A Cross-layer Approach for Using Multiple Radio Channels with Directional Beams in a Suburban Ad Hoc Network

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Abstract—**The capacity of wireless ad hoc networks can be increased by using multiple radio channels. But due to interference the capacity is still not fully utilized. This is caused by the limited number of available radio channels. The interference problem can be reduced using directional beams instead of omni-directional beams. This paper presents a novel cross-layer approach to use multiple radio channels with directional antennas. We are using three different radio channels. Each node has three fixed directional beams having fixed beamwidth and with different radio frequency. Two nodes can communicate when both the sending and receiving beams are pointing towards each other using the same frequency channel. In this study the directions of beams cannot be changed dynamically. A modified version of Ad hoc On-demand Distance Vector (AODV) routing protocol has been used. Simulation results show that our approach outperforms other methods using three different radio channels with omni-directional antennas.**

Index Terms—**directional antenna, medium access control, network layer, radio channel, suburban ad hoc network**

I. INTRODUCTION

Wireless ad hoc networks are self-configuring distributed systems. Our Suburban Ad-Hoc Network (SAHN) [1]–[3] has no centralized infrastructure support. An ad hoc network can be envisioned as a collection of routers - which could be mobile. Due to their low cost and self-configuring, self-healing and rapid deployment capabilities wireless ad hoc networks are used in many ways [4]. They may be used to form community networks, to build up an emergency response networks, for a military network in the battlefield, for distributed file backup, video surveillance and last-mile broadband internet access, etc.

When nodes in a wireless ad hoc network use omni-directional antennas, they radiate energy in all directions while transmitting. In such case if two nodes which are within the transmission range of each other transmit at the same time, there will be a collision. To avoid this problem, ad hoc networks can use contention-based protocols (e.g. IEEE 802.11) at the Medium Access Control (MAC) level. These protocols force neighboring nodes of a transmitting node to keep silent in order to avoid collision. In a highly dense and congested network this degrades the network performance, as fewer nodes can transmit at the same time, and the neighboring nodes need to wait for their chance of transmission. Interference is a major limiting issue in a dense and congested wireless ad hoc network with omni-directional antennas. Due to this the network capacity is not fully utilized. This 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 [5]. Note we are not considering co-site interference from antennas at the same site explicitly in this study, but are considering this matter and propagation in a complex urban environment as part of our SAHN project.

To reduce the interference problem and therefore to increase the capacity of wireless ad hoc networks we use three different radio channels with directional antennas. Current IEEE 802.11 physical (PHY) standards divide the available frequency into several orthogonal channels which can be used simultaneously in a neighborhood. Therefore capacity can be increased by using multiple channels. We are using three separate non-overlapping channels of IEEE 802.11b. But the interference problem is still present if the radio signals are broadcast in all directions. To lessen this problem we use directional antennas. Directional antennas can reduce interference by directing beams towards a desired destination and away from other nodes that may cause interference. By using directional antennas, a node also receives signals only from a certain desired direction, thereby increasing the signal to interference and noise ratio (SINR) [6]. But both the sending and receiving nodes need to beamform toward each other and use the same frequency channel while communicating.

In our design, each network node has three directional antennas, each with its own transceiver. Thus each node can concurrently produce three directional beams where each beam may have a different radio frequency. Also there may be three transmissions and receptions by a node at the same time

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As there is no omni-directional transfer of information the routing protocol needs to be changed.

DSR [7] and AODV [8] are two well known and widely used ad hoc routing protocols. These protocols have been studied extensively in a single radio channel network. We are using a modified version of AODV routing protocol in our design.

The rest of the paper is organized as follows: Section II reviews related work. We describe our proposed design using multiple radio channels with directional beams in Section III. Section IV presents our simulation model. Simulation results are presented and analyzed in Section V. Section VI concludes the paper.

II. RELATED WORK

Many researchers have worked with directional antenna systems and multiple frequency channels. Deng et al. [9] propose a new Medium Access Control (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.

Dynamic Channel Assignment (DCA) [10] 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 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. The dedicated channel for MAC level control packets can be costly.

So et al. [11] 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.

Hyacinth [12] is a multi-channel wireless mesh network (WMN) architecture that equips each mesh network 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 wired network or backbone infrastructure support.

Pirzada et al. [4] 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. It generates a lot of routing control traffic. AODV-MR maintains an interface number in the routing table.

Bandyopadhyay et al. [13] presents a MAC protocol for directional antennas that uses additional message to inform neighborhood nodes about ongoing communication. This increases the MAC overhead.

Takai et al. [14] and Choudhury et al. [6] propose Directional Virtual Carrier Sensing (DVCS) and DNAV mechanisms for their directional MAC protocol which require several changes to the MAC protocol.

III. MULTIPLE RADIO CHANNELS WITH DIRECTIONAL BEAMS

Many researchers in the wireless network community are using multiple radio channels with a single transceiver to use off-the-shelf IEEE 802.11 devices. IEEE 802.11b physical layer has 14 channels, 5 MHz apart in frequency [15] whereas IEEE 802.11a provides 12 channels [16]. If a suitable channel switching and allocation algorithm is available, multiple communications are possible in the same neighborhood using different radio channels. However, still the network capacity is not fully utilized and nodes need to switch between different frequency channels with some small overhead (80 μs) [17]. Also both sending and receiving stations need to have some coordination as both of them must operate on the same frequency channel at the same time. In wireless ad hoc networks communications may be multi-hop, and with a single transceiver the channel allocation becomes more complex.

We use three different non-overlapping channels of IEEE 802.11b. Each channel has its own transceiver and so can operate concurrently. We also tried one radio channel and two radio channels with omni-directional antennas. When there is more than one radio channel we allocate a dedicated channel for routing control traffic. This channel is called the Control Channel. We tried different approaches to allocate channels to data packets, depending on the interface queue size or MAC layer status. But the throughput didn't scale up that much. The main reason is interference.

To reduce the interference we use directional antennas. Directional antennas can beamform toward a particular direction with a fixed beamwidth. Directional antennas can substantially improve the spatial reuse of the system. Thus, multiple communications are possible in the same neighborhood depending on the beamwidth and the direction of beam, which in turn improves the overall network capacity. In this study each node has three antennas, each with its own transceiver. Each antenna can operate in a different frequency channel and they are capable of producing directional beams toward a desired direction. Each node has three different beams, each operating with separate frequency channels as depicted in Fig. 1.

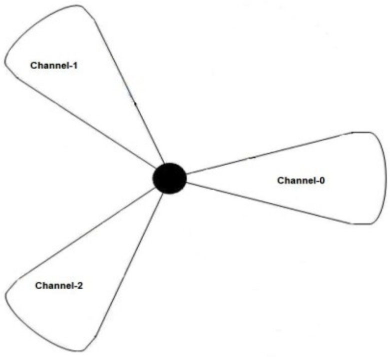


Fig. 1. Node with 3 directional beams with separate frequency channels.

In this case, two nodes will be able to communicate with each other when both of their beams operating on the same frequency channel point towards each other. So, each node can communicate with only a subset of its neighbors – its directional neighbors. The network designer creates the network topology by selecting the beam directions and neighbors of network nodes. The aim is to create a fully connected network while allowing reasonable traffic balance. As we have only three directional beams, each node may have different number of neighbors depending on the beamwidth and beam direction. We have chosen three neighbors for each node to form a connected topology. Fig. 2 shows one such topology.

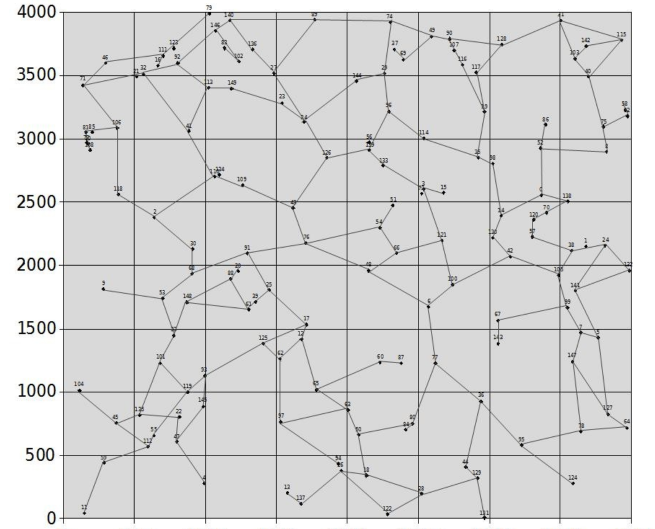


Fig. 2. A network topology using three directional antennas on each node

This topology has been formed using three directional beams per node, where the beamwidth of each beam is 30 degree. It is clear that each node has selected a subset of its omni-directional neighbors to form the topology. We call these neighbors the 'directional neighbors'. So each node has a option to select a subset of its potential directional neighbors as real directional neighbors. Selecting these directional neighbors will depend on the node distribution and communication pattern. We also want to make a fully connected topology. In this study we have tested two different fully connected topologies with different direction sets.

While not the subject of this paper, we are investigating suitable algorithms for dynamically selecting the network topology using the directional beams. We base our algorithm on the current traffic needs of the network, taking into account quality of service requirements for the communications. Of course changing the network topology then has consequent changes for routing. We are also considering different numbers of beams and more interestingly, the use of Smart Antenna technology to allow dynamic redirecting of directional beams. This work with a highly dynamic topology and routing is quite different from most other work in ad hoc networking and will be the subject of future papers.

Most routing protocols for ad hoc networks broadcast routing control packets like Route Request (RREQ) and Route Error (RERR) to all neighbors. Thus, none of the off-the-shelf routing protocols are suitable in our case. We have used a modified version of the AODV routing protocol which is described below.

The AODV routing protocol maintains the next hop for each destination in the routing table. In our case the routing table entry will also contain the interface number as in Fig. 3. The interface number will indicate the beam/channel number which to use to reach the next hop.

Dest. Addr.	Dest. Seq. no.	Hop count	Next hop	Interface no.	Lifetime

Fig. 3. Routing Table Entries for modified AODV Routing Protocol.

When a route discovery is needed the Route Request (RREQ) packets are transmitted in all three beams or in all three channels. The directional neighbors receive the RREQ packets and if it is not a duplicate then a reverse routing path towards the source is created. After updating their routing tables the intermediate nodes transmit the RREQ packet in all directional beams except the incoming one. If the RREQ is received by the destination node or any intermediate node with a fresher route to the destination, a Route Reply (RREP) is created and sent back to the source using the reverse path. All intermediate nodes after receiving the RREP creates a routing table entry for that particular destination, which includes the interface number or channel number.

Now, when a data packet arrives at the network layer, the routing protocol will look for the next hop and also the interface number to reach the next hop and will pass the data packet to the appropriate interface.

All MAC level control packets like Request to Send (RTS), Clear to Send (CTS) are also transmitted directionally, leaving the MAC layer protocol unchanged. In other words, there are no omni-directional transmissions in our proposed design, resulting in less interference and better spatial reuse.

IV. SIMULATION MODEL

A. Environmental Setup

We evaluated the performance of our two proposed designs via simulations. We used the GloMoSim [18] simulator which is designed using PARSEC [19]. We established a wireless network of 150 nodes placed randomly on a 16 sq. km area as shown in Figure 4. There are 20 simultaneous communications of UDP traffic between randomly selected source-destination pairs. Packets are generated using exponential distributions with some fixed mean. We tested different mean values for packet inter-arrival time and also tested two different sized data packets. We tested two sets of directions for the beams. The simulation parameters are listed in Table I.

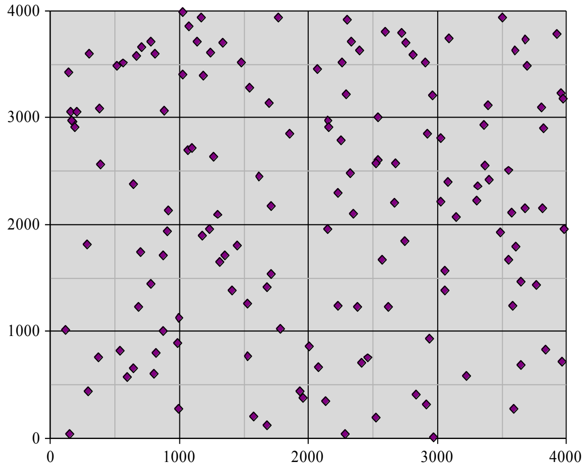


Fig. 4. 150 nodes in a 16 sq. km area.

TABLE I
SIMULATION PARAMETERS

Terrain Size	4000m X 4000m
Number of node	150
Node placement	Random
Simulation time	120 seconds
Number of communications	20
Packet size	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	802.11
Routing protocol	Modified AODV

B. Performance Metrics

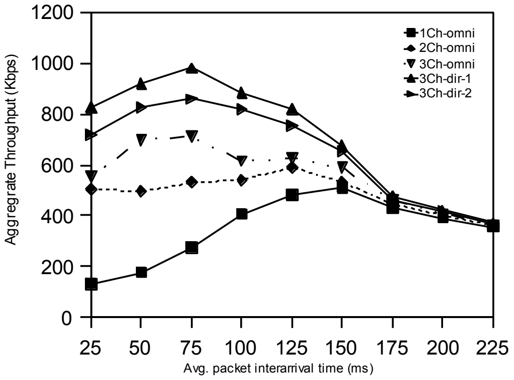
We used the following metrics to evaluate the performance of our protocols:

1) *Aggregate Throughput*: The number of data bits successfully received by the application layer of the destination node.

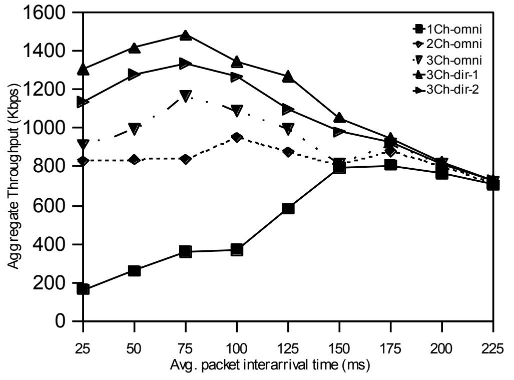
2) *Average end-to-end delay for data packets over all communications in the network:* This is the duration between the time when a data packet is generated by the sender, and the time the packet reaches the destination application layer. So it includes delays at the queues, different delays at the MAC layer and transmission delay. The average delay has been calculated only for the successfully received packets [8].

V. SIMULATION RESULTS

In the graphs, the curves labeled as “1Ch-omni” represent the basic AODV routing algorithm with a single channel, the curves labeled as “2Ch-omni” indicate AODV routing algorithm with two radio channels where one channel is dedicated for routing control traffic and the other for data traffic. The curves labeled as “3Ch-omni” represent AODV routing algorithm with three different omni-directional channels where one channel is used for routing control traffic and the other two channels are used for data traffic. The curves labeled as “3Ch-dir-1” and “3Ch-dir-2” represents our modified AODV routing protocol with three different directional channels but with two different direction sets.



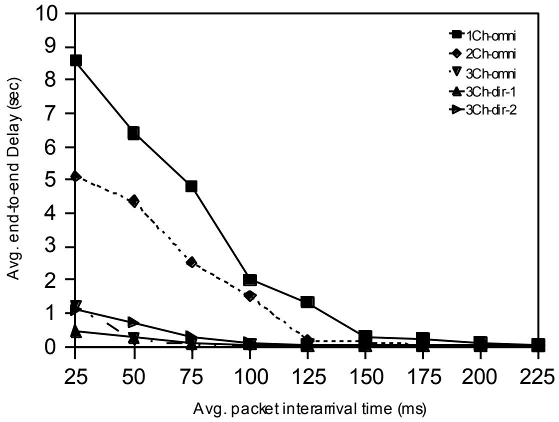
(a) Packet size: 512B



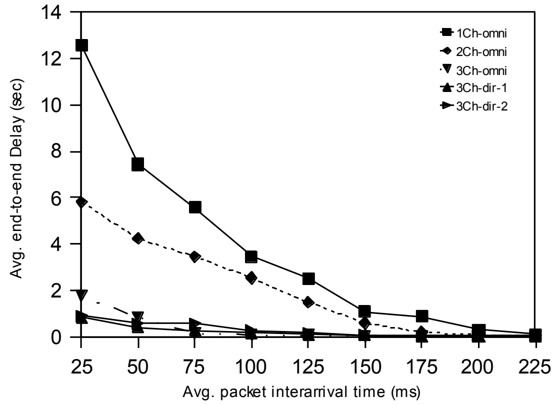
(b) Packet size: 1024B

Fig. 5. Aggregate throughput vs. average packet interarrival time

In Fig. 5, we represent the aggregate throughput over all communications as the network load decreases. The data packet sizes we tested are 512B and 1024B in Figure 5(a) and (b). When the network is lightly loaded, all the protocols perform similarly. As network load is increased, "3Ch-dir-1" and "3Ch-dir-2" perform significantly better than the other three which indicates that network with directional beams are performing better in term of throughput. The main reason is less interference. That means multiple communications are possible in the same neighborhood, but the degree to which it is possible depends entirely on the beam directions and beamwidth which is reflected in our results. In our simulation we didn't change the beamwidth, but we changed the beam directions. Both "3Ch-dir-1" and "3Ch-dir-2" use three directional beams with separate frequency channels but use two different sets of beam directions. And interestingly "3Ch-dir-1" outperforms "3Ch-dir-2" in term of aggregate throughput which is a result of selecting better directions for the beams. Thus, selecting the beam directions depending on the neighbor nodes and source-destination pairs will affect the aggregate throughput of the network.



(a) Packet size: 512B



(b) Packet size: 1024B

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

Fig. 6(a) and 6(b) shows the average end-to-end delay of all five protocols as the network load decreases for 512B and 1024B data packets. For a lightly loaded network the end-to-end delay for all the protocols is almost the same. But as the network load increases the difference becomes significant.

With high load, the delay of "1Ch-omni" is very high. 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 and data packets need to wait for long in the interface queue. But, when we have separate channels for control and data packets in "2Ch-omni", the average end-to-end delay is decreasing. The average end-to-end delay is reduced by a large factor when three radio channels are used. In this case each node has three interface queues and three different radio channels, so data packets need to wait less in the interface queue. Of the three protocols using three different radio channels "3Ch-dir-1" has the lowest delay. This result again indicates a better set of directions for the nodes and also the advantage of directional transmission. When using directional transmissions there is the potential for less interference if better directions are selected and multiple communications are possible in the same neighborhood. In this case data packets need to wait for less time in the interface queues. The delays for "3Ch-dir-1" and '3-Ch-dir-2" clearly indicate this.

In summary, multiple directional beams with different frequency channels provide greater improvement in aggregate throughput and average end-to-end delay compared to omni-directional beams with different frequency channels. Our results also indicate that for networks with directional beams selecting the direction of the beams is important.

VI. CONCLUSION

We have presented a cross-layer approach using three directional beams in each node where each beam operates using different frequency channels. There are no omni-directional transmissions and we used a modified version of the AODV routing protocol. Our results show that networks with directional beams perform better than their omni-directional counterparts.

In this research we have used simple directional antennas. That means each node has three fixed directional beams and the beam directions cannot be changed dynamically. We have tested two different sets of directions to form the fully connected directional topology and their performances differ. This indicates that the beam directions are very crucial, and performance depends on the traffic pattern and the topology of the network. Better performance can be achieved if the beam directions are adaptive, using a dynamically steerable 'Smart' antenna. Smart antenna systems can change their beamwidth and beam direction if proper control parameters are passed to them. We are investigating the control of smart antenna systems with multiple frequency channels.

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