Multiple Directional Antennas in Suburban Ad-Hoc Networks

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Abstract

A suburban ad-hoc network (SAHN) interconnects a co-operative group at broadband speed using wireless links. The nodes are stationary. A SAHN involves low installation and service costs for SAHN specific traffic. Some current routing solutions for mobile ad-hoc networks may be used in the SAHN after certain optimizations. Efficiency can be improved by using smart directional antennas. Neighboring nodes falling outside the transmission region of a directional antenna are less vulnerable to co-channel interference. Additionally, increased transmission range can be achieved by reducing noise, interference and multi-path fading. In this paper, we emphasize the interference reduction capability of directional antennas and investigate the routing performances using three antenna schemes; multiple fixed directional, multiple omnidirectional and single omnidirectional antennas. We present an estimate of the achievable performance in a SAHN through extensive simulations. We also discuss the impact of using omnidirectional antennas on routing performance where different networks, using overlapping frequency channels, exist within each other's transmission ranges.

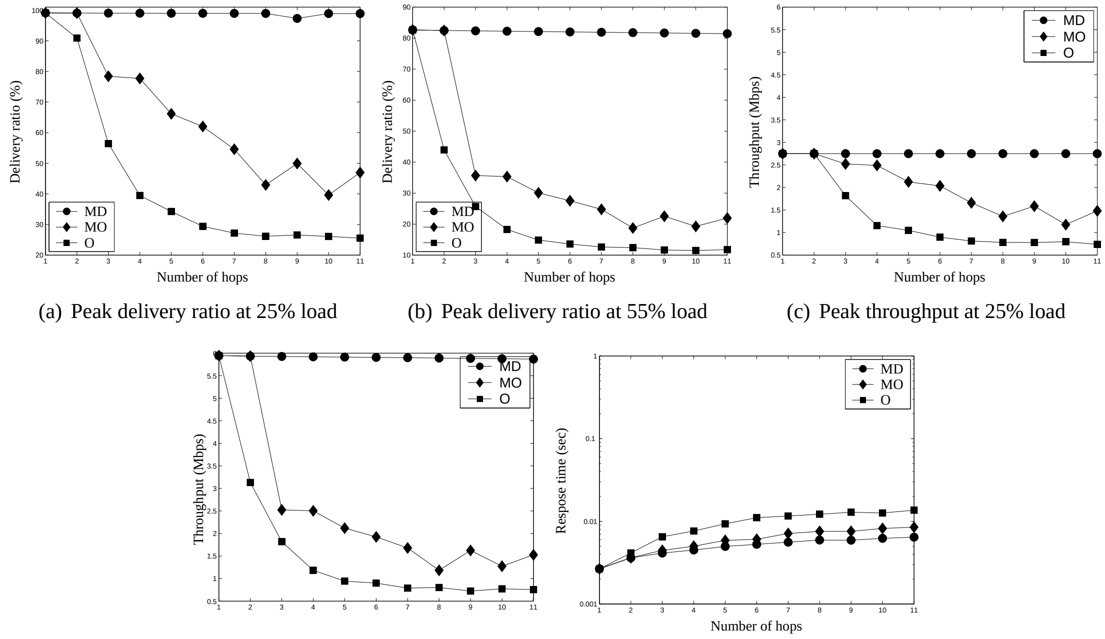
1. Introduction

Like Nokia RoofTop and RoofNet of MIT, the 'Suburban Ad-Hoc Network' [5] (SAHN) has been proposed as an alternative to expensive broadband solutions to provide networking facilities within a group of cooperative users. The aim is to alleviate existing expensive, oversubscribed, area limited and low security solutions and to extend the Internet infrastructure to areas of inadequate wired facilities. The inherent symmetric throughput in both upstream and downstream channels at reasonably high rates allows the facility to provide traditional costly broadband throughput at low cost. Unlike Nokia RoofTop, an efficient ad-hoc routing protocol at each node makes the network independent of any centralized gateway. The security scheme at the network layer, absent in both Nokia RoofTop and MIT's RoofNet, is particularly appealing to security conscious business users. Moreover, provision for smart directional antennas makes routing in the SAHN more efficient than others. In this paper, we focus our discussions on routing performance using multiple fixed directional (MD) antennas. Only interference related effects on the routing protocol are presented. The results found are compared with the performance of networks using multiple (MO) and single omnidirectional (O) antennas. Each of the antenna elements in multiple antenna schemes are allocated distinct non-overlapping frequency channels. The term "multiple omnidirectional" antenna is used here to represent an omnidirectional antenna scheme that can operate simultaneously in multiple non-overlapping frequency channels.

An omnidirectional antenna scheme may provide more connecting links than a directional antenna scheme if nodes in a network are located within each other's transmission range. However, closely located nodes are very likely to face co-channel interference during simultaneous transmission. The number of collisions and packet drops increases and hence the network performance degrades. A directional antenna scheme may provide fewer links in a network. Fewer links may seem to cause poor routing performance, but we believe that using directional antenna schemes can outperform omnidirectional antenna schemes. Our simulation results support this.

Omnidirectional antennas radiate energy in all directions. For a given transmission power, the range using omnidirectional antennas is lower than when using directional antennas. Ad-hoc routing algorithms with omnidirectional antennas and fixed transmission power have an upper bound to the number of intermediate hops between a pair of source and destination. Directional antennas may resolve this problem using the same amount of transmission energy. They can focus beams at narrow angles. This can decrease channel interference of other nodes falling beyond the transmission angle, increase the transmission range and contribute to bridging voids in a network. Gain of a directional antenna over its omnidirectional counterpart depends on how narrow the primary beam (lobe) is. Interference by secondary lobes can reduce the effective transmission range of the primary lobe. In this paper, we ignore the effect of secondary lobes.

We have discussed some related work in Section 2. Then



(a) Peak delivery ratio at 25% load
(b) Peak delivery ratio at 55% load
(c) Peak throughput at 25% load
(d) Peak throughput at 55% load
(e) Minimum response time

Figure 1. Possible peak performance.

we have investigated the effects of various antenna schemes on a routing protocol for the SAHN in Section 3. In this section we have also evaluated peak performance and average performance of DSR with various traffic patterns. We have briefly discussed the effects of omnidirectional antennas on routing performance while two different networks operate close to each other's transmission range.

2. Related Work

Impacts of using directional antennas have been studied extensively in the context of cellular networks. Most of the past research regarding directional antennas in ad-hoc environments have been confined to the MAC layer. Work on routing protocols using directional antennas is still inadequate [2][1][7].

Nasipuri et al[1] have used directional antenna elements intelligently in order to minimize routing overhead. The authors have used equal transmission range for directional and omnidirectional antennas. As a result, the potential of using directional beam forming was not utilized to discover shorter routes. [1] uses a conservative MAC layer.

Ramanathan [7] discusses the possibilities of taking advantage of higher transmission range of beam-forming antennas. He mainly emphasizes the MAC layer and does not focus on the routing layer.

Bandyopadhya et al[2] proposes a proactive routing algorithm over an ESPAR (Electronically Steerable Passive Array Radiator) antenna. The MAC protocol proposed in [2] is more complicated and requires several exchanges of control packets before actual data transmission.

Roy et al[6] addressed the issues, particularly in the network layer, of using directional antennas in ad-hoc networks. Their paper optimized a reactive routing protocol, DSR, to efficiently perform in ad-hoc networks using directional antennas. Furthermore, a simple MAC protocol, called DiMAC, was proposed to enhance the performance of the routing protocol.

Marvin [4] has proposed a combined routing and scheduling procedure to improve performance of STDMA (Spatial Time Division Multiple Access) in multi-hop ad-hoc networks (both rough and flat terrain) with smart antennas. He has also investigated the possible performance gain in CSMA with handshaking using simple Switch Beam antenna system as the smart antenna technology.

Unlike others, we want to get the maximum performance results achievable to consider as a benchmark for evaluating routing protocols optimized for the SAHN. We also want to investigate the effect of non-SAHN networks on a SAHN network if they operate close by. To our knowledge, none of the previous work has explored these areas.

3. Performance Evaluation

We use GloMoSim (version 2.02) for simulating various layers and wireless media. We have modified the radio layer to use multiple directional and omnidirectional antennas. While using directional antennas, the effect of secondary lobes on the primary lobe is ignored. We have used a two-ray path loss scheme to calculate propagation path loss. The two-ray model uses free space path loss for nearby nodes and plane earth path loss for distant nodes. We have used DSR as a routing protocol. We have divided our simulation work in three different sections; (a) find maximum achievable performance, (b) study the average network performance, and (c) investigate the impact on network performance in the presence of other networks operating nearby.

3.1. Maximum performance

At first, we would like to find the maximum achievable performance in terms of (a) throughput, (b) delivery ratio (total amount of data successfully received divided by total amount of data transmitted) and (c) response time. The first two metrics are essential for measuring the performance of realtime traffic and file transfers. The last metric is necessary for measuring the performance of interactive traffic. We have also investigated the effect of different packet sizes on network performance.

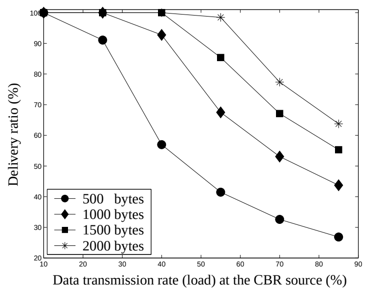
To measure the maximum performance possible with 802.11b (11Mbps) in the SAHN, we have chosen two adjacent nodes separated by 350 meters. Conventional TCP/IP is best suited for wired networks and may not perform well in multi-hop wireless networks [3]. To avoid additional delays for hand shaking and end-to-end acknowledgements in TCP, we have used UDP packets.

We have varied loads, keeping the source and destination fixed, at the source from 10% to 85% to get the critical point beyond which performance degrades or remains unchanged. A node operating at 25% load means that it is generating traffic at 2.75Mbps (maximum bit rate is 11Mbps). Since this is a single hop scenario where only one node is sending data to one of its nearby neighbors, the impact of directional and omnidirectional antenna was the same. So, the results presented in Figure 1 are valid for all three types of antennas we have mentioned in this paper.

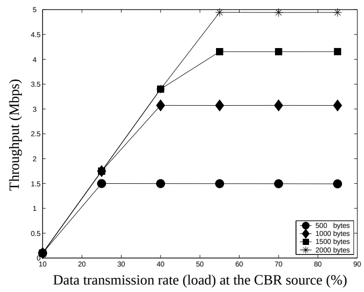
At around 55% load, the communicating link seems to saturate (Figure 2). Above 55% load, the minimum time required to serve each data frame becomes more than the time slot needed to sustain the data rate.

The size of each data packet can play an important role for determining the peak performance of the network. Figure 2 shows that smaller packets (e.g 500 bytes) can reduce the peak performance of the network by almost 50%. Since each data frame involves various delays (e.g. time for RTS, CTS, DIFS, SIFS etc), smaller packets increase the delay overhead per bit, hence reduce network efficiency.

To find the peak performance for multiple hops, we have varied the hop count between the source and destination pair. Once again, only one pair of source and destination was chosen to ensure that interference from other nodes, except the participating nodes in the routing process, does not influence the peak performance. Figure 1(a-b) and Figure 1(c-d) show



(a) Delivery ratio



(b) Throughput

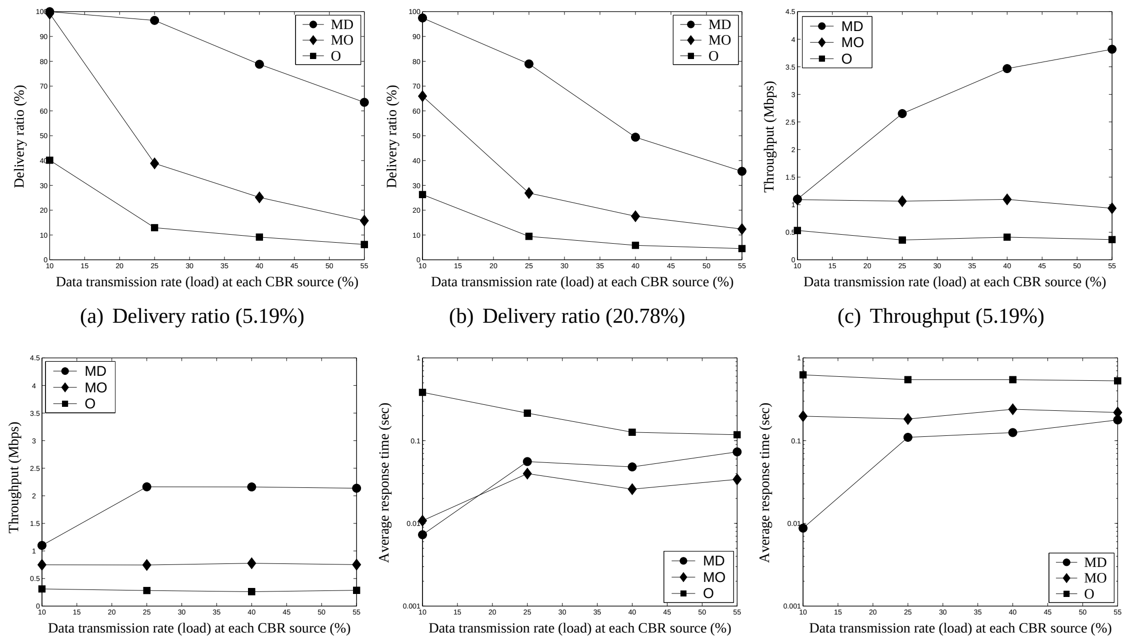
Figure 2. Effect of different packet sizes.

the delivery ratio in percentage and throughput in bps respectively. It was observed that with the increase of number of hops and loads, performance with single and multiple omnidirectional antennas reduced almost by 60% in most cases whereas the performance achieved with multiple directional antennas remained almost unchanged.

In order to resolve channel contention and reduce hidden and exposed terminal problems, 802.11 uses a distributed channel coordination mechanism known as DCF. Therefore, some of the nodes along a route have to wait while others are transmitting if omnidirectional antennas are used. As a result, data transmission via multiple hops, using omnidirectional antennas, suffers more back-off delays and collisions than single hop communication. Directional antennas can solve this problem with the sacrifice of a range of directions.

To measure minimum response time, we have sent small (50-200 bytes) UDP packets to a destination. Upon reception, the receiver sends a reply packet (100 bytes) to the sender. The response time is the total time required to generate a request and to get the reply. If the sender does not receive a response within a maximum period of time (3 seconds in this simulation), it re-sends that request once again. Retransmission is possible up to a limit. After that limit, the request is discarded and reported to the application layer to take a different action.

Figure 1(e) shows an estimate of minimum response times for different number of hops. With the increase of number of hops, distance travelled by a packet also increases. Hence more time is needed to get a reply for a request. Moreover, time required for resolving interference can make a response more delayed. The later problem is



(a) Delivery ratio (5.19%) (b) Delivery ratio (20.78%) (c) Throughput (5.19%)

(d) Throughput (20.78%) (e) Average response time (5.19%) (f) Average response time (20.78%)

Figure 3. Average performance at various traffic loads.

more common for omnidirectional antennas than directional ones. Our simulation result justifies our statement. Response time can be as small as 2.6 milliseconds for single hop communication. With the increase of number of hops, response time rises rapidly for single omnidirectional antennas. With multiple directional antennas, a response time of 6.4 millisecond is possible for the eleventh hop. At this distance, response times for a single and multiple omnidirectional antennas are 13.6 milliseconds and 8.4 milliseconds respectively. This may not be as pronounced using TDMA schemes.

3.2. Average performance

During previous analysis, we had a chain of nodes and only one pair of nodes were active at a time. This type of network is appropriate for getting peak performance results. The results found so far can be used as benchmarks for different types of networks with varying traffic. In this section we have taken a dense network to investigate attainable average performance. We wanted to find out when performances of a routing protocol using different antenna schemes start to converge.

A densely populated network can represent a SAHN in a city. 77 nodes were placed on a 3000x3000 square meters flat terrain where each node had at most 6 neighbors. Separation between neighboring nodes was fixed at 350 meters. All three antenna configurations had the same transmission range.

Allocation of channels to multiple omnidirectional antenna elements was done randomly. On an average, each antenna component had two neighbors. The number of links in the network remained same for both the single and the multiple omnidirectional antenna scheme. However, multiple directional antennas were allowed to communicate to at most 3 neighbors at 3 different frequency channels which effectively reduced the degree of connectivity per node. To get a graph of degree 3 (maximum), we constructed a minimum spanning tree and allocated channels. The number of links in the network came down to almost 38.97%. In this topology, each node had only one route to any other node. To make use of multiple paths, we have connected some neighboring node pairs having unallocated antennas. The number of links increased to 92.37% of the original.

For random traffic, we used CBR and interactive applications. The number of nodes for interactive traffic was kept fixed at 6. To vary traffic, the number of nodes for CBR terminals were increased in 5 steps (4, 8, 12, 16 and 20). For each configuration, loads at CBR sources were varied at 4 different levels (10%, 25%, 40% and 55%). Data packets used in this analysis were 1500 bytes each. Interactive applications were configured according to the previous section. Values enclosed in brackets in Figure 3 indicate the percentage of active CBR sources in the network.

We believe that at low load and for same number of hops, multiple omnidirectional and multiple directional antennas should perform similarly. Our simulation result justifies our belief. For example Figure 3(a), Figure 3(c) and Figure 3(e) show that multiple directional and multiple omnidirectional antennas perform almost similarly at the beginning.

As the loads at each CBR sources increases, their performance start to differ significantly up to a certain limit (i.e. for moderate traffic). As the number of nodes and the rate of traffic generation increase, fewer routes remain unsaturated to balance the aggregated network load. As a result, a little performance gain can be achieved with multiple directional antennas over multiple or single omnidirectional antennas (Figure 3(b), Figure 3(d), and Figure 3(f)).

With the increased demand for wireless networks, it is quite possible that more than one network will operate in the same geographical area. If all networks share the same channel, then a node may get a lot of unwanted packets from a different network. Nodes listening from all directions can not ignore transmissions from a nearby node operating at the same frequency channel. If the nearby node belongs to the same network, this may not be a problem as nodes in the same network are supposed to co-operate, e.g. routing others' packets. On the other hand, a node can decide not to allow packets coming from other nodes belonging to a different network. However, a node cannot stop nodes of a different network from transmitting. Instead, it can stop listening from that direction to avoid interference. This can be done in two ways; (a) operating in different frequency channel or (b) using directional antennas. In this section we present a simple scenario to understand what is the benefit of directional antennas over omnidirectional antennas when more than one networks exist within each other's transmission range.

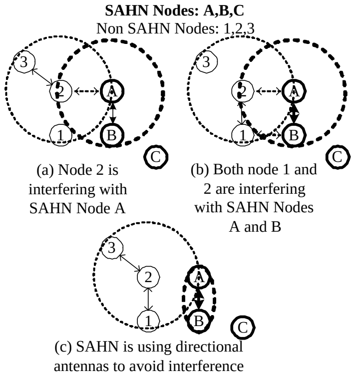


Figure 4. Interference problem while multiple networks exist together.

Figure 4 shows a simple setup where a non SAHN network (node 1, node 2 and node 3) are operating close to a SAHN (node A, node B and node C). We assume that in omnidirectional mode, both networks are using the same frequency channel. In this experiment (Figure 4(a)), Node 1 and node 2 send packets to node 2 and node 3 respectively at varying rates. At the same time node A sends packets to node B at a constant rate (4.3 Mbps). We assumed that in the multiple omnidirectional antenna scheme, SAHN used a frequency channel different from the neighboring network. Simulation result (Figure 5(a)) showed that directional and multiple omnidirectional antenna achieved similar performance (i.e. throughput was constant) despite of the increasing load at the nearby non SAHN node whereas omnidirectional antenna failed to do so due to interference.

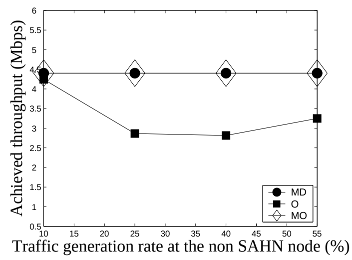


Figure 5. Effect on throughput.

4. Conclusion

During this study we have used multiple fixed directional antennas and assumed that there is at least one route from a source to its destination. If no route exists in configured directions antennas may need to be redirected. This may be difficult with multiple fixed directional antennas. Moreover, multiple fixed directional antennas may be expensive to buy and install. A smart directional antenna can be an alternative solution at low cost. We plan to optimize a routing protocol and the MAC layer to efficiently handle the real life problems with smart antennas in the context of SAHN.

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