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Energy-Efficient Topology Control for Wireless Ad Hoc Sensor Networks[*]

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Energy-saving is a critical issue in mobile computing. Given a set of hosts which forms a wireless ad hoc network and an initial energy for each host, this paper considers the *topology control problem* by tuning the transmission powers of hosts to control the structure of the network. The target topology includes 1-edge-, 1-vertex-, 2-edge-, and 2-vertex-connected graphs. The goal is to maximize the *lifetime* of the network, i.e., the amount of time when all hosts remain alive. Two variations of the problem, where hosts' powers can be *fixed* or *variable* during the lifetime of the network, are discussed. We show that optimal lifetimes can be obtained by using a simple *minimum spanning tree* construction under the fixed power assumption.

Keywords: ad hoc network, energy saving, power control, sensor network, topology control, wireless communication

1. INTRODUCTION

Smart sensors, which are created by combining tiny sensing materials with electrical circuits, have been proposed recently for various applications, such as military and environment surveillance. A *wireless sensor network* is established by enhancing each sensor with wireless communication capability and networking the sensors together [5, 7]. Another similar development is the *wireless ad hoc network*, which is characterized by independent mobile hosts without support of a fixed infrastructure [8]. Both sensor networks and ad hoc networks share the feature of *multi-hop* communication.

Portable devices are typically powered by batteries. One major concern for almost all kinds of portable devices is how to manage the limited battery resource that constrains the life of the network. Extensive research has been devoted to ad hoc sensor networks in this respect. Using power control to reduce interference and improve throughput was addressed in [4, 16]. Topology control achieved by tuning transmission powers was discussed in [3, 9, 14]. Power-aware routing for ad hoc networks was studied in [1, 10-12]. Both IEEE 802.11 and Bluetooth support low-power modes [2, 15]. How to design low-power modes on 802.11-based multi-hop networks was addressed in [13].

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In this paper, we consider the topology control problem in an ad hoc sensor network. Topology in ad hoc networks is not static since it changes as we change the transmission powers of hosts. Given a set of hosts which forms a wireless ad hoc network, an initial energy of each host, and the traffic ratio of each host, we consider the problem of determining the best transmission power of each host such that the network topology is 1-edge-, 1-vertex-, 2-edge-, or 2-vertex-connected. The goal is to maximize the *lifetime* of the network, i.e., the amount of time when all hosts remain alive. Two variations of the problem, where hosts' powers can be *fixed* or *variable* throughout the lifetime of the network, are discussed. We show that optimal lifetimes can be obtained by using a simple *minimum spanning tree* construction under the fixed power assumption.

Our work is most related to [9], where topology control algorithms to form 1-vertex and 2-vertex-connected graphs were presented. However, the initial energies of all hosts were assumed to be the same, which thus can be regarded as a special case of ours. The goal in [9] was different: to minimize the maximal transmission power of each host in the network. Despite this difference, that approach basically also employs a minimum spanning tree construction. The result is optimal (but the resulting graph is not necessarily the same as that found by ours). Therefore, our contribution is to extend the applicability of [9] to an environment where hosts' initial energies are not necessarily equal.

The remainder of this paper is organized as follows. Section 2 formally defines the problem under consideration. Sections 3 and 4 present our solutions under the fixed and variable power constraints, respectively. Conclusions are drawn in section 6.

2. PROBLEM DEFINITION

We are given a set V of nodes on a 2-D Euclidean plane. The distance between two hosts, x and y, is denoted by $dist(x, y)$. Since wireless communication suffers from propagation loss, the least transmission power needed for x and y to communicate correctly is modeled by

$$\lambda(x, y) = c \times dist(x, y)^d,$$

where c is a constant and d is an environment-dependent constant. The energy level of host x is a function of time and is denoted as $B_x(t)$, where $t \geq 0$ represents time. $B_x(0)$ is a given parameter representing x's initial energy. We adopt the following energy consumption model. Suppose x has energy $B_x(t)$ at time t and uses power P_s to send. Then after time interval Δt, its remaining energy becomes

$$B_x(t + \Delta t) = B_x(t) - (P_s \times \alpha_x \times \Delta t + P_r \times \Delta t),$$

where α_x is the fraction of time that x transmits during Δt and P_r is the power consumed in data reception. Note that P_s can be a variable, while P_r should remain constant. For example, suppose that at time t, we would like to connect two hosts, x and y, together using the least power $\lambda(x, y)$. Then this link can be sustained for the following length of time:

$$\min\left\{\frac{B_x(t)}{\lambda(x,y)\times\alpha_x + P_r}, \frac{B_y(t)}{\lambda(x,y)\times\alpha_y + P_r}\right\}.$$

This work considers topology control by tuning transmission powers. Therefore, the transmission power of x is also a function of time, denoted as $P_{s,x}(t)$, which is yet to be determined. Here, we assume that x's traffic ratio α_x remains constant at all times[1]. But different hosts' traffic ratios are not necessarily the same. By tuning transmission powers, we can control the network topology. Specifically, for two hosts x and y, if at instant t, both $P_{s,x}(t)$ and $P_{s,y}(t) \geq \lambda(x, y)$, then we say that there is a communication link between x and y. As a result, the network topology is also a function of time, denoted as $G(t) = (V, E(t))$, where $E(t)$ is the link set induced by the power setting at time t. Our goal is to maintain a certain property of $G(t)$ while keeping its lifetime as long as possible.

Definition 1 Given a set of hosts V, the initial energy function $B_x(0)$ and traffic ratio α_x of each host x, and an integer k, the power adjustment problem $PA_e(k)$ (resp., $PA_v(k)$) is to determine the transmission power of each host such that the induced network $G(t) = (V, E(t))$ remains k-edge-connected (resp., k-vertex-connected) during the time interval $[0, T]$, and such that T is maximized.

We make three remarks below. First, a graph is k-edge-connected if the deletion of any $k - 1$ links in the network does not partition the network; and a graph is k-vertex-connected if the deletion of any $k - 1$ vertices in the network does not partition the network [6]. Under these definitions, 1-edge-connected is equivalent to 1-vertex-connected, but this is not true when $k \geq 2$. Typically, vertex-connected is stronger than edge-connected. Second, if all the hosts have the same initial energy, then this problem degenerates to the case considered in [9]. Third, unidirectional links may exist in the network since hosts may have different transmission powers. However, only bi-directional links are included $G(t)$ since in practice, unidirectional links are difficult to use.

3. TOPOLOGY CONTROL UNDER FIXED POWERS

By "fixed powers," we mean that for any host x, its power function $P_{s,x}(t)$ remains unchanged throughout the lifetime of the network. As a result, the topology $G(t)$ remains unchanged, too. Below, we first present an optimal solution for $PA_e(1)$ and $PA_v(1)$, followed by one for $PA_e(2)$ and $PA_v(2)$.

Our solution for $PA_e(1)$ and $PA_v(1)$ is similar to the typical minimum spanning tree construction in graph theory. However, here, we use how long a link can be sustained as the metric in the construction. Specifically, given two nodes $x, y \in V$, the *lifetime* of link (x, y) is defined as

$$t_{(x,y)} = \min\left\{\frac{B_x(0)}{\lambda(x,y)\times\alpha_x + P_r}, \frac{B_y(0)}{\lambda(x,y)\times\alpha_y + P_r}\right\}.$$

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[1] We believe that solving the topology control problem is very difficult, if not infeasible, if hosts have changing traffic ratios. In practice, sensor network applications may impose constant traffic ratios on hosts if sensors collect data at a regular speed, and if a data fusion technique is applied.

A link with a longer lifetime implies a lower cost and, thus, will be considered for inclusion earlier. The solution for $PA_e(1)$ and $PA_v(1)$ is formally derived below. Initially, for each host x, its transmission power is set to 0 and will be increased gradually.

```
Algorithm FPA(1)        // Fixed power adjustment for $PA_e(1)$ and $PA_v(1)$
1. From $V$, construct all possible $C_2^{|V|}$ node pairs. Sort these node pairs into a list (denoted as PAIR), based on their lifetimes in descending order.
2. Construct $|V|$ clusters of node(s) by placing each node into one separate cluster.
3. Retrieve the first node pair $(x, y)$ from PAIR. If $x$ and $y$ are not in the same cluster, proceed to the next step. Otherwise, repeatedly retrieve more node pairs from PAIR until one $(x, y)$, such that $x$ and $y$ are in different clusters, is found.
4. Connect link $(x, y)$ by performing the following two steps.
   a) If $P_{s,x}(t) < \lambda(x, y)$, set $P_{s,x}(t) = \lambda(x, y)$.
   b) If $P_{s,y}(t) < \lambda(x, y)$, set $P_{s,y}(t) = \lambda(x, y)$.
5. Merge the two clusters containing $x$ and $y$ into one cluster. If all the nodes in $V$ are already in one cluster, terminate the algorithm; otherwise, go to step 3 and repeat.
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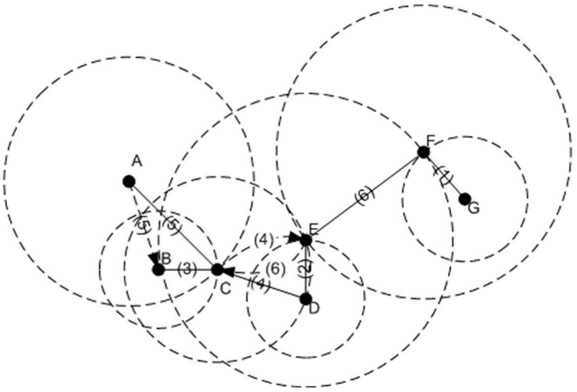
FPA(1) employs a greedy approach similar to the standard minimum spanning tree construction by using the lifetimes of links as the costs. However, one interesting property is that the resulting network is not necessarily a spanning tree — cycles may exist. The reason is that whether or not two nodes are connected is not determined by their link lifetime, but by how much power they use. With sufficiently large powers, links can be connected. Thus, two separate clusters may already have links (or unidirectional links). This is why we need to check the nodes' powers in step 4.

Fig. 1 shows an example (here we assume that the traffic ratio is the same for all hosts). By means of *FPA*(1), we will first connect link (F, G), followed by links (D, E) and (B, C) (the order is shown by the numbers in parentheses). The next link connected is (C, D). While (C, D) is being connected, a side-effect directed link from C to E will appear. This is because C can reach E, but the reverse is not true. The next link connected is (A, C), with a side-effect from A to B. The last link is (E, F), with two side-effect links from E to B and C. Thus, we have a cycle from C to D to E.



Node	L(x)	Bx(0)
A	(-5, 15)	300
B	(0, 0)	150
C	(10, 0)	350
D	(25, -5)	200
E	(25, 5)	190
F	(45, 20)	400
G	(52,12)	300

Fig. 1. Example of the execution of *FPA*(1). Dashed arrows are side-effect links.

Lemma 1 The lifetime of the network constructed by means of *FPA*(1) is the lifetime of the link (x, y), which is used to merge the last two clusters in step 4.

Proof: This is a natural result based on the fact that *PAIR* is sorted in descending order.❑

Lemma 2 Consider the last link (x, y) included in step 4 of *FPA*(1). Let C_1 and C_2 be the two clusters before link (x, y) is connected. The following property holds:

$$t_{(x,\, y)} = \max\{t_{(x',\, y')} \mid x' \in C_1, y' \in C_2\}.$$

Proof: Consider any link (x', y') other than (x, y) that also connects the two clusters C_1 and C_2. Suppose, for the sake of contradiction, that the lifetime of (x', y') is longer than that of (x, y). Then in the sorted list *PAIR*, (x', y') will appear before (x, y). This implies that (x', y') will be examined for making the connection in step 3 earlier than (x, y). Since by step 4, C_1 and C_2 are not yet connected when (x, y) is connected, such a link (x', y') can not exist. Thus, this lemma is proved. ❑

Theorem 1 Under the fixed power constraint, the network lifetime obtained by means of *FPA*(1) is optimal for both the $PA_e(1)$ and $PA_v(1)$ problems.

Proof: Consider the last link (x, y) included in step 4 of *FPA*(1). Let C_1 and C_2 be the two clusters before link (x, y) is connected. It is clear that any algorithm must establish at least one link between C_1 and C_2. Lemma 2 guarantees that (x, y) is the link that has the maximum lifetime among all the links connecting C_1 and C_2. Therefore, $t_{(x,\, y)}$ is an upper bound on the network lifetime that can be obtained by any algorithm. Lemma 1 states that the lifetime of the network found by means of *FPA*(1) is $t_{(x,\, y)}$, which proves this theorem. ❑

Next, we will extend our result to the $PA_e(2)$ and $PA_v(2)$ problems. The algorithm utilizes the resulting network of *FPA*(1) and further extends the network to the 2-edge- or 2-vertex-connected cases. Note that although the same algorithm is used for $PA_e(2)$ and $PA_v(2)$, the resulting networks are not necessarily the same.

```
Algorithm FPA(2)        // Fixed power adjustment for $PA_e(2)$ and $PA_v(2)$
1. Run FPA(1) to obtain the transmission power $P_{s,x}(t)$ of each host $x$. Identify all 2-edge-/
   2-vertex-connected components in the resulting network (refer to [6] for details).
2. Again, let PAIR be the sorted list of all $C_2^{|V|}$ node pairs.
3. Retrieve the first node pair $(x, y)$ from PAIR. If $x$ and $y$ are not in the same 2-edge-/
   2-vertex-connected component, then proceed to the next step. Otherwise, repeatedly
   retrieve more node pairs from PAIR until one $(x, y)$, such that $x$ and $y$ are in different
   components, is found.
4. Connect link $(x, y)$ by performing the following two steps.
   a) If $P_{s,x}(t) < \lambda(x, y)$, set $P_{s,x}(t) = \lambda(x, y)$.
   b) If $P_{s,y}(t) < \lambda(x, y)$, set $P_{s,y}(t) = \lambda(x, y)$.
5. Identify all 2-edge-/2-vertex-connected components in the network. If only one com-
   ponent remains, terminate the algorithm; otherwise, go to step 3.
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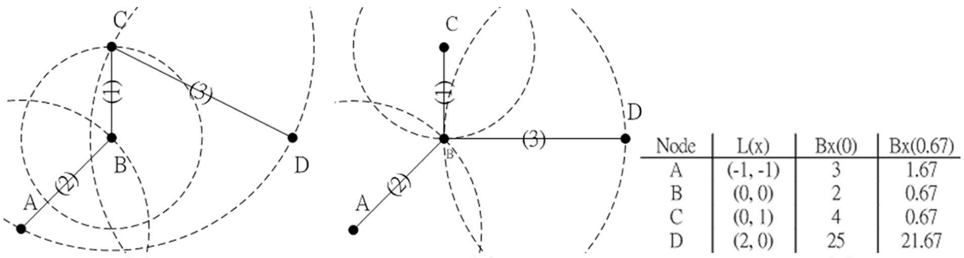
Theorem 2 Under the fixed power constraint, the network lifetime obtained by means of *FPA*(2) is optimal for both the $PA_e(2)$ and $PA_v(2)$ problems.

Proof: Before the last link, say (u, v), is added by *FPA*(2), there must exist at least two 2-vertex/2-edge-connected components and at least one articulation point or cut-edge. Let C_1 and C_2 be the two connected components where u and v are located, respectively. If any algorithm wishes to avoid using (u, v) to achieve a longer network lifetime than *FPA*(2) does, it must construct two vertx/edge-disjoint paths between u and v without using the direct link (u, v). Furthermore, each link on these two disjoint paths must have a lifetime longer than that of (u, v).

On these two disjoint paths, there must exist at least one link, say (x, y), which is not selected by *FPA*(2), and is located at two distinct connected components such that the articulation point or cut-edge between these two components can be eliminated. Note that in the degenerated case, it is possible that these two components will be equal to C_1 and C_2. However, observe that step 3 of *FPA*(2) will retrieve links according to the *PAIR* list, and that the *PAIR* list is sorted in descending order of link lifetimes. Any link that connects different connected components and has a lifetime longer than that of (u, v) will be selected by *FPA*(2) to make a connection in step 3. This contradicts our earlier assumption that (x, y) is not selected; thus, this theorem is proved. ❑

4. TOPOLOGY CONTROL UNDER VARIABLE POWERS

FPA(1) and *FPA*(2) are optimal only when the nodes' transmission powers, once selected, remain unchanged. Under the variable power assumption, *FPA*(1) and *FPA*(2) are not necessarily optimal, as proved by the following counterexample. Fig. 2 shows a 4-node network. By running *FPA*(1) at time $t = 0$, the optimal power setting is that shown in Fig. 2 (a). With this setting, at time $t = 0.67$, if we run *FPA*(1) again, a new optimal setting is changed to that in Fig. 2 (b). Therefore, a variable power setting is better in this case. The detailed parameters are shown in Fig. 2 (c).



Node	L(x)	Bx(0)	Bx(0.67)
A	(-1, -1)	3	1.67
B	(0, 0)	2	0.67
C	(0, 1)	4	0.67
D	(2, 0)	25	21.67

(a) (b) (c)

Fig. 2. An example of using variable powers: (a) first power setting, (b) second power setting, and (c) detailed parameters.

To dynamically adjust hosts' transmission powers, we first derive a naive solution by periodically reevaluating the network topology as shown below.

```
Algorithm VPA(k)    // Variable power adjustment for $PA_e(k)$ and $PA_v(k)$, $k = 1$ or 2
1. Run FPA(k) on the current network to determine hosts' transmission powers.
2. After a fixed interval $\Delta t$, check hosts' remaining energies. If none of the hosts are dead,
   go back to step 1; otherwise, terminate the algorithm.
```

The above algorithm has an unspecified parameter Δt. It can be chosen based on experience. However, it is desirable that Δt can be determined dynamically. Below, we identify some sufficient conditions which indicate that rerunning *FPA*(1) and *FPA*(2) is unnecessary.

Lemma 3 Given the same set V of hosts with two different sets of initial energies for the hosts, as long as the sorted link list *PAIR* remains unchanged, the same set of links will be connected when *FPA*(1) and *FPA*(2) are run.

Proof: (sketched) The correctness proof for *FPA*(1) and *FPA*(2) only counts on the *order* of links in the list *PAIR*, not on the *absolute values* of these links. ❑

This implies that we only need to reevaluate the network topology when the order of links in *PAIR* changes. Specifically, we only need to monitor each pair of neighboring links in *PAIR*, say (x_1, y_1) and (x_2, y_2), for possible changes in their order in *PAIR*. Suppose that we run *FPA*(1) or *FPA*(2) at time t and (x_1, y_1) is before (x_2, y_2) in *PAIR*. Let P_{s,x_1}, P_{s,y_1}, P_{s,x_2}, and P_{s,y_2} be these hosts' transmission powers, and let $B_{x_1}(t)$, $B_{y_1}(t)$, $B_{x_2}(t)$, and $B_{y_2}(t)$ be their remaining energies at time t. As time passes, we need to determine the smallest positive Δt such that the following condition becomes true during the lifetime of the network:

$$
\begin{aligned}
& \min\left\{ \frac{B_{x_1}(t) - (P_{s,x_1}(t)\alpha_{x_1} + P_r)\Delta t}{\lambda(x_1, y_1)\alpha_{x_1} + P_r}, \frac{B_{y_1}(t) - (P_{s,y_1}(t)\alpha_{y_1} + P_r)\Delta t}{\lambda(x_1, y_1)\alpha_{y_1} + P_r} \right\} \\
\le \quad & \min\left\{ \frac{B_{x_2}(t) - (P_{s,x_2}(t)\alpha_{x_2} + P_r)\Delta t}{\lambda(x_2, y_2)\alpha_{x_2} + P_r}, \frac{B_{y_2}(t) - (P_{s,y_2}(t)\alpha_{y_2} + P_r)\Delta t}{\lambda(x_2, y_2)\alpha_{y_2} + P_r} \right\}
\end{aligned}
$$

Since all the factors are constants, the two components in *min* can be regarded as two linear functions of Δt; i.e., they form two lines on a 2-D plane with respect to Δt. Thus, this problem becomes a simple one of finding the earliest intersection of four lines on a 2-D plane after time t and before the network lifetime expires.

The above discussion gives a sufficient condition when we need to reevaluate the network topology for possible changes of hosts' transmission powers. A further relaxation of this condition is as follows.

Corollary 1 Suppose that at time t, we run *FPA*(1) or *FPA*(2) in order to select a transmission power for each host and that at time $t + \Delta t$, the first pair of neighboring links in *PAIR* change in terms of their order in *PAIR*. If neither of these two links is chosen to make a connection in the corresponding algorithm (in step 4), then rerunning *FPA*(1) or *FPA*(2) at time $t + \Delta t + \in$ will result in the same power setting as that with time t, where $\in$ is an infinitely small value.

Intuitively, a link in *PAIR* that is not chosen to make a connection does not contribute to the connectivity of the network. As a result, two such links that change in terms of their order in *PAIR* will not result in a different power setting.

5. SIMULATION RESULTS

To evaluate the performance of the proposed *FPA*(i) and *VPA*(i) schemes, $i = 1, 2$, we have developed a simulator to observe the power consumption factor. A number of randomly generated hosts are placed in a 10×10 plane on the real domain, where each unit is 1 kilometer. The electricity in each host is randomly set between 80 to 120 units with a uniform distribution. A time unit is one hour long. The power-consumption constant c is set to 1. As a result, a pair of hosts with 100 units of electricity separated by 1 km has a lifetime of 100 hours, while such hosts separated by 10 km has a lifetime of 1 hour. Note that the absolute values in the above settings are, in fact, nonessential since we wish to focus on the relative benefits that can be obtained by the proposed schemes.

Fig. 3 shows two simulation scenarios with 50 and 100 randomly generated hosts. The solid lines represent the network constructed by algorithm *FPA*(1), while the dashed lines represent the additional links added by *FPA*(2). The networks that would be constructed by the work in [9] are not shown, but the obtained network lifetimes are denoted by “RH” in the figure. The networks that would be obtained by *VPA*(1) and *VPA*(2) are not shown either since the resulting topologies would in fact change by time. The numbers at the bottom of each subfigure represent the network lifetimes obtained by different algorithms. As can be seen, significant improvement can be obtained, both from the RH scheme to the FPA scheme and from the FPA scheme to the VPA scheme.

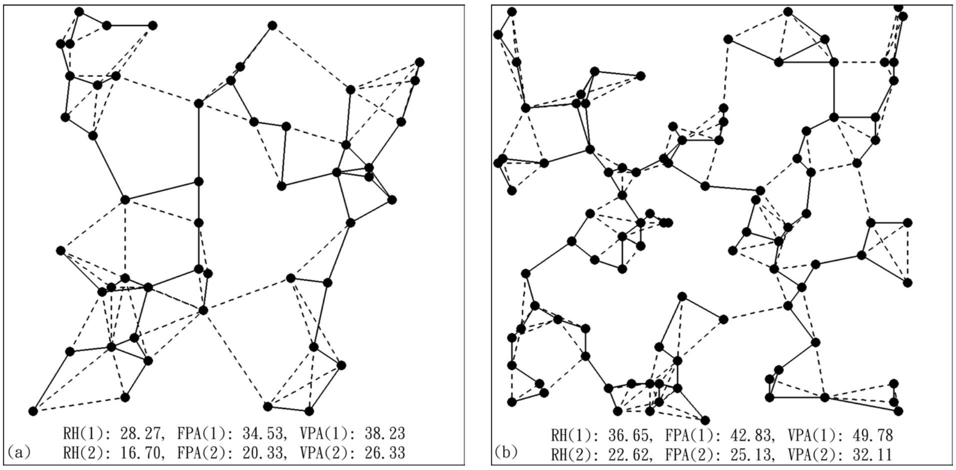


Fig. 3. Comparison of network lifetimes obtained by different schemes: (a) 50 nodes and (b) 100 nodes. Solid links are obtained by *FPA*(1), while dashed links are extra links added by *FPA*(2).

Finally, it should be noted that we have used the same simulator to observe the effects of various factors, such as the initial battery levels and host density, on network lifetimes. However, we have found that the results vary greatly and that there are no clear trends. We believe that this is because the performance depends highly on the distribution of the hosts on the 2D plane while the number of possible host distributions could be extremely large, making it very difficult to see a clear trend.

6. CONCLUSIONS

To the best of our knowledge, this work is the first one to address the ad hoc network topology control problem by taking into account hosts' remaining energies. Algorithms for constructing 1-edge-, 1-vertex-, 2-edge-, and 2-vertex-connected networks have been presented. While the basic approach employs a minimum spanning tree construction, the result is optimal under the fixed power model. Thus, our contribution lies in extending the applicability of the work in [9] to the case where hosts' initial energies can differ. Under the variable power assumption, several sufficient conditions have been proposed to reflect when reevaluating the network topology may be necessary.

Under the fixed power model, [9] discussed how to reduce individual hosts' powers (an approach called *PerNodeMinimize*). This technique can remove some side-effect links, but the network lifetime cannot be improved. The result can be applied to our work under the variable power model since side-effect links may potentially become critical links in the future. Distributed topology control was also discussed in [9]. While this is desirable, extending our schemes to obtain distributed ones will make less sense since determining a graph's connectivity requires global information.

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