 implies that, similar to LBNR–LM, if TPC is not supported, we can simplify selection of energy-efficient routes in LBNR–WSA by considering a two-level weight for links and finding the shortest paths among nodes. If a link is originating from an MP node, its weight is $a \times 0 + 1 - a = 1 - a$. If a link is originating from a BP node, its weight is $a \times 1 + 1 - a = 1$.

5. Minimum battery cost with Least battery-powered Nodes Routing (MLNR) algorithms

MLNR defines a suit of energy-aware routing algorithms which consider the type of power supply of nodes, the energy consumption of nodes for packet transmission and reception over wireless links, and the remaining battery energy of nodes to compute the energy cost of routes. In the sequel, we introduce MLNR–LM and MLNR–WSA.

5.1. MLNR–LM

MLNR–LM uses the lexicographic method to find optimal routes. Similar to LBNR–LM, MLNR–LM considers a higher priority for minimizing the energy cost of routes rather than minimizing their number of hops. In MLNR–LM, the energy cost of a link $\phi_{mlnr}(n_k,n_{k+1})$ is defined as the fraction of the remaining battery energy of the two end nodes of the link which is used for sending and receiving a packet. That is,

$$\phi_{mlnr}(n_k,n_{k+1}) = \frac{\varepsilon_{n_k,n_{k+1}} f(n_k)}{C_{n_k} - C_{th}} + \frac{\omega f(n_{k+1})}{C_{n_{k+1}} - C_{th}} \qquad (28)$$

in which $C_{n_k} - C_{th}$ is the residual battery energy of n_k before its battery runs out.

Suppose that nodes support TPC. We can find an alternative expression for $\phi_{mlnr}(n_k,n_{k+1})$ by replacing $\varepsilon_{n_k,n_{k+1}}$ and ω in (28) from (7) and (8), respectively, and normalizing the energy cost of links to the packet size L. This alternative expression is as follows:

$$\phi_{mlnr}(n_k,n_{k+1}) = \frac{\left(\beta_1 + \beta_2 d^{\eta}_{n_k,n_{k+1}}\right) f(n_k)}{C_{n_k} - C_{th}} + \frac{\beta_3 f(n_{k+1})}{C_{n_{k+1}} - C_{th}}. \qquad (29)$$

Theorem 3. *Let $C_{n_k} \to \infty$, if n_k is mains powered. If TPC is not supported, the energy cost of a link as defined by MLNR–LM is the same as the energy cost of a link as defined by MBCR [2] algorithm.*

Proof. If nodes do not adjust their transmission power according to distance to the receiver, we can compute $\phi_{mlnr}(n_k,n_{k+1})$ as follows:

$$\phi_{mlnr}(n_k,n_{k+1}) = \frac{\varepsilon_{max} f(n_k)}{C_{n_k} - C_{th}} + \frac{\omega f(n_{k+1})}{C_{n_{k+1}} - C_{th}}. \qquad (30)$$

Using similar linear operations that we used to derive (22), we can show that the link cost in MLNR–LM without TPC could be alternatively computed as

$$\phi_{mlnr}(n_k,n_{k+1}) = \frac{f(n_k)}{C_{n_k} - C_{th}} \qquad (31)$$

without changing the ranking of routes between a source and a destination with regard to the energy cost. On the other hand, MBCR defines the energy cost of a link as [2]

$$\phi_{mbcr}(n_k,n_{k+1}) = \frac{1}{C_{n_k} - C_{th}} \qquad (32)$$

and finds routes with the minimum energy cost. Since we assumed $C_{n_k} \to \infty$ when n_k is mains powered, we have $\phi_{mlnr}(n_k,n_{k+1}) = \phi_{mbcr}(n_k,n_{k+1})$. □

MBCR is a single objective routing algorithm, while MLNR–LM is a bi-objective routing algorithm which considers minimizing the hop count as the second criterion for route selection. Thus, according to Theorem 3, MLNR–LM without TPC may turn to the MBCR algorithm, if we assume the remaining battery energy of MP nodes is infinity. Theorem 3 also implies that without TPC, the weight of a link according to MLNR–LM is simply the inverse of the remaining battery energy at the sender-side of the link. If the sender is connected to mains, its remaining battery energy must be considered infinity. Similar to LBNR–LM, MLNR–LM directs the relay traffic to MP nodes. Nevertheless, MLNR–LM also considers the remaining battery energy of BP nodes to avoid relaying over battery-depleted BP nodes.

5.2. MLNR–WSA

MLNR–WSA defines the WSA energy cost of a link as follows:

$$\phi_{wmlnr}(n_k,n_{k+1}) = \frac{a}{b}\phi_{mlnr}(n_k,n_{k+1}) + 1 - a, \qquad (33)$$

where $\phi_{mlnr}(n_k,n_{k+1})$ is the actual energy cost of a link as defined by (28). If we replace $\phi_{mlnr}(n_k,n_{k+1})$ from (28) in (33), the general expression for the WSA energy cost of a link in MLNR–WSA is as follows:

$$\phi_{wmlnr}(n_k,n_{k+1}) = \frac{a}{b}\left[\frac{\varepsilon_{n_k,n_{k+1}} f(n_k)}{C_{n_k} - C_{th}} + \frac{\omega f(n_{k+1})}{C_{n_{k+1}} - C_{th}}\right] + 1 - a. \qquad (34)$$

For MLNR–WSA, we define b as the fraction of the maximum battery energy of a BP node which is consumed to transmit and receive a packet over a wireless link when nodes transmit with their maximum transmission power. That is,

$$b = \frac{\varepsilon_{max} + \omega}{C - C_{th}} = \frac{(\beta_3 + \beta_4)L}{C - C_{th}}.$$

Suppose that nodes utilize TPC. The WSA energy cost of a link in MLNR–WSA can alternatively be expressed as

$$\phi_{wmlnr}(n_k,n_{k+1}) = \frac{a(C - C_{th})}{\beta_3 + \beta_4}\left[\frac{\left(\beta_1 + \beta_2 d^{\eta}_{n_k,n_{k+1}}\right) f(n_k)}{C_{n_k} - C_{th}} + \frac{\beta_3 f(n_{k+1})}{C_{n_{k+1}} - C_{th}}\right] + 1 - a. \qquad (35)$$

Theorem 4. *Without TPC, the WSA energy cost of links as defined by MLNR–WSA reduces to*

$$\phi_{wmlnr}(n_k,n_{k+1}) = a\frac{C - C_{th}}{C_{n_k} - C_{th}} f(n_k) + 1 - a.$$

Proof. The proof is straightforward if we use the similar method that was used to prove Theorem 1. □

As Theorem 4 implies, the link weight in MLNR–WSA without TPC is a function of the type of power supply of nodes as well as their residual battery energy (in case they are BP). When TPC is utilized, again the energy consumption for transmission and reception of a packet come to the picture. In both cases, we can tune the link cost by changing the value of a. As we will show in Section 7, this can change the performance of MLNR–WSA algorithm.

In summary, we observed that various algorithms introduced in the current section and in the previous section use different ways to compute the energy cost of routes for end-to-end transmission of packets. This helps in selecting a suitable routing algorithm depending on requirements as well as the composition of the nodes in the network. We will further discuss these issues in Section 7. In Table 2, we have consolidated the expressions introduced for the energy cost of LBNR–LM and MLNR–LM algorithms, and also for the WSA energy cost of LBNR–WSA and MLNR–WSA algorithms with and without TPC.

It is worthwhile to mention that while we designed LBNR and MLNR algorithms for networks with both MP and BP nodes, they can easily be deployed in networks

Table 2
Definition of energy cost in LBNR–LM and MLNR–LM and WSA energy cost in LBNR–WSA and MLNR–WSA.

	With power control	Without power control
LBNR–LM	$f(n_k)\left(\beta_1+\beta_2 d^{\eta}_{n_k,n_{k+1}}\right)+\beta_3 f(n_{k+1})$	$f(n_k)$
LBNR–WSA	$\frac{a}{\beta_3+\beta_4}\left[f(n_k)\left(\beta_1+\beta_2 d^{\eta}_{n_k,n_{k+1}}\right)+\beta_3 f(n_{k+1})\right]+1-a$	$af(n_k)+1-a$
MLNR–LM	$\frac{f(n_k)\left(\beta_1+\beta_2 d^{\eta}_{n_k,n_{k+1}}\right)}{C_{n_k}-C_{th}}+\frac{\beta_3 f(n_{k+1})}{C_{n_{k+1}}-C_{th}}$	$\frac{f(n_k)}{C_{n_k}-C_{th}}$
MLNR–WSA	$\frac{a(C-C_{th})}{\beta_3+\beta_4}\left[\frac{f(n_k)\left(\beta_1+\beta_2 d^{\eta}_{n_k,n_{k+1}}\right)}{C_{n_k}-C_{th}}+\beta_3\frac{f(n_{k+1})}{C_{n_{k+1}}-C_{th}}\right]+1-a$	$af(n_k)\frac{C-C_{th}}{C_{n_k}-C_{th}}+1-a$

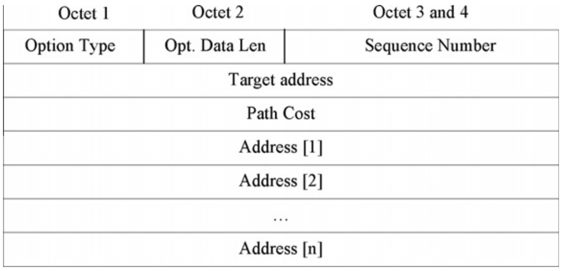
with only BP nodes. Suppose $\mathbb{V}_m=\emptyset$ (i.e., $\mathbb{V}_b=\mathbb{V}$). In such a case, $f(n_k)=1\ \forall n_k\in\mathbb{V}$. We can use MLNR and LBNR algorithms in such networks without any change. Nevertheless, since in networks with all BP nodes we may not face with the problem of increased hop count (see Section 3), we may not need to consider minimizing the hop count as the second criterion in route selection. We can only consider minimizing the energy cost of routes as the route selection criterion. In such a case, the actual energy cost of links as defined for LBNR–LM and MLNR–LM could be used to select optimal routes.

6. Practical considerations for implementing proposed algorithms

We can modify the existing ad hoc routing protocols to find optimal routes according to LBNR and MLNR algorithms. The routing protocol in a wireless ad hoc network discovers and maintains valid routes between nodes to keep them connected to each other. Routing protocols in ad hoc networks may use a reactive or a proactive route discovery mechanism. In the sequel, we explain a modified version of the reactive route discovery mechanism utilized by DSR (dynamic source routing) [28], in order to give an insight into implementation of LBNR and MLNR algorithms in practice.

To discover a route reactively, the source node broadcasts a single local route request (RREQ) message, which is received by (approximately) all nodes currently within the transmission range of the source node. The RREQ contains the source node and the destination node identifiers and a unique sequence number determined by the source node. Each replica of the RREQ collects the energy cost (in LBNR–LM and MLNR–LM) or the WSA energy cost (in LBNR–WSA and MLNR–WSA) of the links that it traverses. Address of each intermediate node that forwards a particular copy of the RREQ is also recorded by that replica of the RREQ. The format of a RREQ is shown in Fig. 2, which is the modified version of the Route Request Option in DSR [28]. The only difference between the RREQ in Fig. 2 and the original Route Request Option in DSR is the Path Cost field, which records the accumulated energy cost of the traversed routes.

When a node other than the destination receives the RREQ for the first time, it checks whether it has a valid route to the destination. If the node knows a valid route, it sends the valid route to the source node using a unicast route reply (RREP) message. Otherwise, the node records the route that the RREQ has traversed so far as well as the accumulated energy cost (or WSA energy cost) of the traversed route. If the accumulated energy cost (or WSA energy cost) of the received RREQ is smaller than the last recorded value from other replicas of the RREQ, then the node forwards the RREQ. Otherwise, it drops the RREQ. In case of LBNR–LM and MLNR–LM, if the energy cost of two routes is the same, the node compares their hop counts to determine which route is better. The filtering procedure at each node helps in reducing the routing overhead.

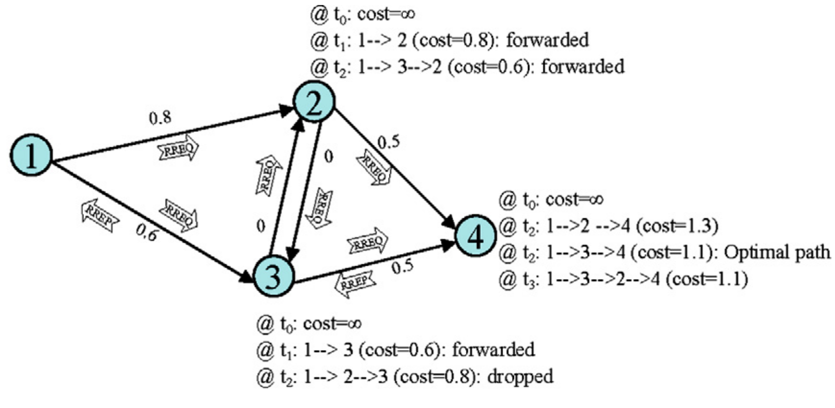


Octet 1	Octet 2	Octet 3 and 4
Option Type	Opt. Data Len	Sequence Number
Target address		
Path Cost		
Address [1]		
Address [2]		
…		
Address [n]		

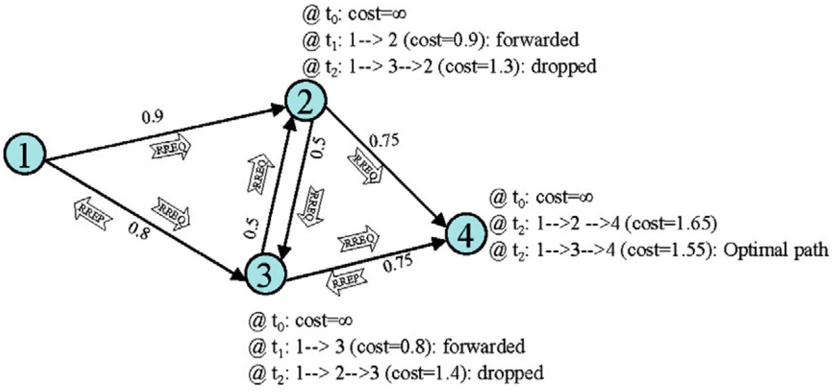
Fig. 2. The format of a RREQ message. According to [28], Option Type must be Route Request. Opt. Data Len specifies the length of the option in octets excluding the length of Option Type and Opt. Data Len fields. Target Address specifies the address of the destination node. Path Cost is the accumulated cost of the path. Address[i] is the address of the *i*th intermediate node recorded in the RREQ message.

The destination node follows the same procedure as other nodes, but it does not forward the RREQ. Instead, it waits to receive all replicas of the same RREQ. Then, it chooses the optimal route according to the algorithm in force, and sends a unicat RREP message to the source node. The waiting times at the destination node will depend on the network size and traffic conditions, and usually is a design choice. A simple example of the reactive route discovery mechanism which could be used by LBNR and MLNR algorithms is depicted in Fig. 3.

Measuring the energy cost of a link as defined by LBNR and MLNR algorithms is another issue in implementation of these algorithms. According to Theorems 2 and 4, in LBNR–LM without TPC, each nodes must know only the type of its power supply to be able to calculate its energy cost for packet forwarding, while in MLNR–LM without TPC, each BP node must also know its remaining battery energy. Discovering whether a node is connected to the mains or runs on a battery and specifying its remaining battery energy are implementation issues. In LBNR–WSA



(a) Lexigographic-based algorithms



(b) Weighted sum approach algorithms

Fig. 3. Reactive route discovery using RREQ and RREP messages in LM-based routing algorithms and WSA-based routing algorithms. In Figure (a), values on each link show the actual energy cost of the links. In Figure (b), they are the WSA energy cost of the links which are related to the actual energy cost of the links according to (14) assuming $a = 0.5$. Here, t_0, t_1, t_2, and t_3 are time samples.

and MLNR–WSA, the weighing coefficient a must be known as well, which is a design parameter fixed for all nodes.

When TPC is supported, nodes may need to know distance to their neighboring nodes to determine the energy cost of packet transmission over wireless links. To this aim, a lightweight localization technique proposed for wireless networks could be used (e.g., [29–32]). Knowing the distance to the receiver and the value of parameters β_1, β_2, and β_3 as well as the value of the path-loss exponent of the environment (i.e., η), the energy cost (or WSA energy cost) of each link could be computed using expressions summarized in Table 2 for various algorithms.

Another way of computing the energy cost of a link when TPC is utilized is the proposed algorithm in [33]. In this algorithm, a node sends a number of training packets to its neighboring nodes in order to measure the minimum required transmission power such that its neighbors can detect the signals successfully. The neighboring nodes send back the measured value to the transmitting node. In other words, in this method, the value of $P_{i,j}$, as introduced in Section 2, is measured by node j and sent back to node i. The energy cost in each algorithm is then computed using the general expression given for them in Sections 4 and 5. In this method, the distance between nodes and the path-loss component of the environment are not needed to be known. Furthermore, this method can cope with different channel conditions, because the transmission power is measured continuously [33].

Another important issue which in practice may affect performance of energy-aware routing protocols is congestion. Congestion can increases energy consumption of nodes in ad hoc networks due to the increased energy consumption for sensing the achannel. Therefore, nodes in energy-efficient routes may consume more energy than what is predicted. This, in turn, may deplete energy of BP nodes quickly. However, congestion may happen only in heavily loaded networks (e.g., those used for steaming applications). In some application of wireless ad hoc networking (e.g., sensing and monitoring) there might be no congestion at all. Furthermore, distinguishing between MP and BP nodes (as being done by our proposed algorithms) can be beneficial with regard to the impact of congestion. Since

MLNR and LBNR algorithms try to avoid relaying over BP nodes, increased energy consumption of nodes due to congestion may not affect lifetime of nodes along a path.

7. Performance evaluation of the proposed algorithms

To evaluate the performance of our proposed routing algorithms, we assume that nodes are distributed uniformly in the network. We generate sessions between randomly chosen source–destination nodes with exponentially distributed random inter-arrival time with mean value μ_1. Each node may establish several sessions to different destinations, or be the destination for several sessions at the same time. The duration of a session is also an exponentially distributed random variable with mean value μ_2. Upon generation of a session, the source node discovers a route to the destination node using the mechanism described in the previous section. To reduce the variability when we compare various algorithms, we assume source nodes generate data packets with a constant rate λ packets/s, and nodes have the same initial battery energy. Each point in our simulation results is obtained by taking the average over values obtained in 300 simulation runs. In each simulation run, a network is generated randomly and sessions are generated randomly too.

The MAC layer in our simulations is IEEE 802.11b MAC operating at 2 Mbps data rate. RTS/CTS messages are used to avoid collision, and packet retransmission is supported to recover lost packets due to link error probability. The maximum number of transmissions of a packet (including the first transmission) allowed on each link is seven. For each transmitted packet (data or control packets) by a BP node, $\varepsilon_{i,j}$ is subtracted from the remaining battery energy of the node. Similarly, for each received packet by a BP node, ω is subtracted from the remaining battery energy of the receiver. Note that $\varepsilon_{i,j}$ and ω depend on size of the packet (see (7) and (8)). Even if a node overhears a packet, ω is subtracted from its remaining battery energy. Furthermore, nodes consume a small amount of energy when they are idle (i.e., they do not transmit or receive any data or control packet) and when they sense the medium. For the sake of simulations, the consumed energy at idle mode and for channel sensing are assumed to be a fraction of the energy that a node consumes during reception of a packet. More specifically, we assume the energy consumption in idle mode in $k_{idle}\beta_3 T_{idle}$, where β_3 is as defined in (8) and T_{idle} is the duration that a node is idle. We also assume the energy consumption during channel sensing is $k_{sense}\beta_3 T_{sense}$, where T_{sense} is the duration of sensing the channel.

We evaluate the performance of the routing algorithms in different scenarios: static ad hoc networks, mobile ad hoc networks, and networks with and without TPC. The value of a parameter in our simulations unless explicitly stated in each experiment is as specified in Table 3. Network lifetime and mean hop count are used as the performance measures to compare the performance of various algorithms. *The network lifetime in all scenarios (i.e., static and mobile networks and in networks with and without TPC) is defined as the time at which the first BP node fails due to battery depletion.* Other definitions for network lifetime used in the literature include, the time until the network is partitioned [34] and fraction of surviving nodes in the network [35]. There are some reasons to believe that our definition is meaningful for networks with heterogeneous power supplies. First, the presence of MP nodes in the network may prevent the network to be partitioned due to node failure. Second, if our proposed algorithms can delay the first node failure, failure of other nodes will be delayed as well. Nonetheless, other definitions of network lifetime could be used in our study without loss of generality.

Table 3
Default value of simulation parameters.

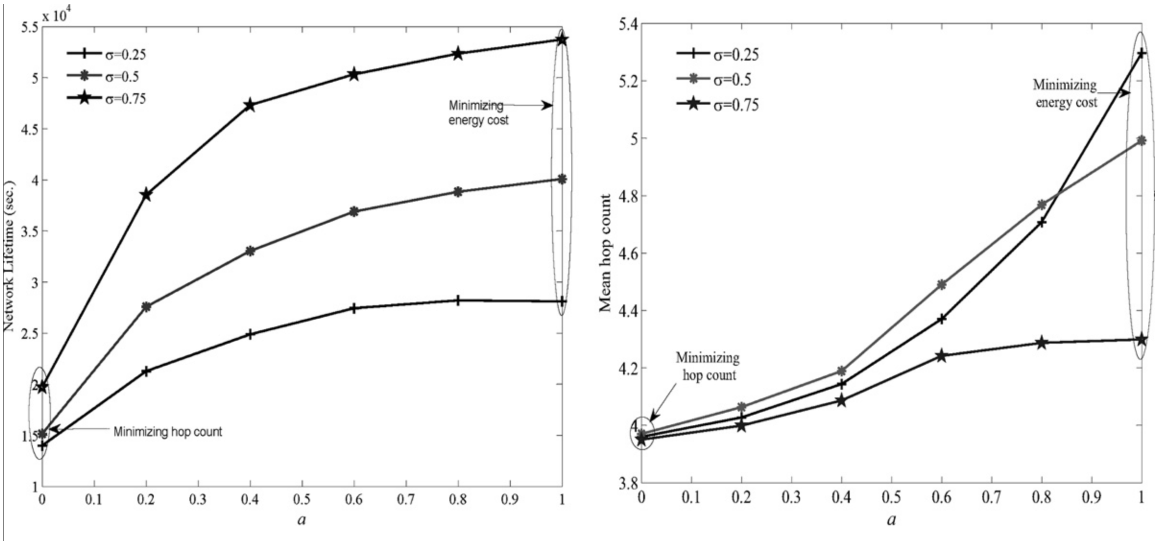
Parameter	Value
Maximum battery capacity (C)	500 J
Mean session inter-arrival time (μ_1)	10 s.
Mean session duration (μ_2)	50 s.
Packet rate (λ)	1 packet/s.
Path loss exponent (η)	3
Data rate of physical links (R)	2 Mbps
Energy consumption parameter β_2	100×10^{-12}
Energy consumption parameters β_1 and β_3	50×10^{-9}
Energy consumption parameters β_4	21.65×10^{-6}
Length of data packets (L)	256 Byte
Length of RREQ packets	54 + 4 × hopcount Byte
Length of RREP packets	50 + 4 × hopcount Byte
Transmission range (d_{max})	60 meter
Battery death threshold (C_{th})	1 J
Network area	$5d_{max} \times 5d_{max}$
Weighing coefficient of WSA algs. (a)	0.5
Number of nodes (N)	100
Fraction of MP nodes (σ)	0.5
Maximum speed of a mobile node ($\mathcal{V}$)	5 s.
Maximum pause time of a mobile node ($\mathcal{T}$)	50 s.
k_{idle}	0.2
k_{sense}	0.4
T_{sense}	50 µs (based on IEEE 802.11 standard)

7.1. Performance of proposed algorithms in static networks without TPC

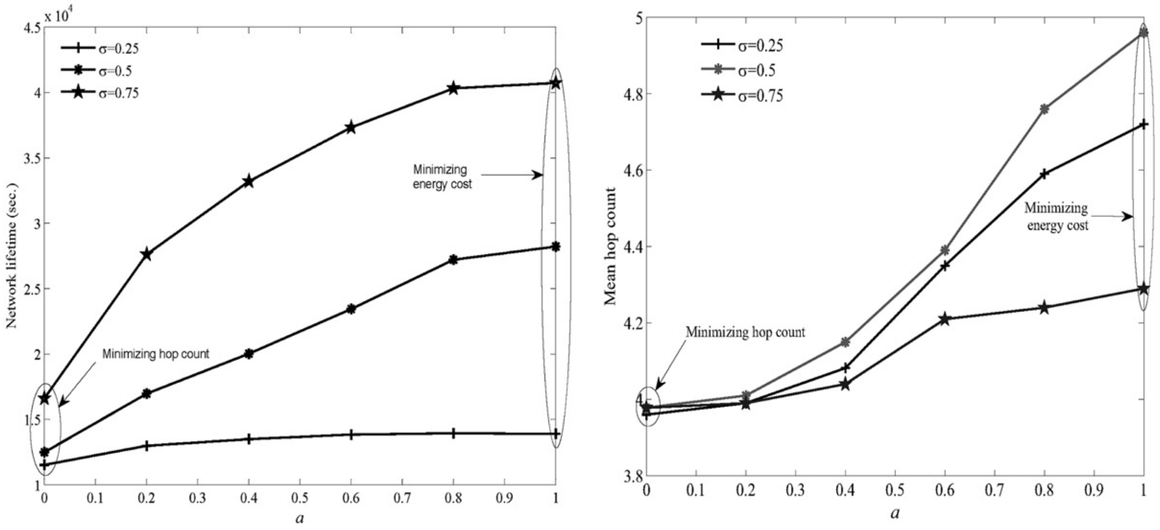
Here, we consider a network in which all nodes are static and do not employ TPC. We first investigate impact of coefficient a on the performance of WSA-based algorithms (i.e., LBNR–WSA and MLNR–WSA), and then we compare the performance of various algorithms (i.e., LBNR–WSA, MLNR–WSA, LBNR–LM, and MLNR–LM) with each other.

7.1.1. Performance of WSA-based algorithms

If the value of coefficient a increases from 0 to 1, the network lifetime increases for both MLNR–WSA and LBNR–WSA algorithms. This is with the cost of increased mean hop count (see Fig. 4). Nevertheless, if majority of nodes in the network are mains powered, the rate of increase of the network lifetime is much more than that of



(a) MLNR-WSA (b) MLNR-WSA



(c) LBNR-WSA (d) LBNR-WSA

Fig. 4. Impact of the coefficient a on the network lifetime and mean hop count for MLNR–WSA and LBNR–WSA algorithms in static networks without transmission power control. Here, σ denoted the fraction of MP nodes in the network.

the mean hop count (relatively). For example, when 75% of nodes are mains powered (i.e., $\sigma = 0.75$), the network lifetime increases for MLNR–WSA from 20,000 [s] at $a = 0$ to 54,000 [s] at $a = 1$ (i.e., 166% increase), while the mean hop count increases from 3.95 to 4.3 (i.e., only 8% increase). However, if majority of nodes are battery powered, the mean hop count increases more than one hop (see the plots depicting the mean hop count for $\sigma = 0.25$ in Fig. 4(b)). In the sequel, we explain why the network lifetime for WSA algorithms with $a = 1$ is higher than the network lifetime for these algorithms when $a = 1$.

As mentioned in Section 3, when $a = 0$, WSA-based algorithms act similar to the SHR algorithm, which finds the path with the minimum number of hops. In SHR, BP nodes are overused, because their remaining battery energy is not considered in route selection. Therefore, some nodes (e.g., those in the center of the network) might be selected frequently as intermediate nodes between different pairs of source–destination nodes. On the other hand, when $a = 1$, WSA-based algorithms act similar to their corresponding LM-based algorithm. That is, MLNR–WSA acts like MLNR–LM, and LBNR–WSA acts like LBNR–LM. MLNR–LM and LBNR–LM avoid using BP nodes as relaying nodes. Even if the use of BP nodes is inevitable, MLNR–LM and LBNR–LM minimize the energy cost of BP nodes for end-to-end packet transfer. These are the reasons for increased network lifetime when these algorithms are deployed instead of SHR.

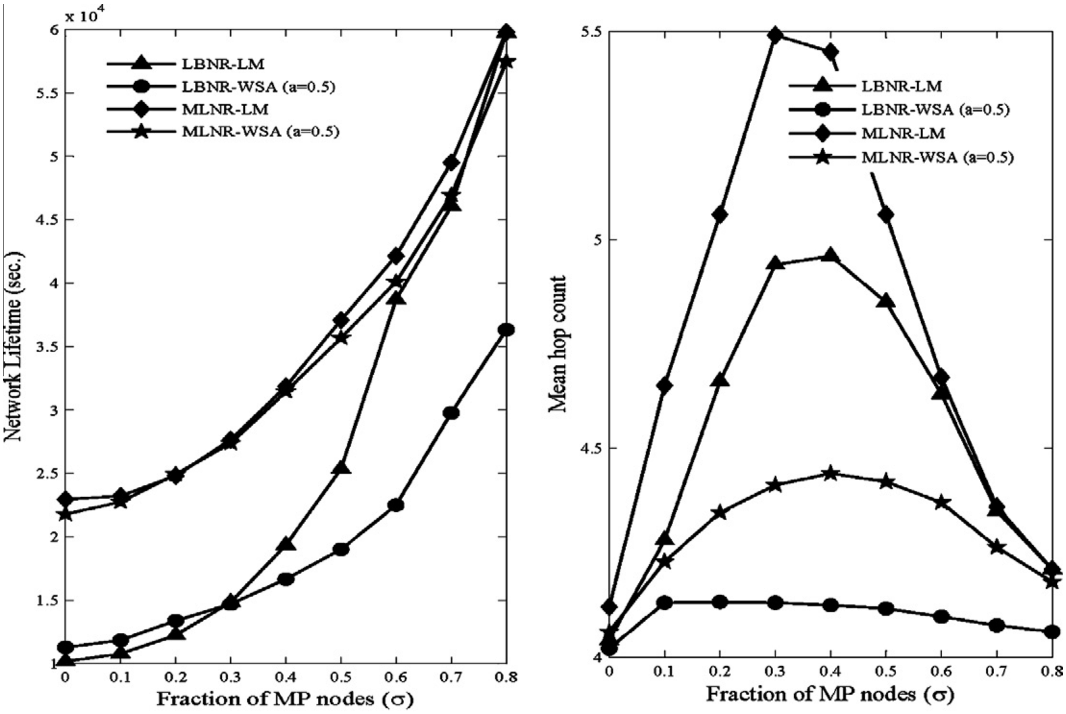
An interesting point in Fig. 4(c) is that the network lifetime does not change considerably when the value of a in the LBNR–WSA algorithm changes and 25% of nodes are mains powered. This implies that when there is a small set of MP nodes in the network, LBNR–LM may not increase the network lifetime compared to SHR. Remember that LBNR–LM directs the traffic to MP nodes. However, if there is a small set of MP nodes in the network, then directing the traffic load to them may cause overuse of those BP nodes which are around MP nodes. This phenomenon does not happen in MLNR–WSA, as Fig. 4(a) shows an increasing trend for the network lifetime when $\sigma = 0.25$. MLNR–WSA uses information about the battery energy of BP nodes in route selection. This prevents BP nodes around the small set of MP nodes to be overused, which in turn can increase the network lifetime. In summary, *even if we try to avoid using BP nodes as relaying nodes in LBNR algorithms, such nodes might still be overused when there are few MP nodes in the network. The problem can be resolved by considering the remaining battery energy of BP nodes in route selection similar to MLNR algorithms.*

7.1.2. Impact of density of MP nodes

In this experiment, we change the number of MP nodes keeping the total number of nodes in the network constant. When there are many MP nodes in the network, the network lifetime increases for all algorithms (see Fig. 5), because the probability of energy-depleted BP nodes acting as relaying nodes decreases. Nevertheless, the mean hop count when there are many MP nodes in the network is the same as the mean hop count when there are few MP nodes. The reason lies on the fact that, when most nodes are MP or BP, most links will have the same weight in all the algorithms. Therefore, in either case, LBNR–LM and MLNR–LM will and LBNR–WSA and MLNR–WSA may choose routes minimizing the hop count.

As Fig. 5(a) shows, MLNR–WSA achieves either a higher or the same network lifetime compared to the other algorithms regardless of the number of MP nodes in the network. Its mean hop-count is greater than that of LBNR–WSA, but lower than that of MLNR–LM and LBNR–LM. This means, MLNR–WSA could be considered as a good solution for scenarios in which the combination of MP and BP nodes in the network is not known a priori (e.g., a meeting room scenario). It not only achieves the highest network lifetime, but also it has an acceptable hop-count compared to the other algorithms.

For scenarios in which most nodes are mains powered (e.g., in a home-network), and hop-count is not of primary concern, LBNR–LM is suitable to be deployed. In such scenarios, LBNR–LM achieves the highest network lifetime similar to MLNR–WSA (in our simulation set-up for $\sigma > 0.6$ as shown in Fig. 5(a)). However, LBNR–LM uses only information about the type of power supply of nodes. This can generate a lower overhead, since the type of power supply of a node should be re-propagated only if it has changed (e.g., when the node is being disconnected from the mains). On the other hand, MLNR–WSA considers the remaining battery energy of nodes for route selection. Therefore, nodes have to propagate regularly their remaining battery energy. This indeed generates higher routing overhead compared to LBNR–LM, which is a very simple scheme.



(a) (b)

Fig. 5. Impact of the fraction of MP nodes in the network on the network lifetime (Plot (a)) and on the mean hop count of the selected routes (Plot (b)) for various routing algorithms in static networks without transmission power control.

When most nodes in the network are battery powered, MLNR–WSA can be considered as a good choice. In such cases, MLNR–WSA achieves the same network lifetime as MLNR–LM (in our simulation set-up for $\sigma < 0.3$ as shown in Fig. 5(a)), while its mean hop-count is lower than that of MLNR–LM. Finally, if the hop-count (latency) is the absolute concern (e.g., in streaming applications), we can choose LBNR–WSA as a good choice, because the lowest mean hop count belongs to LBNR–WSA.

7.1.3. Impact of packet rate of source nodes

So far, we assumed source nodes transmit 1 packet per second. In this section, we investigate the impact of packet rate of source nodes on the network lifetime for various algorithms. We fix the number of nodes to 100, where half of them are MP (i.e., $\sigma = 0.5$). There are several factors affecting energy consumption rate of nodes in different directions when packet rate increases. First, when packet rate of source nodes increases, energy consumption rate of source, destination, and intermediate nodes in between increases as well. Second, since there will be more packets in the network, nodes need to consume more energy for sensing the busy medium when they back-off. Third, since nodes forward more packets, they will be at idle mode for a shorter duration. Hence, they consume less energy at the idle mode. As we may expect, the first and second factors are dominant factors in determining the network lifetime when packet rate increases. Fig. 6 clearly shows this fact. The figure shows that the network lifetime decreases for all algorithms if the packet rate of source nodes increases. However, we observe that their performances get closer to each other as the packet rate increases. This means, if the packet rate of source nodes is relatively high, various algorithms may not achieve a big performance gain with respect to each other. Nonetheless, MLNR algorithms, which consider the remaining battery energy of nodes, can still outperform LBNR algorithms, which only consider the type of power supply of nodes.

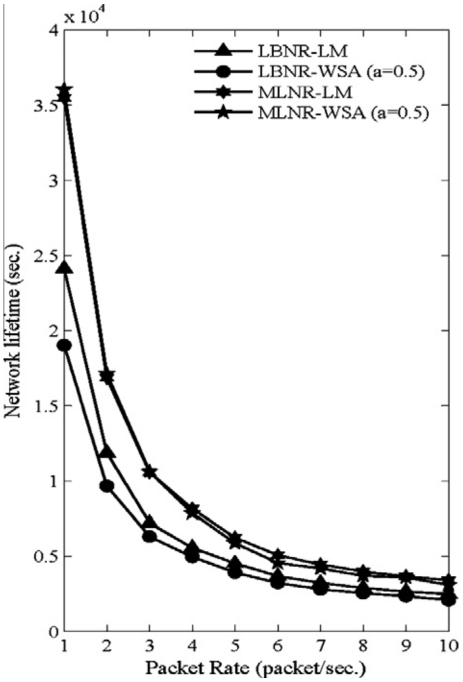


Fig. 6. Impact of packet rate of source nodes on the network lifetime for various algorithms. Nodes are static and do not deploy transmission power control.

Due to increased congestion as a sign of increased packet rate, packet drop at intermediate nodes increases because of buffer overflow. Hence, intermediate nodes between source and destination may forward less packets. Therefore, we may expect that their energy consumption rate decreases. However, we should notice that the size of receiving buffer at each node is a key factor with this regard. With the increasing memory storage of electronic devices, we can assign enough memory to a buffer to prevent buffer overflow. Considering this fact and as a practical assumption, we set the buffer size of each node to 10 MByte for which we observed a low packet drop due to congestion.

7.2. Performance of proposed algorithms in static networks with transmission power control

In this part, we consider static networks with TPC, and analyze the performance of various algorithms in such networks.

7.2.1. Performance of WSA-based algorithms

When TPC is supported, increasing the value of parameter a from 0 to 1 in MLNR–WSA and LBNR–WSA algorithms (we skipped the results of LBNR–WSA to save the space) has a similar influence as we explained earlier. That is, both the network lifetime and the mean hop count increase if a increases (see Fig. 7). However, the increase rate of the network lifetime when majority of nodes are mains powered is much greater compared to the case that TPC is not supported. On the other hand, when most nodes are battery powered, the increase rate of the mean hop count is also greater compared to the case that TPC is not supported. For example, see results for $\sigma = 0.75$ and $\sigma = 0.25$ in Fig. 7. The network lifetime increases from 3400 [s] at $a = 0$, to 18,600 [s] at $a = 1$ (i.e., 440% increase), while the mean hop count changes from 4 to 4.5. Nevertheless, for $\sigma = 0.25$, the mean hop count increases from 4 at $a = 0$, to 8 at $a = 1$ (i.e., 100% increase). Here, we explain the reason for these phenomena.

As mentioned in Section 2, in wireless channels, the signal power decays exponentially with distance. Hence, adjusting the transmission power according to the distance to the receiver can save a large amount of energy for BP nodes, especially when they are a minority and we try to avoid using them as relaying nodes. However, if the adjusted power is considered in route selection, shorter links are preferred to longer links, because they require less transmission power [15,16]. As a result, the hop count of the selected routes will increase. Nevertheless, since MLNR–WSA and LBNR–WSA do not consider any cost for signal transmission by MP nodes, the hop count with TPC increases only when most constituent nodes of a route are battery powered. This, in turn, happens when most nodes in the network are battery powered, because we

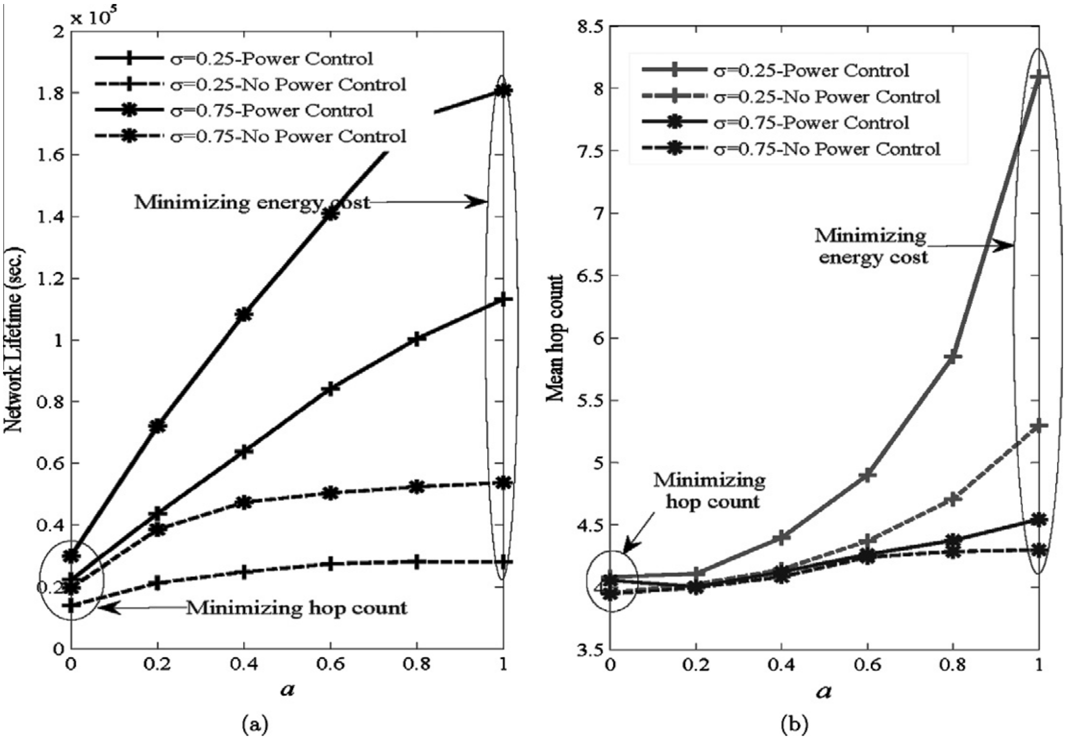


Fig. 7. Impact of the transmission power control on the performance of MLNR–WSA algorithm in static networks. Plot (a) shows the network lifetime. Plot (b) shows the mean hop count of the selected routes.

assumed BP and MP nodes are distributed uniformly. In summary, if majority of nodes in the network are mains powered, TPC can increase the lifetime of BP nodes tremendously if we choose a value close to one for the weighing coefficient *a* in WSA-based algorithms.

7.2.2. Impact of density of MP nodes

Similar to the networks without TPC, in networks with TPC, the network lifetime increases as the density of MP nodes increases (see Fig. 8(a)). We observed that in static networks without TPC, the MLNR–WSA could achieve a network lifetime similar to MLNR–LM (the best-performing algorithm in this case), regardless of the number of MP nodes in the network. In networks with TPC, MLNR–LM still achieves the highest network lifetime. However, there is a big difference between the network lifetime for MLNR–LM and MLNR–WSA when most nodes are mains powered (here for $\sigma > 0.6$ as shown in Fig. 8(a)).

When most nodes are mains powered and TPC is supported, we can choose LBNR–LM as a good choice. It achieves the highest network lifetime compared to the other algorithm, while its hop count is also close to the hop count of the other algorithms (see Fig. 8(b)). As mentioned earlier, LBNR–LM generates less routing overhead compare to MLNR–LM. The interesting point in LBNR–LM is the increasing trend of the network lifetime and the decreasing trend of the mean hop count as the number of MP nodes in the network increases. This is in fact our primary design goal: increasing the network lifetime and decreasing the mean hop count. We observe that LBNR–LM with TPC can appreciably achieve this design goal.

If most nodes in the network are battery powered, we can choose MLNR–WSA as a good solution. It achieves the highest network lifetime similar to MLNR–LM, but its hop count is much lower than that of MLNR–LM. Finally, if the minimum hop count is our primary concern, we can choose LBNR–WSA, because it achieves the lowest hop count.

7.3. Performance of proposed algorithms in mobile networks

In this section, we consider networks with mobile nodes and without TPC. Only BP nodes in the network can be mobile, and MP nodes are assumed to be static. In mobile networks, we assume nodes do not deploy TPC, because adjusting the transmission power according to distance may not be feasible in practice. It might be difficult to have an accurate estimation of distance when nodes are mobile. The mobility model that we consider is Random Waypoint [36], in which speed and pause time of nodes have uniform distribution over $(0, \mathcal{V})$ and $(0, \mathcal{T})$, respectively. Similar to static networks, in mobile networks, changing the value of the weighing coefficient *a* in MLNR–WSA and LBNR–WSA can increase the network lifetime and the mean hop cont (we skipped the plots to save the space).

In mobile networks, various algorithms achieve a comparable network lifetime when density of MP nodes varies (see Fig. 9). That is, MLNR–LM which considers the battery

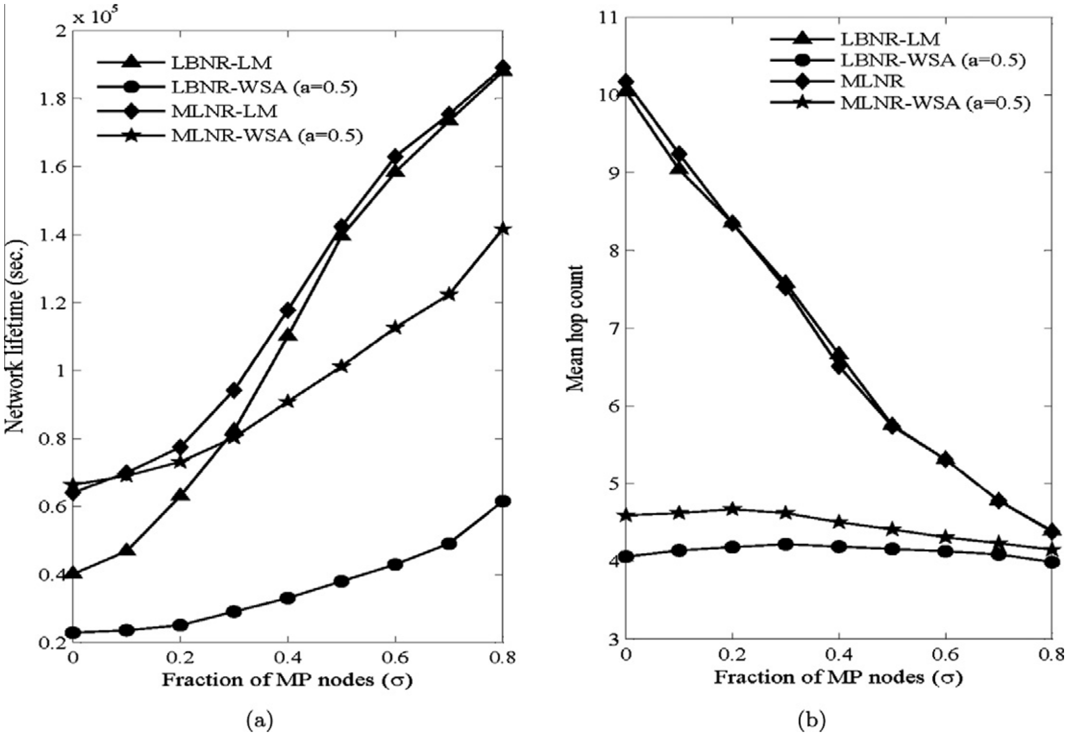


Fig. 8. Impact of the fraction of MP nodes in the network on the performance of various algorithms in static networks with transmission power control. Plot (a) shows the network lifetime. Plot (b) shows the mean hop count of the selected routes.

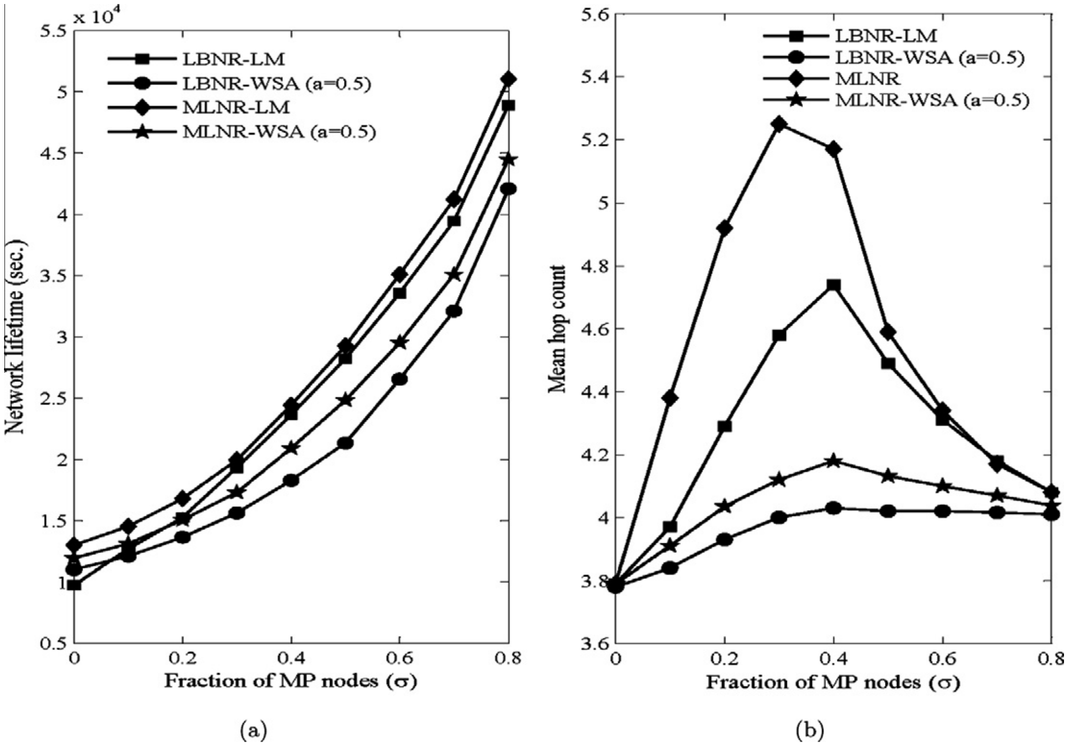


Fig. 9. The impact of fraction of MP nodes on the performance of various algorithms in mobile networks without transmission power control. Plot (a) shows the network lifetime. Plot (b) shows the mean hop count of the selected routes.

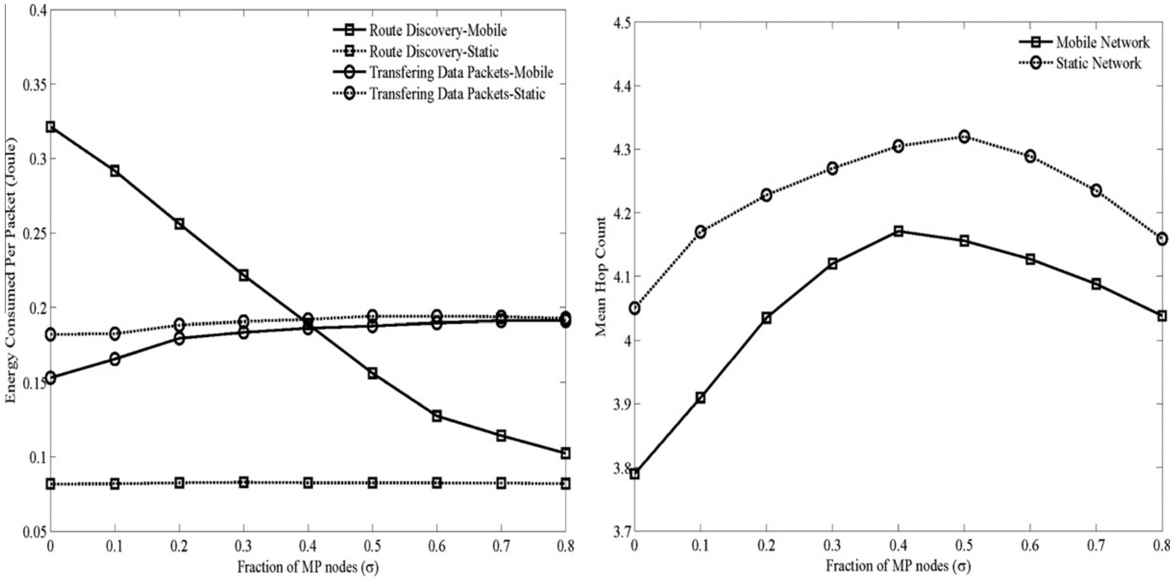
level of BP nodes and LBNR–LM which only considers the type of power supply of nodes achieve almost the same network lifetime. The reason for this phenomenon lies in the fact that mobility of nodes can decrease the network lifetime. More energy is consumed for route discovery in mobile networks due to frequent route failures. High energy consumption for route discovery can drain the batteries of BP nodes almost at the same rate. Therefore, MLNR–LM, which achieves the highest network lifetime in static network, may not benefit from considering the remaining battery energy of nodes in route selection in mobile networks. Here, we provide an insight into this issue.

We have compared in Fig. 10(a) the average amount of energy consumed by all nodes in mobile and static networks per transmitted data packet by source nodes. The results have been shown only for MLNR–WSA algorithm. However, we had the same observation for other algorithms. Fig. 10(a) shows that the consumed energy for route discovery per transmitted packet by source nodes is higher in mobile networks specially when all nodes are battery powered ($\sigma = 0$). Note that as the number of MP nodes increases in the network, the number of mobile nodes decreases, because MP nodes are assumed to be static. This explains why energy consumed for route discovery in the mobile network gets closer to that of the static network when the number of MP nodes in the network increases.

As we observe in Fig. 10(a), the amount of energy consumed by nodes to transfer a packet from its source to its destination is almost the same in the static and the mobile network. The small difference that we observe between mobile and static networks is because of smaller mean hop count in the mobile network as shown in Fig. 10(b). Since source nodes and destination nodes might also be mobile, they may move towards each other. This can reduce the number of hops between the source and the destination nodes. Hence, less energy will be consumed for end-to-end transmission of a packet.

As shown in Fig. 9, in mobile networks MLNR–WSA can provide a network lifetime very close to that of MLNR–LM (the best-performing algorithm w.r.t the network lifetime). The mean hop count for MLNR–WSA is also close to that of LBNR–WSA (the best-performing algorithm with regard to the hop count), regardless of the number of MP nodes in the network. Therefore, we can choose MLNR–WSA as an algorithm which provides an acceptable balance between network lifetime and mean hop count in mobile networks.

From a different perspective, we should notice that reactive (as well as proactive) route discovery may not be effective in mobile networks, where communication between nodes is frequently disrupted when there is no multi-hop path between nodes. We observed that the reactive route discovery profoundly increases the energy consumption of nodes in mobile networks. To mitigate the problem, delay-tolerant routing (DTR) [37–39] has been considered as an alternative solution for mobile networks. Nodes can store messages to forward them only when they have a neighbor which can carry the message to the ultimate recipient. Hence, frequent route discoveries could be avoided in the network. We should notice that the primary goal in DTR is to deliver the message from a source node to its destination. Energy-efficiency is of secondary importance even though we can still investigate energy-efficiency of DTR protocols for mobile networks. Recently, there has been some initiatives in design of energy-efficient DTR protocols (e.g., [40]), but further investigation is needed for networks with heterogonous power supplies,



(a) (b)

Fig. 10. Plot (a) shows the average amount of energy consumed by all nodes in the network per transmitted packet from a source node to a destination node in mobile and static networks without transmission power control. Plot (b) shows the mean hop count of the selected routes in mobile and static networks by MLNR–WSA algorithm.

where MP nodes are static and only BP nodes are mobile. Efficient usage of static MP nodes for message forwarding can increase efficiency of DTR protocols.

8. Conclusion

In this paper, we studied energy-aware routing in wireless ad hoc networks which comprise both battery and mains powered devices. We proposed several energy-aware routing algorithms for these networks. The proposed algorithms consider the type of power supply of nodes, the hop count of selected routes, and the energy cost for end-to-end transmission of packets. They find energy-efficient routes which dynamically direct the traffic to mains-powered nodes of the network in order to avoid relaying over battery-powered nodes. The hop count of selected routes is also kept low. We unified the proposed algorithms into a framework for energy-aware route selection. The route selection in this framework is a bi-criteria decision making problem. Minimizing the energy cost of routes for end-to-end traversal of packets and minimizing their hop counts are the two criteria. Various algorithms that we proposed under this framework differ in the way they define the energy cost of links for packet forwarding or in the way they solve the bi-criteria decision making problem. We explained how these algorithms could be implemented using Dynamic Source Routing protocol. Performances of the proposed routing algorithms were evaluated in static and mobile ad hoc networks and in networks with and without transmission power control. Simulation studies showed that directing the traffic load to mains-powered nodes of the network (as being done by our proposed algorithms) can profoundly increase the operational lifetime of battery-powered nodes of the network. We also discussed the scenarios and conditions in which each of these algorithms is more suitable to be deployed. The next step is to study energy-ware routing in multi-rate ad hoc networks.

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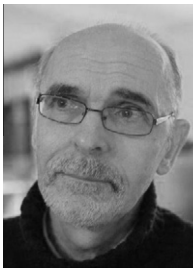

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