An Adaptive MAC and Directional Routing Protocol for Ad Hoc Wireless Network Using ESPAR Antenna

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ABSTRACT

Use of directional antenna in the context of ad hoc wireless networks can largely reduce radio interference, thereby improving the utilization of wireless medium. To achieve this, we have proposed an adaptive MAC protocol, where each node keeps certain neighborhood information dynamically so that each node can avoid interference by keeping track of other communicating nodes at that instant of time. Moreover, appropriate mechanism for null steering of directional antennas in user terminals can help exchanging the neighborhood information in presence of on-going communication and can drastically improve the medium utilization through overlapping communications in different directions. Subsequently, we have proposed a modified link-state based table-driven routing protocol that captures the approximate network status periodically without generating lot of control traffic. It uses the directional capability of adaptive antenna for capturing, disseminating and using the network information for directional routing.

General Terms

Algorithms, Performance, Design, Experimentation.

Keywords

Ad hoc networks, Adaptive antenna, Medium access control.

1. INTRODUCTION

Ad hoc wireless networks [1,2] are envisioned as infrastructure-less networks where each node is a mobile router, equipped with a wireless transceiver. Recently, there is a growing interest in ad hoc networks and its applications. We are working towards implementing Wireless Ad Hoc Community Network (WACNet) testbed and have developed the key technologies to realize the WACNet. One of the key features of WACNet user terminals is the use of small, low-cost directional antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna, with each user terminal [3]. The objective of this paper is to illustrate the adaptive MAC and directional routing protocol in the context of WACNet.

The adaptive array antennas are normally digital beamforming antennas. On the other hand, ESPAR antenna that has been developed here relies on RF beamforming which drastically reduces the circuit complexity. 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 [3]. It has also been observed that simultaneous formation of *multiple directed beams and multiple nulls are possible* with seven-element ESPAR antennas. Since the ESPAR antenna would be a low-cost, low-power, small-sized antenna, it would help to reduce the power consumption of the user terminals in WACNet and would be able to deliver all the advantages of directional antenna.

It has been shown earlier that the use of directional antenna can largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [4-6]. 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. Thus, developing a suitable MAC and routing protocol in ad hoc network using directional antenna is a challenging task.

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. Moreover, probability of control packet collisions [5] is one of the major problems in this context. So, an appropriate null-steering mechanism needs to be implemented to avoid control packet collisions and to increase the system throughput through overlapping communication.

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In the context of ad hoc networks, several researchers feel that on-demand, reactive routing schemes that do not use periodic message of any kind would be more suitable [1,2]. However, it has been observed that these protocols perform well under light traffic and low mobility, but performance degrades significantly under high mobility and high traffic load [7]. On the other hand, several researchers have proposed proactive routing schemes based on classical distance vector or link-state routing [1]. Unfortunately, as these schemes rely on flooding of routing updates, excessive control overhead may be generated, especially in a highly mobile environment. Thus, in the context of ad hoc networks, researchers have focused on restricting the propagation of routing updates, thereby reducing the control overheads. [8] .

Whatever may be the routing scheme, they all rely on *using omni-directional antenna*. The use of directional antenna to find out a route and use it in data communication has not been explored properly. For example, if we assume that we use reactive protocol, the route discovery will have to be done using omni-directional broadcast of route request packets and omni-directional reception of route-reply packets. If we assume that we use proactive protocol, we need to find out a suitable mechanism for updating routing tables that could exploit the capability of adaptive antenna even in routing phase.

In this paper, we have proposed an adaptive MAC protocol, where 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. Moreover, appropriate mechanism for null steering of directional antennas in user terminals can help exchanging the neighborhood information in presence of on-going communication and can improve the medium utilization drastically through overlapping communications in different directions. 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 neighbor. We have proposed a modified link-state based table-driven routing protocol that captures the approximate network status periodically without generating lot of control traffic. It uses the directional capability of adaptive antenna for capturing, disseminating and using the network information for directional routing.

2. THE PROPOSED MAC PROTOCOL

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. 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 $a^{w}_{n,m}(t) = Max\ [SINR^{u}_{n,m}(t), 0 < u < 360]$. 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

In our MAC protocol, 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.

3. A MODIFIED LINK-STATE ROUTING PROTOCOL

We have designed a modified link-state protocol to make the nodes in the network *topology aware* [9]. Our primary aim is to collect all topology-related information from each node in the network and distribute them periodically (as updates) to only one of its neighbor, without flooding the network with topology-update packets. A node maintains a complete (but approximate) topology map of the entire network, called Global Link State Table(GLST). It not only depicts the connectivity between any two nodes but also the strength of connection or **affinity** value of the connection. In order to use the directional antenna, a node propagates its perception of the topology-information to only one of its neighbors at a periodic interval. Selection of target neighbor to propagate topology-map based on a criterion termed as least-visited-neighbor-first. Each node monitor a metric called recency of its neighbors to decide which of them has received least number of update messages. The neighboring node that has received least number of update messages so far will be the target node for updating.

Initially when the network commences, all the nodes are just aware of their own neighbors and are in a don't-know-state regarding the other nods in the system. However with periodic update messages from its neighbors about their neighbors, the nodes slowly get information about the other nodes and their neighbors. . It is to be noted that by controlling the periodicity of updates (P_T), it is possible to control the topology-update-traffic in the network and the accuracy of topology map stored in each of the node. So, the network would never get flooded with propagation of topology updates. The total number of update packets moving around the network will be equal to the number of nodes in the network.

A major aspect underlying the infiltration of topology information into mobile nodes is that the information carried must be recognized with a degree of correctness. Since the propagation of topology updates from different nodes is asynchronous, it becomes imperative to introduce a concept of recency of information. To implement that, every node in the network has a counter that is initialized to 0. When a topology-update-packet leaves a node, it increments that counter by one. We term this counter as recency token. The topology-update-packet while leaving a node stores the new value of the incremented recency token against the node's ID within its data structures. Thus at any point of time, the magnitude of the recency token of any node represents the number of times that node has been updated since the commencement of the network. This also implies that if two update-packets have a set of data concerning the same node, say node n, then the update-packet carrying the higher recency token value of node n has more current information about it. The concept is similar to DSDV [1] where the distance are updated according to the time-stamp or sequence number assigned by the node originating the update. However, the recency token has another role to play. Any node, say n, selects a target neighbor to propagate topology-update-packet based on the value of recency of its neighbors. The value of recency would help the node n to decide which of its neighbors has received least number of update messages. The neighboring node that has received least number of update messages so far, i.e. having lowest value of recency token, will be the target node for updating.

Whenever, a source S wants to communicate with a destination D, it computes the most stable route from its GLST. However, due to mobility and slow link-information percolation, this may not be the most stable route. As discussed earlier, the mechanism does not guarantee that each node would know the exact topology of the network. It is merely a *topology awareness* that helps each node to figure out the approximate topology of the network. However, a node closer to destination will have more accurate information about the destination. So, an intermediate node corrects the routing decision and takes alternative path to route data packets towards destination.

4. PERFORMANCE EVALUATION

Our scheme and Link-State algorithm (LS) have same memory complexity and computation complexity as both maintain the topology for the whole network and use similar path finding algorithm on the topology to compute the routes. As LS transmits one short packet for each link up-date, its packet complexity, which is defined as the average number of routing packets exchanged by a node in each time slot, can be as high as O(N) when the mobility is high. In our scheme, each node transmits one update packet to only one of its neighbors at each time slot. It also uses longer packets to optimize MAC throughput. So, it is a distinct advantage over conventional LS.

Lastly, the convergence time for LS is obviously superior to our scheme. However, it is to be noted that our aim is to collect approximate topology information at each node in order to reduce the packet complexity. The convergence time in our case depends on the periodicity of updates (P_T) and size of the network (number of nodes, N). When a node detects a change in link-status, it will be conveyed to one of its neighbor within P_T. It implies that after $2P_T$, 4 nodes in the network will be informed about this new information. Similarly, after 3 P_T, 8 nodes will be informed, assuming no loss of packets due to collisions and assuming the uniformity of information propagation among different nodes. So, P_T(logN/log2) would be the approximate time required to disseminate a new link information to all the nodes.

By adjusting $P_{T,}$ we can improve the convergence time. But at the same time, we need to look here into the congestion introduced in the system due to variation in P_T. Let us assume that an update packet would take t millisecond to physically migrate from one node to another. Let us assume that our bounded region of ad hoc operation is A, our transmission range R, the transmission zone limited by the directional antenna is 90 degree, i.e. when a node is communicating with another node, one quadrant (limited by the transmission zone) is busy but nodes in the other three quadrants can communicate with other nodes. Thus, in an average case where the topology is evenly distributed over the region A, the number of zones in area A in which update packets could migrate between nodes simultaneously, without mutual interference, equals ($4A / (\pi R^2)$). Now since the nodes are evenly distributed, the number of nodes (and consequently the number of update packets) confined in a zone will be:

P = N . (π R^2) /4A. In other words, P is the number of update packets that would from one node to another sequentially. As each update packet migrates at a time gap of P_T milliseconds and takes t millisecond to do so, the medium will be occupied by update traffic [t.P*100 / P_T] % of the time.

The proposed protocol has been evaluated on a simulated environment under a variety of conditions to estimate the basic performance of the protocol. To evaluate the improvement in one-hop communication efficiency, each node is assumed to establish a connection and communicate with one of its neighbors (randomly selected) for one second at a fixed frequency (f) of communication. For example, when f=6 per minute, it means that each node will establish a connection and communicate with one of its neighbors six times in a minute and the duration of this communication is one second. So, assuming 50 nodes, the frequency of total number of one-hop communication events (F) will be 300 per minute. The ratio of number of successful communication events per minute and the number of intended communication per minute will be the communication efficiency of the system. The result is shown in figure 1. The performance improvement is significant at a higher offered load. Moreover, the degradation in performance with increasing load is slow and gradual in case of directional antenna. 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 communication efficiency.

In order to see the efficiency of the routing protocol, the average connectivity convergence of an ad hoc network for 50 nodes at a transmission range of 250 is shown in figure 2. We have used a metric, *average connectivity convergence* [9], to quantify the deviation of actual network topology with the network topology perceived by individual nodes at any instant of time. It is to be noted that this metric is used for performance evaluation only using an off-line algorithm to determine this deviation from the actual network topology. P_T is assumed to be 50 msec. If the mobility is high, more links information would change per unit time. However, the average connectivity convergence is 98% at moderate mobility (15m/s), indicating that the nodes, on the average, can estimate the topology with 98% correctness at any instant of time.

Fig 1 Communication Efficiency at different offered load

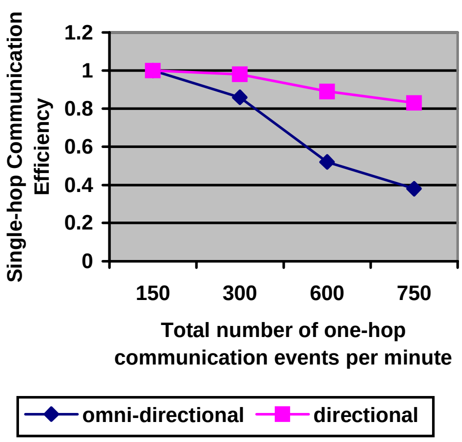

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Fig. 2 Average Connectivity Convergence at P_T=50 msec.