On Mitigating the Broadcast Storm Problem with Directional Antennas

Chunyu Hu†, Yifei Hong‡, and Jennifer Hou‡
† Department of Electrical and Computer Engineering
‡ Department of Computer Science
University of Illinois at Urbana-Champaign
Urbana, IL 61801
E-mail: chunyuhu@, yhong@uiuc.edu; jhou@cs.uiuc.edu

Abstract— **Broadcast has been widely used in mobile ad hoc networks (MANETs) as a communication means to disseminate information to all reachable nodes. However, the conventional broadcast scheme that broadcast packets omnidirectionally suffers from several drawbacks: excessive amount of redundant traffic, exaggerated interference/contention among neighboring nodes, and limited coverage (as a result of contention/collision). This is termed as the broadcast storm problem in [20]. In this paper, we address this problem in MANETs with the use of directional antennas. We propose three schemes: *on/off directional broadcast, relay-node-based directional broadcast* and *location-based directional broadcast,* in the increasing order of implementation complexity. We implement the proposed schemes in *QualNet* and compare their performances against the conventional broadcast scheme. The simulation results indicate that the proposed schemes outperform the conventional omnidirectional scheme with respect to coverage, latency, and redundancy over a wide spectrum of network topology and node mobility.**

I. Introduction

Broadcast has been widely used in mobile ad hoc networks (MANETs) as a communication means to disseminate information to all reachable nodes. It has been used in, for example, routing protocols such as DSR [7], AODV [6], ZRP [24] and LAR [22], to discover routes. The simplest way of realizing broadcasts is via flooding – upon receipt of a broadcast packet, a node simply sends it out in all directions. In particular, packets are conventionally transmitted with the use of omnidirectional antennas, and neighboring nodes receive and forward these packets omnidirectionally. This, however, generates an excessive amount of redundant traffic and exaggerates interference in the shared medium among neighboring nodes. Moreover, because of the frequent contention and transmission collision among neighboring nodes, some nodes may not receive the broadcast packet. This is termed as *the broadcast storm* problem in [7].

Recently, use of directional antennas for data transmission has received much attention as it demonstrates the capability of increasing the network capacity with spatial reuse, and mitigating the interference and contention among neighboring nodes. Succinctly, directional antennas [15, 16] concentrate more energy in a certain direction, and hence can achieve higher signal-interference-ratio and narrower beam width and mitigate inter-symbol interference (ISI) due to multipath fading. These features have been judiciously used to maximize the number of on-going connections and to reduce the interference and contention [12, 13, 16, 23].

Motivated by the above research work, we consider in this paper use of directional antennas to mitigate the broadcast storm problem. The objective is to ensure broadcast packets reach most, if not all, nodes, and yet reduce the amount of redundant traffic. We propose three schemes: *on/off directional broadcast, relay-node-based directional broadcast* and *location-based directional broadcast*, in the increasing order of implementation complexity. In the *on/off directional broadcast* scheme, on receipt of a broadcast packet that has not been forwarded before, a node only forwards it in three directions other than the direction in which the packet arrives. This is achieved by setting the directional antennas in the active/passive (or on/off) mode. In the *relay-node-based directional broadcast* scheme, a node forwards a broadcast packet only if the immediate upstream sender assigns it to be the relay node in the angle of arrival (AOA) direction. Determination of relay nodes is facilitated by a neighbor discovery mechanism and is determined based on the relative signal strength of received hello/data packets. In the *location-based directional broadcast* scheme, the delay in forwarding broadcast packets in each of the three directions are determined by the location information of both the immediate upstream sender and the node. We implement the proposed schemes in *QualNet* [14] and conduct a simulation study over a wide spectrum of network topologies, node mobility, and system configurations. The simulation results indicate that the proposed schemes improve the coverage and reduce the amount of redundant traffic substantially.

Use of directional antennas to mitigate MAC level contention and interference and to improve the performance of routing protocols has been reported, respectively, in [1, 13, 16, 18, 19, 23] and in [2, 17, 19]. However, to the best of our knowledge, there exists little work on exploiting directional antennas for broadcasts.

The rest of the paper is organized as follows. In Section II, we present the network model, and describe the conventional broadcast scheme that exploits omnidirectional antennas.

0-7803-7802-4/03/$17.00 © 2003 IEEE

(This conventional broadcast scheme will be used as a baseline in the simulation study.) In Section III, we elaborate on the three proposed schemes that take advantage of directional antennas. Following that, we summarize the related work in Section IV and present the simulation results in Section V. We conclude the paper in Section VI with our plan for future research.

II. Background Materials

In this section, we first give a succinct overview of directional antennas that pertains to the problem addressed. Then we present the network model and describe the conventional broadcast scheme that uses omnidirectional antennas.

A. Overview of Directional Antennas

In general, there are two types of directional antennas, i.e., switched beam directional antennas and adaptive antennas. Switched beam antennas form multiple fixed beams with heightened sensitivity in particular directions. Adaptive array antennas, on the other hand, can steer the main lobe to virtually any direction. By using sophisticated signal processing algorithms, adaptive array antennas can effectively locate and trace signals dynamically to minimize interference and to maximize targeted signal reception. However, they are more expensive than switched beam antennas.

B. Network Model

We consider a mobile ad hoc network in which all the nodes communicate with one another based on the IEEE 802.11 MAC protocol. Each node is equipped with one transceiver and four switched-beam directional antennas, each spanning 90 degrees and by combination covering all the directions. We use the directional antenna model proposed in [16] in which each directional antenna has a main lobe with beamwidth $\theta_m = 90°$ and a side lobe with beamwidth 270°, and has two operating modes: *active* and *passive*. Only active antennas are used to transmit or receive. This implies that if all four antennas of a node are active, it can transmit or receive omnidirectionally.

The transmission range for both omnidirectional and directional antennas are assumed to be the same. The rationale behind this assumption is two-fold: first, the assumption ensures symmetric links that are required for most routing protocols in the course of discovering routes. Second, this assumption enables us to compare in a fair manner schemes that utilize directional antennas against conventional schemes that use omnidirectional antennas. Otherwise, the directional-antenna-based schemes may take advantage of their larger transmission range to achieve better coverage.

We assume that the MAC layer has control of each antenna's mode and can learn the angle-of-arrival (AOA) and the strength of incoming signal power. Finally, we assume all nodes use the same directional antenna patterns and can maintain the orientation of their directional antennas all the time regardless of mobility. As mentioned in [1], this can be achieved with the aid of a direction-locating device such as a compass.

For the first two proposed schemes, *on/off directional broadcast* and the *relay-node-based directional broadcast*, we assume that several directional antennas are available simultaneously to transmit signals. For the third scheme, *location-based directional broadcast*, we assume that nodes are equipped with positioning devices, e.g., GPS. Moreover, only one directional antenna is needed. The fact that it requires fewer antennas makes it a more cost-effective choice.

C. Omnidirectional Broadcast (Scheme 0)

As specified in IEEE 802.11, broadcasts in MANET use neither RTS/CTS handshaking prelude nor ACK to maintain reliability. It is simply done by flooding packets almost "blindly". A broadcast packet is uniquely identified by <nodeID, seqNo> attached in the packet header. On receipt of a broadcast packet, a node will forward it to all its neighbors if it has not received any packet with the same <nodeID, seqNo>, and the packet has not traveled up to its maximum hops yet. To avoid global synchronization and consequent contentions and collisions, every node waits for a random delay (drawn from a uniform distribution) before forwarding the packet. The packets that arrive by the time the delay timer expires will not change the delay value. Because of its simplicity, most routing algorithms with the route request/discovery mechanism use this scheme. However, as demonstrated in [20], although this omnidirectional scheme attempts to maximize the number of nodes that broadcast packets can reach, it also consumes significant network resources (by generating a significant amount of redundant traffic), causes serious interference/contention among neighboring nodes that attempt to relay broadcast packets at the same time, and in some cases, is unable to cover all the nodes because of contention and collision.

III. Directional Broadcast Schemes

A. On/Off Directional Broadcast (Scheme 1)

As the name suggests, in this scheme the MAC layer is able to set each directional antenna to the *active/on* or *passive/off* mode. Similar to the omnidirectional broadcast scheme, when a node receives a broadcast packet that it has not seen before, it forwards it after a uniformly distributed random delay. However, it will only forward the packet in the directions other than that in which the packet arrives. Specifically, if a broadcast packet arrives from a certain angle-of-arrival (AOA) and is received by one of the four directional antennas, say, AOA1, the packet will only be forwarded in the other three antennas by setting AOA1 *passive*. To further reduce broadcast redundancy, if the same packet is received by another antenna AOA2 before the delay timer expires, antenna AOA2 will also be set to *passive*. In this manner, by the time the delay timer expires and the channel is sensed idle, only

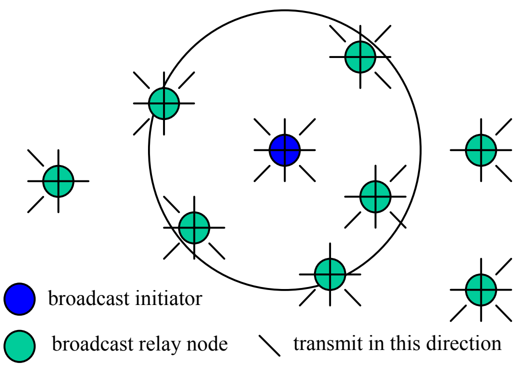


Figure 1. On/Off Directional Broadcast

antennas that have not received the packet will be set to *active* and forward the packet. Figure 1 illustrates the idea.

B. Relay-Node-Based Directional Broadcast (Scheme 2)

To further reduce the possibility of multiple nodes relaying the same broadcast packet, we use the notion of *relay* nodes. Each node *n* designates, for each direction, one and at most one relay node to forward broadcast packets, where a relay node in a direction is the one-hop node that is farthest from node *n* in that direction (and thus the signal strength of packets sent from the relay node is the weakest in that direction). To help discovering one-hop neighbor nodes and assigning relay nodes, every node sends *hello* messages periodically to its neighbor nodes. A node updates its neighbor information and relay nodes assignment by snooping all packets received. Based on the signal strength of received packets, each node chooses, for each direction, a *relay* node, if one exists. Associated with the relay node information is a refresh timer, and each node re-assigns relay nodes (if any) upon timer expiration. A node attaches the information of relay nodes in the head of each broadcasting packet.

Upon receipt of a broadcast packet for the first time, a node *n* forwards the packet in the directions other than the incoming AOA, only if (i) node *n* is assigned to be the relay node in the incoming AOA as indicated in the packet header, or (ii) no relay node is assigned in the incoming AOA. Note that case (ii) occurs when the sender is not aware of any neighbor in the corresponding direction or the relay node information is outdated by the time the broadcast packet is sent. Similar to the omnidirectional broadcast scheme, a designated relay node will delay for a random time before it sends the broadcast packet. If the same packet arrives in a direction before the delay timer expires, the directional antenna in that direction will be set to *passive* to disable packet forwarding in that direction. On the other hand, if a node that is not assigned as the relay node by the first broadcast packet it receives, it will not perform relaying even if later it receives the same packet from other sender, which assigns it a relay node. Figure 2 illustrates the scheme.

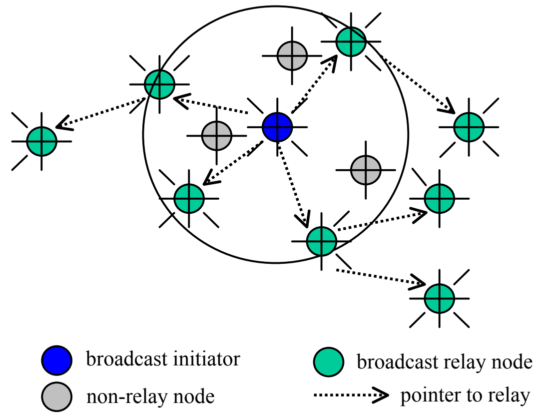


Figure 2. Relay-Node-Based Directional Broadcast

C. Location-Based Directional Broadcast (Scheme 3)

Ideally a relay node should be a node that covers the largest extra area that the broadcast packet has not reached in certain direction. Unfortunately the relay-node-based directional broadcast scheme does not fully realize this, as the neighbor node that is farthest away from the sender does not necessarily cover the largest extra area. Another important factor that should be considered is the relative orientation of two nodes. The *location-based directional broadcast* scheme is proposed to improve the performance along this avenue.

Similar to the on/off directional broadcast scheme, upon receipt of a broadcast packet for the first time, a node forwards the packet in the directions other than the incoming AOA. However, the delay is no longer uniform for all the directions. Instead, the delay in forwarding a broadcast packet in different directions varies, and is determined by the extra coverage that can be made if the packet is forwarded along a direction. The larger the extra coverage is, the smaller the delay will be. If the node receives the same packet in certain direction by the time the delay timer expires, it does not forward the broadcast packet in that direction. Figure 3 illustrates the idea. The delay for each direction is proportional to the extra coverage ratio, where the extra coverage ratio is defined as the extra coverage over ¼ of the circle area.

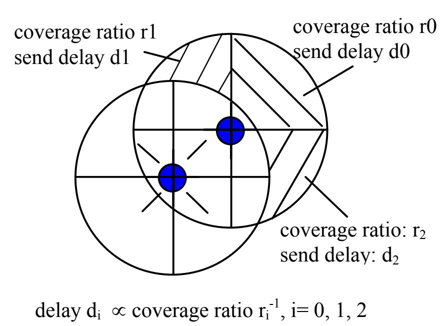
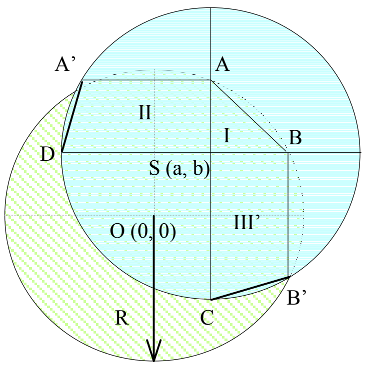


Figure 3. Location-Based Directional Broadcast

To calculate the extra coverage, we assume every node is aware of its location via, for example, GPS, and attaches in the header of an outgoing packet its current location. To obtain the exact extra coverage, one has to calculate the integral of the overlapped area. For simplicity and without loss of much accuracy, we use polygraphs to approximate the areas. For example, in Figure 4, ΔSAB and the trapezoids AA'DS and BB'CS are used to approximate area I, II and III, respectively. Upon receipt of a broadcast packet, a node calculates the extra coverage in each of the three directions based on the relative positions of the sender and the receiver.



Circle O (0, 0) : $x^2 + y^2 = R^2$

Circle S (a, b) : $(x-a)^2 + (y-b)^2 = R^2$

$$S_0 = \frac{1}{4} \times \pi \times R^2$$

$S_{I'} \approx S_{\Delta SAB}$, $S_{II'} \approx S_{AA'DS}$, $S_{III'} \approx S_{BB'CS}$

$$r_0 = 1 - S_{I'} / S_0 \text{ , } r_1 = 1 - S_{II'} / S_0 \text{ , } r_2 = 1 - S_{III'} / S_0$$

Figure 4. Calculation of Extra Coverage Areas in Three Directions

IV. RELATED WORK

Earlier research efforts on broadcasting in wireless networks assume a packet-radio network environment with synchronous medium access – time division multiple access (TDMA) [e.g. 4, 10, 11]. They can be cast into scheduling problems, with the objective of developing contention-free and reliable broadcast schemes. Most of the problems have been proved to be NP hard. Moreover, since they assume synchronous medium access, they usually use centralized control and require global or partial topology information.

A variety of distributed, broadcast schemes based on IEEE 802.11 [9] have been recently proposed, some of which are variations of the above scheduling schemes. They can be roughly categorized into the following categories [5]: *simple flooding*, *probability based methods*, *area based methods* and *neighbor knowledge methods*. Williams *et al.* [5] give a good taxonomy of existing omnidirectional broadcast schemes and make a comprehensive comparison among several representative schemes in each category. Among all the existing schemes, the ones that come closest to our work include the *location-based* scheme [20], the *dominant pruning* scheme [8], the *multipoint relaying* scheme [3] and the *ad hoc broadcast* protocol [21].

In the *location-based* scheme [20], all the nodes in the network are assumed to be aware of their locations. When a node receives a broadcast packet for the first time, it calculates the extra coverage area, denoted by *AC*, by approximating it as a convex polygon. The node only forwards the packet after a random delay if *AC* is greater than or equal to some pre-determined threshold *A*; otherwise it discards the packet. During the random delay, if the node receives the same broadcast packet again, it updates *AC*, compares it against *A*, and will not forward the packet if *AC* < *A*. Our proposed *location-based directional broadcast* scheme exploits location information as well. However, it differs from the above scheme in that in our scheme the location information is used to calculate the delay. Our scheme is also simpler in that the calculation is only made for the broadcast packet that is first seen but not for later duplicate packets.

Dominant pruning [8], *multipoint relaying* [3] and *ad hoc broadcast* [21] are all proactive neighbor knowledge methods, in which every node makes use of 2-hop neighbor information to choose a set of relay nodes based on some greedy set cover algorithms. They differ in the heuristics used to choose the relay node sets. In contrast, the proposed *relay-node-based directional broadcasting* scheme is based on 1-hop neighbor information. Every node chooses a relay node in each sector covered by a directional antenna that is farthest away in that sector. Only the relay nodes will perform the forwarding in that sector.

It has also come to our attention that concurrent with our work, R. Roy Choudhury [17] devised a broadcast scheme in their directional antenna-based routing protocol that is similar to our proposed On/Off directional broadcast scheme.

V. PERFORMANCE EVALUATION

We have implemented in QualNet the proposed broadcast schemes (by taking advantage of QualNet's fundamental support for switched beam directional antennas), and conducted a simulation study to evaluate the proposed schemes (with the omnidirectional broadcast scheme as the base line approach). The schemes are implemented in the MAC layer based on IEEE802.11, and the layers above MAC are left intact. For briefness, sometimes we mention the *omnidirectional broadcast*, the *on/off directional broadcast*, the *relay-node-based directional broadcast* and the *location-based directional broadcast* as scheme 0, 1, 2 and 3, respectively.

Simulation environment: We assume a mobile ad hoc network in which 100 nodes are randomly distributed in an area of 1500m x 1500m. All the nodes have uniform transmission range of 250m. The wireless link bandwidth is 2Mbps. Each simulation run lasts for 300 seconds, during which 100 nodes take turns to initiate a broadcast one by one at 3 seconds intervals. The packet sizes are 118/118/134/122 bytes for *scheme 0, 1, 2* and *3*, respectively. The results are averaged over all the broadcasts in one simulation run. We carry out two sets of simulations for each scheme: one uses random seeds to generate different topologies, and assesses the performance in a wide spectrum of network topologies;

and the other uses the four typical mobility levels and aims to study the impact of mobility on the performance.

Performance metrics: The performance metrics of interest are (i) *coverage:* the number of nodes that receive a broadcast packet identified by <nodeID, seqNo>; (ii) *latency*: the time span from the instant a broadcast packet is sent till the instant all the nodes receive the packet; (iii) *redundancy:* the total number of duplicate packets received by nodes in a simulation run; and (iv) *collisions*: the number of packets erroneously received as a result of collision. The first two metrics measure the effectiveness of a broadcast scheme, while the latter two reflect to what extent network resources are unnecessarily consumed.

Fig. 5 topo. 1 (random seed = 1)

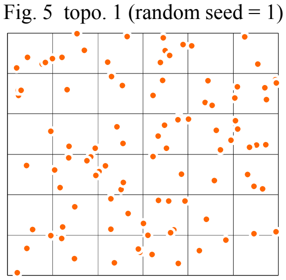


Fig. 6 topo. 2 (random seed = 10)

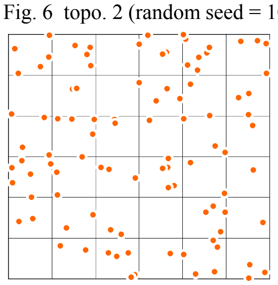


Fig. 7 topo. 3 (random seed = 50)

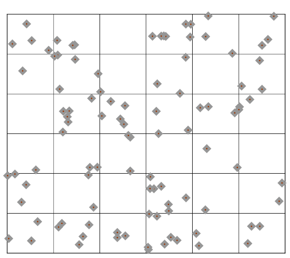
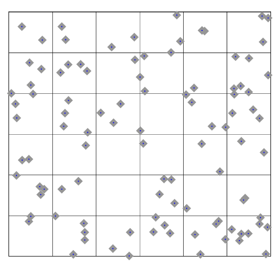


Fig. 8 topo. 4 (random seed = 100)



A. Simulation Results in Static Wireless Networks

In this set of simulation runs, 100 nodes are randomly distributed (with random seeds ranging from 1, 10, 50 to 100) in an area of 1500m x 1500m. Figures 5~8 give the resulting network topologies.

Figures 9-12 give the simulation results of coverage, latency, redundancy, and collisions under each of the four network topologies. Table 1 gives the results averaged over those obtained under the four topologies. The performance of the four schemes varies under the four topologies; however, the average result is still quite representative, as we will analyze below.

Table 1. Average Performance Comparison

Average ...	Coverage (# of nodes)	Latency (msec.)	Redundancy (# of pkts / node)	Collision (per node)
Scheme 0	75.5	14.32	312.4	99.2
Scheme 1	87.7	14.38	200.5	53.6
Scheme 2	79.8	11.04	63.9	78.2
Scheme 3	88.9	24.07	196.2	63.0

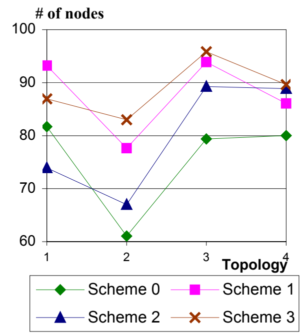


Fig. 9 Average Coverage

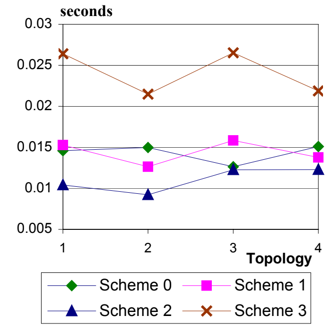


Fig. 10 Average Latency

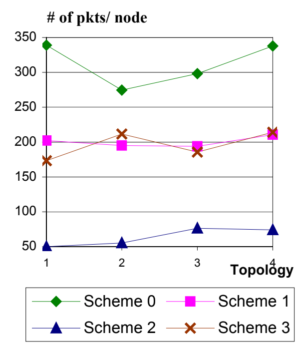


Fig. 11 Redundancy

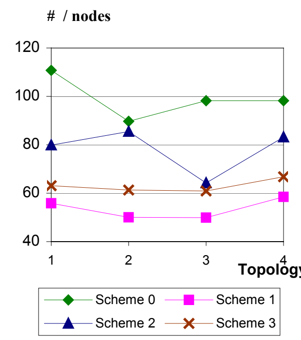


Fig. 12 Average Collisions

Several observations are in order. First, all the three directional broadcast schemes outperform the omnidirectional broadcast scheme. Specifically, the three proposed schemes improve the coverage by 16%, 6% and 18%, respectively, and except for the *location-based directional broadcast* scheme, maintain the latency at the same level. (In particular, the *relay-node-based directional broadcast* scheme achieves the performance improvement of 23% with respect to latency.) Moreover, all three schemes reduce the redundant traffic substantially, i.e., an improvement of 36~80% and 21~ 46% with respect to redundancy and collision, respectively.

Second, the *location-based directional broadcast* scheme incurs twice as large latency as compared to the other schemes. This is because in this scheme a node forwards a packet individually in each of the three directions and, moreover, has to carrier sense the channel before each transmission as specified by IEEE 802.11. As a result, to forward a packet in the three directions, it takes approximately three times as much time. The fact that it takes only twice as much time is because during the delay, some of the forwarding operations in the three directions may be cancelled.

Third, the *location-based directional broadcast* scheme achieves the best performance in terms of coverage but the worst in terms of latency. The *relay-node-based directional broadcast* scheme achieves the best performance in terms of latency and redundancy. The *on/off directional broadcast* scheme achieves the best performance in terms of collisions.

B. Simulation Results in the Case of Mobility

In this set of simulation runs, we use the network topology generated with random seed = 1 and assume the random-waypoint mobility model. Each node randomly selects a destination from the physical terrain, and moves in the destination direction at a speed uniformly distributed in [0, 2], [0,10], or [0, 25]. After the node reaches its destination, it stays there for 0.1 second and then the process repeats. The maximum speeds, 2/10/25 m/s are chosen as the typical walking/city driving/free way driving speeds.

Figures 13-16 give the simulation results of coverage, latency, redundancy, and collision under different maximum speeds. All the relative performance, except the coverage under *the relay-node-based directional broadcast* scheme, exhibits the same trend as in the static network scenarios. Also, all the schemes except the *relay-node-based directional broadcast* scheme, achieve better coverage in the case of mobility. The *relay-node-based directional broadcast* scheme gives the worst performance because it relies on the neighbor information to determine the relay nodes and in the case of mobility the information becomes less reliable (as "hello" messages are not sent frequently enough to keep every node updated of its neighbor information). All the schemes also incur smaller latency but more redundancy and collision in the case of mobility.

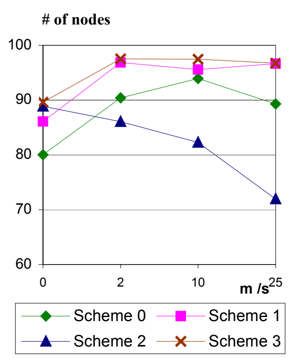


Fig. 13 Average Coverage

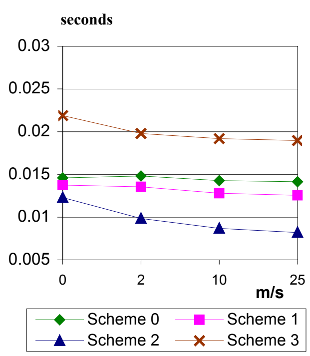


Fig. 14 Average Latency

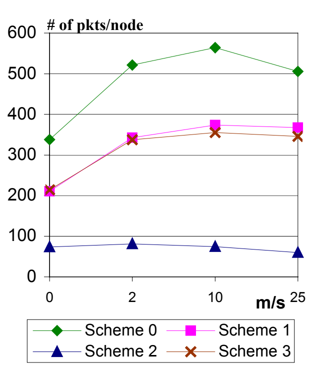


Fig. 15 Redundancy

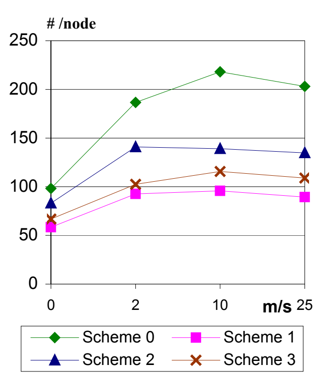


Fig. 16 Average Collisions

C. Discussions

In all the simulation runs, the proposed directional antenna-based schemes consistently outperform the omnidirectional broadcast scheme. This demonstrates the advantages of using directional antenna to mitigate the broadcast storm problem.

Of the three proposed schemes, the *on/off directional broadcast* scheme overally achieves the best performance at the least computational complexity. The *location-based directional broadcast* scheme achieves the best performance in terms of coverage, and hence is the best candidate in the case that broadcast messages should reach most, if not all, nodes. Its performance with respect to redundancy and collision is comparable to that of the *on/off directional broadcast* scheme. However, it performs worst with respect to latency, due to the fact that a node forwards a broadcast packet sequentially in each of the (at most) three directions. On the other hand, due to the same reason, only one switched beam antenna or adaptive antenna is needed at each node in the location-based directional broadcast scheme. In contrast, other schemes require use of three switched beam antennas at a node.

With the use of neighbor information, the *relay-node-based directional broadcast* scheme introduces the least redundant traffic and incurs the smallest latency. However, it also renders the smallest coverage among the three proposed schemes. This is partially because the relay-node assigning rule is rather simple. By employing more complex rules (such as those in [3, 8, 21]), we expect the performance can be further improved (but at the increased implementation complexity).

As far as the overhead that each scheme incurs is concerned, the *on/off directional broadcast* scheme requires no extra overhead like "hello" messages. Nor does it require location information. The *location-based directional broadcast* scheme does not require "hello" messages, either. On the other hand, the *relay-node-based directional broadcast* scheme requires nodes to exchange "hello" messages periodically. And the period of sending "hello" messages has an impact on the performance in the case of mobility. We varied the frequencies of sending "hello" messages and observed that more frequent sending of "hello" messages helps improving the performance, but the improvement levels off as the amount of control traffic thus introduced increases. If the neighbor discovery mechanism is part of some other protocols that coexist with the broadcast scheme, the *relay-node-based directional broadcast* scheme could be a good candidate.

VI. Conclusions

In this paper, we present three directional antenna-based schemes to mitigate the broadcast storm problem. In the *on/off directional broadcast* scheme, on receipt of a broadcast packet that has not been forwarded before, a node only forwards it in the three directions other than the direction in which the packet arrives. This is achieved by setting the directional antennas in the active/passive mode. In the *relay-node-based directional broadcast* scheme, a node forwards a broadcast packet only if the immediate upstream sender assigns it to be the relay node in the AOA. Determination of relay nodes is facilitated by a neighbor discovery mechanism and is determined the relative signal strength of received packets. In the *location-based directional broadcast* scheme, the delay in forwarding broadcast packets in each of the three directions other than AOA is determined by the location information of both the immediate upstream sender and the node.

We have carried out a simulation study using QualNet to evaluate the three proposed schemes, with the conventional omnidirectional broadcast scheme as the base line. The simulation results indicate that by using directional antennas, the broadcast storm problem can be mitigated to a great extent. Specifically, in static wireless networks, the performance improvement with respect to coverage, redundancy, and collision is on average 6~18%, 36~80%, and 21~46%, respectively. The performance with respect to latency is comparable or slightly improved, except for the *location-based directional broadcast* scheme. All the relative performance, except the coverage under *the relay-node-based directional broadcast* scheme, exhibits the same trend in the case of mobility.

We have identified several avenues for future research. As mentioned in Section V.C, we will continue to refine the rule for selecting relay nodes in the *relay-node-based directional broadcast* scheme. We will also study the performance of the proposed schemes (as well as the omnidirectional broadcast scheme) in conjunction with power management. Note that in power-managed MANETs, some of the nodes may be put into sleep and awakened periodically to check for transmission activities. How the proposed schemes perform in a power-managed MANET and how they should be modified is a subject of future study.

ACKNOWLEDGMENT

We thank Professor Nitin H. Vaidya and R. Roy Choudhury for their constructive comments on this manuscript, R. Roy Choudhury for his help with the use of QualNet, and Scalable Network Technologies, Inc. for providing an educational version of QualNet.

REFERENCES

[1] A. Nasipuri, S. Ye et al., "*A MAC Protocol for Mobile Ad Hoc Networks Using Directional Antennas*", In *Proc. of WCNC*, Sept. 2000

[2] A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, *"On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks"*, in *Proc. of the IEEE International Conference on Computer Communication and Networks* (ICCCN2000), Oct. 2000.

[3] A. Qayyum, L. Viennot, and A. Laouiti, *Multipoint Relaying: An Efficient Technique for Flooding in Mobile Wireless Networks*, Technical Report 3898, INRIA – Rapport de recherché, 2000

[4] B. S. Shlebus, L. Gasieniec, A. Gibbons, A. Pelc and W. Rytter, *Deterministic Broadcasting in unknown Radio Networks*, Symposium on Discrete Algorithms, in Proc. 11th ACM-SIAM Symp. On Discrete Algorithms, San Francisco, CA, 2000, pp. 861-870

[5] B. Williams and T. Camp, *Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks*, in *Proc. ACM Mobihoc*, pp. 194-205, 02

[6] C. E. Perkins and E. M. Royer, *Ad-Hoc On Demanding Distance Vector Routing*, IEEE *WMCSA'99,* New Orleans, LA, Feb. 1999

[7] D. B. Johnson, D. A. Maltz, *Dynamic Source Routing in Ad Hoc Wireless Networks*, in Mobile Computing, editor T. Imielinksi and Hank Korth, Kluwer, 1996

[8] H. Lim and C. Kim, *Multicast Tree Construction and Flooding in Wireless Ad Hoc Networks*, in *Proc. ACM Mobicom*, pp. 151-162, 99

[9] *International Standard ISO/ISO/IEC 802-11*: 1999 (E), ANSI/IEEE Standard 802.11, 1999 Edition.

[10] I. Chlamtac and S. Kutten, *On Broadcasting in Radio Networks – Problem Analysis and Protocol Design,* IEEE Trans. on Communications 33 (1985), 1240-1246

[11] I. Chlamtac and O. Weinstein, *The Wave Expansion Approach to Broadcasting in Multihop Radio Networks*, IEEE trans. on Communications, VOL 39, NO. 3, Mar. 1991

[12] M. Sanchez, T. Giles, and J. Zander *"CSMA/CA with Beam Forming Antennas in Multi-hop Packet Radio"*, Proc. Swedish Workshop on Wireless Ad Hoc Networks, Mar. 5-6, 2001

[13] M. Takai, Jay Martin, Rajiv Bagrodia and Aifeng Ren *"Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks"*, *Proc. of the ACM MobiHoc* 2002, June 2002.

[14] *QualNet Simulator*, Scalable Network Technologies, www.scalable-networks.com

[15] R. Janaswamy, *Radiowave Propagation and Smart Antennas for Wireless Communications*, Kluwer Academic Publishers, 1958

[16] R. Ramanathan, *On the Performance of Ad Hoc Networks with Beamforming Antennas*, in *Proc. of MobiHoc*, pp.95-105, Oct. 2001.

[17] R. Roy Choudhury, and N. H. Vaidya *"On Ad Hoc Routing Using Directional Antennas"*, Illinois Computer Systems Symposium (ICSS) May 2002, UIUC

[18] R. Roy Choudhury, X. Yang, R. R. and N. H. Vaidya *"Using Directional Antennas for Medium Access Control in Ad Hoc Networks"*, Mobicom 2002

[19] S. Bandyopadhyay, K. Hausike, S. Horisawa and S. Tawara "*An Adaptive MAC and Directional Routing Protocol for Ad Hoc Wireless Networks Using ESPAR Antenna*", *Proc. of the ACM MobiHoc 2001*, Oct. 2001.

[20] S.Y.Ni et al, "*The Broadcast Storm Problem in a Mobile Ad Hoc Network"*, *Proc. ACM MobiCom*, 1999

[21] W. Peng and X. Lu, *AHBP: An Efficient Broadcast Protocol for Mobile Ad Hoc Networks*, Journal of Science and Technology – Beijing, China, 2002

[22] Y.-B Ko and Nitin Vaidya, *Location-Aided Routing (LAR) in Mobile Ad Hoc Networks*, in *Proc. ACM MobiCom*, pages 66-75, Dallas, Texas, Oct. 1998

[23] Y.-B. Ko, V. Shankarkumar and N. H. Vaidya, "*Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks*", In *Proc. of IEEE INFOCOM*, Mar. 2000

[24] Z. J. Haas and M. R. Pearlman, *The Zone Routing Protocol (ZRP) for Ad Hoc Networks* (Internet-Draft), Mobile Ad hoc Network (MANET) Working Group, IETF, Aug. 1998