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Battery-Aware Routing in Personal Networks

Javad Vazifehdan · R. Venkatesha Prasad ·
Ignas Niemegeers

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Abstract A Personal Network (PN) is a network of devices belonging to a person. It may consist of a number of ad hoc sub-networks which are linked together through the Internet or any other means. We study battery-aware routing in PNs, and propose a new battery-aware routing algorithm for multi-hop communication in sub-networks of PNs. The proposed algorithm considers the remaining battery energy of nodes and takes the advantage of having mains-connected devices in a PN to avoid relaying over nodes with scarce battery energy and direct the traffic load to mains-powered nodes. A consequence of this strategy is directing the traffic load to static nodes of the network as well, since mains-connected nodes are static while battery-powered nodes could be mobile. This results in less route failures due to mobility of nodes. We comprehensively compare the performance of our proposed algorithm with the performance of some well-known algorithms from the literature. In our comparison, we consider the effect of node density, routing overhead, heterogeneity of nodes in terms of their power supplies, gateway-oriented communication, mobility of nodes, and transmission power control on the performance of battery-aware routing algorithms in personal networks. Taking into account various parameters and different scenarios, we show that directing the traffic to mains-powered nodes, as being done by our proposed algorithm, can profoundly increase operational lifetime of the network. Our algorithm, as well as the results of our work, can also be applied to other types of ad hoc networks with heterogeneous power supplies such as wireless mesh networks.

Keywords battery-aware routing · personal network · ad hoc network · wireless communication

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Delft University of Technology, Mekelweg 4, 2628 CD, Delft, The Netherlands
Tel.: +31-15-2786446
Fax: +31-15-2781774
E-mail: {j.vazifehdan,r.r.venkateshaPrasad,i.niemegeers}@tudelft.nl

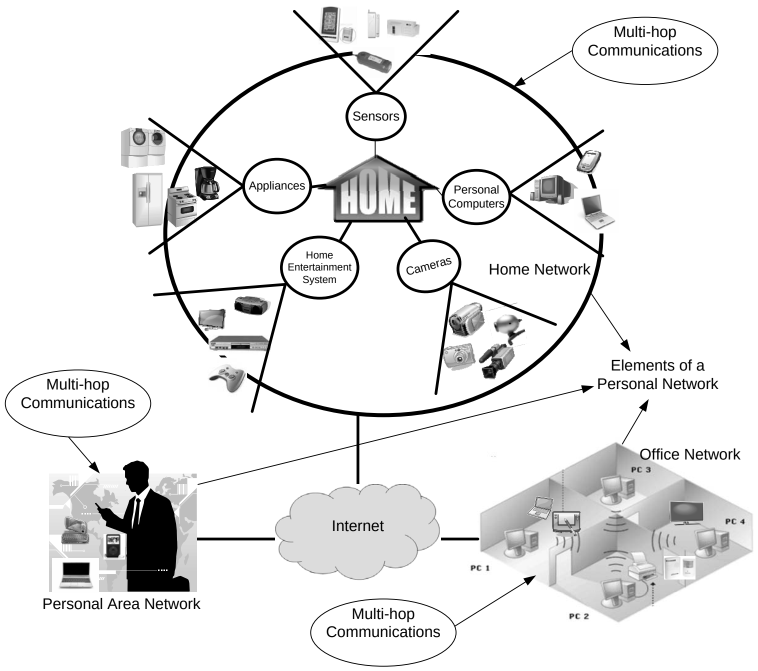

Fig. 1 A schematic view of a personal network.

1 Introduction

Personal Networks (PNs) [23] extend the concept of Personal Area Networks (PANs) to a global level. A PAN consists of devices around a user, while a PN works on a broader level. It links a PAN to other devices of the user located farther away (Fig. 1). A PN may include several sub-networks, referred to as clusters [14], which are inter-connected through the Internet. Home cluster, office cluster, and PAN are examples of clusters of a PN. Potentially, there is no limit on how large a PN cluster can grow in terms of the number of nodes. People in the near future are expected to use up to hundreds of personal devices; everything from mobile phones to sensors [1]. A home cluster may include many diverse devices such as appliances, personal computers, handheld devices, entertainment devices, sensors and actuators. Due to self-organizational capability of PNs, communication within PN clusters is usually ad hoc [23]. Nodes communicate using multi-hop routes. Similar to any ad hoc network, relay traffic within PN clusters can quickly drain the battery of battery-powered devices (e.g., handheld devices). This, in turn, may result in service failure, because a failed node might be the node which is providing the service for the user. Node failure may also result in cluster partitioning, which disconnects some nodes from the rest of a PN cluster. As a matter of fact, we need to deploy communication mechanisms which balance the traffic load in PN clusters such that nodes with limited battery energy are prevented from being overused and failed quickly. To this end, we can consider remaining battery energy of nodes in the process of route selection.

The idea of considering the remaining battery energy of nodes for routing in wireless and mobile ad hoc networks (i.e., battery-aware routing) has been proposed by Singh et. al [26] and Toh [27]. They have proposed several battery-aware routing schemes considering different ways of using information about remaining battery energy of nodes in routing. We can consider [26,27] as pioneering studies which laid the foundation of battery-aware routing in wireless ad hoc networks and present simple and effective solutions. Many other follow up studies (e.g., [17,5,22,24,21,29,20]) have proposed routing schemes which are principally similar to the schemes in [26,27]. Some other studies have tried to enhance the proposed algorithms in [26,27] by also considering other factors such as bandwidth [19], hop-count [30], position of nodes [31], and the delay [4] in route selection. As communication within a PN cluster is multi-hop, battery-aware routing could be deployed in PN clusters as well to prolong the operational lifetime of nodes. Nevertheless, an important question to be answered is, whether the existing schemes are optimized solutions for PN clusters.

Studies related to battery-aware routing usually targeted ad hoc networks with only battery-powered nodes. PN clusters have some characteristics which differentiate them from regular ad hoc networks that battery-aware routing mechanisms have been designed or evaluated for them. In PN clusters, we usually face with a situation that most nodes are connected to mains (grid network). There might be few devices which are running on battery (e.g., in a home cluster). This heterogeneity in power supply of nodes has not been considered in the design of existing battery-aware routing algorithms. We believe that neglecting this heterogeneity results in sub-optimum solutions for PNs (we shall verify this in this article). Although in recent years some studies (e.g., [9,8,7]) have addressed routing in heterogeneous multi-hop networks, their proposed schemes are neither battery-aware routing algorithms nor explicitly consider heterogeneity of power supply of nodes in routing. On the other hand, studies related to PNs usually targeted architecture and service discovery in these networks (see [15,14,18, 10,2]). Many issues and aspects of PNs were investigated in the context of European projects IST MAGNET (2004-2006)[1] and MAGNET Beyond (2006-2008)[2], and Dutch project PNP2008 (2006-2008)[3]. Investigation on battery-aware routing mechanisms in PN clusters is still missing.

In this paper, we propose a new algorithm for battery-aware routing in PN clusters. The proposed algorithm takes the advantage of heterogeneity of PN nodes in terms of their power supplies to avoid relaying over battery-powered nodes. The basic idea behind our proposed algorithm is that packet forwarding does not have any *battery* cost for a mains-powered node. Hence, we can design a battery-aware routing algorithm which distinguishes between mains-powered and battery-powered nodes in route selection. Our proposed algorithm combines information about power supply of nodes, remaining battery energy of battery-powered nodes, and required power for packet transmission over physical links to find routes which minimize the energy cost of packet forwarding for battery-powered nodes. Through comprehensive simulation studies and taking into account the effect of various parameters such as node density, routing overhead, and mobility, we show that our proposed algorithm can profoundly extend the lifetime of battery-powered nodes in PN clusters.

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[1] www.telecom.ece.ntua.gr/magnet

[2] www.magnet.aau.dk

[3] www.freeband.nl

Distinguishing between mains-powered and battery-powered nodes as being done by our algorithm provides a further gain in PN clusters with mobile nodes. In a PN cluster, only battery-powered devices (e.g., a smart phone) could be mobile while mains-powered nodes (e.g., appliances) are static. Hence, directing the relay traffic to mains-powered nodes means that we implicitly consider heterogeneity of nodes in terms of mobility to relay over static nodes of the network. This prevents frequent route failure due to mobility and re-routing.

The rest of this paper is structured as follows: In Section 2, we describe the notations that we use in this work. In Section 3, a background knowledge on battery-aware routing is presented to show how remaining battery energy of nodes could be used in route selection. We explain working principles of three battery-aware routing algorithms presented in [26,27]. We also present an algorithmic representation for these algorithms, which is missing in [26,27]. Our proposed algorithm is presented in Section 4. In Section 5, the simulation model for performance evaluation of the proposed algorithm is described. Simulation studies are presented in Section 6. Section 7 summarizes the paper and draws conclusions.

2 Notations

A PN cluster is modeled by a graph $G(\mathbb{V},\mathbb{E})$, in which $\mathbb{V}$ is the set of nodes (vertices) and $\mathbb{E}$ is the set of links (edges). The distance between two nodes u and v is denoted by $d_{u,v}$. We assume $\mathbb{V}=\mathbb{V}_b \cup \mathbb{V}_m$, where $\mathbb{V}_b$ is the set of battery-powered (BP) nodes, and $\mathbb{V}_m$ is the set of mains-powered (MP) nodes in the cluster. We define $\sigma = N_m/N$ as the fraction of MP nodes in the cluster, in which $N_m = |\mathbb{V}_m|$ is the number of MP nodes, and $N = |\mathbb{V}|$ is the total number of nodes in the cluster.

The residual battery energy of a BP node u is denoted by $B_u \leq B$ (Joule), where B is the maximum battery energy of nodes. Without loss of generality, we assume that at the start of the operation of the network, $t = 0$, all BP nodes have the maximum battery energy B. However, this is not a hard constraint. We take the same initial battery energy for all BP nodes to enable a fair comparison between different algorithms. If the residual battery capacity of a BP node is less than a threshold denoted by B_{th}, the node is considered to be dead [11].

In a PN cluster, some nodes might be mobile and the rest might be static. For example, the user may pick a handheld device and walk inside his home, where other devices such as appliances have fixed positions. Here, we assume MP nodes, which are plugged to the mains, are static, and BP nodes could be mobile. We defined θ as the fraction of BP nodes which are mobile. θ can vary from 0 (all BP nodes are static) to 1 (all BP nodes are mobile). Table 1 summarizes the definitions of various parameters introduced in this section and will be introduced in next sections.

3 Background on Battery-Aware Routing

In this section, we explain three battery-aware routing algorithms from the literature, which could be deployed in PN clusters. These algorithms are Minimum Battery Cost Routing (MBCR) [26], Max-Min Battery Cost Routing (MMBCR)[26], and Conditional Max-Min Battery Cost Routing (CMMBCR) [27]. We explain these algorithms for the sake of completeness of our work. The importance of these three algorithms is that

Table 1 Numenclature

Parameter	Description
$\mathbb{V}$	The set of nodes in the cluster
$\mathbb{V}_m$	The set of mains-powered nodes in the cluster
$\mathbb{V}_b$	The set of battery-powered nodes in the cluster
B_u	Residual battery energy of node u
B	Maximum battery energy a node
ζ_1	Energy consumed to transmit a bit to 1 meter distance
ζ_2	Energy consumed to receive a bit
η	Path-loss exponent
B_{th}	Battery death threshold
N	Total number of nodes in the cluster
N_m	The number of mains-powered nodes in the cluster
σ	Fraction of mains-powered nodes in the cluster
θ	Fraction of mobile battery-powered nodes in the cluster
$\mathcal{V}_m$	Maximum speed of a mobile node
$\mathcal{T}_p$	Maximum pause duration of a mobile node
L	Packet length
e_{tx}	Energy consumed to transmit a packet
e_{rx}	Energy consumed to receive a packet
$d_{u,v}$	Distance between nodes u and v
γ	Decision threshold for CMMBCR algorithm
R	Transmission range
χ	To/from a gateway node communication probability

they present three different ways of using information about remaining battery energy of nodes in route selection. These methods have been used in many other algorithm proposed latter (e.g., in [17,20]).

Here, we also need to emphasize that in general clusters of a PN may have different forms. For instance, a home cluster of a PN might contains many devices while a car cluster may only consist of a mobile phone, and an office cluster may only contain a PC and a laptop which are connected to each other using a direct link. Even clusters of different PNs could be completely different from each other both in terms of the number of devices and type of devices. Some people who have luxury houses may have many devices at different rooms a floors which are connected to each other in a multi-hop way. Some people may have small clusters consisting of a few devices in which no multi-hop communication is required. The battery-aware routing algorithms that we describe here are generally designed for and applicable in multi-hop clusters.

3.1 Minimum Battery Cost Routing Algorithm

MBCR selects a path which minimizes the accumulated battery cost of nodes to send a packet from a source node to a destination node. Battery cost of a node is defined as the inverse of its residual battery energy. If a node has lower battery energy compared to other nodes, its battery cost for packet forwarding is higher. MBCR defines the optimal path between a source and a destination node as follows:

$$P_{mbcr} = \text{ argmin } \{W_{mbcr}(P_k)\}, \forall P_k \in Q$$

Algorithm 1 Implementation of MBCR as well as MTPR and MMCR using Dijkstra's shortest-path routing algorithm. For MBCR, $w(u, v)$ is as defined in (2), for MTPR, it is as defined in (7), and for MMCR, it is as defined in (8). Here, s is the source node. After running the algorithm, $\mathcal{P}(s, v)$ will contain the optimal path from the source node s to node v in the network ($\forall v \in \mathbb{V}$), and $C(s, v)$ will be the weight of the optimal path.

```
Shortest-Path($G(\mathbb{V}, \mathbb{E})$, $s$)
for each node $v \in \mathbb{V}$ do
    if $v$ is a neighbor of $s$ then
        $C(s, v) \leftarrow w(s, v)$ //Cost of the path from $s$ to $v$
        $\mathcal{P}(s, v) \leftarrow \{(s, v)\}$ //Constituent links of the path from $s$ to $v$
    else
        $C(s, v) \leftarrow \infty$
        $\mathcal{P}(s, v) \leftarrow \emptyset$
    end if
end for
$A \leftarrow \mathbb{V}$
while $A \neq \emptyset$ do
    $u \leftarrow v \in A \mid C(v)$ is minimum
    $A \leftarrow A - u$
    for each neighbor $v \in A$ of $u$ do
        $temp \leftarrow C(s, u) + w(u, v)$
        if $temp < C(s, v)$ then
            $C(s, v) \leftarrow temp$
            $\mathcal{P}(s, v) \leftarrow \mathcal{P}(s, u) \cup (u, v)$
        end if
    end for
end while
```

in which, the path weight $W_{mbcr}(P_k)$ is defined as,

$$W_{mbcr}(P_k) = \sum_{i=1}^{n_k} \frac{1}{B_i - B_{th}} \tag{1}$$

where, B_i is the residual battery energy of the i^{th} node of the path.

Eq. (1) implies that the path weight in MBCR is the summation of the weight of individual links of the path, where the weight of a link is the battery cost of the sender node of the link. Therefore MBCR could be implemented using Dijkstra's shortest-path routing algorithm, if we define the weight of (u, v) link as,

$$w_{mbcr}(u, v) = \frac{1}{B_u - B_{th}} \qquad \forall (u, v) \in \mathbb{E}. \tag{2}$$

We can use Algorithm 1 to find P_{mbcr} from a source node to any other node in the network.

By finding a path with the minimum accumulated battery cost, MBCR tries to find routes in which nodes are *likely* to have more remaining battery energy. This can balance the traffic load in the network. However, since the total battery cost of a path is the summation of the battery cost of individual nodes, MBCR may not completely prevent selection of nodes with low battery energy as relaying nodes [27]. In the next subsection, we explain a battery-aware routing algorithm which can mitigate this problem.

3.2 Max-Min Battery Cost Routing Algorithm

MMBCR finds a path that the residual battery energy of its critical node is higher than that of the other paths. The critical node of a path is a node which has the lowest battery energy in that path. In other words, the optimal path in MMBCR is defined as:

$$P_{mmbcr} = \text{ argmax } \{W_{mmbcr}(P_k)\} \qquad \forall P_k \in Q \tag{3}$$

in which, Q is the set of all available paths between the source node and the destination node, and the path weight $W_{mmbcr}(P_k)$ is defined as follows:

$$W_{mmbcr}(P_k) = \text{ min } \{B_i\} \qquad \forall i \in P_k. \tag{4}$$

Eq. (4) implies that the weight of a path in MMBCR algorithm is the minimum residual battery energy in that path. As suggested by (3), MMBCR selects a path with the maximum weight between a source and a destination node. This means MMBCR uses a max-min route selection scheme, which could not be implemented using Dijkstra's shortest-path routing algorithm. Nevertheless, if we consider the path weight as the width of the path, the optimal path in MMBCR algorithm will be *the widest path* between the source and the destination node. Algorithm 2 shows how to find the widest path between a source node and any other node in the network according to MMBCR. To this end, we need to define the weight of (u, v) link in the network as the residual battery energy of the sender node u. That is,

$$w_{mmbcr}(u, v) = B_u \qquad \forall (u, v) \in \mathbb{E}. \tag{5}$$

The max-min route selection scheme of MMBCR can prevent selection of nodes with low battery energy as relaying nodes. Nevertheless, it could also result in selection of long routes as we will verify in Section 6. Using long routes for packet transfer can increase the total energy consumption in the network. Consequently, the average energy consumption rate of individual nodes will increase. This in turn reduces the lifetime of BP nodes in the network. The battery-aware routing algorithm described in the next subsection can partially mitigate this problem.

3.3 Conditional Max-Min Battery Cost Routing Algorithm

CMMBCR is a hybrid routing algorithm that arbitrates between MMBCR algorithm and an energy-efficient routing algorithm named MTPR (Minimum total Transmission Power Routing [26]). Before we explain how CMMBCR works, we explain working principles of MTPR algorithm.

MTPR finds routes that minimizes the total power required to *transmit* a packet from a source node to a destination node. Due to path-loss, the required power is proportional to the distance between the transmitter and the receiver. MTPR defines the optimal path from source to destination as follows:

$$P_{mtpr} = \text{ argmin } \{W_{mtpr}(P_k)\}, \forall P_k \in Q$$

in which, $W_{mtpr}(P_k)$ (the path weight) is defined as,

$$W_{mtpr}(P_k) = \sum_{i=1}^{n_k} d_{i,i+1}^{\eta}. \tag{6}$$

Algorithm 2 Implementation of MMBCR algorithm. Here, s is the source node. After running the algorithm, $\mathcal{P}(s,v)$ will contain the optimal path from the source node s to node v, $\forall v \in \mathbb{V}$, and $C(s,v)$ will be the weight of the optimal path.

```
MMBCR($G(\mathbb{V},\mathbb{E})$, $s$)
for each node $v \in \mathbb{V}$ do
  if $v$ is a neighbor of $s$ then
    $C(s,v) \leftarrow w_{mmbcr}(s,v)$ //Cost of the path from $s$ to $v$
    $\mathcal{P}(s,v) \leftarrow \{(s,v)\}$ //Constituent links of the path from $s$ to $v$
  else
    $C(s,v) \leftarrow 0$
    $\mathcal{P}(s,v) \leftarrow \emptyset$
  end if
end for
$A \leftarrow \mathbb{V}$
while $A \neq \emptyset$ do
  $u \leftarrow v \in A \mid C(v)$ is maximum
  $A \leftarrow A - u$
  for each neighbor $v \in A$ of $u$ do
    $temp \leftarrow \min(C(s,u), w_{mmbcr}(u,v))$
    if $temp > C(s,v)$ then
      $C(s,v) \leftarrow temp$
      $\mathcal{P}(s,v) \leftarrow \mathcal{P}(s,u) \cup (u,v)$
    end if
  end for
end while
```

where, $d_{i,i+1}$ is the distance between the sender and the receiver in the i^{th} hop of P_k, and η is the path-loss exponent of the environment. Parameter η usually takes a value between 2 (free-space) and 6 (heavily-built urban areas). Eq. (6) implies that the path weight in MTPR algorithm is the summation of the weight of individual links of the path, where the weight of a link is power η of the distance between the sending and the receiving nodes of the link. Hence, MTPR algorithm could also be implemented using Dijkstra's shortest-path routing algorithm, if the weight of (u,v) link is defined as follows:

$$w_{mtpr}(u,v) = d_{u,v}^{\eta} \quad \forall (u,v) \in \mathbb{E}. \tag{7}$$

Algorithm 1 shows how a node can find P_{mtpr} to any other node in the network given the network topology.

MTPR does not consider the remaining battery energy of nodes in route selection. Nevertheless, it is used by CMMBCR to reduce the adverse effects of MMBCR. CMMBCR acts in two different modes, namely MTPR mode and MMBCR mode. CMMBCR acts in MTPR mode, if there are some paths between a source and a destination node that the residual battery energy of their critical node lies above a certain threshold $0 \leq \gamma \leq B$. Among such paths, CMMBCR finds the path minimizing the total power required to transmit a packet from the source to the destination node similar to MTPR. However, if there are not such paths between the source and the destination node, CMMBCR acts in MMBCR mode. That is, when the residual battery energy of *at least* one node in each available path between the source and the destination falls below γ, CMMBCR selects a path similar to MMBCR algorithm.

To explain the operation of CMMBCR algorithm better, we define $X \subset Q$ as a set containing all paths in Q which satisfy the following condition:

$$W_{mmbcr}(P_k) > \gamma, \quad \forall P_k \in Q$$

Algorithm 3 CMMBCR algorithm.

```
CMMBCR($G_1(\mathbb{V},\mathbb{E}_1)$, $G_2(\mathbb{V},\mathbb{E}_1)$, $\gamma$, $s$)
for each $(u,v) \in \mathbb{E}_2$ do
    if $w_{mmbcr}(u,v) < \gamma$ then
        $\mathbb{E}_1 \leftarrow \mathbb{E}_1 - (u,v)$
    end if
end for
$\mathcal{P}_1(s,v)$ = Shortest-Path($G_1(\mathbb{V},\mathbb{E}_1)$, $s$)
$\mathcal{P}_2(s,v)$ = MMBCR($G_2(\mathbb{V},\mathbb{E}_2)$, $s$)
for each $v \in \mathbb{V}$ do
    if $\mathcal{P}_1(s,v) = \emptyset$ then
        $\mathcal{P}(s,v) \leftarrow \mathcal{P}_2(s,v)$
    else
        $\mathcal{P}(s,v) \leftarrow \mathcal{P}_1(s,v)$
    end if
end for
```

where, $W_{mmbcr}(P_k)$ is as defined in (4). If $X \neq \emptyset$, ($\emptyset$ is the empty set), CMMBCR selects a path from X which minimizes total power required to transmit a packet from the source node to the destination node. If $X = \emptyset$, then a path is selected from Q according to MMBCR algorithm.

Algorithm 3 shows how to implement CMMBCR using Algorithm 1 and Algorithm 2. In this algorithm, $G_1(\mathbb{V},\mathbb{E}_1)$ is the network topology in which link weights are calculated according to MTPR algorithm using (7). $G_2(\mathbb{V},\mathbb{E}_2)$ is the network topology in which link weights are calculated according to MMBCR algorithm using (5). In fact, the two graphs are the same, but their link weights are different.

To find the optimal path according to CMMBCR, we first remove those links in $G_1(\mathbb{V},\mathbb{E}_1)$ that their link weight is smaller than γ. Let the resulting graph be $G_1^{'}(\mathbb{V},\mathbb{E}_1)$. Then, we find the shortest-path between the source node s and each node in the network by running Algorithm 1 on $G_1^{'}(\mathbb{V},\mathbb{E}_1)$. If no route could be found to a node, it means there is at least one node in each path between the source node and that node, whose remaining battery energy is less than γ. In such a case, the optimal path to such a node must be found by running Algorithm 2 on $G_2(\mathbb{V},\mathbb{E}_2)$.

To find energy-efficient routes, CMMBCR necessitates that nodes adjust their transmission power according to the distance to their neighboring nodes located at different locations. This could be done using the protocol proposed in [25]. If, however, nodes do not deploy such a scheme to adjust their transmission power, they all transmit with their maximum power to reach any node within the transmission range. In such a case, the consumed power to transmit a packet will be the same for all the links. Therefore, the path minimizing the total power required to transmit a packet will be the path with the minimum number of hops. In other words, when transmission power control is not utilized, CMMBCR in its MTPR mode selects a path with the minimum number of hops amongst all available paths between the source and destination nodes.

4 MMCR: A Power-Supply and Battery Aware Routing Algorithm for PNs

In a PN cluster, usually there are both MP and BP nodes. The introduced battery-aware routing algorithms in the previous section do not explicitly distinguish between MP and BP nodes in the process of route selection. An MP node does not loose

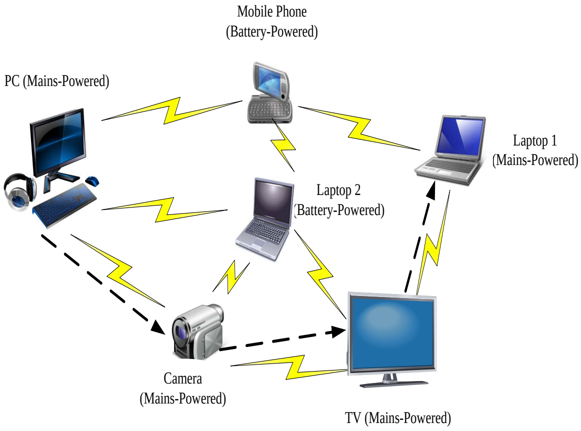


Fig. 2 A schematic of multi-hop communication in a PN cluster in which MP nodes could be preferred for packet forwarding.

battery energy for packet forwarding, but a BP node consumes part of its limited battery energy. We can distinguish between MP and BP nodes in route selection to avoid choosing BP nodes as relaying nodes as much as possible.

MMCR (Mains-aware Minimum battery Cost Routing) algorithm distinguishes between MP and BP nodes. In principle, MMCR acts similar to MBCR. That is, it minimizes the battery cost of nodes for packet forwarding. Nevertheless, MMCR has two added advantages compared to MBCR. First, MMCR considers type of power supply of nodes. Second, in addition to the remaining battery energy of BP nodes, MMCR considers the required power to forward a packet over a link (similar to MTPR). More specifically, MMCR defined the weight of (u, v) link as,

$$w(u,v) = \begin{cases} \frac{d_{u,v}^{\eta}}{B_u - B_{th}} & \forall u \in \mathbb{V}_b, \\ 0 & \forall u \in \mathbb{V}_m, \end{cases} \tag{8}$$

and finds the path with the minimum accumulated weight (i.e., the shortest-path) as the optimal path. In (8), $d_{u,v}$ is the distance between u and v, η is the path-loss exponent of the environment. The definition of link weight in (8) suggests that no weight is considered for links going out from MP nodes (MP links). On the other hand, the weight of a link going out from a BP node (a BP link) is a function of its residual battery energy and required power for packet transmission over a physical link.

The advantage of the definition given for weight of a BP link in (8) is combining the information about the required transmission power of links (as considered by MTPR) and the remaining battery energy of nodes (as considered by MBCR). This allows us to benefit from capability of MTPR in selecting energy-efficient routes and the load balancing effect of MBCR. Higher energy consumption for packet transmission over a link and/or lower battery energy increases the cost for packet forwarding by a BP node. Furthermore, by defining no weight for MP links, MMCR tries to direct the relay traffic as much as possible to MP nodes instead of using BP nodes with limited battery energy as the relaying nodes. Sometimes, however, the use of BP nodes as relaying nodes might be inevitable, because there might be no other way to reach a node.

MMCR could be implement using Dijkstra's shortest-path routing algorithm (see Algorithm 1) as well, if we define the link weights as in (8). In the expression given for link weights in (8), it is assumed that nodes can adjust their transmission power to distance to their neighboring nodes. However, if nodes always use their maximum transmission power, the consumed energy for packet transmission over all links will be same. Hence, we can neglect this constant term to simplify the link weights in MMCR as,

$$w(u,v) = \begin{cases} \frac{1}{B_u - B_{th}} & \forall u \in \mathbb{V}_b, \\ 0 & \forall u \in \mathbb{V}_m, \end{cases} \tag{9}$$

when transmission power control is not supported by nodes. The weight of a BP link in (9) is the same as that of a link in MBCR algorithm. Nevertheless, MMCR can still generalize MBCR such that the power supply of nodes is considered in the process of route selection. We will show in Section 6 that MMCR can increase the operational lifetime of nodes in PN clusters compared to other algorithms, whether transmission power control is supported or nodes transmit with their maximum power. Before that, we explain the simulation setup in the next section.

A simple example showing how MMCR finds routes through MP nodes in a PN cluster has been depicted in Figure 2. We observe that for sending packets from PC to Laptop 1, the route going through Camera and TV, which are connected to mains, could be selected. There are other routes available as well. For instance, we can use the two-hop route going through Mobile Phone, or the three-hop route going through Laptop 2. Nevertheless, since these nodes are running on battery, it is better to avoid them as intermediate nodes.

5 Simulation Model

We use simulation results to compare the performance of various battery-aware routing algorithms explained in the previous section. As mentioned before, clusters belonging to the same PN or different PNs may have different forms. To compare the performance of various algorithms with each other we consider a multi-hop cluster with a random topology where nodes are distributed uniformly over a square area. We assumed the MAC layer is based on IEEE 802.1lb (CSMA/CA). RTS/CTS is used to avoid collision due to hidden node problem. The MAC layer also supports packet loss recovery. The receiver transmits an acknowledgment to the sender for each correctly received packet. If the sender does not receive an acknowledgment, it will retransmit the packet. This may happen because either the packet or its acknowledgment is lost. The sender retransmits the packet until it receives an acknowledgment, or the maximum number of transmission attempts M is reached. Therefore, a packet or its acknowledgment might be transmitted up to M times.

Traffic Generation: To generate traffic in the network, we assume sessions are generated randomly between randomly chosen source and destination nodes. Each node may establish concurrent sessions to different nodes, or be the destination node of several sessions at the same time. The inter-arrival time between two successive sessions generated in the network is assumed to be exponentially distributed with mean ρ. The duration of each session is also assumed to be exponentially distributed with mean μ. The source node of each session generates packets with the rate λ packets per unit of time. Note such a traffic model may not always be the case in a PN cluster. However, by changing values of parameters μ, ρ, and λ we can have a flexible model which may

Table 2 Typical Values of Simulation Parameters

Parameter	Simulation value
Maximum battery energy (B)	1 (Joule)
Transmission range (R)	10 (meter)
Network area	$5R \times 5R$ (square meter)
Mean session inter-arrival time (ρ)	3 (second)
Mean session duration (μ)	50 (second)
Data packet size	512 (Byte)
Minimum packet delivery ratio ($p_{d_{min}}$)	0.7
RREQ packet size	54+4(hop-count) (Byte)
RREP packet size	50+4(hop-count) (Byte)
MAC acknowledgment size	30 (Byte)
Number of retransmissions allowed	3
Preamble size	4 (Byte)
Physical layer header size	2 (Byte)
Request to Send (RTS) packet size	26 (Byte)
Clear to Send (CTS) packet size	20 (Byte)
Energy consumption parametr ζ_1	50 (nJoule/bit)
Energy consumption parametr ζ_2	100 (pJoule/bit/m$^\eta$)
Energy consumption parametr ζ_3	50 (nJoule/bit)
Path-loss exponent (η)	4
Battery death threshold (B_{th})	0.1 (Joule)
Decision threshold for CMMBCR (γ)	0.5 (Joule)
Packet rate (λ)	1 (packets/sec)
Total number of nodes in the cluster (N)	100
Fraction of MP nodes (σ)	0.5
Fraction of BP mobile nodes (θ)	0.5
To/from gateway comm. probability (χ)	0
Maximum speed of a mobile node ($\mathcal{V}_m$)	1 (meter/sec)
Maximum pause time of a mobile node ($\mathcal{T}_p$)	15 (sec)
Route refreshment interval (δ)	10 (sec)
k_{idle}	0.2
k_{sense}	0.4
T_{sense}	50 μs (based on IEEE 802.11 standard)

fit different sessions in PNs. If we increase ρ, then sessions will be generated more frequently. If we increase μ, then sessions last for a longer time and more concurrent sessions may exist in the network.

Route Discovery: We used a reactive route discovery mechanism in our simulation model, which is similar to that of DSR (Dynamic Source Routing [16]) protocol. Upon generation of a session, the source node broadcasts a route request (RREQ) message to discover a route to the destination node of the session. Each node in the network broadcasts the received RREQ message. Hence, the destination node may receive several replicas of the RREQ message. Each replica traverses on different routes, and gathers weights of the traversed links. The destination node chooses the route according to the routing algorithm in place, and replies to the source node by a route reply (RREP) message.

To take into account the effect of the routing overhead, we introduce δ as the route refreshment interval. After δ unit of time, the source node will propagate another RREQ to refresh its route to the destination node (if the session is still alive). The newly discovered route might be different from the previously discovered route. Route refreshing is needed for battery-aware routing algorithms to avoid overusing the same set of BP nodes. With time, the battery level of nodes change and route re-discovery will probably find routes other than the in-use routes. Another cause which may trigger route re-discovery is route failure due to mobility of nodes.

Communication Pattern: In practice, the source and the destination of a session in a PN could be located in the same cluster or in different clusters. Clusters of a PN are connected to each other through their gateway nodes. When the source and the destination nodes are in different clusters, the gateway node within the source cluster receives packets from the source node, and forwards them to the gateway node of the destination cluster. Then, the gateway node of the destination cluster forwards packets to the destination node. This means, when the source and the destination are in two different clusters, they communicate using gateway nodes. However, when they are in the same cluster, they communicate without the need of gateway nodes to provide a service locally for the user. To model this in our simulations, we introduce χ as the probability that the source or the destination of a generated session within a cluster is the gateway node of the cluster. If $\chi = 0$, all sessions are established between two regular nodes of the cluster (no cluster-to-cluster communication). $\chi = 1$ means all sessions in the cluster are established between a regular node and the gateway node (only cluster-to-cluster communication).

Performance Metrics: Network lifetime and mean hop count are the two metrics that we use to evaluate the performance of battery-aware routing algorithms. We define the network lifetime as the time at which the first node fails due to battery exhaustion. Other definitions for network lifetime used in the literature include the time until the network is partitioned [6], and fraction of surviving nodes in the network [12]. There are some reasons to believe that the definition we use here is meaningful for PNs. Firstly, the first failed node might be the node that provides the required service for the PN user. Hence, failure of such a node interrupts the service delivery. Secondly, the presence of MP nodes in a PN cluster may prevent the cluster from being partitioned due to node failure. Thirdly, if a battery-aware scheme can delay the first node failure, failure of other nodes will be delayed as well. Instead of using time as a measure to represent the network lifetime, we consider the total number of data packets transmitted by all source nodes before the first node failure happens. The higher the network lifetime, the more is the number of transmitted data packets. This will make our results independent of the hardware platform which runs the simulation model.

Energy Consumption Model: Similar to [13], we assume that the consumed energy to transmit and receive a packet over a physical link increases linearly with packet size. The energy consumed to transmit a packet of length L bits between two neighboring nodes u and v at distance $d_{u,v}$ is computed as

$$e_{tx}(L, d_{u,v}) = \zeta_1 L + \zeta_2 L d_{u,v}^{\eta}, \tag{10}$$

in which ζ_1 (Joule/bit) is the energy consumed by processing part of transmitter circut to transmit a single bit of the packet. ζ_2 (Joule/bit/m$^{\eta}$) is the energy needed by the transmitter to send a packet over a distance of one meter with an acceptable power in an environment where the energy decays with path-loss exponent η. The energy consumed to receive a packet of length L bits is also computed as

$$e_{rx}(L) = \zeta_3 L, \tag{11}$$

where ζ_3 (Joule/bit) is the energy required to receive a single bit of the packet. If the transmitting node is BP, e_{tx} is deducted from its battery energy upon transmission of a packet. Similarly, if the receiving node is BP, e_{rx} is deducted from its battery energy upon reception of the packet. When a packet is transmitted, all neighboring nodes which receive the packet consume e_{rx} as well. If the residual battery capacity of a BP node is less than a threshold denoted by B_{th}, the node is considered to be dead. We also have assumed that each node consumed a small amount of energy at the idle mode (when it neither transmits nor receive a packet). 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 $k_{idle}\zeta_3 T_{idle}$, where T_{idle} is the duration that a node is idle. We also assume the energy consumption during channel sensing is $k_{sense}\zeta_3 T_{sense}$, where T_{sense} is the duration of sensing the channel.

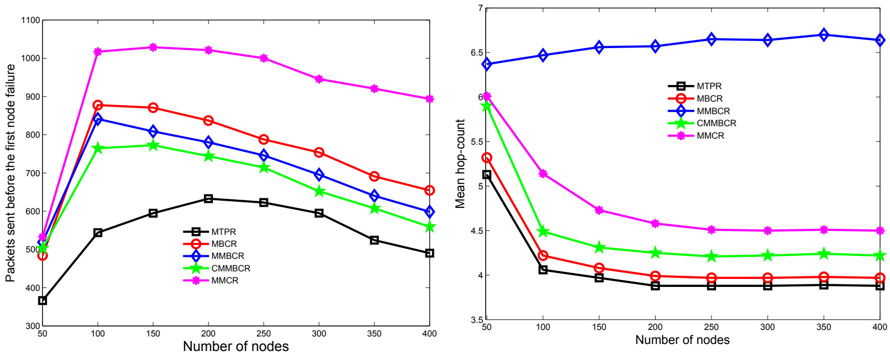
Mobility Model: We use Random Waypoint [3] mobility model in our simulations. Although this model may not be applicable to any PN cluster, we may use it as a benchmark to compare performance of various algorithms. According to this model, the velocity of nodes is assumed uniformly distributed over $(0, \mathcal{V}_m)$. The pause time is uniformly distributed over $(0, \mathcal{T}_p)$.

Collection of Results: To collect simulation results, different algorithms are compared in a completely similar setting. To this end, we deploy a network randomly in each simulation run. We then create five replicas of the deployed network to measure its lifetime when different routing algorithms are used (MBCR, MMBCR, CMMBCR, MTPR, MMCR respectively). Sessions generated randomly in one replica is used in all the other replicas of the network. In other words, we have five samples of the same randomly deployed network which are completely the same (even the active sessions in these networks), but the deployed routing algorithms are different. To increase the confidence of our results, we repeated this procedure 300 times and plotted the average values for each algorithm.

Table 2 shows the default values of various parameters that we used in our simulations. Here, we emphasize that the explained simulation setting is only to comparison of various battery-aware routing algorithms in a multi-hop cluster. Due to diversity of devices and clusters of a PN, it is difficult to find a single setting for these networks.

6 Performance of Energy-Aware Routing Algorithms

We evaluate the performance of battery-aware routing algorithms through analyzing the effect of various parameters on their performance. These parameters are the number of nodes, the route refreshment interval, density of MP nodes, to/from gateway communication probability, and mobility-related parameters. To study the effect of each parameter, we set other parameters to their default values as given in Table 2, and we vary the parameter under examination whose effect we want to study. In our evaluations, we distinguish between clusters with all static nodes and clusters with some mobile nodes. We also distinguish between packet transmission with and without transmission power control.



(a) (b)

Fig. 3 (a) Network lifetime and (b) mean hop-count for various routing algorithms in terms of the number of nodes. All nodes are static and do not control their transmission power.

6.1 Clusters with Static Nodes and No Transmission Power Control

6.1.1 The Number of Nodes (N)

The impact of the number of nodes on the network lifetime and mean hop count is shown in Fig. 3 for various routing algorithms. In this experiment, the network area is fixed, which means the node density increases as the number of nodes increases. Results are provided for up to 400 nodes *only* to observe the performance trend at higher densities. However, we may consider $N < 150$ as a reasonable limit for the number of nodes in PN clusters in the near future (e.g., in home clusters).

Performance of battery-aware Algorithms: MMCR algorithm explicitly distinguishes between MP and BP nodes in the process of route selection. This is the reason that this algorithm achieves the highest network lifetime amongst all battery-aware routing algorithms (see Fig. 3(a)). Compared to MBCR (the next best-performing algorithm), the network lifetime with MMCR is 17% higher at $N = 100$ nodes, and 38% higher at $N = 400$ nodes. In other words, the performance gain of MMCR algorithm with respect to the other algorithms increases as the number of nodes increases.

MTPR achieves the lowest network lifetime. We recall that in this experiment nodes do not deploy transmission power control. In such a case, MTPR finds routes with the minimum number of hops. Hence, nodes could be overused, because the same set of nodes may be selected frequently as relaying nodes. As a result, they die quickly. Other battery-aware routing algorithms consider the residual battery energy of nodes for route selection. This can balance the traffic load among BP nodes, and increase the network lifetime.

After MTPR, CMMBCR results in the lowest network lifetime. As shown in Fig. 4, CMMBCR acts mostly in its MTPR mode, which will result in node overuse as explained before. For the threshold of $\gamma = 0.5$ and $N = 150$ nodes, 80% of routes selected by CMMBCR during the simulation are chosen in MTPR mode. Only 20% of them are chosen in MMBCR mode. However, the possibility that CMMBCR can act in MMBCR mode explains why CMMBCR achieves a higher network lifetime compared to MTPR.

As seen in Fig. 3(b), the lowest mean hop count belongs to MTPR which finds routes with the minimum number of hops. CMMBCR results in a mean hop-count

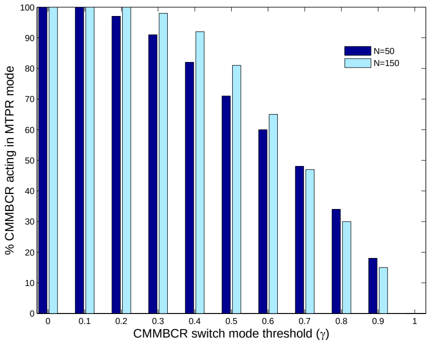
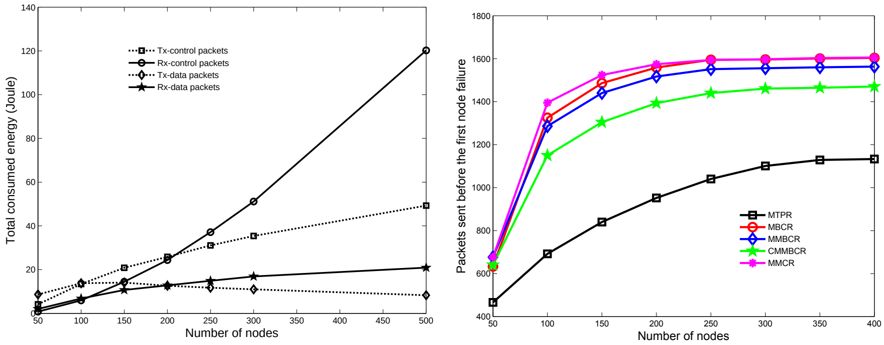


Fig. 4 Percentage of times that CMMBCR acts in MTPR mode when all nodes are static and do not control their transmit power.



(a) (b)

Fig. 5 (a) Total energy consumed for transmission and reception of data and control packets in the cluster as a function of the number of nodes. Illustrated results are for MMCR algorithm. (b) Network lifetime for various routing algorithms when no energy is consumed for packet reception. All nodes are static and do not adjust their transmit power per link.

close to MTPR, since it acts mostly in MTPR mode. Furthermore, the mean hop count of MBCR is very close to that of MTPR.

While MMCR achieves a higher network lifetime compared to MBCR, its corresponding mean hop count is also higher (see Fig. 3(b)). Since no weight is considered in MMCR for MP links, long routes consisting of many MP nodes might be selected. Nevertheless, the mean hop count of MMCR is still lower than that of MMBCR. As mentioned before, MMBCR uses a max-min route selection scheme which increases the hop-count unboundedly. We observe in Fig. 3(b) that while the mean hop count decreases for other algorithms as the number of nodes increases, it has an increasing trend for MMBCR.

Concave Shape of Network Lifetime Plots: An interesting phenomenon in Fig. 3(a) is the concave shape of network lifetime plots for all algorithms. Here, we explain this behavior.

As the number of nodes in the network increases, we face with two phenomena affecting the network lifetime in different directions:

1. The probability that a node is selected frequently as part of a route decreases. This can reduce the possibility that a node is overused. Hence, the lifetime of nodes (and consequently the network lifetime) increases.
2. The number of neighbors of a node (node degree) increases as the number of nodes increases (the network area is fixed). As a result, each node will receive more unicast and broadcast packets transmitted by its neighboring nodes. This increases the energy consumption rate of nodes. Therefore, the lifetime of nodes and consequently the network lifetime decreases.

Fig. 3(a) shows that before a specific number of nodes, the first phenomenon is the dominant factor in determining the network lifetime. After this threshold, the second phenomenon becomes the dominant factor, where the network lifetime decreases as the number of nodes increases.

To verify the second phenomenon, we showed in Fig. 5(a) the total energy consumed by all nodes in the network to transmit and receive control packets (RREQ which is broadcast) and data packets. The figure clearly shows that as the number of nodes in the network increases the energy consumed by nodes to *receive* broadcast RREQ messages becomes the dominant source of energy consumption. To show the effect of this source of energy consumption on the network lifetime, we repeated the results of Fig. 3(a) in Fig. 5(b) for the case that energy consumed for packet reception is not taken into account in the simulations (i.e., $\zeta_2 = 0$ in (11)). We can see that in such a case the network lifetime tends to increase as the number of nodes increases (no concave shape is observed). This also shows the significance of a realistic energy consumption model for evaluating the performance of battery-aware routing algorithms.

6.1.2 Density of Mains-Powered Nodes (σ)

The impact of the density of MP nodes on the network lifetime is shown in Fig. 6. In this experiment, the number of nodes and the network area is fixed to their default values as in Table 2. We changed the value of σ, which results in a varying density for MP nodes.

When the density of MP nodes increases, the probability that a BP node is being overused decreases. Hence, the network lifetime increases for all algorithms, as seen in Fig. 6. However, when the fraction of MP nodes increases, MMCR can offer a higher network lifetime with respect to other algorithms.

6.1.3 Route Refreshment Interval (δ)

The impact of the route refreshment interval on the network lifetime is shown in Fig. 7 for various algorithms. In this experiment, we fixed the mean session duration μ, and we changed the value of the route refreshing interval δ. This means, the route refreshment interval increases when the ratio of $\frac{\delta}{\mu}$ increases. We have provided results for a network in which all nodes are BP and a network in which half of nodes are BP to show that the behavior of some of algorithms depend on the network configuration.

General Performance Trend of Algorithms: When the route refreshment interval increases, we encounter with two phenomena that have contradictory effects on the network lifetime.

1. Since nodes along a discovered route will be used for a longer time, they might be overused. This reduces the network lifetime.

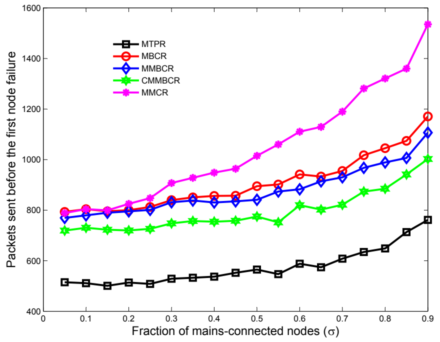
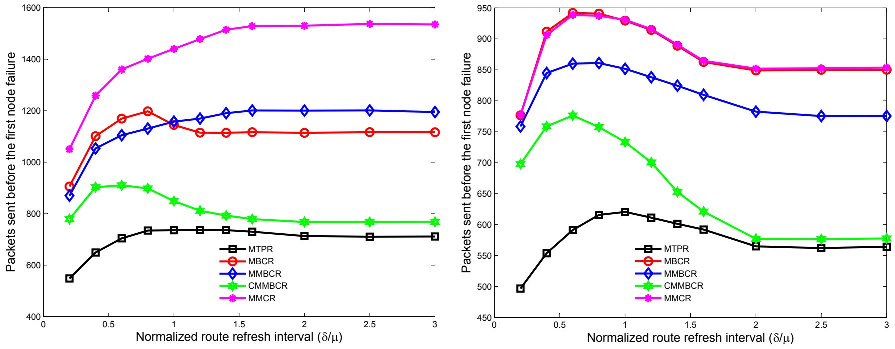


Fig. 6 Network lifetime for various routing algorithms in terms of the fraction of MP nodes in the cluster (σ). All nodes are static and do not adjust their transmit power.



(a) Half of nodes are BP. (b) All nodes are BP.

Fig. 7 Network lifetime for various routing algorithms in terms of the ratio of the route refresh interval δ to the mean session duration μ. All nodes are static and do not adjust their transmit power.

2. Since route refreshing will happen less frequently, the overhead of route discovery decreases. Consequently, the energy consumption rate of nodes reduces. This increases the network lifetime.

The fact that which of these two phenomena is dominant depends on the network configuration and the deployed routing algorithm. For example, when MMCR is used and half of the nodes are BP, the network lifetime increases when route refreshing interval increases (see Fig. 7(a)). This means the second phenomenon is always the dominant factor. Nevertheless, if all nodes are BP, a different behavior is observed for MMCR (see Fig. 7(b)). For some values of route refreshment interval, the network lifetime increases (i.e., the second phenomenon is dominant), while after a specific value, the network lifetime tends to decrease (i.e., the first phenomenon becomes the dominant factor).

We also observe in both plots of Fig. 7 that after $\frac{\delta}{\mu} = 2.5$, the network lifetime remains unchanged for all the algorithms. In general, when the refreshment interval is much higher than the average lifetime of a session, route refreshment may not happen during the lifetime of the session. Therefore, the discovered route at the session start-up may remain unchanged. Hence, changing the value of route refreshment interval does not change the network lifetime.

Table 3 The mean hop-count of selected routes and the average energy consumed by all nodes during one simulation run in terms of the probability of to/from gateway communication χ. All nodes are static, and do not adjust their transmit power. The table shows that as χ increases, the mean hop-count of the selected routes and the energy consumption of nodes decreases. Results are for MMCR. The same observation was made for the other algorithms.

χ	Mean Hop-count	Total Consumed Energy (Joule)
0	5.06	54.78
0.2	4.67	53.59
0.4	4.50	52.20
0.6	4.24	51.39
0.8	3.96	50.37
1	3.71	49.39

Relative Performance of Algorithms: Fig. 7(a) and Fig. 7(b) also show that MMCR again results in the highest network lifetime for various values of the route refreshment interval. It is worthwhile to mentioned that when all nodes are BP and transmission power control is not utilized, MMCR turns out to be MBCR as stated in Section 3. This is why the network lifetime is the same for the two algorithms in Fig.7(b). Nevertheless, when half of the nodes are BP, the network lifetime is different for them.

6.1.4 Probability of To/From Gateway Communication (χ)

The impact of the probability of selecting a gateway node as the source or the destination of a session on the achieved network lifetime is shown in Fig. 8 for various algorithms. In this experiment, one gateway node (which is MP) is located at the center of the network area. We changed χ from 0 to 1. $\chi = 0$ means the gateway is never selected as the source or the destination of a generated session, while $\chi = 1$ means the gateway is always either the source or the destination of a generated session.

As the probability of to/from gateway communication increases, two phenomena affect the network lifetime in opposite directions.

1. Since most of the communication will be towards or from the gateway, nodes around the gateway are overused. Hence, the lifetime of these nodes reduces. Consequently, the network lifetime decreases.
2. Since the gateway is in the centre of the network, the hop-count of the selected routes reduces as χ increases. This in turn reduces the overall energy consumption in the network (see Table 3). As a result, the energy consumption rate of each node (on an average) will also decrease. Consequently, the network lifetime increases.

When MTPR is utilized, the first phenomenon is the dominant factor, as the network lifetime tends to decrease, when χ increases (see Fig. 8). For MBCR, MMBCR, and MMCR, the second factor is the dominant factor, since the network lifetime tends to increase, when χ increases. These three algorithms consider the battery level of nodes in route selection. This can reduce the negative effect of the first phenomenon on the network lifetime, because the traffic load on nodes around the gateway will be balanced. When CMMBCR is utilized, the network lifetime remains almost constant as χ increases. We remember that CMMBCR works in MTPR and MMBCR modes. In each of these two modes one of the above mentioned phenomena is the dominant

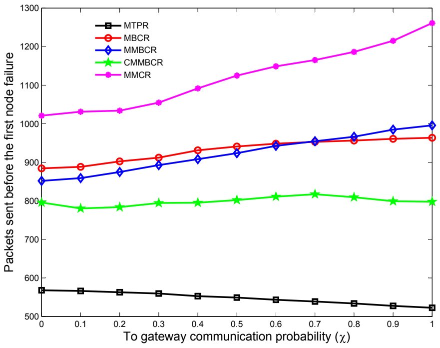
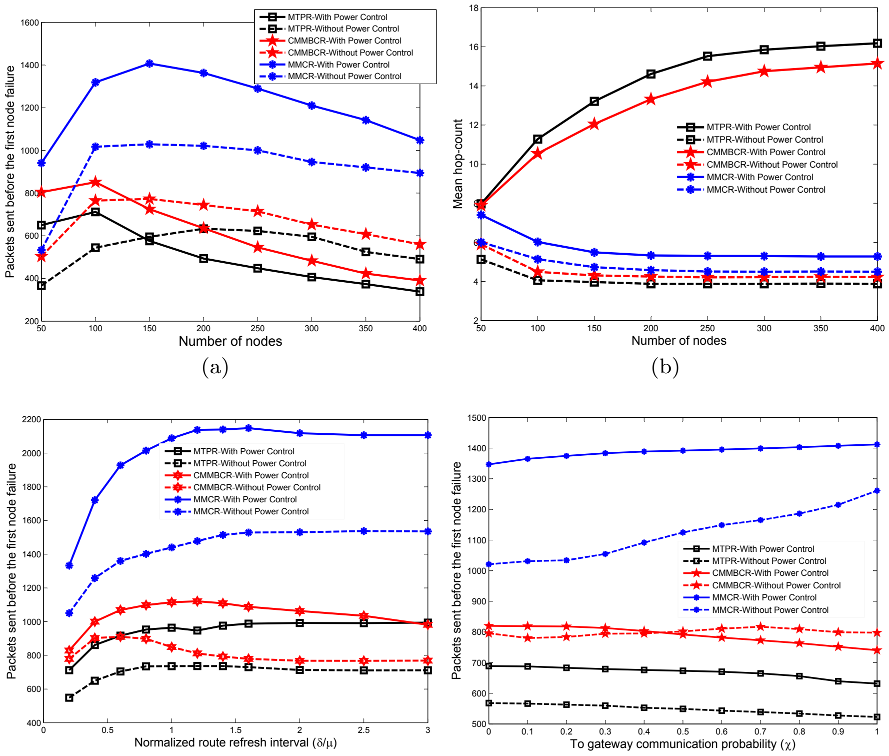


Fig. 8 Network lifetime for various routing algorithms as a function of to/from gateway communication probability. All nodes are static.



(a)

(b)

(c)

(d)

Fig. 9 The network lifetime and mean hop-count for MTPR, CMMBCR, and MMCR with and without power control (all nodes are static).

factor. For the network configuration considered here, the two conflicting phenomena neutralize each other's effect. We also observe in Fig. 8 that MMCR results in the highest network lifetime for all values of χ.

6.1.5 Summary of Results

So far, we analyzed the effect of the number of nodes, density of MP nodes, route refreshment interval, and to/from gateway communication probability on the performance of battery-aware routing algorithms when nodes are static and do not deploy transmission power control. We summarize our findings as follows:

1. There can be an optimal node density and route refreshment interval maximizing the network lifetime for all battery-aware routing algorithms.
2. Increasing density of MP nodes increases the network lifetime for all algorithms. Our proposed algorithm benefits more from the higher density of MP nodes.
3. Gateway-oriented communications increases the network lifetime for our proposed algorithm.
4. In all configurations, MMCR results in a higher network lifetime. The next best-performing algorithm is MBCR, except at high values of route refreshment interval in which MMBCR outperforms MBCR. The worst-performing algorithm is MTPR. The network lifetime of CMMBCR lies between that of MMBCR and MTPR.

6.2 Clusters with Static Nodes and Transmission Power Control

The routing metric of MTPR, CMMBCR (in its MTPR mode), and MMCR algorithms is a function of the minimum power required to transmit a packet over a physical link. Hence, the selected routes by these three algorithms when transmission power control is supported will be different from the selected routes by them when transmission power control is not supported. On the other hand, the routing metric of MBCR and MMBCR algorithms is only a function of the residual battery energy of nodes. Therefore, transmission power control has no effect on selected routes by these two algorithms. In this subsection, we study the impact of transmission power control on the performance of MTPR, CMMBCR, and MMCR algorithms.

6.2.1 The Number of Nodes

The network lifetime for MTPR, CMMBCR, and MMCR algorithms with respect to the number of nodes is shown in Fig. 9(a) with and without power control. Transmission power control improves the performance of MMCR algorithm in terms of the network lifetime at all densities. The maximum network lifetime for MMCR with power control is 1400 at $N = 150$ nodes, which is 40% greater than the maximum network lifetime for MMCR without power control, which is 1000 at $N = 100$ nodes.

Nevertheless, transmission power control may not improve the performance of CMMBCR and MTPR algorithms. At high number of nodes ($N > 150$), transmission power control reduces the network lifetime of CMMBCR and MTPR algorithms. The reason for this behavior can be found in Fig. 9(b), which shows the mean hop count in terms of the number of nodes. The mean hop count for CMMBCR and MTPR algorithms with power control increases as the number of nodes increases. MTPR (and CMMBCR in its MTPR mode) finds minimum energy paths. Such a path may consist of many short links, because the transmission power increases exponentially with distance. Finding the minimum energy path reduces the energy consumption of nodes for packet transfer. However, the use of longer routes increases the probability that some nodes are overused, because they might act as relaying nodes for several concurrent sessions. Therefore, the network lifetime may decrease.

6.2.2 Route Refreshment Interval

Fig. 9(c) shows that transmission power control increases the network lifetime for each algorithm at each route refreshing interval. However, MMCR benefits more than MTPR and CMMBCR, when power control is utilized. As mentioned earlier, MTPR and CMMBCR suffer from having long routes when power control is deployed. On the other hand, the mean hop count for MMCR is much lower.

6.2.3 To/From Gateway Communication Probability

Power control profoundly increases the network lifetime for MMCR at different values of the probability of to/from gateway communications (see Fig. 9(d)). The behavior of MTPR with power control is the same as MTPR without power control, but CMMBCR shows slightly different behavior. Network lifetime for CMMBCR without power control remains almost constant, if χ increases. With power control, however, it has a descending trend.

6.2.4 Summary of Results

When all nodes are static and use transmission power control, we can summarize our findings as follows:

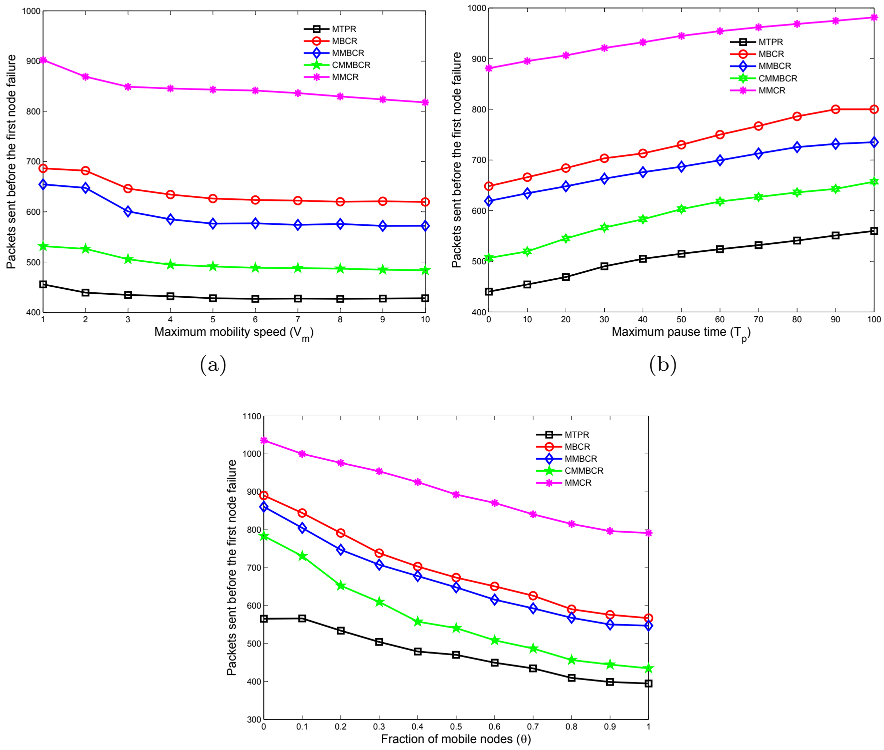
1. Transmission power control boosts the performance of MMCR more than that of MTPR and CMMBCR for all the considered values for the number of nodes, route refreshment interval, and to/from gateway communication probability.
2. Transmission power control increases the mean hop-count of MTPR and CMMBCR as node density increases. This results in decreased network lifetime for these two algorithms compared to the case that nodes transmit with maximum power.

6.3 Clusters with Mobile Nodes

Now, we evaluate the performance of battery-aware routing algorithms, when there are some mobile nodes in the cluster. Here, we assume nodes use no power control scheme, and they transmit with their maximum power. With mobile nodes, this can even be a realistic assumption. Adjusting the transmit power when nodes are mobile may not be feasible, because it is not easy to have an accurate and up-to-date estimation of the varying distance between mobile nodes.

6.3.1 Mobility Parameters

The impact of mobility parameters maximum node speed, maximum pause time, and the fraction of mobile nodes on the performance of the battery-aware routing algorithms are shown in Fig. 10. If the maximum pause time decreases, or maximum node speed increases, or the fraction of mobile nodes increases, the rate of topology change



(a)

(b)

(c)

Fig. 10 Network lifetime verses mobility parameters. Nodes do not use power control.

Table 4 The average ratio of energy consumed by each node in the network to the total number of packets sent before the first node failure. Results are for MMCR algorithm as a function of the ratio of battery-powered mobile nodes in the network (θ). Half of nodes are battery-powered and the rest are mains-powered. The table shows that the average energy consumed by each node per transmitted packet in the network increases, when the fraction of mobile nodes increases. The same result is valid when the maximum node speed increases or the pause time decreases.

Ratio of Mobile Nodes	Consumed Energy (Joule/packet)
0	0.053
0.2	0.062
0.4	0.067
0.6	0.072
0.8	0.075
1	0.076

increases, because the source and the destination node of a session as well as the intermediate nodes between them may change their position more frequently. This will cause frequent route failures. As a result, the energy consumption rate of nodes increases due to increased rate of route discovery in the network (see Table 4). This is why the network lifetime tends to decrease, if the maximum pause time decreases (Fig.

Table 5 Average number of times that route failure happens due to mobility of nodes during the lifetime of generated sessions. The results are presented for various values of the fraction of battery-powered mobile nodes θ. Half of nodes are battery-powered and the rest are mains-powered.

θ	MMCR	MBCR	MMBCR	CMMBCR	MTPR
0.1	0.24	0.5	0.52	0.73	0.53
0.2	0.43	0.89	1.88	1.27	0.96
0.4	0.74	1.63	2.60	2.31	2.065
0.6	1.15	2.22	3.14	2.96	2.77
0.8	1.51	2.66	3.48	3.47	3.38
1	1.79	3.06	3.82	3.80	3.78

10(b)), or maximum node speed increases (Fig. 10(a)), or the fraction of mobile nodes increases (Fig. 10(c)).

Even if there are some mobile nodes in the cluster, MMCR achieves a higher network lifetime compared to other algorithms; regardless of the value of mobility parameters (see Fig. 10). MMCR always tries to find routes consisting of MP nodes. As we assumed, MP nodes are static, MMCR directs the relay traffic *not only to MP nodes, but also to static nodes of the network*. This is another advantage of our proposed algorithm, which reduces the probability of route breakage due to mobility of the relay nodes. Table 5 shows that MMCR has the lowest route failure rate due to mobility of nodes.

6.3.2 Definition of Network Lifetime

So far, we considered the time at which the first node fails as the network lifetime. However, this definition of the network lifetime may not be a suitable definition for mobile networks, because the first node failure may not be very crucial for the connectivity of the network. A mobile node may move to the position of the failed node, and resolve the temporary partitioning. In static networks, a failed node might be a crucial node, which will not be replaced by another node.

Nevertheless, to see whether the first node failure is a good measure for mobile networks as well, we consider the number of survived nodes as another indication of the network lifetime. However, as Fig. 11 shows, after the first node failure, other nodes die quickly. This implies that the first node failure could be a good indication of the network lifetime in mobile networks as well. Fig. 11 also shows that even with this new definition of the network lifetime, MMCR still performs much better than other algorithms. This shows the effectiveness of our proposed algorithm in keeping the network operational as long as possible compared to other battery-aware routing algorithms.

6.3.3 Summary of Results

When there are some mobile nodes in the network, we can summarize our findings as follows:

1. Mobility of nodes reduces the network lifetime, because the consumed energy for route re-discovery increases.

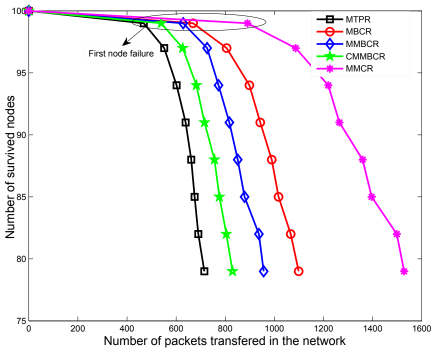


Fig. 11 The number of survived nodes in the network as an alternative definition of the network lifetime for clusters with mobile nodes. Half of nodes are BP and half of these BP nodes are mobile. Nodes do not use power control.

2. The benefit of MMCR in mobile network is two-fold: First, it directs the traffic load towards MP nodes, which increases the network lifetime. Second, it directs the traffic load towards static nodes of the network, which reduces the rate of route failure due to node movement.
3. Time at which the first node fails could be considered as a good measure of network lifetime for both static and mobile networks.

7 Conclusion

In this paper, we proposed a new battery-aware routing algorithms for personal networks in which nodes communicate in a multi-hop fashion. The proposed algorithm uses the advantage of having mains-powered nodes in personal networks to direct the relay traffic towards such nodes as much as possible. To this aim, our proposed algorithm it distinguishes between mains-powered and battery-powered nodes in route selection. We compared the performance of our proposed algorithm with the performance of several battery-aware routing algorithms from literature. Minimum total Transmission Power Routing, Minimum Battery Cost Routing, Min-Max Battery Cost Routing, and Conditional Max-Min Battery Capacity Routing are the four well-known algorithms that we considered. We studied the effect of various factors on the performance of these five algorithms. These factors are *node density, density of mains-powered nodes, route refreshment interval, probability of communication with the gateway nodes within clusters of personal networks, transmission power control, and mobility.* Our study showed that our proposed algorithm always achieves the highest lifetime for the network in all conditions. Although, we targeted our work for personal networks, our findings could be applied to any network with a similar structure. For instance, in wireless mesh networks, there might be both battery-powered and mains-powered nodes as well. Furthermore, gateway-oriented communication pattern could also be found in wireless mesh networks. In our future work, we will focus on extending the network lifetime in personal networks, while reliability requirements are addressed as well.

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