An Adaptive Framework for Multipath Routing via Maximally Zone-Disjoint Shortest Paths in Ad hoc Wireless Networks with Directional Antenna

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Abstract— **Application of multipath routing techniques in mobile ad hoc networks has been explored earlier, as multipath routing may help to reduce end-to-end delay, perform load balancing and consequently improve throughput. However, it has also been shown that the success of multipath routing in ad hoc wireless network depends on network topology and channel characteristics can severely limit the gain offered by multipath routing strategies. The most significant challenge to making the use of multipath routing protocols effective in this environment involves considering the effects of route coupling. Route coupling in wireless medium occurs when two routes are located physically close enough to interfere with each other during data communication. As a result, the nodes in multiple routes are constantly contending for access to the medium they share and can end up performing worse than a single path protocol. In this paper, we propose a notion of zone-disjoint routes in wireless medium where paths are said to be zone-disjoint when data communication over one path will not interfere with data communication in other path. The notion of zone-disjointness is used as route selection criteria. However, zone-disjointness alone is not sufficient for performance improvement. If the path-length (number of hops) were large, that would increase the end-to-end delay even in the context of zone-disjointness. So, it is imperative to select maximally zone-disjoint shortest paths. However, getting zone-disjoint or even partially zone-disjoint routes in ad hoc network with omni-directional antenna is difficult, since the transmission zone of each node is larger compared to that with directional antenna. Hence, one way to reduce this transmission zone of a node is to use *directional antenna*. In this paper, we investigate the effect of directional antenna on zone-disjoint multipath routing and evaluated its effectiveness in QualNet Network Simulator.**

Keywords-Ad hoc Networks; Directional Antenna; Route-Coupling; Multipath Routing

I. INTRODUCTION

The routing schemes for ad hoc networks usually employ single-path routing [1]. However, once a set of paths between source s and destination d is discovered, it may be possible to improve end-to-end delay by splitting the total volume of data into separate blocks and sending them via selected multiple paths from s to d. This would eventually reduce congestion through load balancing and improve throughput [2]. The application of multipath techniques in mobile ad hoc networks seems natural, as multipath routing also allows to diminish the effect of unreliable wireless links and the constantly changing topology. An on-demand multipath routing scheme is presented in [3] as a multipath extension of Dynamic Source Routing (DSR) [1], in which alternate routes are maintained, so that they can be utilized when the primary one fails. It has been shown that the frequency of searching for new routes is much lower if a node keeps multiple paths to the destination. However, the performance improvement of multipath routing on the network load balancing has not been studied extensively. M. R. Perlman et al. [4] demonstrates that multipath routing can balance network loads in their recent paper. However, their work is based on multiple channel networks, which are contention free but may not be available in most cases. The Split Multipath Routing (SMR), proposed in [5], focuses on building and maintaining maximally disjoint multiple paths.

However, it has also been shown that deployment of multiple paths does not necessarily result in a lower end-to-end delay [4,6]. In [4], the effect of Alternate Path Routing (APR) in mobile ad hoc networks has been explored. It was argued that the network topology and channel characteristics (e.g., *route coupling*) can severely limit the gain offered by APR strategies.

Suppose, a source S is trying to communicate data to destination D in wireless medium. Let us assume that we select two node-disjoint paths for communication: S-a-b-D and S-c-d-D (Fig. 1). Even if the paths are node-disjoint, flow of data from S over these two paths may not happen simultaneously, if the members of these two routes are neighbors and interfere with each other. This is a phenomenon known as *route coupling*. Route coupling occurs when two routes are located physically close enough to interfere with each other during data communication. As a result, in a multipath communication between S-D, the nodes in those multiple routes may constantly contend for access to the medium they share and may end up performing worse than single path routing between that S-D pair. Thus, node-disjoint routes are not at all a sufficient condition for improved performance in this context. Hence, efforts to find out routes that are node-disjoint or maximally node-disjoint [4,5,6] may not be effective because of route coupling.

In this paper, we propose a notion of zone-disjoint routes in wireless medium where paths are said to be zone-disjoint when data communication over one path will not interfere with data communication in other path. We have used this notion as a route selection criterion. However, zone-disjointness alone is also not sufficient for performance improvement. If the path-length (number of hops) were large, that would increase the end-to-end delay even in the context of zone-disjointness. So, it is imperative to select maximally zone-disjoint shortest paths.

However, getting zone-disjoint or even partially zone-disjoint routes in ad hoc network with omni-directional antenna is difficult, since the transmission zone of each node is larger compared to that with directional antenna. Hence, one way to reduce this transmission zone of a node is to use *directional antenna*.

It has been shown that the use of directional antenna can largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [7,8]. In this paper, we investigate the effect of directional antenna on zone-disjoint multipath routing and evaluated its effectiveness in QualNet Network Simulator. We have used a notion of correlation factor to measure route coupling among multiple routes [6,10] and used it as one of the metric in selecting multipath.

As shown in Fig. 1, with directional antenna, it is possible to de-couple these two routes, making them fully zone-disjoint. For example, if each of the nodes in Fig. 1 uses directional antenna and sets their transmission beam towards its target node only, then the communication between S-a-b-D will not affect the communication between S-c-d-D. On the other hand, if we use omni-directional antenna that uses RTS-CTS based floor reservation scheme, these two communications will interfere with each other, since c is the omni-directional neighbor of a, and d is the omni-directional neighbor of b.

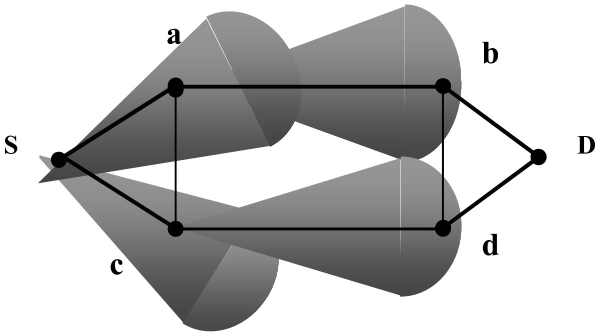

Figure 1. Zone-disjoint multipath communication between S and D.

II. SYSTEM DESCRIPTION

A. Antenna Model

We are working towards implementing Wireless Ad Hoc Community Network testbed [11] where each user terminal uses a small, low-cost adaptive antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna [7,11]. 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. In this work, we are using ESPAR antenna as a quasi-switched beam antenna. The advantage of using ESPAR antenna as generalized switched beam antenna is that, with small number of antenna element, continuous tracking is possible and we can have variable number of beam-pattern. 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.

B. Definition of Some Important Terms

Definition 1. When a node n forms a directional transmission beam with a beam-angle α and a transmission range R_{dir} with respect to n, the coverage area of n at an angle α is defined as **transmission_zone$_n$ (α)**.

Definition 2. We define **neighbors of node n (G^n)** as a set of nodes within the omni-directional transmission range R_{omni} of n.

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

Definition 4. **Communication-id** is essentially a unique id that specifies a source-destination pair for which the communication is on. In case of multipath communication from a source to a destination, a sub-id of that communication-id represents each of the multipath flow.

Definition 5. **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. Each active node in the list is associated with a **set C of communication-ids** for which it is active.

Definition 6. **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)). So, $ActG^n_\alpha(t) = G^n_\alpha(t) \cap ANL(t)$.

Definition 7. **Correlation factor of node n_i in a path P for Communication-id c** [$\eta^{ni}_c(P)$], 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 sum of the number of communication-ids handled by each active directional neighbor of node n_i at transmission zone$_{ni}$ ($\alpha(n_i \rightarrow n_j)$) excluding the communication-id c. So, $\eta^{ni}_c(P) = \sum_{\forall n \in ActG\text{-}ni\text{-}\alpha(ni \rightarrow nj)(t)} (|C \cap c|)$. For example, if n_i has 2 active directional neighbors one is handling 2 communications and the other is handling 4 communications and if one of them is handling communication-id c, then $[\eta^{ni}_{c}(P)]$ will be 2+4-1 = 5. So, it is important to note that, if an active directional neighbor of a node n_i is active for current communication-id c, then the activity-status of that node for that communication-id is ignored for calculating $\eta^{ni}_{c}(P)$. Informally speaking, correlation factor of a node measures the activity-status of a node.

Definition 8. **Correlation factor η of path P for Communication-id c** $[\eta(P)]$ is defined as the sum of the correlation factors of all the nodes in path P. So, $\eta(P)= \sum_{\forall ni \in P}(\eta^{ni}_{c}(P))$. When $\eta(P)=0$, 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. Correlation factor is used to measure route coupling. It has been shown that larger the correlation factor, the larger will be the average end-to-end delay for both paths [6].

C. Information Percolation Mechanism in the Network

The purpose of an information percolation mechanism is to make each node aware of the *approximate topology* and the *communication events going on in the network.* The objective here is to get accurate local perception, but approximate global perception of the network information. This approximate network awareness would be helpful to implement both MAC and an adaptive routing protocol with multipath, as will be discussed subsequently. In order to track the direction of its neighbor, each node n periodically *collects* its directional neighborhood information so that a node can determine the best possible direction of communication with any of its neighbor.

Each node n in the network maintains the following two network-status information:

- **Active Node List (ANL_n):** It contains the perception of node n about communication activities in the entire network. It is a list in node n containing all active nodes in the network and the communication-ids for which they are active.
- **Global Link-State Table ($GLST_n$):** It contains the global 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 $GLST_n$ to include node i, j and k as its neighbors and records the best possible direction of communicating with each of them. Node n records the communication activity status of node i, and similarly for other neighbors, thus forming its own ANL, depending on the recency of the received information [9]. 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, depending on the recency of the received information [9].

ANL needs to be propagated faster than GLST because 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. GLST reflects the change of topology with respect to physical mobility (which is much slower compared to signal propagation) so, it need not be propagated very fast. The overhead can be controlled by adjusting T_A and T_G. Current values of T_A and T_G are 200 milliseconds and 5 seconds respectively.

III. Location Tracking and MAC Protocol

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. In this work, 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 30 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. ANL and GLST are periodic signal, transmitted from each node at a pre-defined interval. At each periodic interval, each node, say, m, broadcast 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 beacon. 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 receives RTS and 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.* This mechanism, i.e., generation of RTS/CTS under different conditions to realize a directional medium access control strategy, is a modified version of our earlier work [7].

IV. ADAPTIVE MULTIPATH ROUTING

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 via multiple paths such that the interference with the nodes that are already involved in some communication gets minimized. Our goal is to distribute the network load along a set of diverse paths to achieve load balancing through multipath for an effective gain in throughput. In our earlier work [10] it was shown that two paths are sufficient to improve network performance in case of multi-path routing using directional antenna. So, in our proposed routing mechanism, each source node in the network is trying to distribute the data packets alternately along two zone-disjoint paths. Each node consults its own active node list (ANL) to calculate zone-disjoint paths, so that, the nodes, that are already handling multiple communications (nodes with high correlation factor), may be avoided as far as possible in the current route selection process. However, under some communication scenario, it may so happen that, for a particular destination each intermediate node tries to select a route avoiding the active zone and ultimately ends up traversing the entire network in search of a zone-disjoint route. To alleviate that problem we propose to use two metrics as route selection criteria: correlation factor and propagated hop count, as will be explained below:

Initially when a packet is transmitted from the source it gives preference to the zone-disjoint path selection criteria. If a packet already traversed multiple hops then *progressively shortest hop route* towards the destination will be selected. So this adaptive route calculation mechanism guarantees the convergence of the proposed routing algorithm. We have used the following function to calculate the link-weight that will ensure the selection of lower η path for low propagated hop count and selection of lower hop path for higher propagated hop count.

Link-weight (n_i, n_j) during the current communication having Communication Id c = $\alpha + \beta\eta + \gamma H$ where,

α = Initial link-weight (.01 in our case)

η = The sum of the total number of communications (excepting the current communication c) handled by each directional active neighbor in the directional zone (n_i->n_j) i.e., $\eta^{ni}{}_{c} = \sum_{\forall n \in \text{ActG-ni-}\alpha(ni \rightarrow nj)\,(t)} (|C \cap c|)$ (As explained in section II).

H = propagated hop-count of the current packet for which route is being calculated.

β, γ = Weight factors (1 and .5 respectively in our case).

Weight factors are to be adjusted in such a way that initially diverse paths will be selected but progressively shortest hop route will get preference over η-driven route to ensure convergence. When H and η is zero, α is used to find out the shortest path. Dijkstra's shortest path algorithm has been modified to select a path having smallest link-weight, i.e., total link-weight of all the links on that selected path will be minimum.

Initially**,** *when a packet is to be transmitted by the source node* for a communication Id c then it is assigned a sub-id cs_1, then the source S consults its ANL and GLST, assign link-weights and selects a suitable nexthop towards the destination to forward the packet along least-weight path. Communication sub-id cs_1 and the current nexthop are kept as a history information in the source S for future route calculation. So, when the next packet comes to S for the same destination i.e., communication Id c then new sub-id will be assigned to the packet, say cs_2 so that the packet may be routed along a path which is zone disjoint compared to the earlier path selected by S. For the second packet, S tries to avoid the earlier zone (zone containing the next-hop of the first packet), and calculate next-hop for the second packet in similar fashion. Then the history is overwritten with the new next hop and communication sub-id cs_2. Next time, the communication sub-id assigned to a third packet will be cs_1. So sub-ids will toggle between cs_1 and cs_2 which ensures the selection of alternate zone disjoint shortest routes by the source node S. So, basically the source will transmit data packets along two zone-disjoint paths alternately.

Each intermediate node will adaptively select a suitable next hop towards the destination according to their ANL and GLST and assigning suitable link-weights, but will not keep any history information as source node. Since the mechanism does not guarantee that each node would know the exact status of the network, each node n in a path will compute its *best-next-hop* to reach the destination.

V. PERFORMANCE EVALUATION

Initially we have developed our own simulator to study the performance of multipath routing with omni- and directional antenna. Initially, we have used ideal directional beam pattern in an environment of 40 nodes and observed that with increasing number of simultaneous communications, the average end-to-end delay per packet increases much more sharply with omni-directional antenna compared to that with directional antenna as shown in Fig. 2. So, it can be concluded that the routing performance using multiple paths improves substantially with directional antenna compared to that with omni-directional antenna. This is a consequence of reduced route coupling with directional antenna.

Subsequently, we have evaluated the performance of our proposed protocol on QualNet simulator [12]. We have simulated ESPAR antenna in the form of a *quasi-switched beam antenna*, which is steered discretely at an angle of 30 degree, covering a span of 360 degree. We have done the necessary changes in QualNet simulator to implement MAC and Routing protocol as described earlier. The parameters used are listed in Table I.

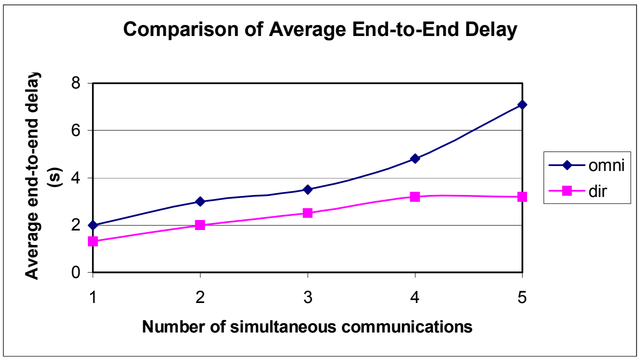

Figure 2. Incresae in average end-to-end delay with multiple multipath communications using omni- and directional antenna

We have used AODV [1] with IEEE 802.11 as its MAC as a benchmark to compare and evaluate the performance of our proposal, termed as MPR-E (MultiPath Routing with ESPAR). The result in Fig. 3 shows that with increase in mobility (static, 0-10 mps, 0-20 mps) the average throughput in both the cases decreases but the comparative gain in performance at each mobility in our protocol is much more significant. This is an obvious consequence of load-balanced routing with multipath. It is also to be noted that with increasing mobility, the relative gain also increases (3.3 times in static, 4.5 times at mobility 0 to 10mps and 4.9 times at mobility 0 to 20mps). This is also one of the consequences of multipath routing; if a link in one of the multipath fails due to mobility then packets can reach destination through other path also, until the broken path is recalculated.

TABLE I. PARAMETERS USED IN SIMULATION

Parameters	Value
Area	1000 x 1000 m
Number of nodes	60
Transmission Power	10 dBm
Receiving Threshold	-81.0 dBm
Sensing Threshold	-91.0 dBm
Data Rate	2Mbps
Packet Size	512 bytes
CBR Packet Arrival Interval	5 ms
Number of simultaneous communication	5

VI. CONCLUSION

We have implemented ESPAR antenna beam pattern in QualNet Simulator and evaluated the performance with real-life directional antenna pattern. The improvement in performance suggests that the concept of zone-disjoint multipath routing is truly effective with directional antenna for improved throughput. We are currently working towards a predictive technique for topology tracking in order to reduce the overhead due to network information percolation.

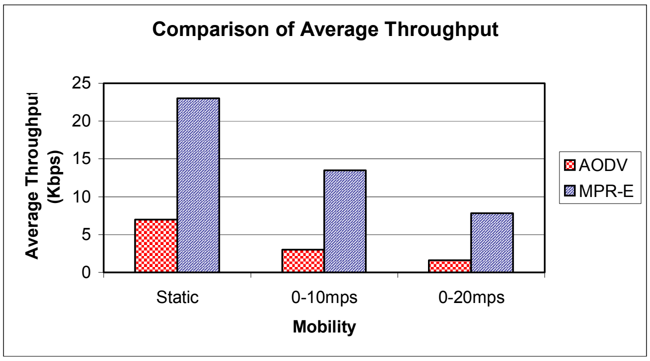

Figure 3. Comparison of average throughput in QualNet at different mobility with AODV (as in QualNet) as Benchmark

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