A Network-Aware MAC and Routing Protocol for Effective Load Balancing in Ad Hoc Wireless Networks with Directional 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. Our major contribution in this paper is to devise a routing strategy, along with a MAC protocol, that exploits the advantages of directional antenna in ad hoc networks for improved system performance. In this paper, we have illustrated a MAC and routing protocol for ad hoc networks using directional antenna with the objective of effective load balancing through the selection of *maximally zone disjoint routes.* Zone-disjoint routes would minimize the effect of route coupling by selecting routes in such a manner that data communication over one route will minimally interfere with data communication over the others. In our MAC protocol, each node keeps certain neighborhood status information dynamically in order that each node is *aware of its neighborhood and communications going on in its neighborhood* at that instant of time. This status information from each node is propagated periodically throughout the network. This would help each node to capture the approximate network status periodically that helps each node to become *topology-aware* and *aware of communications going on in the network*, although in an approximate manner. With this status information, each intermediate node adaptively computes routes towards destination. The performance of the proposed framework has been evaluated on QualNet Network Simulator with DSR (as in QualNet) as a benchmark. Our proposed mechanism shows four to five times performance improvement over DSR, thus demonstrating the effectiveness of this proposal.

Categories and Subject Descriptors
C.2.1. [**Computer-Communication Networks**]: Network Architecture and Design – *wireless communication*; C.2.2. [**Computer-Communication Networks**]: Network Protocols – *routing protocols*

General Terms
Algorithms, Performance, Design, Experimentation.

Keywords
Ad hoc networks, Directional antenna, Medium access control, Routing Protocol.

1. INTRODUCTION
It has been shown earlier that the use of directional antenna in the context of ad hoc wireless networks can largely reduce the radio interference, thereby improving the utilization of wireless medium and consequently the network performance [1-10]. But, at the same time, it is difficult to find ways to set and control the directions of such antenna at each node in order to achieve the expected performance improvement in a multi-hop communication environment of ad hoc networks. This difficulty is mainly due to mobility and lack of centralized control in ad hoc networks. Thus, developing a suitable MAC and routing protocol in ad hoc network to exploit the advantages of directional antenna for overall performance improvement is a challenging task.

Recently, several MAC protocols with directional antennas have been proposed in the context of ad hoc networks in order to improve the medium utilization with increased number of simultaneous communications. However, even if we have an efficient directional MAC protocol, it alone would not be able to guarantee good system performance, unless we have a proper routing strategy in place that exploits the advantages of directional antenna. Our major contribution in this paper is to devise a routing strategy, along with a MAC protocol, that exploits the advantages of directional antenna in ad hoc networks.

Let us consider the scenario in Figure 1 where source S_1 is communicating with destination D_1 through N_1 and N_2. At the same time, suppose another source S_2 also wants to communicate with destination D_2. Suppose, there are three possible paths: {S_2, N_1, N_2, D_2}, {S_2, N_3, N_4, D_2} and {S_2, N_5, N_6, D_2}. If S_2 uses the first path that overlaps with the path used by S_1, then simply using directional antenna cannot improve the routing performance. If S_2 uses the second path, then also routing performance will deteriorate because of the phenomenon known as route coupling [11, 12, 16]. Route coupling occurs when two routes are located physically close enough to interfere with each other during data communication. As a result, the nodes in those two routes are constantly contending for access to the medium they share. In Figure 1, since the nodes belonging to these two routes are within the transmission zone of one another (even if we use directional antenna, as shown), these two communications cannot happen simultaneously: N_1 and N_3 cannot receive data simultaneously from S_1 and S_2 respectively; similarly, N_2 and N_4 cannot receive data simultaneously from N_1 and N_3 respectively.

So, the routing performance between any source and destination does not depend only on the congestion characteristics of the nodes in that path. Pattern of communication in the neighborhood region will also contribute to this delay. This is a phenomenon known as *route coupling*. Thus, even if $\{S_1, N_1, N_2, D_1\}$, $\{S_2, N_3, N_4, D_2\}$ are node-disjoint, routing performance will deteriorate in this context, even if we use directional antenna.

The impact of directional antenna on routing would be visible, if S_2 selects the third path i.e. $\{S_2, N_5, N_6, D_2\}$. These two routes $\{S_1, N_1, N_2, D_1\}$ and $\{S_2, N_5, N_6, D_2\}$ are coupled with each other, if we use omni-directional antenna (as shown with dotted line in Figure 1). But they are *completely decoupled*, if we use *directional antenna*, as shown in Figure 1. These two routes are said to be *zone-disjoint,* since data communication over one path will not interfere with data communication over the other path.

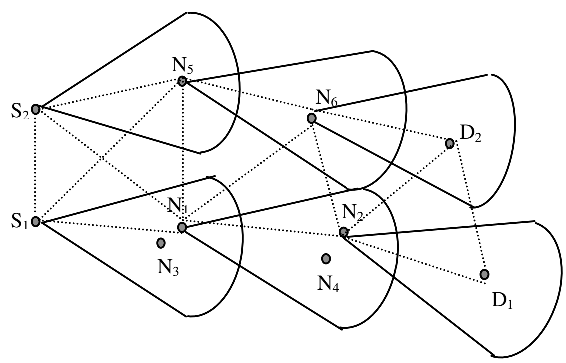

Figure 1. Zone Disjoint Communications between S_1 -D_1 and S_2 -D_2. with Directional Antenna

Thus, it is imperative that a routing strategy with *effective load balancing* has to be in place in order to exploit the capacity of directional antenna towards improved medium utilization. In recent times, some researchers have developed routing strategies with load balancing in ad hoc networks using omni-directional antenna [13,14]. They consider intermediate node routing loads or nodal activity information of all nodes as the primary route selection metric. The application of multipath routing techniques in mobile ad hoc networks has also been explored to reduce end-to-end delay and perform load balancing. M. R. Perlman et al. [12] demonstrates that the multipath routing can balance network loads in their recent paper. The Split Multipath Routing (SMR), proposed in [15], focuses on building and maintaining maximally disjoint multiple paths. But none of the proposals have considered the route-coupling phenomenon for effective load balancing.

Distributing the routing tasks evenly throughout the network has two major advantages in this context. First, it prevents loads concentrating on a set of nodes and spreads it among other nodes in a uniform manner, thereby reduces the possibility of power depletion of a set of heavily-used nodes; and, secondly, it distributes the traffic all over, thus reducing congestion and improving end-to-end delay. Most of the current proposals on load balancing in this context would help to distribute traffic all over and thus, can achieve the first advantage as mentioned above. However, because of route coupling in wireless medium, as illustrated in Figure 1, distribution of traffic alone cannot guarantee improved end-to-end delay. As illustrated in Figure 1, $\{S_1, N_1, N_2, D_1\}$ and $\{S_2, N_3, N_4, D_2\}$ are node-disjoint and consequently satisfies the criteria for load balancing. But, since they are coupled with each other, end to end delay will increase. Larger the degree of coupling, the larger will be the average end-to-end delay for both paths [11]. This is because two paths have more chances to interfere with each other's transmission due to the broadcast feature of radio propagation. That is why it is important to discover *zone disjoint routes* for *effective load balancing*.

But getting zone-disjoint or even partially zone disjoint paths using omni directional antenna is difficult since transmission zone is larger. Transmission zone for each node in case of omni-directional antenna = πR^2 where beam angle $\theta = 360^\circ$ and transmission range is R. By controlling the beam angle θ (<360°) using directional antenna, coverage area of each node may be reduced to $\theta.(R^2/2)$. In our example, two routes $\{S_1, N_1, N_2, D_1\}$ and $\{S_2, N_5, N_6, D_2\}$ are zone-disjoint, only if we use directional antenna. It has been shown [16] that it is much easier to get zone-disjoint routes and, consequently, the effect of route coupling can be drastically reduced, if we use directional antenna instead of omni-directional antenna with each user-terminal forming an ad hoc network.

In this paper, we have illustrated a MAC and routing protocol for ad hoc networks using directional antenna with the objective of effective load balancing through the selection of *maximally zone disjoint routes*, as explained above. In our MAC protocol, each node keeps the neighborhood information dynamically in order that each node is *aware of its neighbors and the communications going on in its neighborhood* at that instant of time. This would help each node to avoid interference by keeping track of other communicating nodes in its neighborhood at that instant of time. At the same time, it keeps track of directional access information of its neighborhood nodes. This helps each node to determine the best possible direction of communication with any of its neighbors. This information from each node is propagated periodically to its neighbors; each of them assimilates this information and further propagates to its neighbors at a periodic interval. Thus, information percolated throughout the network would help each node to capture the approximate network status periodically without generating lot of control traffic. Thus, each node becomes *topology-aware* and *aware of communications going on in the network*, although in an approximate manner. We have proposed a table-driven routing protocol for load-balanced routing. We have defined and developed a metric for measuring *maximally zone-disjointness* and used it as route selection criteria for load balancing. However, since network awareness at each node is only a *perception* about network status rather than *actual* network status, each intermediate node adaptively corrects and modifies routing decision during routing. The performance of the proposed framework has been evaluated on QualNet Network Simulator [22], where we have used DSR (Dynamic Source Routing) [23] (as implemented in Qualnet) as a benchmark. Our proposed mechanism shows five times performance improvement over DSR, thus demonstrating the effectiveness of this proposal.

The paper is organized as follows. Section 2 starts with system description. Section 3 illustrates the information percolation mechanism in the network. Section 4 illustrates a location tracking mechanism and a receiver-oriented, rotational sector based directional MAC protocol that uses neighborhood awareness for generating RTS/CTS. Section 5 illustrates the routing protocol where each node uses the network status information, as perceived by that node, to compute maximally zone-disjoint route from that node to destination. Section 6 depicts the performance evaluation on QualNet followed by concluding remarks in section 7.

2. SYSTEM DESCRIPTION

2.1 Antenna Model

We are working towards implementing Wireless Ad Hoc Community Network testbed where each user terminal uses a small, low-cost adaptive antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna [17,18]. The adaptive array antennas are normally digital beamforming antennas. On the other hand, ESPAR antenna 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, the parasitic elements form 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. The advantage of using ESPAR antenna as generalized switched beam antenna is that, with small number of antenna elements, continuous tracking is possible and we can have variable number of beam-patterns. Since ESPAR antenna would be a low-cost, low-power, small-sized antenna, it would help to reduce the power consumption of the user terminals and would be able to deliver all the advantages of switched beam antenna.

In this study, we assume an ad hoc network consisting of N nodes, each equipped with directional antenna and distributed over a two-dimensional space of area A. Each node $n \in N$ is having a unique node identifier. Each node has a transmission range R and transmission beam-width β that is assumed to be same for all nodes in this study. When β is set to 360 degree, it operates in omni-directional mode. In our simulation environment, directional β is assumed to be 45 degree. As the mobility model, we have assumed Random Way-Point model**:** a node randomly chooses a destination point and moves to the target point with a constant speed v, uniformly selected from the set of velocities between a specified v_{max} and $v_{min.}$ Once the target is reached, the node stops for a fixed time called Pause Time, then the process is repeated.

2.2 Some Important Definitions

Definition 1. When a node n forms a transmission beam at an angle α and a beam-width β with a transmission range R, the coverage area of n at an angle α is defined as **transmission_zone$_n$ (α,β,R)** (Figure 2) of node n. It implies that if a node $m \in N$ is within the transmission_zone$_n$ (α,β,R) and m is in receive mode, then, whenever n transmits a message at that transmission angle α with respect to n and beam-width β and transmission range R, it will be received by m. When node m moves out of the transmission_zone$_n$ (α,β,R), the connectivity between n and m is lost. Since transmission beam-width β and transmission range R are fixed here in our study, we will refer **transmission_zone$_n$ (α,β,R)** as **transmission_zone$_n$ (α)** in subsequent discussions.

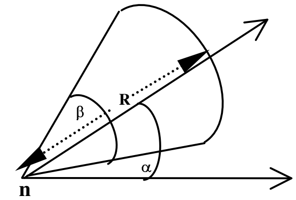

Figure 2. Transmission Zone$_n$(α,β,R)

Definition 2. We define **neighbors of n** (G^n) $\in$N as a set of nodes within the omni-directional transmission range R of n.

Definition 3. A subset of G^n, $G^n_\alpha \in G^n$, is defined as the **directional neighbors of n**, where the nodes in G^n_α lie within its transmission_zone$_n$ (α).

***Definition 4*. Active Node List** [ANL(t)] is a set of nodes in the network actively participating in any communication process at an instant of time t.

***Definition 5*. Active Directional Neighbors of node n at transmission_zone$_n$ (α)** [$ActG^n_\alpha$ (t)] is a set of nodes within the transmission_zone$_n$ (α) that are actively participating in any communication process at that instant of time (i.e. belongs to ANL(t) at that instant of time t). So, $ActG^n_\alpha(t)=G^n_\alpha(t) \cap ANL(t)$.

***Definition 6*. Correlation factor of node n_i in a path P** [η^{ni} (P)], where n_j is the next-hop from n_i in path P and $\alpha(n_i \rightarrow n_j)$ is the transmission zone formed by n_i towards n_j in order to communicate with n_j, is defined as the number of active directional neighbors of node n_i at transmission_zone$_{ni}$($\alpha(n_i \rightarrow n_j)$). So, $\eta^{ni}(P) = (\lvert ActG^{ni}_{\alpha(ni \rightarrow nj)}(t) \rvert)$.

Definition 7. **Correlation factor η of path P** [η (P)] is defined as the sum of the correlation factors of all the nodes in path P. So, $\eta(P)= \sum_{\forall n \in P} (\lvert ActG^{ni}_{\alpha(ni \rightarrow nj)}(t) \rvert)$. Correlation factor is used to measure route coupling [11,16].

When η (P) =0, path P is said to be *zone-disjoint* with all other *active paths*, where active paths are those paths participating in communication process at that instant of time. Otherwise, the path P is η – related with other active paths.

As an example, let us refer back to Figure 1. Initially, source S_1 is communicating with destination D_1 through N_1 and N_2. So, ANL(t) contains {S_1, N_1, N_2, D_1}. Now, S_2 wants to communicate with D_2 and selects a path P={S_2, N_5, N_6, D_2}. Let us first consider the case with omni-directional antenna (Figure 1). Both S_1 and N_1 are within the transmission zone (which is 360 degree in this case) of S_2. So, η^{S2}(P)=2. Since S_1 and N_1 are within the omni-directional transmission zone of N_5, η^{N5} (P)=2. Similarly, η^{N6}(P)=2. So, η (P)= 6, when we use omni-directional antenna.

When we use directional antenna, the transmission zones formed by S_2, N_5, and N_6 do not contain any node from ANL(t), as shown in Figure 1. So, η (P)= 0, when we use directional antenna.

It has been shown that larger the correlation factor, the larger will be the average end-to-end delay for both paths [11]. This is because two paths with larger correlation factor have more chances to interfere with each other's transmission due to the broadcast feature of radio propagation. Based on this study, it can be concluded that the efficient routing in ad hoc network is heavily dependent on the correlation factor among multiple routes.

However, it is difficult to get routes with low correlation factor using omni-directional antenna. As evident from Figure 1, with directional antenna, it is possible to de-couple multiple routes, which enables us to get routes with much lower correlation factor as compared to that with omni-directional antenna.

3. NETWORK-AWARENESS

In this paper, we propose a mechanism such that each node is not only neighborhood-aware but also network-aware. This network awareness would be helpful to implement a proactive routing scheme, as will be discussed in section 5.

Each node n in the network has the following four network-status information:

- **Neighborhood Link-State Table ($NLST_n$)**: In order to track the direction of its neighbor, each node n periodically *collects* its neighborhood information and forms a Neighborhood Link-State Table (NLST). For each neighbor $m \in G^n$, $NLST_n(t)$ of node n specifies the maximum strength of radio connection, $SIGNAL^{\theta}_{n,m}(t)$, as perceived by n, at a particular direction. Thus, *$SIGNAL^{\theta}_{n,m}(t)$ is the maximum strength of received signal at node n from its neighboring node m at an angle θ with respect to n and as perceived by n at any point of time t.* The NLST of node n will help us to determine the best possible direction of communication with any of its neighbors.
- **Neighborhood Active Node List ($NANL_n$):** NANL at node n contains the communication-activity-status of its neighbors. In other words, if any of the neighbors of node n is actively participating in a communication process or inactive, node n records that information in a list called Neighborhood Active Node List [$NANL_n(t)$]. This helps a node to become neighborhood-communication-aware.
- **Active Node List (ANL_n):** It contains the perception of node n about communication activities in the network. It is a list in node n containing all active nodes in the network, as perceived by n at that instant of time.
- **Global Link-State Table ($GLST_n$):** It contains the network topology information as perceived by n at that instant of time.

Each node *broadcasts its ANL at a periodic interval*, say T_A. Broadcast of ANL serves two purposes: when a node n receives ANL from all its neighbors (say node i, j and k),

- Node n forms the $NLST_n$ to include node i, j and k as its neighbors and records the best possible direction of communicating with any of them.
- Node n also records the communication activity status of node i, and similarly for other neighbors, thus forming its own NANL, and subsequently upgrades its ANL.

Each node *broadcasts its GLST at a periodic interval,* say, T_G. When a node n receives GLST from its neighbors, it updates its own GLST, as will be illustrated later.

In our system, T_A = 2 seconds and T_G = 10 seconds without mobility. With mobility, T_A and T_G are 1 second and 5 seconds respectively. The reason for broadcasting two packets at two intervals is as follows: ANL captures the communication activity and once a communication starts, immediately a set of nodes will be affected. So, ANL needs to be propagated faster than GLST. Moreover, ANL serves as beacon. So, by the faster propagation of ANL, not only the critical information of active nodes can be percolated faster, but also accurate neighborhood information (direction, signal level) can be obtained. Since we are implementing fisheye concept [20], accurate neighborhood information is required faster.

On the other hand, GLST is the global information about connectivity of all nodes. It reflects the change of topology with respect to physical mobility (which is much slower compared to signal propagation). Moreover, GLST at any node need not be so accurate. That is why GLST, the larger packet, propagates slowly and ANL, the smaller packet, propagates faster.

3.1 Formation of NLST and NANL

Any node, say n, forms its $NLST_n$ incrementally on receiving ANL packets from any of its neighbors, say m. Since n will receive ANL packet from m by setting its antenna at a particular angle, it knows the best possible direction to communicate with m and the maximum strength of radio connection, $SIGNAL^{\theta}_{n,m}(t)$, as perceived by n, at that particular direction Here, we are assuming symmetric links.

Any node, say n, forms its $NANL_n$ with its own activity status first. Whenever n needs to issue RTS, indicating that it has a desire to communicate, it sets itself as *active node;* whenever it is not issuing RTS for a threshold period of time, it sets itself as inactive. Additionally, whenever node n receives an RTS from its neighbor, say, m, it sets m as active node in its $NLST_n$. Whenever node m de-activates itself, this information reaches n through periodic broadcast of ANL from m. On receiving that, n sets m as inactive in its $NANL_n$.

3.2 Formation of ANL

Each node periodically broadcasts its Active Node List that contains its perception about communication activities in the network. On receiving periodic ANL from different nodes, each node combine them to form revised ANL and waits for a periodic interval to broadcast it to its neighbors.

At each node, ANL first gets updated by Neighborhood Active Node List (NANL) of that node. So, initially when the network commences, all the nodes are just aware of the activity status of their own neighbors and are in a *don't-know-state* regarding the other nodes in the system. Periodically, each node broadcasts its ANL as update to its neighbors. With this periodic update messages from its neighbors about their neighbors, the nodes slowly get activity information about the other nodes and their neighbors. Thus, each node updates its own ANL based on received update messages from other nodes.

A major aspect underlying the infiltration of network status information into mobile nodes is that the information carried must be recognized with a degree of correctness. Since the propagation of updates from different nodes is asynchronous, it becomes imperative to introduce a concept of recency of information [21, 24]. For example, let us assume two ANL packets A_1 and A_2 arrive at node n, both of them carrying information about node m which is multi-hop away from node n. In order to update the information at node n about node m, there has to be a mechanism to find out who carries the most recent information about node m: A_1 or A_2?

To implement this, we have used the same concept of recency token [24] and a mechanism to increment it appropriately. If two update messages have a set of data concerning the same node, say node n, then the update message carrying the higher recency value of node n has more current information about it. The structure of ANL at a node n is given in Table 1.

Table 1. The Structure of ANL

Nodes	n_1	n_2	…	n_N
Recency	R_1	R_2	…	R_N
State	S_1	S_2	…	S_N

Here, R_i is the recency of node n_i in a network of N nodes and S_i denotes the corresponding activity status of each node, which can be either 0(inactive) or 1(active).

3.3 Formation of GLST

Each node maintains a Global Link State Table (GLST) to capture network connectivity information. At each node, GLST first gets updated by Neighborhood Link State Table (NLST) of that node. So, 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 nodes in the system. Periodically, each node broadcasts its GLST as update to its neighbors. With this periodic update messages from its neighbors about their neighbors, the nodes slowly get information about the other nodes and their neighbors. Thus, each node updates its own GLST based on received update messages from other nodes. It is to be noted that by controlling the periodicity of updates, it is possible to control the update-traffic in the network and the accuracy of network status information stored in each of the node. For example, if the propagation of update messages is too frequent, the control traffic will increase but the accuracy of network status information stored in each node will also be better. However, the network would never get flooded with propagation of updates. The maximum number of update packets in the network at any point of time is always less than the number of nodes in the network. In this case also, we need to implement the concept of recency as explained in the context of ANL propagation. This implies that if two GLST update messages have a set of data concerning the same node, say node n, then the update message carrying the higher recency token value of node n has more current information about it.

As and when a node n receives GLST from other nodes, it updates its GLST. In order to do that, the recency tokens of all the nodes stored in the GLST of n and the recency tokens of all the nodes stored in the recently arrived update packet are compared. If the recency token of any node, say X, in GLST of n happens to be less than that in the update packet, then it is obvious that the update packet is carrying more recent information about node X. So, the entire information about node X in the GLST of node n is overwritten by the received information of X in the update packet. This step is performed asynchronously for all the update packets as they arrive at that host node n. This step helps the node n to acquire all the recent information that it can gather from the update packets.

It is to be noted that the mechanism does not guarantee that each node would know the exact status of the network. It is merely an *awareness* that helps each node to figure out the approximate status of the network. This is similar to *fisheye* approach [20] that helps to maintain accurate status information about the immediate neighborhood of a node, with progressively less accurate details as the distance increases. The structure of GLST at any node n is given in Table 2.

Table 2. The structure of GLST

Nodes	**Recency**	**Neighbors**
n_1	R_1	→ {…………}
n_2	R_2	→ {…………}
…	…	→ {…………}
n_i	R_i	→ {$\langle n_j,\alpha(n_i,n_j)\rangle$ $\langle n_k,\alpha(n_i,n_k)\rangle$………}
…	…	→ {…………}
n_N	R_N	→ {…………}

Here, R_i is the recency of node n_i in a network of N nodes and $\langle n_j,\alpha(n_i,n_j)\rangle$ denotes that n_j is a neighbor of n_i where $\alpha(n_i,n_j)$ indicates the transmission beam-angle α at which n_i can best communicate with n_j.

4. LOCATION TRACKING AND MAC PROTOCOL

Usually, in ad hoc networks, all the nodes are equipped with omni-directional antenna. However, ad hoc networks with omni-directional antenna uses RTS/CTS based floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. Consequently, lot of nodes in the neighborhood of transmitter and receiver has to sit idle, waiting for the data communication between transmitter and receiver to finish. To alleviate this problem, researchers have proposed to use directional antenna that would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [2-5].

In order to fully exploit the capability of directional antenna, all the neighbors of a source and destination should know the direction of communication so that they can initiate new communications in other directions, thus preventing interference with on-going data communication between source and destination. Thus, it becomes imperative to have a mechanism at each node to track the direction of its neighbors.

However, this direction tracking mechanism in the context of wireless ad hoc networks with directional antenna is a serious problem, since it incurs a lot of control overhead. Direction tracking has been done in [1] 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 [4], the proposed MAC protocol need not know the location information; the source and destination nodes identify each other's direction during omni-directional RTS-CTS exchange in an on-demand basis. 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, because of omni-directional transmission of RTS and CTS packets, this protocol provides no benefits in the spatial reuse of the wireless channel. In [2], the use of GPS is proposed to track the location of each node but the exact mechanism of information exchange and the consequent overhead have not been discussed. For example, in [3], it has been assumed that a node knows the direction of transmission to access its neighbor directionally, but the location tracking mechanism has not been illustrated. Moreover, both the methods in [2] and [3] require additional hardware in each user terminal. In earlier work of Bandyopadhyay, et al [5,10], a MAC protocol has been proposed, where each node keeps its neighborhood information dynamically through the maintenance of an Angle-SINR Table (AST). In this method, in order to form AST, each node periodically sends a directional beacon in the form of a directional broadcast, sequentially in all direction at 30-degree interval, covering the entire 360-degree space. However, the overhead due to control packets is very high in this method.

In this work, our MAC protocol is basically a *Receiver-oriented, Rotational Sector Based Directional MAC protocol* which also serves as a Location Tracking mechanism. Here, each node waits in omni-directional-sensing-mode while idle. Whenever it senses some signal above a threshold, it enters into *rotational-sector-receive-mode*. In rotational-sector-receive mode, node n rotates its directional antenna sequentially in all direction at 45-degree interval, covering the entire 360-degree space in the form of the sequential directional receiving in each direction and senses the received signal at each direction. After one full rotation, it decides the best possible direction of receiving the signal with maximum received signal strength. Then it sets its beam to that direction and receives the signal.

However, in order to enable the receiver decoding the received signal, each control packet is transmitted with a preceding tone with a duration such that the time to rotate a receiver's rotational receive beam through 360 degree is little less than the duration of the tone (200 microseconds in our case). The purpose of this transmitted tone before any control packet is to enable the receiver to track the best possible direction of receiving the signal. Once it sets its beam to that direction, the purpose of tone signal is over and subsequently the control packet is transmitted.

In this proposed framework, we have used four types of broadcast (omni-directional) control packets: Active Node List (ANL), Global Link State Table (GLST), RTS (Request to send) and CTS (clear to send) for medium access control. Another control packet ACK is directional control packet. Data is transmitted directionally after RTS/CTS handshaking is done. ANL and GLST are periodic signal, transmitted from each node at a pre-defined interval. At each periodic interval, each node, say m, broadcasts ANL to its neighbors, if the medium is free. As indicated earlier, ANL is transmitted with a preceding tone signal that helps the receivers to detect the best possible direction of receiving the signal. Then each receiver sets its beam to that direction and receives and decodes the packet.

Whenever node n wants to start data communication with, say j, it checks the medium and if it is free, n issues an omni-directional RTS. The target node j on receiving RTS, issues omni-directional CTS. The objective of RTS/CTS here is not to inhibit the neighbors of n and j from transmitting or receiving (as is the case with omni-directional antenna) but to inform the neighbors of j and n that j is receiving data from n. It also specifies the approximate duration of communication. All the neighboring nodes of n and j keep track of the communication between n and j by setting their Directional Network Allocation Vector (DNAV) towards n and j. Thus, nodes in the neighborhood of n and j can initiate communication in other directions *without disturbing the existing communication between n and j*. The source and destination nodes wait for Acknowledgement and Data respectively in directional receive mode.

5. ADAPTIVE ROUTING PROTOCOL WITH MAXIMALLY ZONE DISJOINT SHORTEST PATH

Conventional routing protocols in the context of ad hoc networks rely on using *omni-directional antenna*. Exploiting the advantages of directional antenna for routing, as illustrated in our Introduction, has not been explored properly [10,19]. We observe that, along with a directional MAC protocol, a routing strategy with *effective load balancing* has to be in place in order to exploiting the capacity of directional antenna towards improved medium utilization. We propose a table-driven routing protocol for load-balanced routing. We have used a correlation factor η (section 2) to measure *maximally zone-disjointness* as route selection criteria for load balancing. However, since network awareness at each node is only a *perception* about network status rather than *actual* network status, each intermediate node adaptively corrects and modifies routing decision during routing. We implement the following routing strategy for effective load balancing with maximally zone-disjoint routes:

Each node in the network uses its current network status information (approximate topology information and ongoing communication information) to calculate the ***suitable next hop*** for reaching a specified destination. It uses the following strategy to choose a suitable path between a pair of source and destination in such a way that the new path will try to minimize the interference with the nodes, which are already involved in some communication.

***Step I*:** Find out all paths between s-d pair with number of hops H less than H_{max} (=6 in this experiment).

***Step II*:** Consult the active node list for finding out the nodes involved in ongoing communications at that point of time for computing route correlation factor η (Section 2)

***Step III*:** If the active node list is empty (i.e. No communication is going on in the network) then any one of the minimum hop paths available to the destination will be selected.

***Step IV*:** Otherwise, if some communications are already present in the network, as recorded in ANL, then:

- If the source is multiple hops (more than 2 hops) away from destination then it will search for lowest η path among all possible paths for that source destination pair.
- If the source is only 2 hops away from destination then it will search for lowest η path among all possible 2 hop paths for that source destination pair

This process ensures that each intermediate node will select a minimum η path if it is far away from destination so that interference with on going communication is reduced. But if an intermediate node finds itself only two hops away from the destination, it gives more priority to lowest hop path with low η than lowest η path with higher hop count.

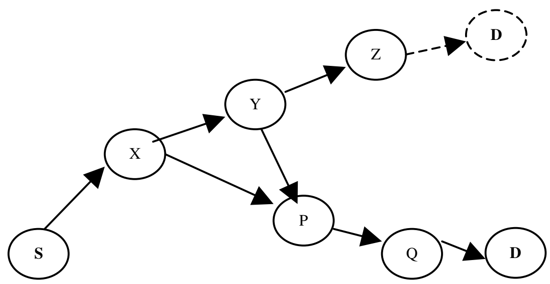

Figure 3. Adaptive Route Selection by Intermediate node to reach Destination D

Since the mechanism does not guarantee that each node would know the exact status of the network, an intermediate node corrects the routing decision and takes alternative path to route data packets towards destination. However, a node closer to destination will have more accurate information about the destination and communication status in its neighborhood. This is illustrated in Figure 3. Source S has initially determined an approximate route S-X-Y-Z-D to reach D, where the dotted circle shows the initial position of D. However, due to mobility, node D changes its location, where the current position of node D is shown in solid line. As soon as this information of change of location of node D reaches the intermediate node Y, it decides to correct the path to node D since it has a more accurate information about node D and can determine a better path towards node D through P and Q. Thus, path is getting selected and modified adaptively depending on the accuracy of available information, without generating a lot of control packets. Since each node is having a GLST and ANL, this will improve the routing performance.

In our case, each node n in a path will compute its *best next hop* to reach the destination. Once computed, n will use this next-hop for that particular communication, so long as it is reachable with same antenna pattern with respect to n. In other words, when this next-hop is not accessible to n with same antenna pattern or this next-hop is unreachable, node n re-computes the next hop to reach the destination using the same route-computation strategy.

6. PERFORMANCE EVALUATION

6.1 Simulation Environment

The simulations are conducted using QualNet 3.1 [22]. Our directional antenna can steer discretely at an angle of 45 degree, covering a span of 360 degree. As the beam pattern of sector, 15.6dBi sector pattern is used. We have implemented the MAC protocol as illustrated in section 4 and the routing protocol as illustrated in section 5 in QualNet simulator.

30 nodes are randomly placed over 1000 x 1000 sq. meter area. Eight nodes are randomly chosen to be CBR (constant bit rate) sources, with a time lag, each of which generates 1024 bytes data packets to a randomly chosen destination at a rate of 2 to 500 packets per second. So, all eight sources do not start data communication simultaneously. After the selection of a source, the next source is selected after 15 seconds. However, all communications last till end of simulation. In order to test the performance of network with multiple source-destination pairs communicating data simultaneously but with a varying start time, we have used this technique. The set of parameters used is listed in Table 3.

Table 3. Parameters used in Simulation

Parameters	Value
Area	1000 x 1000 sq. m
Number of nodes	30
Transmission Power	15 dBm
Receiving Threshold	-81.0 dBm
Sensing Threshold	-91.0 dBm
Packet Size	1024 bytes
CBR Packet Arrival Interval	2 ms to 500 ms
Simulation Time	5 minutes
Number of simultaneous communication	8 with a starting time lag of 15 second
ANL Periodicity (T_A)	2 second (static); 1 second (mobile)
GLST Periodicity (T_G)	10 second (static); 5 Second (mobile)

6.2 Impact of Overhead

Since both GLST and ANL are periodic update packets and their propagation are limited to one-hop broadcast, network would never get flooded with ANL or GLST, as shown in the following analysis. In fact, we rely on approximate global network status information and accurate local status information similar to fish-eye concept as in [20]. So, intermediate node adaptively modifies routing decision based on more accurate local information around that node.

Let us assume that each update packet migrates at a time gap of T milliseconds and takes t millisecond to physically migrate from one node to another. Let us also assume that our bounded region of ad hoc operation is A sq.mt., N is the number of nodes within A and the omni-directional transmission range of each node is R. When a node is broadcasting an update packet to its neighbors, the nodes within the circular transmission zone around that node are busy, but nodes in other regions of area A can broadcast packets. 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 $(A / (\pi R^2))$. Now since the nodes are evenly distributed, the number of nodes (and consequently the number of update packets P) confined in a zone will be

$$P = \frac{N}{A / (\pi R^2)} = \frac{N(\pi R^2)}{A}$$

In other words, P number of update packets has to migrate from one node to another sequentially. As each update packet migrates at a time gap of T milliseconds and takes t millisecond to do so, the medium will be occupied by update traffic [t.P*100 / T] % of the time. For example, in case of GLST, if the bounded region of operation is 1000 × 1000 sq. m. and R is 300 m, and T_{GLST} is 5 second for a 30 node network and t=2 msec., then P=8.48. So, the medium would be occupied with GLST traffic only 0.34% of the time. In case of ANL, T_{ANL} is 1 sec. and t=1 msec. So, the medium will be occupied with ANL traffic only 0.85% of the time. So, the medium will be free from update packets 98.8% of the time. In other words, *for only 1.19 % of the total time, the medium gets blocked by update traffic and the medium is free for 98.8 % of the total time for data communication processes.* This is the real gain in this scheme and serves as the single major motivation to replace the conventional link-state routing.

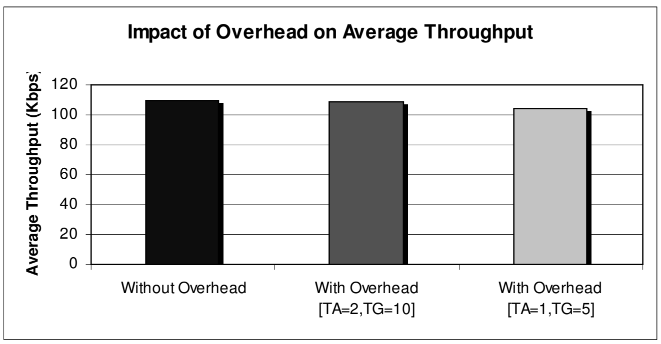

Figure 4(a). Impact of Overhead on Average Throughput

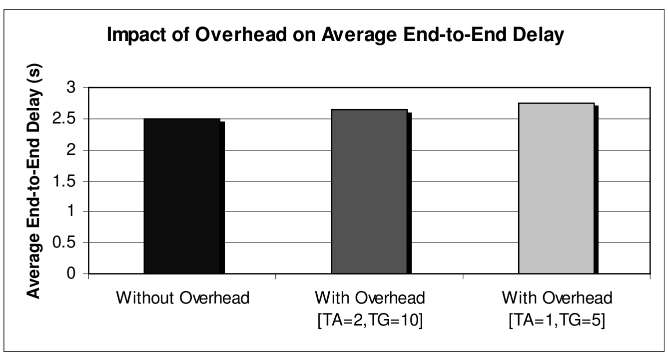

Figure 4(b). Impact of Overhead on Average End-to-End Delay

Simulation for overhead analysis has been performed on QualNet with static routes on a static topology of 30 nodes where nodes are randomly placed. The use of static route is to study the performance with and without control traffic overhead irrespective of the routing strategy. The results of simulation study, given in Figure 4(a) and 4(b), show that the impact of overhead due to update packets is not really significant. Here first experiment is performed without any overhead, second one is performed with overhead of ANL periodicity=2 sec. and GLST periodicity=10 sec. (T_A=2, T_G=10), and third one is performed with overhead of ANL periodicity=1 sec. and GLST periodicity=5 sec. (T_A=1, T_G=5).

6.3 Results and Discussions

We have used DSR with IEEE 802.11 as its MAC as a benchmark to compare and evaluate the performance of our proposal. Our evaluation is based on four criteria: *average throughput, average end-to-end delay*, *average packet retransmission due to ACK timeout* and *Average packet drops due to retransmission limit.*

Initially, we have taken 20 static snap-shots and observe the performance on these four criteria, as compared to DSR. The average of our observations are shown in Figure 5(a-d) at a CBR packet arrival rate of 2 packets per second to 500 packets per second with packet size 1024 bytes. Our mechanism is captioned as ESPAR. At high data rate, the average throughput is 500 Kbps which is 5 times as compared to that of DSR and average end to end delay is 1 second which is 3.5 times less as compared to that in DSR. Number of packet retransmission due to ACK timeout is insignificant in our case as compared to 175 in DSR. Similarly, Average packet drops are far less in our case as compared to that in DSR.

With multiple source destinations communicating at a time at high data rate, the utilization of the medium can be increased to a large extent using directional antenna. Along with this, if we select maximally zone-disjoint paths, this will further reduce the contention among routes for getting access to the medium they share and we can get a scenario where the network load is balanced across all the nodes in the network. The combined effect of these two aspects will eventually improve the system performance drastically with improved throughput and reduced end-to-end delay, as shown in Figure 5(a-d).

In Figure 6(a-d), we have evaluated the performance of ESPAR under low mobility of 5m/second at a data rate of 200 packets/second. In order to cope up with mobility, the network information percolation has to be done faster, so both ANL periodicity and GLST periodicity (T_A and T_G) has been changed from 2 sec to 1 sec and 10 sec to 5 sec respectively. Due to increase in control traffic, we observe some deterioration in performance, although not significant.

7. CONCLUSION

Use of directional antenna in ad hoc wireless network can drastically improve system performance, if we consider the issue of routing with load balancing along with suitable directional MAC protocol. Maximally zone disjoint routes will be helpful in this context to reduce route coupling among selected paths and thereby improving end to end delay and throughput. In spite of the control overhead incurred due to periodic propagation of GLST and ANL in the network, the performance is far better than conventional reactive routing with omni-directional MAC protocol. Our table-driven adaptive routing with maximally zone-disjointness exploits the advantages of directional antenna and improves system performance. Currently, we are working towards more detailed study on mobility to observe the performance under high mobility. However, since our routing strategy is table-driven, the success depends on information percolation. We feel that the current control overhead (as determined from the value of T_A and T_G) is sufficient to cope up with high mobility. We also need to compare our performance with other protocols under mobility. Additionally, we will also investigate the scalability issue by increasing the number of nodes in the network. Our current study is restricted to 30 nodes only.

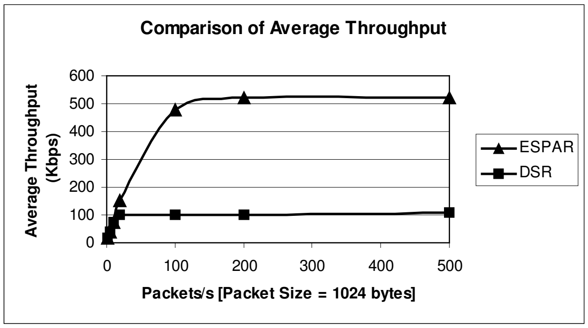

Figure 5(a) Average Throughput: DSR and ESPAR with different packet arrival rate

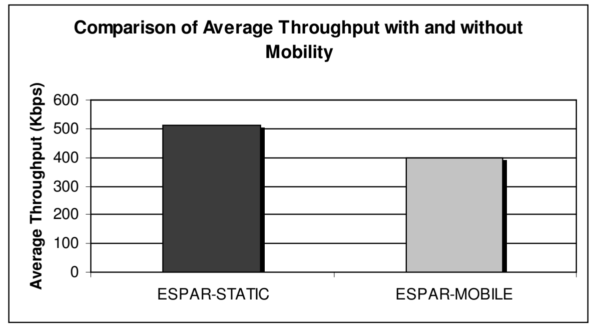

Figure 6(a). Average Throughput: ESPAR (static and mobile) with 200 packets/sec

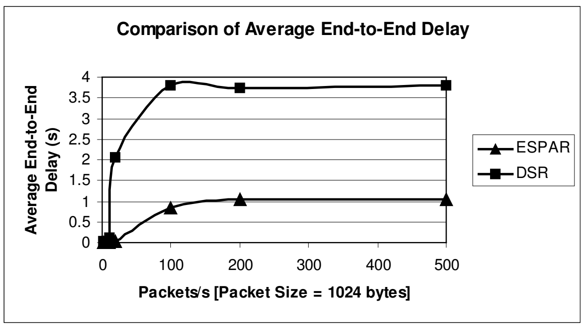

Figure 5(b). Average End-to-End Delay: DSR and ESPAR with different packet arrival rate

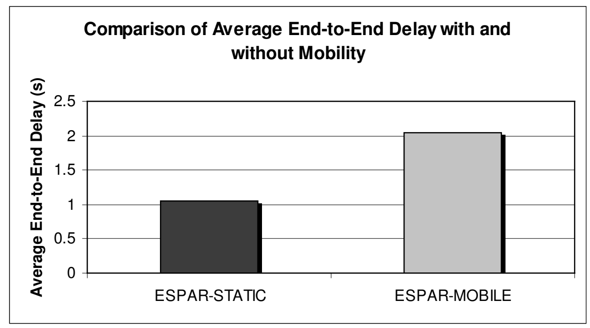

Figure 6(b). Average-End-to End Delay: ESPAR (static and mobile) with 200 packets/sec

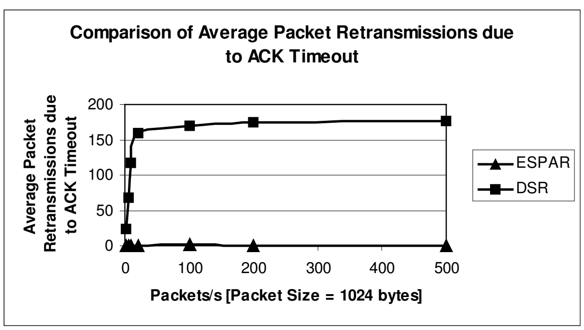

Figure 5(c). Average Packet Retransmission: DSR and ESPAR with different packet arrival rate

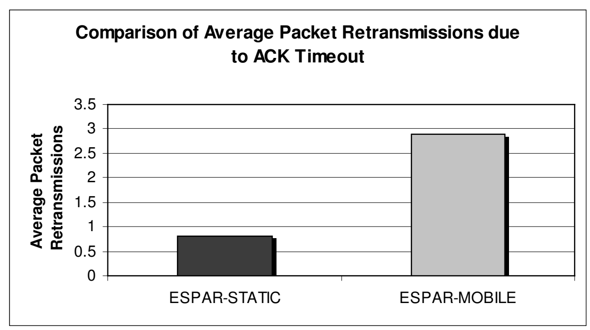

Figure 6(c). Average Packet Retransmission: ESPAR (static and mobile) with 200 packets/sec

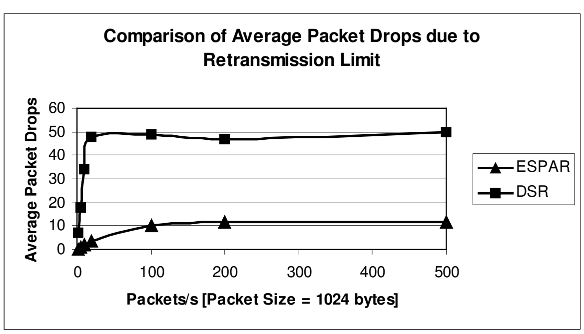

Figure 5(d). Average Packet drops: DSR and ESPAR with different packet arrival rate

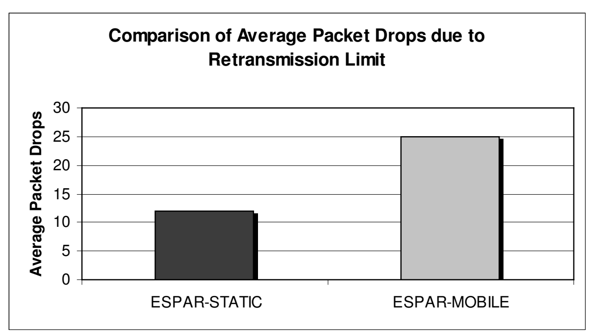

Figure 6(d). Average Packet Drops: ESPAR (static and mobile) with 200 packets/sec

8. REFERENCES

[1] T. S. Yum and K. W. Hung, ‘‘Design algorithms for multihop packet radio networks with multiple directional antennas stations,” IEEE Transactions on communications, vol. 40, no. 11, pp. 1716--1724, 1992.

[2] Y. B. Ko, V. Shankarkumar and N. H. Vaidya, ‘‘Medium access control protocols using directional antennas in ad hoc networks,” Proc. Of the IEEE INFOCOM 2000, March 2000.

[3] Romit Roy Choudhury , Xue Yang , Nitin H. Vaidya , Ram Ramanathan, “ Media Access Control for Ad Hoc Networks: Using directional antennas for medium access control in ad hoc networks” Proceedings of the eighth annual international conference on Mobile computing and networking September 2002

[4] Nasipuri, S. Ye, J. You and R.E. Hiromoto, “A MAC Protocol for Mobile Ad Hoc Networks Using Directional Antennas”, Proc. of the IEEE WCNC 2000.

[5] S. Bandyopadhyay, K. Hasuike, S. Horisawa, S. Tawara, "An Adaptive MAC Protocol for Wireless Ad Hoc Community Network (WACNet) Using Electronically Steerable Passive Array Radiator Antenna", Proc. of the GLOBECOM 2001, November 25-29, 2001, San Antonio, Texas, USA

[6] R. Ramanathan, "On the Performance of Ad Hoc Networks with Beamforming Antennas", ACM MobiHoc, October 2001.

[7] M. Takai, J. Martin, R. Bagrodia and A. Ren, "Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks", ACM MobiHoc, June 2002.

[8] Lichun Bao and J.J. Garcia-Luna-Aceves “Transmission scheduling in ad hoc networks with directional antennas”, Proceedings of the eighth annual international conference on Mobile computing and networking, Atlanta, Georgia, USA**,** 2002.

[9] Asis Nasipuri, Kai Li, and Uma Reddy Sappidi, “Power Consumption and throughput in Mobile Ad Hoc Networks using Directional Antennas” in Proceedings of the *IEEE International Conference on Computer Communication and Networks (ICCCN2002),* October 14-16, 2002, Miami, Florida.

[10] S. Bandyopadhyay, K. Hasuike, S. Horisawa, S. Tawara, "An Adaptive MAC and Directional Routing Protocol for Ad Hoc Wireless Network Using Directional ESPAR Antenna" Proc. of the ACM Symposium on Mobile Ad Hoc Networking & Computing 2001 (MOBIHOC 2001), Long Beach, California, USA, 4-5 October 2001

[11] Kui Wu and Janelle Harms, On-Demand Multipath Routing for Mobile Ad Hoc Networks EPMCC 2001, Vienna, 20th – 22nd February 2001

[12] M. R. Pearlman, Z. J. Haas, P. Sholander, and S. S. Tabrizi, On the Impact of Alternate Path Routing for Load Balancing in Mobile Ad Hoc Networks, MobiHOC 2000, p. 150, 3-10.

[13] Hossam Hassanein and Audrey Zhou, Routing with load balancing in wireless Ad hoc networks, Proceedings of the 4th ACM international workshop on Modeling, analysis and simulation of wireless and mobile systems **,** 2001 , Rome, Italy

[14] Sung-Ju Lee and Mario Gerla, "Dynamic Load-Aware Routing in Ad hoc Networks", Proceedings of IEEE ICC 2001, Helsinki, Finland, June 2001.

[15] S.J. Lee and M. Gerla, Split Multi-path Routing with Maximally Disjoint Paths in Ad Hoc Networks, ICC 2001.

[16] Somprakash Bandyopadhyay, Siuli Roy, Tetsuro Ueda, Kazuo Hasuike, “Multipath Routing in Ad Hoc Networks with Directional Antenna”, Proc. of the IFIP TC6/WG6.8 Conference on Personal Wireless Communications (PWC 2002), October 2002, Singapore.

[17] T. Ohira and K.Gyoda, “Electronically Steerable Passive Array Radiator (ESPAR) Antennas for Low-cost Adaptive Beam forming”, IEEE International Conference on Phased Array Systems, Dana Point, CA May 2000

[18] K. Gyoda and T. Ohira, “Beam and Null Steering Capability of ESPAR Antennas, Proc. of the IEEE AP-S International Symposium, July 2000.

[19] Asis Nasipuri, Jothsna Mandava, Hanumantha Manchala, and Robert E. Hiromoto, On-Demand Routing using Directional Antennas in Mobile Ad Hoc Networks, IEEE ICCCN2000

[20] Guangyu Pei, Mario Gerla and Tsu-Wei Chen, “Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks” in Proc. of the IEEE International Conference on Communication, New Orleans, LA, June 2000.

[21] Romit Roy Choudhury, Somprakash Bandyopadhyay and Krishna Paul, “A Distributed Mechanism for Topology Discovery in Ad hoc Wireless Networks using Mobile Agents”, Proc. of the First Annual Workshop On Mobile Ad Hoc Networking & Computing (MOBIHOC 2000), Boston, Massachusetts, USA, August 11, 2000.

[22] *QualNet Simulator Version 3.1*, Scalable Network Technologies, www.scalable-networks.com

[23] J. Broch, D. A. Maltz, D. B. Johnson, Y. C. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols,' Proc. *ACM/IEEE Mobile Comput. and Network.*, Dallas, TX, Oct. 1998.

[24] Romit Roy Choudhury, Krishna Paul, and S. Bandyopadhyay, "An Agent-based Connection Management Protocol for Ad Hoc Wireless Networks", Journal of Network and System Management, December 2002.