Improving End-to-End Delay through Load Balancing with Multipath Routing in Ad Hoc Wireless Networks using Directional Antenna

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Abstract. Multipath routing protocols are distinguished from single-path protocol by the fact that they use several paths to distribute traffic from a source to a destination instead of a single path. Multipath routing may improve system performance through load balancing and reduced end-to-end delay. However, two major issues that dictate the performance of multipath routing - *how many paths are needed* and *how to select these paths*. In this paper, we have addressed these two issues in the context of ad hoc wireless networks and shown that the success of multipath routing depends on the effects of route coupling during path selection. Route coupling, in wireless medium, occurs when two routes are located physically close enough to interfere with each other during data communication. Here, we have used a notion of *zone-disjoint routes* to minimize the effect of interference among routes in wireless medium. Moreover, the use of directional antenna in this context helps to decouple interfering routes easily compared to omni-directional antenna.

1 Introduction

Multipath routing protocols are distinguished from single-path routing by the fact that they look for and use several paths to distribute traffic from a source to a destination instead of routing all the traffic along a single path. Utilization of multiple paths to improve network performance, as compared to a single path communication, has been explored in the past [1,2]. Classical multipath routing has focused on the use of multiple paths primarily for load balancing and fault tolerance. Load balancing overcomes the problem of capacity constraints of a single path by sending data traffic on multiple paths and reducing congestion by routing traffic through less congested paths. The application of multipath techniques in mobile ad hoc networks seems natural, as it may help to diminish the effect of unreliable wireless links, reduce end-to-end delay and perform load-balancing [2]. In addition, due to the power and bandwidth limitations, a routing protocol in ad hoc networks should fairly distribute the routing traffic among the mobile hosts. However, most of the current routing protocols in this context are single-path protocols and have not considered the load-balancing issue. An unbalanced assignment of data traffic will not only lead to congestion and higher end-to-end delay but also lead to power depletion in heavily loaded hosts. An on-demand multipath routing scheme is presented in [3], where alternate routes are maintained, so that they can be utilized when the primary one fails. However, the performance improvement of multipath routing on the network load balancing has not been studied extensively. The Split Multipath Routing (SMR), proposed in [6], focuses on building and maintaining maximally disjoint multiple paths.

Two key issues that dictate the performance of multipath routing are - *how many paths are needed* and *how to select these paths*. In this paper, we have addressed these two issues in the context of ad hoc wireless networks. It is shown that the performance of multipath routing through proper load balancing improves substantially, if we consider the effect of route coupling and use directional antenna instead of omni-directional antenna with each user terminal. In the context of ad hoc networks, the success of multipath routing depends on considering the effects of route coupling during path selection. In [5], the effect of route coupling on 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. Route coupling is a phenomenon of wireless medium which 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 constantly contend for access to the medium they share and can end up performing worse than a single path protocol. Thus, node-disjoint routes are not at all a sufficient condition for improved performance in this context.

In this paper, we use 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 along other paths. Our basic multipath selection criterion for load balancing depends on zone-disjointness. However, getting zone-disjoint or even partially zone-disjoint routes in ad hoc network with omni-directional antenna is difficult, since the communication zone formed by each transmitting node with omni-directional antenna covers all directions. 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]. In our earlier work, we have developed the MAC and routing protocol using directional ESPAR antenna [7] and demonstrated the performance improvement. In this paper, we have investigated the effect of directional antenna on path selection criteria for multipath routing and obtained a substantial gain in routing performance through load balancing using multiple paths with directional antenna.

The paper is organized as follows. In section 2, we define the notion of zone disjointness and propose multipath selection criteria based on this notion. In section 3, we evaluate the performance of proposed mechanism in a simulated environment to show the effectiveness of our algorithm using directional antenna, followed by concluding remarks in section 4.

2 Selection of Paths for Multipath Routing

2.1 Zone Disjoint Routes with Omni-directional and Directional Antenna

Most of the earlier works on multipath routing in ad hoc networks try to find out multiple node-disjoint/ maximally node-disjoint paths between source s and destination d for effective routing with proper load balancing. [5,6,7]. Two (or multiple) paths between s and d are said to be node-disjoint, when they share no common node except s and d. However, because of route coupling in wireless environment, node-disjoint routes are not at all a sufficient condition for improved performance in this context. Suppose, two sources, s_1 and s_2 are trying to communicate data to destinations, d_1 and d_2 respectively. Let us assume that two node-disjoint paths are selected for communication- s_1-x_1-y_1-d_1 and s_2-x_2-y_2-d_2. Since the paths are node-disjoint, the end-to-end delay in each case should be independent of the other. However, if x_1 and x_2 and/or y_1 and y_2 are neighbors of each other, then two communications can not happen simultaneously (because RTS / CTS exchange during data communication will allow either x_1 or x_2 to transmit data packet at a time, and so on). So, the end-to-end delay 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 phenomenon of interference between communicating routes is known as *route coupling*. As a result, the nodes in multiple routes will constantly contend for access to the medium they share and can end up performing worse than a single path protocol.

In this paper, we use 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 along other paths. In other words, two (or multiple) paths between s and d are said to be zone-disjoint, when route-coupling between them is zero.

The effect of route coupling has been measured in [8] using a correlation factor η. In this paper, the correlation factor of a node n in a path P, η^n (P), is defined as the number of *active neighbors* of n not belonging to path P, where *active neighbors* of n is defined as those nodes within the transmission zone of n that are actively participating in any communication process at that instant of time. For example, in figure 1, S and D are communicating using two paths: S-a-b-c-D and S-d-e-f-D. So, all are active nodes in this context of communication. Now, the active neighbors of node a is {S, d,e,b}. So, correlation factor of node a in path {p= S-a-b-c-D}, η^a (p)= number of active neighbors not belonging to path p, i.e. 2.

The correlation factor η of path P, η (P), is defined as the sum of the correlation factor of all the nodes in path P. 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

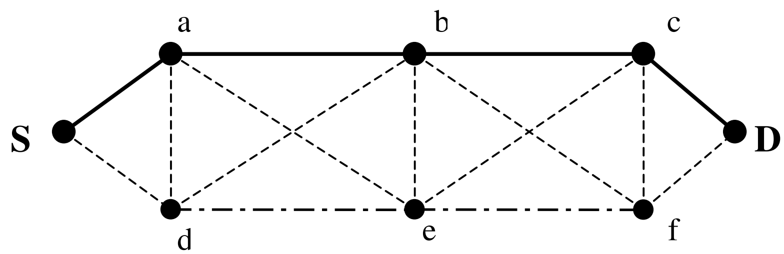

Fig. 1. . Two node-disjoint path with $\eta = 9$

communication processes at that instant of time. Otherwise, the path P is η–related with other active paths.

Route coupling has a serious impact on path selection for load balancing via multiple path. Let us refer figure 1 and assume that source S is sending data traffic to destination D along the path {S,a,b,c,D}. If S selects another path {S,d,e,f,D}, which is closely coupled with the first path (as shown), and tries to distribute traffic across both the path for load balancing, it may not result in performance improvement. In fact, it has been observed that larger the correlation factor, the larger will be the average end-to-end delay for both paths [8]. 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. In addition, larger the correlation factor, the larger will be the difference of end-to-end delay along multiple paths [8]. Based on this study, it can be concluded that the path selection criterion for multipath routing in ad hoc network needs to consider the correlation factor among multiple routes. In an environment of multiple communication among several source-destination pairs, even if a path is less-loaded, that path may not be a good candidate for distributing traffic, if the route coupling of that path with respect to other active paths is high. One way to alleviate this problem is to use zone-disjoint routes or maximally zone disjoint route for load balancing. However, it is difficult to get fully zone-disjoint routes using omni-directional antenna. As in figure 1, since both a and d are within omni-directional transmission range of S, a RTS from S to node a will also disable node d. Similarly, since both c and f are within omni-directional transmission range of D, a CTS from D will disable both c and f. So, even if {a,b,c} and {d.e.f} are zone-disjoint, the lowest possible η in case of omni-directional antenna with two multipath between s and d is 2. We call it minimal correlation factor η^{min}. 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 figure 1 uses directional antenna where each node sets their transmission beam towards its target node only, then the communication between S-a-b-c-D will not affect the communication between S-d-e-f-D. Hence η^{min}(omni)=2 whereas η^{min}(dir)=0. This will be further illustrated in the next section.

2.2 Number of Paths in a Multipath Route

Even if we get multiple zone-disjoint routes with minimal correlation factor [η^{min}(omni)=2] using omni-directional antenna, the best-case packet arrival rate at the destination node will be 1 packet at every $2*t_p$, where t_p is the average delay per hop per packet of a traffic stream on the path p. The best-case assumption is, traffic stream in the network from S to D only with error-free transmission of packets. In contrast, if we use directional antenna, best-case packet arrival rate at destination will be one packet at every $t_{p.}$ It was illustrated analytically in [10] that the destination D will receive packets in alternate time-tick with omni-directional antenna and *even if we increase the number of paths between s and d beyond 2, the situation will not improve*.

However, with directional antenna, when node a is transmitting a packet to node b, S can transmit a packet to node d simultaneously. Thus, destination D will receive a packet at every time-tick with two zone-disjoint paths using directional antenna. It is to be noted here that *two zone-disjoint paths with directional antenna are sufficient to achieve this best-case scenario* [10].

2.3 Selection of Paths Based on Correlation Factor η

Till now, we have considered communication over single s-d pair. However, situation will deteriorate, if we consider multiple s-d pairs, engaged in simultaneous communications. Let us assume that each s-d pair selects two paths between them with lowest possible η between them for effective load balancing. However, in the context of multiple s-d pairs, even if two multipaths between, say, s_1 and d_1 are zone disjoint, they may be coupled with other active routes between, say, s_2 and $d_{2.}$ So, it is imperative to consider all active routes and to find out η for each of them with respect to other active routes in order to determine *maximally zone-disjoint multipath* between a s-d pair such that it is not only maximally zone-disjoint with respect to each other but also with respect to all active routes in the system.

However, it is a difficult task in the dynamic environment of ad hoc networks with changing topology and communication pattern. An approximate solution to alleviate this difficulty will be discussed in the next section. In this section, we will discuss the mechanism of finding maximally zone disjoint multipaths with multiple s-d pairs and, in the next section, will show the effectiveness of directional antenna over omni-directional antenna in this context. To do this, initially we have assumed a static scenario in our simulation environment. It has been assumed that each node is aware of the topology and the communication pattern in the network. We use the following algorithm to find out *maximally zone-disjoint path between s-d:*

Step I: Find out all node-disjoint paths between a s-d pair with number of hops H less than H_{max} (=5 in this experiment).

Step II: Find out η for each path between that s-d pair with respect to *other active paths*.

Step III: Discard the path with highest η

Step IV: Repeat the process from Step II to step III with remaining paths between that s-d pair until number of paths between them is two. These two paths are *maximally zone-disjoint path between that s-d pair.*

2.4 Additional Criterion For Path Selection: Hop Count

However, zone disjointness alone is not sufficient for performance improvement. Path length is also another important factor in multipath routing. A longer path with more number of hops (H) will increase the end-to-end delay and waste more bandwidth. So, even if a longer bypass route between a s-d pair has a low η, it may not be very effective in reducing end-to-end delay. To deal with this problem, our route-selection criteria would be to minimize the product of η and H. Minimizing this factor will result in *maximally zone-disjoint shortest path*. We call this factor γ (=η*H). We use the following algorithm to find out *maximally zone-disjoint shortest path between s-d:*
Step I: Find out all node-disjoint paths between a s-d pair with number of hops H less than H_{max} (=5 in this experiment).
Step II: Find out η for each path between that s-d pair with respect to other active paths.
Step III: Find out γ for each path between that s-d pair.
Step IV: Discard the path with highest γ
Step V: Repeat the process from Step II to step IV with remaining paths between that s-d pair until number of paths between them is two. These two paths are *maximally zone-disjoint shortest path between that s-d pair.*

3 Multipath Routing Performance

The proposed mechanism has been evaluated on a simulated environment under a variety of conditions to estimate the basic performance. In the simulation, the environment is assumed to be a closed area of 1500 x 1000 square meters in which mobile nodes are distributed randomly. We present simulation results for networks with 40 mobile hosts, operating at a transmission range of 350 m. In order to evaluate the effect of changing topology due to mobility, several snap-shots of random topology with varying source-destination pairs are considered during our experiments. The effective width of directional beam in case of directional antenna is assumed to be 60º.

In order to implement any routing protocol using directional antenna, each node should know the best possible directions to communicate with its neighbors. So, each node periodically collects its neighborhood information and forms a Neighborhood-Link-State Table (NLST) at each node [7]. Through periodic exchange of this NLST with its neighbors each node becomes aware of the approximate global network topology and NLST at each node is upgraded to GLST (Global Link State Table). A directional MAC protocol, as discussed in our earlier work [7], has been implemented in our simulator using information kept in GLST. Implementation of omni-directional

MAC follows the basic IEEE 802.11 scheme. A modified link-state routing protocol, based on our earlier work [7,9] has been implemented. In the context of directional antenna, GLST not only depicts the connectivity between any two nodes but also maintains the best possible directions to communicate with each other. Moreover, each node periodically propagates its knowledge about *active-node-list*, a list containing the node-ids of all nodes involved in any communication process at that instant of time. It is to be noted that the perception of each node about the network topology or number of active nodes in the network is only approximate. However, periodic re-computation of routes by each intermediate node on a path will adaptively adjust itself to the changing scenario.

Whenever a source s wants to communicate with a destination d, it computes multiple node-disjoint routes from s to d. From these multiple routes, it consults active node list and computes *maximally zone-disjoint multipath,* or, *maximally zone-disjoint shortest multipath* between s-d (as illustrated in previous section). However, due to mobility and slow information percolation, it may not be possible for a source node to perfectly compute maximally zone-disjoint multipath between s-d. To improve performance under this condition, each intermediate node periodically recomputes the same and adaptively modifies its routing decision.

We have compared the performance of (i) unipath routing with shortest path using omni-directional antenna, (ii) maximally zone disjoint multipath with directional and omni-directional antenna, and (iii) maximally zone disjoint *shortest* multipath with directional and omni-directional antenna. In order to evaluate the impact of offered load, we have experimented with 5, 10, 15 and 20 simultaneous communication. Observations are recorded for 20 snap-shots in each case and the average values of different parameters are computed. We evaluate the performance according to the following metrics:

Load balancing: To measure load balancing in each case, we observe the number of data packets forwarded at each node n [8]. If f(n) represents the number of data packets forwarded at each node n, the load balancing factor is the ratio of standard deviation of f / mean of f, taken over all 40 nodes. Smaller the load balancing factor, better the load balancing [8].

Average end-to-end delay: Average end-to-end delay per packet between a set of selected s-d pairs is observed with increasing number of simultaneous communications and with omni-directional and directional antenna. The timing assumptions are the same as indicated in section 2.2.

Initially, to analyze average route-coupling among active routes, the experiment starts with finding *maximally zone-disjoint paths* between selected s-d pairs. In order to observe the impact of multiple simultaneous communications on route coupling factor η, number of simultaneous communications are taken as 5, 10, 15 and 20. In each case, we have found out average η, using omni-directional and directional antenna. The result (figure 2) shows that the increase of η is much sharper in case of omni-directional antenna. This implies that, as the number of s-d pair increases in the system, the route-coupling among active routes increase much more sharply in

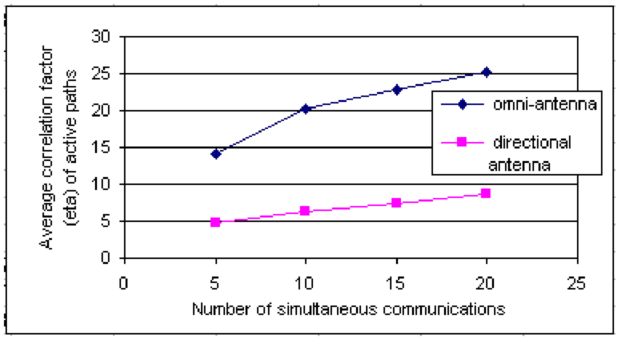

Fig. 2. Increase in route coupling with multiple multipath communications with omni-directional and directional antenna

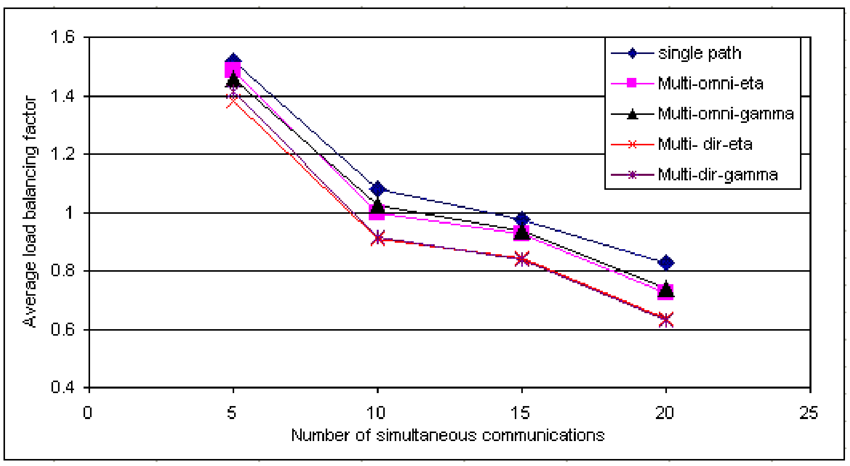

Fig. 3. Variation of load balancing factors with increasing number of simultaneous communications

case of omni-directional antenna compared to that with directional antenna. This has an impact on end-to-end delay, as will be illustrated later.

As illustrated in figure 3, load balancing improves with increasing load with *maximally zone disjoint multipaths,* as compared to that with single shortest path. This improvement is more pronounced when we use directional antenna. It is to be noted that, smaller the load balancing factor, better the load balancing.

However, better load balancing does not imply better performance in this context. Because of the possibility of high route coupling with omni-directional antenna (as shown in figure 2), especially with increased number of simultaneous communication, average end-to-end delay using multipath with omni-directional antenna will

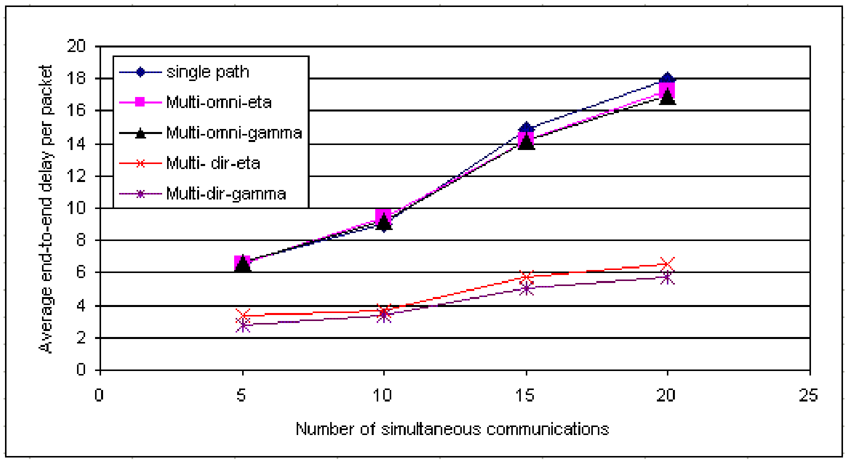

Fig. 4. Variation of Average End-to-End Delay per packet with increasing number of simultaneous communications

[*Multi-omni-eta*: Multipath communication with maximally zone-disjoint path with omni-directional Antenna
Multi-omni-gamma: Multipath communication with maximally zone-disjoint shortest path with omni-directional Antenna
Multi-dir-eta: Multipath communication with maximally zone-disjoint path with directional Antenna
Multi-dir-gamma: Multipath communication with maximally zone-disjoint shortest path with directional Antenna]

not show any significant improvement as compared to that with single path. Since route coupling is far less with directional antenna, average end-to-end delay will be substantially less with directional antenna than that with omni-directional antenna. This is shown in figure 4. At the same time, path length is also another important factor in multipath routing. A longer path with more number of hops (H) will increase the end-to-end delay and waste more bandwidth. So, even if a longer bypass route between a s-d pair has a low η, it may not be very effective in reducing end-to-end delay. That is why, *maximally zone disjoint shortest path with directional antenna* will show best performance, so far as both end-to-end delay and load balancing are concerned (figure 4).

4 Conclusion

Multipath routing strategies in the context of ad hoc networks may improve load balancing, but may not improve system performance to the expected level through reduced end-to-end delay, unless we consider the effects of route coupling. However, high degree of route coupling among multiple routes between any source and destination pair is inevitable, if we use omni-directional antenna. The situation will worsen, if we consider multiple simultaneous communications with multipath routing scheme. This paper has analyzed the problem and proposed a mechanism to alleviate the problem of route coupling using directional antenna. The paper also considers the advantage of selecting maximally zone-disjoint as well as shorter route instead of longer bypass routes for effective load balancing and better network performance. Thus, all active paths are maximally zone disjoint shortest paths. The final result shows that the routing performance using multiple paths improves substantially with directional antenna compared to that with omni-directional antenna.

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