A Framework for a QoS Based Adaptive Topology Control System for Wireless Ad Hoc Networks with Multibeam Smart Antennas

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Abstract

Wireless ad hoc networks are self-configurable distributed systems. One of the major problems in traditional wireless ad hoc networks is interference. The interference could be reduced using smart directional antennas. In this study, multibeam smart antennas have been used. When using this type of antenna, two nodes can communicate when both the sending and receiving beams are pointing towards each other. Also, a node can only communicate with a subset of nodes in its neighborhood depending on the number of beams and their beamwidth. Thus, the network topology needs to be dynamic in this case, and by controlling the topology network, performance can be increased. In this paper, we present a framework of a cross layer approach of topology control that interacts with the Routing layer and MAC layer and meets the required QoS of different data streams. The approach is fully distributed. When the network is initialized, the algorithm builds an initial connected topology and the routing algorithm uses this topology to find paths for the current communications. Then, depending on the network scenario, current communications and the required QoS, the topology control layer changes the topology to optimize the network performance. This study concerns Suburban Ad Hoc Networks (SAHN) where nodes tend to be fixed and are aware of their locations.

1. Introduction

A Suburban Ad Hoc Network (SAHN) is a wireless cooperative ad hoc network without any centralized infrastructure. It is a self-organized and self-configured distributed system. Communications in wireless ad hoc networks can be single-hop or multi-hop. Thus, each node of a wireless ad hoc network can be considered as a router which forward traffic for other nodes. For these features wireless ad hoc networks have advantages like, low cost, easy maintenance, robustness and scalability and they may be used to form community networks, in case of disaster management to build up emergency response networks, vehicular networks, for a military network in the battlefield, and to form sensor networks.

Our SAHN is typically organized as end-user owned nodes located in their homes, with roof-mounted antenna systems. Thus SAHN nodes are fixed and can know their own location. SAHNs can be extended to include mobile nodes, but in such cases we assume location-determining technology such as GPS is employed.

Traditional wireless ad hoc networks 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 with other transmissions. In a highly dense and congested network this approach degrades the network performance and leads to underutilization. Interference is a major limiting issue for such networks. 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 [1]. But, omni-directional antennas can manage the connectivity of the network well and can guarantee shortest paths.

Interference problems of wireless communications can be reduced using directional antennas. By using directional antennas, a node receives signals only from a certain desired directions, thereby increasing the signal to interference and noise ratio (SINR) [6]. But both the sending and receiving nodes need to steer one of their beams toward each other and use the same frequency channel while communicating. Directional antennas have greater transmission range for the same transmission power than their omni-directional counterpart. The transmission range is also related with beamwidth, it increases as the beamwidth decreases for the same transmission power.

In our network model each node will have one omni-directional antenna with its own transceiver and also a number of directional antennas. All of the directional beams may operate under the same radio frequency or different radio frequencies, but the omni-directional antenna always operates using a separate frequency channel with respect to the directional beams. We call this omni-directional channel the 'Control Channel', and the network topology generated by this omni-directional antenna the 'Control Network'. The control channel is used to transfer topology control messages. All data packets are sent by using the directional beams.

Multibeam smart antenna systems can generate multiple directional beams using adaptive beamforming techniques. This antenna system is not like a simple directional antenna. The number of beams, beamwidth and also the beam orientation can be changed during runtime. If there are *m* beams each with a beamwidth of $\theta_1, \theta_2, \theta_3 \ldots \theta_m$ like Figure 1, then the total beamwidth,

$$\alpha = \sum_{i=1}^{m} \theta i \qquad \text{where, } 0 < \alpha \leq 2\pi.$$

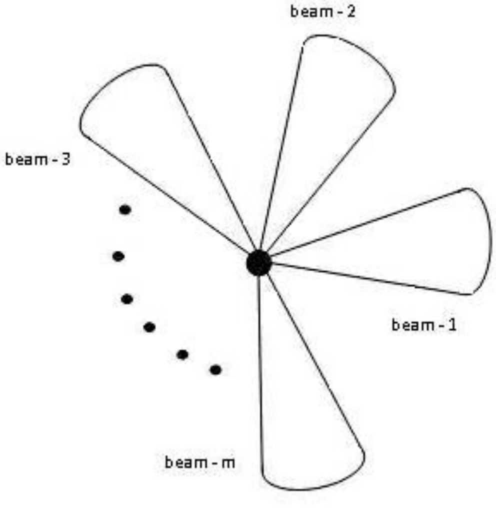

Figure 1. A multibeam smart antenna with *m* beams

In multibeam directional antenna systems we need to select a subset of potential neighbors as real neighbors, thus forming a network topology with lower connectivity. Now, the question is how do we choose this subset of neighbors to form the topology? In this paper, we are suggesting a framework for an Adaptive Topology Control System that will change the network topology dynamically depending on the current communications, the required QoS and link status.

The rest of the paper is organized as follows: Section 2 reviews QoS routing and MAC protocols. The topology formation using multibeam directional antennas is presented in Section 3. Section 4 presents the framework of the adaptive topology control process. The simulation results are presented and analyzed in Section 5. Section 6 concludes the paper.

2. QoS routing and MAC

QoS routing is the most important part of having a successful QoS architecture. Many routing protocols have been proposed to meet the QoS requirements of current communications [3,4,5,6,7]. QoS routing protocols need to have knowledge of link status, resource availability and QoS requirements of the current communications. Depending on this information the protocol computes the appropriate paths for a communication.

There are several MAC protocols for providing QoS support. Most of these MAC protocols rely on centralized control and are feasible only for infrastructure-based architectures. IEEE 802.11e [8,9] is a recent MAC protocol with QoS features that are an extension of the existing IEEE 802.11 standard. IEEE 802.11e supports eight priority traffic classes so that time-sensitive packets will take priority over other types of packets.

3. Topology formation

There could be many directional topologies given a number of nodes and number of directional beams. It also depends on the node distribution, distance between nodes and radio propagation environment. During the network initialization phase we will form a connected topology using directional beams. All of the topology formation messages will be transferred using the omni-directional control network. The initial topology formation process has the following phases –

1) Omni-neighbors discovery,
2) Potential Directional-neighbors discovery, and
3) Forming an initial connected topology by selecting a subset of potential directional neighbors.

Note that it is not strictly necessary to begin with a fully connected initial directional network topology since our adaptive topology control system will be changing the topology dynamically to satisfy the QoS demands of actual communications. However for this study we begin with a fully connected topology for baseline comparison purposes and because it is probably a good starting point for topology fine tuning. Our topology control system can deal with the directional network not being fully connected.

3.1 Omni-neighbors discovery

When the network is initialized, all the nodes will perform Neighbor Discovery by exchanging ‘HELLO’ packets which will include the node’s location. The ‘HELLO’ packets are broadcast using the omni-directional antenna, which also operates using a different frequency channel. We call this the ‘Control Channel’. By exchanging ‘HELLO’ packets, each node will know up to its one-hop omni-neighbors. But, we need to know beyond this because when the transmissions are directional the transmission range increases as the beamwidth decreases for the same transmission power.

We want to know the map (location of each node) of the whole network. To do this, each node will broadcast the ‘HELLO’ message using the omni-directional control channel. Each ‘HELLO’ message will have a unique id (combination of source address and sequence number) and each node will keep track of the ‘HELLO’ messages its transmitting and will not transmit the same ‘HELLO’ message twice.

Each node will maintain a Location-Distance-Direction-Reachable (LDDR) Table. The structure of the table is given in Table 1.

Table 1. LDDR table after phase-1

Node ID	Location	Distance	Direction (Angular Distance)	Directionally Reachable
1	(x_1, y_1)	d_1	β_1	…
…	…	…	…	…
n	(x_n, y_n)	d_n	β_n	…

The first four columns will be filled up by this stage. The last column which indicates whether a node is a potential directional neighbor or not of the node the table belongs to will be tested in the next stage. This table will be populated in ascending order of distance.

Note that in our SAHN all nodes are either fixed, and can reasonably be assumed to know their own location, or are equipped with GPS or other location determining technology. SAHN is not a sensor network where power and cost constraints make location awareness impractical.

We need to know the map of the whole network (location of each node), as one of our possible Topology Control heuristics is to connect the nodes along the direction of destination node for a particular communication. If we do not know the location of each node, this is not possible.

3.2 Potential directional-neighbors discovery

Now each node will create its Potential Directional-neighbors table. Potential Directional-neighbors are those nodes which are reachable when both nodes communicate using directional beams. We get an extended range when both nodes communicate using directional beams. So, Potential Directional-neighbors may be beyond one-hop omni-neighbors. In general, all the one-hop omni-neighbors are directionally reachable, but this is not always true. Some omni-neighbors may be reached by reflected paths as there may be a blockage between those two nodes. In this case, these two neighbors are not directionally reachable. So, we need to do testing. Also all two-hop or three-hop omni-neighbors are not directionally reachable. But as we know the location of these neighbors we can estimate whether they are reachable using the directional antenna and then test it. After calculating the transmission range of a directional antenna for a specific transmission power, beamwidth and propagation model, we then roughly estimate the directional transmission range of a beam. But some of these nodes may not be reachable using directional antenna due to other environmental factors. So, we want to make sure of this by testing. To do this, we will ask these two nodes to beamform towards each other. We have introduced two new control messages for this purpose. One of the nodes will send the “Request For Beam (RFB)” message to the other node, using the omni control channel in a multi-hop fashion, and will point one of its directional beam towards that node. The ‘RFB’ message will contain the node id of the sender node and the channel frequency of the directional beam. The other node after receiving the ‘RFB’ message will point one of its directional beams towards the node using the same frequency channel and will send a “ACK For Beam (AFB)” message directionally and will wait for a ‘AFB’ message from that node. After receiving the ‘AFB’ message from the other node the node will consider this node as a potential directional-neighbor and will send an ‘AFB’ message directionally to the other node, which will allow the other node to consider this node as a directional neighbor. In this way, this two-way handshake process allows nodes to find out their actual potential directional neighbors.

As described in stage-1, the last column of the LDDR table will be filled by this stage. As this table is sorted by distance from the particular node, we will start testing from the first node and continue until there is a failure in the testing. Then the distance of that node will be checked. If that distance is directionally reachable then there are other factors behind this failure and we will continue testing. But if the distance is more than our calculated directional range, we will test two more nodes to see whether they are reachable or not and to confirm the validity of our calculated directional range. So, at this stage the LDDR table is like Table 2.

Table 2. LDDR table after phase-2

Node ID	Location	Distance	Direction (Angular Distance)	Directionally Reachable
1	(x_1, y_1)	d_1	β_1	*y/n*
…	…	…		…
n	(x_n, y_n)	d_n	β_n	*y/n*

3.3 Forming an initial connected topology by selecting a subset of potential directional-neighbors

After the first two phases, we have knowledge of all the potential-directional neighbors. Our network topology will always be formed using the potential directional neighbors. All the control messages for topology formation will be transferred using the omni-directional control channel. We need to select a subset of the potential directional-neighbors to build the directional connected topology. In this case, each node will try build up its Local Minimum Spanning Tree (LMST), provided that it has a fixed number of beams. To build the MST Prim's algorithms will be used. Two nodes will be neighbors of each other when both of the nodes have beams pointing towards each other. The topology generated by our algorithm will always be a bidirectional topology. A bidirectional topology is needed for IEEE 802.11 MAC, otherwise CTS and ACK messages cannot be received. Our topology has made the wireless network close to that of a wired network.

4. Adaptive QoS based topology control

We build a connected topology using directional beams during the network initialization phase. The routing protocol uses this directional topology to find out the paths between source and destination pairs. As the topology is fully connected using directional beams, there will be a path between any source-destination pairs. But for current communication sets some of these paths may not met the required QoS. If QoS is not met, then the routing protocol tries to find out some alternate paths that meet the required QoS. If there is no such path, then we need to change the network topology.

We do not want to change the topology very frequently. As each topology construction will take some time and that will be followed by the routing discovery process. Communications affected by this topology change may be disrupted. Depending on the traffic rates, queues may be filled up and packets maybe lost due to queue overflow.

For a new communication in the current topology two things could happen:

1. a suitable path is found that meets the required QoS without disrupting any other communications.
2. a path is not found that meets the required QoS.

For case 1, we use that path for the time being, even if a better path may be found by changing the topology. But that topology change may break some other existing communications. So, we do not want to make that change at this time. But while the communications are running, the Topology Control Layer will check if a better topology can be found. All control messages for this purpose will be exchanged using the omni-directional control channel. It may happen that some nodes are overloaded in the current topology and creating bottlenecks. In this case, using another topology could be a good idea, which will distribute the load. So, our topology is also a *load balancing topology*.

For case 2, the current topology cannot accommodate the new communication, so needs to be changed. The Routing layer will inform the Topology Control Layer of this routing path unavailability and will ask for a topology change.

As we do not have any centralized control of the network, the topology control process needs to be distributed. Each node by its local knowledge of the network and communications will change the topology. This change may affect many other nodes and many ongoing communications. The topology change needs to make sure that it can accommodate all the current communications, otherwise it will lead to another topology change.

To have a QoS based topology control system, we need to define the QoS metrics first. Potential QoS metrics could include, a) end-to-end delay for a communication, b) inter-packet delay difference (IDD), c) short-term throughput of a communication, d) bandwidth. We can have many kinds of communications in our network, e.g. Real Time (RT) traffic like VOIP and video conferencing, and Best Effort (BE) traffic. For all communications the thresholds for these metrics will have some pre-defined values.

Next we need to consider the QoS state propagation and maintenance. We use a cross-layer approach for this. The lower network layers as in Figure 2, collect different network statistics at run time. These layers will then exchange this information and depending on that, the topology change decision will be made by the topology control layer, which sits between the MAC and Network layers.

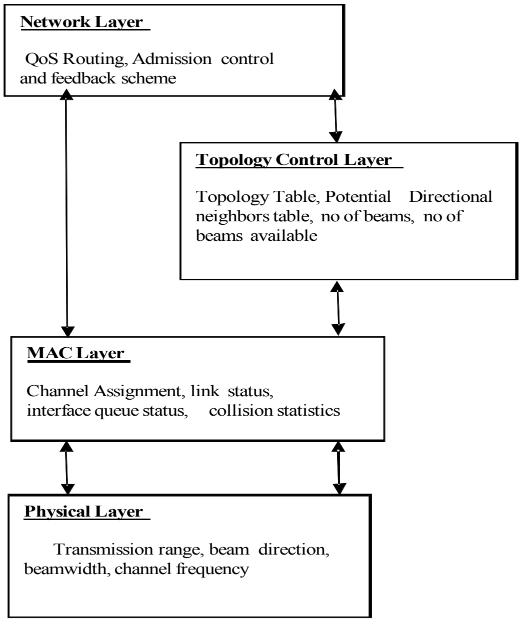

Figure 2. A cross-layer approach for topology control

The QoS will be checked by the destination node. If the QoS is not met it will notify the last intermediate node about the QoS failure. This message will be transferred using the omni-directional control channel. This message will also contain the QoS parameters and their threshold. As the last intermediate hop is one hop away from the destination node, it will not be able to improve the QoS parameters by a topology or routing change. So, this node will forward the QoS violation message to the second last intermediate node. Now this second last intermediate node will approximate the QoS parameter values that it needs to receive from the previous intermediate node to maintain the QoS asked by the destination. If the previous intermediate node has not met the QoS then it will forward the QoS violation message to the node it received the data from. But if this node has received the data packets with sufficient QoS parameter values so far, then the QoS is failed form this node. In this case, this node will try to find out some alternate path using the current topology which will meet the QoS and if there is no alternate path or again the QoS is not met, then this node will initiate a local topology change.

So, we are not notifying the source of a QoS violation immediately. Instead, we are trying to find out the point of failure of QoS violation by approximate the QoS parameter values on each intermediate node.

The routing protocol and topology control process are heavily coupled in our cross-layer design. The topology control layer determines the connectivity between nodes to form the current topology. The routing protocol finds all the paths between a source and destination that meets the required QoS using the current network topology. If the QoS cannot be met using the current network topology, then the routing protocol asks for a topology change and the topology control layer changes the topology locally. Change of each directional link is associated with at least two nodes and may involve multiple communications. Thus, some of the communications may be broken and we need to re-discover routes for these broken communications. So, each topology change will be followed by a routing discovery process. For RT traffic we may have very little time to react. But when a communication starts, we have some time to find out the best route for this communication for the current topology and if there is no such route in the current topology we can try to make a topology change.

5. Simulation results

Some preliminary simulation results of the proposed framework are presented here. We used the GloMoSim [10] simulator which is designed using PARSEC [11]. We established a wireless network of 150 nodes placed randomly on a 2000m X 2000m area. There are 20 simultaneous communications of CBR (Constant Bit Rate) UDP traffic between randomly selected source-destination pairs. Each node in our network model has three transceivers. The simulation parameters are listed in Table 3.

Table 3. Simulation Parameters

Terrain Size	2000m X 2000m
Number of node	150
Node placement	Random
Simulation time	120 seconds
Number of communications	20
Packet size	1024B
Packet interarrival time	25ms - 225ms
Traffic type	UDP
Interface Queue size	100 packets
Transmission rate	11 Mbps
Propagation-Pathloss model	TWO-RAY
MAC protocol	802.11
Routing protocol	AODV

In the graph, the curve labeled as “Topo-omni” represents the topology with 3 omni-directional antennas, the curve labeled as “Dir-Con-Topo” indicates a connected topology using 3 directional beams per node. The curve labeled as “Dyn-Topo” represents a dynamic topology using 3 beams per node. In this case we change some of the directions of the beam dynamically. We used a simple heuristic to do that, we change the topology dynamically using an idle or less used beam.

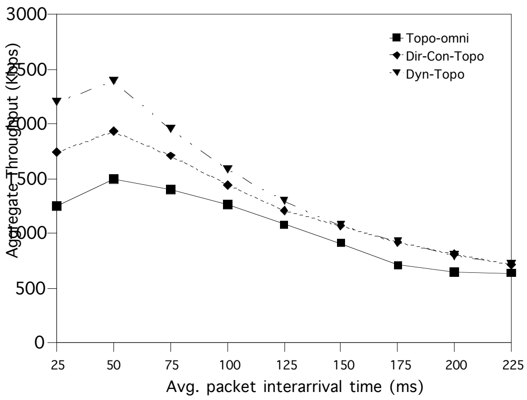

Figure 3. Aggregate throughput vs. packet interval

In Figure 3, we represent the aggregate throughput over all communications as the network load decreases. We tested different sized data packets, but due to space constraints only the throughput of 1024B packet size is presented. For other different size data packets we obtained similar type of results. Note that each point in the graph is the average of 10 different simulation runs. When the network is lightly loaded, both directional topologies perform similarly but better than the omni-directional topologies with three radio channels. The main reason is less interference or an increased SINR as in all cases three radio channels are used. That means multiple communications are possible in the same neighborhood while using multiple directional beams, but the degree to which it is possible depends on the network topology. Both "Dir-Con-Topo" and "Dyn-Topo" use three directional beams with 30 degree beamwidth. In "Dir-Con-Topo", we did not change the beam directions, so the topology is static. But we changed the beam directions for "Dyn-Topo" dynamically. In this case, we re-allocated the idle or less used beams to some other neighbor nodes and the throughput is increased comparing to a static topology. Thus, if we can have a dynamic topology by selecting the beam directions depending on the link status, neighbor nodes and current communications the performance of the network is improved. This method can be extended to maintain QoS for different data streams in wireless ad hoc networks.

6. Conclusion

In wireless ad hoc networks use of multibeam directional antennas is an effective way of reducing interference and increasing the spatial re-use. This type of antenna system can be best utilized if the topology can be dynamically changed. We have presented a framework of dynamic topology control using multibeam directional antennas. We use a separate omni-directional control channel for sending and receiving the topology control messages. QoS and current link status are considered when the topology is changed. This is not a trivial process. Future work will extend and evaluate this framework.

Our future research is focused on the algorithms for creating updated topologies and the implementation thereof while trying to maintain QoS of currently running communications. An approach currently being considered is to create alternate routes in advance so that when the topology change takes effect, the new routes can be switched in immediately and disruption to existing communication is minimized.

Questions to be addressed include the stability of the system. Some adaptive QoS topology change and routing algorithms may lead to chaotic behaviour rather than converging to a stable state.

7. References

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