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An Adaptive MAC Protocol for Ad Hoc Networks with Directional Antenna

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Summary
In wireless environment, use of directional antenna can improve the utilization of wireless medium and consequently the network throughput. However, in the context of ad hoc networks, it is difficult to find ways to control the direction of such antenna for transmission and reception in each terminal in order to achieve an effective multi-hop communication between any source and destination. We have developed an adaptive MAC protocol, where each node keeps certain neighborhood information dynamically so that each node can avoid interference by keeping a track of the direction of communication events going on in its neighborhood at that instant of time. This can drastically improve the medium utilization through overlapping communications in different directions.

Key words:
Ad hoc networks, Directional Antenna, Medium access control protocol, ESPAR antenna.

1.Introduction

Recently, there is a growing interest in ad hoc networks [1] and its applications. We are working towards implementing Wireless Ad Hoc Community Network (WACNet) testbed [2] and have developed small, low-cost directional antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna, with each user terminal [3,4]. The objective of this paper is to propose an adaptive MAC protocol in the context of WACNet.

The ESPAR antenna consists of one center element connected to the source (the main radiator) and several surrounded parasitic elements (typically four to six) in a circle. Each parasitic element (the passive radiators) will be reactively terminated to ground. By adjusting the value of the reactance that terminates the parasitic elements forms the antenna array radiation pattern into different shapes. The features of ESPAR are : controlling beam direction, multiple beams (with same frequency) formation, steerable beam (360 degree sweeping) and controlling null steering. For receiver application, the null should be steered in the direction from which an interfering signal is coming. It has been observed that 360 degree continuous beam / null steering is possible with seven-element ESPAR antenna, with a simultaneous 8 dBi beam gain and –30 dBi null [4]. ESPAR antenna would be a low-cost, low-power, small sized antenna, suitable for the proposed application domain.

It has been shown earlier that the use of directional antenna can largely reduce the radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [5-9]. However, in the context of ad hoc networks, it is difficult to find ways to control the direction of such antenna for transmission and reception in each terminal in a distributed fashion in order to achieve an effective multi-hop communication between any source and destination.

Some researchers in the past have tried to address this issue in several ways [5-9]. Recently, MAC protocols that rely on RTS-CTS type handshaking as in IEEE 802.11 have been suggested in the context of ad hoc networks with directional antennas [8,9]. In [8], a set of D-MAC (Directional MAC) schemes was proposed. Here, the mobile nodes are assumed to know the physical locations of themselves and their neighbors using GPS. In [9], the proposed MAC protocol need not know the location information; the source and destination nodes identify each other's direction during RTS-CTS exchange. It is assumed that all the neighbors of s and d, who hear this RTS-CTS dialog, will use this information to prevent interfering with the ongoing data. However, in order to fully exploit the capability of directional antenna, whenever a source S and destination D engage in a communication, all the neighbors of source and destination nodes should know the direction of communication so that they can initiate new communication in other directions, thus preventing interference with on-going data communication between S and D. This has been achieved in [6] by using set of tones and maintaining extensive network status information at each node in the network. However, this is unrealistic in a dynamic scenario. In [9], it has been assumed that all nodes are able to maintain a unified and common coordinate system to mark the orientation of antenna with respect to each other at all times, irrespective of their movements. They suggested to use some direction-finding instrument in each node. However, this requires additional

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hardware in each user terminal. Moreover, probability of control packet collisions [8] is one of the major problems in this context.

In our adaptive MAC protocol, an appropriate null-steering mechanism has been implemented to avoid control packet collisions and to help exchanging the neighborhood information in presence of on-going communication. In this protocol, each node keeps certain neighborhood information dynamically through the maintenance of an Angle-SINR Table in order that each node knows the direction of communication events going on in its neighborhood at that instant of time. The Angle-SINR table will also improve the performance of directional routing, since it helps each node to determine the best possible direction of communication with any of its neighbors.

2. The MAC Protocol

Forming Angle-SINR Table: In order to make the directional routing effective, a node should know how to set its transmission direction effectively to transmit a packet to its neighbors. So, each node periodically collects its neighborhood information and forms an Angle-SINR Table (AST). $SINR^{u}_{n,m}(t)$ (Signal -to- Interference and Noise Ratio) is a number associated with each link $l^{u}_{n,m}$, and is a measurable indicator of the strength of radio connection from node n to node m at an angle u with respect to n and as perceived by m at any point of time t. AST of node n specifies the strength of radio connection of its neighbors with respect to n at a particular direction. Angle-SINR Table for Node n at time t is shown below (Table I) where we assume that nodes i, j and k are the neighbors of n.

Table I: Angle-SINR table (AST) for node n

Azimuth Angle (degree)	**SINR value as perceived by neighbors of node n at different angle w.r.t node n**		
	i	**j**	**k**
0	$SINR^{0}_{n,i}(t)$	$SINR^{0}_{n,j}(t)$	$SINR^{0}_{n,k}(t)$
30	$SINR^{30}_{n,i}(t)$	$SINR^{30}_{n,j}(t)$	$SINR^{30}_{n,k}(t)$
60	$SINR^{60}_{n,i}(t)$	$SINR^{60}_{n,j}(t)$	$SINR^{60}_{n,k}(t)$
…..	…..	…..	…..
330	$SINR^{330}_{n,i}(t)$	$SINR^{330}_{n,j}(t)$	$SINR^{330}_{n,k}(t)$

In order to form AST, each node periodically sends a directional request in the form of a directional broadcast, sequentially in all direction. In this work, it has been done at 30 degree interval, covering the entire 360 degree space sequentially. A node i in the neighborhood of n will wait until it receives all the request packets generated by n in all direction at that occasion. In other word, node i accumulates the entire column of the AST of n for node i. Here, node i, after receiving the first request from n, has to wait a pre-specified amount of time to make sure that the directional broadcasts by n in all direction are over. Node i sends this information to node n as a data packet. After receiving this information from all the neighbors of n, the Angle-SINR Table of n would be complete.

Neighborhood-Link-State Table : Affinity of node m with respect to node n, $a^{w}_{n,m}(t)$, is a number associated with a link $l^{w}_{n,m}$ at time t , such that $a^{w}_{n,m}(t) = \text{Max}\ [SINR^{u}_{n,m}(t), 0< u <360]$. In other words, the transmission angle w with respect to n maximizes the strength of radio connection from n to m, as perceived by m at any point of time. This maximum SINR value is affinity of m with respect to n and this is obtainable when the antenna at n is directed towards m at an angle w with respect to n. Based on this, a Neighborhood-Link-State Table (NLST) at each node is formed as shown below (Table II). The NLST of node n, at any instant of time, will help us to determine the best possible direction of communication with any of its neighbor. This information will be helpful in realizing both adaptive MAC protocol and directional routing protocol.

Table II: NLST at node n

Neighbors of n	**Affinity**
i	Max $[SINR^{u}_{n,i}(t), 0< u<360]$
j	Max $[SINR^{u}_{n,j}(t), 0< u <360]$
k	Max $[SINR^{u}_{n,k}(t), 0< u <360]$

MAC Protocol : In IEEE 802.11 MAC protocol standard, RTS-CTS-DATA-ACK exchange mechanism is used to ensure reliable data communication. In our scheme, initially, when node n wants to communicate with m, it sends omni-directional RTS to inform all the neighbors of n, including m, that a communication from n to m has been requested. It also specifies the approximate duration of communication. All the neighboring nodes of n keep a track of this request from node n, whose direction is known to each of them from the respective AST. The target node m sends an omni-directional CTS to grant the request and to inform the neighbors of m that m is receiving data from n. It also specifies the approx. duration of communication. All the neighboring nodes of m keep a track of the receiving node m, whose direction is known to each of them from the respective AST.

On receiving CTS, node n issues omni-directional start-of-data-communication (SDC) to inform that the data communication will start from n to m. If, after getting RTS, SDC is not received within a time-out, RTS is ignored. Receiver acknowledges completion of a successful data communication by sending an ACK to transmitter.

Other nodes in the neighborhood of n and m can issue both RTS and CTS without disturbing the communication between n and m, which is illustrated below.

Let us assume, another pair of nodes X and Y, both in the neighborhood of n and m, desires to communicate. Both of them have already received RTS/CTS from n-m. From their respective ASTs, both X and Y knows the direction of n and m. If the directional beam from X to Y captures n or m, then the node X has to sit idle and defer its desire. Otherwise, node X can issue a RTS. In other words, X can issue RTS only if this communication does not interfere with n or m. However, the RTS issued by X will be selectively omni-directional : X will issue RTS avoiding interference with n and m. Similarly, Y will respond to this RTS by sending a CTS if the directional beam from Y to X does not captures n or m, and the CTS issued by Y will also be selectively omni-directional : Y will issue CTS avoiding interference with n and m.

Now, some nodes in the areas around n and m will not receive RTS/CTS from X and Y and therefore will be unaware of this communication event between X and Y. So, some of these nodes (including n or m, after the communication between n and m is over) may initiate another communication, which may disturb the communication between X and Y. To avoid this, both the antennas in X and Y will steer its nulls in the directions towards n and m so that they will be unaffected by the communication situation described above.

Any other nodes within the transmission beam of an ongoing communication will sit idle during the communication process. But, each of them will be waiting in omni-directional receive mode with its null steer towards the direction of communication. This will enable the idle nodes to receive RTS /CTS exchange from nodes that are unaware of the communication process. This will happen in the following scenario: When X and Y are communicating simultaneously with n and m, some nodes around n and m will not receive RTS and/or CTS from X and Y (as mentioned earlier). So, these nodes will be unaware of this communication between X and Y. So, some of these nodes may initiate another communication. But, they will issue omni-directional RTS / CTS, since they are unaware of any communication process. All nodes in the X-Y beam (excluding X and Y) need to receive this RTS /CTS to become aware of this new communication. So, during the communication between X and Y, all other nodes in this region will steer their nulls towards X-Y and wait in the omni-directional receive mode. Node X and Y, as mentioned earlier, will steer their nulls in the directions of n and m so that they will be unaffected by the probable communication in those regions. After the communication between X and Y is over, X and Y will collect this information from their neighbors during the next cycle of Angle-SINR formation of X and Y.

This can be extended to ensure conflict-free multiple communication simultaneously. However, the number of simultaneous communication depends on the null-steering capability and also on the current topology of the network.

Some basic experiments have been conducted on a simulated environment to evaluate the performance of directional MAC protocol. The environment consists of 50 mobile nodes, randomly distributed over an area of 1000x1000 squire meter. Experiments were conducted on different random samples. So far as medium utilization is concerned, number of simultaneous communication possible with directional antenna is on the average 18 (thus, involves 36 nodes out of 50) at a transmission range of 250. The corresponding value for omni-directional antenna is 7, indicating 2.5 times improvement in medium utilization. As a consequence, single-hop throughput also shows similar improvement at varying load condition as shown in fig 1. The link bandwidth is assumed to be 1 Mb/sec.

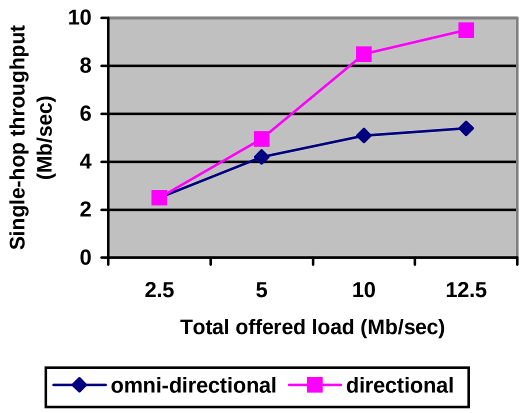

Fig.1. Throughput improvement

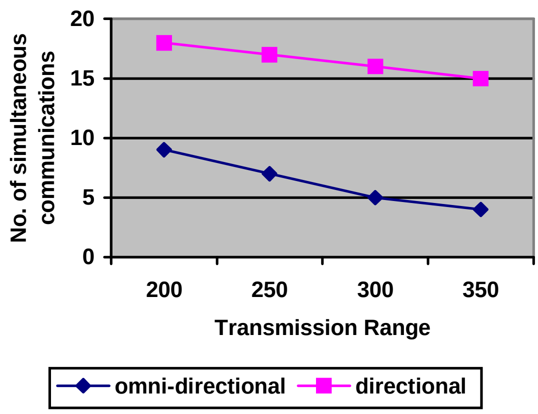

Fig.2. Number of simultaneous communication possible with (i) omni-directional and (ii) directional antenna, when all nodes are ready to communicate.

In order to evaluate the improvement in wireless medium utilization, the possibility of simultaneous overlapping communication has been investigated with omni-directional and directional antenna. 50 nodes are randomly distributed over an area of 1000x1000 sq meter and all of them are ready to transmit. For each sample, the transmission range is same for all the nodes. 20 such random node distributions are taken for each transmission range. The *average number of node-pairs* involved in simultaneous overlapping communications under this condition in both the cases is shown in figure 2 for different transmission range. With increase in transmission range, the possibility of simultaneous communication reduces more drastically in the case of omni-directional antenna. Depending on the transmission range, the proposed MAC protocol with directional antenna improves the medium utilization with an average gain of 2 to 3.5.

Since the communication direction is chosen based on affinity (from NLST), the chosen communication link is stable and mobility has little impact on one-hop throughput.

3. Conclusion

The performance results indicate that our adaptive MAC protocol improves the medium utilization through overlapping communication among nodes using directional antenna. We are now working on a directional routing scheme based on a modified link-state based table-driven routing protocol that captures the approximate network status periodically without generating lot of control traffic.

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