Mobile Networks and Applications 10, 897–910, 2005

DOI: 10.1007/s11036-005-4446-4

Energy Efficient Broadcast in Wireless Ad hoc Networks with Hitch-hiking

MANISH AGARWAL and LIXIN GAO
Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01002, USA

JOON HO CHO
Department of Electronic and Electrical Engineering, Pohang University of Science and Technology (POSTECH), Pohang, Kyungbuk Korea

JIE WU
Department of Computer Science and Engineering, Florida Atlantic University, Boca Raton, FL 33431, USA

Abstract. In this paper, we propose a novel concept called *Hitch-hiking* in order to reduce the energy consumption of broadcast application for wireless networks. Hitch-hiking takes advantage of the physical layer design that facilitates the combining of partial signals to obtain the complete information. The concept of combining partial signals using *maximal ratio combiner* [15] has been used to improve the reliability of the communication link but has never been exploited to reduce energy consumption in broadcasting over wireless ad hoc networks. We study the advantage of Hitch-hiking for the scenario when the transmission power level of nodes is fixed as well as the scenario when the nodes can adjust their power level. For both scenarios, we show that Hitch-hiking is advantageous and have proposed algorithms to construct broadcast tree with Hitch-hiking taken into consideration. For fixed transmission power case, we propose and analyze a centralized heuristic algorithm called SPWMH (Single Power Wireless Multicast with Hitch-hiking) to construct a broadcast tree with minimum forwarding nodes. For the latter case, we propose a centralized heuristic algorithm called Wireless Multicast with Hitch-hiking (WMH) to construct an energy efficient tree using Hitch-hiking and also present a distributed version of the heuristic. We also evaluate the proposed heuristics through simulation. Simulation results show that Hitch-hiking can reduce the transmission cost of broadcast by as much as 50%. Further, we propose and evaluate a protocol called Power Saving with Broadcast Tree (PSBT) that reduces energy consumption of broadcast by eliminating redundancy in receive operation. Finally, we propose an algorithm that takes advantage of both Hitch-hiking and PSBT in conserving energy.

Keywords: wireless ad hoc networks, broadcast algorithms, distributed algorithms, maximal ratio combiner, simulations

1. Introduction

Wireless networks in the form of ad hoc networks and sensor networks have gained lot of attention in recent years. The rapidly increasing capabilities and declining costs of computing and communication devices have made it possible to use wireless networks in a wide range of applications that can improve quality of life, and even save lives. Sensor networks find their application in healthcare (e.g., health monitoring and coordination among doctors and nurses), aircraft flight control, weather forecasting, home appliance control, and protection against bioterrorism. Ad hoc networks can be used for communication in ad hoc settings such as in conferences or classrooms. One of the key challenges in the deployment of wireless networks is how to prolong the lifetime of the networks. The lifetime of wireless networks is limited by the battery energy in wireless devices. Sensor networks will stress power sources because of their need for long operating lifetimes and high energy density [5,9,21]. Furthermore, the lifetime of batteries has not been improved as fast as processing speed of microprocessors. Therefore, energy efficiency is critical for the wide deployment of wireless networks.

Power saving techniques for ad hoc networks can be broadly classified into two categories: power saving protocols and power control for transmission. A *power saving protocol* [3,18,25] aims to put wireless nodes into periodical sleep state in order to reduce the power consumption in the idle listening mode. *Power control for transmission* [16,22] manages energy consumption by adjusting transmission ranges. Our work deals with conserving power by employing power control for transmission.

Broadcast is a very important communication primitive used in wireless networks. Wireless networks, due to their ad hoc nature and mobile environment, make frequent use of broadcast primitives to adapt to network changes. Broadcast is also widely used in sensor networks to disseminate information about environmental changes to other nodes in the network. Therefore, it is essential to develop efficient broadcast protocols that are optimized for energy consumption.

In this paper, we investigate the problem of minimizing the total energy consumed in broadcasting data. Our key idea is to reduce energy consumption of the broadcast application by taking advantage of the physical layer design that facilitates the combining of partial information to obtain complete information. We refer to this as *Hitch-hiking* since partial signals are analogous to cars passing on the road carrying messages as Hitch-hikers and delivering them to their destinations at no extra cost. By the effective use of partial signals, a packet can be delivered with less transmission power. The concept of combining partial signals using *maximal ratio combiner* [15] has been used in physical layer design of wireless systems to increase reliability but has never been exploited to reduce energy consumption at the network layer.

We study the performance gain due to Hitch-hiking for the scenario when nodes in the network have fixed transmission power as well as for the scenario when nodes can adjust their power level. For fixed transmission power case, we propose and analyze a centralized heuristic algorithm called SPWMH and a distributed algorithm to construct a broadcast tree with minimum number of forwarding nodes. For variable transmission power case, we propose and analyze a centralized heuristic algorithm called Wireless Multicast with Hitch-hiking (WMH) and a distributed algorithm that can take advantage of Hitch-hiking to reduce the overall energy consumption of broadcast. The performance analysis shows that Hitch-hiking can reduce the energy consumption of the broadcast application by as much as 50%. We have also shown that the energy consumed in receiving a packet can cause wastage of energy in broadcast due to redundant reception of the same packet by nodes. Further, we propose and evaluate a protocol called Power Saving with Broadcast Tree (PSBT) to conserve the energy wasted by a node's reception of redundant message in a broadcast. Finally, we propose an algorithm that takes advantage of both Hitch-hiking and PSBT in conserving energy.

The rest of the paper is organized as follows. In Section 2, we give an overview of the related work concerning minimum-energy broadcast problem. In Section 3, we describe the signal and system design behind Hitch-hiking. In Section 5, we study the advantage of Hitch-hiking for the case when the nodes in the network cannot change their power levels. In Section 6, we study a more general scanrio when nodes in the network can adjust their power levels and propose heuristic algorithms that use Hitch-hiking to reduce energy consumption in broadcast application. In Section 7, we propose and analyze a protocol called PSBT to reduce the effect of energy consumed in receiving a packet on the overall energy consumption of the broadcast. We also propose an algorithm that works with PSBT and takes advantage of Hitch-hiking to reduce the energy consumption. Finally, we conclude in Section 8.

2. Related work

Both power saving protocols and power control for transmission have been studied in various settings. In [18], Singh et al. proposed a protocol called PAMAS that uses a second low-power radio channel to detect activity from neighbors and turns on a node only when a neighbor communicates with the node. In SPAN [3], a small dominating set is selected locally and nodes outside the set are put into the sleep state. Power control has been studied for broadcast taking either a source-independent approach or a source-dependent approach. In the source-independent approach, all nodes can be a source and are able to reach all other nodes by assigning appropriate ranges. The problem of minimizing the total transmission power consumption was shown to be NP-complete for both 2-D space [4] and 3-D space [10]. There are several heuristic solutions [12] for this problem. In source-dependent approach, even though the source is given but the problem is still NP-complete.

Broadcast Incremental Power (BIP) [22] is a widely used heuristic approach to construct a minimum-energy broadcast tree rooted at the source node. BIP constructs the broadcast tree by starting with the source node as the only node in the tree and adds one node at a time to the tree. Each time BIP has to add a node to the tree, it chooses the uncovered node which can be added to the tree at minimum additional cost. This process is continued until all the nodes in the network are added to the tree. It is important to understand that BIP takes advantage of *Wireless Multicast Advantage*, referred to as WMA, to some extent. WMA is the property of wireless channel through which a single transmission can be received by all those nodes that fall in the transmission range of the transmitting node. Several approximation methods with bounds have also been proposed [11,20]. In Wan et al. [20], gave the analytical results for different algorithms to construct a minimum energy broadcast tree. They proved that the approximation ratio of Minimum Spanning Tree (MST) is between 6 and 12 and that of BIP is between 13/3 and 12. Wan et al. also found that BIP fails to take full advantage of WMA for many cases, because it adds just one node at a time to the broadcast tree. BIP can be improved by allowing it to add more than one node at a time, but that process requires a different selection criteria than one proposed in [22].

In Cagalj et al. [2], proposed a heuristic called EWMA that builds an energy efficient broadcast tree by improving upon an initial feasible solution using wireless multicast advantage. In EWMA, every forwarding node in the initial solution is given a chance to increase its power level if the overall cost of the tree decreases at the new power level. Each node finally chooses the power level at which the overall decrease in cost of the final tree is maximized. The authors of EWMA have also given a distributed version of the algorithm called DEWMA.

All of the aforementioned studies assume that a node can only decode a signal whose signal strength is above a certain threshold and rest of the signals are ignored. In the following section, we describe a mechanism that exploits signals with signal strength below a threshold to reduce the overall cost of the broadcast tree.

3. Background

In this section, we describe the signal and system design for the physical layer of the wireless ad hoc network and introduce related concepts that play crucial roles in our network layer design for Hitch-hiking.

3.1. Packetization

We assume that messages are packetized. A packet consists of a preamble, a header, and a payload. A preamble is a sequence of pre-specified uncoded symbols assigned to facilitate timing acquisition, a header contains the error-control coded information sequence about the source/destination addresses and other control flags, and a payload contains the error-control coded message sequence.

We also assume that the header and the payload in a packet are the outputs of two different channel encoders, and that the two channel codes are used by all the nodes in the system. The separation of a header and a payload in channel coding enables a receiver to retrieve the information in a header without decoding the entire packet. The use of the same channel codes enables a receiver to enhance the signal-to-noise ratio at the input to the channel decoder by combining the payloads of multiple packets containing the same encrypted message. For the details of packet combining see Section 3.4.

3.2. Signal-to-noise ratio and interference

One of the most important properties of a wireless channel is that a transmitted signal can reach any receiver, as long as the channel gain between the transmitter and the receiver is not zero. Hence, when the kth node transmits a packet to the lth node, the l'th node, with l' not necessarily equal to l, can receive the signal with the signal-to-noise ratio (SNR) per symbol given by

$$\gamma_{k,l'} = \frac{\alpha_{k,l'} E_k}{N_0}, \tag{1}$$

where $\alpha_{k,l'}$ is the gain of the wireless link from the kth node to the l'th node, E_k is the energy of the transmitted signal by the kth node, and N_0 is the noise density. The gain $\alpha_{k,l'}$ includes the effects of propagation loss, antennas and amplifiers, and channel fading and shadowing [17, Chaps. 3, 4].

When there are K nodes transmitting packets at the same time, a receiver suffers the degradation in the SNR due to the interference. For example, if direct-sequence spread-spectrum (DS/SS) technique is employed as the modulation scheme and the conventional matched filter receiver is employed as the detector, the SNR of the packet transmitted by the kth node and received by the lth node is given by

$$\gamma_{k,l} = \frac{\alpha_{k,l} E_k}{N_0 + \frac{1}{N}\sum_{k'=1,k'\neq k}^{K} \alpha_{k',l} E_j} \tag{2}$$

where N is called the processing gain, which determines the level of interference suppression. However, when the processing gain is very large or the scheduling algorithm is designed to avoid the collision of packets, the SNR (2) becomes the same as (1).

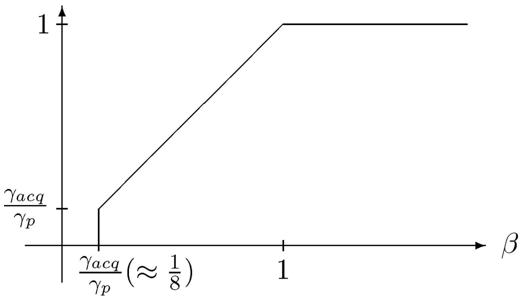


Figure 1. The coverage function when $\Gamma p/\Gamma acq$ is 9 (dB).

3.3. Partial reception

We introduce two[1] thresholds on the SNR (Signal-to-noise ratio): one is the threshold γ_p to successfully decode the payload and the other is the threshold γ_{acq} to successfully acquire the timing. We assume that the system is designed to have $\gamma_{acq} < \gamma_p$ which is a reasonable assumption. Due to the discrepancy in the two thresholds, we observe the following three cases when a packet is received with the SNR per symbol γ: (1) When $\gamma_{acq} < \gamma_p \leq \gamma$, the node can successfully retrieve the payload message and this is called full reception, (2) When $\gamma_{acq} \leq \gamma < \gamma_p$, the node can successfully decode the header information, though it cannot successfully decode the payload message. This is called partial reception, and (3) When $\gamma < \gamma_{acq} < \gamma_p$, the node can neither decode the header or payload message and is called failed reception. *The key idea of Hitch-hiking is to take advantage of not only full reception but also partial reception of signals.*

When the kth node transmits a packet, the amount of reception by the lth node is quantified by the coverage of the lth node defined as

$$C\left(\frac{\gamma_{k,l}}{\gamma_p}\right) \tag{3}$$

where $C(\beta)$ is the coverage function given by

$$C(\beta) = \begin{cases} 1, & \text{for} \quad \beta > 1 \\ \beta, & \text{for} \quad \frac{\gamma_{acq}}{\gamma_p} < \beta \leq 1 \\ 0, & \text{for} \quad 0 < \beta \leq \frac{\gamma_{acq}}{\gamma_p}. \end{cases} \tag{4}$$

The lth node is fully covered by the kth node, if the coverage is equal to 1. Figure 1 shows an example of the coverage function when the difference of the thresholds γ_p and γ_{acq}, in dB, is 9, i.e., $\gamma_{acq}\gamma_p \approx 1/8$.

A channel gain is often modeled as a function of the distance such as a power of the distance. That is, the channel gain $\alpha_{k,l}$ is given by $\alpha_{k,l} = \frac{c}{(d_{k,l})^{\alpha}}$ with the path loss exponent $2 \leq \alpha \leq 4$ [17], where $d_{k,l}$ is the distance between the kth node and the lth node, and c is a constant. When the lth node is just 100% covered by the kth node, the coverage of the l'th node

---

[1] We assume that the threshold for successful decoding of a header is less than or equal to the threshold for successful timing acquisition. So, the header is successfully decoded whenever the timing is successfully acquired and, consequently, the threshold for successful decoding of a header does not play any role.

can be easily obtained as

$$C\left(\left[\frac{d_{k,l}}{d_{k,l'}}\right]^{\alpha}\right) \tag{5}$$

in terms of the distances, because $\gamma_p = \frac{cE_k}{(d_{k,l})^{\alpha}N_0}$. For example, when $\gamma_{acq}/\gamma_p = 1/8$ and $\alpha = 2$, the coverage of the l'th node is 0.25 if $d_{k,l}/d_{k,l'} = 1/2$, while it is 0 if $d_{k,l}d_{k,l'} = 1/3$.

3.4. Combining partial receptions

Suppose that a node receives two packets containing the same information and the SNRs γ_1 and γ_2 of the packets satisfy $\gamma_{acq} \leq \gamma_1 < \gamma_p$, $\gamma_{acq} \leq \gamma_2 < \gamma_p$, and $\gamma_1 + \gamma_2 \geq \gamma_p$. These two packets can be combined by a maximal ratio combiner [15] and can be successfully decoded as the resultant SNR $\gamma_1 + \gamma_2$ at the output of the combiner is greater than or equal to the threshold γ_p.

The above idea of combining two partial receptions can be easily extended to combine multiple partial receptions, where the output SNR of the maximal ratio combiner is given by $\gamma = \sum_{j=1}^{J} \gamma_j$ with J being the number of packets containing the same information, and with γ_j being the SNR of the jth packet, satisfying $\gamma_j \geq \gamma_{acq}, \forall j$.

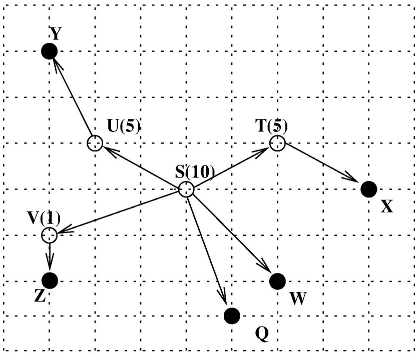
This process of combining partially received packets to successfully decode the message in the payload is called *Hitch-hiking*.

In next section, we will study the problem of constructing energy efficient broadcast tree with Hitch-hiking advantage.

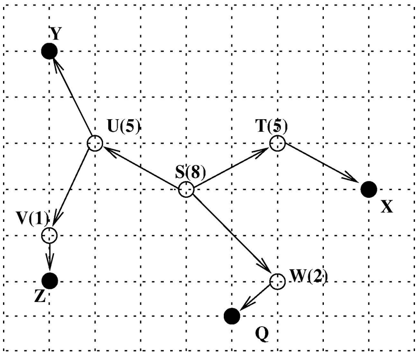
4. Hitch-hiking advantage

In this section, we will demonstrate the advantage of Hitch-hiking to reduce the energy consumption in a broadcast through an example shown in figure 2. In a broadcast, the same packet is transmitted many times by different nodes in order to cover the entire network. With Hitch-hiking, we can take advantage of this multiple transmission of the same packet to effectively reduce the energy consumption. We assume that nodes can buffer the partial packets that they receive so that these can later be combined with other partial packets to decode the complete packet. In figure 2, the power level used at each relay node is indicated at the node. Channel loss exponent α is taken as 2 for this example. The black nodes are the non-forwarding nodes while white nodes are the relay nodes that forward packets to other nodes. Figures 2(a) and (b) show the broadcast trees constructed with Broadcast Incremental Power (BIP) [22] and Minimum Spanning Tree (MST) respectively. Figure 2(c) shows the broadcast tree constructed with Hitch-hiking advantage. The energy consumption is reduced by Hitch-hiking due to the following two factors.

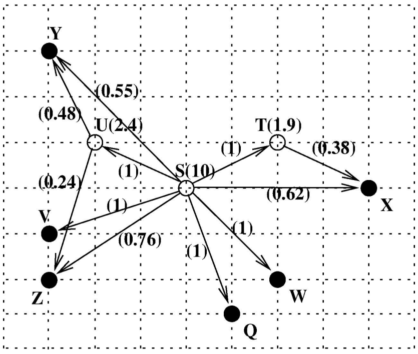
First, *Hitch-hiking can reduce the number of relay nodes needed*. For example in figure 2(c), the broadcast from node S covers 76% of node Z and the broadcast from node U covers remaining 24% of node Z. Thus node Z is fully covered by combining the broadcasts from node S and node U. Node V no longer needs to relay to node Z. This reduces the number of relay nodes needed, in contrast to the broadcast without Hitch-hiking as shown in figure 2(a). Second, *Hitch-hiking can reduce the power level of relay nodes*. For the example in figure 2(c), since node S covers 55% of node Y, node U needs to cover only 45% of node Y. So node U can broadcast with reduced power level. Please note that due to Hitch-hiking, the cost of the broadcast tree was reduced from 21 to 14.30 in the given example.



(1) BIP: cost 21



(2) MST: cost 21



(3) Hitch-hiking: cost 14.30

Figure 2. Comparison of energy consumption for broadcast between BIP, MST and Hitch-hiking. The number on each node indicates the power level used for broad-cast. The number on each edge indicates the coverage provided by the edge to the destination node. (1) refers to full coverage while values less than 1 indicate the amount of partial coverage.

In next section, we will study the advantage of Hitch-hiking for the case when the transmission power level of the nodes in the network is fixed. This makes a good starting point to understand the advantage of Hitch-hiking for broadcast application as it is simpler than the scenario where nodes can adjust their power levels and practically useful for the scenarios where the nodes are not equipped with network cards capable of power adjustment.

5. Single power broadcast with hitch-hiking

The problem of reducing broadcast redundancy has been studied in detail in [14,19,23]. Flooding is traditionally used for broadcasting where the same message is transmitted by all nodes that receive it. In [14], authors showed that blind flooding can lead to serious redundancy, contention, and collision because the radio propagation is omnidirectional and transmission from different hosts overlap. Flooding has been replaced in [18,24] where only a set of forwarding nodes are responsible for forwarding the message. The problem of finding forwarding nodes is equivalent to finding the Minimum Connected Dominating Set (MCDS) in unit-disk graph for a given set of nodes. A *unit-disk graph* is a geometric graph in which there is an edge between two nodes if and only if their distance is at most one. Reducing broadcast redundancy can also lead to overall power saving in the network as less number of nodes make the transmission.

In [8], the authors showed that the general graph version of MCDS problem is NP-Complete and proposed several greedy heuristics to find connected dominating set. We give a brief description of one of the greedy heuristic proposed in [8] that has been used for comparison with the heuristic proposed later in this paper. The idea behind the heuristic for constructing MCDS is to grow a tree T, starting from the vertex of maximum degree. At each step, the algorithm picks a node in T that covers maximum uncovered nodes in the graph and marks it black. It then marks all the nodes covered by the chosen node as gray and adds them to T. This continues till all the nodes in the graph are added to the tree. The set of black nodes forms the Connected Dominating Set (CDS) in the end.

As shown in Section 4, the Hitch-hiking advantage can reduce the number of forwarding nodes and the advantage remains even when the transmission power of the nodes is fixed. We will show that the problem of finding mininum set of forwarding nodes for making a broadcast with Hitch-hiking advantage is NP-Complete. Thus, we propose and evaluate a centralized and a distributed heuristic algorithm to construct broadcast tree with Hitch-hiking advantage. In next subsection, we will develop the network model for studying broadcast with Hitch-hiking when the transmission power level of the nodes is fixed.

5.1. Network model

We assume a static ad hoc network with N nodes containing omnidirectional antennas. The nodes are assumed to be capable of receiving and combining partial signals to decode the message contained in the signal. Thus, nodes in the networks can take advantage of Hitch-hiking. We represent a network by a directed graph $G = (V, E)$ where V is the set of nodes corresponding to the wireless devices in the network and E is the set of edges corresponding to the communication link between the devices. All the nodes in the network transmit with the same transmission power that fully covers nodes lying within range R from the point of transmission. There exists a communication link between transmitting node i and any other node j if transmission from node i is received at node j with SNR greater than γ_{acq}. Associated with each edge $(i, j) \in E$ is the coverage provided by the edge to the destination node. In the following paragraph, we make some assumptions and describe the method for calculating coverage provided by a transmitting node k with power level E_k to other nodes in the network. The assumptions and method for calculating coverage holds for the rest of the paper.

We assume that $\gamma_p = 1$ which implies that if SNR of a received signal is greater than or equal to 1, then the signal can be successfully decoded, which is a reasonable assumption. Thus, coverage of a node l by a transmission from a node k becomes $C(\gamma_{k,l}) = C(\frac{cE_k}{d_{k,l}^{\alpha} N_0})$. We further simplify the model by taking $\frac{c}{N_0} = 1$ and thus making the coverage function as $C(\frac{E_k}{d_{k,l}^{\alpha}})$. We have taken α to be 2 and 4. γ_{acq} is taken to be 0 because γ_{acq} is practically so small that the partial coverage provided by signals having SNR below γ_{acq} does not contribute much in energy saving. Thus, we assume that the results presented in the paper are not affected much by the choice of $\gamma_{acq} = 0$.

In this section, every node makes a transmission with fixed power R^{α} so the coverage function becomes $C((\frac{R}{d_{k,l}})^{\alpha})$.

5.2. Problem definition

We assume a specified source node which has to broadcast a message to all other nodes in the network. Nodes that receive a message but do not retransmit it are called *leaf nodes*. Nodes, including the source node, that retransmit the message are called *forwarding nodes*.

The objective function: For the given source node S, we want to find a minimum set of forwarding nodes such that the message sent by S is received by all the nodes in the network. We call this problem as *Single Power Broadcast Problem* (SPB).

For the same problem statement, we call the problem *Single Power Broadcast with Hitch-hiking* (SBH) when the nodes in the network are capable of receiving and combining partial signals as well.

5.3. Complexity of SBH

The SPB problem is equivalent to finding Minimum Connected Dominating Set (MCDS) problem in unit disk graph which has been shown to be NP-Complete [13]. In order to prove that SBH problem is NP-complete, we will show that SBH belongs to NP and SPB is a special case of SBH.

Theorem: SBH problem is NP-complete.

Proof: It is easy to see that SBH belongs to the NP class since it can be verified in polynomial time whether a given set of forwarding nodes cover all the nodes in the network and whether the cost of the final solution is less than a fixed value. Now we need to show that SPB is a special case of SBH.

Recall the thresholds $\gamma_{\mathbf{p}}$ and $\gamma_{\mathbf{acq}}$ described in Section 3 4 for Hitch-hiking. When $\gamma_{\mathbf{p}} = \gamma_{\mathbf{acq}}$, we will have no case of partial reception of signals (Section 3). Thus the problem of SPB will be reduced to SBH where only full or failed signals exist. Hence, we can say that SPB is a special case of SBH for $\gamma_p = \gamma_{acq}$.

Since SPB is NP-complete and is a special case of the SBH problem, and because SBH belongs to NP class, we can therefore say that SBH problem is NP-complete.

As SBH is NP-complete, we propose a centralized heuristic and its distributed counterpart in the next subsections to construct MCDS with Hitch-hiking. We assume static network so the tree has to be constructed only once. Thus the cost of constructing the tree is not considered.

5.4. Centralized algorithm

In this subsection, we propose a heuristic algorithm to find a feasible solution for SBH problem. We call the proposed algorithm as SPWMH (Single Power Wireless Multicast with Hitch-hiking). SPWMH constructs a CDS with Hitch-hiking advantage. SPWMH is a centralized greedy algorithm and grows a tree T starting from the source node. The SPWMH algorithm is motivated from the greedy heuristic proposed by Guha et al. [8] for constructing CDS in a graph.

During the execution of SPWMH, each vertex in the graph is either unmarked or marked as gray or black. For every vertex in the graph, SPWMH maintains a variable called *pc* that keeps the total coverage provided by the incoming edges on that vertex from its black neighbors. Thus, for a vertex u, $pc(u)$ refers to the total coverage of vertex u from its black neighbors. A vertex is marked gray when its *pc* value exceeds 1 which means that the vertex is fully covered by the transmissions from its neighboring black vertices. A vertex is added to the tree T once it becomes gray. The coverage provided by a node v to its neighbor u depends on the coverage value of the edge (v,u) as well as the *pc* value of node u and is given as min $(Coverage(v,u),(1 - pc(u)))$ where $Coverage(v,u)$ refers to the coverage provided by link (v,u) to vertex u.

Initially all the vertices are unmarked. Starting with the source node, at each step, SPWMH picks a gray vertex v in T that provides maximum coverage to its unmarked neighbors and marks it black. When a vertex say v is marked black, the *pc* value of its unmarked neighbors is increased by the coverage value of the edge from vertex v to the unmarked neighbors. Then all those nodes whose *pc* value exceeds 1 are marked gray and added to the tree T. This process is repeated till all the vertices in the graph are added to the tree.

The complexity of the above algorithm is $O(n^3)$ where n is the total number of vertices in the graph. Starting with the source vertex, it takes at most $O(n)$ iterations to add all the nodes in the tree. In each iteration, it takes $O(n)$ operation to find the vertex that can provide maximum coverage and to update the *pc* values of the vertices neighboring to the recently marked vertex. It takes $O(n^2)$ operations to update the coverage provided by a gray vertex to its unmarked neighboring vertices based on the new *pc* value of its neighboring vertices. Thus, the entire algorithm runs in $O(n^3)$ steps.

5.5. Distributed SPWMH

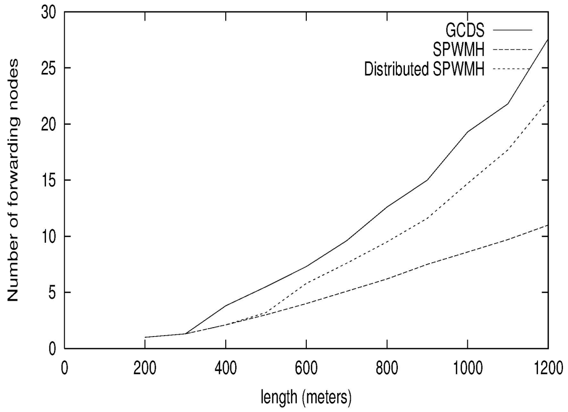
In this subsection, we present a distributed implementation of the SPWMH given in the previous section. In order to reduce the message complexity of the algorithm, the vertices that can get partial coverage from any vertex u is restricted to the two hop neighbors of the vertex u. Each vertex maintains *pc* value for itself and for all its two hop neighbors. Each node in the network is capable of determining its coverage value from a received signal. Thus, whenever a node becomes black, it sends a signal and based on the received signal strength, every other node in the networks updates its *pc* value. As soon as the *pc* value of a node changes, it informs its new *pc* value to its one hop neighbors which further propagates it to its one hop neighbors. Thus, the knowledge of a vertex about the *pc* values of a neighbor is reasonably accurate at any time. A node marks itself gray as soon as its *pc* value exceeds 1. As soon as a node becomes gray and has any unmarked neighbor (which it can check based on the *pc* value it has for its neighbors), it starts a timer inversely proportional to the total coverage it can provide to its unmarked neighbors. In the meantime, if it gets an update of *pc* value from its neighbor, it restarts its timer. If the timer expires and there are still some unmarked nodes that can be covered by the node, the node marks itself black and makes a transmission. This process continues till all the nodes in the network are marked.

5.6. Performance evaluation

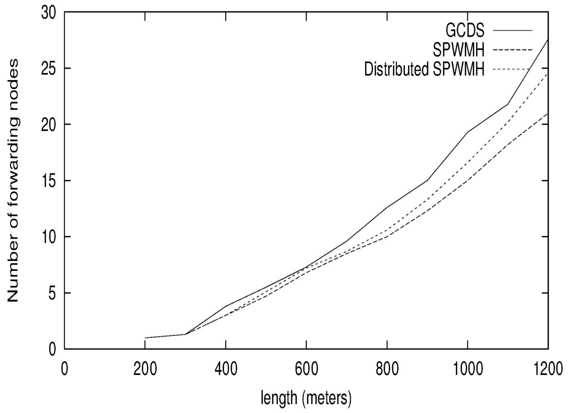
We performed simulation study to evaluate the performance of SPWMH and its distributed version. We compared the proposed heuristic algorithms with the greedy heuristic proposed by Guha et al. [8] for constructing CDS in a graph (Section 5) referred as *GCDS* (Greedy CDS).

All the algorithms are compared for the same network settings. The number of nodes in the network is fixed at $n = 100$ for all the simulations and the transmission range $R = 200$ meters. The area of the network is taken as $l \times l$ where l is varied from 200 to 1200 as shown in figure 3. The propagation loss constant α is taken as 2 and 4. We ran 100 simulations for each simulation setup and took the average of all 100 outcomes for a particular setting. The performance metric is the size of the forwarding nodes set returned by the algoritms.

Figure 3(a) compares the performance of GCDS, SPWMH and Distributed SPWMH for propagatation loss constant 2. It shows that Hitch-hiking can significantly reduce the number of forwarding nodes required for broadcast even when the tramsmission power level of the nodes in the network is fixed. The figure also shows that the advantage increases with the increasing area of deployment. The distributed SPWMH algorithm also performed better than GCDS and shows that it is feasible to take Hitch-hiking advantage in real networks.



(1) Propagation loss exponent=2



(2) Propagation loss exponent=4

Figure 3. Performance comparison of SPWMH and Distributed SPWMH with GCDS for propagation loss exponent 2 and 4.

Figure 3(b) compares the performace of GCDS, SPWMH and Distributed SPWMH for propagation loss constant 4. From the figure, we can see that the advantage of Hitch-hiking is small compared to case when the propagation loss constant was 2 but Hitch-hiking is still able to reduce the number of forwarding nodes. As the propagation loss constant increases, the energy contained in the signals degrades faster with distance thus reducing the advantage of Hitch-hiking.

In next section, we will study a more general scenario of SBH problem where the nodes in the network are capable of adjusting their transmission power level.

6. Adjustible power broadcast with Hitch-hiking

In this section, we will assume that the nodes in the network are capable of adjusting their transmission power level and also capable of taking Hitch-hiking advantage. Our objective function is to determine the power level for each node in the network for broadcasting the message generated from a source node. We will first develop a network model for this problem definition and then propose heuristic algorithms to solve the problem.

6.1. Network model

We assume a static ad hoc network with N nodes containing omnidirectional antennas. The nodes are assumed to be capable of receiving and combining partial signals to decode the message contained in the signal. Thus, nodes in the network can take advantage of the Hitch-hiking model described in the last section. We represent a network by a directed graph $G = (V, E)$ where V is the set of nodes corresponding to the wireless devices in the network and E is the set of edges corresponding to the communication link between the devices. There exists a communication link between node i and node j if transmission from node i is received at node j with SNR greater than γ_{acq}. Associated with each node $i \in V$ is a transmission power level of the node (p_i) and with each edge $(i, j) \in E$ is the coverage provided by the edge to the destination node. The method for determining the coverage value is same as described in Section 5.1.

6.2. Problem definition

We assume a specified source node which has to broadcast a message to all other nodes in the network. Nodes that receive a message but do not retransmit it are called *leaf nodes*. Nodes, including the source node, that retransmit the message are called *forwarding nodes*.

The objective function: For the given source node S, we want to find a set of forwarding nodes and determine their power level such that the message sent by S is received by all the nodes in the network, and the total energy consumed for this task is minimized. In other words, for a given graph G, we want to determine p_i for all $i \in V$ such that $\sum_{\forall\, i \in V} p_i$ is minimum and all the nodes are covered. This problem is called *Minimum-Energy Broadcast Problem* (MBP) [2].

For the same problem statement, we call the problem *Minimum-Energy Broadcast with Hitch-hiking* (MBH) when the nodes in the network are capable of receiving and combining partial signals as well.

In [1], we have shown that MBH problem is NP-complete. Thus, in next subsection, we will propose a centralized heuristic and its distributed counterpart to construct energy efficient broadcast tree with Hitch-hiking.

6.3. Centralized algorithm

First we give a brief overview of the proposed algorithm. The algorithm starts by constructing a Minimum Spanning Tree (MST) for a given network using either Prim's or Kruskal's algorithm. Then, starting from the source node, at each step the algorithm picks a fully covered node say u whose power level has not been determined till then, and decides its power level. While deciding the power level of node u, only its child and grandchild nodes are considered, i.e the decision is based on local optimization. These nodes (including u) form u's local region. Node u's final power level corresponds to the "maximum power reduction" in u's local region. That is, the summation of u's power level and u's children power level should be minimized while still ensuring full coverage of u's child and grandchild nodes. The reduction comes by the extra coverage (partial as well as full) provided by the increased power level of node u to its grandchild nodes in exchange for the decrease in power level of its child nodes. Finally, the coverage and power level of all uncovered nodes in the network are updated based on the coverage provided by the new power level of node u. Both centralized and distributed version of the algorithm is given. We call the proposed algorithm for improving upon the initial solution as WMH (Wireless Multicast with Hitch-hiking).

Before describing the algorithm in detail, we introduce some terminologies and attributes associated with each node in the network (Table 1). An attribute called pc associated with each node stores the total coverage of the node at any instant of time. The value of pc for node i is represented as $pc(i)$. A node i is said to be *fully covered* if $pc(i)$ becomes 100. In the beginning, only source node has its pc value as 100 and all other nodes have their pc value initialized to 0. Attribute called p_i keeps the transmission power level for node i and $CH(i)$ is the set of child nodes of node i in the broadcast tree.

We start with link-based MST as the initial feasible solution. MST is chosen because of its good performance even as a final solution for MBP problem as shown in [2]. MST could be constructed using any well-known algorithm for constructing MST. So let us assume that we have the MST for a given network and that each node in the network has knowledge of its parent in the MST. Once the MST is constructed, each node is assigned a minimum power level such that it can reach all its neighboring nodes in the MST with that power level. To decrease the cost of the MST, we apply the WMH algorithm over it. As we go along with the explanation of WMH algorithm, we will also run it over the example given in figure 2. The MST for the example is shown in figure 2(b). Figure 4 gives the pseudocode of the WMH algorithm.

The WMH algorithm determines the final power level for each node by considering one node at each step. Once the final power level of a node is decided, it is not changed throughout the execution of the algorithm. A set F keeps all those nodes whose final power level has been decided by the algorithm. Starting with the source node, at each step the algorithm picks a node say i such that $pc(i) = 100$, $p_i > 0$ and $i \notin F$ and determines its final power level. In other words, WMH picks the node that is fully covered, has transmission power greater than 0 and whose power level has not already been decided. If more than one node qualifies at the same time, the node with least node ID is picked by the algorithm. Since only the source node satisfies the condition in the beginning, WMH starts by deciding the power level of the source node.

In order to determine the final power level of a node say i, WMH calculates its gains for various power levels and assigns the power level to node i for which the gain is maximum. Since power level of node i can take arbitrary values over a range, WMH first constructs a discrete set of power levels for node i referred to as $PL(i)$ and then determine the gain for each of the power level in $PL(i)$. $PL(i)$ contains the current power level of node i and all those power levels at which node i covers all the child nodes of node j for at least one $j \in CH(i)$. In other words, $PL(i)$ contains all those power levels at which node i can reduce the power level of any one of its child node to 0 by covering all the child nodes of that child node. In the example given in figure 2, node S can reach nodes V and Q through power level 10, node X through power level 16 and node Y through power level 18. Thus, $PL(S)$ is a set {8,10,16,18}. It is easy to see that $PL(i)$ can be populated in polynomial time by taking each child node j of node i one at a time and considering all the child nodes of node j to find a power level which covers them all. In the next step, WMH finds the gain for each power level in $PL(i)$.

Table 1
Notations used in WMH.

$pc(i)$	Coverage of node i in percent
pi	Transmission power level of node i
$CH(i)$	Set of child nodes of node i
F	Set of nodes whose final power level is decided
$PL(i)$	Set of transmission power levels of node i
$gi(p)$	Gain of node i at power level p
p_j^{init}	Initial power level of node j
p_j^{red}	Reduced power level of node j
$d_{j,k}$	Distance between node j and k
N	Set of all nodes in the network

The gain $g_i(p)$ of node i is defined as the decrease in the total energy of the broadcast tree obtained by reducing the power level of some of the transmitting nodes in the MST, in exchange for the increase in node i's transmission power level to p. In other words, when the power level of node i increases, it provides partial and full coverage to more nodes in the networks. Due to the increase in the partial or full coverage of the node say k, the parent node of node k can reduce its power level such that it provides less or no coverage to node k. The reduction in power level of some of the nodes reduces the overall energy consumption of the tree. To simplify the algorithm, the reduction in the power level of only the child nodes of node i is considered in the calculation of gain of node i. Gain $g_i(p)$ is given by the following equation:

$$g_i(p) = \sum_{\forall j \in CH(i)} \left(p_j^{\text{init}} - p_j^{\text{red}}\right) - \delta \qquad (6)$$

where p_j^{init} is the initial power level of node j, p_j^{red} is the reduced power level of node j due to the increase in the power level of node i and δ is the increase in power level of node i. In order to calculate p_j^{red}, WMH first calculates the coverage provided by node i at power level p to the child nodes of node j. If k is any child node of node j, the increased partial coverage of node k due to power level p of node i, $pc(k, p)$ is calculated by the following equation:

$$pc(k, p) = \min\left\{\left(\frac{p}{d_{i,k}^{\alpha}} \times 100 + pc(k)\right), 100\right\} \qquad (7)$$

Please note that $pc(k, p)$ is just a temporary variable required to calculate gain achieved by node i at power level p

```
Algorithm WMH
    /* Continue till all the nodes are fully covered */
    while($\exists i \in N \mid pc(i) < 100$)
        /* Find a node that is fully covered, has transmission power > 0
            and has not decided its power level */
        Find $i \in N \mid (pc(i) \geq 100 \ \& \ p_i > 0 \ \& \ i \notin F)$

    /* Find local optimal power level for node i */
    Find discrete power level set $PL(i)$ for node $i$
        $Gain(i)$
        $p_i \leftarrow$ power level of node $i$ for which gain is maximum
        F $\leftarrow i$

    /* Increase coverage value of other nodes based on the final power level of node i */
    for all $j \in N$
        if $(j \notin F \ \& \ pc(j) < 100)$
            $pc(j) = \min\{pc(j) + (\frac{p_i}{d_{i,k}^{\alpha}} \times 100), 100\}$

    /* Reduce power level of all the nodes due to change in the coverage value
        of the child nodes */
    for all $j \in N$
        if $(j \notin F \ \& \ p_j > 0)$
            $Reduce(i, p_i, j)$

    Gain($i$)
    /* Find gain for all the power levels in $PL(i)$ */
    for all $p \in PL(i)$
        for all $j \in CH(i)$
            $Reduce(i, p, j)$
            $g_i(p) = \sum_{\forall j \in CH(i)} (p_j^{init} - p_j^{red}) - \delta$

    Reduce($i, p, j$)
    /* Reduce the power level of node j on the basis of partial coverage provided
        by node i at power level p */
    for all $k \in CH(j)$
        $pc(k,p) = \min\{pc(k) + (\frac{p}{d_{i,k}^{\alpha}} \times 100), 100\}$
        $p_j(k) = (1 - \frac{pc(k,p)}{100}) \times d_{j,k}^{\alpha}$
    $p_j^{red} = \max_{\forall k \in CH(j)} p_j(k)$
```

Figure 4. Algorithm for WMH. Refer to Table 1 for meaning of notations.

and the value of $pc(k)$ is not changed till node i has decided its final power level.

In the example of figure 2(b), while calculating the gain for node S at $p = 10$, $pc(Y,10) = (10/18 \times 100) = 55$. This means that if node S transmits at power level 10, it will provide 55% coverage to node Y.

Based on the pc value of the child node k of node j, the reduced power level required by node j to fully cover node k ($p_j(k)$) is calculated by the following equation:

$$p_j(k) = \left(1 - \frac{pc(k,\, p)}{100}\right) \times d_{j,k}^{\alpha} \tag{8}$$

where $(1 - pc(k,\, p)/100)$ gives the remaining coverage required by node k to get fully covered. Finally, p_j^{red} is given by:

$$p_j^{\text{red}} = \max_{\forall k \in CH(j)} p_j(k) \tag{9}$$

In the example, $p_U(Y) = (1 - 0.55) \times 5 = 2.25$. Thus, $p_U^{\text{red}} = 2.25$. Note that, only when node U finds that maximum gain can be achieved by increasing its power level to 2.4 where it can provide full coverage to node Z, it increases its power level to 2.4 as shown in the figure.

$p_j^{\text{red}} \leq 0$ implies that all the child nodes of node j are already covered so p_j^{red} is made equal to 0. Once WMH has calculated p_j^{red} for all $j \in CH(i)$, it can calculate $g_i(p)$ by putting the values in equation (6).

In the example, node S at power level 10 provides 72% coverage to node Z thus reducing the required power level of node V from 1 to 0.24. Thus, gain of node S at power level 10 is:

$$g_S(10) = \sum_{x \in U,T,W,V} \left(p_x^{\text{init}} - p_x^{\text{red}}\right) - \delta$$
$$= 2.75 + 3.1 + 2 + 0.76 - 2 = 6.61.$$

Please note that, it is only after node U decides its final power level, node Z gets full coverage by combining signals from node S and node U and node V reduces its power level to 0 as shown in figure 2(b).

This completes the calculation of gain of node i at power level p. The process of finding gain is applied for each power level $p \in PL(i)$. Once the gain for all the power levels in $PL(i)$ is determined, final power level of node i is chosen to be the one for which the gain is maximum. If for no power level p, $g_i(p) > 0$, p_i does not change. Once the final power level of node i is decided, WMH performs following steps in the given order:

- For all $j \notin F$ and having $pc(j) < 100$, calculate $pc(j, p_i)$ using equation (7) and assign it to $pc(j)$. In the example, when node S has decided its final power level as 10, $pc(Y,10)$ is 55 so $pc(Y)$ changes from 0 to 55. Similarly for nodes Z and X.
- Reduce the transmission power of all nodes j having $p_j > 0$ and $j \notin F$ based on the new pc value of their child nodes in the MST. The reduced transmission power is obtained using equation (8) such that the nodes continue to provide full coverage to the child nodes even with the reduced power level. In the example, the power level of node T is reduced from 5 to 1.9 once node S is assigned power level 10. Similarly for nodes U and W.

The WMH algorithm continues till all the nodes in the network are fully covered. The algorithm is guaranteed to end because while deciding the power level of a node say i, it is ensured that all its child nodes are fully covered by the final power level of node i. Since in the initial MST, every node except the root node in the network had a parent node, thus every node is guaranteed to be covered after finite number of steps.

Next we show that the complexity of the WMH algorithm is polynomial in the total number of nodes n. To calculate $g_i(p)$, it takes $O(n)$ time as it has to find the final power level for each of the child node of node i. Thus, in order to calculate gain for all $p \in PL(i)$, it takes $O(n^2)$ time. Finally, it repeats all the above steps till all the nodes in the network are fully covered which will thus take $O(n^3)$ time. So, the complexity of the algorithm is $O(n^3)$.

6.4. Distributed WMH

In this section, we will extend the WMH algorithm to run in distributed fashion. We assume that the construction of the minimum-weight spanning tree can be done in a distributed manner by running the distributed algorithm proposed by Gallager et al. [7]. Once the MST is constructed, each node knows the information about the cost of its two hop neighbors in the MST.

We assume that each node can determine its coverage by a transmission from a node say i, based on the SNR of a received signal from i using equation (3). A node i can also determine when it can decide its final power level based on $pc(i)$ and the conditions mentioned in Section 6.3. We call the node deciding its final power level as *Deciding node*. The main problem for a deciding node i in the distributed setting is to know the $pc(j)$ and p_j where node j is within two hops neighbors of node i.

To solve this problem, each node maintains a table called PCTable containing the $pc(j)$ and p_j, for all node j that are its two hop neighbors. Whenever $pc(j)$ or p_j for a node j is changed, node j informs the change to its one hop neighbors. This information can be piggybacked on HELLO packets. The neighboring nodes further propagate the change to their neighbors so that each node within two hops of node j gets the information and can update the entry corresponding to node j in their PCTable. Also, on getting an update, all nodes in the MST whose power level is greater than 0 and who has not yet done decided its final power level, if possible reduces its power level based on new value of $pc(j)$ using equation (8).

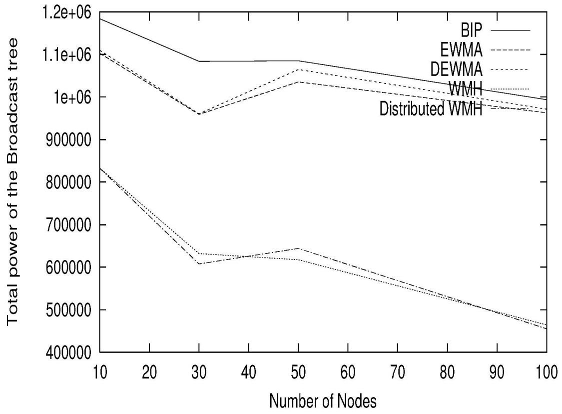
Now each deciding node has sufficient information to calculate gain. When a node i becomes a deciding node, it starts a timer for fixed interval during which it waits for an update from its neighboring nodes. The timer value is equal to the HELLO packet interval. This is to ensure that the gain calculated by node i is based on the latest state of its neighbors. When the timer expires, the node starts deciding its final power level based on the entries in its PCTable. Decision steps are the same as in Section 6.3. After the node has decided its power level, the node backs off for certain period of time inversely proportional to its calculated gain. This allows the nodes with higher gain to broadcast first. If the node receives an update during this interval, it re-calculates its power level and repeats again. If the timer expires without any update, the node transmits the packet with the final power level.

The construction of the broadcast tree is started by the source node and as new nodes become fully covered, they decide on the their power level and make broadcast to cover more nodes. This is continued till all the nodes in the network are covered.

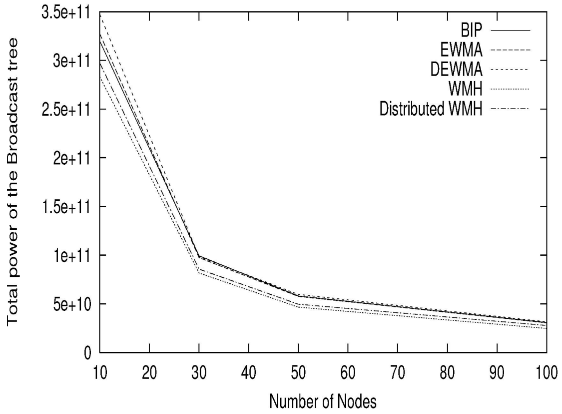
6.5. Performance evaluation

We performed a simulation study to evaluate the performance of our centralized algorithm (WMH) and its distributed version. We wrote our own simulator for the purpose of performance evaluation.

We compared our proposed algorithms with EWMA, BIP and MST algorithms for the same network settings. We performed the simulations for four different network sizes: 10, 30, 50 and 100 nodes similar to [2]. To fully cover distance d, the transmission power is taken to be d^α with propagation loss constant α taken as 2 and 4.



(1) Propagation loss exponent=2



(2) Propagation loss exponent=4

Figure 5. Performance comparison of WMH with other protocols for propagation loss exponent 2 and 4.

The nodes in the networks are distributed according to a spatial poisson distribution over the same deployment region. Thus the network density increases with increasing number of nodes. We ran 100 simulations with different node distribution for each simulation setup and the average was taken. Total power of the broadcast tree is the power consumed in making the broadcast of one message from a source node. The source node of the broadcast message was chosen randomly for each run.

Figure 5(a) shows the performance of the proposed algorithm compared to BIP, EWMA and DEWMA for propagation loss constant 2. From the figure, we can see that power of the broadcast tree constructed using WMH and Distributed WMH is almost 50% less than that of BIP, EWMA and DEWMA. We can also see that the advantage of Hitch-hiking increases with the increase in the number of nodes. The distributed version of the algorithm performs almost as well as the centralized version.

Figure 5(b) shows that with the increase in propagation loss exponent α from 2 to 4, the advantage of WMH and Distributed WMH over other protocols decreases. This is expected because with the increase in α, energy contained in partial signals decreases faster with distance thus providing less advantage of Hitch-hiking.

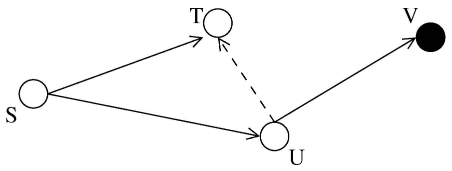


Figure 6. An example showing multiple receive of same packet in a broadcast.

7. Broadcast with power saving

Till now, we have considered only the transmission cost of the broadcast tree. An important observation about the broadcast application is that spatial overlapping of transmission zones may cause same message to be received multiple times by the nodes within the overlapping zones. For example in the broadcast tree shown in figure 6, node T received the broadcast message from node S but when node U makes the broadcast of the same message to cover its child nodes, node T received the same message again. This wastes energy if the cost of receiving a packet is significant. Feeney et al. [6] have shown that the cost of receiving a packet is nearly one fifth the cost of sending the packet for the Lucent IEEE 802.11 WaveLAN PC Card which shows that the cost of receiving a packet is indeed significant. In this section, we propose and analyze a protocol called PSBT (Power Saving with Broadcast Tree) that saves energy by allowing the nodes to discard those packets that have already been received by the node. In [18], the authors gave an idea on how to extend PAMAS to conserve energy in the case of broadcast but have not given any analysis of the protocol for broadcast.

7.1. The PSBT protocol

PSBT assumes that the broadcast tree is already constructed. Thus, nodes are assumed to have the knowledge of their parent in the broadcast tree. The broadcast tree can be constructed by any algorithm and the choice of algorithm will not affect PSBT.

In PSBT, any node which has to make a transmission of broadcast message, first sends a small header packet containing the $\langle sourceID \rangle$ associated with the broadcast message. The header packet also contains the duration of the transmission based on the available bandwidth and the size of the packet. As the energy consumed in receiving a packet is directly proportional to the size of the packet [6], and the size of the header packet is assumed to be very small as compared to the size of the data packet, we can ignore the energy consumed in sending and receiving the header packet. We assume that the cost of receiving a partial signal whose SNR is greater than γ_{acq} (Section 3) is the same as the cost of receiving a complete signal because the timing of partial signals can be acquired correctly. To prevent nodes from receiving unwanted partial signals, the header packets are transmitted with maximum power irrespective of the transmission power level of the transmitting node in the broadcast tree.

Every node in the network has the knowledge of its parent node in the broadcast tree corresponding to a source. When a node receives a header packet, it continues to listen to the ongoing transmission if the transmitting node is the parent node in the broadcast tree corresponding to the source of the broadcast message. Otherwise, the node discards the packet by going to sleep mode. Thus, each node receives a broadcast packet only from its parent in the broadcast tree.

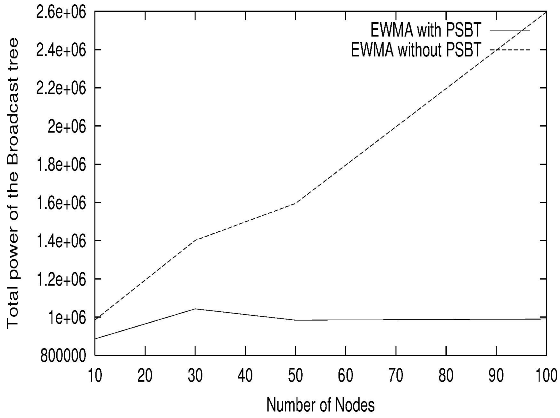
For example shown in figure 6, node *T* receives the message from node *S* as node *S* is the parent node of node *T* in the broadcast tree. When node *T* receives the header packet for the same message from node *U*, it goes to sleep mode for the duration mentioned in the header packet. Thus, node *T* saves the energy that would have been consumed in receiving the message from node *U*.

7.1.1. Performance evaluation of PSBT

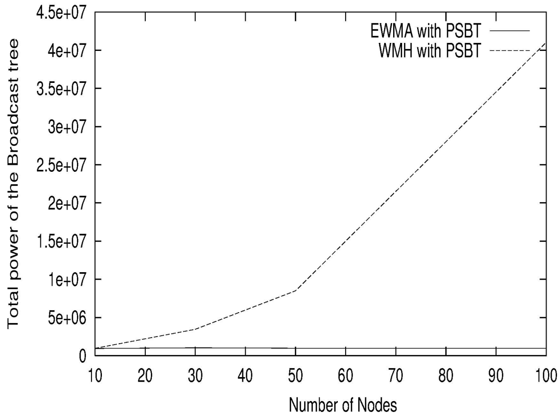
In this subsection, we evaluate the performance of PSBT through simulation. For the simulation purpose, the receive cost is taken to be $d^2/5$ where *d* is the maximum possible range that can be covered by a transmission. This choice of receive cost is taken on the basis of the statistics provided by Feeney et al. [6]. The rest of the simulation environment is the same as in Section 6.5. Figure 7(a) compares the cost of a broadcast tree constructed using EWMA with and without PSBT running over the nodes in the network. The figure shows that PSBT is very effective in conserving energy and the advantage increases with an increase in the number of nodes. For fewer nodes, the energy saving obtained is around 10% with PSBT. For a large number of nodes, the energy saving is more than 50% with PSBT. The energy consumption without PSBT increases with the increase in the number of nodes in the network because as the number of nodes increases over the same deployment region, node density increases resulting in increased redundant messages being received by the nodes. With PSBT, since each message is received only once irrespective of the node density, the overall cost of the broadcast tree does not increase with the increase in the number of nodes.

Figure 7(b) compares the cost of the broadcast tree constructed using EWMA and WMH protocol with PSBT running on all the nodes in the network. It can be seen that the cost of the broadcast tree constructed using WMH is much higher than the cost of the tree constructed using EWMA. This is mainly because in EWMA, the cost of receiving a broadcast message is added only once for each node while in WMH, many partial packets are required to be received to decode one message adding many receive cost for each message. The number of times the cost of receiving a packet is added to the cost of the broadcast tree depends on the number of partial packets required by a node to decode the message completely.

Please note that the advantage of WMH as shown in Section 6.5 is still there if PSBT is not used. This is mainly because without PSBT, all the protocols will receive all the transmissions (partial as well as full), thus incurring equal receive cost overhead. So in Section 6.5, only transmission cost was taken into consideration while calculating the cost of the tree. Thus, WMH was designed by taking only the transmission cost into consideration. When PSBT is used, we need to modify WMH so that it can take advantage of Hitch-hiking with minimum receive cost overhead. In the next section, we propose a modified version of WMH called WMHP (WMH with PSBT) which can take advantage of Hitch-hiking even in the presence of PSBT.



(1) EWMA Tree



(2) EWMA and WMH

Figure 7. Comparing energy consumption for broadcasts with and without PSBT for propagation loss exponent 2.

7.2. Hitch-hiking with PSBT

Before going into the details of WMHP, we will look at the disadvantage of WMH in the presence of PSBT from a different perspective. It can be said that many of the partial signals received by a node, say *n*, had more cost in receiving them than the amount of energy saved by them, thus increasing the overall cost of the tree. As we have shown in Section 6, a partial signal received by a node *n* can save energy by reducing the power of the parent node of node *n*. Thus, if the decrease in the power of the parent node of node *n* due to a partial signal received by *n* is less than the cost of receiving the partial signal, then that partial signal will increase the cost of the tree and should be discarded by *n*. WMHP protocol takes this fact into consideration for constructing the broadcast tree.

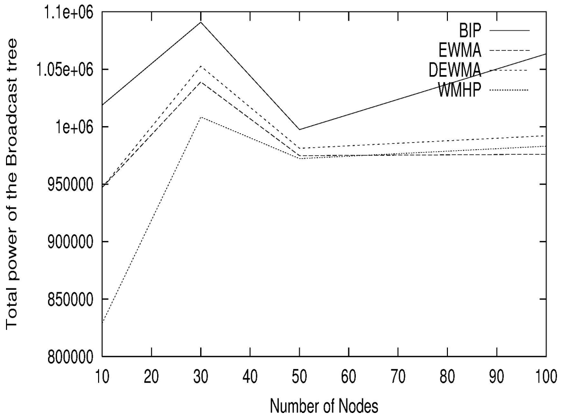


Figure 8. Performance comparison of WMHP with other protocols for propagation loss exponent 2.

WMHP is a distributed protocol which is similar to distributed WMH except that a node does not accept all the partial signals it can receive to increase its coverage value. On receiving a partial signal s from a transmission, node i first calculates the function $A_{i,s}$ that measures the advantage of receiving the partial signal given by the following equation:

$$A_{i,s} = \left(1 - \frac{C(s)}{100}\right) \times (p_j) - R \tag{10}$$

where j is the parent of node i in MST, $C(s)$ is the coverage provided by signal s to node i and R is the fixed cost of receiving a signal.

If $A_{i,s} > 0$, node i will accept the partial signal s to increase its coverage. If $A_{i,s} \leq 0$, it will discard the partial signal s.

To minimize the overhead of receive cost, WMHP tries to combine minimum number of partial signals. Thus, each node maintains a table called CPTable that stores the coverage provided by the signals for which $A_{i,s} > 0$ and the transmitting node of the signal. The entries in the table are sorted in the decreasing order of coverage. When the parent node of node i in MST has decided its final power level, node i chooses the first x signals from its CPTable such that

$$\sum_{\forall s \in x} C(s) \geq 100 \tag{11}$$

In other words, the node will take first x entries that can together provide full coverage to node i. As the signals are sorted in the decreasing order of coverage, it is ensured that minimum number of partial signals are combined by a node to get full coverage.

The rest of the algorithm of WMHP is the same as that of distributed WMH. It is important to understand that the above steps are part of tree construction phase only and need to be executed only once. Once the broadcast tree has been constructed, a node using PSBT can decide on which signals to receive or discard based on the knowledge of the tree.

7.2.1. Performance evaluation of WMHP

Figure 8 compares the performance of WMHP against BIP, EWMA and DEWMA with PSBT, for the same network setting as in Section 6.3. The cost of receiving a packet is taken to be $d^2/5$ where d is the maximum possible range that can be covered by a transmission. It can be seen that WMHP saves nearly 10% of the energy for less number of nodes in the network (lower node density). As the number of nodes increases, the advantage of WMHP over other protocols decreases. For number of nodes greater than 50, the performance of WMHP merges with that of EWMA for the given network setting. The reason behind the decrease in performance of WMHP with the increase in number of nodes is that as the node density increases, the average distance between parent and child nodes in MST decreases. Thus the average power required by transmitting nodes in MST to cover the entire network also decreases. In equation (10), we saw that $A_{i,s}$ is directly proportional to p_j. As R is fixed, the probability of finding $A_{i,s} > 0$ decreases with increase in node density. Hence Hitch-hiking advantage decreases with increase in node density.

8. Conclusion

We have proposed a novel concept called *Hitch-hiking* to reduce the overall cost of broadcast in an ad hoc network. We studied the advantage of Hitch-hiking for the scenarios when the transmission power level of the nodes in the network is fixed as well as when it can vary. For both the scenarios, we proposed a centralized algorithm and its distributed counterpart that can take advantage of the Hitch-hiking concept for energy efficient broadcasts. We showed through simulation that Hitch-hiking can reduce the cost of broadcast by as much as 50%.

We also analyzed the effect of cost of receiving a packet on the overall cost of broadcast in ad hoc networks. Then we proposed a protocol called PSBT that can save energy of broadcasts by preventing the nodes from receiving the same packet again. We also evaluated the amount of savings obtained by using PSBT through simulation.

Finally, we proposed and evaluated an algorithm to take advantage of Hitch-hiking with PSBT. The simulation result shows that with PSBT, the advantage of Hitch-hiking is limited to low density networks.

In the future, we want to extend the use of Hitch-hiking for reliable energy efficient broadcast. We would also like to investigate the use of Hitch-hiking in reducing energy consumption in the propagation of unicast traffic.

Acknowledgments

This work was supported in part by POSTECH New Faculty Research Grant, NSF CAREER Award grant ANI-0196039, NSF grants CCR-0329794, CCR-0329741, ANI-0073736, EIA-0130806, CNS 0422762, CNS 0434533 and Alfred Sloan Fellowship. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] M. Agarwal, J.H. Cho, L. Gao and J. Wu, Energy efficient broadcast in wireless ad hoc networks with Hitch-hiking, in: *Proc. IEEE INFOCOM* (2004).

[2] M. Cagalj, J.-P. Hubaux and C. Enz, Minimum-energy broadcast in all wireless networks: NP-completeness and distribution issues, in: *Proc. IEEE INFOCOM* (2002).

[3] B. Chen, K. Jamieson, H. Balakrishnan and R. Morris, SPAN: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. ACM Wireless Networks Journal 8(5) (2002) 481–494.

[4] A. Dementi, P. Penna and R. Silvestri, The power range assignment problem in radio networks on the plane, in: *Proc. IEEE INFOCOM*, (2000) pp. 651–660.

[5] D. Estrin, R. Govindan, J. Heidmann and S. Kumar, Next century challenges: Scalable coordination in sensor networks, in: *Proc. IEEE INFOCOM* (1999).

[6] L. Feeney and M. Nilsson, Investigating the energy consumption of a wireless network interface in ad hoc networking environment, in: *Proc. IEEE INFOCOM* (2001).

[7] R. Gallager, P. Humblet and P. Spira, A distributed algorithm for minimum-weight spanning trees, in: *Proc. IEEE INFOCOM* (1983).

[8] S. Guha and S. Khuller, Approximation algorithms for connected dominating sets, in: *Proc. IEEE INFOCOM* (1996) pp. 179– 193.

[9] C.E. Jones, K.M. Sivalingam, P. Agrawal and C. Chen, A survey of energy efficient network protocols in wireless networks, in: *Proc. IEEE INFOCOM* (2001).

[10] L. M. Kirousis, E. Kranakis, D. Krizanc and A. Pelc, Power consumption in packet radio networks, in: *Proc. IEEE INFOCOM* (1997) pp. 363–374.

[11] W. Liang, Constructing minimum-energy broadcast trees in wireless ad hoc networks, in: *Proc. IEEE INFOCOM* (2001) pp. 112–122.

[12] E.L. Lloyd, R. Liu, M.V. Marathe, R. Ramanathan and S.S. Ravi, Algorithmic aspects of topology control problems for ad hoc networks, in: *Proc. IEEE INFOCOM* (2001) pp. 123–134.

[13] M.V. Marathe, H. Breu, H.B. Hunt III, S.S. Ravi and D. J. Rosenkrantz, Simple heuristics for unit disk graphs, Networks 25 (1995) 59–68.

[14] S. Ni, Y. Tseng, Y. Chen and J. Sheu, The broadcast storm problem in a mobile ad hoc networks, in: *Proc. IEEE INFOCOM* (1999) pp. 151.

[15] J.G. Proakis, *Digital Communications*, 4th edition (McGraw Hill, 2001).

[16] R. Ramanthan and R. Hain, Topology control of multihop wireless networks using transmit power adjustment, in: *Proc. IEEE INFOCOM* vol. 2 (2000) pp. 404–413.

[17] T.S. Rappaport, *Wireless Communications: Principles and Practice* (Prentice Hall, 1996).

[18] S. Singh, C. Raghavendra and J. Stepanek, Power-aware broadcasting in mobile ad hoc networks, in: *Proc. IEEE INFOCOM* (Sept. 1999).

[19] I. Stojmenovic, M. Seddigh and J. Zunic, Dominating sets and neighbor elimination-based broadcasting algorithms in wireless networks, in: IEEE Transactions on Parallel and Distributed Systems 13(1) (2002) 14–25.

[20] P.-J. Wan, G. Calinescu and X.-Y. Li, Minimum energy broadcast routing in static ad-hoc wireless networks, in: *Proc. IEEE INFOCOM* (2001) pp. 1162–1171.

[21] X. Wang and I.F. Akilydiz, A survey on sensor networks, in: *Proc. IEEE INFOCOM* (2002).

[22] J.E. Wieselthier, G.D. Nguyen and A. Ephremides, On constructing minimum spanning trees in k-dimensional spaces and related problems, in: *Proc. IEEE INFOCOM* (2000) pp. 585–594.

[23] B. Williams and T. Camp, Comparison of broadcasting techniques for mobile ad hoc networks, in: *Proc. IEEE INFOCOM* (2002) pp. 194–205.

[24] J. Wu and F. Dai, Broadcasting in ad hoc networks based on self-pruning, in: *Proc. IEEE INFOCOM* (IEEE, San Francisco, USA, 2003).

[25] W. Ye, J. Heidemann and D. Estrin, An energy-efficient mac protocol for wireless sensor networks, in: *Proc. IEEE INFOCOM* (2002).

Manish Agarwal is an engineer at Microsoft, Redmond. He received his Masters degree in Electrical and Computer Engineering from University of Massachusetts, Amherst in 2004. He received his undergraduate degree from Indian Institute of Technology, Guwahati. His research interest lies in the field of mobile ad hoc networks.

Lixin Gao is an associate professor of Electrical and Computer Engineering at the University of Masschusetts, Amherst. She received her Ph.D. degree in computer science from the University of Massachusetts at Amherst in 1996. Her research interests include multimedia networking and Internet routing. Between May 1999 and January 2000, she was a visiting researcher at AT&T Research Labs and DIMACS. She is an Alfred P. Sloan Fellow and received an NSF CAREER Award in 1999. She is a member of IEEE, ACM, and Sigma Xi.

Joon Ho Cho received the B.S. degree (summa cum laude) in electrical engineering from Seoul National University, Seoul, Korea, in 1995 and the M.S.E.E. and Ph.D. degrees in electrical and computer engineering from Purdue University, West Lafayette, IN, in 1997 and 2001, respectively. From 2001 to 2004, he was with the University of Massachusetts at Amherst as an Assistant Professor. Since July 2004, he has been with Pohang University of Science and Technology (POSTECH), Pohang, Korea, where he is presently an Assistant Professor in the Department of Electronic and Electrical Engineering. His research interests include wideband systems, multiuser communications, adaptive signal processing, packet radio networks, and information theory. Dr. Cho is currently an Associate Editor for the IEEE Transactions on Vehicular Technology.

Jie Wu is a Professor at Department of Computer Science and Engineering, Florida Atlantic University. He has published over 300 papers in various journal and conference proceedings. His research interests are in the area of mobile computing, routing protocols, fault-tolerant computing, and interconnection networks. Dr. Wu served as a program vice chair for 2000 International Conference on Parallel Processing (ICPP) and a program vice chair for 2001 IEEE International Conference on Distributed Computing Systems (ICDCS). He is a program co-chair for the IEEE 1st International Conference on Mobile Ad-hoc and Sensor Systems (MASS'04). He was a co-guest-editor of a special issue in IEEE Computer on "Ad Hoc Networks". He also editored several special issues in Journal of Parallel and Distributing Computing (JPDC) and IEEE Transactions on Parallel and Distributed Systems (TPDS). He is the author of the text "Distributed System Design" published by the CRC press. Currently, Dr. Wu serves as an Associate Editor in IEEE Transactions on Parallel and Distributed Systems and three other international journals. Dr. Wu is a recipient of the 1996–97 and 2001–2002 Researcher of the Year Award at Florida Atlantic University. He served as an IEEE Computer Society Distinguished Visitor. Dr. Wu is a Member of ACM and a Senior Member of IEEE.