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Efficient Broadcast in Mobile Ad Hoc Networks Using Connected Dominating Sets*

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Abstract: Broadcast is a common operation in mobile ad hoc networks (MANETs). Many on-demand ad hoc routing protocols resort to it to discover the route between any two nodes. It is also an important means to disseminate information in many MANET applications. An intuitive way for broadcast is flooding. However, without well-designed control mechanisms, flooding will lead to serious message redundancy, contention and collision. This paper proposes an efficient broadcast scheme based on the concept of connected dominating set (CDS) in graph theory. The proposed scheme can reduce message redundancy significantly, while retaining the merits of flooding. Simulation results show that the proposed scheme outperforms a distributed CDS-based algorithm and a cluster-based approach.

Key words: broadcast; wireless communication; ad hoc network; connected dominating set; algorithm; simulation

A mobile ad hoc network (MANET) is a wireless network self-organized with mobile hosts communicating over a shared wireless channel. Without the aid of fixed routing facilities, hosts in a MANET are required to forward packets for those located outside their radio coverage, thus forming a multi-hop network. Some characteristics of MANETs can be summarized as the absence of a wired backbone or fixed infrastructure, dynamically changing topology due to unconstrained mobility, collision due to the broadcast feature of wireless communication, and so on. Recent research efforts are mostly focused on the unicast and multicast routing in MANETs. The Internet Engineering Task Force (IETF) has established a working group called "manet"[1] to study the network issues in MANETs.

Broadcast is an important operation and is expected to be performed frequently in MANETs. For example, many on-demand (or reactive) ad hoc routing protocols (e.g., DSR[2], AODV[3], ODMRP[4]) resort to broadcast to discover a route between two hosts or to update group membership and multicast routes. Broadcast is also a viable candidate for reliable multicast in MANETs with rapid changing topology[5]. Broadcast will be a common operation in many MANET applications that occur in battlefield or major disaster areas.

Current approaches for broadcast in a MANET can be divided into three categories:

- Flooding and its variations, including the distance-based and location-based schemes[6,7].

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- Cluster or dominating set-based schemes[5,8,9].
- Connected dominating set-based schemes[10~12].

Flooding is an intuitive way for broadcast. It requires minimal state retention except for a mechanism to detect duplicate messages (e.g., by associating a sequence number with each broadcast message). Other merits of flooding include minimal transfer delay because messages are propagated along the shortest path from the source to each receiver. However, without an effective control mechanism, flooding may result in serious redundancy, contention and collision, which is referred to as broadcast storm problem[6]. In contrast with the former two categories, the schemes based on connected dominating set (CDS) provide a most efficient way for broadcast because they attempt to minimize the total number of transmitted messages. The main point of current approaches is to construct a subnetwork called spine or virtual backbone that approximates the minimum CDS of a network. Only the hosts in the subnetwork are permitted to perform rebroadcast operations. Current approaches are costful in maintaining a backbone structure in MANETs with frequently changing topology.

In this paper, we propose an efficient broadcast scheme based on the distributed calculation of a CDS in a network. Assuming that radio propagation is omni-directional and each host has the same invariant transmission range, a MANET can be represented by an unweighted, undirected graph. Given a graph $G=(V,E)$, where V is the set of mobile hosts and E is the set of edges, an edge (u,v) exists only if both host u and v are within their radio coverage. Hosts u and v are said to be adjacent and called neighbors. A node set is a connected dominating set if each node not in the set is adjacent to at least one node in the set and the subgraph induced by the set is connected. Since it is an NP-complete problem to find a minimum CDS in a general graph[13], we develop a distributed algorithm that approximates the minimum CDS effectively. The algorithm starts from the broadcast source and selects other hosts as dominating nodes recursively. Only local topology information is required in the calculation of new dominating nodes. All the nodes picked out then form a CDS of the network. Broadcast messages are propagated in the network along with the calculation of the CDS. Simulation results have shown that our algorithm can reduce the broadcast redundancy significantly.

Section 1 briefly reviews the related work. Section 2 presents our broadcast algorithm. Simulation results are given in Section 3 and we conclude the paper in Section 4.

1 Related Works

The broadcast storm problem is identified and analyzed in Ref. [6]. Several schemes are classified, namely probabilistic, counter-based, distance-based, location-based and cluster-based schemes. The probabilistic scheme is the simplest way, while the counter-based one diminishes duplication by utilizing the statistical information of duplicate messages. Both can not guarantee a message to be delivered to each host even if all hosts are statically connected and no loss occurs due to collision. Distance-based and location-based schemes try to reduce broadcast redundancy by utilizing the geometric information of mobile hosts. They require additional facilities (e.g., positioning devices) to perform the operations. The cluster-based approach uses only topological information to improve the performance of broadcast. It is also called dominating set-based approach because the cluster heads (or cores) form a dominating set of the network. It is scalable and effective, but requires additional cost to maintain the cluster structure. Besides, it is sub-optimal in terms of message redundancy.

Connected dominating sets have been used to solve the routing problem in MANETs[10,11]. These schemes have been reviewed in Ref. [12]. Their main principle is to construct a virtual backbone that approximates the minimum CDS of the network. Due to the dynamic nature of MANETs, it is costly to update the CDS while the network topology changes frequently. Wu's approach[12] can generate a CDS quickly (in 2 rounds), but the CDS size is not optimized.

Multipoint Relaying (MR) is proposed to minimize the overhead of flooding throughout a MANET[14]. In MR approach, each router independently selects its MR set periodically and all MR routers can form a CDS of the network. As control overhead expenditure is required to support MR, it is proposed as an optional mechanism used only when sufficient flooding traffic exists. Ho et al. argued that flooding can be a viable candidate for multicast protocols in very dynamic ad hoc networks[5]. Their simulation results show that even flooding is insufficient for reliable multicast when mobility is very high. We believe that by reducing the broadcast redundancy, we can reduce the packet loss due to contention or collision, and potentially enhance the reliability of broadcast.

2 CDS-Based Broadcast Algorithm

2.1 Graph notation

Given an undirected graph $G=(V,E)$, where V is the node set and E is the edge set, the neighbor set of nodes u is denoted as $N(u)$. The k-hop neighbor set of u, denoted as N_k, is the set of nodes which can be reached by exactly k hops from u. The distance of two nodes is the shortest path length between them, denoted as $d(u,v)$ for nodes u and v. Hosts periodically exchange their neighbor sets with their neighbors. So, each host can obtain the local topology information in two hops. For host u, the two-hop neighbor graph of u is denoted as $GN_2(u)=(VN,EN)$, where $VN=\{u\}\cup N(u)\cup N_2(u)$, $EN=\{(w,v)\mid(w,v)E \text{ and } w\in N(u)\}$.

We denote a CDS of G by C. Each node in C is called a dominating node (abbreviated to DNODE in the following text). For broadcast, we call the dominating node as broadcast relay gateway. Each node u in G has a unique dominator, dom(u), which is a DNODE adjacent to u, or itself if u is a DNODE. If dom$(u_2)=u_1$, dom$(u_3)=u_2$,..., dom$(u_i)=u_{i-1}$, and dom$(v)=u_i$, then $u_1,u_2,\ldots,u_i$ are said to be the upper DNODEs of u. The set of upper DNODEs of u is denoted by $U(u)$.

2.2 Broadcast algorithm

When a host s attempts to broadcast a user message to all other hosts in a MANET, it propagates the message along with the CDS calculation. Only the hosts in the CDS will rebroadcast the message. To distinguish whether a host is a DNODE or not, we assign each host u a marker $M(u)$, which is 0, 1, or 2. Initially, each marker is set to 0 and will be changed to 1 or 2 after the algorithm finishes. A host whose marker is 1 is not a DNODE but adjacent to at least one DNODE. All hosts whose markers are set to 2 make up a CDS of the network.

In our algorithm, the host from which u receives the broadcast message firstly is designated as the dominator of u. Therefore, $U(u)$ is just the set of hosts in the message path from the source to u. Local topology information, that is, the two-hop neighbor graph of u, is utilized by u to calculate new DNODEs, if u is a DNODE. $U(u)$ is used by host u to get rid of the hosts that have been counted in previous calculations. Then, like MR[14], new DNODEs are chosen from $N(u)$ to cover the remaining nodes in $N_2(u)$ so that a host in $N_2(u)$ will be adjacent to at least one DNODE which is chosen previously or chosen by u. Let the set of new DNODEs chosen by u be $DN(u)$. After $DN(u)$ is determined, u rebroadcasts the user message piggybacking with the information of $DN(u)$ and the upper DNODE set of the new DNODEs. The new DNODEs perform the same operations to select other dominating nodes.

Assume the source node is s. The algorithm consists of the following steps.

A. All markers are set to 0. $U(s)$ is set to be an empty list.

B. Set $M(s)$ to 2. Let s execute the node operations in Steps (2)～(6) described below. New DNODE set $DN(s)$ will be generated. (Note the operations in Steps (2.1) and (2.2) will not be executed by s.)

C. For each DNODE, let it execute the node operations described below. Then new DNODEs will be picked out. This procedure is recursively executed until there is no new DNODE generated.

♦ Node operations

When host u receives a broadcast message from r, it knows $DN(r)$ and its upper DNODE set $U(u)$ determined by r. Then it performs the following operations.

(1) If $M(u)\neq 0$, then stop; else, let $dom(u)=r$. If $u\in DN(r)$, then let $M(u)=1$, stop; else let $M(u)=2$, $DN(u)=\varphi$ (empty list), continue the following steps.

(2) Reduce the two-hop neighbor graph $GN_2(u)$ according to the following rules:

(2.1) If a node is or is adjacent to a DNODE previously selected, then remove it. That is, remove the nodes in $U(u)$; remove the nodes adjacent to any node in $U(u)$; remove the edges associated with these nodes.

(2.2) If a node is in $DN(r)$ or adjacent to a node listed before u in $DN(r)$, then remove the node and remove the edges associated with it.

(2.3) Remove the edge between two neighbors of u.

(2.4) Remove the node whose degree decreases to zero.

Denote the remaining graph as $G_r=(V_r,E_r)$. Then we have $V_r\subseteq N(u)\cup N_2(u)$, $E_r=\{(w,v)\mid w\in N(u)$ and $v\in N_2(u)\}$.

(3) Let $S_1=V_r\cap(u)$, $S_2=V_r\cap N_2(u)$. If $S_2=\varphi$, then goto (6); else continue.

(4) Calculate the degrees of nodes in G_r. If there is a node in S_2 whose degree is 1, then let the node in S_1 adjacent to it be v; or else, let the node in S_1 with maximum degree be v.

(5) Let $DN(u)=DN(u)\cup\{v\}$. Remove node v and any node in S_2 adjacent to v from G_r. Goto (3).

(6) Broadcast user message to all neighbors of u, piggybacking the information of $DN(u)$ and the upper dominating node set which is $U(u)\cup\{u\}$. Stop.

By simple analysis, we obtain the following results.

Lemma 1. Given an undirected connected graph G, the dominating node set computed by the above algorithm forms a CDS of G.

Proof. Firstly, we note that if a node is chosen as DNODE, then it will execute the node operations to select new DNODEs. The operations of DNODE u ensure that any node in $GN_2(u)$ will be a DNODE or is adjacent to at least one DNODE. Let C be the resultant DNODE set.

For any node u in G, we will prove that u is in C or adjacent to at least one node in C. Assign the length of each edge to be 1. Assume u is not in C. As the source s is the first DNODE, if $d(u,s)<3$, then u is in $GN_2(s)$ and we come to the conclusion. Assume any node whose distance to s is less than K ($K>2$) hops is in C or adjacent to at least one node in C. For node u, where $d(u,s)=K$, we denote the next hop on the shortest path from u to s by v. If v is in C, then the conclusion is true. Or else, because $d(v,s)<K$, v will be adjacent to a DNODE according to the assumption. Denote this DNODE as w, then u must be in $GN_2(w)$ and the conclusion is proved.

Because G is connected, the distance from any node to s is finite. So, in summary, C will be a dominating set of G. Since a DNODE always chooses new DNODEs from its neighbor net, then C must be a CDS of G. □

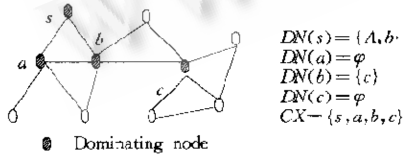


Fig. 1 Sample CDS computed by the algorithm

Lemma 2. Assume all links have the same transfer delay and all hosts take the same time to process a broadcast message and no loss occurs due to collision. In the above algorithm, broadcast messages are propagated along the shortest path from the source to any host in a MANET.

Proof. Firstly, we note, by executing the operations described above, a DNODE selects new DNODEs to cover all the nodes in its 2-hop neighbor set which are not covered by other DNODEs. If it takes k hops to transfer a broadcast message from source s to u, then the message will be delivered to any host in less than $k+2$ hops.

For the hosts in $GN_2(s)$, we come to the conclusion by considering the operations of s. Assume the shortest path is taken to transfer a broadcast message from s to any node whose distance to s is less than K hops ($K>2$). For node u, where $d(u,s)=K$, we denote the next hop on the shortest path from u to s as v. According to the assumption, a broadcast message will take $K-1$ hops to arrive at v. If v is a dominating node, a broadcast message will be propagated to u in K hops. Or else, u is in $GN_2(\mathrm{dom}(v))$ and broadcast messages will be delivered to dom(v) in $K-2$ hops. (Note that v receives a broadcast message from dom(v).) The message will be transferred to u in no more than K hops. Therefore, it takes K hops to transfer a broadcast message from s to u. □

We can apply the following rule upon the resultant CDS to reduce its size.

Rule 1. If v is a dominating node, but for each node w in $N(v)$, $\mathrm{dom}(w)v\neq v$, then set $M(v)$ to 1.

After the broadcast algorithm finishes, a spanning tree rooted at s is formed according to the dominator relationship. By applying the above rule, the dominating nodes that are leaf nodes of the tree will be removed.

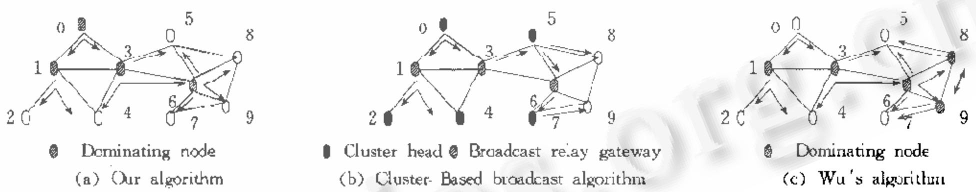
3 Performance Evaluation

To compare the performance of our algorithm with others, we adopt a cluster-based broadcast algorithm (CBBA) as follows. Clusters are formed according to the algorithm in Ref.[9]. The cluster formation rules are:

- If there is no cluster head adjacent to host u, then set u to be the cluster head;
- If two heads are neighbors, then change the one with lower ID (or IP address) to cluster member.

The hosts in the shortest path between two heads whose distance is at most 3 hops are designated as broadcast relay gateways. Obviously, the cluster heads plus these gateways constitute a CDS of the network.

Figure 2 is an example that illustrates the broadcast procedures in our algorithm, the CBBA and Wu's algorithm (referred to as WL)[12]. Node 0 is the broadcast source. The arrows show the directions of the data flows. (Not all are shown.) Note, the neighbors of a node can receive a message in one transmission because of the broadcast feature of wireless channel.



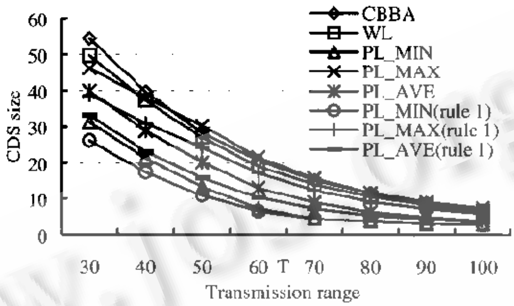
(a) Our algorithm (b) Cluster-Based broadcast algorithm (c) Wu's algorithm

Fig.2 An example

Random graphs are generated in maps with sizes of 100×100, 300×100, and 500×100 units. Mobile hosts are placed in the map randomly. For each host, its position in the map is assumed as (x,y). The value of x coordinate is a random number distributed uniformly between 0 and the map length, while that of y coordinate is distributed uniformly between 0 and the map width. There is a link between two hosts only if their geometric distance is less than the wireless transmission range. If the generated graph is disconnected, we simply discard it and regenerate a graph with the same parameters. Given the experiment parameters, we generate a random connected graph 100 times. For each case, we run our algorithm, Wu's algorithm and the CBBA and take the average. Movement of mobile hosts is not considered here, for we are focused on the broadcast redundancy in this paper. The experiment parameters are summarized in Table 1. The experiment results are shown in Figs. 3~5.

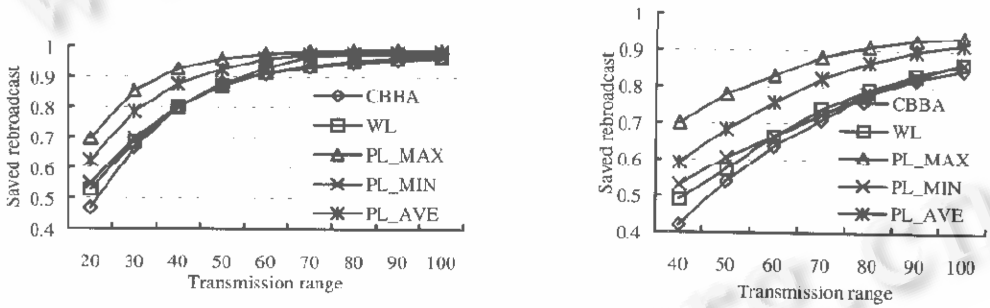
Table 1 Experiment parameters

Para.	Value	Description
L	100,300,500	Map length
W	100	Map width
N	20,40,...,160	Number of mobile hosts
R	20,30,...,100	Wireless transmission range



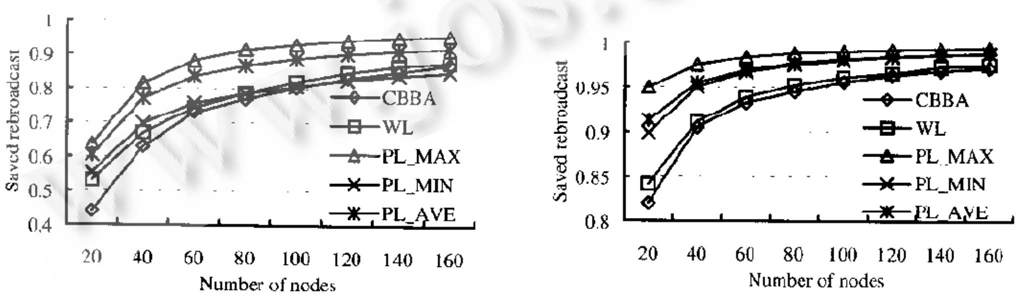
$L=300$, $W=100$, $N=100$

Fig. 3 CDS size vs. wireless transmission range



(a) $L=100$, $W=100$, $N=80$ (b) $L=500$, $W=100$, $N=80$

Fig. 4 Saved rebroadcast vs. wireless transmission range



(a) $L=100$, $W=100$, $R=80$ (b) $L=500$, $W=100$, $R=80$

Fig. 5 Saved rebroadcast vs. node number

Figure 3 shows the CDS size obtained from these algorithms. Because our algorithm is source-dependent, it is tested with each node as a source. Then we calculate the minimal, maximal and average CDS sizes, which are shown by the curves PL_MIN, PL_MAX and PL_AVE. Applying rule 1 to optimize the results in our algorithm, we get other three curves. From Fig. 3, we can see that the CDS size of all approaches decreases with the increasing of wireless transmission range. As we note, large transmission range will result in dense networks with rich connections. So, the network diameter is expected to decrease and the CDS size will decrease also. While the performance of CBBA and Wu's scheme is close to the worst case in our algorithm (curve PL_MAX), our algorithm gets smaller CDSs on average, especially with small radio coverage. Optimizing with rule 1, we can reduce the CDS size further. Figures 4 and 5 illustrate the saved rebroadcast ratio with respect to map size, network size and transmission range. The saved rebroadcast ratio is defined as $(N-TX)/N$, where N is the total number of mobile hosts and TX is the number of hosts that actually rebroadcast the message. Similar results can be observed from these figures. The broadcast redundancy is reduced significantly. Our algorithm outperforms the CBBA and WL in each case. Wu's scheme achieves slightly better performance than CBBA, which assures us of the superiority of CDS-based approaches over cluster-based approaches.

4 Conclusions

In this paper, an efficient broadcast algorithm for mobile ad hoc networks is proposed. In the algorithm, a broadcast message is propagated to every host along with the distributed calculation of a CDS of the network. Only local topology information is required and no backbone or cluster structure should be maintained. The simulation results show that the proposed scheme can reduce the broadcast redundancy significantly. Future work includes producing a refined broadcast protocol for MANETs and the simulation involving the movement of mobile hosts.

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移动自组网络中采用连通支配集的有效广播技术

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摘要: 广播是移动自组网络(MANET)中的一种常用操作.许多移动自组网络的按需路由协议依赖于它来发现任意两个节点之间的路径.广播也是许多MANET应用中发布信息的重要手段.实现广播的直接途径是洪泛(flooding).然而,在没有有效的控制机制下,洪泛将带来严重的消息冗余、传输冲突和碰撞问题.基于图论中的连通支配集(CDS)概念,提出了一种有效的广播途径.它能较大地减小消息的冗余度,同时保持了洪泛的优点.模拟结果表明,提出的广播途径优于一个基于CDS的分布式算法和一个基于簇(cluster)的途径.

关键词: 广播;无线通信;自组网络;连通支配集;算法;模拟

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