Using Directionality in Mobile Routing

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Abstract

The increased usage of directional methods of communications has prompted research into leveraging directionality in every layer of the network stack. In this paper, we explore the use of directionality in layer 3 to facilitate routing in highly mobile environments. We introduce Mobile Orthogonal Rendezvous Routing Protocol (MORRP), a lightweight, but scalable routing protocol utilizing directional communications (such as directional antennas or free-space-optical transceivers) to relax information requirements such as coordinate space embedding, node localization, and mobility. This relaxation is done by introducing a novel concept called the directional routing table (DRT) which maps a set-of-IDs to each directional interface to provide probabilistic routing information based on interface direction. We show that MORRP achieves connectivity with high probability even in highly mobile environments while maintaining only probabilistic information about destinations. We also compare MORRP with various proactive, reactive, and position-based routing protocols using single omni-directional interfaces and 8 directional interfaces and show that MORRP gains over 10-14X additional goodput vs. traditional protocols and 15-20% additional goodput vs. traditional protocols using multiple interfaces. [1]

1. Introduction

A recent trend in wireless communications has been the desire to leverage directional forms of communications (e.g. directional smart antennas [9], Free-Space-Optical transceivers [11], and sector antennas) for more efficient medium reuse, increased scalability, enhanced security and potential for higher achievable bandwidth. In previous work with directional antennas [9] [10], it was shown that capacity *improvements* using directional over omnidirectional antennas are dramatic - even just 8 directional interfaces results in a theoretical capacity gain of 50X.

Additionally, there has been a large push in the free space optical (FSO) community to use FSO to compliment traditional RF methods [4]. FSO has several attractive characteristics like *(i) dense spatial reuse*, *(ii) low power usage*, *(iii) license-free band of operation*, and *(iv) relatively high bandwidth compared to RF* but suffers from *(i) the need for line of sight (LOS)* and *(ii) reduced transmission quality in adverse weather conditions*. Yuksel et al. [11] proposed several ways to mitigate these issues by tessellating low cost FSO transceivers in a spherical fashion and replacing long-haul point-to-point links with short, multi-hop ones.

Given the seemingly large increases in medium reuse and potential for higher bandwidth in directional forms of communications, it becomes interesting to investigate how *directionality* can be used to complement and even enhance wireless networks in all layers of the stack. There are several challenges associated with using directionality in mobile networks. Unlike omnidirectional antennas where neighbor reach depends almost exclusively on range, nodes using directional antennas need also take into account the neighbor's direction and map it to a specific interface in that direction. Additionally, nodes closer to a source seemingly incur more relative dynamism than nodes farther away. In this paper, we address these issues and propose utilizing directionality for a novel purpose: to facilitate layer 3 routing in *highly mobile environments* without the need for flooding either in the route dissemination or discovery phase.

Our protocol, Mobile Orthogonal Rendezvous Routing Protocol (MORRP) is based on two fundamental primitives: a) local directionality is sufficient to maintain forwarding of a packet on a straight line, and b) two sets of orthogonal lines in a plane intersect with high probability even in sparse, bounded networks. Cheng et al. [5] showed that in *static* wireless mesh networks, by forwarding packets to nodes intersected by a pair of orthogonal lines originating from a source and destination, one can successfully route

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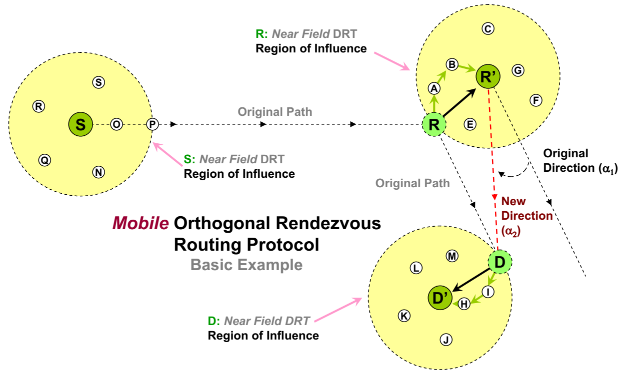

Figure 1. MORRP Basic Example

packets to a high degree of connectivity (98%) without the need for coordinate space. Furthermore, it was shown that forwarding using this method state-scales to $O(N^{3/2})$ with the states spread evenly throughout the network, while incurring a path stretch vs. shortest path of only 1.2. Unfortunately, the proposed protocol fails under even slight mobility as straight-line paths and rigid "destination - next-hop" routes are hard to maintain.

MORRP facilitates high mobility by abstracting the concept of rendezvous *points* to rendezvous *regions* and forwards packets *probabilistically* based on which direction a destination or rendezvous node is most likely found. These directions shift accordingly to a node's *local* velocity. For example, if a source node is moving north, a node originally *east* of the source will *seem* to be moving *south*.

Figure 1 illustrates a basic example. Suppose source S wants to send packets to destination D and through announcement and route request (RREQ) packets, the path "Original Path" is established between S and D with node R as the rendezvous node. After some time, node R has moved to R' and node D has moved to D'. With *infrequent updates* in a mobile environment, node R wishes to maintain a general direction to node D based solely on *local* information (its own mobility pattern) and adjusts its direction of sending to D from angle α_1 to α_2. All nodes maintain a "field of influence" where each node knows the relative direction to all nodes in its region. The data packets S sends to D will traverse the original path, "gravitating" toward R' once it hits R's field of influence. Then, it will be sent in the modified direction of D until it hits D's field of influence and "gravitates" toward the destination.

MORRP routes packets using directionality in highly mobile environments by 1) shifting destination node directions based on a node's *local* velocity and 2) increasing probability of finding nodes by introducing "fields of influence". All of this is done through a novel replacement to routing tables we formulate called the *directional routing table* (DRT). We detail DRTs in section 2.

Key contributions of MORRP include 1) Using only local direction information to address issues with high mobility and 2) a replacement for traditional routing tables that uses *probabilistic hints* to forward packets (the DRT). In comparing with several classes of routing protocols, MORRP shows high data delivery (93%), low packet overhead, and over 10-14X goodput gains vs. traditional routing protocols and 15-20% goodput gains vs. traditional routing protocols modified with multiple directional interfaces in highly mobile (30m/s) environments.

The rest of the paper is organized as follows: Section 2 and 3 outline the concept of MORRP including a detailed explanation of DRTs and several decaying strategies and route information dissemination and maintenance. Section 4 gives some simulation performance evaluations and section 5 concludes with some thoughts on future work.

2. The Directional Routing Table

One of the underlying mechanisms behind MORRP's *probabilistic* forwarding strategy is the directional routing table (DRT). Unlike traditional routing tables which map *destination-IDs* to *next hop IDs*, DRTs map a *set of IDs* to a specific interface direction. The number of entries in the DRT remains constant based on the number of interfaces and does not grow with the number of destinations. This is done through decaying bloom filters [8].

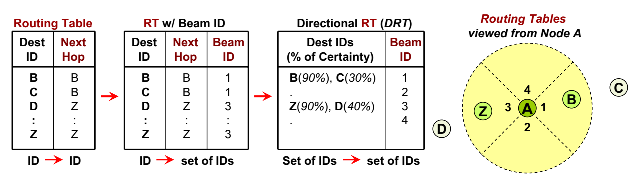

Figure 2. The Directional Routing Table

Figure 2 outlines the structure for the DRT. In short, a *set-of-IDs* stored in a decaying bloom filter (DBF) is mapped to each specific *interface direction*. To find the probability of reaching a node by sending out a specific interface direction, the node ID is hashed through each hash function in the DBF associated with that interface and the total number of "hits" counted. By taking the number of "hits" with respect to the number of hash functions, we come up with a probability of reaching that node by sending out that particular interface. This probability drops as time goes on and without frequent updates. We simulate this by "decaying" bits in the bloom filter (i.e. randomly changing bits in the DBF from 1 to 0). Decaying methods can be broken up into two main thrusts: *intra-node decay* which simulates node positioning uncertainty over *time*, and *inter-node decay* which simulates node positioning uncertainty over *distance* (i.e. nodes know more information about closer nodes than farther nodes). In the following subsections, we overview each method. More details can be found in our technical paper [6].

2.1. Intra-Node Time Decay

Current routing strategies employ hard timeouts for routing entries, updating them periodically through route dissemination or route discovery. While effective for low mobility situations, routes become stale quickly under high mobility without frequent updates. As a result, maintaining accurate routing entries network-wide poses a huge overhead problem. MORRP attempts to mitigate this issue by decreasing the certainty a node can be reached by sending out an interface as time moves on. In stationary environments, the probability of a neighbor being in a specific region decays at a constant rate (bits from the bloom filter are removed randomly at a constant rate).

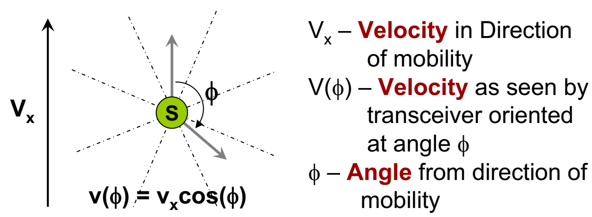

Figure 3. Relative node velocity varies with each interface

In mobile environments, as a node moves away from its original position, the probability of neighbors in the direction of movement should decay slower than the nodes directly opposite of the direction of movement. In short, the velocity with which each interface perceives itself to be moving at is dependent on the angle the transceiver is from the direction of movement. This idea is captured in figure 3 and factored into our time decay heuristic. The bits removed because of time decay are discarded.

2.2. Intra-Node Spread Decay

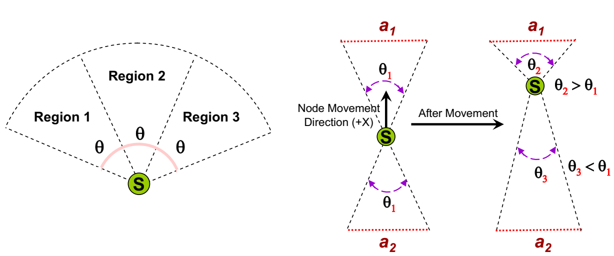

Figure 4. Transceiver coverage varies with mobility

In a mobile environment with directional interfaces, the probability a neighbor will be in a certain transmission region/sector is *stretched* over time, increasing the area a neighbor is possibly located. Figure 4a illustrates this concept. Suppose a neighbor announces its position to be within region 2. Without knowing what direction and velocity the neighbor is traveling at, as time progresses, there is a greater possibility that the neighbor will be in region 1 and region 3 and a lessened probability that the neighbor will be in region 2. We say that as time goes on, the "spread" for the area the neighbor is in, is increased.

In much the same way, a mobile node traversing in a certain direction will need a greater spread to cover the same area in the direction it is traveling in. Figure 4b illustrates this. As a node trying to cover range θ_1 moves in the "+x" direction, it will need a greater spread, θ_2 to cover the same transmission region *in* the direction it is traveling while at the same time, a smaller spread, θ_3 to cover the same region in the direction *away* from the direction it is traveling. Each direction other than the direction the node is traveling in and the direction directly opposite has varied stretch in between these two extremes based on the angle from the direction the node is traveling.

We attempt to capture this effect in our spread decay formulation. The bits removed from certain interface directions are *relocated* to surrounding interfaces. The inherent nature of bloom filters allows us to move bits in the DBF associated with a specific interface, to surrounding DBFs, keeping the bits set to 1 *in the same hash locations*. It is important to note the *duality* of *time* and *spread* decay: A neighbor in the direction of travel will incur *less* time decay but at the same time, *more* spread decay.

2.3. Inter-Node Decay

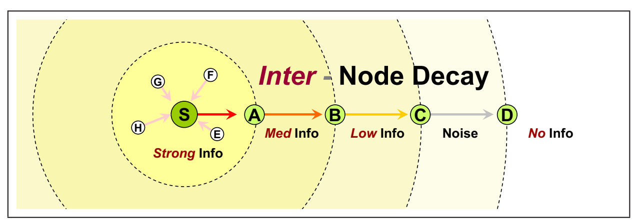

Figure 5. Neighbor information is less certain going farther from the source.

The general idea behind decaying the information transferred *between* nodes is that nodes "closer" to a specific source will most likely have more accurate information about the location of the source than nodes "farther" away. Nodes that are much farther away from the source will have so little information on the source that it will be indistinguishable from "noise". Figure 5 illustrates this principle: Node A is a 1-hop neighbor of Node S. Node S aggregates its information about all its neighbors and decays this information before sending it to node A. Node A does the same thing with all its neighbors and what results is less and less accurate information about any node in a network depending on the distance that node is from the source. We follow the exponential distance decay aggregate and dissemination techniques presented in [8] to perform distance decay except we merge DRT entries instead of individual node DBFs.

3. Mobile Orthogonal Rendezvous Routing Protocol

MORRP relies heavily on DRTs to provide probabilistic routes from source to destination. Routing is broken into two major arenas of operation, each with a separate DRT updated at different intervals: *near field* and *far field*. The near field handles information about 2-3 hop "neighbors" while the far field handles everything beyond the near field's "region of influence". Near field operation and information dissemination is fairly straight forward and follows what is described in section 2.1. In this section, we will focus mainly on reaching nodes that are not in the immediate vicinity of the source (i.e. nodes in the far-field).

To facilitate routing in the *far-field*, MORRP uses a similar hybrid proactive/reactive scheme like ORRP [5] to find probabilistic routes. Figure 6 illustrates the process.

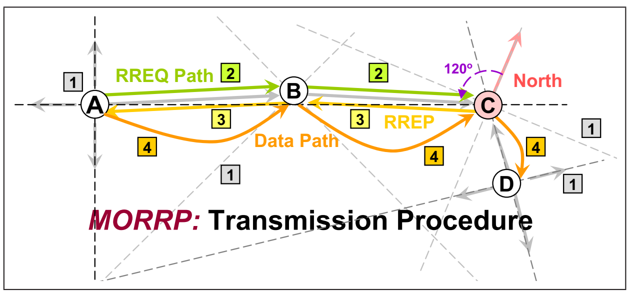

Figure 6. 1: MORRP Announcements used to generate rendezvous node-to-destination paths 2-3: MORRP RREQ and RREP Packets to generate source-to-rendezvous node paths 4: Data path after route generation

In order for a source to find a rendezvous node to the destination path, pre-established "routes" from the rendezvous node to the destination must be in place. Periodically, each node sends announcement packets to its neighbors in orthogonal directions starting from its local north as shown in figure 6. When these neighbors receive the packets, the source ID is stored into the DBF of the received interface in the far-field DRT. The number of hops is also recorded if it is not a duplicate packet or if the hop count is less than in the entry. Note that this "hop count" table is only used as reference and is not maintained. The packet is then forwarded out the interface opposite in direction from the interface it received the packet. If no neighbor is found in the opposite interface, a multiplier angle method (MAM) [5] is employed to attempt to maintain straight paths or forward along the perimeter as much as possible.

The entries in the far-field DRT are decayed using the *intra-node* techniques described in section 2. This way, even mobile nodes maintain a general sense of direction for any node they receive an announcement from. Time decaying methods ensure that node locations become less and less certain over time. Unlike the near-field DRT, however, far-field DRT is *not* shared with neighbors (no *inter-node* decay). This is to minimize indirection confusion.

In order to build the source to rendezvous path, an on-demand, reactive element is employed. The reactive element is similar to ORRP and we defer the reader to [5] for more information. For data delivery, if the packet is at the source, first the neighbor list and near-field DRT is queried for the destination. If destination is not found in these two tables, then the far-field DRT is checked to see if the number of bits associated with the destination hash is above the threshold. If destination is still not found in the far-field DRT, then the destination-rendezvous table is queried to see if there is a rendezvous node we need to send to. If it is found, then the far-field DRT is queried for the rendezvous node ID. If after all these steps the destination is unreachable, then a RREQ is sent out in orthogonal directions. For forwarding packets, a similar approach is taken except that if no matches are found, the packet is forwarded to the interfaces exactly 180° from the receiving interface.

4. Performance Evaluation

In this section, we compare MORRP against several proactive, reactive, and position-based routing protocols with one omni-directional interface and several directional interfaces. The simulations were performed using NS2 [2], with nodes using the standard IEEE 802.11 MAC and a 250m antenna range (NS2 default).

Table 1. Default Simulation Parameters

Parameter	Values
# Interfaces	8 Directional Ant.
Topology Boundaries	1300m x 1300m
# of Nodes / Sim. Time	100 / 70s
Annc. Interval / Mobility (m/s)	4s / RWP 0 - 30m/s
Distance Decay Factor (D_d)	.7 (frac. bits drop/hop)
Time Decay Factor (D_t)	.3 (frac. bits drop/sec)
# of BF Hash Funcs / BF Size	30 / 16000 bits
NF Threshold / FF Threshold	6 bits / 6 bits

The performance metrics we evaluated are *packet delivery ratio*, *control packet overhead*, *average path length*, *aggregate network goodput* and *end to end latency*. We examine these metrics under conditions of varying *node mobility speeds*, and *transmission rates*. All simulations were averaged over 3 runs of 5 different random topologies (total 15 trials). Implementations and defaults for GPSR/GLS and

OLSR can be found at [1] and [3] respectively. Table 1 outlines our default simulation parameters.

In order to explore whether MORRP gains were merely from capacity gains with multiple directional antennas or *actual* design improvements, we modified AODV and OLSR implementations to support multiple directional interfaces in the same way as MORRP and ORRP. Since AODV and OLSR rely on omni-directional broadcast to disseminate information, sending out all interfaces simulates the behavior of AODV and OLSR broadcasts. Transmitting data packets, however, require only one interface to be active at a time freeing the medium and other interfaces for other nodes to use. In most of our simulations, we focus heavily on *reachability/delivery success* because in mobile adhoc networks, reachability comes primary over throughput, latency, etc. The reason is because our results show that for high mobility, even limited-flooding protocols like AODV and OLSR simply cannot deliver the majority of the packets (low reachability).

4.1. Effect of Increased Velocity

In this subsection, we evaluate the effect of increasing velocity on traditional routing protocols like AODV, GPSR/GLS, and OLSR and compare it to MORRP, ORRP, and multi-interfaced versions of AODV and OLSR. Our initial simulations involve relatively light load (1000 random 5 second connections). While protocols like GPSR/GLS provide high reach under light load, as the load increases to 10,000 connections, we see a significant drop in reachability. Figure 7 shows our results in comparing MORRP to traditional routing protocols with one omni-directional antenna under varying number of connections.

It is clear that in conditions of high mobility with few connections, MORRP with atleast 8 interfaces provides high reach probability (93% for $1300 \times 1300m^2$ networks) even under conditions of infrequent announcements sent (4 second intervals). As maximum velocity increases, AODV and OLSR fail because of stale routes. With high mobility, it becomes increasingly hard to maintain end-to-end routes without increasing state dissemination rate or route requests. Both options lead to network congestion. Although GPSR with GLS seemingly performs well, end-to-end packet latency is extremely high (3-4 seconds per packet) and the requirement for node localization potentially incurs additional overheads and require devices like GPS receivers which are reliant on "sky access".

When we increase the number of connections to 10,000, protocols that utilize omnidirectional antennas saturate the medium with control packets and reach probability drops significantly. To test whether the gains came as a result of using directional antennas, we modified AODV and OLSR to support multiple directional antennas. The modified AODV and OLSR still send out all interfaces when performing route requests or dissemination (by protocol design) resulting in comparatively large gains with MORRP.

4.2. Effect of Increased Data Rate

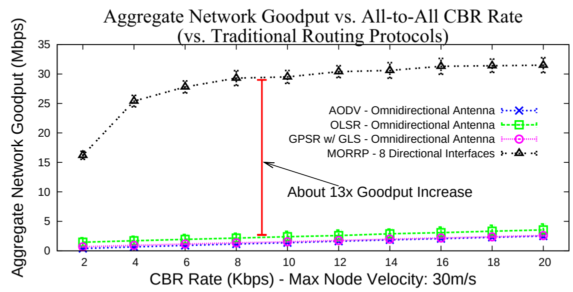

Figure 8. MORRP achieves about 10-14X more aggregate goodput compared to traditional routing protocols.

Although in mobile environments, high reachability naturally leads to high aggregate network goodput, it is important to quantify these gains. In this subsection, we evaluate the effect of increased data rate on network goodput. To do so, we make all-to-all connections simultaneously network-wide and send packets at a set data rate for 20 seconds. By slowly increasing the rate, we can measure the amount of data that actually gets sent. All nodes are moving at a uniformly distributed velocity with a max of 30m/s.

We first compare MORRP to AODV, OLSR, and GPSR/GLS to highlight the gains from simply moving from omnidirectional antennas to directional antennas. Figure 8 shows our results. As expected, MORRP with 8 interfaces achieves much higher goodput than all the other protocols (roughly 10-14X more than OLSR the closest competitor).

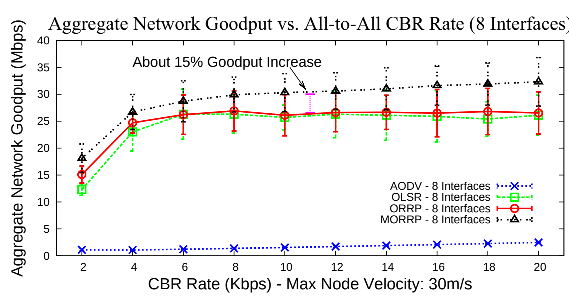

Figure 9. MORRP achieves 15-20% more aggregate goodput over protocols with 8 directional interfaces.

Figure 9 shows that MORRP performs 15-20% better than OLSR and ORRP both with 8 directional interfaces. ORRP fails because it was never designed for mobility and

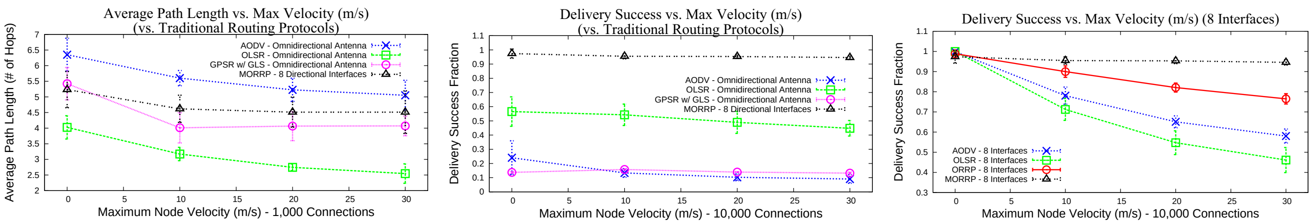

Figure 7. MORRP yields 93%+ data delivery success even in highly mobile environments.

maintenance of straight-line paths becomes difficult in mobile environments. The gains from MORRP come from protocol design. Much like the majority of previous work in using directional interfaces in layer 3 routing [7][9], the modified versions of OLSR and AODV simply *adapt* the protocol to support directionality rather than leveraging the *inherent properties* of directionality to route. Whereas OLSR and AODV even with multiple directional interfaces simply "broadcast" out all intervals for dissemination or route discovery, MORRP utilizes local directionality to send packets along lines to limit flooding. Therefore, it is understandable to see large gains with MORRP over OLSR and AODV with multiple interfaces.

5. Conclusion

In this paper, we presented Mobile Orthogonal Rendezvous Routing Protocol (MORRP), an *unstructured*, *probabilistic*, and *high mobility tolerant* forwarding scheme based on directional communication methods. By utilizing directional routing tables (DRTs), a novel replacement for traditional routing tables, information about nodes in a specific region and nodes along a straight line path is maintained probabilistically. DRTs map interface *directions* to a probabilistic *set-of-IDs* which are decayed and spread locally within a node based on time and *local* node velocity and decayed by number of hops from the source. DRTs provide *regions* where a node can be found in the near-field case and *directions* to send in the far-field case.

When a destination is outside the near-field region, MORRP relies on taking intersections of orthogonal lines originating from source and destination and forwarding packets from the source to rendezvous nodes which in turn hand them over to the destination providing simplified routing. We compared MORRP against AODV, OLSR, GPSR/GLS, and ORRP under varying conditions of mobility and node densities and found that: 1) MORRP yields above 93% reachability even in highly mobile environments for medium-sized networks with medium density. 2) Routing using MORRP accounts for an almost 10-14x higher aggregate goodput compared to AODV, OLSR and GPSR/GLS. These gains come primarily through more efficient reuse of the medium under heavy load. 3) MORRP yields 15-20% higher aggregate goodput compared to modified versions of AODV and OLSR for 8 directional interfaces and also ORRP. These gains come by using directionality constructively and scalably to overcome problems inherent with directionality.

While we have only considered the base case of MORRP in square topologies with random waypoint mobility, there are several directions for future work. First, it would be interesting to see how MORRP fits into hybrid routing environments with networks having a mixture of nodes with omnidirectional and directional communications. Additionally, it would be interesting to see how to incorporate routing metrics into MORRP and DRTs to provide for even better path selection and obstacle avoidance. Another area of consideration is a more detailed evaluation of MORRP under various topologies and traffic patterns.

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