Variable power broadcast using local information in ad hoc networks

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Abstract

Network wide broadcast is a frequently used operation in ad hoc networks. Developing energy efficient protocols to reduce the overall energy expenditure in network wide broadcast can contribute toward increasing the longevity of ad hoc networks. Most of the existing work in energy efficient broadcast protocols use either a fixed transmission power model or assume global knowledge of the entire network at each node. Variable power broadcast with local knowledge has recently been proposed as a promising alternative approach for network wide broadcast in ad hoc networks.

In this paper, we present a novel approach, called INOP, for network wide broadcast. INOP is a variable power broadcast approach that uses local (two-hop neighborhood) information. INOP utilizes a novel technique for determining the transmission power level at each transmitting node. We also propose two alternative methods to cover the nodes that are not covered by the transmission of the source or a retransmitting node.

Our simulation based evaluations show that, compared to other approaches, INOP achieves better results in terms of energy efficiency, and competes with and exceeds other approaches in terms of a number of other performance metrics including traffic overhead, coverage, and convergence time. Based on these results, we can conclude that INOP improves the current state-of-the-art approaches for energy efficient broadcast in ad hoc networks.

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1. Introduction

Network wide broadcast is a frequently used operation in ad hoc networks. In addition to data broadcast, it is used for various protocol operations including route discovery and address assignment [1–5]. Nodes in ad hoc networks work with limited energy and the efficient utilization of this energy is important for increasing the lifetime of the individual nodes as well as the overall network. Depending on the size and topology of an ad hoc network, network wide broadcast may require multiple nodes to participate in the dissemination of the messages to the entire network. Hence, network wide broadcast is an energy intensive operation. As a result, it is important to develop energy efficient algorithms to
implement network wide broadcast in ad hoc networks.

Energy efficient broadcast protocols can be classified into two main groups\(^1\): (1) fixed power approach and (2) power adaptive or variable power approach. In the fixed power approach, nodes use a pre-determined fixed power level for transmission. Here, the aim is to reduce energy expenditure by reducing the overall number of transmissions by selecting a minimal number of relay nodes to cover all the nodes in the network [6] provides an excellent overview and comparison of the proposals in this group.

In the power adaptive approach, nodes adjust their transmission power levels to reduce the overall energy consumption in network wide broadcast. In this case, energy expenditure can be reduced by transmitting with just enough power to reach only the nodes that need to be reached. In has been shown that building a topology structure that would yield a minimum energy in a broadcast operation is an NP-hard problem [7].

The initial proposals in power adaptive approach assume global state knowledge [8–11]. That is, information about the entire topology including the nodes, the links, and the power costs of each link is assumed to be available at a centralized location. More recently, several heuristics have been proposed to implement network wide broadcast using local one- or two-hops neighborhood information [12–16]. Considering the difficulties of collecting and maintaining an accurate global topology information in an ad hoc network, the local information based algorithms (or localized algorithms) are considered more practical for their actual deployment in ad hoc networks.

In this paper, we present a novel localized algorithm for power adaptive broadcast in ad hoc networks. Our approach is called INOP (INside-Out Power adaptive approach). The main goal in INOP is to make a better use of the available two-hop local neighborhood information to achieve a better energy utilization in covering the one-hop neighbors. This is achieved by carefully calculating the overall energy budget needed to cover all one-hop neighbors either directly or indirectly via neighbors. On the other hand, the existing approaches [12–16] make a more limited use of the available two-hop neighborhood information and often result in less energy savings as compared to INOP.

In INOP, starting from the closest neighbor and moving outwards (i.e., centrifugal or inside-out direction), a transmitting node computes the optimal transmission strategy to (directly or indirectly) reach all neighbors within its coverage range. Each transmitting node first sorts its neighbors based on the required power to reach them. Then, starting from the closest neighbor, the node compares the required power levels to reach the next neighbor either directly or indirectly via some other neighbor. Based on this comparison, the transmitting node decides on the transmission power level to use in its broadcast. In this work, we extend upon our preliminary work presented in [17]. We provide an improvement in choosing the power level by a transmitting node. In multi-hop ad hoc networks, energy savings in network wide broadcast depends on the selection of the relay (or rebroadcasting) nodes. If the relay nodes are not chosen carefully, the overall gain in energy savings will be low. In this work, we present two approaches in choosing the rebroadcasting nodes. The first approach is borrowed from the previous work in which each node reactively decides for itself if it will perform a rebroadcast or not. We then propose a second approach where a transmitting node pro-actively selects a subset of its neighbors to perform the rebroadcast operation so that all its one-hop and two-hop neighbors are covered. Our simulation based comparisons show that our approaches provide better overall performance in terms of several performance metrics such as energy consumption per covered node, coverage, number of rebroadcasts, and convergence time.

Finally, in this study, we use a disk to represent the coverage area of wireless transmission [18]. In this model, when a node transmits a packet with a transmission range of \( r \), the packet propagates omni-directionally and all the neighbors within the circular area of radius \( r \) are assumed to receive the packet. In practice, wireless channel exhibits randomness due to multi-path propagation or shadowing. These factors may affect the shape of the actual coverage area of wireless transmissions. This may then cause some nodes within the circular coverage range to miss the packet resulting in a potential decrease in the overall coverage of a network wide broadcast operation. These factors introduce similar coverage issues for all broadcast protocols considered in this paper. Given the difficulty level of the broadcast problem (i.e., minimum energy broadcast

\(^1\) See [3–5] for more detailed classification schemes for network wide broadcast protocols.
tree construction is NP-hard even for unit disk graphs [18]), studying the problem under a disk-based coverage model makes it easier to build solutions and easier to compare these solutions with each other. Due to this fact, most previous studies in the area use a disk-based coverage model for wireless transmission. In this work, we follow the same trend and use the disk-based coverage model to build our algorithms and compare them with the previous work. We expect that a similar performance relation follows in more practical coverage models for wireless transmissions.

The rest of the paper is organized as follows. Section 2 presents a classification of the available broadcast approaches. Section 3 describes the communication and the energy models. Section 4 describes INOP, the proposed algorithm. Section 5 presents the simulation based evaluations and Section 6 concludes the paper.

2. Related work

Energy efficient broadcast techniques aim at reducing the total energy consumption during network wide broadcast operations in ad hoc networks. There is a large volume of related work in energy efficient broadcast and several survey papers provide classifications of the existing work in the area [3–6]. In [3], the authors provide a classification of the broadcast algorithms as centralized, distributed, and localized algorithms. Centralized algorithms assume global topology information at all nodes. Localized algorithms need neighborhood information only up to a certain number of hops. Distributed algorithms lie between centralized and localized algorithms. These algorithms are distributed implementations of the centralized approaches.

Broadcast techniques in ad hoc networks can also be classified as (1) fixed power broadcast approaches and (2) variable power broadcast approaches. In fixed power broadcast, nodes broadcast with a predefined fixed power level [5] further classifies these approaches into several groups including cluster based approach [19–22], distance-based and probabilistic approaches [23,24], neighbor elimination based approach [25–27], connected-dominating set (CDS)-based approach [28–32], multipoint relay (MPR)-based approach [33,34], and several others.

Variable power broadcast is a more recent approach for reducing energy consumption during broadcast in ad hoc networks. It is based on the assumption that nodes in the network can dynamically change their transmission power levels. In this paper, we propose a new algorithm for variable power broadcast. In order to put our work into context, we provide a more detailed discussion on the related work in variable power broadcast approaches. There have been several methods proposed for variable power broadcast in ad hoc networks. These approaches can be classified into global knowledge and local knowledge approaches.

2.1. Global knowledge approaches

Global knowledge approaches assume that each node has global state information. It includes the neighborhood information for all the nodes in the network as well as the minimum transmission power needed by each node to reach its neighbors. In [9], the author proves that the minimum energy broadcast tree problem in ad hoc networks is an NP-complete problem. Hence, all the algorithms proposed in this area are approximation algorithms. In [8], the authors propose a global knowledge scheme called broadcast incremental power (BIP) algorithm. The global state information at each node includes knowledge of the topology of the entire network along with the power costs of the links. In this scheme, a minimum power tree is constructed with the source node as the root of the tree. The source node includes its neighbor node which can be reached with least power into the minimum power tree. Then, each node in the tree calculates the additional power needed to reach a node not in the tree. The node that can be reached with the least additional power is then chosen to be included in the tree. This process is repeated until all the nodes are included in the tree. Finally, the source node begins the broadcast and the packets are propagated down the constructed minimum power tree. The number of rebroadcasts can be further reduced by utilizing the omnidirectional transmission of the packets.

In [8], the authors also propose an alternative approach where they define a minimum spanning tree (MST)-based topology control approach where each node adjusts its transmission power level to cover its neighbors in the MST-based structure only.

A simple improvement to the BIP algorithm called broadcast average incremental power (BAIP) was proposed in [10]. In this method, the metric
considered when adding a new node to the tree is the average incremental cost, which is defined as the ratio of the minimum additional power increased by some node in the current tree to reach some new nodes to the number of these new nodes. In [9], the author proposes an approximation algorithm using Steiner Trees.

In [11], the authors propose a center-oriented broadcast routing algorithm to improve energy efficiency in broadcast. The main idea in this approach is that the center of the deployment area of an ad hoc network is the best place to take advantage of the broadcast advantage property in a statistical sense. In other words, a broadcast tree rooted at a node at the center of the deployment region would result in more energy savings as compared to a broadcast tree rooted at a node at the periphery of the deployment region. Based on this observation, the authors propose an approach where a broadcast originator node uses unicast based forwarding to forward the broadcast message to a node at the center of the deployment region. The actual network wide broadcast operation then starts at this central node that uses an optimal algorithm such as BIP to broadcast the packet to all the nodes in the network. The authors provide different definitions for the “center” node and provide simulation based evaluations of their approach. Other approaches that use global knowledge include [35–39].

Global knowledge methods have the advantage that they provide solutions that are nearer to the optimal solution. However, they are considered to be prohibitively expensive for practical usage as they incur a large communication overhead that is required to maintain global network knowledge in the nodes. In addition, as the network size increases, these approaches become unscalable.

2.2. Local knowledge approaches

Local knowledge approaches use local state information at each node. The local state information of a node \( u \) includes knowledge of all the neighbors and the transmission power to reach each neighbor, as well as the neighbors of its neighbors and the corresponding transmission power levels and so on up to a fixed number of hops. Most of the existing approaches assume two-hop neighborhood information. That is, each node needs to know the transmission power needed to reach its neighbors and the transmission power needed by its neighbors to reach their neighbors. This information is collected by exchange of periodic Hello messages which contain the information of the one-hop neighbors of a node.

[15 and 12] present two topology control based broadcast protocols. [15] uses a reduced neighborhood graph (RNG)-based approach and [12] uses an Localized MST (LMST)-based approach to implement energy efficient broadcast. Later on in their follow up work, the authors of [15] propose some improvements on both RNG-based and LMST-based approaches [16]. Finally, [13] proposes a broadcast oriented protocol to implement network wide broadcast in ad hoc networks. In our work, we use these protocols to compare our approach and, therefore, in the rest of this section, we provide more details on each of these approaches.

An RNG-based approach for power adaptive broadcast in ad hoc networks is described in [15]. Here, RNG graph is constructed by using two-hop neighbor information at each node. Each node identifies the edges with its neighbors that belong to the RNG graph and attempts to choose the transmission power level so that it can reach only its RNG neighbors. The RNG graph of a graph \( G = (V,E) \) is denoted by \( \text{RNG}(G) = (V, E_{\text{RNG}}) \) where \( V \) is the set of nodes in the network and \( E_{\text{RNG}} \) is defined as follows:

\[
E_{\text{RNG}} = \{ (u,v) \in E | \exists w \in V \text{ such that } (u,w), (w,v) \\
\in E \land d(u,w) \leq d(u,v) \land d(v,w) \leq d(u,v) \},
\]

where \( d(u,v) \) is the perceived distance between nodes \( u \) and \( v \) in \( G \). This condition is shown in Fig. 1. In the figure, edge \( (u,v) \) is not considered to be in the RNG because of node \( w \). In other words, the RNG consists of all edges \( (u,v) \in E \) such that there is no node \( w \in V \) in the intersection of the circles centered at nodes \( u \) and \( v \) and radius \( d(u,v) \). Each node then transmits with power enough to reach its neighbors in \( \text{RNG}(G) \). This is one of the first works in variable power broadcast using local information. The evaluations provided in [15] assume

\[
\text{Fig. 1. Edge } (u,v) \text{ not included in RNG.}
\]
ideal MAC layer conditions and the effects of collisions is not considered.

LMST is proposed by Li, Hou, and Sha in [40]. Later on, the authors propose a broadcast approach using the LMST-based local structure [12]. In this approach, each node $u$ of a network graph $G$ uses its one-hop neighborhood information $N(u)$ to build a MST for its neighborhood $MST(N(u))$. A link $(u,v)$ of the original graph $G$ is included in the final $LMST(G)$ if and only if this link belongs to both $MST(N(u))$ and $MST(N(v))$. The authors show that the resulting structure preserves network connectivity and the maximum node degree is bounded by 6.

Most recently, Cartigny et al. [16] present improvements on both RNG-based and LMST-based broadcast protocols.

Another approach proposed for energy efficient broadcast using local information is a broadcast oriented protocol presented in [13]. In this paper, we refer this approach as centripetal (outside-in) approach. In this approach, the main idea is to reduce the transmission power level by eliminating distant neighbors from the coverage set. This approach has been followed in the PABLO protocol presented in [13]. The algorithm works as follows: Consider a network where the source node $s$ has a set of neighbors $NSet(s) = \{1,2,\ldots,k\}$. Let $P_{sj}$ be the power to reach neighbor $j$ directly. Let node $k$ be the farthest neighbor of node $s$, $P_{sk} = \max(P_{sj}, j \in NSet(s))$. Node $s$ checks if node $k$ can be reached by any of $s$'s one-hop neighbors. Let node $r$ be the one-hop neighbor with the least value of $(P_{sr} + P_{rk})$, $r \in NSet(s)$.

The scenario is as shown in Fig. 2. In case a relay node $r$ is found, node $s$ can reduce its transmission power to $P_{sr}$ where node $l$ is the next farthest node after eliminating node $k$. Now, node $s$ attempts to reach node $l$ through a relay node as described earlier. This process continues until no further energy reduction can be achieved. Algorithm is shown in Fig. 3. In lines 1 and 2 of the algorithm, we are finding the best relay node $r$ to reach the farthest node $k$ of the source node $s$. In lines 3 to 6, we make the decision whether to eliminate the farthest node or not, based on the comparison $((P_{sr} + P_{rk}) < P_{sk})$. The process of eliminating the farthest node from the neighbor set of the source node is continued until no further elimination is possible. Finally, the source node performs a transmission with a power level enough to reach the farthest node in its current reduced neighbor set. There have been some minor improvements proposed on this approach by the same authors in [14].

3. Communication and energy models

We consider ad hoc networks where nodes cooperate with each other to support broadcast operation. The network is modelled as a graph $G = (V,E)$ where $V$ is the set of nodes in the network and $E \subseteq V^2$ is the set of edges indicating the available communication links in the network. The set $E$ can be defined as

$$E = \{(u,v) \in V^2 | P_{uv} \leq P_{\text{max}}\},$$

where $P_{uv}$ is the transmission power needed to reach node $v$ from node $u$ in a direct transmission and $P_{\text{max}}$ is the maximum transmission power level of node $u$.

The channel model used follows the power law model widely used in the literature [41]:

$$P_{\text{arrival}} \propto P_{tx}/r^n,$$

where $P_{\text{arrival}}$ is the power needed to reach a node at distance $r$.

![Fig. 2. An example network to show the optimization used in PABLO [13].](image)

![Fig. 3. Power adaptive broadcast using PABLO [13].](image)

1. Find $k \in NSet(s)$ such that $(P_{sk} \geq P_{si}) \forall i \in NSet(s)$;
2. Find $r \in NSet(s) \setminus \{k\}$ such that $(P_{sr} + P_{rk}) \leq (P_{sq} + P_{qk}) \forall q \in NSet(s) \setminus \{k\}$;
3. if $(P_{sr} + P_{rk}) < P_{sk}$
4. Eliminate $k$ from $NSet(s)$; /* $k$ can be reached via $r$ */
5. else
6. Transmit directly to $k$;
where $P_{\text{arrival}}$ is the strength (or power) of the signal when it arrives at a receiver, $P_{\text{tx}}$ is the transmission power at the sender, $r$ is the distance between sender and receiver, and $n$ is the power loss exponent, where $2 \leq n \leq 4$.

In order to adjust the transmission power levels, each node needs to know the transmission power level that it needs to use for reaching each of its neighbors within the maximum transmission range. This can be computed, by using the above channel model and assuming power symmetry in channels, as follows: Each node uses periodic Hello messages to discover and exchange information about its one-hop neighbors with its neighbors. Each node uses the maximum transmission power to send out Hello messages. When a node $u$ transmits a Hello message, it records the power with which the packet is transmitted, $P_{\text{tx}}$, in a field in the packet header. For the successful reception of this packet at a neighbor node $v$, a minimum power level $P_{\text{threshold}}$ is needed when the packet is received. If the signal strength of the packet at reception is below $P_{\text{threshold}}$, it is not comprehensible and hence, ignored. Thus, the receiving node $v$ can estimate the power needed to reach the transmitting node $u$ by computing the required minimum transmission power $P_{\text{req}}$ as

$$P_{\text{req}} = (P_{\text{tx}}/P_{\text{arrival}}) \cdot P_{\text{threshold}}. \quad (3)$$

Once each node learns the set of its one-hop neighbors and the corresponding minimum transmission power levels needed to reach them, it includes this information in its Hello message and sends it out to its neighbors. This way, each node comes to know about its two-hop neighbors in the network.

When a node $u$ sends a broadcast packet to reach its neighbors, the total amount of energy used in the operation includes the energy spent at $u$ for the transmission and the energy spent at each receiver for the reception. As communication in ad-hoc networks is asynchronous in nature, when the transceiver is not in the transmit mode, it is in the receive mode (e.g., 802.11 DCF mode). In this (receive) mode, the energy consumed by the network card can be assumed to be the same whether the transceiver is actually receiving a frame meant for it or simply listening on the channel $[42]^{2}$. Based on this observation, variable power broadcast algorithms consider only the transmitter node energy expenditure in their calculations. Following this trend, we also consider the transmitter node energy expenditure only in building our algorithms. On the other hand, for completeness purposes, in our simulation based performance evaluation section we report the total number of packet reception events to compare the performance of different broadcast protocols with each other (see Fig. 11).

Based on the above discussion, when a node $u$ sends a broadcast packet with some power $P_{\text{tx}}$, the total amount of power used in the operation is given by

$$P_{\text{one-hop}} = P_{\text{tx}}. \quad (4)$$

From this, the energy expenditure during a one-hop transmission of a message can be calculated as

$$E_{\text{one-hop}} = P_{\text{one-hop}} \cdot t \quad (5)$$

where $t$ represents the duration for the transmission of the packet. Finally, the total energy consumption during a network wide broadcast of a packet is given by:

$$E_{\text{total}} = \sum_{u \in U} E_{\text{one-hop}}. \quad (6)$$

where $U$ is the set of nodes that perform transmission during the broadcast and $E_{\text{one-hop}}$ is the energy spent during the one-hop transmission of the packet by a node $u$.

4. INOP: A centrifugal approach

In this section, we describe our algorithm, INOP, for variable power broadcast. INOP uses a centrifugal approach to calculate the power with which a node transmits. The main difference between INOP and the existing approaches is that in INOP we make a more careful use of the existing two-hop neighborhood information to minimize the total energy expenditure for covering two-hop neighborhood. Starting from the closest neighbor and moving outwards (i.e., centrifugal or inside-out approach), a transmitting node computes the optimal transmission strategy (direct or indirect) to reach all neighbors within its coverage range. On the other hand, the existing approaches utilize the two-hop neighborhood information differently in their decision making. More specifically, RNG and LMST approaches aim at reducing the transmission power to a minimal level while maintaining local connectivity with the

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2 Also note that, due to the asynchronous nature of broadcast operation, idle mode energy conservation approaches $[43]$ may negatively affect the coverage of a broadcast operation and therefore are not considered for network wide broadcast operations.
assumption that multiple short distance transmissions are always better than one long distance transmission. In PABLO, a transmitting node considers the amount of power needed to reach each neighbor separately and may result in suboptimal performance as shown in the example in Fig. 2.

The overall energy consumption per node depends on the selection of relay nodes that rebroadcast the message to achieve global coverage. We use two different schemes, a reactive and a proactive scheme, for selecting the rebroadcasting nodes. In the reactive scheme, we use a self pruning approach similar to the one used in [13]. In the proactive scheme, we use a neighbor designation approach where the source node identifies a set of its neighbors as relay nodes. The algorithms are explained in detail in the following subsections.

4.1. INOP with self pruning (INOP-1)

In this approach, the transmitting node selects its power level by considering its neighbors starting from the closest one and moving outwards. The transmitting node computes the cumulative energy needed to reach the nodes either directly or using intermediate nodes. It then selects the minimum power with which to transmit so as to reduce the overall energy consumption in covering all one-hop neighbors. The detailed algorithm is presented below.

In INOP, a transmitting node \( s \) computes \( P_{sp}^{cumu} \), the cumulative power to reach each neighbor node \( p \). The transmitting node \( s \) starts from \( n \), the nearest node. In order to reach \( n \), \( s \) has to transmit directly. So, the cumulative power to reach node \( n \) is \( P_{sn}^{cumu} = P_{sn} \). If \( s \) were to transmit with a minimum power of \( P_{sn} \), the neighbor \( n \) would be covered by that transmission. Next, the cumulative power to reach the second nearest node \( m \) is calculated as the minimum of (1) the power to reach \( m \) directly from node \( s \) and (2) the sum of the cumulative power to reach node \( n \), \( P_{sn}^{cumu} \), and the power to reach \( m \) from the only intermediate node \( n \). In general, the cumulative power to reach any node \( i \) is computed as follows. Let the cumulative power to reach the previous nearest node \( h \) be \( P_{sh}^{cumu} \). Let \( r \) be a covered node that could reach \( i \) by using the least power, \( P_{ri} \), among all covered nodes. Then, we set \( P_{si}^{cumu} = \min(P_{sh}^{cumu} + P_{ri}, P_{si}) \). The value of \( P_{si}^{cumu} \) is calculated for all \( i \in NSet(s) \) where \( NSet(s) \) represents the set of one-hop neighbors of \( s \). Finally, the transmitting node \( s \) transmits with enough power to reach node \( p \), where \( p \) is the farthest node with \( P_{sp}^{cumu} = P_{sp} \).

The algorithm is shown in Fig. 4. In line 1, the neighbors of the transmitting node \( s \) are sorted based on the power level to reach them. \( F \) is the set of the nodes to which \( s \) decides to perform a direct transmission in the course of its computation. For each neighbor \( i \) (line 3), we calculate \( P_{si}^{cumu} \). Initially, we find the relay nodes that could be used to reach node \( i \) (line 4). If there are no relay nodes found, the value of \( P_{si}^{cumu} \) is equal to the direct transmission power level from \( s \), \( P_{si} \) (lines 5–6). Otherwise, the best relay node is selected as the one that can reach node \( i \) with the least power (line 8). \( P_{si}^{cumu} \) is set to a value equal to the minimum of

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1. Sort NSet(s)={1, 2, …, n} such that P_1 ≤ P_2 ≤ … ≤ P_n;
2. n = |NSet(s)|, F = φ;
3. for (i = 1; i ≤ n; i++)
4.   Let R ⊂ NSet(s) such that ∀ q ∈ R, P_{sq} < P_{si} and P_{qi} < P_{si};
5.   if (R = φ)
6.     P_{si}^{cumu} = P_{si};
7.   else
8.     Find r ∈ R such that P_{ri} ≤ P_{qi} ∀ q ∈ R;
9.     P_{si}^{cumu} = \min(P_{si}^{cumu} + P_{ri}, P_{si});
10.    if (P_{si}^{cumu} = P_{si})
11.       F = F ∪ {i};
12. Source s transmits with P_{si}, such that i ∈ F and i ≥ j, ∀ j ∈ F;
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Fig. 4. INOP Approach (INOP-1).
and the power level to reach node $i$ from the best relay node, with the direct transmission power level from $s$. If the direct transmission is better, then $i$ is added to the set $F$ (lines 10–11). Finally, $s$ performs a transmission to the farthest node in set $F$ (line 12).

We expect INOP to perform better than the earlier approaches as it considers the cumulative power to reach a node and in the process covers all nodes up to this distance during a broadcast. For example, consider the scenario shown in Fig. 5. All the nodes are within the maximum transmission power range of the source node $s$. The node $s$ needs unit power ($P$) to reach each of the four nearest neighbors and four units of power ($4P$) to reach all the nodes. Each of the nearest neighbors can reach the farthest neighbors using unit power $P$. Using PABLO will not ensure reduced energy consumption in this example case. According to PABLO, the source node $s$ eliminates the four farthest neighbors, assuming that the four nearest neighbors will cover these nodes. The total power usage in this case will be $P + (4 \times P) = 5P$, which includes one unit of power for the first transmission from the source node $s$ and one unit each for the four nearest neighbors to do a rebroadcast to cover the four farthest neighbors. The RNG and LMST-based approaches will provide a similar performance with a total power usage of $5P$.

In the case of INOP, the algorithm starts from the closest node and moves outward. Based on the algorithm presented in Fig. 4, the source node chooses to transmit with a power level of four units to reach all its neighbors directly. Thus, INOP consumes the optimal energy in this situation. This is because in INOP, the protocol considers the bigger picture rather than focusing on individual nodes to make a decision. The transmitting node $s$ considers each neighbor by moving from the nearest nodes to the farthest node and calculates the cumulative power level at each stage. At the end, it chooses to transmit with a power level enough to reach the node whose cumulative power equals the direct transmission power level from the source node.

So far, we worked on optimizing the energy expenditure in covering the first hop neighbors of $s$ or $NSet(s)$. Let $CSet(s)$ be the set of nodes covered by the broadcast originating node directly. Let $\overline{CSet}(s) = NSet(s) – CSet(s)$. The overall performance of a broadcast approach partly depends on how to choose the set of rebroadcast nodes to cover the remaining nodes (including the uncovered first hop neighbors of $s$ and others) in the network. The problem of finding the minimum set of relay nodes to cover the uncovered neighbors is known to be an NP-complete problem [33]. In this version of INOP, we use a simple heuristic for neighbor selection.

The neighbor selection scheme that uses a self pruning approach is described as follows. Consider a node $n$ that is covered by the broadcast of some node $s$. When $n$ receives a broadcast packet from $s$, it calculates a rebroadcast backoff timer (RBT) and delays its rebroadcast for RBT seconds. RBT is randomly selected from an interval that is inversely proportional to the number of uncovered neighbors of $n$. The main goal of this delay interval is to reduce collisions and avoid redundant rebroadcasts by allowing nodes that have a larger set of uncovered neighbors to rebroadcast first. During RBT seconds, $n$ listens to the channel for rebroadcasts coming from other covered neighbors of $s$. At the end of RBT seconds, $n$ identifies set of its neighbors, $CSet(n)$, that must have been covered by the broadcast of $s$ or by the rebroadcasts of some of the neighbors of $s$. If the set $NSet(n) – CSet(n)$ is empty, all the neighbors of $n$ are covered and, hence, $n$ cancels its rebroadcast. Otherwise, it uses INOP approach to determine its transmission power level and rebroadcasts the packet. The advantage of this scheme is that each node can make its own independent decision. This may be desirable as each node has more information to make its own decision as compared to any other node making the decision for this node. However, the drawback of this scheme is that since each node does a random backoff, the exact order in

![Fig. 5. An example scenario to compare different approaches.](image-url)
which the rebroadcast occurs is not deterministic. Hence, the nodes may perform rebroadcast in an order which may result in unnecessarily high energy consumption.

4.2. INOP with neighbor designation (INOP-2)

In this section, we present an alternative approach using INOP. In this approach, the first part of the algorithm where the transmitting node computes the transmission power level is similar to the previous one. We propose an alternative proactive scheme for covering the nodes that are not covered by the transmission of the source. In this scheme, the transmitting node identifies a set of nodes as relay nodes who are responsible for forwarding the broadcast packet. The actual algorithm is described below.

In the INOP-1 approach above, a transmitting node \( s \) considers two alternatives to cover a neighboring node \( p \) as (1) direct transmission or (2) relay by an already covered neighbor of \( s \). In INOP-2, we introduce a third possibility as follows. The current transmitting node \( s \) maintains the list of relay nodes among its currently covered neighbors. The node \( s \) also maintains the power levels that these relay nodes are currently expected to use for their transmission. While deciding on the cumulative energy needed to cover an uncovered neighbor \( p \), in addition to the two alternatives above, the node \( s \) will also consider the possibility of increasing the current coverage range of one of the relay nodes. The intuition in this approach is that increasing the coverage range of an already scheduled relay node may result in less increase in the energy expenditure for covering \( p \) as compared to (1) making a direct transmission from \( s \) or (2) choosing a new relay node among the currently covered neighbors of \( s \) to transmit to \( p \). This algorithm is shown in Fig. 6. The algorithm is similar to the one shown in Fig. 4, except for a simple improvement. Sets \( S \) and \( P \) are initialized in lines 2 and 3. \( S \) is the set of relay nodes chosen by the source node to perform rebroadcast and \( P \) is the set of power levels for these relay nodes. The computations in lines 4 to 10 are similar to those in INOP-1. Here, we also find the best relay node \( p \) from the set of chosen relay nodes, which can reach the node \( i \) with the minimum increase in its chosen power level (line 11). \( P_{\text{cumu}}^{\text{st}} \) is set to a value equal to the minimum of the \( P_{\text{cumu}}^{\text{st}}(i) + P_{\text{p}} \), \( P_{\text{cumu}}^{\text{st}}(i) + P_{\text{p}} - P[p] \), and \( P_{\text{st}} \) (line 12). In summary, we are considering increasing the power level of a chosen relay node as an alternative to adding a new relay node. The sets \( S \) and \( P \) are updated in lines 15–17, 19,20 and 22, based on the decision whether to choose the direct transmission by the source node or to add a new relay node or to increase the power level of an already chosen relay node.

So far, we have described the algorithm used to choose the power level for the first transmission by the source node. For covering the nodes not covered by the first broadcast by the source node, we use a proactive approach, wherein the source node decides on a set of its one-hop neighbors that will rebroadcast to cover the uncovered nodes. The uncovered nodes include the set of one-hop neighbors not covered by the first broadcast by the source node as well as the set of its two-hop neighbors. The source node checks if the current set of relay nodes could cover the two-hop neighbors, by increasing their power level. If this is better in terms of energy consumption than a new node doing a rebroadcast, this is done. Otherwise, a new node is chosen and added to the relay node set. This process is continued until all the uncovered neighbors can be covered by the relay nodes.

The algorithm is shown in Fig. 7. \( T \) is the set of two-hop neighbors of the source node. \( U \) is the set containing sets of one-hop neighbors that can cover the corresponding two-hop neighbor in \( T \). \( C \) is the set indicating if the corresponding two-hop neighbor in \( T \) is covered or not. Sets \( S \) and \( P \) are obtained from the first run of INOP-2 described in Fig. 6. In line 5, the set \( T \) is sorted based on the number of one-hop neighbors covering the nodes in \( T \). This ensures that the two-hop neighbor which can be covered by a single one-hop neighbor is considered before a two-hop neighbor which can be covered by a higher number of one-hop neighbors. This helps in improving the performance of the algorithm. We find the best one-hop neighbor \( r \) which can cover the two-hop neighbor \( i \) with the least amount of power (line 8). We also find the best relay node \( p \) from the set of already chosen relay nodes \( S \), which can reach node \( i \) with the least increase in power level (line 9). We compare the power level of the best one-hop neighbor \( r \) to reach node \( i \) with the increase in the power level of the best relay node \( p \) to reach node \( i \) (line 10). Sets \( S \) and \( P \) are updated in lines 11–12 and 17 based on the decision whether to add a new relay node or increase the power level of an already chosen relay node. Set \( C \) is updated in lines 13–15 and 18–21 to consider the two-hop
neighbors who get covered by the addition of a new relay node or increasing the power level of an existing relay node. This process is repeated until all the two-hop neighbors are covered. Finally, set $S$ contains the relay nodes selected by the source node to perform a rebroadcast.

Consider the network shown in Fig. 8. The power levels to reach the nodes are as indicated in the figure. Using the algorithm described in Fig. 6, the source node $s$ decides to transmit with power level equal to $3.5P$ to reach its neighbors until node $D$. The values of the sets $S = \{B\}$ and $P = \{P\}$. Now, in order to find the set of relay nodes to cover all the uncovered nodes within two-hop neighborhood of $s$, algorithm in Fig. 7 is used. After the sorting operation in line 5 of the algorithm, $T = \{G,F\}$, $U = \{E\}, \{B,C\}$, $C = \{0,0\}$. After the first pass through the loop in line 6, node $E$ is chosen as the relay node to cover node $G$. In the second run, to cover node $F$, there are two choices, nodes $B$ and $C$. Since increasing the power level of node $B$ from $P$ to $1.2P$ is better than having the new node $C$ doing a new transmission with power $0.8P$, node $B$ is chosen as the relay node to cover $F$. So, finally, set $S = \{B,E\}$. When these nodes get the packet from $s$, they do a random backoff. When the timer expires, they use INOP-2 again to perform a rebroadcast. The value of the random backoff time is proportional to the number of uncovered neighbors of the node. This random backoff reduces the probability of collisions at other nodes.

In summary, the main difference between INOP-1 and INOP-2 is the way of covering the nodes that are not covered by the first broadcast by the source node. In INOP-1, we use a reactive approach, wherein the nodes make an independent decision

---

**Fig. 6. INOP Approach (INOP-2).**

1. Let $s$ be the current transmitting node and N be list of its neighbors
2. Sort $N=\{1, 2, \cdots, n\}$ such that $P_{s1} \leq P_{s2} \leq \cdots \leq P_{sn}$;
3. $S = \phi$ /* $S$ is the set of relay nodes chosen to perform rebroadcast */
4. $P = \phi$ /* $P$ is the set of power levels of the corresponding relay nodes in $S$ */
5. $n = |N|$, $F = \phi$;
6. for (i = 1; i $\leq$ n; i++)
7. Let $R \subset N$ such that $\forall q \in R$, $P_{sq} < P_{si}$ and $P_{qi} < P_{si}$;
8. if ($R = \phi$)
9. $P_{sv}^{\text{sum}} = P_{si}$;
10. else
11. Find $r \in R$ such that $P_{ri} \leq P_{qi}$ $\forall q \in R$;
12. Find $p \in S$ such that $P_{pi} - P[p] \leq P_{qi} - P[q]$ $\forall q \in S$;
13. $P_{sv}^{\text{sum}} = \min((P_{sv}^{\text{sum}} + P_{ri}), (P_{sv}^{\text{sum}} + P_{pi} - P[p]), P_{si})$;
14. if ($P_{sv}^{\text{sum}} = P_{si}$)
15. $F = F \cup \{i\}$;
16. for each $r \in S$
17. $P[r] = 0$;
18. $S = \phi$;
19. else if ($P_{sv}^{\text{sum}} = (P_{sv}^{\text{sum}} + P_{ri})$)
20. $S = S \cup \{i\}$;
21. $P[r] = P_{ri}$;
22. else
23. $P[p] = P_{pi}$;
24. Source $s$ transmits with $P_{si}$, such that $i \in F$ and $i \geq j, \forall j \in F$;
whether they will rebroadcast or not. In INOP-2, we use a proactive approach, wherein the source node decides on a set of relay nodes who will do a rebroadcast to cover the uncovered nodes. INOP-2 also has an additional improvement in the selection of the power level for the initial transmission by the source node.

5. Performance evaluations

In this section, we present our simulation based comparison results between INOP and several other broadcast algorithms. We first describe our simulation environment and the comparison metrics used in the evaluations. For our comparisons, we use a simulation environment similar to the one used by Williams and Camp in their recent comparisons of broadcast algorithms study [6]. More specifically, our simulations are conducted using the ns-2 simulator (ns-2 version ns-2.1b7a) on a Linux PC (kernel 2.6) running Fedora Core 2 Linux distribution. We use a simulation area of 500 \( \times \) 500 m\(^2\). We set the peak transmission power to \( P_{tx\text{-max}} = 7.214 \text{ mW} \), the threshold power at the receiver to \( P_{\text{arrival}} = 3.652 \times 10^{-10} \), the power loss exponent to \( n = 2 \),
and the maximum transmission range to \( r_{\text{max}} = 100 \text{ m} \). For the channel model at the MAC layer, we assume 802.11 MAC protocol operating in the DCF mode. We use transmission rate of 2 Mbps and broadcast packets of 512 bytes in size.

The performance metrics used in the previous work [6,15,13] include the total energy consumption during the broadcast operation, coverage, number of rebroadcasts and convergence time. We use these metrics with one modification where we use energy consumption per node as a more representative metric instead of the total energy consumption. The metrics that we use for comparing the different algorithms are:

- **Energy consumption per node (ECN):** Energy consumption per node is defined as energy spent per covered node and is calculated as the ratio of the total energy consumption to the number of covered nodes. ECN indicates the average energy spent in reaching any covered node in the network. Broadcast in ad hoc networks is an unreliable operation and complete coverage is not guaranteed. As a result, compared to total energy consumption, ECN is a more representative metric to compare the performance of different broadcast approaches.

- **Coverage:** Coverage refers to the number (or fraction) of the nodes that correctly receive the broadcasted packet in a network wide broadcast operation. This metric indicates the degree of coverage provided by different protocols.

- **Num. of Rebroadcasts:** Number of rebroadcasts indicates the traffic overhead introduced into the network. It includes the initial broadcast by the source node and the following transmissions of the broadcast packet by the relay nodes until the broadcast operation terminates. Note that each node in the network does at most one transmission of a broadcast packet and therefore rebroadcast should not be confused as a retransmission by the same node. With each rebroadcast, there is a possibility for collision which may affect the network capacity. Therefore, number of rebroadcasts is a useful metric for comparison.

- **Convergence time:** Convergence time is the time period from the start of the broadcast operation at the source node up to the time when the last node receives the broadcast packet.

- **Broadcast busy area (BBA):** This is the area of the network that is busy during a broadcast operation. We compute this metric by taking the snapshot of the network at some small time intervals and by adding the size of the area covered by ongoing transmissions during each snapshot. This metric gives an indication of the (non-busy) area of the network that is available to be used by other traffic, without causing collisions. This metric has a similar purpose as the number of rebroadcasts and can additionally indicate the actual area being occupied by the broadcast traffic.

In the following, we first compare the variable power broadcast approaches with each other. We then compare INOP approaches with one of the best performing fixed power approach called AHBP. We finally present a comparison between the broadcast trees constructed by different variable power broadcast approaches.

### 5.1. Comparisons of variable power broadcast approaches

Here, we present our simulation based comparison results on the performance of the variable power broadcast algorithms including BIP, RNG, LMST, PABLO and the two variants of INOP. In each simulation, one of the nodes is randomly selected to be the broadcast originator node. This node generates periodic broadcast packets every second until the end of the simulation time which is 10 s. Each broadcast packet is marked by a sequence number that helps the nodes distinguish different broadcast packets from each other. BIP uses global knowledge of the network topology and achieves an optimal performance in terms of energy consumption per node. However, due to the difficulties of maintaining topology knowledge, it is considered to be impractical. In our evaluations, we use BIP as a yardstick to compare the other approaches, especially in terms of their energy consumption per node (ECN). We use 20, 40, 60, 80, and 100 node topologies for our simulations. For each network size, we ran simulations on 20 randomly generated topologies where the nodes are uniformly randomly placed at points in the \( 500 \times 500 \text{ m}^2 \) area. Our topology construction approach follows a common assumption that nodes in ad hoc networks are somehow randomly placed in a given area or are often considered to follow a random mobility model which we attempt to capture by the random placement of the nodes in the simulation area. The results presented below are
the average values of the results obtained from these different simulation runs for each of the considered network sizes.

**Comparisons based on ECN and Coverage:** For energy efficiency comparisons, we use the relative performance of the approaches with respect to the optimal approach BIP. For each data point, we compute the relative performance as 

\[
\text{relative performance} = \frac{(x - y)}{y}
\]

where \(x\) is the ECN of an approach (INOP, PABLO, LMST, or RNG) and \(y\) is the ECN of BIP. 

Fig. 9a presents a comparison of the approaches based on their average values for 20 different simulations for each network size. As seen in the figure, INOP approaches outperform the other power adaptive approaches in almost all cases. According to the figure, in the case of 20 node networks, INOP-2 gives the best performance. It performs within 8% of the optimal whereas LMST performs within 20% of the optimal. On the other hand, the worst performance of INOP-2 and LMST approaches are seen for the 60 node network case where INOP-2 performs within 29% of the optimal and LMST performs 34% of the optimal. The results presented in this figure show that the relative performance of INOP is consistently better than the other approaches. We also observe that INOP-1 outperforms the existing approaches in all cases except for one for the 60 node network case. As the network becomes denser, the difference in performance between the approaches reduces and INOP-1 outperforms INOP-2. In addition, as the network gets denser, the global knowledge based BIP approach performs relatively better than the local knowledge based approaches. Finally, Fig. 9b shows that the approaches have similar coverage. The coverage of all the approaches remains about 97–100%.

The comparison results presented in Fig. 9a are the averages of 20 simulation cases for each network size. For each simulation case, we use the same topology, the same randomly selected node, and the same sequence of random numbers to run the different broadcast algorithms to obtain the energy expenditure values. Therefore, the performance results obtained by different approaches on the same simulation case are dependent with each other. However, the results for 20 different simulations are independent from each other. In the next step of our evaluations, we consider the confidence intervals for the obtained energy efficiency comparison results presented in Fig. 9a. For this task, we use “common random number” (CRN) approach to compare the different algorithms under the same conditions. CRN is a general variance reduction method used in similar simulation studies [44]. In this approach, we first compute the ECN values (relative to BIP as shown in Eq. (7)) for each algorithm for each of the 20 simulation cases. We then compute the differences between the ECN values for INOP approaches and the others as

\[
\text{DIFF}_i(INOP1) = ECN_i^{INOP1} - ECN_i^x
\]

\[
\text{DIFF}_i(INOP2) = ECN_i^{INOP2} - ECN_i^x
\]

where \(x = \{\text{RNG, LMST, PABLO}\}. After obtaining DIFF\(_i\)(INOP1) and DIFF\(_i\)(INOP2) values for 20 different simulation cases, we compute the 95% confidence intervals for these differences. The results at the end of this operation show the general performance trend of INOP approaches as compared to others as observed in these 20 simulations cases. Fig. 9c and d presents the results for INOP-1 and INOP-2 separately. The confidence intervals are shown by vertical bars in the figures. Since the ECN values represent the proximity of the performance to the base BIP approach, in most of the cases the average DIFF values stay in negative range indicating the superiority of INOP approaches over the others. Fig. 10d indicates that except for the 60 node topology case, INOP-1 approach outperforms all the other approaches (i.e., confidence interval stays in the negative region in the figure). The figure shows that for 60 node case, LMST-based approach performs consistently better than INOP-1. Similarly Fig. 9e indicates that except for the 100 node topology case, INOP-2 approach outperforms all other approaches. At 100 node topology case for LMST, the confidence interval includes zero in it indicating that the two approaches (INOP-2 and LMST) perform comparably.

**Comparisons based on Num. of rebroadcasts and convergence time:** The number of rebroadcasts is an indication of the traffic overhead introduced into the network during a network wide broadcast. This is a commonly used metric in the previous work [6,15,13]. In Fig. 9e, the approaches are compared based on the number of rebroadcasts. According to the figure, INOP approaches use a relatively small number of rebroadcasts and are closely followed by the LMST-based approach. Also, among the local knowledge approaches, PABLO has the highest number of rebroadcasts. The BIP approach...
results in the highest number of rebroadcasts and yet gives the best performance in terms of energy efficiency as shown in Fig. 9a. This is due to the fact that BIP has the global knowledge of the network and therefore can achieve an optimal power control and energy efficiency among the other approaches. The fact that BIP has a high number of rebroadcasts indicates that the algorithm uses a large number of
likely short range transmissions to achieve the observed performance. This observation is also supported by the results presented in Table 2 where we present a comparison of broadcast tree properties for each broadcast protocol on a sample simulation. As seen in the table, on the average each rebroadcast operation covers the least number of nodes and the tree depth is the largest among the other approaches. Fig. 9e shows a trend that as the network gets denser the relative performance of INOP approaches gets better compared to other approaches. This is desirable as it may reduce contention for medium access and collisions of transmitted packets, depending on the area being covered by the broadcast operation. Finally, the convergence times of the algorithms are similar as can be seen in Fig. 9f. In general, INOP approaches perform slightly better than the others but the difference is not substantial.

Comparisons based on BBA: The last metric that we consider for comparisons is the area of the network, i.e., broadcast busy area (BBA), that is busy during a broadcast propagation period. As stated before, this metric gives an indication of the area of the network that is available to be used by other traffic during a broadcast operation. BBA is proportional to the total energy consumed during the broadcast operation. BBA is proportional to the total energy consumed during the broadcast operation. Fig. 10 shows a comparison of the approaches based on the BBA metric with respect to time. A network with a high diameter gives good insight into the behavior of the algorithms with respect to this metric. For this comparison, we use a network with 200 nodes in a 1000 m × 1000 m area. For each algorithm we use the following procedure. First, a single broadcast is initiated at a randomly chosen node (we use the same node for each algorithm) and at every 100 ms interval, we computed the BBA value by calculating the total area being covered by the currently ongoing broadcast (re)transmissions. We repeat this until the broadcast operation terminates. Even though the broadcast operation is a continuous operation, we look at the snapshot of the BBA values at 100 ms intervals to observe the size of the area in the network that is affected by the propagation of the broadcast operation. As can be seen from the figure, BIP has the least BBA as compared to other approaches but it lasts longer. This is expected as BIP provides the best performance in terms of ECN. Among the local knowledge approaches, we observe a mixed performance behavior during the progress of broadcast. Next, we look at the total BBA values for different approaches when the broadcast terminates. Table 1 presents the total area of coverage and the number of rebroadcast at the end of broadcast. The total area presented in the table corresponds to the summation of the areas obtained at each snapshot. As expected, BIP results in the smallest total BBA and largest number of rebroadcasts as it is an optimal approach that use global information. Among the local knowledge based approaches, INOP approaches have smallest total BBA and smallest number of rebroadcast values. This means that INOP approaches use less network resources (i.e., smaller area of the network...
is kept busy during the broadcast) as compared to other approaches.

Before ending this section, we report the average number of reception events that occur during the simulations. Recall from the end of Section 3 that most broadcast protocols use the transmission power energy to build their algorithms and they ignore the reception power values. The main reason for this approach is the assumption that the reception power is the same as the idle time power while a wireless node is in the receiver mode [42]. Therefore, during the algorithm construction, receiver power is considered as the base and the transmit power is used to control the propagation of a broadcast operation in the network. Fig. 11 presents a comparison of the total number of packet reception events during a broadcast operation (averaged over 20 simulations for each network size). According to the figure, broadcast based localized algorithms (INOP and PABLO) have much smaller number of reception events as compared to BIP and the topology control based localized algorithms (RNG and LMST). The performance of the latter algorithms is expected as these algorithms try to minimize the transmission power range for each broadcast operation increasing the probability of multiple packet receptions by each node. As an example, the node in Fig. 5 receives the broadcast packet 4 times when each of its 4 closeby neighbors do their retransmissions to cover the distant neighbors in BIP and LMST-based broadcast approach. In this particular example, INOP approaches prefer direct transmission and reduces the total packet reception events significantly. The results presented in Fig. 11 indicates that in terms of the receiver side energy consumption, INOP based approaches are more economical as compared to the other approaches.

In summary, the simulation results show that the centrifugal approaches using INOP have important advantages in terms of energy efficiency and perform as good as or better than the others in terms of coverage, traffic overhead (i.e., number of rebroadcasts), and convergence time. Considering
the energy efficiency as the primary motivation in variable power broadcast approaches, INOP clearly improves on the existing approaches without sacrificing on the other metrics commonly used to evaluate network wide broadcast algorithms.

5.2. Comparisons with fixed power broadcast approaches

In this section, we compare INOP with one of the best fixed power broadcast approaches, namely, the Ad Hoc Broadcast Protocol (AHBP) [45]. This comparison is useful since the fixed power approaches are an important class of broadcast techniques. Fig. 12 presents the results for ECN and number of rebroadcasts. Both approaches have almost the same coverage and convergence time (figures not shown). According to the Fig. 12, on the average, AHBP requires about 2.5 times more energy as compared to the INOP approaches. Also, even though INOP approaches require about 3.5 times higher number of rebroadcasts, this does not necessarily

Fig. 13. Broadcast trees for variable power approaches: (a) Broadcast tree for INOP-1 (b) Broadcast tree for INOP-2 (c) Broadcast tree for RNG (d) Broadcast tree for PABLO (e) Broadcast tree for BIP (f) Broadcast tree for LMST.
indicate a significant disadvantage compared to AHBP. This behavior can be attributed to the very nature of variable power broadcast approaches where each node dynamically adjusts its power range so as to improve on energy savings. As seen earlier, INOP approaches have the least number of rebroadcasts among the variable power approaches and they have a significant gain in the energy savings with only local knowledge. Compared to AHBP, INOP approaches require a larger number of rebroadcasts but each rebroadcast uses much less energy and therefore cover much less area. This helps reduce the possibility of collisions with competing traffic. In addition, both the INOP approaches as well as AHBP have similar behavior in terms of coverage and convergence time indicating that the difference in the number of rebroadcasts does not necessarily indicate a disadvantage for the approach.

As a result, we can conclude that our approaches take the advantage of power adaptive techniques in order to improve the energy efficiency and at the same time reduce the traffic overhead in the network as in the case of fixed power approaches.

5.3. Comparison of trees constructed by different approaches

In this section, we use a sample simulation case to examine the characteristics of the broadcast trees built by alternative approaches. This study helps us understand the characteristics of different algorithms considered in this paper from another perspective. We consider a simulation case where an 80 node network topology is used to generate broadcast trees formed by different algorithms. The trees along which the broadcast packet is propagated during the broadcast operation for the different algorithms are shown in Fig. 13.

Average outdegree, average transmission range, and depth of the tree are interesting aspects that can be compared among the trees. Outdegree of a node refers to the number of children that the node has on the tree. Average outdegree gives an indication of the number of rebroadcasts used in the broadcast operation. If average outdegree is high, it indicates that a large number of neighbors are covered with each rebroadcast. Hence, the number of rebroadcasts will be lesser. The average transmission range provides information about the transmission power of broadcast at each node. If this value is high, then the nodes broadcast with a higher power, covering a higher number of nodes in a single broadcast. Depth of the tree is the number of hops from the source node to the farthest node in the tree. The higher the depth of the tree is, the higher the number of rebroadcasts and the higher the convergence time are.

Table 2 provides a comparison of these parameters for the six trees shown. Our overall observation from these results is that, in INOP approaches, nodes use larger transmission ranges to cover more number of nodes that results in broadcast trees with smaller depths. The observed performance of the INOP approach is inline with the nature of the protocol in that the protocol tend to construct trees that have lower depths as a result of the local optimizations used by each transmitting node. In contrast, the other approaches, including PABLO, RNG, and LMST, use a strategy where transmitting nodes try to decrease their transmit power levels to reduce energy expenditure of each transmission. Contrary to the INOP approach that uses the entire two-hop neighbor information for its decisions, these approaches make a more limited use of the two-hop neighbor information and therefore result in higher energy consumption. In other words, we believe that we make a better use of the available two-hop neighbor information as compared to other local knowledge based approaches. Finally, BIP uses the global knowledge of the overall network to create an optimal broadcast distribution tree in the network.

6. Conclusion

In this work, we have discussed different approaches available for broadcast in ad hoc networks. We have provided a classification of the broadcast techniques and presented a brief overview of the approaches. We have then proposed a novel approach called INOP for energy efficient broadcast in ad hoc networks. INOP is a variable power broadcast approach that uses local (two-hop neighborhood) information. INOP utilizes a novel tech-
nique for determining the transmission power level at each node. We have explored different methods of covering the nodes not covered by the initial broadcast by the source node and presented two alternative approaches.

We have provided a comparison of the proposed algorithms with the other approaches on a wide range of simulation scenarios. Our evaluations have shown that compared to other variable power approaches, INOP approaches achieve better results in terms of energy efficiency, and compete and exceed other approaches in terms of a number of other performance metrics including traffic overhead, coverage and convergence time. Considering energy efficiency as the primary motivation in our context, INOP approaches clearly improve the state-of-the-art in energy efficient broadcast in ad hoc networks.

References


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