Multiple Radio Channels and Directional Antennas in Suburban Ad Hoc Networks

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Abstract

The Suburban Ad Hoc Network (SAHN) is a cooperative ad hoc wireless mesh network. Nodes are owned and operated by end-users without reliance on central infrastructure. It provides symmetrical bandwidth allowing peer-to-peer services and distributed servers. We minimize the use of scarce unlicensed RF spectrum supported by Smart Antenna technology. RF interference in such networks and techniques and strategies to reduce it are examined. Traffic is spread across multiple frequency channels, and multiple directional beams to achieve improved spatial re-use. We focus on the control of Smart Antennas rather than their design. By dynamically adjusting our network topology using Smart Antennas and dynamically re-routing current communications we optimize the network for its current traffic needs.

1. Introduction

The Suburban Ad Hoc Network (SAHN) was devised by Kopp and Pose.[1] It provides symmetrical high bandwidth communication among a community of users who want to stream audio and video, run peer-to-peer applications, support distributed file servers, and connect to the Internet when required. Telecommunications companies do not provide such service at an affordable price. Off-the-shelf wireless technology such as IEEE 802.11 is used with a purpose built optimized protocol suite. SAHN protocols provide Quality-of-Service (QoS) routing [2][3] and security [4][5][6], and deal with antenna and channel characteristics[7][8][9] The topology includes multiple, possibly redundant links, for robustness, reminiscent of Pose's multiprocessor interconnection network [10].

Finite RF spectrum is used efficiently to ensure network scalability and robustness. Unrelated network and non-network RF emissions can cause interference, and nearby nodes in our own network can interfere with us, even if performing unrelated communications.

Typically wireless network nodes use omni-directional antennas with a single radio channel. When such a node uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as its Medium Access Control (MAC) protocol, nodes in the neighborhood of that node should stay silent in order to avoid interference. In a dense and congested network this approach degrades the network performance and leads to underutilization. Interference is a major limiting issue. The problem is worsened in multi-hop networks due to intra-flow interference introduced by adjacent nodes on the same path, and inter-flow interference generated by nodes from neighboring paths [11].

Some researchers have used multiple channels with multiple transceivers. Dynamic Channel Assignment (DCA) [12] has one dedicated channel for MAC level control messages and other channels for data. The sender includes a list of preferred channels in the RTS packet and on receiving the RTS the receiver selects a channel and includes it in the CTS message. Then, DATA and ACK packets are transferred on the agreed data channel. Each host has two transceivers. Thus a dedicated channel for MAC level control packets can be costly.

Hyacinth [13] is a multi-channel wireless mesh network (WMN) architecture that equips each node with multiple 802.11 network interface cards (NICs). The central design issues of this architecture are channel assignment and routing. It implements a fully distributed channel assignment algorithm which dynamically adapts to varying traffic loads and uses a spanning-tree based routing algorithm. Each gateway node that has access to the wired network is the root of a spanning tree, and each WMN node attempts to participate in one or more such spanning trees. This architecture is not applicable to ad hoc networks where there is no backbone infrastructure support.

Pirzada et al. [14] propose AODV-MR, a multi-radio extension of AODV for a wireless mesh network. When a route is required the Route Request (RREQ) is broadcast on all interfaces. Neighbor nodes which share at least one common channel with the sender, receive the packet. If the RREQ is not a duplicate, a reverse route pointing toward the source is created. The intermediate nodes, after updating their routing tables, broadcast the RREQ on all interfaces except the one on which the RREQ was initially received. This generates a lot of routing control traffic. AODV-MR maintains an interface number in the routing table.

This paper examines the problems of RF interference and other congestion effects in SAHN. In Section 2 we characterize the types of SAHN nodes and the classes of traffic. Section 3 gives two methods of using two omni-directional radio channels. In Section 4 we consider different antenna configurations and network topologies. A simulation model is described in Section 5. Section 6 provides simulation results and discussion for the various configurations and topologies. Then in Section 7 we argue the case for Smart Antennas. Section 8 concludes the paper.

2. Classes of SAHN nodes

SAHN nodes typically consist of a computing device attached to a SAHN interface comprising one or more wireless transceivers, each connected to a roof-mounted antenna forming a wireless link to one or more neighboring nodes. End users own, operate, manage and control their SAHN node. SAHN nodes form a cooperative network. SAHN communication protocols provide self-configuring neighbor discovery and quality-of-service routing based on communication requirements. They also handle node authentication, admission control, security, flow control and load balancing, and account for traffic being relayed to and from Internet gateways. Different classes of traffic are handled appropriately to their requirements.

3. Sharing two omni-directional channels

We use two non-overlapping RF channels. Two channels can be used with a single transceiver or two transceivers per node.

3.1. Single transceiver

It has been suggested to use multiple radio channels with a single transceiver, mainly to use off-the-shelf IEEE 802.11 devices. IEEE 802.11b physical layer has 14 channels, [15] whereas IEEE 802.11a provides 12 channels [16]. With a suitable channel switching algorithm, multiple communications are possible in the same neighborhood using different channels.

Deng et al. [17] propose a new MAC protocol – Dual Busy Tone Multiple Access (DBTMA). It splits a single common channel into two sub-channels: a data channel and a control channel. MAC layer control packets (RTS/CTS) and two busy tones are transmitted on the control channel to avoid hidden terminals, while data is transmitted on the data channel. This scheme improves the hidden terminal problem but it's not using both channels for sending data.

So et al. [18] present a MAC protocol that utilizes multiple channels with a single transceiver. In this scheme, clock synchronization is required among all the nodes. At the start of each interval, all nodes are required to listen to a common channel in order to exchange traffic indication message. During this interval nodes do not exchange data packets, which is an overhead. Also, with a single transceiver a node can have only one transmission at a time

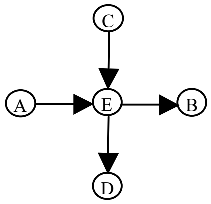


Figure 1. A simple scenario of a common intermediate node.

If a single transceiver is used in a multi-channel ad hoc network, the network capacity is not fully utilized and there are some other issues such as:

1) Nodes need to switch between different frequency channels and though small, there is some overhead associated with it (80 μs) [19].
2) Both sending and receiving stations must operate on the same channel. Thus, there needs to be some coordination between them. In a multi-hop wireless ad hoc network this makes the job of channel allocation harder.
3) With a single transceiver, when a node is operating on a particular channel, it is totally deaf to other frequency channels.
4) RREQ packets are broadcast in all radio channels resulting in a high volume of control traffic. As nodes are switching their radio channels during the route discovery process, deafness problems may occur.
5) In many cases, it is not possible to find node-disjoint routes. In multi-hop networks many flows may share some common nodes. Consider Figure 1 where two communications A->B and C->D are taking place at the same time. Both of them are sharing a common intermediate node E. To make these two communications possible both of the flows need to operate on the same frequency channel and having multiple channels is of no use. This may be a common case as numbers of communications increases in the network.

The above shortcoming could be avoided using separate transceivers for each radio channel.

3.2. Proposed design with two transceivers

We use two different radio channels, each with its own transceiver. This is not overly expensive. The network layer decides how to utilize both channels, leaving the MAC layer unchanged.

3.2.1. A dedicated control channel for routing control traffic. In preliminary studies of a dense network using a single radio channel and a high traffic volume, we found very low throughput. With time, the network becomes more congested and many nodes cannot transmit due to other interfering nodes. Eventually routing entries become stale. With only a single radio channel available many nodes cannot even transmit routing control packets when they need to rediscover new routes, even with a higher priority than data packets. This is due to other interfering nodes. So, after a time many routing entries become inactive and nodes cannot even transmit or receive control packets to find out active routes.

To alleviate these problems, we use a separate channel for routing control traffic. The network layer sees two types of traffic – 1) Routing Control traffic, like Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) packets, and 2) Data traffic. One radio channels is dedicated for routing control traffic and is called the Control Channel. The other channel is used for data traffic. We call this method "AODV-2Ch". See Figure 2.

Here, control packets face no interference from ongoing communications and do not need to wait for channel availability while currently transmitting data uses the channel. The result is more stable routing paths and consequently higher throughput.

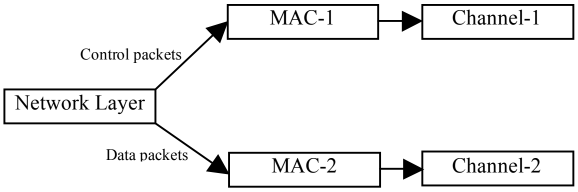


Figure 2. Separate radio channels for control and data traffic in "AODV-2Ch".

3.2.2. Interface queue based load balancing. The above is good for high traffic. As the routing paths are stable, the Control Channel will be largely idle after some time as there will be less routing control traffic. Thus, the Control Channel is not well utilized. In another method, which we name as "AODV-SCh", we aim to use the Control Channel when it is idle, for load balancing. We monitor the interface queues. The Control Channel has two queues, one for control packets and the other for data packets, whereas the Data Channel has a single data packet queue. When a data packet arrives, the network layer first checks the status of interface queues for the Control Channel and if empty the data packet is inserted in the Control Channel queue, and will be processed immediately. The algorithm for "AODV-SCh" to share both channels for data packets is as follows.

```
when a data packet arrives at the network layer for transmission
    check the status of MAC-1 queues
    if (MAC - 1 queues are empty)
        Send the data packet to MAC-1 queue
    else
        Send the data packet to MAC-2 queue
```

When the routing paths are established a node will use both channels for transmitting data traffic. This results in higher throughput and less delay compared to a single channel system, which is shown in Section 6.

The same method can be used if we have more than two radio channels per node. The idea is to dedicate a channel, the 'Control Channel', for routing control traffic, so it is not delayed by the data traffic. The 'Control Channel' can even be used to transfer data packets when the routing paths are well established as there will be little routing control traffic.

4. Directional antennas & RF environment

SAHN capacity can be increased using multiple non-overlapping RF channels in a kind of cellular network, but given the finite RF spectrum resource this still saturates with moderate sized networks.

Also a sparsely populated network using omni-directional antennas may have connectivity problems due to insufficient reception range.

The use of directional antennas can relieve both of these problems. Using higher gain directional antennas focusing the RF signal towards the destination node, longer range is possible. Using narrow directional beams one minimizes interference with nearby nodes with which communication is not desired. A directional network indeed scales much better and higher node densities are possible. There is also a small improvement in network security and robustness since the signal is only available along the narrow beam.

However the number of possible neighbors is reduced along with the beam width. Two nodes need to steer beams towards one another using the same frequency channel. Thus interconnection richness is reduced, and multiple directional beams are required for a fully connected network. Multiple beams and antennas and transceivers will be employed. Costs are reasonable with current technology.

We trade off the degree of interconnection for a reduction in RF interference and congestion and improved scalability. This leads to slightly longer average path lengths for communication, hence an increase in latency, but using multiple beams concurrently enables increased throughput.

5. Simulation model

We simulated a variety of topologies and antenna configurations. The environment comprised 150 nodes scattered randomly across a 4 km square area. We selected 20 source-destination pairs, and examined performance at various traffic loads, looking especially at very heavily loaded situations since that is where naïve networking approaches break down.

As a baseline we considered the approach with an omni-directional antenna (figure 3), with all nodes within range being effectively connected as neighbors.

We then considered a topology with three directional antennas pointing in different directions, and using three different frequency channels. This is depicted in Figure 4. The directions were chosen to give a fairly uniformly distributed set of connections across the geographic area to make the network fully connected. One can see clearly that the interconnection density is lower than in the omni-directional case. The thin lines between nodes indicate actual wireless connections. The 20 thicker arrows indicate the 20 concurrent communications being simulated.

What is clear is that the majority of links in the network are not being used at any time. To explore this further we created another topology also using three beams, but biased the antennas directions towards the actual communications that are taking place. The idea is to put the links in the network where they are most useful. Of course in so doing we may not have a fully connected network. Figure 5 shows this topology.

Simulations were conducted with the three topologies. We also tried different beam widths for directional antenna. Omni-directional is, in effect, a 360 degree beam width. We also tried 10, 20, 30 and 40 degree beam widths. As expected the narrower the beam, the lower the degree of network connectivity.

We used GloMoSim [20], a simulator designed using PARSEC [21]. Twenty simultaneous UDP traffic communications span randomly selected source-destination pairs. Exponential distributions are used. Several mean packet interarrival times are tested, as are two sets of beam directions and beamwidths (Table 1).

6. Simulation Results

6.1. Omni-directional antenna (two channels)

In the table and graphs, “AODV-1Ch” represents the basic AODV routing algorithm with a single channel, and “AODV-2Ch” and “AODV-SCh” indicate our first and second methods of using two radio channels respectively.

In Table 2, we represent the receiving time of the last packet in our simulation for each of the twenty communications when the data packet size is 512B and the average packet interarrival time is 25ms. For AODV-2Ch all communications are going throughout the whole simulation period (recall that our simulation time is 120 seconds).

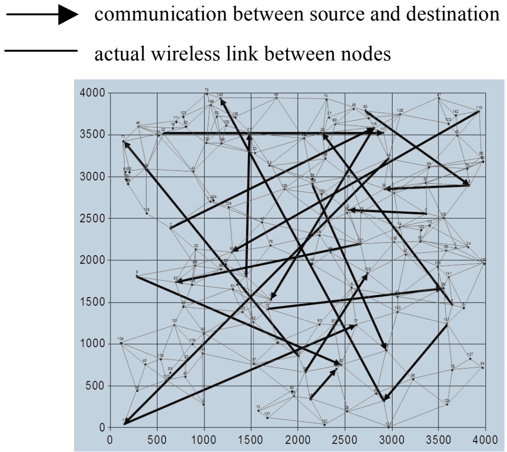


Figure 3. Network topology-1 (omni-directional)

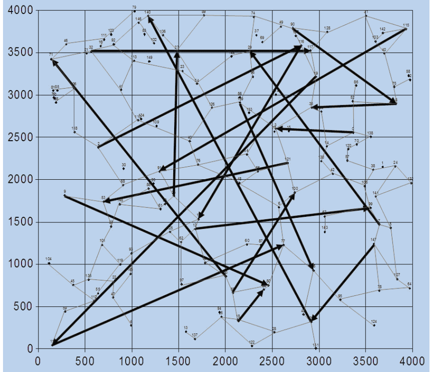


Figure 4. Network topology-2 (3 x 10° beams) uniformly distributed fully connected network

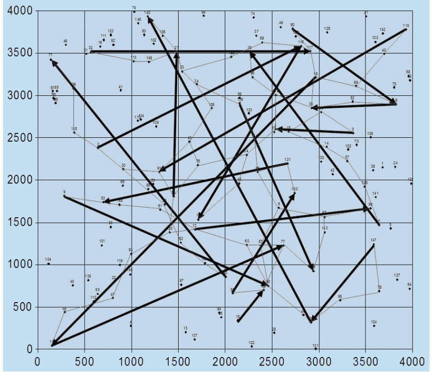


Figure 5. Network topology-3 (3 x 10° beams) connections biased towards communicating nodes

Table 1. Simulation parameters

Terrain Size	4000m X 4000m
Number of node	150
Node placement	Random
Simulation time	120 seconds
Number of communications	20
Packet size	64B,128B, 512B, 1024B
Avg. packet interarrival time	25ms - 225ms
Traffic type	UDP
Interface Queue size	100 packets
Transmission rate	11 Mbps
Propagation-Pathloss model	FREE-SPACE
MAC protocol	802.11b
Routing protocol	Modified AODV
Beam direction	Two different sets of directions
Beamwidth	360 (omni), 40,30,20,10 degree

Table 2. Receiving time of last packet

Source -> Destination	Receiving Time of the Last Packet (seconds)		
	AODV-1Ch	AODV-2Ch	AODV-sCh
0 -> 3	92.1593	119.9673	114.8934
90 -> 8	117.8132	119.3876	118.7902
19 -> 11	-	23.1729	2.0201
116 -> 17	-	119.977	35.6913
25 -> 27	6.2247	119.719	6.0435
7 -> 29	27.925	114.8119	119.7162
8 -> 35	57.5565	119.9687	114.1104
139 -> 36	3.3889	113.4799	52.7444
121 -> 53	21.7854	119.3306	64.7613
63 -> 71	15.8766	95.3989	81.816
11 -> 77	64.9655	118.0568	107.6411
9 -> 80	62.1140	110.67	69.6079
18 -> 84	119.3808	119.9462	119.9913
115 -> 91	23.8172	118.5845	115.6725
12 -> 99	13.8691	119.8429	94.0522
50 -> 100	15.5277	119.7276	111.3186
2 -> 116	59.0013	118.8496	71.8321
32 -> 117	43.8854	119.9816	97.8192
147 -> 129	59.1106	118.7463	116.4266
129 -> 140	28.7307	117.4207	57.3136

This is also true for most of the communications in AODV-SCh. But, in case of AODV-1Ch the scenario is totally opposite. Only a few communications are running throughout the whole simulation and even for two of the communications (19 -> 11 and 116 -> 17) no packets are received. This is due to the interference problem. As the network is dense and the traffic volume is high, many nodes cannot communicate due to other interfering nodes. Eventually, the routing table entries become stale. Then the nodes try to discover new routes but cannot find new routes due to other interfering communications. But, when we dedicate a separate channel for routing control packets, this problem is not present anymore.

In Figure 6, we represent the average end-to-end delay over all communications as the network load decreases. The data packet sizes we tested are 128B, 512B and 1024B depicted in Figure 6(a), (b) and (c). When the network is lightly loaded, all three protocols perform similarly.

As network load is increased, “AODV-SCh” performs significantly better than the other two and “AODV-2Ch” performs better than “AODV-1Ch”. “AODV-2Ch” uses a separate channel only for data packets and so, data packets do not need to wait for control packets at the interface queue. Control packets have higher priority than data packets. Thus, in the single channel system data packets will always wait for the control packets to go through and also for the channel availability due to other interfering nodes. In “AODV-SCh” when the routing paths are established both the channels are used for sending data packets and so packets are incurring less delay compared to the other two protocols.

Figure 7 shows the aggregate throughput of all three protocols as the network load decreases. For a lightly loaded network the throughput for all the protocols is almost the same. But as the network load increases the difference becomes significant.

With high load, the throughput of AODV-1Ch is very low. Nodes cannot transmit due to other communications in the neighborhood, and the routing entries become stale. The effective communication time for all nodes is much less in this case. But, when we have separate channels for control and data packets in “AODV-2Ch”, the throughput is increased by a factor of 3 to 7. In this case, as routing paths are always stable more data packets can be sent. Even if any routing entry becomes stale, the control channel can be used to find another route without interfering with other ongoing data communications. With high load “AODV-SCh” has less throughput than “AODV-2Ch”, though both channels are used for sending data.

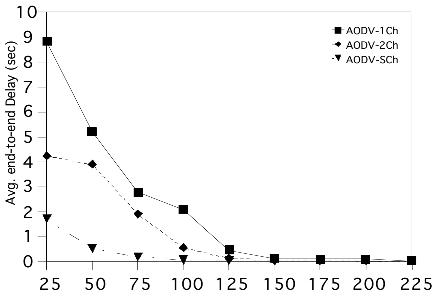
In “AODV-SCh” we use the control channel for data packets when it is idle. As the control channel is idle it will start handling the data packet immediately. In the mean time there could be some control packets arriving at the interface queue of the control channel. But these control packets cannot be sent unless the data packet has been transmitted successfully. If the data packet size is large, control packets need to wait more. That’s why the difference in term of throughput between “AODV-2Ch” and “AODV-SCh” increases as data packet size is increased. Figure 7(a), (b) and (c).

It is clear that both “AODV-2Ch” and “AODV-SCh” provide great improvement in end-to-end delay and throughput compared to “AODV-1Ch”.

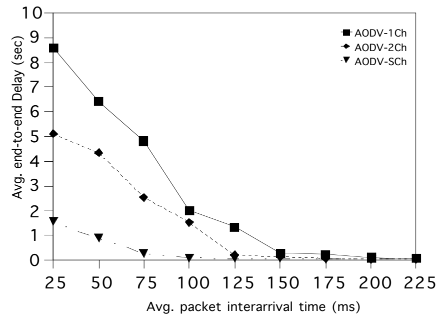
“AODV-SCh” performs better in term of average end-to-end delay, but “AODV-2Ch” performs better in throughput.

6.2. Multiple directional antennas

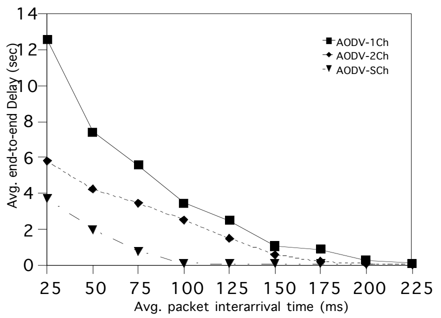
We tested the topologies (Figures 3, 4 & 5) for data packet size 512B. In Figure 3 we use three omni-



(a) Packet size: 128B

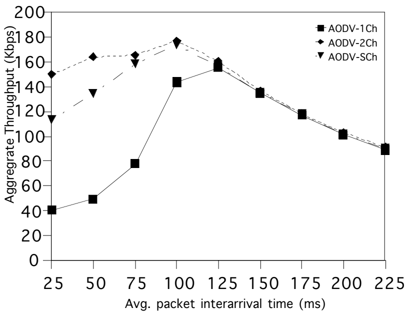


(b) Packet size: 512B

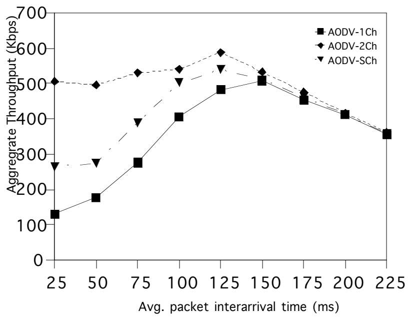


(c) Packet size: 1024B

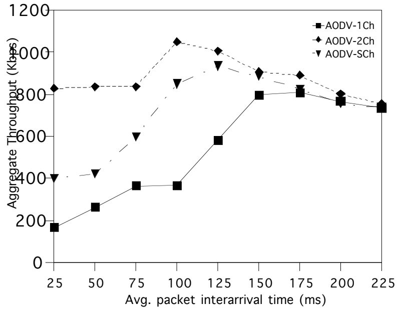
Figure 6. Average end-to-end delay vs. average packet interarrival time.



(a) Packet size: 128B



(b) Packet size: 512B



(c) Packet size: 1024B

Figure 7. Aggregate throughput vs. average packet interarrival time.

directional antennas with their own transceivers and three different radio frequencies. Nodes within the transmission range are neighbors of that node and cannot transmit using the same radio frequency.

The topologies of Figures 4 and 5 were formed using directional antennas. Each node has three antennas and can form three directional beams of fixed beamwidth using different radio frequencies. In the plots of Figures 8, 9, 10 and 11, the curves labeled as "3Ch-360d" represent topology-1, where each node has three omni-directional antennas. The curves labeled as "3Ch-40d", "3Ch-30d", "3Ch-20d" and "3Ch-10d", all indicate the use of three directional beams with beamwidths of 40, 30, 20 and 10 degrees respectively.

In Figures 8 and 9, we represent the aggregate throughput over all communications as the network load decreases. The uniformly connected topology-2 (Figure 8) and the biased topology-3 (Figure 9) were simulated. With a lightly loaded network the performance is similar regardless of beamwidth. As network load is increased, networks with directional beams perform significantly better than their omni-directional counterparts, mainly due to less interference. That means multiple communications are possible in the same neighborhood, but this depends on the beamwidth. With decreased beamwidth, throughput increased due to less interference, hence more simultaneous communications are possible.

Figures 10 and 11 show average end-to-end delay of the topologies with different beamwidths as the network load decreases for 512 byte data packets. As the network load increases the differences become significant. With high load, the delay of the omni-directional case *3Ch-360d* is relatively high. Nodes cannot transmit due to other communications in the neighborhood and routing entries become stale. The effective communication time is much worse and data packets need to wait in the interface queue. The average end-to-end delay is reduced significantly when the beams are directional. As we decrease the beamwidth, delay is reduced. These results support the case for directional beams, with less interference and multiple communications possible in the region.

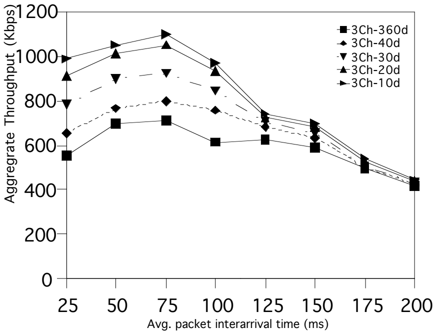


Figure 8. Throughput for topology-1 (omni-directional) and topology-2 (unbiased directional).

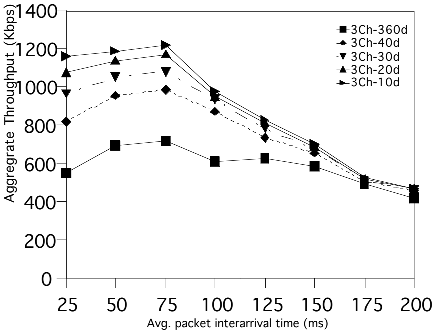


Figure 9. Throughput for topology-1 (omni-directional) and topology-3 (biased directional).

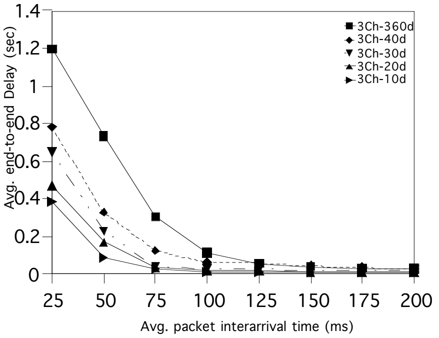


Figure 10. Delays for topology-1 (omni-directional) and topology-2 (unbiased directional).

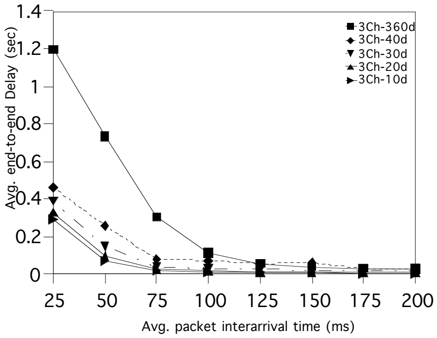


Figure 11. Delays for topology-1 (omni-directional) and topology-3 (biased directional).

Our biased topology performs better in terms of end-to-end delay than the unbiased topology. This indicates that the choice of antenna directions is important, but it this is highly dependent on the communication paths currently in use.

Multiple directional beams with different frequency channels provide significant improvements in aggregate throughput and average end-to-end delay compared to omni-directional beams with different frequency channels. Next we examine dynamically steered beams and a dynamic network topology.

7. The case for Smart Antennas

Biasing the directional beams towards nodes that can currently use the wireless links improves performance. The network is initialized as a connected topology like Topology-2 of Figure 4. All communications are possible, but some may not meet user QoS requirements. We change the topology by changing the directions of the beams to improve performance. Topology-3 in Figure 5 is one such topology. For other communication sets Topology-3 may not perform well. Some communications may not be possible. For each communication set there are suitable topologies, created dynamically.

How to achieve this? One could use antenna rotators with directional antennas. This is expensive and slow. Advances in mass-produced high-speed electronics make electronically steered phased array antennas affordable. This proven military technology until recently was prohibitively expensive, unsuitable for domestic use. We use the term Smart Antenna for devices with electronic beam forming and steering.

It is OK to allow beam directions to be changed dynamically, but how can one negotiate such direction changes, in effect network topology changes? Unless a nearby node has an antenna pointing towards you, you cannot ask it to establish a link to you. If the network lost its fully connected state, could it ever be restored?

If one maintains full connectivity there must be paths available to negotiate topology changes, but it is advantageous to allow nodes to become temporarily disconnected if there is no current need for those links. A separate control network can be used to configure the directional links and establish and maintain the directional network topology. This control network need not be high performance. Separate omni-directional antennas are used for a fully connected common control and signaling network using a separate frequency channel.

This control network is like topology-1, but its performance will be adequate, with spare capacity for limited data communication where necessary.

8. Conclusion

Using a separate control channel throughput increased up to 7 times for various packet sizes. End-to-end delay is also reduced. The approach can be used with multiple radio channels. However omni-directional beams lead to significant interference.

The use of directional beams and Smart Antennas in mitigates the problems of RF interference in SAHNS. Changing beam directions and beamwidths can reduce interference We used three directional beams and choose a subset of neighboring nodes to form the topology. Our dynamically changing topology depends on current communications. Smart Antennas provide the technology to change beam direction and beamwidth. An 'Adaptive Topology Control' algorithm is being developed. It constructs a topology for current communications by setting antenna parameters. This non-trivial algorithm also includes other factors like load balancing and QoS routing in this unusual dynamic environment.

9. References

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