# Distributed Network Protocols for Wireless Communication

*Invited Paper*

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## Abstract

This paper describes a network design strategy that focuses on energy conservation. This position-based network protocol is optimized for minimum energy consumption in wireless networks that support peer-to-peer communication. Given any number of randomly deployed communication nodes over an area, we show that a simple local optimization scheme executed at each node guarantees strong connectivity of the entire network and attains the global minimum energy solution for both stationary and mobile networks.

## 1. Introduction

Improvements in RF transceiver design and low-power electronics have made it possible to implement portable light-weight communication devices using wireless links. To realize such ubiquitous wireless connection, we first need to develop a reconfiguring network technology to accommodate randomly positioned devices and form a globally connected network.

In wireless network protocol design, the emphasis has traditionally been focused on increasing system capacity (e.g. the number of users a base station can support), maximizing point-to-point throughput in packet-switching networks, and minimizing network delay [3,9]. Our thesis is that significant reductions in energy consumption can be achieved if wireless networks are designed specifically for minimum energy.

In this paper we address the following problem. Since each communication device can be constantly on the move, we assume no pre-arranged network topology. These devices can be randomly placed and global network connectivity is guaranteed by a robust and self-reconfiguring network protocol that is fault-tolerant and consumes minimal energy. Our network protocol takes advantage of the low-power GPS receiver technology [8]. It uses position information and the characteristics of radio propagation in the terrestrial environment to arrive at a solution that is localized and independent of the number of nodes in the network. We will show by both theory and simulation that significant reduction in energy consumption can be achieved when the entire network is optimized based on a localized algorithm [10].

There have been only a few works in this area so far, most notably the papers by Scott and Bambos. In their recent paper [7], they proposed a routing and channel assignment scheme for low power transmission in PCS. Our work differs in the following respects: (1) We do not assume a fixed and connected graph topology. Instead, we introduce a local optimization procedure which finds the minimum energy links and dynamically updates them. (2) We show that our protocol is self-reconfiguring in mobile scenarios.

The GeoCast scheme proposed by Navas and Imielinski [5] for geographic addressing and routing is also based on the availability of GPS position information. Major differences between this work and ours are: (1) GeoCast assumes an existing wired infrastructure. Our scheme assumes no underlying infrastructure or protocols. (2) GeoCast assumes fixed routers with stationary distribution areas (polygons). Our protocol, instead, can be used for mobile nodes. (3) GeoCast does not address energy considerations. In our work, energy consumption is the key metric.

## 2. Minimum Energy Network

In peer-to-peer communication, each node is both an information source and an information sink. This means that each node wishes to both send messages to and receive messages from any other node. An important requirement of such communication is strong connectivity of the network. A network topology is said to be *strongly connected* if there exists a path from any node to any other node in the graph. A peer-to-peer communication protocol must guarantee strong connectivity.

### 2.1. Network Connectivity

For mobile networks, since the position of each node changes over time, the protocol must be able to dynamically update its links in order to maintain strong connectivity. A network protocol that achieves this is said to be *self-reconfiguring*.

In order to simplify the discussion of our protocol, we take one of the nodes to be the information sink for all nodes in the network. We call this node the *master-site*. Each node knows its own instantaneous position via GPS, but not the position of any other node in the network, and its aim is to send its messages to the master-site whenever necessary.

A protocol that solves the minimum energy problem with a single master-site simultaneously solves the general peer-to-peer communication problem because each node can independently be taken as a master-site and the optimal topologies can be superposed. We take advantage of this simplification and concentrate on the problem with a single master-site without loss of generality.

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### 2.2. Transmit and Transceiver Power Consumption

In terrestrial wireless communication, radio propagation can be modeled effectively with a $1/d^n$ transmit power roll-off, where $n$ is determined from field studies [6]. Our algorithm does not depend on the particular value of $n$ ($n \geq 2$ for outdoor propagation models) and thus offers the flexibility to be applied in various propagation environments.

The total power consumed by a node is the sum of its transmit and transceiver powers. Transmit power refers to the power radiated by the antenna, and transceiver power refers to the power consumed by transceiver circuits. Transmit power follows the propagation law described above, whereas transceiver power usually has no spatial dependence. The processing power can be made insignificant compared to these two in recent low-power processor design [2].

The fact that transmit power falls as $1/d^n$, $n \geq 2$, raises the possibility that relaying information between nodes may result in lower power transmission than communicating over long distance. Since it consumes transmit power to obtain information about the location of other nodes, a node has to know when to stop its search for more neighbors and ascertain that one of its neighbors will be on the global minimum energy path.

For stationary networks, minimum energy and minimum power are equivalent, since the network consumes a constant power once the optimal topology has been found. Because of this equivalence and because radio propagation and circuit measurements are conventionally presented in Watts, we formulate and present our results in terms of power in this section. In the next section, we show how the results can be applied to conserve energy in mobile networks.

### 2.3. Enclosure

Consider three nodes in $\Re^2$. Let the transmit node be denoted by $i$, the relay node by $r$, and the receive node by $j$. Our aim is to transmit information from $i$ to $j$ with minimum power. By varying the position of $j$, we investigate under which conditions it consumes less power to relay through $r$.

**Definition 1 (Relay region)** The relay region $R_{i \to r}$ of the transmit-relay node pair $(i, r)$ is defined to be

$$R_{i \to r} \equiv \{(x,y) \mid P_{i \to r \to (x,y)} < P_{i \to (x,y)}\}$$

where $(x, y)$ denotes any point in $\Re^2$, $P_{i \to r \to (x,y)}$ denotes the power required to transmit from node $i$ to $(x, y)$ through the relay node $r$, whereas $P_{i \to (x,y)}$ denotes the power required to transmit from $i$ to $(x, y)$ directly.

Figure 1 below illustrates a typical relay region in a propagation environment with $1/d^4$ transmit power roll-off.

We now consider a finite set $\aleph$ of randomly deployed stationary nodes over $\Re^2$ and examine any node $i$ in this set that wishes to transmit information.

**Definition 2 (Enclosing set)** The enclosing set of transmit node $i$ is defined to be

$$E(i) \equiv \left\{ n \mid n \neq i, (x_n, y_n) \in \bigcap_{k \in \aleph \setminus \{i\}} R^c_{i \to k} \right\},$$

where $(x_n, y_n)$ is the position of node $n$ on $\Re^2$. $A^c$ denotes the complement of any set A, and \ denotes the set difference.

In other words, the enclosing set of node $i$ is the set of all nodes distinct from $i$, which do not lie in any of the relay regions that $i$ forms with other nodes.

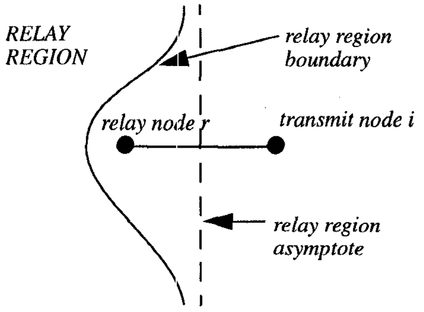

Figure 1. Relay region of the transmit-relay node pair $(i, r)$.

**Definition 3 (Enclosure)** The enclosure of transmit node $i$ is defined to be

$$\varepsilon_i \equiv \bigcap_{k \in E(i)} R^c_{i \to k}$$

**Definition 4 (Neighbor)** A node $n$ is said to be a neighbor of $i$ if $(x_n, y_n) \in \varepsilon_i$. The set of neighbors of $i$ is denoted by $N(i)$.

**Definition 5 (Enclosed node)** A node $i$ is said to be enclosed if it has communication links to each of its neighbors and to no other node.

Figure 2 illustrates the enclosure for a transmit node $i$ with 3 nodes in its enclosing set $\{k_1, k_2, k_3\}$ in an environment with $1/d^4$ transmit power roll-off.

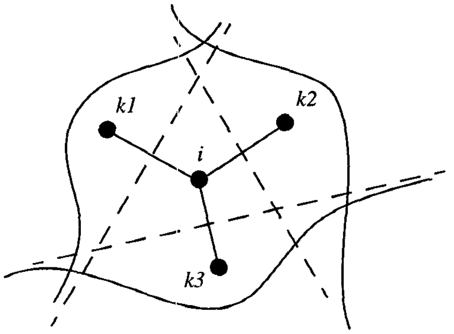

Figure 2. Enclosure of node $i$

**Definition 6 (Enclosure graph)** The enclosure graph of a set of nodes $\aleph$ is the graph whose vertex set is $\aleph$ and whose edge set is

$$\bigcup_{i \in \aleph} \bigcup_{k \in N(i)} l_{i \to k}$$

where $l_{i \to k}$ is the directed communication link from $i$ to $k$.

**Theorem 1 (Strong connectivity)** For propagation laws with $1/d^n$ transmit power roll-off, $n \geq 2$, the enclosure graph of a set of nodes $\aleph$ is strongly connected.

This theorem states that if each node is properly enclosed, then the entire network is guaranteed to be strongly connected. The proof of this theorem can be found in [10]. The next step is to consider its power implication.

## 2.4. Minimum Power Topology

**Definition 7 (Minimum power topology)** A graph on the stationary node set $\aleph$ is said to be a minimum power topology on $\aleph$ if (1) every node has a directed path to the master-site, and (2) the graph consumes the least total power over all possible graphs on $\aleph$ for which (1) holds.

After the enclosure graph has been found, we apply the distributed Bellman-Ford shortest path algorithm [4] on the enclosure graph using power consumption as the cost metric. The cost of a node $i$ is defined as the minimum power necessary for $i$ to establish a path to the master-site.

Each node calculates the minimum cost it can attain given the costs of its neighbors. Let $n \in N(i)$. When $i$ receives the cost information $C(n)$, it computes

$$C_{i,n} = C(n) + P_{transmit}(i, n) + P_{receive}(n)$$

where $P_{transmit}(i, n)$ is the power required to transmit from $i$ to $n$, and $P_{receive}(n)$ is the marginal transceiver power that $i$'s connection to $n$ would induce at $n$. $P_{receive}(n)$ is either known to $i$, if for instance every user carries an identical transceiver, or can be transmitted to $i$ as a separate piece of information along with $C(n)$. Then, $i$ computes

$$C(i) = \min_{n \in N(i)} C_{i,n}$$

and picks the link corresponding to the minimum cost neighbor. The data transmission from $i$ to the master-site can then start on this link, which is proved to be the global minimum power link by the next theorem [10].

**Theorem 2 (Minimum power)** The distributed protocol described above finds the minimum power links on $\aleph$.

We now simulate a stationary network with nodes deployed over a square region of 1 kilometer on each side. The $(x, y)$ coordinates of the nodes are generated as independent and identically distributed (i.i.d.) uniform random variables over this region. Since the nodes are stationary, once each node is enclosed and obtains a valid cost, the network remains in the minimum power topology.

In this simulation, we investigate how the total power consumption of the minimum power topology varies with the number of nodes. Figure 3 illustrates this relationship. As the number of nodes grows larger, the average power decreases towards its asymptote of 100 mW transceiver power per node. The plot has been normalized to the transceiver power.

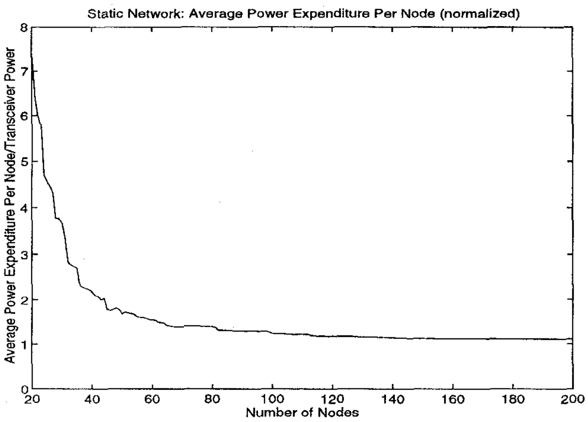

Figure 3. Average power expenditure per node

## 4. Minimum Energy for Mobile Networks

The protocol developed so far has been for stationary networks. However, due to the localized nature of enclosure, it proves to be an effective energy-conserving protocol for the mobile case as well.

Synchronization in a mobile network can be achieved by use of the absolute time information provided by GPS up to 100 ns resolution. In a synchronous network, each node wakes up regularly to "listen" for change and goes back to the sleep mode to conserve energy. We call the time between successive wake-ups the *cycle period* of the network. If the cycle period is too long, the power costs to the master-site can change significantly from one wake-up to the next. In this case, the network may not be able to track the correct costs. If the cycle period is too short, then the network consumes unnecessary energy to compute costs that change only slowly. The choice of the cycle period for energy-efficient operation of a wireless mobile network must address this trade-off. In our simulation, we assume that the cycle period has been chosen to meet these two constraints.

The protocol is self-reconfiguring since strong connectivity is ensured within each cycle period and the minimum power links are dynamically updated. It can be seen that this protocol is also fault-tolerant. A network protocol is *fault-tolerant* if it is self-reconfiguring when nodes leave or new nodes join the network. Under such a scenario, each node employing our protocol would compute its new enclosure at each wake-up and find the minimum power topology.

Next, we simulate a mobile set of nodes and measure its energy consumption. The initial positions of 100 nodes are generated as i.i.d. uniform random variables over a square field, 1 kilometers on each side. The velocities are uniformly distributed on the interval $(-v_{max}, v_{max})$, and $v_{max}$ is varied to observe how the energy consumption changes.

Let $T$ be the cycle period of the network. Assume that node $i$ is enclosed at the $n$ th wake-up, and let $e_n$ be the distance of $i$ to its furthest neighbor. At the next wake-up, if $i$ sets its search radius to

$$r_{n+1} = e_n + 2\sqrt{2}\, v_{max} T$$

then its neighbors must fall within this radius. Because the cycle period is small enough to allow positions to vary only slightly from one iteration to the next, in most cases the node will have its previous neighbors in its new enclosure at the next wake-up.

From a system perspective, the measure of mobility is not the velocities but rather the displacements of nodes within a cycle period of the network. The maximum displacement of a node in a cycle period is $\sqrt{2}\, v_{max} T$. Figure 4 displays the search-period power level per node averaged over 10000 iterations and averaged over all the nodes. The horizontal axis on this graph is the maximum displacement in meters during one cycle period. The figure indicates that the power consumption per node scales better than linearly with the maximum displacement within the range of displacements for which the network can track the correct costs.

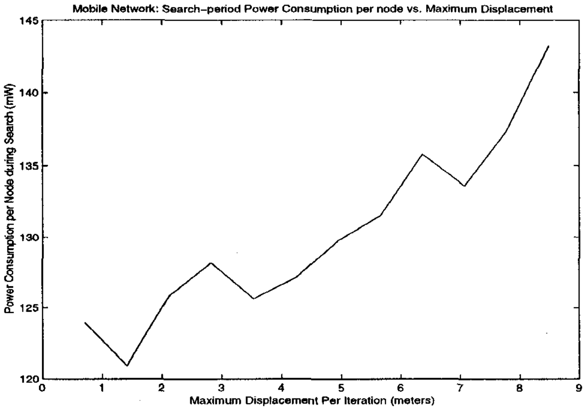

Figure 5. Power consumption per node during search period

The energy expenditure during the enclosure search depends on the search duration. For the particular network in this simulation, a two-way propagation delay between a node and its neighbors is estimated to be on the order of 10 $\mu$s. The time that it takes for the transceiver circuits to ramp up and transmit at full power is estimated to be on the order of 1 ms, which is much longer, and hence is the determining factor for the length of the search period. The energy expenditure per node during search can then be found by multiplying the search-period power consumption by this delay.

The energy consumption of a mobile network which uses this protocol is very low. As an example, for $v_{max}$ = 10 meters/sec and for a cycle period of $T$ = 210 ms, the maximum displacement is about 3 meters. Then, the average power consumption per node during the search period is about 127 mW from Figure 4. If the node goes to the sleep mode after the search, the search period is simply the "on" period of 1 ms per cycle which is the time required for transceiver circuits to operate. Then, the average power that the protocol consumes over a cycle period is only 0.6 mW per node.

## 6. Conclusion

In this paper we described a distributed network protocol which finds the minimum energy topology. We have applied it to both stationary and mobile networks and demonstrated that this protocol is very energy-efficient while maintaining strong network connectivity. Future work includes the integration of such a protocol into the radio transceiver design and a better quantification of the actual power consumption and the degree of fault-tolerance when applied to highly dynamic mobile networks.

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