Broadcast Traffic in Ad Hoc Networks with Directional Antennas

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***Abstract*— We explore the use of directional antennas to improve the performance of broadcasting in ad hoc networks. We investigate both the performance of unicast traffic in the presence of broadcast traffic and the performance of broadcast traffic when mixed with unicast traffic, which is different from previous investigations reported in the literature in which broadcast traffic is investigated in isolation. Through extensive simulation experiments with three MAC schemes, we show that throughput and delay can vary widely even in networks in which nodes are uniformly distributed. We also show that the use of a MAC protocol that utilizes directional antennas can help to improve the performance of broadcast traffic in ad hoc networks, in terms of both throughput and delay, through a more aggressive channel access scheme that maximizes spatial reuse.**

I. Introduction

Broadcasting is used extensively in routing protocols for multi-hop ad hoc networks. For example, route discovery (including route queries and replies) and neighbor information exchange rely on broadcasting which is much more cost effective than sending copies of unicast data packets to each interested node, especially when high reliability is not required. Because simple flooding wastes considerable channel resources and can lead to excessive collisions, how to disseminate information from one source node to all the other nodes in the network with a small number of broadcast packets has become an intensely researched topic in recent years. Some work (e.g. [1]–[3]) focus on efficient time-slot assignments in a channel access environment similar to dynamic-TDMA, which is not readily applicable to contention-based random access environment with no time-slotted structure. Some recent work addresses the problem of efficient broadcast in ad hoc networks without global time synchronization.[1] For example, Ni et al. [4] propose and evaluate several approaches that make use of distance information, location information, or clustering to reduce the number of copies of broadcast packets sent. Lim and Kim [5] prove that the problem of finding the minimum-cost flooding tree is similar to the minimum connected dominating set (MCDS) and that it is an NP-complete problem. Then the authors propose self-pruning and dominant pruning schemes that utilize topology information to approximate the theoretical minimum of broadcast packets sent from one source to all the other nodes. In fact, there is already considerable work on this topic, and Williams and Camp [6] have given a detailed comparison of these broadcasting techniques for multi-hop ad hoc networks.

On the other hand, the goals for reliable broadcasting are different from that of best-effort broadcasting which is to reduce the redundancy of broadcast packets. In contention-based MAC protocols such as IEEE 802.11 MAC protocol [7], the usual collision avoidance handshake that requires a pair of sending and receiving node to exchange short request-to-send (RTS) and clear-to-send (CTS) packets before actual data packet transmissions does not work for sending broadcast packets as it is one-to-many communication. Hence, broadcast packets are sent whenever a node senses the channel idle, which may collide with the transmissions from hidden nodes [8]. Tang and Gerla [9], [10] address the unreliable MAC layer broadcast problem by extending the RTS/CTS collision avoidance scheme. Tang and Gerla [9] first propose broadcast support multiple access (BSMA) protocol, which depends on a node's direct sequence (DS) capture capability to receive the CTS with the strongest signal without being affected by other CTS packets. If the neighbors that have sent CTS packets fail to receive the ensuing broadcast data packets, they will send negative acknowledgments (NACKs) to notify the source node. The broadcast medium window (BMW) proposed by the the same authors [10] provides more reliable broadcast support, although with much more complexity.

However, all these enhancements to broadcasting in multi-hop ad hoc networks have been analyzed when there exists only broadcast traffic and some investigations are limited to low and medium traffic load so as to isolate the effects of loss due to contentions. In an operational ad hoc network, a mix of unicast and broadcast traffic is quite common and it is important to investigate both the effects of broadcast traffic on unicast traffic and the performance of broadcast traffic in the presence of unicast traffic of these proposed schemes. This motivates our work in investigating the interaction between unicast and broadcast traffic.

It would be just a simple extension to the work done by Williams and Camp [6] if we just investigated these schemes with a mix of unicast and broadcast traffic. Instead, we are interested in exploring another dimension in the solution

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[1]Global time synchronization is necessary and sufficient for a time-slotted system, which is not easily achievable in multi-hop ad hoc networks.

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space for broadcast in ad hoc networks: *directional antennas*. With the use of directional antennas, a node may either limit its transmission or direct its receiving to certain directions. As the use of directional antennas in the design of MAC protocols has received increased interest in recent years and improved performance has been shown in the literature [11]–[13], in this paper we focus our attention on how the use of directional antennas may influence the performance of both unicast and broadcast traffic.

In Section II, we describe in detail the three MAC schemes to be analyzed. They use either all omni-directional transmissions, directional transmissions only, or a combination thereof. In Section III, we elaborate on the directional antenna and network models to be used in our simulations. In Section IV, we present the results of simulation experiments. It is shown that, even in relatively regular network configurations such as the uniform distribution of nodes used in the simulation experiments, the performance of the MAC schemes can fluctuate considerably when the number of nodes competing in a region is small. Thus, it is very important to conduct performance evaluation with different network configurations and to consider both mean value and variance of interested metrics such as throughput and delay. Then it is shown that the MAC scheme that maximizes the use of directional transmissions has the best throughput-delay performance among all the schemes for both unicast and broadcast traffic. Finally, in Section V, we summarize the findings in this paper and propose some future work.

II. Directional MAC Schemes

With the deployment of directional antennas, it is possible to direct transmissions to a certain direction while leaking as little energy as possible to other directions, or to direct receiving to a certain direction while filtering out interferences from other directions. The former can be called directional transmitting capability, while the latter can be called directional receiving capability. The major benefit of using directional antennas in multi-hop ad hoc networks is spatial reuse, because two concurrent handshakes that are competing in the original omni-directional case may coexist.

There have already been some MAC schemes [11], [12] proposed in the past that make use of directional antennas. These schemes are usually designed around the CSMA/CA framework stipulated in the IEEE 802.11 protocol, which consists of an RTS-CTS-data-ACK four-way handshake between a pair of sending and receiving nodes. As the original omni-directional RTS-CTS handshake is used to silence all the overhearing neighboring nodes of both sending and receiving nodes and the possibility of collisions is reduced, in these proposed directional schemes the omni-directional transmission of RTS/CTS packets or at least that of CTS packets is preserved and then data and acknowledgment packets are sent directionally. However, the presence of omni-directionally transmitted control packets such as CTS largely nullifies the benefits of spatial reuse. For example, consider a typical scenario shown in Fig. 1. In Fig. 1, the traffic can be divided into inter-group and inner-group traffic. The benefit of partition into groups is that each inner-group communication can have minimal interference on one another and concurrent transmissions are possible, e.g. flow A–B and flow C–D, and that interferences only occur inevitably when inter-group communications take place. When all transmissions are carried out directionally, any combination of flows A–B and C–D is possible without interference to each other. In addition, even when inter-group communications take place such as flow A–C, the inner-group communications such as flow B–E may still take place concurrently. Thus the gain in spatial reuse is quite substantial. However, if during the handshake, some packets such as CTS are transmitted omni-directionally, it is impossible for flows A–B and C–D to coexist in most cases.

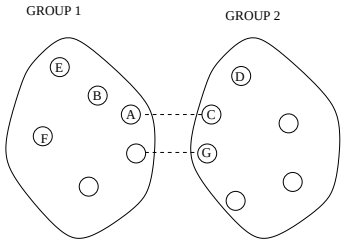


Fig. 1. A Typical Ad Hoc Network Communication Paradigm

It should also be noted that the scheme in which all transmissions are sent directionally is not fail-proof due to the increased possibility of collisions. For example, when node G sends a packet to C, it may well interrupt the ongoing communications between C and D if any. Additionally, broadcast traffic can also have negative effects on the performance of the spatial-reuse maximization scheme. Hence, it is very important to investigate which combination of omni-directional and directional transmissions can achieve the best performance. In the work reported in this paper, three typical MAC schemes are investigated. In the first one, all packet transmissions are omni-directional, which is just the scheme used in popular MAC protocols that emphasizes collision avoidance. For the sake of simplicity, we call this scheme "ORTS-OCTS." Though there are quite a few "dialects" of this scheme, we choose the IEEE 802.11 MAC protocol as the example. In the second case, an RTS packet is transmitted directionally and CTS packet is transmitted omni-directionally and then data packet and acknowledgment packet are transmitted directionally. This is the scheme that provides tradeoff between collision avoidance and spatial reuse, and it is called "DRTS-OCTS" scheme. The third case is called "DRTS-DCTS," in which all packet transmissions are directional. Obviously, this scheme emphasizes spatial reuse. The use of all directional transmissions has been shown more promising than the other two schemes for unicast traffic (e.g. [14]), though its impact on broadcast traffic has not been investigated so far.

III. Simulation Models

In this section, we elaborate on the models of directional antennas and networks used in our simulation experiments. As discussed before, in a system with directional antennas, different antenna capabilities can be assumed.[2] In our investigation, we focus on the case in which directional transmitting capability is assumed. We also simplify the model of directional antennas by assuming a simple transmission model with one parameter, the beamwidth θ. When a node transmits with beamwidth θ, nodes outside the beamwidth will not receive any signal from the node. In addition, when a node is transmitting, it appears "blind" to all the other directions. This agrees with the normal radio characteristic that a node cannot transmit and receive at the same time.

In our network model, all nodes are distributed uniformly in a circular area which is different from the usual grid model. In this way, nodes are distributed much less regularly as any one node can have quite different number of one-hop and two-hop neighbors[3] in different directions. In addition, we focus on the performance of MAC schemes in a local neighborhood, rather than that of a whole network. This helps to filter out some boundary effects, because totaling and averaging the interested metrics (throughput, delay, etc.) with regard to all the nodes in the center and at the edge of a network can lead to some askew results. Hence, in our network model, nodes are placed in concentric circles or rings. Assume that each node has the same transmission and receiving range R and there are on average N nodes in a region of area size πR^2. We first place N nodes uniformly in a circle of radius R. Because there are on average 2^2N nodes within a circle of radius $2R$, we place $2^2N - N = 3N$ nodes outside the previous circle of radius R but inside the concentric circle of radius $2R$, i.e., the ring with radii R and $2R$, subject to the same uniform distribution. Then $3^2N - 2^2N = 5N$ nodes can be placed in an outer ring with radii $2R$ and $3R$, and so on. As reasoned before, we just focus our attention on the average performance of the innermost N nodes.

According to our experiments, conclusions drawn from a circular network of radius of more than $3R$ do not affect the conclusion to be drawn in the next section. Therefore, we present only the results for a circular network of radius $3R$.

As stated before, even when nodes are distributed uniformly, the number of one-hop and two-hop neighbors that any node can have still varies considerably. To avoid some extreme cases, we only use the generated network topologies that satisfy the following requirements:

- For the inner N nodes, each node should have at least 2 neighbors and at most $2N - 2$ neighbors.
- For the intermediate outer $3N$ nodes, each node should have at least 1 neighbor and at most $2N - 1$ neighbors.

[2]It is trivial to extend the work to antenna systems with directional receiving capabilities.

[3]Here we refer to those nodes that have at least one common neighbor with a node but are not direct neighbors of the node as the node's two-hop neighbors.

IV. Simulation Results

In our simulation experiments, we investigate both the effects of broadcast traffic on unicast traffic and the performance of broadcast traffic in the presence of unicast traffic. The latter is different from the work reported in some literature where performance of broadcast traffic is investigated isolatedly without the presence of unicast traffic.

A brief description of the simulation environment is in order. We use GloMoSim 2.0 [15] as the network simulator. The popular IEEE 802.11 MAC protocol just uses the ORTS-OCTS scheme. We implement the other two schemes based on the existing IEEE 802.11 implementation for fair comparison. Direct sequence spread spectrum (DSSS) parameters are used throughout the simulations. The raw channel bit rate is 2Mbps.

A. Unicast traffic performance in the presence of broadcast traffic

In our simulation experiments, each node in the innermost circular region of radius R is a constant bit rate (CBR) generator that continuously generates unicast data packets and broadcast data packets alternately. For unicast packets, the destination node is chosen randomly from the node's neighbors. The size of a unicast data packet is 1460-byte and the size of a broadcast data packet is 500-byte, about one third the size of a unicast data packet. We use r to denote the ratio of the number of broadcast data packets generated to the total number of data packets generated.

We vary the number (N) of nodes in the innermost circular region of radius R as well as r to obtain three metrics. The first one is unicast throughput which is the aggregate throughput contributed by the innermost N nodes sending unicast data packets that are acknowledged. The second one is broadcast throughput. We count the number of broadcast packets from the innermost N nodes that are received by the neighbors of the innermost N nodes as well as these nodes themselves.[4] Then we divide it by the number of broadcast data packets that can be transmitted in the total simulation time to obtain the normalized broadcast throughput. The third one is the average delay of unicast data packets. In addition, for the two schemes (DRTS-DCTS and DRTS-OCTS) that utilize directional transmissions, we also investigate their performance under different values of beamwidth θ: 30°, 90°and 150°.

For each configuration, we generate 30 random topologies and for each topology we run the simulations with three different seed numbers. For each run, we calculate the interested metrics and take the average over the three different seed numbers. Then we calculate the mean values and standard variance of these metrics. The results are shown

[4]A broadcast packet may be counted more than once if more than one node receive it correctly.

in Figs. 2–5. In these figures, the vertical lines show the range of metrics achieved by each scheme, that is, *mean* $\pm$ *standard variance*. These lines are shifted a bit for clarity.

Figs. 2–3 show that all the throughput of the three schemes degrades rather elegantly even when on average each node sends 30% of broadcast traffic. Here the only exception is that the throughput of DRTS-OCTS scheme increases a bit for $N = 8$ when r increases from 0 to 0.1. It seems that in these cases a small percentage of broadcast traffic helps to interrupt some nodes' long waiting time for collision avoidance and thus nodes are more aggressive in access to the shared channel. However, for other cases, broadcast traffic can degrade unicast throughput almost definitely. In addition, for small values of N (such as 3), the three schemes perform almost the same, considering both mean and standard variance. When N increases, the DRTS-DCTS scheme with small beamwidth θ performs indisputably much better than the other two schemes. This can be explained as follows. At first for unicast traffic, when the network becomes more congested, it is very difficult for a pair of sending and receiving nodes to get coordinated with their one-hop and two-hop neighbors in the ORTS-OCTS scheme. If coordination is not achieved, then their handshake may be very probably disrupted by the omni-directional transmissions of neighboring nodes. Even if coordination is achieved, all their one-hop and two-hop neighbors are prohibited from transmitting and spatial reuse is greatly reduced. The same reason applies to DRTS-OCTS scheme due to the omni-directional transmission of CTS packets. In the DRTS-DCTS scheme, transmissions are confined to much smaller regions and multiple flows may coexist at the same time. When the network is less congested, tradeoff between collision avoidance and spatial reuse is much more balanced and all schemes work similarly. For broadcast traffic in congested networks (large values of N), although all the three schemes use the basic CSMA to send broadcast packets, however as more unicast packets can be sent in the DRTS-DCTS scheme, hence are broadcast packets. Accordingly, the DRTS-DCTS scheme can achieve the highest broadcast throughput for large values of N.

It should also be noted that, the performance metrics can vary a lot even when the same uniform distribution is used throughout the simulation experiments, especially when N is small. Hence we argue that it is very important to experiment with enough network topologies before conclusions can be drawn, otherwise misleading results may be obtained.

Figs. 4–5 show that the broadcast throughput increases almost linearly with the increase of percentage of broadcast traffic and with the number of innermost nodes. Besides, the DRTS-DCTS scheme is shown to have larger marginal gain in broadcast throughput. This is due to the more aggressive channel access scheme in DRTS-DCTS where the gain in spatial reuse outweighs the gain in conservative collision avoidance. It is also evident that the DRTS-DCTS scheme has more distinct advantage when beamwidth is narrow, say $\theta = 30^\circ$. We also find that the DRTS-DCTS scheme with small beamwidth also achieves the least delay for unicast traffic as nodes spend less time in collision avoidance. Due to the limited space, the results are not shown here and interested readers can contact the authors for the results.

TABLE I
PACKET INTERARRIVAL TIME CONFIGURATIONS

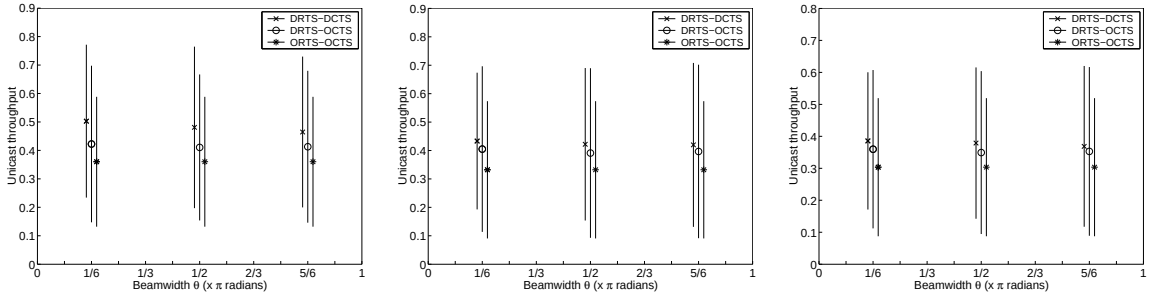
	conf 1	conf 2	conf 3
N=3	108ms	72ms	54ms
N=5	180ms	120ms	90ms
N=8	288ms	192ms	144ms

B. Broadcast traffic performance in the presence of unicast traffic

We still use the circle and ring topology with $R = 3$ and focus on the broadcast packets received as well as their delay recorded by the innermost N nodes under light to medium traffic load. We show the results when $r = 0.3$, i.e., about 30% of the packets sent by any node are broadcast packets, and $\theta = 30^\circ$ when applicable. Table I shows the three configurations for different values of N in which the packet interarrival time is varied to change the offered load to the shared channel. Configurations one and two roughly correspond to light load and configuration three medium load. Table II shows the average delay and standard variance of broadcast packets observed by the innermost N nodes. Table III is the average and standard variance of the delivery ratio of broadcast packets observed by the innermost N nodes. Here the ratio is the total number of broadcast packets received to the total number of broadcast packets generated by the innermost N nodes.

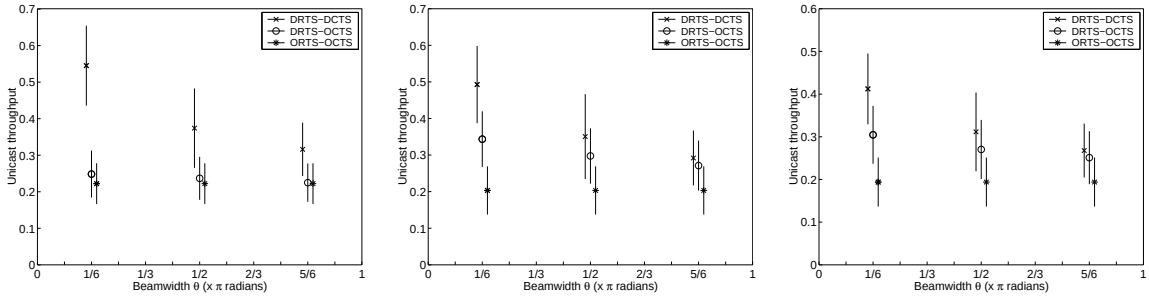
It can be observed that, with regard to delay in light load scenarios, in general DRTS-DCTS has no distinct advantage over DRTS-OCTS scheme, although both schemes perform better than the ORTS-OCTS scheme; in medium load scenarios, in general DRTS-DCTS has distinct advantage over the other two schemes in that both the average delay and variance are much smaller. The difference lies in the fact that unicast packets can be delivered much faster in the DRTS-DCTS scheme whose channel access is more aggressive, while the other two use more conservative channel access scheme. We also note that the variance of all three schemes is quite large. Thus it again supports our argument that, in the simulation of ad hoc networks, it is very important to run simulations with different topologies extensively even when the topology distribution seems quite regular, such as the uniform distribution, otherwise it is very probable to get misleading results.

Table III also shows that in general the nodes can receive more broadcast packets in the DRTS-DCTS scheme than the other two schemes. In summary, the DRTS-DCTS scheme can achieve the best delay-throughput curve among the three schemes investigated.



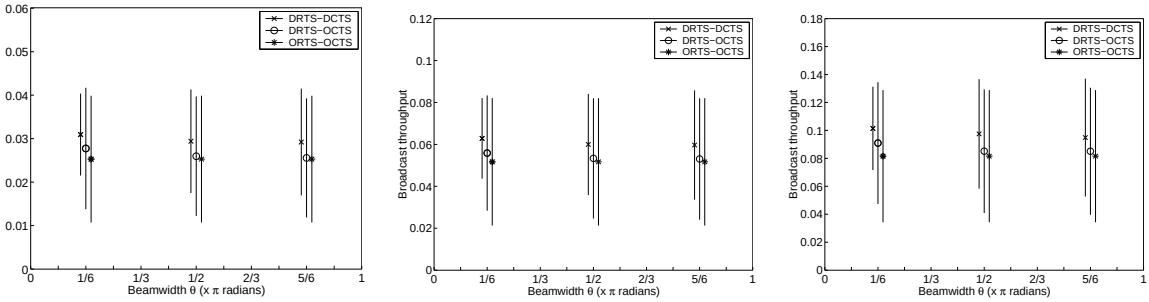
(a) $N = 3, r = 0.0$ (b) $N = 3, r = 0.1$ (c) $N = 3, r = 0.3$

Fig. 2. Unicast Throughput ($N = 3$)



(a) $N = 8, r = 0.0$ (b) $N = 8, r = 0.1$ (c) $N = 8, r = 0.3$

Fig. 3. Unicast Throughput ($N = 8$)



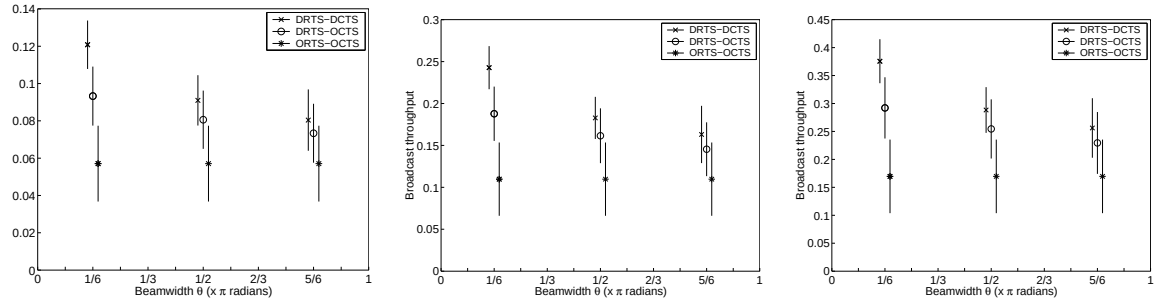
(a) $N = 3, r = 0.1$ (b) $N = 3, r = 0.2$ (c) $N = 3, r = 0.3$

Fig. 4. Broadcast Throughput ($N = 3$)

TABLE II

BROADCAST PACKET DELAY COMPARISON (UNIT: MS)

	DRTS-DCTS			DRTS-OCTS			ORTS-OCTS		
	conf 1	conf 2	conf 3	conf 1	conf 2	conf 3	conf 1	conf 2	conf 3
N=3, mean	11.7	24.6	113.5	6.8	18.1	251.3	11.5	80.7	480.1
N=3, std	4.0	11.0	185.9	1.8	27.5	560.5	5.4	236.2	672.5
N=5, mean	8.1	16.9	35.7	8.5	12.3	112.8	14.1	52.6	590.3
N=5, std	2.0	6.0	26.7	1.5	6.7	336.0	3.9	67.0	835.4
N=8, mean	7.5	9.3	17.3	10.3	11.4	26.2	16.3	39.8	569.6
N=8, std	1.2	1.5	3.7	1.8	2.9	22.3	4.1	25.1	778.2



(a) $N = 8, r = 0.1$ (b) $N = 8, r = 0.2$ (c) $N = 8, r = 0.3$

Fig. 5. Broadcast Throughput ($N = 8$)

TABLE III

BROADCAST PACKET DELIVERY RATIO COMPARISON

	DRTS-DCTS			DRTS-OCTS			ORTS-OCTS		
N=3, mean	0.32	0.95	2.27	0.23	0.82	2.08	0.19	0.72	1.75
N=3, std	0.15	0.48	1.13	0.17	0.58	1.25	0.15	0.51	0.98
N=5, mean	0.14	0.50	1.29	0.13	0.39	1.44	0.06	0.31	1.03
N=5, std	0.05	0.19	0.51	0.06	0.18	0.78	0.03	0.29	0.39
N=8, mean	0.10	0.31	0.67	0.08	0.25	0.87	0.03	0.13	0.66
N=8, std	0.03	0.07	0.13	0.04	0.09	0.52	0.01	0.12	0.27

V. CONCLUSION AND FUTURE WORK

In this paper, we investigated the effects of directional antenna on the performance of both broadcast and unicast traffic through extensive simulation experiments. We show that it is very important to experiment with different configurations, even when relatively regular network topologies are used and both mean value and variance of the performance metrics should be considered. We also show that the collision avoidance scheme that maximizes spatial reuse by making transmissions all directional achieves the best performance among the three schemes investigated. Its more aggressive channel access scheme helps to achieve higher throughput and reduced average delay for both unicast and broadcast traffic.

Though the proposed enhancements to broadcasting in the literature have not been incorporated in our investigations, it can be reasoned that the use of directional antennas as another dimension in the solution space to enhance broadcasting in multi-hop ad hoc networks, is orthogonal to the proposed enhancements reported in the literature [4]–[6], [9], [10] and using them in combination with all-directional collision avoidance may help to improve the performance even further. This topic will be explored in our future work.

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