

Short Paper

Location-Aided Broadcast in Wireless Ad Hoc Networks

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Research in mobile ad hoc networks is a challenging field due to the constant changes in network topology. Broadcast service is fundamental in such networks, as it supports a wide range of important applications and dynamic source routing protocols. The traditional broadcast protocol (*i.e.*, flooding) is known to be inefficient due to the broadcast storm problem, which leads to severe message collisions and channel contention. To alleviate this problem, a number of broadcast protocols are proposed that aim at reducing the number of retransmissions for a broadcast. In this paper, we show that by merely using the immediate (*i.e.*, within a single hop) neighbor's locations, a mobile host can compute a small subset of neighbors (known as the minimum cover set) for broadcast retransmissions. Based on the concept of the cover set, we then propose three new location-aided broadcast protocols for mobile ad hoc networks that effectively broadcast the message with a very competitive number of retransmissions. We then go on to compare and analyze the simulation results of our protocols against others. The results show that the new broadcast protocols are capable of achieving high reachability with a low number of retransmissions and, overall, outperform other protocols.

Keywords: mobile ad-hoc networks, broadcast, location-aided protocols, wireless communications, connected dominating set (CDS), convex hull, α -hull

1. INTRODUCTION

Ad hoc networks enable communication between participating nodes without the burden of cabling and fixed infrastructure. In the past, the primary application of ad hoc networks was for military communications on the battlefield. Today, many commercial technologies, such as IEEE 802.11 Wireless LAN [1] and Bluetooth [2], support the ad hoc mode for exchanges of data and multimedia streaming between users. However,

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communications in ad hoc networks remains a challenging research field due to the constant changes of network topology. One of the fundamental services provided by ad hoc networks is broadcast. Various applications (*e.g.*, emergency reporting), as well as dynamic source routing protocols [3-6], require an efficient broadcast protocol. One of the simple broadcast protocols is flooding. Although flooding theoretically achieves reliable reachability, recent research has shown that the excessive amount of retransmissions generated by flooding can result in severe message collisions and channel contention. This is known as the *broadcast storm problem* [7, 8] in ad hoc networks.

To alleviate the broadcast storm problem, the number of retransmissions for each broadcast must be reduced. On the other hand, no retransmission should be arbitrarily discarded unless this is known to have no ill effect on the reachability. These two goals can both be achieved by having only the nodes in the minimum connected dominating set of the network retransmit a broadcast message. Since the computation of the minimum connected dominating set for ad hoc networks is NP-complete [9], different heuristic approaches have been proposed to approximate the minimum connected dominating set using local network topology information. The main idea of these approaches is to have each node exchange its connectivity information (*i.e.*, neighbor list) with its neighbors. By doing so, a node learns the local network topology within two hops. Each node can then determine a subset of immediate neighbors that covers all nodes within two hops. The protocols in [10, 11] are essentially based on this idea. Other broadcast protocols, such as [12-14], require nodes to elect a cluster head after several rounds of signal exchanges. In these protocols, the cluster heads and gateway nodes connecting them form a connected dominating set for the entire network. A broadcast message will be retransmitted by only the cluster heads and gateway nodes. Because these broadcast protocols treat the entire ad hoc network as a graph, where nodes in the networks function as vertices and wireless links between nodes as edges, we refer to such broadcast protocols as *graph-based* approaches.

Recently, the US Federal Communications Commission (FCC) has requested all wireless carriers to provide a location service for E911 [15]. As a result, commercial wireless systems have incorporated geolocation techniques, such as the Global Positioning System (GPS), into their wireless devices [16]. For instance, the 3G mobile cellular phone system requires every handset to be equipped with a GPS chip [17], which allows the handset to pinpoint its geographic location. This development has encouraged researchers to study uses of the location information in carrying out various functions of wireless networks, such as LAR [18] and GPSR [19] routing protocols. Along this line of research, the use of location information in ad hoc network broadcast protocols has been studied in [7, 8, 20]. The basic assumption made by all these location-based broadcast protocols is that each node in an ad hoc network knows its geographic location — the longitude and the latitude. Furthermore, by sharing the information with its neighbors through beacons, a node can learn the locations of its immediate neighbors. The communication overhead incurred by sharing this location information is thus two coordinates (approximately 20 bits) per beacon.

Compared with the graph-based approach, the location-based one evidently has an edge on the communication overhead — nodal location vs. neighbor list. This advantage, however, does not come without a price. In the graph-based approach, each node knows the topology of its 2-hop neighborhood; in the location-based approach, each node knows

only the locations of itself and its 1-hop neighbors. An interesting question is, using only the relatively limited information about the neighborhood topology, can location-based broadcast protocols compete with the graph-based ones on different performance measures?

In this paper, we show that the location-based approach is *not* inherently handicapped by its lack of knowledge of 2-hop neighbors. While enjoying the advantage of a considerably reduced communication overhead, the location-based broadcast protocols, when well designed, can perform as well as (and sometimes even better than) the graph-based ones on several important metrics. By utilizing the concept of the minimum cover set of a node's immediate neighbors, we developed the Basic Location-Aided Broadcast protocol (LAB-B), which was then refined as the Improved Location-Aided Broadcast protocol (LAB-I). In these two protocols, before a node broadcasts or rebroadcasts a message, it selects a small subset of neighbors to relay the message. The addresses of the selected neighbors are included in the broadcast message. We then show that it is possible to eliminate the necessity of including these addresses by shifting the selection process to the neighbors. That is, a node, say s , simply transmits the broadcast without telling anybody to rebroadcast it. On receiving a broadcast, each of s 's neighbors will decide whether it should rebroadcast the message. This protocol is known as the Distributed Location-Aided Broadcast protocol (LAB-D). All of these three protocols assume that each node knows its own location as well as its 1-hop neighbors' locations (by sharing the location information through beacon signals).

We studied the performance of these proposed protocols in terms of the number of retransmissions, reliability, speed of propagation, communication overhead, data set maintenance cost, optimal route preservation, and distributiveness of the protocol. We found that our proposed location-aided broadcast protocols overall outperform the graph-based counterparts.

2. LITERATURE REVIEW

There are a wide range of broadcast protocols for ad hoc networks, including [7, 8, 10-14, 20]. According to the required information and computing method, these protocols can be classified into two categories: graph-based and location-based. In general, the graph-based protocols, such as [10-14], assume that each node knows its local topology information up to 2 hops, while the location-based ones in [7, 8, 20] assume that each node knows only the geographical locations of itself and its immediate neighbors. In this section, we survey the most recent efforts designed to alleviate the broadcast storm problem in both categories. In graph-based protocols, the one built on Wu's connected dominating set protocols [11, 21] is known to effectively reduce the number of retransmissions. In location-based counterpart, Ni's location-based broadcast scheme in [7, 8] has an edge on its simplicity.

In [11, 21], Wu *et al.* proposed a set of broadcast protocols based on the connected dominating set. A dominating set of a graph is a subset of nodes such that any node in the graph is either in the set or a neighbor of at least a node in the set. A connected dominating set is a dominating set such that its induced graph is connected. Apparently, if a connected dominating set can be constructed beforehand, a broadcast can be accomplished

by having only members in the set retransmit the message. The efficiency of such a broadcast protocol depends primarily on the size of the connected dominating set. In [11, 21], Wu *et al.* proposed several distributed connected dominating set protocols. These protocols share the similar two-phase process. In the first phase, each node collects 2-hop local topology information and excludes itself from the connected dominating set should all its neighbors are interconnected. In the second phase, a set of heuristic rules is applied to further reduce the size of the connected dominating set.

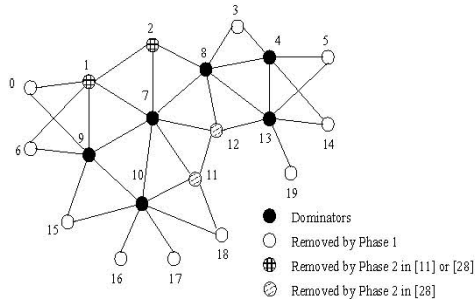


Fig. 1. An example of Wu's connected dominating.

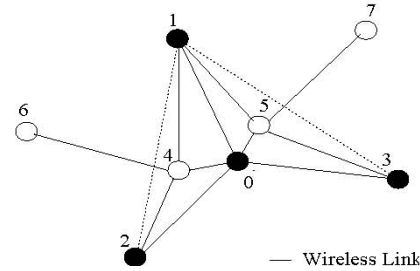


Fig. 2. An example of Ni's location-based broad-set construction cast scheme.

Fig. 1 illustrates a network of 20 nodes, where a link between two nodes indicates that they are neighbors to each other. In Fig. 1, a connected dominating set $\{1, 2, 4, 7, 8, 9, 10, 11, 12, 13\}$ is initially obtained at the end of the first phase by removing nodes that have all their neighbors interconnected. If the heuristic rules in [11] are applied afterwards, node 1 and 2 will be removed because all neighbors of each of them are covered by two of the dominator neighbors and node 1 and 2 have smaller ID than those two dominator neighbors. If the extended heuristic rules in [21] are applied instead, additionally node 11 and 12 will be removed because all neighbors of each of them are covered by two adjacent dominator neighbors.

Wu's connected dominating set protocols are relatively simple, distributed, and most of time computes a connected dominating set with a competitive size if a set of the heuristic rules in the second phase is applied. However, a broadcast message that goes through Wu's connected dominating set may need more hops to reach some nodes. For instance, in Fig. 1 if the heuristic rules in [21] are used and node 2 generates a broadcast, it requires 3 hops to reach node 6 even though node 6 is merely 2 hops away from node 2. The similar case happens at node 0. This can reduce the speed of propagation for a broadcast.

In location-based broadcast protocols [7, 8, 20], each node obtains its own geographic location through one of the location services, such as GPS [16] or Cricket [22], and learns the locations of its immediate neighbors through the exchange of beacon signals. When a broadcast message is (re)transmitted by a node, ideally only neighbors in the cover set of the node will retransmit the broadcast. The cover set is a subset of neighbors whose combined transmission coverage area is identical to that of all neighbors. In [7], Ni *et al.* proposes that after receiving a broadcast, a node randomly

defers its retransmission and determines if it belongs to the cover set when the defer period expires. In Ni's protocol, if a node overhears retransmissions from neighbors that form a convex hull enclosing itself during the defer period, the node removes itself from the cover set and drops its retransmission. However, this convex-hull approach cannot guarantee that a node is in the cover set or not. In other words, Ni's protocol potentially may drop some critical retransmissions and reduce the reachability of a broadcast. This problem is depicted in Fig. 2. In Fig. 2, a solid link between two nodes indicates that they are neighbors to each other. Supposed that node 0 is the source of a broadcast and node 4 overhears the retransmissions of node 0, 1, and 2 before its random defer period expires. According to Ni's protocol, the retransmission of node 4 will be dropped. Consequently node 6 will not be able to hear the broadcast as its only neighbor, node 4, drops the retransmission. The similar situation can happen at node 7 if node 5 overhears the retransmissions from node 0, 1, and 3 before its defer period expires and drops its retransmission.

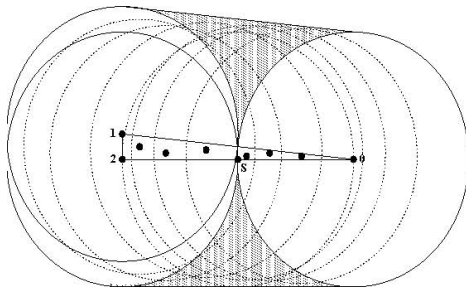


Fig. 3. The maximum the uncovered area of Ni's.

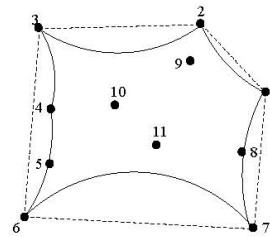


Fig. 4. An example of the α -hull for 11 nodes broadcast protocol.

Fig. 3 shows that in the worst scenario how much area will be missed by Ni's broadcast protocol. Suppose node 0, 1, and 2 happen to have a shorter defer period and the rest of the neighbors of node S are in the narrow triangular region formed by node 0, 1, and 2, the retransmissions of these neighbors will simply be dropped. This will result in the shaded region in Fig. 3 not covered by any retransmission. If some nodes are located in the shaded region, they will not be able to receive the broadcast. (Notice that the neighbors of S that drop their retransmissions were able to reach this shaded region.) According to [7], the percentage of this uncovered area can be as big as 22% in the worst case.

3. LOCATION-AIDED BROADCAST PROTOCOLS

In this section, we introduce a family of three location-aided broadcast protocols. In the first two protocols, a node encodes additional information in a broadcast message to instruct a subset of its neighbors for retransmission. In the third one, a node simply transmits a broadcast with no additional modification and each individual neighbor, after receiving the broadcast, will determine if it should retransmit the message distributively.

3.1 Basic Location-Aided Broadcast Protocol

Given the assumptions that each node knows its own and its neighbors' locations, we are interested in designing a broadcast protocol that successfully alleviates the broadcast storm problem. Our goal is to reduce the number of retransmissions per broadcast without sacrificing the reachability. To achieve it, the first thought is to let the node transmitting a broadcast select a small subset of neighbors for retransmission and encode such information in the message before the transmission.

The major design issue here is which neighbors should be selected for retransmission. To guarantee that the reachability of our broadcast protocol is as good as flooding's, the selected neighbors together should "cover" as much area as all of the neighbors together would cover. On the other hand, to reduce the number of retransmissions, the number of the selected neighbors should be as small as possible. This leads to the notion of the *minimum cover set* as defined in the following.

Given two nodes s_1 and s_2 , the Euclidean distance of them is denoted as $dist(s_1, s_2)$. Assuming the transmission range of a node is R , two nodes s_1 and s_2 are said to be *neighbors* to each other if and only if $dist(s_1, s_2) < R$. The closed neighbor set of a given node s is denoted as $N[s]$, which is defined as $\{n \mid dist(s, n) < R\}$. (Obviously $s \in N[s]$) The coverage area of a node s , denoted as $A(s)$, is the area within the circle of radius R centered at s . The coverage area of a set of nodes S is $A(S) = \cup\{A(s) : s \in S\}$. Now we are in the position to formally define the cover set as follows.

Definition 1 Let S be a set of nodes. A subset S' of S is said to be a cover set for S if $A(S') = A(S)$. If $S = N[s]$ for some node s , then S' is also said to be a cover set of s . If a node p is in the minimal cover set of s , we refer p as a cover node of s , or simply cover node if there is no confusion.

The above definition means that the retransmissions of nodes in S' cover the same geographical area as the retransmissions of all of the nodes in S .

Given the geographic locations of all nodes in $N[s]$, our problem of selecting a smallest subset of neighbors for retransmission becomes that of finding the minimum cover set of s . The heuristic in [7, 8] proposed to approximate the cover set by the vertices of the convex hull. Unfortunately, the convex-hull approach does not necessarily result in a cover set. As we have illustrated earlier, in the worst case up to 22% of the coverage area of $N[s]$ may not be covered by the vertices of the convex hull of $N[s]$.

In [23], it has been shown that the minimum cover set of node s is composed of the vertices of the α -hull [24] of $N[s]$ with $\alpha = -1/R$. Given a closed neighbor set $N[s]$, the α -hull with $\alpha = -1/R$ is defined as the intersection of all closed complements of circle with radius R centered at the points in $N[s]$. Fig. 4 illustrates an example of the α -hull for 11 nodes, which looks just like a curved convex hull. In [23], it has also been shown that the minimum cover set (*i.e.*, α -hull) of $N[s]$ is composed of nodes whose boundary of coverage area contribute to the boundary of the union of coverage areas of nodes in $N[s]$. Based on this idea, a divide-and-conquer algorithm has been developed in [23] to compute the nodes in $N[s]$ that contribute the boundary (*i.e.*, minimal cover set) in $O(n \log n)$, where n is the size of $N[s]$. For the completeness of the presentation, the minimum cover

set algorithm is provided below, but the correctness proof and time complexity analysis are omitted here. Those interested please refer to [23] for detail.

Algorithm Boundary ($\{O_0, O_1, O_2, \dots, O_n\}; i, j$)
 /* $N[s] = \{s = O_0, O_1, O_2, \dots, O_n\}$ */
if $i = j$
 return the boundary of $A(O_0) \cup A(O_i)$
else
 $m := \lfloor (i + j)/2 \rfloor$
 $ArcList_1 := \text{Boundary}(\{O_0, O_1, O_2, \dots, O_n\}; i, m)$
 $ArcList_2 := \text{Boundary}(\{O_0, O_1, O_2, \dots, O_n\}; m + 1, j)$
 return ArcMerge($ArcList_1, ArcList_2$)

Armed with the above divide-and-conquer minimum cover set algorithm, we design the Basic Location-Aided Broadcast Protocol (LAB-B) as follows.

Basic Location-Aided Broadcast Protocol

when node s receives a broadcast m from t
 if s received m before $\vee m$'s TTL has expired $\vee s$'s address is not specified in m (*i.e.*, s is not a cover node of t)
 s discards m 's retransmission
 else
 s computes the minimum cover set of $N[s]$, encodes the addresses in m , and retransmits m

In LAB-B, a node holding a broadcast message first invokes the divide-and-conquer algorithm to compute the minimum cover set and encodes such information in the broadcast message before the transmission. When a node receives a broadcast, it will not retransmit unless it is a member of the minimum cover set specified in the broadcast message. Since nodes in the cover set of $N[s]$ cover the same area as all nodes in $N[s]$, our broadcast protocol guarantees that the broadcast will reach the same number of nodes as flooding.

3.2 Improved Location-Aided Broadcast Protocol

In LAB-B, when a cover node receives a broadcast, it must retransmit unless TTL = 0 or the broadcast has been received earlier. In this section, we refine the protocol by allowing some cover nodes to drop their retransmissions under certain circumstances.

Suppose s is a cover node of t . When s receives a broadcast from t , if s knows that all of its neighbors have been covered by either t or a subset of cover nodes of t (*i.e.*, all nodes in $N(s)$ are within the coverage area $A(t) \cup A(Q)$, where Q contains neighbors of s that are also cover nodes of t), then s does not have to retransmit the broadcast.

To avoid the possibility that cover nodes s and q of t both drop the retransmission because (i) $N(s)$ are covered by $A(t) \cup A(q)$ and (ii) $N(q)$ are covered by $A(t) \cup A(s)$, we add a restriction that s may apply the above elimination strategy only if all nodes in Q have addresses (IDs) smaller than s 's.

Including the above elimination rule, our basic location-aided broadcast protocol can be revised into the following Improved Location-Aided Broadcast Protocol (LAB-I).

Improved Location-Aided Broadcast Protocol

when a node s receives a broadcast message m from t
if s received m before $\vee m$'s TTL has expired $\vee s$'s address is not specified in m (i.e., s is not a cover node of t)
 s discards m 's retransmission
else if all nodes in $N[s]$ are covered by $A(t) \cup A(Q)$, where Q contains neighbors of s that are also cover nodes of $N[t]$ with $ID(q) < ID(s) \forall q \in Q$
 s discards m 's retransmission
else
 s computes its minimal cover set, encodes the addresses of cover nodes in m , and retransmits m

3.3 Distributed Location-Aided Broadcast Protocol

In both LAB-B and LAB-I, a node needs to encode the addresses of its cover nodes in a broadcast message before the transmission. While such an approach guarantees the reachability, it increases the size of a broadcast message. In case if the size of a broadcast is short, such an approach may not be appealing. In this subsection, we show that the computation of the minimal cover set can be shifted to the receiver side. This helps eliminate the need of encoding the cover set information in a broadcast message.

When a node receives a broadcast, if it can determine whether it is a cover node, there will be no need to put the cover set information in the broadcast message. The primary issue here, apparently, is how accurate a node can estimate whether it is a cover node. Notice that when a node s receives a broadcast from t , it only has partial information about $N[t]$, so it is not surprising that s cannot always correctly determine whether it is a cover node of t . However, the estimation of s will still be useful if it has the following two properties:

1. If s is a cover node of $N[t]$, it must correctly determine this.
2. If s is not a cover node, it is allowed to occasionally draw an incorrect conclusion.

The reasoning behind these two properties is that it is important for every cover node to retransmit a broadcast or the reachability of the broadcast may be compromised. On the other hand, if a small number of non-cover nodes incorrectly conclude themselves as cover nodes and retransmit the broadcast, it only slightly increases the message complexity. To guarantee these properties in an estimation, the following theorem stated in [23] can be used.

Theorem 1 If a node $p \in S \subseteq N[s]$ is a cover node of $N[s]$, then p must also be a cover node of S .

The formal proof of Theorem 1 can be found in [23]. Intuitively, a node is selected into the minimum cover set because either it covers some area not covered by any other

node or its coverage area can only be covered by more nodes if it is not selected. In either case, reducing the set from $N[s]$ to a subset S will not change the situation.

Assuming that each node knows the location of its neighbors, Theorem 1 provides an interesting method for a node to estimate if it is a cover node. When node s receives a broadcast from node t , s knows the locations of the nodes in $S = \{x : x \in N[s] \text{ and } dist(x, t) < R\}$. Since S is a subset of $N[t]$, if node s is a cover node of $N[t]$, s must also be a cover node of S according to Theorem 1. Applying this estimation method, we design the following Distributed Location-Aided Broadcast Protocol (LAB-D).

Distributed Location-Aided Broadcast Protocol

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when node  $s$  receives a broadcast  $m$  from node  $t$ 
  if  $m$  has been received before  $\vee m$ 's TTL has expired
     $s$  drops  $m$ 's retransmission
  else
    if  $s$  is a cover node of  $S = \{x : x \in N[s] \text{ and } dist(x, t) < R\}$ 
       $s$  retransmits  $m$ 
    else
       $s$  drops  $m$ 's retransmission

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In LAB-D, all cover nodes of $N[t]$ will retransmit, so the reachability of LAB-D is guaranteed to be as good as flooding's. Theoretically, because some nodes in $N[t]$ may incorrectly conclude their cover-node status, the number of retransmissions may slightly increase. However, in section 4, we will show that in average the number of additional retransmissions resulted from incorrect estimation is really low.

4. PERFORMANCE ANALYSIS

In this section, we analyze the performance of our location-aided broadcast protocols along with others both quantitatively and qualitatively. For the quantitative analysis, the simulation was conducted using ns-2 [25], which allows us to trace and monitor packet-flows at the MAC layer. For the qualitative analysis, we consider various properties of our protocols and provide a list of the communication overhead for each broadcast protocol.

4.1 Quantitative Analysis

4.1.1 Simulation setup and environment

To assess the performance of our location-aided broadcast protocols, the simulations were conducted using ns-2 [25]. Through simulations, we compared the performance of our location-aided broadcast protocols with the traditional broadcast protocol (*i.e.*, flooding), Ni's location-based broadcast scheme in [7], and Wu's protocol in [21]. The parameters used for the simulations are as follows.

- Nodes were randomly placed within a $800\text{m} \times 800\text{m}$ two-dimensional space using

CMU scene generator, a tool provided by ns-2. The number of nodes in our simulations ranged from 40 to 100. The transmission radius was set to be 250m. Thus, the maximum number of hops was limited to 5, which was used for Time-To-Live (TTL) when a broadcast message was generated.

- Each simulation run lasts for 500 seconds. In average, a broadcast was generated at random node every second. The size of a broadcast is set to be 512 byte.
- The basic access method (*i.e.*, CSMA/CA) of IEEE 802.11 was used as MAC in our simulations. Although our simulations were mostly implemented at the network layer, we traced the packet flows at the MAC layer since the packet trace at the MAC layer supports more precise statistics. We marked all packets as a MAC BROADCAST type, which means that all existing nodes in a network are expected to be predestined receivers.
- In our simulations, a jitter timer was introduced to avoid collisions. The jitter time is a special waiting period inserted when a packet at the network layer is passed to the MAC layer. When a new broadcast is generated, many retransmissions will occur at close proximity. Although backoff timer and inter-frame spacing are used in 802.11 to avoid collisions, these are not sufficient to deal with the large number of transmissions for a broadcast in ad hoc networks. Thus, to prevent collisions, a jitter timer is inserted in between the network layer and the MAC layer. For instance, a node receiving a broadcast in LAB-I starts a jitter timer after computing its minimum cover nodes and encodes such information in the packet frame. After the jitter timer expires, the node sends the packet frame down to the MAC layer. In our simulations, jitter time was distributed uniformly between 0 and 0.11 second and used in LAB-B, LAB-I, LAB-D, flooding, and Wu's protocol. Instead of the jitter time, the defer time was used in Ni's protocol. Since in Ni's protocol a node holding a broadcast needs time to overhear retransmissions from some neighbors to determine whether to retransmit the broadcast, the defer time is set to be longer than the jitter time. In our simulations, the defer time of Ni's protocol is distributed uniformly between 0.11 and 0.22.
- In Wu's broadcast protocol [21], we assumed that the connected dominating set had already been constructed before generating any broadcast. Among several broadcast protocols proposed by Ni in [7], we selected the location-based scheme (*i.e.*, convex hull and random timer) broadcast protocol for the simulations.

Since the central aim of our simulation was to measure how many packets would be reliably retransmitted during the 500second simulation time, we did not simulate network mobility *i.e.*, network topology remained static in the duration of the simulation. Notice that our protocol can be used for mobile ad hoc networks without incurring any further cost.

4.1.2 Simulation results and analysis

In this subsection, we compare the performance of our location-aided broadcast protocols with flooding, Ni's broadcast protocol, and Wu's broadcast protocol in terms of scalability, reliability, and latency.

- Scalability – To examine how much protocols can alleviate the broadcast storm prob-

lem, we observed the average number of retransmissions for a broadcast by each protocol. The same metric can be an indication to assess how scalable each protocol is. Fig. 5 shows how nodal density affects the number of retransmissions. In Fig. 5, the x-axis represents the number of nodes in the network and the y-axis shows the average number of retransmissions for a broadcast.

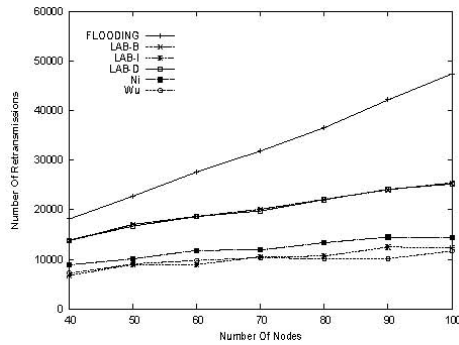


Fig. 5. The number of average retransmissions per broadcast under different nodal density.

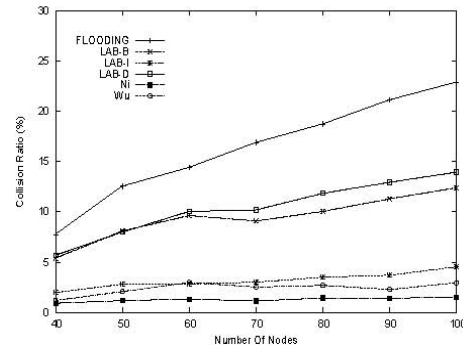


Fig. 6. Collision ratio under different nodal density.

As shown in Fig. 5, all the protocols create more retransmissions as the nodal density increases. As expected, flooding produced the highest number of retransmissions. The number of retransmissions of LAB-I, Wu's, and Ni's protocols appear to be less sensitive to the nodal density in Fig. 5. By examining the Fig. 5, we can conclude that both LAB-I, Wu's, and Ni's broadcast protocols are more scalable to the size of the network. Additionally, although the broadcast message in LAB-D does not carry the cover set information, the number of retransmissions of LAB-D and LAB-B appear to be almost the same.

Other than the number of retransmissions, the collision ratio also gives an indication of scalability. We define collision ratio as the ratio between the number of dropped packets due to collisions and the total number of received packets. In Fig. 6, the x-axis represents the number of nodes and the y-axis is the collision ratio. Fig. 6 tells us that LAB-I, and Wu's, and Ni's broadcast protocols are insensitive to nodal densities in terms of the collision ratio. In other words, those protocols appear to be more scalable in terms of the size of the network.

- Reliability – To demonstrate how reliable each broadcast protocol is, we define a successful broadcast to be a broadcast that reaches the same nodes as flooding and observe the percentage of successful broadcasts under different nodal densities in Fig. 7. Here, the x-axis shows the number of nodes and the y-axis gives the average successful broadcast percentage. As can be seen, all protocols except Ni's constantly produce successful broadcasts. This demonstrates that our location-aided broadcast protocols and Wu's are as reliable as flooding. This result also confirms that Ni's location-based scheme in [7] cannot guarantee the reachability of a broadcast since up to 22% of the coverage area could be missed in the worst case.

- Latency – To see how fast each protocol propagates a broadcast message, we observed the average propagation time at the MAC layer from the source to all nodes in the network. In Fig. 8, the x-axis represents the number of nodes in a network and the y-axis is the average propagation time for a broadcast. As the figure shows, the propagation delay of Ni's broadcast protocol is longer than that of the other protocols, because a longer defer time is inserted before each retransmission to give each node more time to hear its neighbor's retransmissions. Although other protocols also have a jitter time for avoiding collisions, the jitter time is set to be shorter than the defer time.

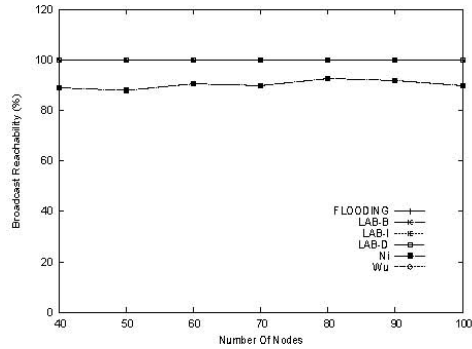


Fig. 7. The successful percentage of broadcast under different nodal density nodal density.

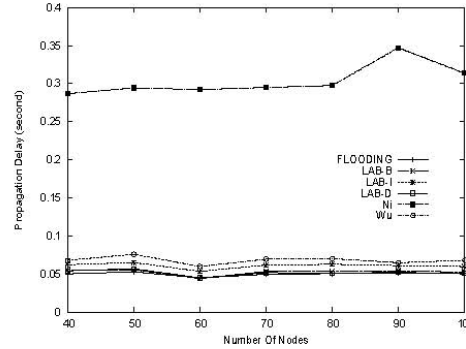


Fig. 8. Average propagation delay under different nodal density.

Table 1. Communication overhead.

Protocol	Message Size	Extra Message Number
Ni's in [7]	$rt \cdot c_l$ per broadcast	0
Wu's in [11]	$n_{nbr} \cdot c_{id} \cdot n$ per broadcast	n per broadcast
LAB-B	$c_l \cdot n$ per beacon period + $rt \cdot n_c \cdot c_{id}$ per broadcast	0
LAB-I	$c_l \cdot n$ per beacon period + $rt \cdot n_c \cdot c_{id}$ per broadcast	0
LAB-D	$c_l \cdot n$ per beacon period	0

4.2 Qualitative Analysis

In this subsection, we compared our location-aided protocols with Ni's and Wu's broadcast protocols in terms of the communication overhead, optimal route preservation, data set maintenance cost, and the degree of distributiveness in each broadcast protocol.

- Communication Overhead – The communication overhead is represented by the size and number of the extra messages required for a broadcast by each protocol. If we denote the number of total retransmission as rt , the size of the location information as c_l , the size of node address as c_{id} , average neighbor number as n_{nbr} , average cover set as n_c and total number of nodes as n , the communication overhead for each protocol can be summarized in Table 1.

The protocols that require the smallest communication overhead are Ni's protocol. Because $rt \cdot n_c$ is the approximation of the cover set for the whole network, according to Fig. 5, it is much smaller than $n \cdot n_{nbr}$. Therefore, when the beacon is not sent too frequently, Wu's protocol requires more communication overhead than LAB-B and LAB-I. The LAB-D communication overhead is better than LAB-B and LAB-I, primarily because the cover set information does not need to be encoded in a broadcast message.

If the extra message number is considered, except for Wu's protocol, the other protocols are equally good because they all incorporate their communication overhead in the broadcast messages and/or beacons.

- **Data Set Maintenance Costs** – Our location-aided protocols allow a node to compute the minimum cover set on-the-fly according to the most up-to-date locations of its neighbors. Other than the locations of the neighbors, there is no extra data set to maintain in our location-aided protocols. In other words, our protocols are “stateless” in terms of the required data set at each node, as described in [19]. While Ni's protocol is as good, Wu's protocol requires each node to maintain the local network topology within 2 hops. If the average number of neighbors for a node is n_{nbr} , the data size needed at each node for Wu's protocol is n_{nbr}^2 . This is clearly less scalable than the other protocols.
- **Optimal Route Preservation** – Defining the distance between two nodes as the lowest number of hops of all possible routes between them, an optimal route between two nodes is defined as the route that has the same number of hops as the distance of these two nodes. We want to show that an optimal route between the source node and any destination is included in the broadcast propagation path in our protocols. In other words, a node n distance away from source node s can receive a broadcast message from s in exactly n hops using our broadcast protocols.

Theorem 2 If the distance of the source node s and a node d is n , d receives a broadcast message from s in exactly n hops using our broadcast protocols.

Proof: We prove this theorem by performing an induction on the distance of s and d .

When s and d are one hop away, d is the immediate neighbor of s . Apparently the broadcast message of s reaches d in exactly 1 hop in our protocols.

Assume that this property holds when the distance between the source and destination is less than n . According to the definition, there exists an optimal route $\langle s, p_1, p_2, \dots, p_{n-1}, d \rangle$ in between s and d , where nodes in any consecutive pairs are immediate neighbors in the network. Apparently, the distance of s and p_{n-1} is $n - 1$. (If the distance of s and p_{n-1} is $m < n - 1$, appending $\langle p_{n-1}, d \rangle$ to the optimal route between s and p_{n-1} , $\langle s, q_1, q_2, \dots, q_{m-2}, p_{n-1} \rangle$, we have a route of $m + 1$ hops from s to d , making the distance between s and d smaller than n .) According to the hypothesis, our protocols allow broadcast messages to reach p_{n-1} from s in exactly $n - 1$ hops. Assume such route to be $\langle s, r_1, r_2, \dots, r_{n-2}, p_{n-1} \rangle$. If p_{n-1} retransmits in our protocols, we have a route from s to d $\langle s, r_1, r_2, \dots, r_{n-2}, p_{n-1}, d \rangle$ that is exactly n hops. If p_{n-1} does not retransmit, according to our protocols, it means that all its neighbors are covered by some r_{n-2} 's neighbors that will retransmit. Let t be the node that is a neighbor of r_{n-2} that covers d and will retransmit in our protocols. The route $\langle s, r_1, r_2, \dots, r_{n-2}, t, d \rangle$ is a route between s and d with n hops.

By induction, it is true for all distances that if the distance of the source s and a node d is n , then d receives broadcast messages from s in exactly n hops in our protocols. \square

With little modification, one can easily show that Theorem 2 is also true for Ni's protocol, assuming the resulting vertices of the convex hull happen to form a cover set. However, this is not true for Wu's protocol if his elimination rules in the second phase are applied.

- Degree of Distributiveness — While all our location-aided broadcast protocols are distributed in nature, LAB-D protocol has a higher degree of distributiveness as it is the only broadcast protocol that allows each receiver to distributively determine whether or not to retransmit the broadcast and still be able to maintain high reachability with a relatively small number of retransmissions.

As shown in the above simulation results and analysis, our location-aided broadcast protocols are competitive against other broadcast protocols in various metrics and are, overall, superior to both Ni and Wu's protocols.

5. CONCLUSION

In this paper, we investigated the graph-and location-based broadcast protocols that alleviate the broadcast storm problem for ad hoc networks. We proposed three location-aided broadcast protocols for wireless ad hoc networks. With the help of location information, our broadcast protocols are able to achieve high reachability with low number of retransmissions. The simulation and analysis results show that our proposed protocols outperform or match the existing graph-based broadcast protocols on the number of retransmissions and communication overhead, and possess various desirable properties.

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