Energy Aware Communication in Ad-hoc Networks

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Abstract

Ad-hoc networks have gained widespread attention in past few years. They are being envisioned for scenarios such as military operations, emergency rescue operations and more recently in sensor networks. The nodes in ad-hoc networks are battery operated and have limited energy resources. This makes energy efficiency a key concern in ensuring system longevity. Further, studies have shown that the communication subsystem consumes a large fraction of total energy and therefore, solutions for energy efficient communication are of great interest.

This paper discusses the current state of research in energy efficient communication in wireless ad-hoc networks. The paper focuses on energy optimizations at the network layer. The research is classified into three categories based on the different aspects they address: 1) power control, 2) routing, and 3) sleep mode control. Issues, current approaches and future directions are discussed in each of the above three categories.

1 Introduction

An ad-hoc network is a collection of wireless devices (or nodes) dynamically forming a network without using any pre-defined infrastructure. For example, soldiers relaying information for situational awareness on a battlefield and personnel coordinating rescue relief operations after a disaster such as an earthquake. The goal of an ad-hoc network is to enable communication between any two nodes in the network. Communication between nodes that are beyond direct communication range is enabled by using intermediate nodes in the network as forwarding agents. An emerging application domain for ad-hoc networks is that of wireless sensor networks. Wireless sensors are small and cheap devices which embed in the environment at large scales (thousands of nodes) and form an ad-hoc network to enable communication [1]. Examples include monitoring physical environments such as tracking animal migrations in remote areas [2], weather conditions in national parks [3] and habitat monitoring on remote islands [4].

Nodes in an ad-hoc network are untethered, battery operated and have limited energy. Therefore, energy conservation is key for long lived operation. Of-course, long-lived is a relative term; in some emergency rescue operations the network may operate for couple of hours and in a sensor network the desired lifetime can be of the order of months. A prime consumer of energy is the communication subsystem. For wireless laptops, communication can consume upto twenty percent of the total energy, and for handheld devices the percentage can be over fifty [5]. The situation is worse for sensor networks because of two reasons: 1) sensors are very small which limits the possible battery size and the available energy resources; 2) the fraction of energy consumed by the communication subsystem is much more because sensors have no display component and have limited CPU operations.

This paper presents the current state of research in energy efficient communication in ad-hoc networks at the network layer. The term "network layer" is used in a loose sense to denote components that are responsible for determining path taken between nodes. Medium access control (MAC) protocols and application level considerations are other layers at which energy efficiency may be achieved. They are not the focus of this paper and are discussed briefly in the end. Only unicast communication is considered and issues surrounding multicast are beyond the scope of this paper.

We classify the current research efforts into three categories based on the different aspects they address: 1) power control, 2) routing, and 3) sleep mode control. We now explain these aspects individually and then discuss relationship between them.

1. **Power control or Topology control:** Wireless nodes can control the transmission power level. The power level of a node determines the nodes it can directly communicate with (or the nodes that are within its range). Thus, the power levels of nodes defines the connectivity structure or the topology of the network. [1] Choosing a low power level at all the nodes may lead to a disconnected network whereas using a very high power level may lead to the consumption of excessive energy. The power control problem is to determine the right power level for each node so that the data can be routed in an energy efficient manner.

2. **Routing:** Multiple routes are present between two nodes and one or more can be used for sending data. The factors affecting path selection are both the cost of transmitting and receiving packets and the resources available at the intermediate nodes. Given a topology, the routing problem is to find an energy efficient route from the source to the destination.

   In comparison to traditional routing[2] , the following aspects of the energy aware ad-hoc networks motivate revisiting the routing problem:

   1) A primary objective in ad-hoc networks is to maximize the time till a node runs out of battery power. This requires taking into account the energy resources available at nodes and significantly increases the complexity of selecting optimal routes.

   2) In ad-hoc networks, the cost of directly transmitting between two nodes depends on the physical distance between the two nodes and increases as the fourth power of distance. Therefore, multiple smaller hops are more energy efficient than a single large hop. This is in contrast to the traditional routing where minimum number of hops is a typical route selection criterion.

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[1] By definition, the topology of an ad-hoc network is the set of communication links between node pairs [6].

[2] Traditional routing here stands for routing in wired world such as intra-domain routing in Internet or early routing work in ad-hoc networks.

3. **Sleep mode control:** Wireless devices suffer from another unique problem of idle listening consumed energy. Ideally, a node that is not sending or receiving data should be in the sleep state. However, a node may have to forward data for other nodes and therefore, by default all nodes are in the listen mode. Listening consumes substantial energy and reducing this overhead is important [7, 8, 9, 10]. The sleep mode control problem is to identify nodes that are not essential for forwarding and transition them to sleep mode.

The above categorization is motivated by our inspection of the current research efforts. The first two aspects address the energy required for data transmission and the last aspect addresses the idle listening energy. Decisions taken by one aspect may affect other aspects. For example, power control algorithm obviously affects the choice of the available routes and as we will see later, it also affects the number of nodes that can go to sleep. To date, most of the research is done independently on each of the above three aspects . For example, research on sleep mode control assumes a fixed power level and research on power control does not take into account the effect on optimizations due to sleep mode control. We discuss how they affect each other and future possibilities for combining them.

An important and unaddressed issue is to understand which aspects of communication are consuming energy and in what proportion. These are the topology discovery overhead, the routing protocol overhead, the actual transmission of data and the idle radio listening. Little conclusive evidence is available in the literature on the relative proportions of the above overhead inspite of the fact that active research has been pursued in addressing all of these. We believe that the primary reason behind this is its sensitivity to both the choice of the routing protocol and scenario specific parameters. For example, the proportion of energy consumed in actual data transmission is largely dependent on the workload. Sensor networks are typically low data rate networks, transmit data occasionally, and therefore have less proportion of energy consumed in actual data transmission. Other than workload, mobility, size and density of the topology are other factors that affect energy consumption. Investigating this issue further will be important step in understanding energy efficient ad-hoc networks.

The paper proceeds as follows. Section 2 describes background on ad-hoc routing protocols and model for radio energy consumption. Sections 3, 4 and 5 discuss in detail each of the three categories: power control, routing and sleep mode control. Section 6 briefly discusses energy efficiency in two other dimensions: MAC layer and application layer. We conclude in Section 7.

2 Preliminaries

This section describes necessary background on radio power consumption characteristics and ad-hoc routing protocols for understanding subsequent sections.

2.1 Radio power consumption model

Each node in an ad-hoc network communicates through a radio transceiver. The power consumption of a radio transceiver depends on its state. This state can be one of transmit, receive, listen or sleep.

1. Transmit: Transmit power is the power required at the sender to transmit a packet. Transmit power primarily depends on the distance between the source and the destination and is given by $p_{transmit} = c_1 + c_2 d^{\alpha}$. Here, d is the distance between the sender and the receiver, c_1 and c_2 are constants, and α is the path loss exponent. $\alpha = 2$ for distances of the order of few tens of meter and $\alpha \geq 4$ for distances over hundred meters [11].

   In general, transmit power also depends on the desired reliability and is greater for more reliable communication. However, for modeling purposes this is abstracted away and every packet transmission is considered reliable. This is a fair assumption in the presence of link layer protocols for reliability.

   Transmit power provides a tradeoff between communication range and energy consumption. This provides a higher degree of freedom in optimizing, albeit at the cost of complex algorithms for power control.

2. Receive: This is the amount of power required to receive one packet. This is a constant and depends on the radio technology. For common technologies, the receive power is comparable to the transmit power for small distances (tens of meters) [7, 12].

3. Listen: In this mode, the transceiver is constantly listening on the channel to detect incoming packets. Power consumed in the listen state is substantial and is close to the receive power. Therefore, it is important to reduce the listening time as much as possible [7, 12, 13].

4. Sleep: In this mode, almost all of the circuitry is off and the radio can not perform any function. Power consumption is almost zero in this state.

Based on above, the following observations play an important role in the design of routing algorithms:

1. Transmit power grows super-linearly with distance. Hence, techniques are required to transmit packets over shorter distances.

2. Power consumed in the listen mode can be substantial. Hence, techniques are required to decrease listen time by transitioning to sleep mode.

2.2 Ad-hoc routing protocols

This section briefly reviews early works on ad-hoc routing protocols, which do not focus on energy optimization. Detailed comparison is presented in [14, 15, 16]. The implicit assumption in most early works in ad-hoc networks is that a node's transmission power level is fixed and hence, the topology is fixed. Earlier ad-hoc routing protocols are broadly divided into two categories based on whether the routes are discovered: *reactively* and *proactively*. In proactive protocols a consistent view of the topology and end-to-end routes is maintained. Destination Sequenced Distance Vector (DSDV) is an example of a proactive protocol [14]. Proactive protocols are similar to traditional wired routing protocols such as distance vector or link-state. In reactive protocols routes are discovered on demand. Two popular flavors of reactive protocol are Dynamic Source Route (DSR) and Ad-hoc On demand Distance Vector (AODV) [14].

The routing protocols mentioned above are unscalable because they are based on global flooding. Scalable ad-hoc routing protocols have been investigated by large number of researchers and the two main approaches are based on hierarchy and location.

Hierarchy is a standard mechanism to achieve scalability. In the context of ad-hoc networks the challenge is to form and maintain the hierarchy dynamically and has been addressed in ZRP [17], LANMAR [18], HSR [19], etc.

The other mechanism of *location based routing* is unique to ad-hoc networks. Nodes are assumed to know geographical positions of other nodes and the next hop is chosen such that it is geographically closer towards the destination. This may result in sub-optimal routes but does not require the knowledge of complete topology. This has been addressed in LAR [20], DREAM [21], GPSR [22], etc.

The next three sections discuss the three aspects of energy efficient communication as mentioned earlier: 1) power control, 2) routing, and 3) sleep mode control. In each discussion, first, the problem is defined briefly, followed by a detailed discussion of challenges and issues surrounding problem. Next, different techniques addressing the problem (sometimes different aspects of it) are described, followed by discussion of future directions.

3 Power Control or Topology Control

Problem Statement

Given a node in the network, determine its transmission power level

(Transmit power level determines the communication range and defines the set of neighbors for a given node. Therefore, the problem of power control is the same as that of topology control.)

3.1 Issues

One simple solution is for each node to use its maximum power level. This will result in a large number of neighboring nodes on average. But this approach is inefficient because of the following reasons: 1) using maximum power level for communication will lead to excessive energy consumption; 2) the cost of maintaining neighboring information will increase because of a large number of neighbors; and 3) the topology will have excessive interference and less opportunity for spatial reuse (see Figure 1(a)). This is because transmitting at a higher power level results in a larger area where no other node can transmit. This can severely limit the aggregate throughput [23, 24].

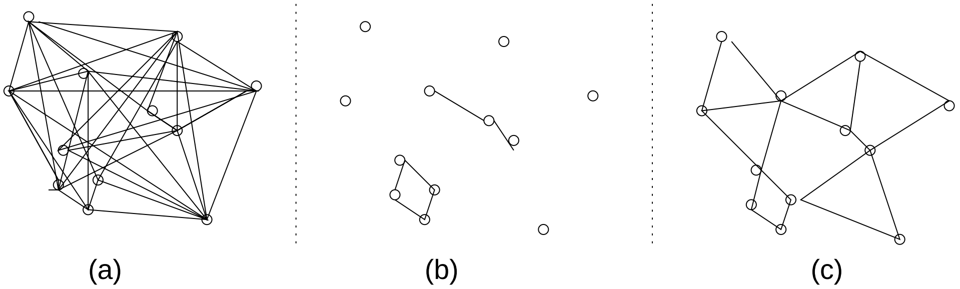

Figure 1: Affect of choice of transmit power levels on topology. (a) nodes transmit at the maximum power level and cause excessive interference. (b) nodes transmit at a small power level and the topology is disconnected .(c) node transmits at an optimum power level and the topology is connected with low interference.

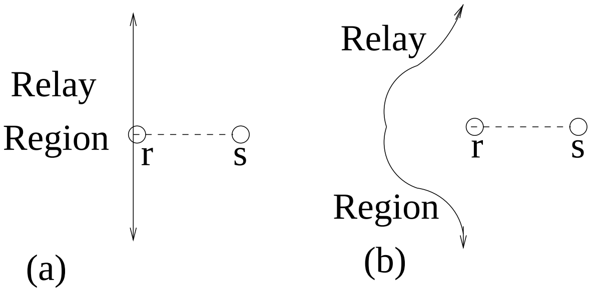

Figure 2: Relay regions of the transmit-relay node pair (s, r) for two different values of path loss coefficient, (a) $\alpha = 2$, and (b) $\alpha = 4$. For any destination node placed in the relay region it will be more energy efficient for s to relay data through r instead of sending it directly.

The other extreme approach is to use a small power level at each node. However, this may result in a disconnected network as shown in Figure 2(b). Ideally, power levels should be chosen just large enough such that the resultant topology is connected as shown in Figure 1(c).

The exact requirements can be precisely defined using graph theoretic terminology [25]. For example, one formulation of the power control problem is to obtain a connected topology with the objective of minimizing the maximum power level [6] used by an individual node. Other variations include minimizing the total power or achieving strong connectivity in the resultant topology. Another popular definition is that of a *minimum power topology or minimum energy graph.* A topology is a minimum power topology if it has all the minimum energy paths, where, a minimum energy path between two nodes is defined as the path which has the least total amount of energy required to send a message between those two nodes.

Another aspect of power control is the knowledge of the radio transmit power model (see Section 2.1). Absence of such a model increases the complexity of the power control algorithm. Most algorithms (except one) assume that the model is known.

Finally, the power control algorithm should be efficient. Efficient here means localized and computationally inexpensive. Localized algorithms are attractive because they have low overhead as the network scales and can be implemented distributedly. They are particularly advantageous in mobile environments, where the large delay associated with dissemination of global information can deteriorate performance. Computational efficiency is important because some topology optimization instances are NP-hard and may not be practical.

3.2 Techniques

We now discuss different approaches to discover optimal power levels. First, algorithms that assume the knowledge of the radio model are discussed, followed by a discussion of algorithms that do no assume so. Knowledge of the radio model allows one to determine an optimal solution, otherwise, only approximate solutions are obtained.

3.2.1 Power control in presence of a radio model

We discuss three classes of approaches here. The first two target power control for obtaining minimum energy graphs and the last one addresses other power control objectives, such as minimizing maximum power level

- **Position based approaches**

These approaches assume that each node knows its geographical position. The seminal work was by Rodoplu et al. [26] on a distributed and localized algorithm to obtain a minimum energy graph. Their key contribution is the concept of a *relay region*. The relay region for a source node s with respect to a relay node r consists of all points j for which relaying through r consumes less power than directly transmitting from s to j. See Figure 2 for an illustration. The algorithm uses a localized search at each node to find enough relay nodes for it such that the entire space can be reached efficiently by relaying through these nodes. Typically, the number of such relay nodes is small, resulting in an efficient topology. The discovered topology is provably strongly connected and is a *minimum power topology.*

A node does not have to consider all nodes in the network to find the minimum power topology. It uses a localized search based on the relay regions of its immediate neighbors (found using smaller power levels) to determine when to stop the search. At each iteration the power level is incremented slightly. The algorithm is completely distributed and localized.

The base algorithm has been refined in [27]. The new algorithm is computationally simpler and the generated topology has fewer edges than the topology generated by the Rodoplu's algorithm. The key innovation in the paper is the concept of *k-redundant* edges. An an edge is *k-redundant* if there is a k hop path of smaller or equal cost. The paper proposes an efficient way to remove all *2-redundant* edges from the original graph.

- **Direction based approach**

This approach assumes that upon receiving a message, the radio communication unit can determine the direction of the sender. Techniques to estimate direction information are known as the Angle of Arrival (AOA) estimation techniques and are studied by the IEEE antenna and propagation community. Obviously, if location information for source and destination is available, it can also be used to estimate the angle of arrival.

The basic idea is that every node continues to increase its transmission power until it has a neighbor in every cone of angle α ($\alpha < \frac{2\pi}{3}$). The parameter α controls the average out-degree. A smaller α results in a larger average out-degree, and by choosing an infinitely small α one can construct a *minimum power topology*. The author indicate that $\alpha = \frac{\pi}{2}$ provides a competitive performance compared to Rodoplu's algorithm. The algorithm also has a second phase in which all the 2 redundant edges are removed. The algorithm is also known as the *distributed cone based topology control* algorithm.

Like Rodoplu's algorithm, the above approach is completely distributed and requires only local information about direction.

- **Graph theoretic approaches**

Literature in this category is of theoretical nature and requires global knowledge of the topology. The power control problem is defined as assigning power values to each node in the ad-hoc network such that the resultant topology has the desired properties. The algorithms require the knowledge of distances between nodes and a model for the transmit power required as a function of distance. This is of interest as it provides a yardstick to measure the performance of other distributed heuristics.

The seminal work was by Ramanathan et al. [6], on the problem of minimizing the maximum power level assigned to a node such that the resultant topology is *k-connected.* A graph is *k-connected* iff there exist k disjoint paths between any two nodes. Two polynomial time algorithms are presented for achieving *1-connectivity* (connected network) and *2-connectivity* (biconnected network). This work has been generalized by Lloyd et al., who consider more general objective functions such as minimizing average power and graph properties such as testing whether a graph is a tree [25].

3.2.2 Power control in absence of a radio model

The approaches discussed so far assume a model for transmit power with distance and also require additional knowledge such as position or direction. This limits there applicability and solutions which do not require such knowledge are attractive.

- **Local connectivity based approaches**

This class of techniques uses local connectivity information to determine an appropriate power level. They are based on choosing a power level such that the resultant topology is connected and has a small average out-degree. Local Information No Topology (LINT) protocol is one such example [6]. In LINT protocol, each node tries to maintain the number of its neighbors between two preset thresholds. If the current neighbor set is too small, the power is increased, and if has too many nodes, the power is decreased. Thus, LINT attempts to achieve a constant preset average degree throughout the network. The scheme is only a heuristic and does not guarantees connectivity. The protocol is extended by the same authors to guarantee connectivity by using information from routing layer (called LILT [6]). If the network is not connected then the power level is increased. Mechanisms based on randomization are used to avoid synchronization affects. The primary challenge is to determine the required average degree. Tamir et al. present a similar technique to improve the end-to-end throughput [28].

A performance comparison among local heuristics and optimal algorithms is given in [6, 29]. The authors indicate that heuristic based approaches provide significantly better performance than using fixed power levels though they do not perform as well as the optimal algorithms.

- **Global connectivity based approaches**

The COMPOW algorithm targets networks where nodes are uniformly deployed and a single power level can be used for all nodes. The COMPOW problem is to find the smallest common power level at which the network is connected.

The COMPOW design is based on two key observations. First, connectivity is a network layer property, and therefore power control must operate at the network layer along with the routing protocol. Second, only discrete levels of power control are present in most commercially availably wireless cards. For example, CISCO Aironet 340 has four levels, 1,5,10 and 30 mw. The main idea in COMPOW is to maintain multiple parallel routing tables at each power level. A separate instance of routing protocol is then run at each of the discrete power levels. The optimum power level selected is the smallest one at which the routing table has the same number of entries as the number of entries as for the maximum power level.

The protocol is completely distributed and can be easily integrated with any proactive routing protocol. The primary concern is the overhead of maintaining multiple routing tables. COMPOW also requires transmission of control messages at the maximum power level in order to determine the potential connectivity of the network.

For ad-hoc networks with non-uniform distribution of nodes, a single common power level is inefficient. To address such situations the same author recently extended the idea of COMPOW to CLUSTERPOW [30]. CLUSTERPOW also maintains multiple routing tables like COMPOW. However, when routing, the next hop is determined by first consulting the routing table corresponding to the lowest power level at which the destination is reachable. This approach does not route using globally minimum energy paths and is only a heuristic.

3.3 Future directions

The above approaches solve the same high level problem but differ in their assumptions and the degree of optimality of the resulting topology. All these algorithms, except COMPOW, require position knowledge or direction information. The work on optimal algorithms in static settings is helpful in gauging the effectiveness of heuristics and may even be practical for small scale and low mobility environments. Characteristics of these different approaches are summarized and compared in Table 1. The following questions provide future research avenues in topology control:

- **Localized topology discovery using distance knowledge**

The existing work on localized discovery requires knowledge of positions or angular information which may not be available in all circumstances. Algorithms based solely on distance knowledge would be interesting in

-	Rodplu [26]	Cone [31]	*k-con nectivity* [6]	LINT [6]	LILT [6]	CLUSTER POW [30]
Knowledge of radio model	Essential	Used for additional optimizations	Essential	Not required	Not required	Not required
Additional requirements	Geographical coordinates	Angle of arrival	Distance between nodes	Average node degree	Average node degree	Assumes few discrete power levels
Guarantees connectivity	Yes	Yes	Yes	No	Yes	Yes
Optimization criteria	Minimum energy paths (optimal)	Minimum energy paths (close to optimal)	Minimize maximum power (optimal)	Minimize maximum power (heuristic)	Minimize maximum power (heuristic)	Minimize maximum power (heuristic)
Local and distributed operation	Yes	Yes	No	Yes	No	No
Discovery overhead	Small	Small	Large	Small	Small	Large
Independent of routing layer	Yes	Yes	Yes	Yes	No	No

Table 1: Comparison of different techniques for power control

this respect. This is because distance information can be obtained directly using signal strength computations. Here one can leverage the work on localization in ad-hoc networks, where the objective is to assign relative geographic positions to nodes in the network based on signal strength computations [32].

- **Distributed and localized implementations of optimal algorithms for achieving** *k-connectivity*

The current optimal algorithms for achieving *k-connectivity* require global knowledge [6]. Investigating distributed and localized heuristics that can ensure connectivity or other interesting topological properties are of interest. The Rodoplu's algorithm is localized and ensures connectivity (same as *1-connectivity*), however it does not minimize the maximum power level. The difference between the performance of Rodoplu's algorithm and the optimal algorithm which minimizes the maximum power level has also not been evaluated.

- **Do we need efficient topology discovery?**

Optimal algorithms based on global knowledge are argued as *inefficient* because they require dissemination of complete topology throughout the network. Initially, due to lack of any information, dissemination is done using the maximum power level and may have substantial overhead. However, it is not clear if this overhead is significant in the overall picture of the lifetime of the ad-hoc network. There are two reasons to believe that this overhead may not be significant. First, most ad-hoc routing protocols require global knowledge of the topology. Therefore, routing overhead would dominate topology discovery overhead. Second, for non-mobile ad-hoc networks topology discovery is an infrequent operation (as frequent as routing updates), and depending upon the workload, topology maintenance overhead may be insignificant. To our knowledge, no comparison of overhead of using a global topology discovery algorithm and a localized algorithm is available. Further, a global discovery algorithm results in more efficient power assignments which may compensate the overhead of global dissemination. The primary need for an efficient topology discovery would be in highly mobile environments where topology changes frequently. A low overhead and low latency protocol is essential in such scenarios.

- **Effect on other metrics**

Finally, the effect of choosing a power efficient topology on other metrics such as latency and throughput needs to be considered in detail. These metrics are intertwined in a complex fashion. For example, a path with multiple small hops is usually more efficient (for both power and throughput) than a single large hop, but at the same time has higher latency.

4 Routing

Problem Statement

Given a topology, find the route(s) taken to transmit data from a given source to a given destination

4.1 Issues

The above problem is the traditional unicast routing problem. The first obvious solution is to route to destination using minimum number of hops. This has been the default choice in wired networks and early work in ad-hoc networks. This approach is attractive because it is well studied and minimizes delay. However, for ad-hoc networks the prime concern is energy utilization and unfortunately the minimum-hop policy does not always achieve this. Singh et al. provides a detailed discussion on different metrics that can be considered for optimization [33]. The metrics can be divided broadly into two categories- minimizing overall energy and maximizing lifetime of the network.

- **Minimizing overall energy consumption**

The objective here is to route a packet such that the minimum amount of energy is consumed network wide. Total energy required to route a packet is the sum of energy required to transmit over hops in the path.

Energy required to transmit over a single hop depends on the transmit power (which depends on the distance between two end points) and the receive power at the destination. In particular, the cost increases superlinearly (typically as the fourth power) with the distance and makes it favorable to use multiple short hops than one long hop.

- **Maximizing lifetime of the network**

Using minimum overall energy routes has two limitations. First, nodes which are near the destination will have to route more packets than others and will run out of battery power sooner. This might be of concern in a non cooperative ad-hoc network where uniform routing load on nodes is desired, or in a sensor network where the death of a node may lead to loss of coverage. Second, routing is done independent of the available energy resources at different nodes.

To overcome above limitations one can route packets such that the network survives for a longer period. More precisely, the following definitions are popular: 1) maximize the time till the first node dies; 2) maximize the time till the network topology partitions. The two metrics are slightly different. The first is more relevant when each node has a crucial role to play. The second is relevant in cooperative environments where the objective is to maintain the connectivity of the network as a whole.

Another issue is the design of scalable and low overhead routing protocols. This is particularly important for large and mobile networks. The research in scalable ad-hoc routing protocols is relevant here and the challenge is to adapt them to incorporate energy awareness.

4.2 Techniques

We now discuss different techniques addressing the following three aspects. Routing for minimizing the overall energy consumption, maximizing the lifetime of the network and minimizing the routing protocol overhead.

4.2.1 Minimizing the overall energy

The objective here is to choose routes such that the total cost of sending each packet (defined as the sum of the cost of each hop) is minimized. This is similar to traditional minimum hop routing with appropriate cost metric and standard link state or distance vector algorithms can be used.

The key is to use appropriate cost metrics. When the cost metric is the taken as the energy required to transmit and receive a packet, the resultant routing minimizes the overall energy consumption. The same algorithm with a different cost metric can also be used to maximize lifetime (discussed later in Section 4.2.2). For reliable transmissions link error rates should also be taken into account when assigning cost to links [34].

4.2.2 Maximizing the lifetime

The algorithms for maximizing lifetime can be categorized based on whether or not the sequence of message arrivals is known. Algorithms which do not require the knowledge of message sequence are called *on-line* algorithms (otherwise off-line). The distinction here is important because it has been shown that the performance of an *on-line* algorithm can be arbitrarily worse than the performance of an *off-line* algorithm.

Online algorithms: Heuristics for maximizing lifetime

- **Minimum cost routing**

This is similar to minimum energy routing with appropriate definition of cost metric. The key is to incorporate both the cost of energy required to send a packet and the energy available at the forwarding node. In particular, a recent algorithm called CMAX, proposes the cost metric of a link between nodes i and j as $e_{ij}(\lambda^{1-\frac{E^i_{current}}{E^i_{initial}}} - 1)$ [35]. Here e_{ij} is the energy required to transmit a packet from node i to next hop node j, $E^i_{current}$ is the current energy level of the node i, $E^i_{initial}$ is the initial energy of the node i and λ is a predefined constant. With above metric the algorithm is shown to have worst case performance within $O(\log(network\ size))$ of the best achievable performance. This is the best theoretical result available in the domain of optimizing lifetime. Empirically, the performance has been shown close to optimal.

An important implementation issue in incorporating energy level of nodes in making routing decisions is that the energy levels of nodes are part of the topology description and need to be updated as the energy level changes. Disseminating changes in energy level throughout the topology can be quite expensive because the energy level of a nodes changes frequently. One can use limited flooding to propagate the energy level information to a limited area and still achieve good performance by using a hop-by-hop algorithm such as distance vector [35].

- **Max-min routing**

In *max-min* routing, routes are chosen such that the minimal residual power in the network is maximized. The optimization criteria is slightly different from the minimum cost routing and is more aggressive towards avoiding bottlenecks and reducing resource variance. The implementation is similar to smallest cost routing and the Bellman-Ford algorithm can be modified appropriately to achieve a distributed implementation.

- $Max - minzP_{min}$ **routing**

$Max - minzP_{min}$ is a combination of minimum cost routing and max-min routing [36]. This attempts to achieve both minimum energy routes as well as tries to maximize the lifetime of the network. The algorithm chose paths that consume atmost z times the minimal power while maximizing the minimal residual power fraction.[3] An adaptive computation of z is provided and the algorithm is shown to have good performance.

Offline algorithms: Optimal algorithms for maximizing lifetime

The seminal work here is a centralized algorithm by Chang et al. [37, 38]. This algorithm requires knowledge of the source data rates, energy levels, distances between nodes and a model of power with distance. The problem is formulated as a linear programming problem. The objective is to maximize the lifetime subject to the constraints of flow rates and energy levels. This approach is quite complex to implement in a distributed

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[3] Residual power fraction is defined as the ratio of the power remaining after routing to the power available initially.

manner and requires the knowledge of source data rate which is not available in most cases. Therefore, this approach is mostly of theoretical interest.

The above solution requires knowledge of future message arrivals (or workload) and an interesting question is whether an online (no knowledge of future message arrival) version of the algorithm can be developed. It has been shown by Li et al. that knowledge of the workload is essential for optimality and an online algorithm can be made to perform arbitrarily bad by injecting messages in a particular manner [36]. Admission control is required to address such scenarios [35].

Chang et al. work has been extended in different directions. The notion of the lifetime of the network (the time till the first node dies) has been extended to the lifetime curve of the network (the sequence of times at which each node dies) in [39]. A dual formulation of the problem of maximizing the data source rates given a constraint on the lifetime of the network has also been studied [40]. More general linear programming formulations for estimating the lifetime of the network in context of sensor networks has been studied by Bhardwaj et al. [41, 42]. They also incorporate data aggregation aspects that are relevant in sensornets. Recently, Zussman et al. extended the maximum lifetime problem for networks where bandwidth is an additional constraint [43].

Probabilistic multipath routing for obtaining uniform power drain has been explored by Rahul et al. [44]. The next hop is determined probabilistically among possible neighbors. The probability depends on the edge cost and the residual energy of the next hop. The overall effect is similar to multipath routing but simpler implementations are viable.

4.2.3 Reducing the routing protocol overhead

The routing protocols discussed above require global knowledge and are undesirable for large and mobile ad-hoc networks. As mentioned in the background Section 2.2, two main approaches for addressing routing scalability are hierarchy and location. Here, we discuss extensions to these ideas to incorporate energy awareness.

- **Hierarchy**

Zone based routing partitions an ad-hoc network into zones.[4] Every zone has a representative which is responsible for routing across that zone. This effectively creates a two level hierarchy. Routing algorithms run at two levels simultaneously: one within a zone and one across the set of zone representatives. Typically, nodes within a zone rotate to take the responsibility of being the representative [8, 45, 7]. This is done to balance overhead across nodes.

Incorporating power awareness while routing within a cluster is simple and any of the above algorithms can be used. The main challenge is to determine a power efficient global route. This requires knowledge of an *aggregate* power level of each zone. Li et al. proposes a mechanism based on virtual routing to estimate the number of messages that can be routed across a zone and uses it as an indicator for its power level [36].

- **Location based routing**

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[4] Partitioning can be done based on geographic locations or other clustering mechanisms.

The basic idea in location based routing is to route packets in a manner such that the next hop is geographically closer to the destination. Ivan et al. discuss how to incorporate power related metrics in such a routing mechanism [46]. The metrics are similar as discussed in shortest cost routing and can be tailored to optimize either the overall energy usage or the lifetime of the network. The decisions, however, are completely local and require information about neighbors only. This may cause routing loops, especially when nodes are mobile. The performance of the resultant algorithm is limited and no guarantee about delivery of messages is made. The problem is particularly acute for mobile networks where the positions of nodes change with time. Li et al. also discuss a location aided power aware routing [47]. Their algorithm is more sophisticated and uses the concept of relay regions to determine next hop. They also provide a theoretical analysis is of the energy efficiency of their routing protocol.

4.3 Future directions

Optimal centralized algorithms (based on global knowledge) for both minimizing overall energy consumption and maximizing network lifetime have been thoroughly investigated. Optimal minimal overall energy consumption can be implemented in a distributed manner using traditional distance vector routing with appropriate cost metrics. By incorporating power level of nodes in the cost metrics, the same technique can be used to maximize network lifetime though it is not optimal. Infact, in the absence of arrival information about future messages, achieving optimal performance is impossible.

- **Evaluating and reducing routing protocol overhead**

Optimal protocols discussed above are based on global knowledge and can have large maintenance overhead for large networks. For power aware protocols, the power levels of nodes also need to be propagated frequently thereby increasing the overhead. No thorough evaluation has been done to understand how much this overhead itself reduces the network lifetime. If the overhead is significant, techniques to reduce the overhead at the cost of suboptimal routes may be the most efficient approach.

- **Transport layer issues: reliability and congestion control**

Most discussion on routing assumes that the transmission is reliable. In practice, this is not true, and an end-to-end protocol for reliability (such as TCP) would be required. Addressing issues to incorporate reliability in an energy efficient manner is another avenue for future investigation.

Another related issue is that of congestion control. In wireless networks the problem is more challenging because of severe bandwidth constraints and MAC level issues. Ideally, a path can be chosen in a traffic aware manner; for example, the chosen path should have minimal overlap with paths that are currently being used for routing. Again, multipath routing can be used to address this. In general, use of multipath routing can also increase aggregate capacity from the source to the destination and improve reliability.

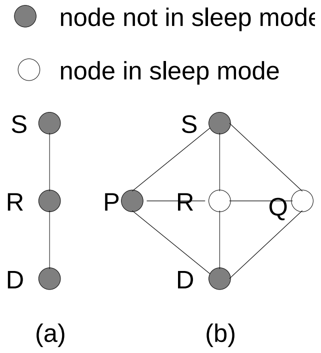

Figure 3: Node redundancy in ad-hoc networks. Two ad-hoc network topologies are shown. In (a) the node R must remain on for the source-destination pair (S, D) to communicate and can not go to sleep. In (b) only one of P, Q and R needs to remain on to provide communication between S, D. If P remains on, Q and R can go to sleep.

5 Sleep Mode Control

Problem Statement

Given a topology, determine the nodes that can go to sleep without affecting the routing capability of the network

5.1 Issues

Power consumption in the idle state is significant and techniques for reducing idle listening, by transitioning to sleep mode, are important. A node may not go to sleep mode because it may be required for forwarding other node's packets. However, if there are a large number of nodes in an area (high density) only a subset of them would be essential for forwarding purposes, as illustrated in Figure 3. The rest of the node's in such a case can go to sleep. Energy is saved because nodes in the sleep state require very less energy.

The nodes which can go to sleep are called non-coordinator nodes, and nodes which remain up are called coordinator nodes. The coordinator nodes stay awake continuously and forward packets as necessary. The non-coordinator nodes remain asleep most of the time and wake up only if any data packet is destined to them or if they have to send some data. Every non-coordinator node is associated with a coordinator node which is responsible for buffering any packets destined for it if it is in the sleep mode. The non-coordinator node occasionally wakes up to check if it's coordinator has any data for it. The following requirements guide the design of algorithms for the selection of coordinators.

1. Connectivity: Enough coordinators need to be chosen so that every node is in the range of atleast one coordinator.

2. Fairness: The coordinators should be rotated in order to ensure that all nodes share the task of forwarding

packets. Moreover, nodes with less energy resources should not be made coordinators.

3. Energy Efficiency: Minimum number of nodes should be coordinators to save maximum energy.
4. Capacity: Enough coordinators should be chosen to preserve the capacity of the network.[5]
5. Local Operation: The algorithm must operate using local information only. This is important for low overhead operation.

5.2 Techniques

We now discuss two techniques for coordinator selection. These techniques appeared at the same time and primarily differ in their assumptions.

- **SPAN** [7]

SPAN is a distributed and randomized algorithm for selecting coordinators. Each node makes the decision of being a coordinator or not. The transition between the two states is done probabilistically. Fairness is achieved by making the node with more energy likely to be a coordinator. Other criteria to become a coordinator is the value a node adds to the overall connectivity of the network. A node connecting more nodes has more chances of becoming a coordinator. Randomization is used to avoid simultaneous multiple coordinators.

Connectivity is guaranteed by the following coordinator eligibility rule: if two neighbors of a non-coordinator node can not reach other directly or via one or two coordinators, then the node should become a coordinator. This rule also favors increasing capacity by avoiding SPAN network with long hops when shorter hops exist in the original network. To determine the connectivity structure, SPAN requires information from the routing layer and also local broadcast of neighbor and coordinator information. For efficiency, these broadcasts are piggy-backed on the routing protocol control messages.

- **Geographic Adaptive Fidelity (GAF** [8]**)**

GAF uses knowledge of geographical positions of nodes to choose coordinators. Geographic positions of nodes are used to divide the complete topology into fixed size (fixed geographical area) zones. Zones are created such that any two nodes in any two adjacent zones can communicate. The size of the zone is thus dictated by the radio range of nodes which is assumed to be fixed. Only one node from each zone needs to be awake and can be the coordinator. Thus, by exploiting knowledge of geographical positions GAF simplifies the coordinator selection procedure. Nodes within a zone still rotate among themselves for the job of the coordinator. GAF performance is biased because of the manner in which zones are created and may lead to more load on some nodes than others.

- **Other approaches**

Another approach is the Adaptive Fidelity Energy Conserving Algorithm (AFECA) protocol [48]. In AFECA, each node alternates between coordinator and non-coordinator. The transition is probabilistic and

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[5] Capacity is the defined as the aggregate throughput that can be achieved by the network.

-	Additional Information	Connectivity Guarantees	Capacity Preservation	Local Operation	Requires Information From Routing Layer	Fairness
SPAN [7]	None	Yes	Yes	Yes	Yes	Yes
GAF [8]	Geographical Coordinates	Yes	Yes	Yes	No	No
AFECA [48]	Neighbor Density	No	No	Yes	No	No
ASCENT [49]	Loss Rate	No	No	Yes	No	No

Table 2: Comparison of different techniques for sleep mode control

proportional to the density of network (determined by number of neighbors in a node's vicinity). ASCENT is another protocol where loss rate is used to elect coordinators [49]. The primary limitation of these approaches is that they do not guarantee connectivity and do not preserve capacity.

Characteristics of different approaches are summarized and compared in Table 2.

5.3 Future directions

- **Integrating topology control with coordinator selection algorithm**

The current algorithms for coordinator selection assume a fixed radio range for all the nodes, i.e, they do not employ any power control. There are opportunities for a combined solution for power control and sleep mode control. There are two objectives. The first is to minimize the number of nodes that need to be coordinator and the second is to minimize their power levels. This is challenging because there is an inherent tension between these two objectives. Decreasing power level of coordinator nodes would decrease the range and hence, more nodes would be required to act as coordinators to retain the connectivity properties. Therefore, there is a tradeoff between using less nodes with higher power and more nodes with lower power. This adds a new dimension to the power control problem and would be an interesting avenue to explore.

- **Reducing coordinator duty cycle based on traffic patterns**

The coordinator nodes stay awake all the time even when there is no traffic to route. Since a node must be awake to identify if there is any traffic, it can not be in the sleep mode all the time. However, it can go to the sleep mode occasionally (reduce duty-cycle). This is particularly advantageous when the traffic load on the network is low. The challenge is to adapt the duty cycle to the traffic load. If the workload is known, one can formulate the problem as a scheduling problem where the goal is to create a schedule such that the sleep time of the nodes is maximized. This direction has not been explored to our knowledge. In practice, however the decision to sleep would have to be taken in a distributed manner and without the knowledge of future arrivals.

Coordinating and exchanging node schedules can also be used to improve the performance. This would allow nodes to predict when to attempt to talk to other nodes and would reduce unnecessary transmissions.

6 Other considerations

We now briefly discuss two other layers at which power awareness can be incorporated.

6.1 MAC protocols

These optimizations are targeted towards reducing overheads at MAC layer such as collisions, error control, coding techniques, efficient channel access, use of directional antennas, reducing idle listening time etc. For example, in PAMAS a node can overhear the environment and stop listening if there is a packet communication in its vicinity that it is not involved in [50]. A separate signalling channel is used to query the state of the nodes in the neighborhood. S-MAC protocol extends this idea so that only in-band signalling is required [51].

Reducing the duty cycle of nodes in ad-hoc networks has been considered in [51, 52, 9, 10]. This is challenging because in ad-hoc networks there is no central entity and decisions about when to listen have to be taken in a distributed and cooperative fashion. Further, the MAC layer has minimal information about overall topology. This is complicated by the lack of time synchronization in large networks. Impact of reducing duty cycle on performance metrics such as latency and throughput has been considered in [51, 9]. Typically the amount of time a node remains active is a pre-configured constant and adapting this to traffic patterns is important. MAC layer protocols have only local knowledge and operate at the scale of individual packets. This limits the kind of optimizations that can be performed at the MAC layer.

6.2 Application Level

Data aggregation inside a sensor network is an example of an optimization at the application level [53, 54]. Aggregation reduces the total amount of data that need to be communicated and can be very effective. For example, often multiple sensors are used to improve the quality of the resultant signal by eliminating noise. These signals are then combined using beamforming algorithm to obtain a single representative signal. Benefits of aggregation on increasing the lifetime of the network has been discussed in [45, 41].

Application level framing (ALF) is another technique to increase the effectiveness of data transfers [55]. In ALF, network protocols choose transmission units that are meaningful to applications. This is particularly relevant for broadcasts or query-reply oriented communication. For example, SPIN proposes explicit negotiation of meta-data and transmits data only when required. This can be beneficial when there is a substantial amount of semantic overlap in the data present at the sensors [55].

7 Conclusions

This paper discussed the current state of research in energy aware communication in ad-hoc networks. The paper focused on energy optimizations at the network layer. Three aspects were discussed: 1) power control; 2) routing; and 3) sleep mode control. Several future directions were discussed individually in each of the above categories. We now highlight some of the more interesting cross layer open issues:

- **Understanding the bottleneck**

  Understanding which aspect of communication is the prime consumer of energy is important . Possible candidates are topology discovery overhead, the routing protocol overhead, the actual transmission of data and the idle radio listening. Little conclusive evidence is available in the literature on the relative proportions of the above overhead inspite of the fact that active research has been pursued in addressing all these.

  Most of the discussion and analysis has been at an algorithmic level. Many practical issues both known (such as wireless contention, measuring available power, CPU overhead etc.) and unknown exist in realizing an application. Much work needs to be done at the higher layers (transport and application) to make ad-hoc networks a reality. Understanding the gap between theory and practice through actual implementation and experimentation will be of great value.

- **Integrated approach for power control, routing and sleep mode control**

  Our discussion indicated that the three aspects have many dependencies. The choices made by one can affect (sometimes in an opposing way) other aspects. We believe, an ideal architecture would integrate power control, routing and sleep mode control. Feedback from one aspect to other can then be used to improve performance. Such an integrated approach for routing and power control has been recently proposed in the COMPOW architecture. Integrating sleep mode control with it is challenging and is an open problem. Research on both the architecture as well as algorithms for exploiting that architecture will be interesting.

- **Traffic based sleep mode control for lightly loaded networks**

  For lightly loaded networks such as sensornets, the network is used only occasionally. Therefore, nodes will be required for forwarding occasionally. Such networks can benefit substantially by an aggressive sleep control mechanism which requires node to be awake only when traffic is present.

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