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Energy Efficient Routing Protocols for Mobile Ad Hoc Networks

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Energy efficient routing protocols for mobile ad hoc networks

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1. Introduction

Mobile devices coupled with wireless network interfaces will become an essential part of future computing environment consisting of *infrastructured* and *infrastructure-less* mobile networks [1]. Wireless local area network based on IEEE 802.11 technology is the most prevalent infrastructured mobile network, where a mobile node communicates with a fixed base station, and thus a wireless link is limited to one hop between the node and the base station. *Mobile ad hoc network* (MANET) is an infrastructure-less multihop network where each node communicates with other nodes directly or indirectly through intermediate nodes. Thus, all nodes in a MANET basically function as mobile routers participating in some routing protocol required for deciding and maintaining the routes. Since MANETs are infrastructure-less, self-organizing, rapidly deployable wireless networks, they are highly suitable for applications involving special

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outdoor events, communications in regions with no wireless infrastructure, emergencies and natural disasters, and military operations [2,3].

Routing is one of the key issues in MANETs due to their highly dynamic and distributed nature. In particular, *energy efficient routing* may be the most important design criteria for MANETs, since mobile nodes will be powered by batteries with limited capacity. Power failure of a mobile node not only affects the node itself but also its ability to forward packets on behalf of others and thus the overall network lifetime. For this reason, many research efforts have been devoted to developing energy-aware routing protocols.

Based on the aforementioned discussions, this paper surveys and classifies numerous energy-efficient routing mechanisms proposed for MANETs [4–15]. They can be broadly categorized based on *when* the energy optimization is performed. A mobile node consumes its battery energy not only when it actively sends or receives packets, but also when it stays idle listening to the wireless medium for any possible communication requests from other nodes. Thus, energy-efficient routing protocols minimize either the *active* communication energy required to transmit and receive data packets or the energy during *inactive* periods.

For protocols that belong to the former category, the active communication energy can be reduced by adjusting each node's radio power just enough to reach the receiving node, but not more than that. This *transmission power control approach* can be extended to determine the optimal routing path that minimizes the total transmission energy required to deliver data packets to the destination. For protocols that belong to the latter category, each node can save the inactivity energy by switching its mode of operation into *sleep/power-down mode* or simply turns it off when there is no data to transmit or receive. This leads to considerable energy savings, especially when the network environment is characterized with low duty cycle of communication activities. However, it requires a well-designed routing protocol to guarantee data delivery even if most of the nodes sleep and do not forward packets for other nodes. Another important approach to optimizing active communication energy is *load distribution approach*. While the primary focus of the above two approaches is to minimize energy consumption of individual nodes, the main goal of the load distribution method is to balance the energy usage among the nodes and to maximize the network lifetime by avoiding over-utilized nodes when selecting a routing path.

While it is not clear whether any particular algorithm or a class of algorithms is the best for all scenarios, each protocol has definite advantages/disadvantages and is well-suited for certain situations. However, it is possible to combine and integrate the existing solutions to offer a more energy-efficient routing mechanism. Since energy efficiency is also a critical issue in other network layers, considerable efforts have been devoted to developing energy-aware MAC and transport protocols [16]. Each layer is supposed to operate in isolation in layered network architecture but, as some recent studies suggested, the *cross-layer design* is essential to maximize the energy performance [17,18]. In fact, many routing protocols introduced in this paper use the same concept, i.e. they exploit lower layer mechanisms, such as transmission power control and sleep mode operation, in their routing layer algorithms.

The remainder of the paper is organized as follows. Section 2 presents a general discussion on ad hoc routing protocols where the goal is to find the shortest path. Section 3 first presents taxonomy of energy-efficient routing protocols based on the various goals and performance metrics used to determine an energy efficient routing path. Then, the rest of the section surveys the three approaches to energy-efficient routing protocols. Finally, Section 4 provides a conclusion.

2. Routing Protocols for MANETs

The routing protocols proposed for MANETs are generally categorized as *table-driven* and *on-demand driven*, based on the timing of when the routes are updated. With table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network. This is done in response to changes in the network by having each node update its routing table and propagate the updates to its neighboring nodes. Thus, it is *proactive* in the sense that when a packet needs to be forwarded, the route is already known and can be immediately used. As is the case for wired networks, the routing table is constructed using either *link-state* or *distance vector* algorithms containing a list of all the destinations, the next hop and the number of hops to each destination. Many routing protocols including *Destination-Sequenced Distance Vector* (DSDV) [19] and *Fisheye State Routing* (FSR) protocol [20] belong to this category, and they differ in the number of routing tables manipulated and the methods used to exchange and maintain routing tables.

With on-demand driven routing, routes are discovered only when a source node desires them. *Route discovery* and *route maintenance* are two main procedures: The route discovery process involves sending **route-request** packets from a source to its neighbor nodes, which then forwards the request to their neighbors, and so on. Once the **route-request** reaches the destination node, it responds by unicasting a **route-reply** packet back to the source node via the neighbor from which it first received the **route-request**. When the route-request reaches an intermediate node that has a sufficiently up-to-date route, it stops forwarding and sends a route-reply message back to the source. Once the route is established, some form of route maintenance process maintains it in each node's internal data structure called a **route-cache** until the destination becomes inaccessible along the route. Note that each node learns the routing paths as time passes not only as a source or an intermediate node but also as an overhearing neighbor node. In contrast to table-driven routing protocols, not all up-to-date routes are maintained at every node. *Dynamic Source Routing* (DSR) [21] and *Ad-Hoc On-Demand Distance Vector* (AODV) [22] are examples of on-demand driven protocols.

3. Energy Efficient MANET Routing

In contrast to simply establishing correct and efficient routes between pair of nodes, one important goal of a routing protocol is to keep the network functioning as long as possible. As discussed in the Introduction, this goal can be accomplished by minimizing mobile nodes' energy not only during active communication but also when they are inactive. *Transmission power control* and *load distribution* are two approaches to minimize the active communication energy, and *sleep/power-down mode* is used to minimize energy during inactivity. Table I shows taxonomy of the energy efficient routing protocols.

Before presenting protocols that belong to each of the three approaches in the following subsections (3.1, 3.2 and 3.3), *energy-related metrics* that have been used to determine energy efficient routing path instead of the shortest one are discussed. They are [4]

- energy consumed/packet;
- time to network partition;
- variance in node power levels;
- cost/packet; and
- maximum node cost.

The first metric is useful to provide the *min-power path* through which the overall energy consumption for delivering a packet is minimized. Here, each wireless link is annotated with the link cost in terms of transmission energy over the link and the min-power path is the one that minimizes the sum of the link costs along the path. However, a routing algorithm using this metric may result in unbalanced energy spending among mobile nodes. When some particular mobile nodes are unfairly burdened to support many packet-relaying functions, they consume more battery energy and stop running earlier than other nodes disrupting the overall functionality of the ad hoc network. Thus, maximizing the network lifetime (the second metric shown above) is a more fundamental goal of an energy efficient routing algorithm: given alternative routing paths, select the one that will result in the longest network operation time.

Table I. Taxonomy of energy efficient routing protocols.

<table>
<tr><th colspan="2">Approach</th><th>Protocols</th><th>Goal</th></tr>
<tr><td rowspan="3">Minimize active communication energy</td><td rowspan="2">Transmission power control (Section 3.1)</td><td>• Flow argumentation routing (FAR) [5]
• Online max-min (OMM) [6]
• Power aware localized routing (PLR) [7]
• Minimum energy routing (MER) [8]</td><td>Minimize the total transmission energy but avoid low energy nodes</td></tr>
<tr><td>• Retransmission-energy aware routing (RAR) [9]
• Smallest common power (COMPOW) [10]</td><td>Minimize the total transmission energy while considering retransmission overhead or bi-directionality requirement</td></tr>
<tr><td>Load distribution (Section 3.2)</td><td>• Localized energy-aware routing (LEAR) [11]
• Conditional max-min battery capacity routing (CMMBCR) [12]</td><td>Distribute load to energy rich nodes</td></tr>
<tr><td>Minimize inactivity energy</td><td>Sleep/power-down mode (Section 3.3)</td><td>• SPAN [13]
• Geographic adaptive fidelity (GAF) [14]
• Prototype embedded network (PEN) [15]</td><td>Minimize energy consumption during inactivity</td></tr>
</table>

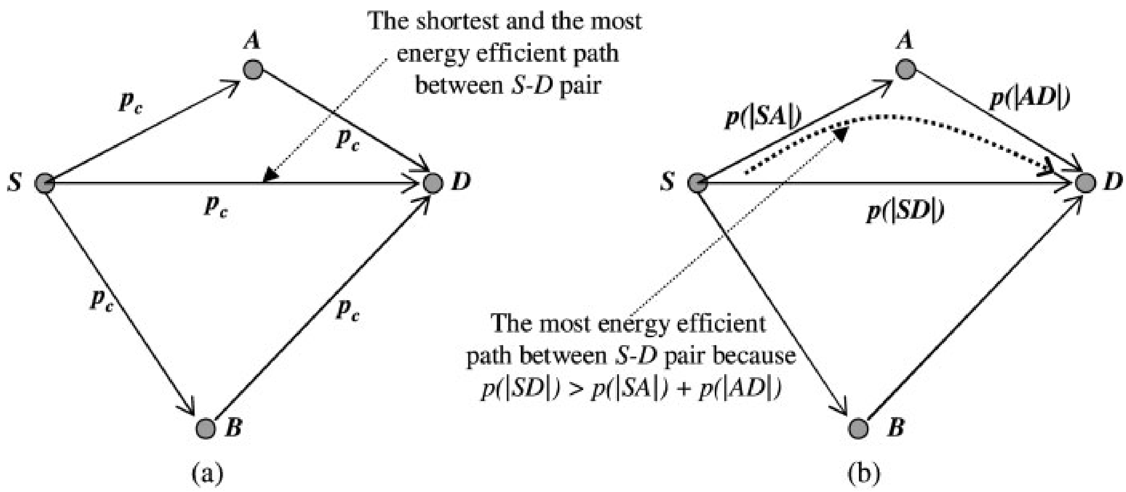

Fig. 1. Constant and variable transmission power model: (a) Constant power model (constant link cost p_c regardless of distance); (b) Variable power model (link cost $p(d)$ depends on distance).

However, since future network lifetime is practically difficult to estimate, the next three metrics have been proposed to achieve the goal indirectly. Variance of residual battery energies of mobile nodes is a simple indication of energy balance and can be used to extend network lifetime. Cost-per-packet metric is similar to the energy-per-packet metric but it includes each node's residual battery life in addition to the transmission energy. The corresponding energy-aware routing protocol prefers the wireless link requiring low transmission energy, but at the same time avoids the node with low residual energy whose node cost is considered high. With the last metric, each path candidate is annotated with the maximum node cost among the intermediate nodes (equivalently, the minimal residual battery life), and the path with the minimum path cost, *min-max path*, is selected. This is also referred to as *max-min path* in some protocols because they use nodes' residual battery life rather than their node cost.

3.1. Transmission Power Control Approach

A routing algorithm essentially involves finding an optimal route on a given network graph where a vertex represents a mobile node and an edge represents a wireless link between two end nodes that are within each other's radio transmission range. When a node's radio transmission power is controllable, its direct communication range as well as the number of its immediate neighbors are also adjustable. While stronger transmission power increases the transmission range and reduces the hop count to the destination, weaker transmission power makes the topology sparse which may result in network partitioning and high end-to-end delay due to a larger hop count.

In order to illustrate the potential benefits of controlling or adjusting transmission power, consider an example shown in Figure 1 which compares two transmission power models: *constant power model* and *variable power model*. If the transmission power is not controllable and thus constant (p_c), as shown in Figure 1(a), the routing path $S \rightarrow D$ is the shortest and at the same time the most energy efficient path. On the other hand, if the transmission power is controllable, it may be more energy efficient to transmit packets using intermediate nodes because the required transmission power, p, to communicate between two nodes has super-linear dependence on distance, d, i.e. $p(d) \propto d^2$ [7]. For example, in Figure 1(b), the routing path $S \rightarrow A \rightarrow D$ is more energy efficient than the route $S \rightarrow D$ since $p(|SD|) > p(|SA|) + p(|AD|)$. Node S conserves energy by lowering its radio power just enough to reach node A, but not enough to reach node D.

There has been active research on topology control of an MANET via transmission power adjustment [23–26] and the primary objective is to maintain a connected topology using the minimal power. Energy efficient routing protocols based on transmission power control find the best route that minimizes the total transmission power between a source–destination pair. It is equivalent to a graph optimization problem, where each link is weighted with the link cost corresponding to the required transmission power (e.g. $p(|SA|)$ for the link $S \rightarrow A$). Finding the most energy-efficient (*min-power*) route from S to D is equivalent to finding the least-cost path in the weighted graph. Section 3.1.1 introduces four such routing protocols and Section 3.1.2 discusses two link layer issues, such as retransmission overhead and bi-directionality requirement, for implementing the transmission power control approach.

3.1.1. Transmission power optimization

Flow Augmentation Routing (FAR) [5], *Online Max-Min Routing* (OMM) [6] and *Power aware Localized Routing* (PLR) [7] protocols fall into this category. Since each node runs the routing algorithm, equivalently the graph optimization algorithm, in a distributed way, it must be supplied with information such as the transmission energy over the wireless link (*link cost*) and the residual battery energy of the node (reciprocal of *node cost*). The latter is used to balance the energy consumption by avoiding low-energy nodes when selecting a route. The main goal of *Minimum Energy Routing* (MER) protocol [8] is not to provide energy efficient paths but to make the given path energy efficient by adjusting the transmission power just enough to reach to the next hop node. Table II shows the types of information required and the approach used to optimize energy efficiency and avoid low energy nodes.

FAR protocol [5]. The FAR protocol assumes a static network and finds the optimal routing path for a given source–destination pair that minimizes the sum of link costs along the path. Here, the link cost for link (i, j) is expressed as $e_{ij}^{x_1} E_i^{x_2} R_i^{-x_3}$, where e_{ij} is the energy cost for a unit flow transmission over the link and E_i and R_i are the *initial* and *residual energy* at the transmitting node i respectively, and x_1, x_2 and x_3 are non-negative weighing factors [5]. A link requiring less transmission energy is preferred ($e_{ij}^{x_1}$). At the same time, a transmitting node with high residual energy ($R_i^{-x_3}$) that leads to better energy balance is also preferred. Depending on the parameters x_1, x_2 and x_3, the corresponding routing algorithm achieves a different goal. For example, with $x_1 = 0$, $x_2 = 0$ and $x_3 = 0$, the link cost is always 1 and the optimal path in this case is equivalent to the minimum hop path.

While e_{ij} and E_i are constant for a wireless link (i, j), R_i continues to drop as communication traffic moves on. An optimal solution at one moment may not be optimal at a later time because R_i's and the corresponding links costs have changed. For this reason, FAR solves the overall optimal solution in an iterative fashion: Solve the optimal route for the first time step, update nodes' residual energy and link costs, and solve another for the next time step etc. Data generation rate at all nodes during each time step is assumed to be available beforehand.

OMM protocol [6]. FAR maximizes the network lifetime when data-generation rate is known. The OMM protocol achieves the same goal without knowing the data-generation rate in advance. It optimizes two different metrics of the nodes in the network: *Minimizing power consumption (min-power)* and *maximizing the minimal residual power (max-min)*. The second metric is helpful in preventing the occurrence of overloaded nodes.

Given all link costs, the OMM protocol first finds the optimal path for a given source–destination pair by using the *Dijkstra's algorithm* (*single-source shortest-path algorithm*). This min-power path consumes the minimal power ($P_{\min}$) but it is not necessarily the max-min path. In order to optimize the second metric, the OMM protocol obtains multiple near-optimal min-power paths that do not deviate much from the optimal value (i.e., less than $zP_{\min}$, where $z \geq 1$) and

Table II. Routing protocols based on transmission power control.

Routing protocol	Required information at each node in addition to that obtained during operation	Approach to optimize energy efficiency and to avoid low energy nodes
FAR [5]	Link costs of all links Node costs of all nodes Data generation rate at all nodes	—Use graph optimization algorithm —Include node cost in the link cost
OMM [6]	Link costs of all links Node costs of all nodes	—Use graph optimization algorithm —Select the max-min path among a number of best min-power paths
PLR [7]	Link costs of some links (from itself to its neighbors and to the destination) Node costs of some nodes (all its neighbors)	—Use graph optimization algorithm —Include node cost in the link cost
MER [8]	None (Each source node will obtain the link costs through the routing algorithm employed.)	—Adjust the transmission power just enough to reach the next hop node in the given routing path

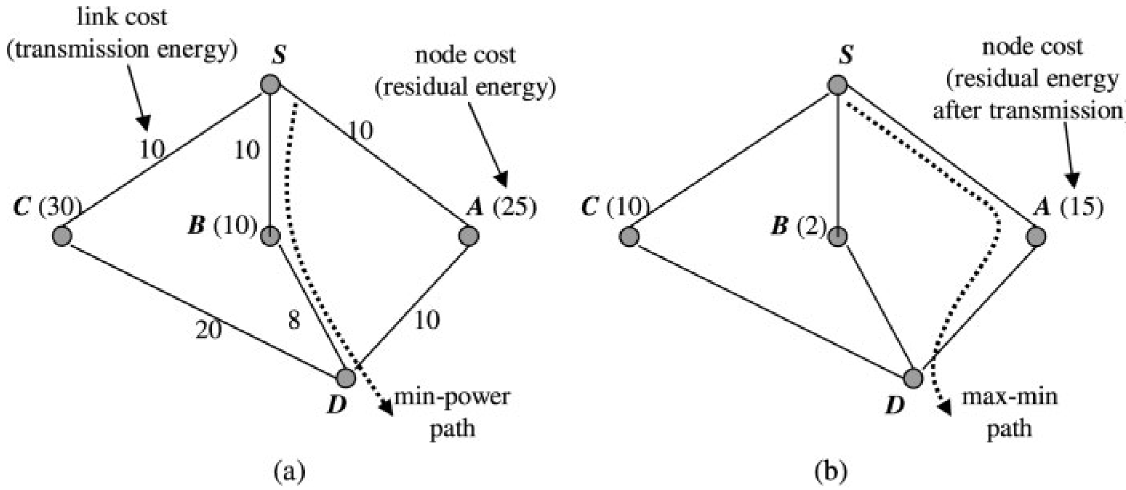

Fig. 2. Min-power path and max-min path in the OMM protocol: (a) Min-power path; (b) Max-min path.

selects the best path that optimizes the max–min metric.

Figure 2 shows an example of the algorithm for a given source (S) and a destination (D) pair. In Figure 2(a), $S \rightarrow B \rightarrow D$ is the min-power path as it consumes the minimal energy ($P_{\min} = 18$). If $z = 2$, alternative paths $S \rightarrow A \rightarrow D$ (path cost $= 22$) and $S \rightarrow C \rightarrow D$ (path cost $= 31$) can also be considered since their path costs are within the tolerance range ($zP_{\min} = 36$). In order to obtain the max-min path among those three path candidates, the node with the minimal residual power in each path must be compared. In this example, each path contains only one intermediate node and thus their residual energies (nodes A, B and C) are compared. Node C has the residual energy of 30 but it will drop to 9 if that path is used to transfer the packets from S to D. Similarly, nodes A and B will have the residual energy of 13 and 2 respectively, as shown in Figure 2(b). Therefore, the max-min path among the three min-power paths is $S \rightarrow A \rightarrow D$.

The parameter z measures the tradeoff between the max-min path and the min-power path. When $z = 1$, there will not be any alternative path candidate other than the optimal min-power path. Total energy consumption is optimized but energy balance is not considered. When $z = \infty$, all possible paths are considered and the min-power metric is ignored. Therefore, the proper selection of the parameter z is important in determining the overall energy performance. A *perturbation method* is used to adaptively compute z [6]. First, an initial value of z is randomly chosen and the residual energy of the most overloaded node, called a *lifetime*, is estimated based on the measurement during a fixed time period of MANET operation. Then, z is increased by a small constant and the lifetime is estimated again after the next time period. If the newly estimated lifetime is longer than the older one, the parameter z is increased accordingly; otherwise, z is decreased. Since the two successive estimates are calculated based on measurements during two different time periods, the whole process is based on the assumption that the network traffic distributions are similar as time elapses.

PLR protocol [7]. Routing algorithms based on global information, such as data-generation rate or power-level information of all nodes (node costs), may not be practical because each node is provided with only the local information. The PLR protocol is a localized, fully distributed energy-aware routing algorithm but it assumes that a source node has the location information of its neighbors and the destination. It is equivalent to knowing the link costs from itself to its neighbors and to the destination. Based on this information, the source cannot find the optimal path but selects the next hop through which the overall transmission power to the destination is minimized.

As discussed previously, a direct communication may consume more energy than an indirect communication via intermediate nodes due to the super-linear relationship between transmission energy and distance. In Figure 3, when node A has data packets to send to node D, it can either send them directly to D or via one of its neighbors (N_1, N_2 or N_3). Note that A to N_i is a direct transmission while N_i to D is an indirect transmission with some number of intermediate nodes

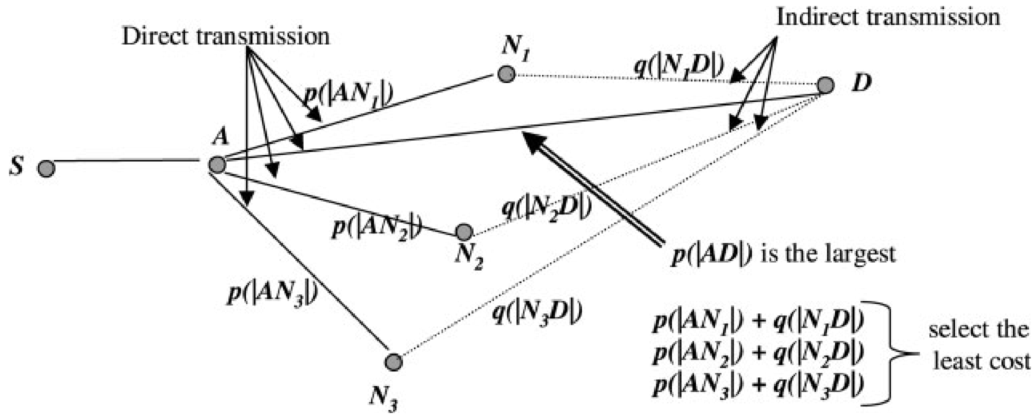

Fig. 3. Selection of the next hop node in the PLR protocol.

between N_i and D. In order to select the optimal route, node A evaluates and compares the power consumption of each path candidate. Power consumption of the direct transmission, $p(d)$, can be calculated if the distance is known, i.e. $p(d) = ad^{\alpha} + c$, where a and c are constants, d is the distance between two nodes and $\alpha \geq 2$. It has been shown that power consumption of indirect transmission is minimized when $(n-1)$ equally spaced intermediate nodes relay transmissions along the two end nodes, and the resultant minimum power consumption is $q(d)^{\dagger}$ [7]. Therefore, the node (A), whether it is a source or an intermediate node, selects one of its neighbors (N_1, N_2 *or* N_3) as the next hop node which minimizes $p(|AN_i|) + q(|N_iD|)$ (Figure 3).

Minimum energy routing (MER) protocol [8]. The transmission power control approach requires power information such as link costs and node costs. In practice, the following issues need to be addressed: (1) how to obtain accurate power information, (2) how much overhead is associated with the energy-aware routing and (3) how to maintain the minimum energy routes in the presence of mobility.

MER protocol [8] addresses these issues and implements the transmission power control mechanism in DSR [21] and IEEE 802.11 MAC protocol [27] with eight selectable options as shown in Table III. Option A modifies the header of a **route-request** packet to include the power used by the sender to transmit the packet. The receiving node uses this information as well as radio power level used to receive the packet to calculate the minimum power required for the successful transmission from the sender to itself. This per hop power information is appended at each intermediate node toward the destination and the destination node informs the source node via the **route-reply** packet. Then, the source node simply inserts this per hop power information in the data packet header so that all the intermediate nodes as well as the source itself transmit the data packet at the controlled power level. Option F applies the same power control mechanism on the MAC layer's ACK packets.

Options B, C and D are related to **route-cache** maintained in the DSR routing algorithm. In Option B, if the source has multiple route candidates in its cache, it calculates the total transmission energy for each possible route based on the power level information obtained via applying Option A and chooses the minimum energy route. In Option G, low-energy routes are dynamically adjusted when the required transmission power changes due to node mobility. Options E and H allow non-participating nodes to snoop on packet exchange and to suggest the sender a more energy efficient route at the routing and the MAC layer respectively.

Table III. Eight options in MER protocol [8].

Options	Implementation level
A: Routing packet-based power control	Routing software/ 802.11 Firmware
B: Minimum energy routing	Routing software
C: Cache replies off	Routing software
D: Internal cache timeouts	Routing software
E: Multi-hop route discovery	Routing software
F: MAC layer ACK power control	802.11 Firmware
G: Route maintenance using power sensing of data packets	Routing software
H: MAC level DATA/ACK snooping/gratuitous replies	802.11 Firmware

† $q(d)$ and n can be expressed as $q(d) = dc(a(\alpha-1)/c)^{1/\alpha} + da(a(\alpha-1)/c)^{(1-\alpha)/\alpha}$ and $n = d(a(\alpha-1)/c)^{1/\alpha}$. see Reference [7] for their derivations.

3.1.2. Power optimization with other practical requirements

As discussed in the previous subsection, the transmission power control is an effective approach to reduce energy consumption in a MANET. However, when applying the technique in routing protocols, some link layer issues need to be considered. This subsection will address these issues.

Link error and retransmission overhead. Transmission power control provides an opportunity to save energy by utilizing intermediate nodes between two distant nodes. However, the resultant path with many short-range links may perform worse than a path with fewer long-range links in terms of latency as well as energy consumption. This is because the path with many short-range links would cause more link errors that would result in more retransmissions [9].

Consider a path from a source node S to a destination node D that consists of $N-1$ intermediate nodes indexed as $2, 3, \ldots, N$ (the index of the source is 1 and that of the destination is $N+1$). The transmission energy over each link is $p_{i,i+1} = a{d_{i,i+1}}^{\alpha}$, where $d_{i,i+1}$ refers to the distance between nodes i and $i+1$, a is a constant determined based on the physical environment, and $\alpha \geq 2$. Assuming that each of N links ($L_{1,2}$, $L_{2,3}, \ldots, L_{N,D}$) has an independent link-error rate of $e_{i,i+1}$, the number of transmissions (including retransmissions) between node i and node $i+1$ is a geometrically distributed random variable X, such that

$$\text{Prob}\{X = x\} = e_{i,i+1}^{x-1} \times (1 - e_{i,i+1}), \quad \forall x$$

The mean number of transmissions for the successful transfer of a single packet is thus $1/(1 - e_{i,i+1})$. Therefore, the effective transmission energy between nodes i and $i+1$, which includes the effect of the transmission link error, is [9]

$$P_{i,i+1} = p_{i,i+1} \times \frac{1}{1 - e_{i,i+1}} = \frac{ad_{i,i+1}^{\alpha}}{1 - e_{i,i+1}}$$

When the packet-error rate ($e_{i,i+1}$) is not negligible, the benefit of indirect transmission via intermediate nodes can be overshadowed by the inflation factor, $1/(1-e_{i,i+1})$. *Retransmission-Energy Aware Routing* (RAR) protocol [9] modifies the optimization problem with the newly defined link cost to minimize the transmission energy while taking into account the effect of transmission link errors.

Bidirectionality requirement. To deliver packets with minimum energy, the transmission power control approach adjusts each node's radio power and allows different transmission power levels at different nodes. However, in order for the link-level connectivity of a MANET to work correctly, any pair of communicating nodes must share a bidirectional link [10]. For example, at the link level, control packet handshaking is usually employed to enhance the link-level reliability in error-prone wireless environment; i.e. when a node receives a packet, it immediately replies back to the sender with the ACK. If no ACK is returned to the sender, it automatically retransmits the packet. In addition, *request to send* (RTS) and *clear to send* (CTS) packets are exchanged to deal with the *hidden terminal problem* [28]. Therefore, when two nodes have different power levels, data communication along one direction (from the node with stronger transmission power to the other node with weaker transmission power) is possible but not in the reverse direction.

Smallest Common Power (COMPOW) protocol [10] presents one simple solution to maintain bidirectionality between any pair of communicating nodes in a MANET. This is achieved by having all the nodes in the MANET maintain a common transmission power level (P_i). If P_i is too low, a node can reach only a fraction of the nodes in the MANET as in Figure 4(a). If P_i is very high, a node can directly reach all other nodes as in Figure 4(b) but results in high energy consumption. In fact, a node can directly or indirectly reach the entire MANET with a smaller P_i as shown in Figure 4(c). Therefore, the optimum power level (P_i) is the smallest power level at which the entire network is connected.

In COMPOW, it is assumed that the transmission power levels cannot be arbitrarily adjusted but instead it must be selected among a small number of discrete power levels ($P_1, P_2, \ldots, P_{\max}$) [10]. Different power levels result in different node connectivity since they cover different radio transmission ranges. Each node maintains a routing table as in table-driven routing mechanism (see Section 2), but one for each power level ($RT_{P1}, RT_{P2}, \ldots, RT_{P\max}$). The number of entries in RT_{Pi}, denoted as $|RT_{Pi}|$, means the number of reachable nodes at P_i. This includes directly connected nodes as well as indirectly connected nodes via intermediate nodes. By exchanging these routing tables, nodes find the minimal P_i that satisfies $|RT_{Pi}| = n$ for all nodes, where n is the total number of nodes in the MANET. Extended solutions are also discussed in Reference [10] for the case where there

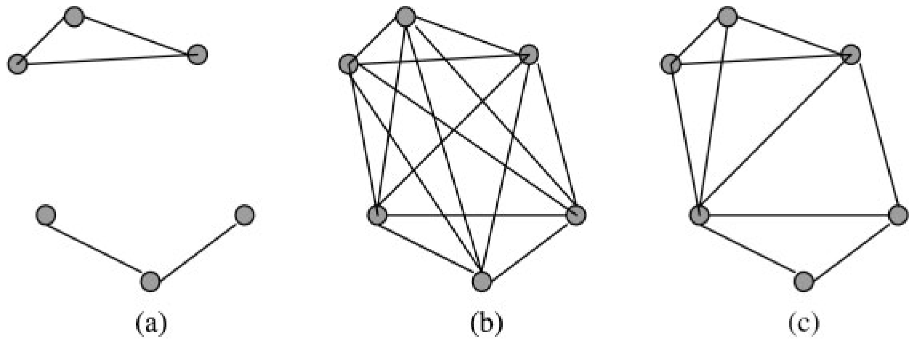

Fig. 4. Proper selection of the common transmission power level in COMPOW: (a) P_i is too low; (b) P_i is too high; (c) P_i is optimal.

are many discrete power levels and where the latency involved with switching power levels is not negligible.

3.2. Load Distribution Approach

The specific goal of the load distribution approach is to balance the energy usage of all mobile nodes by selecting a route with underutilized nodes rather than the shortest route. This may result in longer routes but packets are routed only through energy-rich intermediate nodes. Protocols based on this approach do not necessarily provide the lowest energy route, but prevent certain nodes from being overloaded, and thus, ensure longer network lifetime. This subsection discusses two such protocols: *Localized Energy-Aware Routing* (LEAR) [11] and *Conditional Max-Min Battery Capacity Routing* (CMMBR) [12] protocols.

LEAR protocol [11]. The LEAR routing protocol is based on DSR [20] but modifies the route discovery procedure for balanced energy consumption. In DSR, when a node receives a **route-request** message, it appends its identity in the message's header and forwards it toward the destination. Thus, an intermediate node always relay messages if the corresponding route is selected. However, in LEAR, a node determines whether to forward the **route-request** message or not depending on its *residual battery power* (E_r). When E_r is higher than it's *threshold value* (Th_r), the node forwards the **route-request** message; otherwise, it drops the message and refuses to participate in relaying packets. Therefore, the destination node will receive a **route-request** message only when all intermediate nodes along a route have good battery levels, and nodes with low-battery levels can conserve their battery power.

LEAR is a distributed algorithm where each node makes its routing decision based only on local information such as E_r and Th_r. As E_r decreases with the passing of time, the value of Th_r must also be decreased adaptively in order to identify energy-rich and energy-hungry nodes in a relative sense. For example, if the source node does not receive any reply for a **route-request** message, the source re-sends the same **route-request** message. If an intermediate node receives the duplicate request message, it adjusts (i.e. lowers) its Th_r to allow forwarding to continue. A sequence number is used to distinguish between the original and the re-sent **route-request** message.

A complication can arise when **route-cache** replies are directly sent to the source without evaluating the residual battery levels of all following intermediate nodes. To prevent this from occurring, a new control message, **route-cache**, is used as shown in Figure 5. In the original DSR, when an intermediate node (node B) finds a route in its route cache, it stops broadcast forwarding and sends a **route-reply** back to the source. However, in LEAR, the intermediate node (node B) stops broadcast forwarding the **route-request** message but continues to forward the **route-cache** message ($B \rightarrow C_1 \rightarrow C_2 \rightarrow D$ in this example). This does not add any significant traffic to the network because the **route-cache** message can be delivered in unicast mode.

CMMBCR protocol [12]. As in LEAR, the CMMBCR protocol uses the concept of a threshold to maximize the lifetime of each node and to use the battery fairly. If all nodes in some possible routes between a source–destination pair have larger remaining battery energy than the threshold, the min-power route among those routes is selected. If all possible routes have nodes with lower battery capacity than the threshold, the max-min route is selected. However, unlike LEAR, the threshold value is fixed leading to a simpler design.

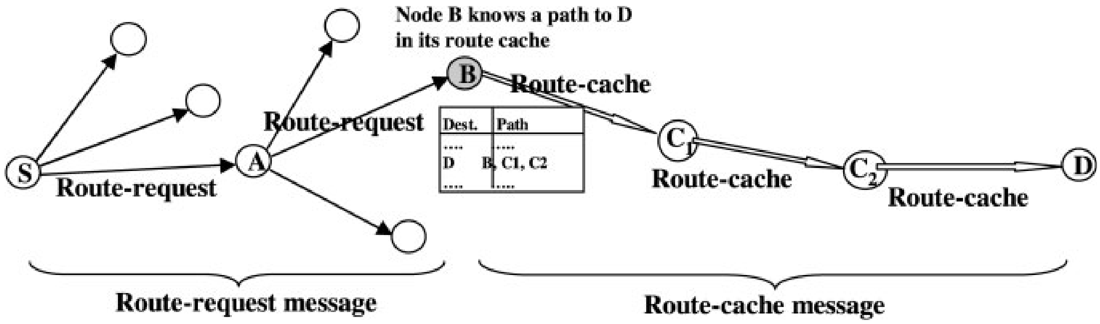

Fig. 5. Route-cache message in the LEAR algorithm.

Table IV. Power down states and modes.

<table>
<tr><th colspan="3">IEEE 802.11
(Lucent's WaveLAN-II supporting 2 Mbps
with radio range up to 250 meters)</th><th colspan="2">Bluetooth
(Nokia's Bluetooth supporting 768 Kbps with
radio range up to 10 ~ 100 meters)</th></tr>
<tr><th>Hardware state</th><th colspan="3">Mode of operation (MAC-level)</th><th>Hardware state</th></tr>
<tr><td rowspan="4">Awake</td><td rowspan="3">Active</td><td>Transmit (300 mA)</td><td rowspan="3">Active (40–60 mA)</td><td rowspan="6">Connection</td></tr>
<tr><td>Receive (250 mA)</td></tr>
<tr><td>Idle or listen (230 mA</td></tr>
<tr><td colspan="2" rowspan="2">Power save</td><td>Sniff</td></tr>
<tr><td rowspan="3">Doze</td><td>Hold</td></tr>
<tr><td colspan="2" rowspan="2">Sleep (9 mA)</td><td>Park</td></tr>
<tr><td>Standby (0.55 mA)</td><td>Standby</td></tr>
</table>

The authors of this protocol proposed an interesting performance metric for measuring the energy balance: *expiration sequence*, defined as the sequence of times when mobile nodes exhaust their battery capacity [12]. Traditional metrics for energy balance are variation of remaining battery capacity, ratio of minimum to average remaining battery capacity and the network lifetime measured as the time when any node exhausts its battery capacity for the first time. Since these metrics provide limited information on energy balance, the expiration sequence gives more accurate information on how fairly energy is expended.

3.3. Sleep/Power-Down Mode Approach

Unlike the previous two subsections, the sleep/power-down mode approach focuses on inactive time of communication. Since most radio hardware support a number of low power states, it is desirable to put the radio subsystem into the sleep state or simply turn it off to save energy. Table IV summarizes hardware low power states and the MAC-level power down modes supported in IEEE 802.11 and Bluetooth wireless LAN protocols as well as typical power consumption values of the devices implementing the protocols. For example, *Lucent*'s *WaveLAN-II* based on *IEEE 802.11 wireless LAN standard* consumes 250 mA and 300 mA when receiving and transmitting respectively, while consumes only 9 mA in sleep mode [29].

However, when all the nodes in a MANET sleep and do not listen, packets cannot be delivered to a destination node. One possible solution is to elect a special node, called a *master*, and let it coordinate the communication on behalf of its neighboring slave nodes. Now, slave nodes can safely sleep most of time saving battery energy. Each slave node periodically wakes up and communicates with the master node to find out if it has data to receive or not, but it sleeps again if it is not addressed.[‡]

In a multihop MANET, more than one master node would be required because a single master cannot cover the entire MANET. Figure 6 shows the master-slave network architecture, where mobile nodes, except master nodes, can save energy by putting

[‡]According to IEEE 802.11 terminology shown in Table IV, each node operates in power save mode by switching between *awake* and *doze* state in synchrony with the master node. See *time synchronization function* defined in IEEE 802.11 [27].

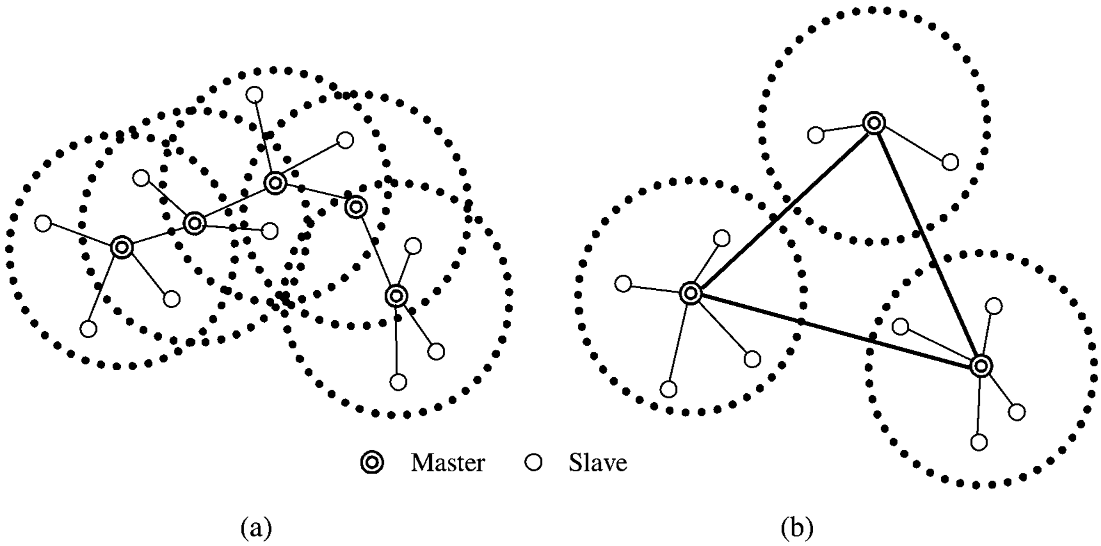

Fig. 6. Master-slave MANET architecture: (a) Symmetric power model; (b) Asymmetric power model.

their radio hardware into low power state. The master-slave architecture in Figure 6(a) is based on symmetric power model, where master nodes have the same radio power and thus the same transmission range as slave nodes. On the other hand, Figure 6(b) shows the asymmetric power model, where master nodes have longer transmission range. While this type of hierarchical network architecture has been actively studied for different reasons, such as interference reduction and ease of location management [3], the problem of selecting master nodes and maintaining the master-slave architecture under dynamic node configurations is still a challenging issue.

This subsection introduces three routing algorithms that exploit the radio hardware's low power states. The *SPAN* protocol [13] and the *Geographic Adaptive Fidelity* (GAF) protocol [14] employ the master-slave architecture and put slave nodes in low power states to save energy. Unlike SPAN and GAF, *Prototype Embedded Network* (PEN) protocol [15] practices the *sleep period operation* in an asynchronous way without involving master nodes.

SPAN protocol [13]. To select master nodes in a dynamic configuration, the *SPAN* protocol employs a distributed *master eligibility rule* so that each node independently checks if it should become a master or not. The rule is that *if two of its neighbors cannot reach each other either directly or via one or two masters, it should become a master* [13]. This is shown in Figure 7 where nodes *B* and *D* become masters. If either *B* or *D* does not elect itself as a

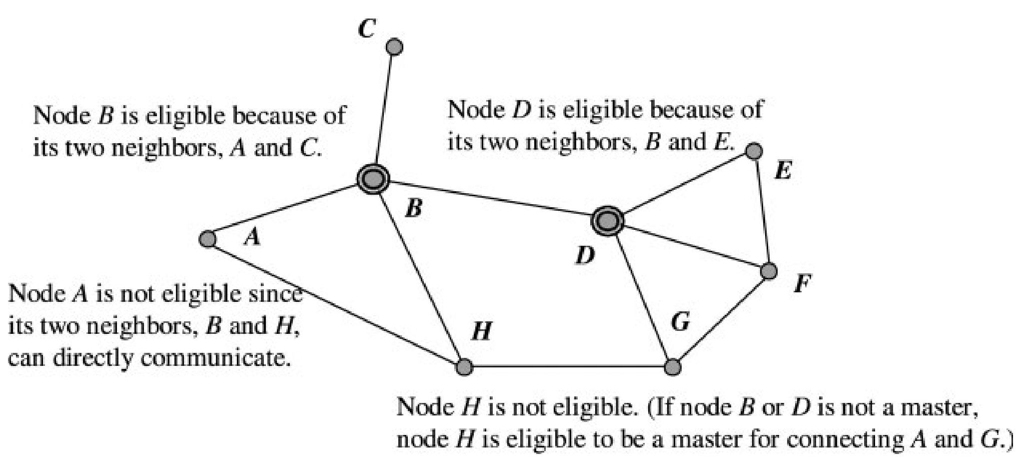

Fig. 7. Master eligibility rule in the SPAN protocol.

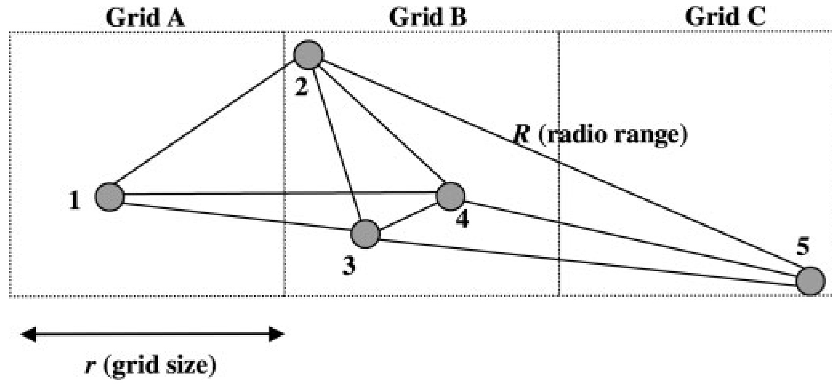

Fig. 8. Virtual grid structure in the GAF protocol.

master, node H is eligible (thus, the master selection process is not deterministic). This rule does not yield the minimum number of master nodes but it provides robust connectivity with substantial energy savings. However, the master nodes are easily overloaded. To prevent this and to ensure fairness, each master periodically checks if it should withdraw as a master and gives other neighbor nodes a chance to become a master. Non-master nodes also periodically determine if they should become a master or not, based on the master eligibility rule.

Another benefit of the master-slave architecture is that master nodes can play an important role in routing by providing a routing backbone as in Figure 6(a). Control traffic as well as channel contention will also be reduced because the routing backbone helps to avoid the broadcast flooding of **route-request** messages.

GAF protocol [14]. In GAF protocol, each node uses location information based on GPS to associate itself with a '*virtual grid*' so that the entire area is divided into several square grids, and the node with the highest residual energy within each grid becomes the master of the grid. Other nodes in the same grid can be regarded as redundant with respect to forwarding packets and thus they can be safely put to sleep without sacrificing the '*routing fidelity*' (or routing efficiency). The slave nodes switch between off mode and listening mode with the guarantee that one master node in each grid will stay awake to route packets. For example, nodes 2, 3 and 4 in the virtual grid B in Figure 8 are equivalent in the sense that one of them can forward packets between nodes 1 and 5 while the other two can sleep to conserve energy. The grid size r can be easily deduced from the relationship between r and the radio range R as $r^2 + (2r)^2 \leq R^2$ or $r \leq R/\sqrt{5}$.

Master election rule in GAF is as follows. Nodes are in one of three states as shown in Figure 9: *sleeping*, *discovering* and *active*. Initially, a node is in the discovery state and exchanges discovery messages including grid IDs to find other nodes within the same grid. A node becomes a master if it does not hear any other discovery message for a predefined duration T_d. If more than one node is in the discovery state, one with the longest expected lifetime becomes a master. The master node remains active to handle routing for T_a. After T_a, the node changes its state to discovery to give an opportunity to other nodes within the same grid to become a master. In scenarios with high

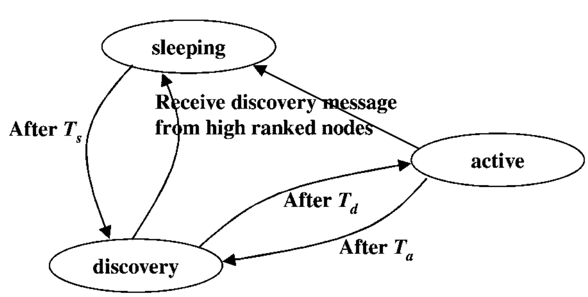

Fig. 9. State transition in the GAF protocol [14].

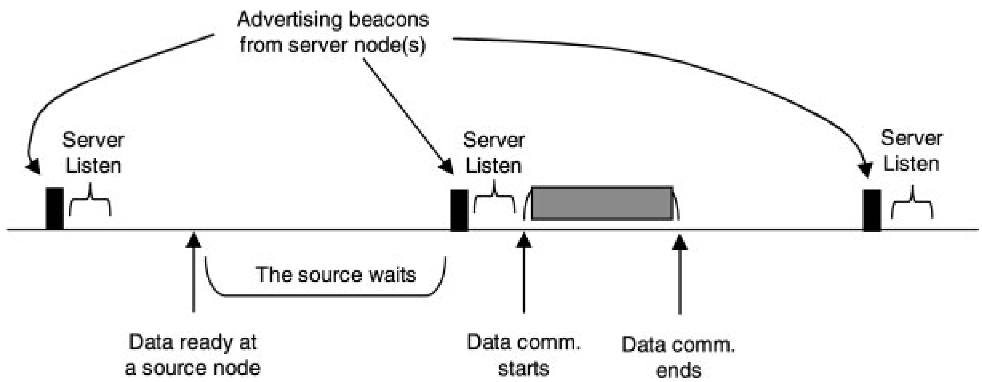

Fig. 10. Source and server node activities.

mobility, sleeping nodes should wake up earlier to take over the role of a master node, where the sleeping time T_s is calculated based on the estimated time the nodes stays within the grid.

PEN protocol [15]. As in SPAN and GAF, the PEN protocol exploits the low-duty cycle of communication activities and powers down the radio device when it is idle. However, unlike SPAN and GAF, nodes interact '*asynchronously*' without master nodes and thus, costly master selection procedure as well as the master overloading problem can be avoided. But in order for nodes to communicate without a central coordinator, each node has to periodically wake up, advertise its presence by broadcasting beacons, and listen briefly for any communication request before powering down again. A transmitting source node waits until it hears a beacon signal from the intended receiver or server node. Then, it informs its intention of communication during the listening period of the server and starts the communication. Figure 10 shows those source and server activities along a time chart.

Route discovery and route maintenance procedures are similar to those in AODV [22], i.e. on-demand route search and routing table exchange between neighbor nodes. Due to its asynchronous operation, the PEN protocol minimizes the amount of active time and thus saves substantial energy. However, the PEN protocol is effective only when the rate of interaction is fairly low. It is thus more suited for applications involving simple command traffic rather than large data traffic.

4. Conclusion

A MANET consists of autonomous, self-organizing and self-operating nodes, each of which communicates directly with the nodes within its wireless range or indirectly with other nodes via a dynamically computed, multi-hop route. Due to its many advantages and different application areas, the field of MANETs is rapidly growing and changing. While there are still many challenges that need to be met, it is likely that MANETs will see wide-spread use within the next few years.

In order to facilitate communication within an MANET, an efficient routing protocol is required to discover routes between mobile nodes. Energy efficiency is one of the main problems in an MANET, especially in designing a routing protocol. In this paper, we surveyed and classified a number of energy-aware routing schemes. In many cases, it is difficult to compare them directly since each method has a different goal with different assumptions and employs different means to achieve the goal. For example, when the transmission power is controllable, the optimal adjustment of the power level is essential not only for energy conservation but also for the interference control (Section 3.1). When node density or traffic density is far from uniform, a load distribution approach (Section 3.2) must be employed to alleviate the energy imbalance problem. The sleep/power-down mode approach in Section 3.3 is essentially independent of the other two approaches because it focuses on inactivity energy. Therefore, more research is needed to combine and integrate some of the protocols presented in this paper to keep MANETs functioning for a longer duration.

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