An Adaptive MAC Protocol for Wireless Ad Hoc Community Network (WACNet) Using Electronically Steerable Passive Array Radiator Antenna

S. Bandyopadhyay, K. Hasuike, S. Horisawa, S. Tawara
ATR Adaptive Communications Research Laboratory
2-2-2 Hikaridai Seika-cho, Soraku-gun, Kyoto 619-0288 Japan

Abstract - **In the context of ad hoc networks, use of directional antenna can largely reduce the radio interference, thereby improving the utilization of wireless medium and consequently the network throughput. However, in order to fully exploit the capability of directional antenna, whenever a source and a destination 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. In our adaptive MAC protocol, each node keeps certain neighborhood information dynamically so that each node can keep a track of 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 drastically improve the medium utilization through overlapping communications in different directions.**

1. INTRODUCTION

Ad hoc wireless networks [1,2] are envisioned as an 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 [3] and have developed the key technologies to realize the WACNet. The key features of WACNet are the use of small, low-cost directional antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna, with each user terminal [4,5,6] and implementation of adaptive MAC and directional routing protocol to exploit the capabilities of directional antenna. The objective of this paper is to illustrate the adaptive MAC protocol in the context of WACNet.

The adaptive array antennas are normally digital beamforming (DFB) antennas. On the other hand, ESPAR antenna that has been developed here (for a detailed description, please see [5][6]) 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 360degree continuous beam / null steering is possible with seven-element ESPAR antenna, with a simultaneous 8 dBi beam gain and –30 dBi null [5]. 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 the radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [7-14]. 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. This difficulty is mainly due to mobility and lack of centralized control in ad hoc networks [14]. Thus, developing a suitable MAC and routing protocol in ad hoc network using directional antenna is a challenging task.

Some researchers in the past have tried to address this challenge in several ways. For example, Zander [12] has proposed to use directional antenna for performance improvement in slotted ALOHA multihop packet radio networks. In [7], a dynamic slot assignment protocol for directional antenna has been proposed in the context of broadband wireless cellular networks. Performance improvement of a slotted ALOHA packet radio network using directional antenna have also been reported in [9][10]. MAC protocols using directional antenna has also been proposed in [11], where each station is assigned a tone which is unique to its neighbors. When a station receives a packet, it broadcasts its tone immediately for a period of time so that its neighbor can identify its presence and avoid transmitting to its direction.

In order to tackle the hidden terminal problems, two MAC protocols that rely on RTS-CTS type handshaking as in IEEE 802.11 have been suggested in recent past in the context of ad hoc networks with directional antennas [13,14].

In [13], a set of D-MAC (Directional MAC) schemes was proposed to show performance improvement over omni-directional MAC as in IEEE 802.11. Here, the mobile nodes are assumed to know the physical locations of themselves and their neighbors using GPS. In [14], 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 transmission.

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 [11] 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 [14], 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 such as a compass in each node. However, this requires additional hardware in each user terminal. Moreover, probability of control packet collisions [13] 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.

In our adaptive MAC 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. 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.

II. Description of the Proposed Framework

A. 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). *$SINR^{\alpha}_{n,m}(t)$ (Signal-to-Interference and Noise Ratio) is a number associated with each link $l^{\alpha}_{n,m}$, and is a measurable indicator of the strength of radio connection from node n to node m at an angle α 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 where we assume that nodes i, j, k and l 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	l
0	$SINR^{0}_{n,i}(t)$	$SINR^{0}_{n,j}(t)$	$SINR^{0}_{n,k}(t)$	$SINR^{0}_{n,l}(t)$
30	$SINR^{30}_{n,i}(t)$	$SINR^{30}_{n,j}(t)$	$SINR^{30}_{n,k}(t)$	$SINR^{30}_{n,l}(t)$
60	$SINR^{60}_{n,i}(t)$	$SINR^{60}_{n,j}(t)$	$SINR^{60}_{n,k}(t)$	$SINR^{60}_{n,l}(t)$
…..	…..	…..	…..	……
330	$SINR^{330}_{n,i}(t)$	$SINR^{330}_{n,j}(t)$	$SINR^{330}_{n,k}(t)$	$SINR^{330}_{n,l}(t)$

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 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.

B. Forming Neighborhood-Link-State Table from AST

Affinity of node m with respect to node n, $a^{\theta}_{n,m}(t)$, is a number associated with a link $l^{\theta}_{n,m}$ at time t , such that $a^{\theta}_{n,m}(t)$ = Max [$SINR^{\alpha}_{n,m}(t)$, 0< α <360]. In other words, the transmission angle θ 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 θ with respect to n. Based on this, a Neighborhood-Link-State Table (NLST) at each node is formed as shown below. 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 [$SINR^{\alpha}_{n,i}(t)$, 0< α <360]
j	Max [$SINR^{\alpha}_{n,j}(t)$, 0< α <360]
k	Max [$SINR^{\alpha}_{n,k}(t)$, 0< α <360]
l	Max [$SINR^{\alpha}_{n,l}(t)$, 0< α <360]

III. An Adaptive Medium Access Control Protocol

A. Assumptions

We assume that a set of nodes N move around in a two-dimensional closed space and share a common wireless channel for communication. Each node is equipped with ESPAR antenna with a capability of 360 degree beam/null steering. We assume that the effective angular width of transmission beam ∂ is 60 degree.

Each node can either receive or transmit at a time and multiple reception/transmission by a node is not possible. However, a node can transmit same signal in multiple direction. Each node as a receiver can steer and adjust nulls to prevent interference from unwanted signals, if the direction of interference is known.

During data communication, if the receiver rotates, the process will not be affected, since the receiver will orient its antenna adaptively to always pick up the strongest signal from the transmitter. However, if the transmitter rotates, the transmission angle will change and the receiver may lie outside this transmission angle. Rotational movement is a major source of instability in this context. For the time being, we assume that the rotational movements of nodes, involved in a data communication, are negligible during data transmission.

B. Single Communication

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 the 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 the 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 subsequently.

B. Multiple Simultaneous Communications

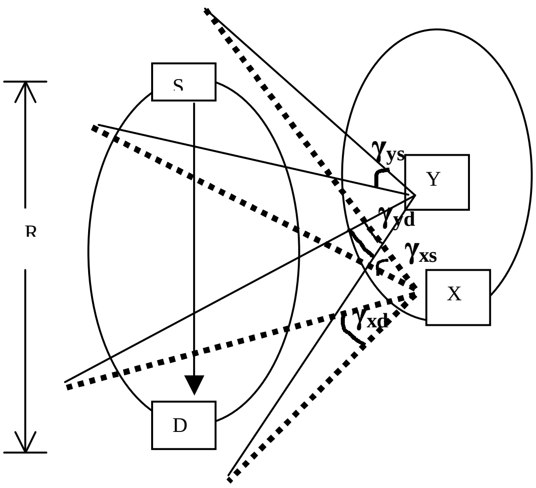

Fig. 1. X and Y is neighbors of S and D

Figure 1 illustrates the mechanism of two simultaneous communications in the same region. Let us assume that nodes S and D are communicating. We define neighbors of $n \in N$ as a set of nodes within the omni-directional transmission range R_n of n.

The directional beam from S covering D is shown in the figure. Now, another pair of nodes X and Y, both in the neighborhood of S and D, desires to communicate (fig. 1). Both of them have already received RTS/CTS from S-D. From their respective ASTs, X knows the value of angle γ_{xs} and γ_{xd} and Y knows the value of angle γ_{ys} and γ_{yd}.. If the directional beam from X to Y captures S or D, i.e. if the area covered by angle γ_{xy} overlaps with that covered by angle γ_{xs} or γ_{xd}, 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 intrude into the area specified by angle γ_{xs} or γ_{xd}. However, the RTS issued by X will be *selectively omni-directional :* X will issue RTS only to nodes lying outside the area specified by angle angle γ_{xs} or γ_{xd}.

Similarly, Y will respond to this RTS by sending a CTS if the directional beam from Y to X does not captures S or D, i.e. if the area covered by angle γ_{yx} does not overlaps with that covered by angle γ_{ys} or γ_{yd}. The CTS issued by Y will also be *selectively omni-directional :* Y will issue CTS only to nodes lying outside the area specified by angle angle γ_{ys} or γ_{yd}.

Now, the nodes in the areas covered by angle γ_{xs} and γ_{xd} and by angle γ_{ys} and γ_{yd} will not receive RTS/CTS from X and Y and therefore will be unaware of this communication event. So, some other nodes in these areas covered by these angles (including S or D, after the communication between S and D is over) may initiate another communication, which may disturb the communication between X and Y. To avoid this, antenna in X will *steer its nulls in the directions specified by angle γ_{xs} and γ_{xd} and* antenna in Y will *steer its* *nulls in the directions specified by angle γ_{ys} and γ_{yd}* 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 existing 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 S and D, nodes in the region specified by angle γ_{xs} and γ_{xd} and by angle γ_{ys} and γ_{yd} will not receive RTS and/or CTS from X and Y. So, all nodes in this region will be unaware of this communication between X and Y. So, some other nodes in the areas 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 specified by angles γ_{x-} and γ_{y-} respectively* 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.

A simpler case is, when node X is within the transmission range of D but outside the range of S. X has received CTS from D, so, it should not form any directional beam towards D to avoid interference. The direction of D is known to X from its AST. Node S is any way out of its range. So, X can communicate in other directions. Same consideration applies when node X is within the range of S but outside the range of D.

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.

To summarize, let us assume that node X wants to communicate with node Y. Let us also assume that $\{n_1, n_2, \ldots, n_n\}$ are the set of neighbors of X who are already involved in some on-going communication processes. Similarly, let us assume that $\{m_1, m_2, \ldots, m_m\}$ are the set of neighbors of Y who are already involved in some on-going communication processes. Nodes X and Y can initiate a communication if

- the directional beam from X to Y does not captures $\{n_1, n_2, \ldots, n_n\}$, i.e. if the area covered by beam-angle γ_{xy} from x to y does not overlaps with that covered by angle $\gamma_{xn1}, \gamma_{xn2}, \ldots,$ or γ_{xnn}; and,
- the directional beam from Y to X does not captures $\{m_1, m_2, \ldots, m_m\}$, i.e. if the area covered by beam-angle γ_{yx} from y to x does not overlaps with that covered by angle $\gamma_{ym1}, \gamma_{ym2}, \ldots,$ or γ_{ymm}.
- X and Y can steer their nulls towards the direction of nodes currently involved in communication process.

Other idle nodes in the region covered by X-Y directional beam will wait in omni-directional receive mode with their nulls steered towards X-Y communication direction.

IV. Performance Evaluation

The proposed protocol has been evaluated on a simulated environment under a variety of conditions to estimate the basic performance of the protocol. In the simulation, the environment is assumed to be a closed area of 1000 x 1000 square meters in which mobile nodes are distributed randomly. We present simulation results for networks with 50 mobile hosts, operating at a transmission range of 200 to 350 m. The speed of movement of individual node ranges from 5 m/sec to 15 m/sec. Each node starts from a home location, selects a random location as its destination and moves with a uniform, predetermined velocity towards the destination. Once it reaches the destination, it waits there for a pre-specified amount of time, selects randomly another location and moves towards that. However, in the present study, we have assumed zero waiting time to analyze worst-case scenario. For simplicity, we assume that $a^{\theta}_{nm}(t)$ to be equal to $a^{\theta}_{mn}(t)$ and the transmission range R for all the nodes are equal. The effective width of directional beam is assumed to be 60° i.e. angle γ as shown in figure 1 is 60°.

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.

In order 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 3. At a low offered load, the performance improvement with directional antenna is not so visible. However, 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.

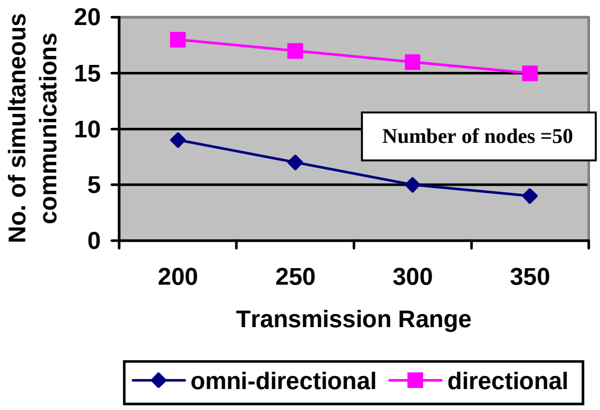

Fig.2. Number of simultaneous communication possible with (i) omni- directional and (ii) directional antenna, when all nodes are ready to communicate.

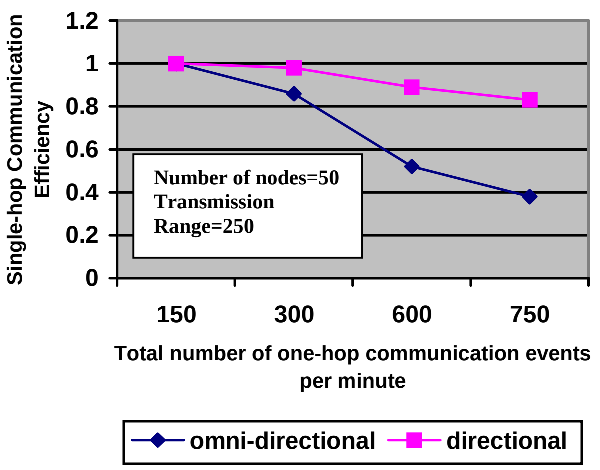

Fig.3 Communication Efficiency at different offered load

V. CONCLUSION

The advantage of adaptive MAC protocols will be more visible, if we have a proper routing scheme above the MAC layer that uses the directional capability of adaptive antenna. Routing schemes that rely on omni directional flooding will not be effective in this context. We are working on 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. Since our current simulator does not capture the effect of environment, we are currently working on OPNET simulation environment [15] to model and study our system behavior. We are in the process of implementing MAC and directional routing protocol on OPNET.

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