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An Analyzing of Cross Layer Design for Implementing Adaptive Antenna Technique in Mobile Ad-Hoc Networks

Reference

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ABSTRACT

A mobile ad-hoc network (MANET) uses an omni-directional antenna, which transmits and receives power from all directions, resulting in higher noise and interference. The interference effects can be minimized with the help of adaptive directional antennas. The proposed model for implementing adaptive antenna techniques in MANET is a cross layer design. Utilizing adaptive antennas, two nodes are able to communicate when both the transmitter's and receiver's unidirectional radiation beams are directing toward each other's nodes. A cross layer methodology for dynamic topology control enables the interaction between medium access control layer and the routing layer for reaching the necessary quality of service (QoS) of various data packets. After the initialization of a network, the algorithm initially develops a topology and the routing techniques use this network topology to find out the route paths for data transmission. Later, based on the network scenario for ongoing transmissions and to obtain the necessary QoS, the topology gets altered by the topology control layer in order to obtain the optimized network with better performance. Simulation results show specifically, throughput and signal-to-noise ratio were increased by 33 % and 42 %, respectively.

Keywords

mobile ad hoc network, dynamic topology, cross layer design, smart antenna, adaptive antenna, medium access control, quality of service

Introduction

A smart antenna ad hoc network (SAAHN) [1,2] can be described as a wireless cooperative network with no backbone support. It can also be referred to as a self-organized distributed structure. There may exist a single-hop or multi-hop communication in this network. Hence, each and every node present in an ad hoc network acts as a router that helps in forwarding the packets to other nodes. The wireless ad hoc networks are advantageous in terms of having a low cost, having easy maintenance, being robust in nature, and supporting scalability. Community networks can be formed during disaster management by building emergency response networks. Vehicular ad hoc networks, military networks and sensor networks can also be formed.

SAAHN consists of all the nodes deployed in homes with the help of omni-directional antennas mounted over roofs. The nodes present in this kind of network are usually fixed, and they are aware of their own location. This may also be adapted to mobile nodes but with additional location awareness technology like GPS.

Usage of single radio frequency channel in omni-directional antenna systems is employed in traditional wireless networks. Carrier sense multiple access-collision avoidance (CSMA/CA) is used as a medium access control (MAC) protocol [3], where nodes available in the neighborhood of any node will remain idle to avoid interference when involved in any other transmissions. This method may degrade the network performance in a high-density network with the presence of congestion, resulting in underutilization. In this kind of network, interference may cause serious issues. This problem is worsened into an intra-flow interference and inter-flow interference in case of multi-hop networks. The former is introduced by the adjacent nodes available on the same path and the latter is introduced by the nodes available on the neighboring paths [4]. The usage of an omni-directional antenna helps in managing the network connectivity and finding the shortest paths.

Adaptive antenna, a kind of multibeam smart antenna helps in overcoming the interference effects caused in wireless networks. These antennas enable the node to receive signals from desired directions, and hence, the signal to interference and noise ratio (SINR) gets improved [5]. The transmitting and the receiving node beams must steer toward each other, and both must employ the same frequency channel during communication. Adaptive antenna supports a high range of transmission with a similar transmission power to the omni-directional counterpart. The transmission distance (range) is inter-related with beam width. If transmission distance increases, the beam width reduces in adaptive antenna for the same transmission power.

In this network, every node will have an omni-directional antenna with a transceiver module, and each will also have a number of directional antennas called adaptive antennas [6,7]. The directional antenna beams may operate on a similar frequency or dissimilar frequencies. But the omni-directional antenna will always operate on a separate frequency channel concerned with the directional antenna beams. The omni-directional antenna channel is referred to as the control channel, and this omni-directional antenna supporting network is referred to as the control network. The control channel is used for transferring topology [8] control packets, and all the data packet transmissions are made with the help of directional antenna beams.

The remaining article is ordered in the following way: the next section presents the Smart Antenna System (SAS); the section titled "Formation of Topology" presents the formation of network topology with an adaptive antenna; the cross-layer design of the adaptive topology control method is presented in the section titled "Adaptive System of

QoS Dependent Topology Control"; "Performances Evaluation" deals with the simulation results and its analysis; and the last section discusses the conclusion of the article.

Smart Antenna System

SAS is a subsystem consisting of multiple antennas that are mainly based on the spatial diversity and signal processing techniques that in turn increase the wireless system performance. The basic factors in SAS are direction finding and beamforming. Direction finding helps in estimating the number of emitting sources and the direction of arrival (DOA) [3], whereas the beamforming technique helps in determining the signal of interest (SOI) during interference [9]. The main thing behind SAS is selecting the smart algorithms in an adaptive antenna array. Beamforming algorithms make use of the weight of antenna arrays for adjusting themselves to form certain amounts of adaptive beam or narrow beam in order to track the corresponding users automatically. SAS helps in minimizing the interference occurring from other users by introducing null effects in their directions and thereby the desired signals can be obtained. The adaptation of weight forms the "smartest" portion of SAS.

The significant benefit of SAS is that a higher network capacity can be achieved. An increase in the network capacity is accomplished through the precise control of the quality of signal nulls and interference mitigation. The classifications of smart antenna [10] systems are switched beam systems and adaptive array systems.

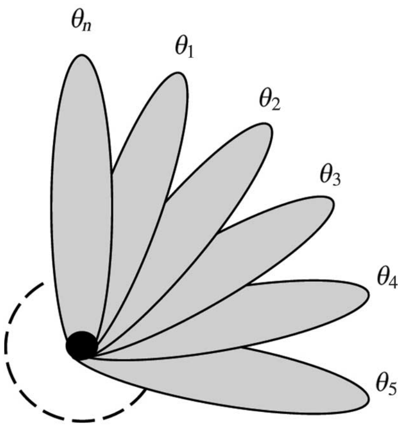
Multibeam SASs are used for generating multiple directional beams with the help of adaptive beamforming methods. This kind of antenna system is not similar to the ordinary directional antenna system. The beam width, beam numbers, and the beam direction can be altered during the runtime also. Considering n beams, each having a beamwidth of θ_1, θ_2, θ_3, … θ_n as in **Fig. 1**, the total beam width is given in Eq 1.

$$\theta = \Sigma_{i=0}^{n}\theta_i \quad \text{where}\, 0 < \theta \leq 2\pi \tag{1}$$

where:

i = beam number;
θ = angle of the radiation pattern; and
n = total number of the beam in antenna.

FIG. 1
n-beam smart antenna.



In this multibeam SAS [11], selecting a set of potential neighbors as real neighbors is of major concern, thereby creating a network with less connectivity. A cross-layer design approach [12–15] is used for choosing the set of neighbors to form a network for an adaptive topology control system, which enables dynamic change of the networking topology based on the ongoing communications [16,17], the quality of service (QoS) needed, and the status of the link [18].

Formation of Topology

Many directional topologies can be formed using a given number of nodes and the directional beams. Distance between the nodes, the distribution of nodes, and the radio transmission environment are also other factors to be considered. A fully linked topology with directional beams is formed at the network initialization phase. The messages related to making topologies are passed with the help of an omni-directional control network. Initially, the formation of the topology process consists of the following steps: (1) discovery of omni-neighbors; (2) discovery of directional-neighbor nodes; and (3) formation of an initial linked topology through the proper selection of potential directional neighbors.

It must be noted that in initial phase, a fully linked and directional network topology need not be created. The adaptive topology control system will alter the topology adaptively in order to satisfy the QoS demands required for communication to take place. For the purposes of this study, a fully connected topology that helps in forming a fine-tuned topology is initially created and used for baseline comparison. The topology control system used here can be applied to a directional network that is not being fully connected.

DISCOVERY OF OMNI-NEIGHBORS

Once the network is being initialized, all the nodes available in the network will perform a neighbor discovery process through the exchange of HELLO packets that include the location of a node. These packets are broadcasted with the help of an omni-directional antenna, which can also work on a dissimilar frequency channel known as a control channel. Now, each node will have a knowledge of its single hop omni-neighbors that is not sufficient, such that additional knowledge is required if the transmissions are to become directional; this is because the transmission range gets increased with the decrease in beam width for similar transmission power.

The location of every node available in the whole network must be known. For this, every node in the network will transmit (in a broadcast fashion) the 'HELLO' message through the omni-directional antenna control channel. Every 'HELLO' message has an exclusive identification address of the source node and sequence number. Every node follows the 'HELLO' messages transmitted, and no two 'HELLO' messages will be transmitted by the same node. A geographic location, distance, direction orientation, and reachable (GDDR) table will be maintained by each node; the structure of the table is shown in Table 1.

In the previous table, the first four column details are collected by every node at this point. The last column represents whether neighbor nodes are in a possible communication range or not for a particular node. This table is arranged based on the distance in ascending order.

TABLE 1
Geographic location, distance, direction orientation and reachable (GDDR) table.

Node Numbers	Geographical Location	Distance	Angle Orientation (Direction)	Nodes are in Reachable Distance
1	(lat_1, lon_1)	d_1	θ_1	–
2	(lat_2, lon_2)	d_2	θ_2	–
–	–	–	–	–
n	(lat_n, lon_n)	d_n	θ_n	–

Note: lat = latitude of neighbor node; lon = longitude of neighbor node.

In SAAHN, all the nodes available in the network are either fixed or random. They are assumed to know their position or else they are equipped with location finding devices like a GPS or some other position determining methodologies. Because SAAHN is unlike a sensor network [11,19], the cost and power constraints will not make predicting the position an impractical one. Each node's location in the network is to be known because the topology control heuristics are used, which help in connecting the nodes to the destination node for a specific communication to take place. If the location of each node is not known, then this becomes impossible.

DISCOVERY OF DIRECTIONAL NEIGHBORS

In this stage, each node will form its possible neighbor's directional table. The nodes referred to as directional neighbors are found to be reachable, and when two nodes are in communication using directional beams, they are referred to as potential nodes. An extended range of communication is possible when two nodes communicate using adaptive directional beams. Hence directional potential neighbors are considered as the nodes away from mono-hop omni-neighbor nodes. Generally, the available single-hop omni-neighbor nodes are found to be reachable directionally; however, this statement does not hold true forever. Some of the omni neighbors may be reached with the help of reflected routes because an obstruction may exist among those nodes. Now these two neighbor nodes are not reachable using the directional antenna. There is a need for testing to find this one. Similarly, all the 2-hop or 3-hop omni-neighbor nodes may not be reachable directionally. Because the location of these neighbor nodes are known, there is a need to determine whether they are directionally reachable and then it must be tested. Using the range of transmission of a directional antenna with a definite transmission power, beam width, and broadcast environment, rough estimation of the directional beam transmission range can be determined. Some of the nodes may not be directionally reachable because of certain environmental factors. This can be done with the help of testing. This is done by making the two nodes to beam form toward each other. The two fresh control messages are employed for doing this activity. A "beam request" (BR) message will be sent by one of the nodes to one of the other nodes using the omni-directional antenna control channel with a multi-hop method, pointing one of its adaptive directional beams onto that particular node. The BR message sends the node's identification and the operating radio frequency of the adaptive directional antenna beam. The receiving node of the BR message positions one of its adaptive directional antenna beams toward the sender node through the similar radio frequency channel and sends an "acknowledgement for beamform" (AB) message directionally. The sender node will tend to wait for an AB message from the receiving node. On the reception of the AB message, the sender node will regard the other node

TABLE 2

Geographic location, distance, direction orientation and reachable (GDDR) table at stage 2.

Node Numbers	Geographical Location	Distance	Angle Orientation (Direction)	Nodes are in Reachable Distance
1	(lat_1, lon_1)	d_1	θ_1	Yes/No
2	(lat_2, lon_2)	d_2	θ_2	Yes/No
–	–	–	–	–
n	(lat_n, lon_n)	d_n	θ_n	Yes/No

Note: lat = latitude of neighbor node; lon = longitude of neighbor node.

as the possible directional-neighbor node. With this, a two-way handshake process occurs and assists in discovering their actual potential directional neighbor nodes [20,21].

As mentioned earlier, the last column present in the GDDR table will be filled in this stage. This table is arranged based on the distance from a specific node; the testing process progresses from the very first node and continues until failure occurs in the testing. After that, the distance between the nodes will be checked. If the distance found is directionally reachable, then it is clear that there are some other factors for this failure and the testing will be continued. But if the distance measured is observed to be more than the calculated directional range, then testing is done with two or more nodes to verify whether they are directionally reachable or not, thereby confirming the validity of the measured directional range. The GDDR table is depicted in **Table 2**.

FORMATION OF AN INITIAL CONNECTED TOPOLOGY THROUGH PROPER SELECTION OF POTENTIAL DIRECTIONAL NEIGHBORS

Now all the potential-directional neighbor nodes are known after the previous two phases. The network topology is always formed with the help of the potential directional neighbor nodes. The control messages used for forming the adaptive topology will be transferred through omni-directional control channels. There is a need to select a subset of the possible directional neighbor nodes in order to build the directional connected topology. Now, each node will attempt to build up its local minimum spanning tree (LMST) when a fixed number of beams are available. In order to build the LMST, Prim's algorithm can be used. Any two nodes will be the neighbors of one another when they both have their beams directing toward one another. A bi-directional topology is likely to be generated by using this algorithm. This kind of topology is necessary in case of IEEE 802.11 MAC for receiving the clear-to-send (CTS) and acknowledgment (ACK) messages [22,23]. This dynamic topology makes the wireless network closely resemble a wired network.

Adaptive System of QoS Dependent Topology Control

A fully linked topology with the help of directional beams is built at the end of the network initialization phase. The routing protocol makes use of this directional topology in order to search for the routes between the source node and destination node. Because of the existence of fully connected topology assisted by directional beams, there surely exists a transmission route between any of the source and destination node pairs. But sometimes the required QoS cannot be attained for an ongoing communication. If it is not satisfied, then the routing protocol will tend to search for some other routes so that the required QoS is met. If no such routes are found, then the network topology has to be modified.

The network topology is not required to be changed very frequently because building a topology will consume some time and it is followed by the route discovery process. It may also be the case that communication will be affected by a change in topology. Based on the rate of traffic, queues may fill up quickly and packets may get lost because of queue overflow.

Two things may occur for a newer communication with the existing topology: (1) a new route meeting the required QoS may be found without causing disruption to other communications; (2) a route may not be found meeting the required QoS.

Considering Case 1, the route is used for the time being, and an enhanced path may also be established by topology alterations. But these alterations may cause disruptions to some other ongoing communications. Hence, during run time transmissions, network topology is not changed. During the ongoing communications, the topology control layer determines whether a better topology can be identified. The control messages related to this process will be transferred with the help of omni-directional control channel. Sometimes, the nodes may be overloaded in the existing topology causing bottlenecks. If this is the case, finding alternate topologies can serve as a better idea so that the load gets distributed. Now a topology that is of the load balancing type gets developed.

Considering Case 2, the existing topology cannot support a new communication and hence it needs to be updated. The routing protocol will ask the MAC layer about the unavailability of routes asking for a change in topology. Because the network with decentralized control is being dealt with, there must be a distributed topology control process. Each node, by gaining its network's local knowledge and transmission, will change the topology. This change may cause various effects on many existing communications and nodes. The change in topology can accommodate all the ongoing communications. Otherwise, it leads to the identification of a new, different topology.

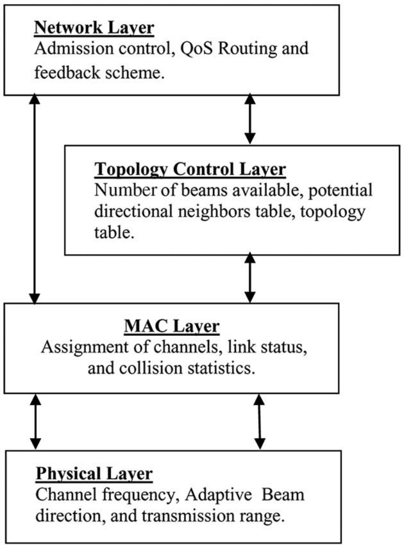
Initially, QoS metrics must be defined in order to have a topology control system based on QoS. The metrics are (i) end-to-end delay, (ii) bandwidth, (iii) jitter, and (iv) throughput. There exist different types of communications in a network like real time (RT) and best effort (BE) traffic. RT traffic includes voice over protocol (VOIP) and video conferencing. There must be a threshold value for these metrics to be set for all types of communications. They are the predefined values.

Then, the consideration of the QoS state transmission and preservation comes into account. Cross-layer methodology is used for this. Various run time network statistics are collected by the network layers at the lower level, as shown in Fig. 2. This information is exchanged with the other layers. Then, the decisions related to topology alterations are made through the topology control layer. This layer lies between the network layer and the MAC layer.

The destination node will monitor the QoS parameters. If it is not satisfied, then it will intimate to the last intermediary node regarding the failure in QoS. This information, which includes the QoS metrics and the threshold values, is transferred with the help of omni-directional control channel. Because the last intermediate node is located at a distance that is a single hop from the target node, it cannot increase the QoS parameters by undergoing a dynamic topology or path change. Hence, this node forwards the QoS violation message to the next-to-last intermediary node. At this time, this second-to-last intermediary node will perform approximations over the QoS parameter values that it will

FIG. 2

Cross-layered topology control.



obtain from the previous intermediary node in order to satisfy the required QoS value needed by the destination node. If the previous intermediate node does not attain the required QoS, the QoS violation message will be forwarded to the node from which the data was obtained. If the data packets received by this node with adequate QoS metrics, then it will be clear that the QoS gets failed from this node. Now, by this method, the node will attempt to search for some other alternate routes with the help of the existing topology in order to meet the required QoS. If no alternate paths are found or the QoS is not satisfied again, then this node will start up change in local topology.

It should be noted that notifications are not immediately made to the source node about the QoS violation. Instead, the point at which the QoS failure occurs is determined by approximating the QoS metric values on each intermediary node.

The coupling of the dynamic routing protocol and adaptive topology control process is achieved in this cross-layered design approach. The topology control layer helps to find the connection between the nodes to build up the existing topology. The routing protocol helps in determining all of the routing paths that are available between a transmitting and receiving node, which satisfies the required QoS with the help of the existing network adaptive topology. If the QoS is not satisfied with the existing adaptive topology formed, then the routing protocol will look for the modification of topology. The topology control layer will look after the alterations in the adaptive topology locally.

Every link alteration needs at least two nodes involving multiple communications. Hence, some communications may get disrupted, and it becomes a necessity to redetermine the routes for those disrupted communications. Therefore, every change in topology will be tagged on by a route discovery process. In the case of RT traffic, there may be a minimum time to respond for it. But if a communication is started, the best route for this communication must be found for the existing topology. If no such route is determined in the existing topology, a changing of topology can be done.

Performances Evaluation

The proposed cross layer design is simulated by using a network simulator (NS-2.33, Lawrence Berkeley National Laboratory, Washington, DC). In this section, some of the simulation parameters used to measure the network performance are discussed.

SIMULATION ENVIRONMENT

The proposed model has considered 50 wireless network nodes placed randomly on an area of 1,000 m by 1,000 m. Here, each node is initially placed at a random position within the defined area. There are 30 instantaneous transmissions of user datagram protocol and constant bit rate traffic among certain source and destination node pairs that are randomly selected. **Table 3** represents the various simulation parameters.

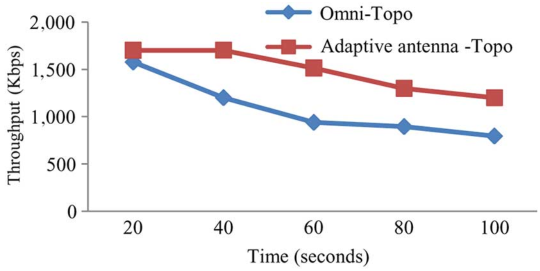
Fig. 3 shows the curve named "Omni-Topo," which represents the static topology with three omni-directional antennas. The curve named "Ada-Topo" depicts a dynamic topology using three adaptive beams per node. Fewer beam directions are dynamically changed in this case. A simple idea is used to accomplish this by changing the adaptive topology dynamically with idle or minimally used beams to other neighbor nodes.

TABLE 3
Simulation environment.

Parameters	Values
Topology area	1,000 m by 1,000 m
Number of nodes	50
Mobility model	Random
Total simulation time	1,000 seconds
Frequency	2.4 GHz
Maximum number of communications	30
Propagation-pathloss model	TWO-RAY
Packet size	1,024 B
MAC protocol	802.11
Packet interarrival time	25–225 ms
Channel capacity	2 Mbps
Type of traffic	UDP
Queue size	100 packets

Note: UDP = user datagram protocol.

FIG. 3
Throughput.



THROUGHPUT

Throughput is the rate of successful data delivery over a communication channel [24]. Throughput is usually measured in bits per second (bps). Throughput is illustrated in Fig. 3, and it is increased compared to static topology. The achieved throughput is often 33 % higher than the static topology.

BIT ERROR RATE

The bit error rate (BER) is the number of bit errors per unit of time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval [25]. BER is a unitless performance measure, often expressed in percentage. Fig. 4 illustrates the BER versus time, where the proposed system BER drops 21 % relative to the static topology.

SIGNAL-TO-NOISE RATIO

The signal-to-noise ratio is the ratio of the average power of the information signal to the accumulated average power of all background and interference noise sources. Fig. 5 shows that 42 % of signal-to-noise ratio gets increased in the proposed method.

DELAY

The delay of a network specifies the length of time that is taken for a bit of data to travel from a source node to a destination node in the network. It is normally measured in fractions of seconds. Fig. 6 shows the delay versus the number of nodes. The result shows that in the proposed method, initially, the delay is introduced because of the discovery of

FIG. 4

Bit error rate.

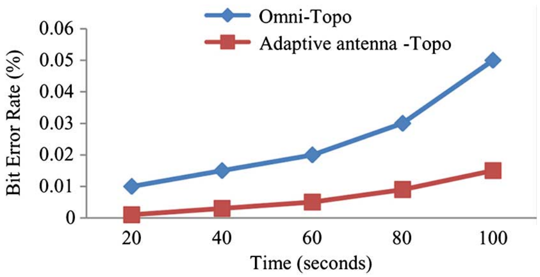


FIG. 5

Signal-to-noise ratio.

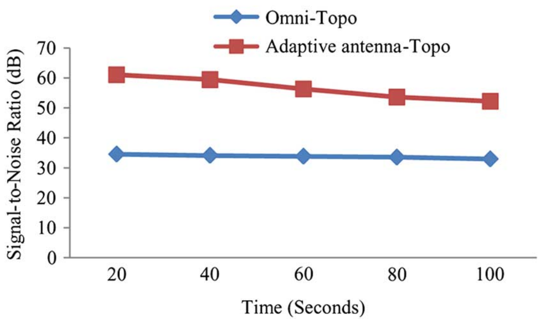
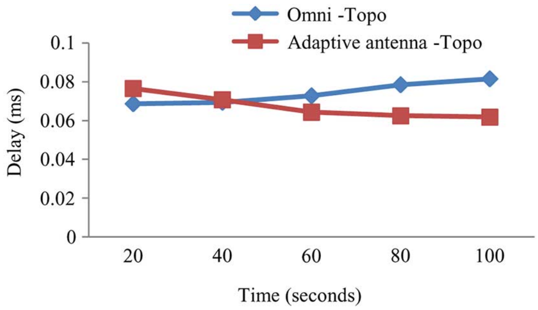


FIG. 6
Delay.



omni-neighbors and directional-neighbors and later delay gets reduced by 37 % compared to the existing method.

Conclusion

Usage of multibeam directional antennas in wireless ad hoc networks is an efficient method of minimizing interference effects and increasing spatial reusage. For dealing with dynamic change of topology, this kind of antenna system can be used effectively. The protocol dealt with here is the dynamic topology control using multibeam directional antennas. Here, a separate omni-directional control channel is employed for transmitting and receiving the control packets related to topology. When modifications occur in the existing topology, QoS and existing link conditions are taken into account, which is a significant process. Future work deals with the extension of the proposed work. Algorithms for developing new topologies and their implementation should be a major concern for maintaining QoS during run time transmissions. The current method deals with finding alternate paths in advance. Hence, when the topological change comes into effect, the switching process to new paths can be done with an immediate effect while minimizing the existing communications from disruptions. While considering the system stability, some of the adaptive topology control and QoS routing algorithms may create hectic behavior rather than being established.

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