Orthogonal Rendezvous Routing Protocol for Wireless Mesh Networks

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***Abstract*— Routing in multi-hop wireless networks involves the *indirection* from a *persistent name (or ID)* to a *locator*. Concepts such as coordinate space embedding help reduce the number and dynamism complexity of bindings and state needed for this indirection. Routing protocols which do not use such concepts often tend to flood packets during route discovery or dissemination, and hence have limited scalability. In this paper, we introduce Orthogonal Rendezvous Routing Protocol (ORRP) for meshed wireless networks. ORRP is 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 and node localization. The ORRP source and ORRP destination send route discovery and route dissemination packets respectively in locally-chosen orthogonal directions. Connectivity happens when these paths intersect (i.e. rendezvous). We show that ORRP achieves connectivity with high probability even in sparse networks with voids. ORRP scales well without imposing DHT-like graph structures (eg: trees, rings, torus etc). The total state information required is O($N^{3/2}$) for N-node networks, and the state is uniformly distributed. ORRP does not resort to flooding either in route discovery or dissemination. The price paid by ORRP is suboptimality in terms of path stretch compared to the shortest path; however we characterize the average penalty and find that it is not severe.**[1]

I. Introduction

Wireless mesh networks have attracted interest because they can complement the cellular model and expand wireless reach in metro-broadband deployment [19]. Routing in multi-hop wireless networks has grappled with the twin requirements of connectivity and scalability. Early MANET protocols such as DSR [8], DSDV [6], AODV [7], among others, explored proactive and reactive routing methods which either flood information during route dissemination or route discovery respectively. Even in mesh networks which are not mobile, link-states need to be flooded more often than in wired networks. Flooding poses an obvious scalability problem. In response, position-based routing paradigms such as GPSR [2] were proposed to reduce the state complexity and control-traffic overhead by leveraging the Euclidean properties of a coordinate space embedding. These schemes require nodes to be assigned a coordinate in the system, and still require a mapping from nodeID to coordinate location. In this paper, we focus on routing with even lesser information, i.e. scalable, efficient routing without explicit positioning.

[1]This material is based upon work supported by the National Science Foundation under Grant Nos. IGERT 0333314, ITR 0313095, and STI 0230787. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

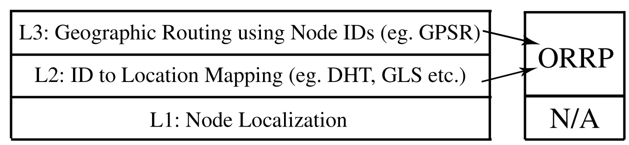

Fig. 1. Classification of research issues in position based routing schemes

A recent trend in wireless communications has been the desire to leverage directional forms of communications (eg. directional smart antennas [11] [10], FSO transceivers [13]) for more efficient medium usage and scalability. Previous work in directional antennas focused heavily on measuring network capacity and medium reuse [10] [11] [12]. In this paper, we utilize directionality for a novel purpose: to facilitate layer 3 routing without the need for flooding either in the route dissemination or discovery phase.

Our protocol, called Orthogonal Rendezvous Routing Protocol (ORRP) is based upon two simple ideas: 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. ORRP assumes that each node has directional communication capability and can therefore have a *local sense of direction* (i.e. orientation of neighbors is known based on a local North). Notice that this is an even weaker form of information than a *global sense of direction* (i.e. orientation of neighbors is known based on a global North) which necessitates additional hardware such as a compass. Figure 2 illustrates an example operation of ORRP.

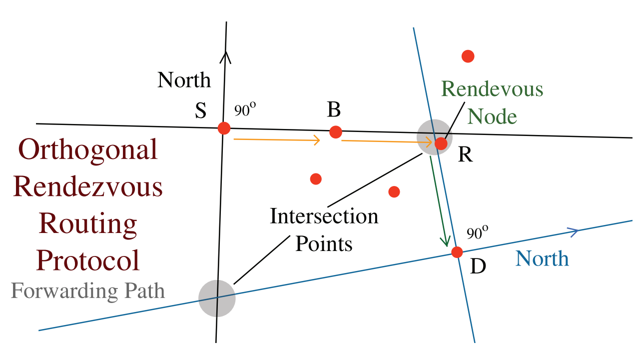

Fig. 2. ORRP Basic Example: Source sends packets to Rendezvous node which in turn forwards to Destination

Consider a source node S that wishes to send packets to a destination node D. Both nodes S and D have their own local notions of orientation. Source S sends route discovery packets in four orthogonal directions and the destination D does likewise for route dissemination packets. The route discovery packets will rendevous at a node touched by a route dissemination packet at up to two rendezvous points on the plane. We refer to the intersection that facilites a shorter path as the rendezvous node R. Node R directs packets from source S to the destination D. Node D's state is only maintained on the two orthogonal lines, which implies that the total state complexity is $O(N^{3/2})$ for an network of N nodes. If each node chooses its local orthogonal directions independently, ORRP state information is fairly evenly distributed throughout the topology resulting in no single point of failure. Further, there is no flooding by either source S or destination D. All these factors enable scalability without imposing the requirement of an explicit hierarchical structure [3], [9]. In other words, ORRP offers a scalable, *unstructured* indirection method for routing in contrast to the hierarchically structured methods suggested in prior work. The ORRP paths chosen however are suboptimal, i.e. have a stretch factor greater than 1 compared to the corresponding shortest paths. However, we show that this factor is not too large on average.

The rest of the paper is organized as follows: We first outline key design issues of ORRP in the next subsection. Section II deals with the specifics of ORRP including assumptions, concepts and examples. Section III provides performance analysis including basic Matlab simulations to formulate upper bounds on reachability and average shortest path while section IV examines these issues in more realistic packetized simulation environments. Finally, section V presents some thoughts on future work and concludes the paper.

A. Key Design Considerations

To fully realize the implications of ORRP, it is important to understand what issues traditional geographic routing protocols face. The problem of end-to-end wireless geographic routing using network localization can be broadly categorized into three layers as shown in Figure 1. The lowest layer L1 is the localization scheme that obtains node coordinates [3] [1] while the second layer L2 maps these coordinates to node "identifiers" like a name or a number. Once these two are established, the third layer L3 uses this information to perform geographic routing. Current research in geographic routing protocols (e.g. GPSR [2], TBR [4], GLS [3], Landmark [17]) often tackle one of the three layers and assume the others to be a given. When taken separately, schemes in each layer can be shown to be extremely scalable. However, combining the effects of maintenance of the three layers can be rather costly. ORRP provides a simple, lightweight alternative to tackle layers L2 and L3 while removing the need for layer L1 all-together.

Specifically, ORRP focuses on and attempts to optimize based on the following considerations:

- *Connectivity Under Less/Relaxed Information* - Protocols such as GPSR [2] or TBR [4] operate under the assumption that each node has a globally consistent view of its own as well as other's geographic positions. ID-to-location mappings (location discovery problem) are assumed to be a given. While this assumption is appropriate given the lowering cost of GPS receivers and several proposed methods of solving the location discovery issue [15], [16], maintaining global view of the network in this way can be costly, unavailable (eg. GPS receivers need "sky access" and cannot be used indoors) and might not be scalable in larger or highly dynamic networks. ORRP eliminates the need for location discovery by utilizing the fact that two pairs of orthogonal lines mostly have intersection points. These "rendezvous points" act as forwarders of the data. This provides for increased scalability.
- *Efficient Medium Reuse* - Topology-based routing protocols often fall into two camps: proactive (eg. DSDV [6]) and reactive (eg. DSR [8], AODV [7]). Proactive protocols consistently flood the network with control packets to maintain up-to-date routing tables at each node. While this ensures high packet delivery success even in mobile environments, scalability is limited due to the sheer number of control packets needed to maintain up-to-date routing tables. Reactive protocols attempt to solve this issue by requesting routes "on demand" and then caching those routes. While this works for less mobile environments, similar issues with scalability arise. ORRP mitigates these issues by forwarding control packets proactively only in orthogonal directions thereby freeing the medium for data, and then reactively requesting routes when one is not cached and is needed. These route requests do not flood the network unnecessarily because they are transmitted only in orthogonal directions and once a rendezvous node receives these request packets, it stops the forwarding.
- *Less State Information Needed to be Maintained* - Because ORRP only maintains routing information in orthogonal directions, scalability is increased.

In order to optimize and bring out the advantages listed above, there are several tradeoffs ORRP performs:

- *Increased Path Stretch* - ORRP optimizes connectivity and efficient medium reuse in contexts of little agreed-upon information. The cost of less information usage is that packets often take paths longer than shortest path. We will show that despite paths taken by ORRP to be suboptimal, under normal circumstances, the average path stretch is close to optimal.
- *Limited Reachability* - Due to possibility of no intersection of orthogonal lines, some source and destination pairs might not have rendezvous points which results in certain paths being unavailable. While several corrective measures are suggested in ORRP, we will show that under normal operation, the packet delivery success is extremely

high.

II. Orthogonal Rendezvous Routing Protocol

In this section, we will detail the assumptions, specifications, and mathematical aspects of ORRP. Specifically, we will address the following:

1) Assumptions made by ORRP including hardware requirements and other cross-layer abstractions
2) Detailed explanation of proactive and reactive elements of ORRP
3) Path deviation correction and void traversing via Multiplier Angle Method (MAM)

A. Assumptions

One of the major aspects of ORRP is that it relaxes many of the assumptions made by position-based routing protocols while still providing connectivity. ORRP makes no assumptions on location discovery and uses packets forwarded in orthogonal directions to find paths to the destination from a given source. To do so, ORRP makes three major assumptions:

- *Neighbor Discovery* - We assume that any given node will know (i) its 1-hop neighbors and (ii) the given direction/interface to send packets to reach this neighbor.
- *Local Sense of Direction* - Each node must have its own local perception of direction with antennas/transceivers oriented in such a way as to be able to consistently send out orthogonal directions. This can easily be done by selecting any of the transceivers as the "local North" and assigning angles to the others based on that selected transceiver.
- *Ability to Transmit/Receive Directionally* - Nodes must be capable of communicating directionally over their transceivers. This can be done by various hardware including directional and smart antennas [10], and FSO transceivers [13]. FSO transceivers are a particular interest due to their fine-grained transmit angle and ability for several dozen to be tesselated together oriented in several directions on a single node [13].

B. Theory

The basic concept behind ORRP is simple: knowing that in 2-D Euclidian space, a pair of orthogonal lines centered at different points will intersect at two points at minimum, rendezvous points can be formed to forward packets as shown in Figure 2. To achieve this, ORRP relies on both a proactive element which makes up the "rendezvous-to-destination" path and a reactive element which builds a "source-to-rendezvous" route on demand. Nodes periodically send ORRP announcement packets in orthogonal directions and at each node along the orthogonal route, the node stores the route to the source of the ORRP announcement and the node it received the announcement from (previous hop). When a source node wishes to send to some destination node that it does not know the path for, it sends out a route request packet (RREQ) in its orthogonal directions and each subsequent node forwards in the opposite direction from which it receives the packet. Once a node containing a path toward the destination receives an RREQ, it sends a route reply packet (RREP) in the reverse direction back to the sender and data transmission begins. In the following subsections, we will detail each element of ORRP and explain tradeoffs and design decisions associated with each part.

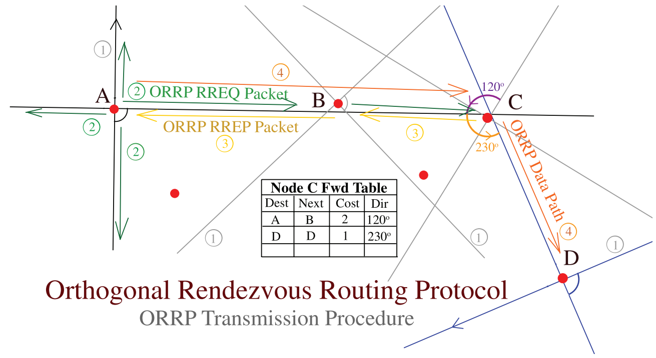

Fig. 3. 1: ORRP Announcements used to generate rendezvous node-to-destination paths 2-3: ORRP RREQ and RREP Packets to generate source-to-rendezvous node paths 4: Data path after route generation

1) Proactive Element: In order for a source and destination to agree upon a rendezvous node, pre-established routes from the rendezvous node to the destination must be in place. Because each node has merely a local sense of direction, making no assumption on position and orientation of other nodes in the network, it can only make forwarding decisions based on its own neighbor list. Upon a set interval, each node sends ORRP announcement packets to its neighbors in orthogonal directions as shown in Figure 3. When those neighbors receive these ORRP announcement packets, it includes the source, previous hop, and hop count into its routing table as a "destination-next-hop pair" and forwards it out the interface exactly opposite in direction from the interface it received the packet. Although we currently only consider hop-count to be the metric for path selection, it is easy to adapt ORRP to use other heuristics such as ETX [20] among others.

It is important to note that each node does *not* maintain a complete picture of the network which limits the state information needed to be updated, and thereby increasing scalability. Moreover, only forwarding in orthogonal directions provides enhanced medium reuse. Based on mobility speeds, energy constraints, and other factors, parameters that can be tweaked for higher performance of ORRP announcements include *announcement send interval* and *forwarding entry expiry time*. Because the forwarding table only maintains information about destination and next hop, overhead in storage and maintenance is minimized as well.

2) Reactive Element: In order to build the path from source to rendezvous node, an on-demand, reactive element to ORRP is necessary. When a node wishes to send packets to an destination that is not known in its forwarding table, it sends out a route request packet (RREQ) in all four of its orthogonal directions. When neighbor nodes receive this RREQ packet, it adds the reverse route to the source into its routing table and forwards in the opposite direction.

In a 2-D Euclidian plane, by sending a RREQ packet in all 4 of its orthogonal directions, it is highly likely to encounter a node that has a path to the destination. When a node with a path to the destination receives the RREQ, it sends a RREP packet back the way the RREQ came. Because each node along the path stored a reverse route to the source, it is able to forward the RREP back efficiently after recording the "next-hop" to send to this particular destination. When the source receives the RREP, it generates a "destination-next-hop" routing entry and forwards packets in the proper direction.

Figure 3 illustrates the process of sending RREQ and RREP packets while showing the ORRP path selected. Unlike AODV, DSR or other reactive protocols, RREQ packets are *not* forwarded until they reach the destination, but only until it intersects a rendezvous node. The proactive element of ORRP takes care of the rendezvous node-to-destination path.

It is important to note that ORRP path is *not* equivalent to the shortest path for most cases. As mentioned earlier, we gained connectivity under relaxed assumptions at the cost of suboptimal path selection (increased path stretch). We will show later, however, that the path selection is comparable to shortest path in majority of situations and therefore the cost is fairly nonexistent.

3) Deviation Correction: Multiplier Angle Method: Up until now, we have considered only situations where nodes forward in orthogonal directions assuming that neighbors are all aligned on a straight line. In reality, however, straight line paths in random networks rarely exist. Although ORRP works on *path intersections* and as a result, does not necessarily need to enforce the rule that packets sent in orthogonal directions must remain true to their path, ensuring that this rule is upheld increases the probability of finding intersections. [14] shows that that two straight lines randomly drawn in a euclidian plane have a 69% chance of intersecting within a given area and as we will show in later sections, two pairs of orthogonal lines have a 98% chance of intersecting.

To address the deviation issue, it is important to clarify a few key concepts and limitations. First, deviation corrections can only be done when the deviation is greater than the conical spread of the directional antenna or transceiver. Directional antennas or FSO transceivers oriented in a circular fashion so that each of the antennas attached to a particular node operate at a set angle from the local "north", have a coverage much like a pizza pie. Depending on the beam width and assuming no overlap in spread, a node can be at various degrees of deviation from the actual orientation of each particular antenna even though it is within the beam spread/coverage area. ORRP does *not* deal with deviations that occur *within* one antenna coverage area.

Next, ORRP assumes that the relative distances from one hop to another are relatively equal. In dense networks, this is a safe assumption due to the sheer volume of nodes. It will be shown that sparse networks do not care about distances either way due to lack of nodes. Finally, all deviation corrections are done at the RREQ and ORRP announcement level so that data transmission does no such calculations per hop.

ORRP addresses the issue of deviation correction by a *multiplier angle method (MAM)*. Each RREQ and ORRP announcement packet has an additional field in the packet header: deviation multiplier. For simplicity, we assume that all nodes have equal number of transceivers each separated with equal distances. The deviation multiplier is used to calculate the deviation angle from the desired angle a packet was sent. Before getting into the algorithm and details, we will define a few key parameters:

Num of Interfaces (ϕ)	The number of interfaces per node
Received Angle (γ)	The angle node received packets from.
Deviation Angle (θ)	The angle to add/subtract that previous node deviated from desired angle when sending.
Desired Angle (α)	The desired angle to send out.
Found Angle (β)	The angle of transceiver found with neighbor closest to desired angle.
Separation Angle (τ)	The angle of separation between each transceiver.
Multiplier (m)	The value to multiply τ by to find new desired angle.

When searching for a next-hop within the corresponding antenna/transceiver beam width, ORRP cycles through all its neighbors and finds one which requires antenna deviation angle yet is still confined to less than $\pm 45°$ (if packet is at originator) or $\pm 90°$ (if packet is merely a forwarder) of the original direction. If a packet is at the originator, only $\pm 45°$ is needed to be searched because each of the four orthogonal directions is sending so giving each direction a $90°$ coverage effectively covers all directions. In the forwarding case, however, because only one direction is considered with potentially "void" spots, a greater angle range is given to traverse "voids" yet ensure packets are not forwarded directly the opposite direction. If no neighbor is found satisfying these conditions, the packet is dropped and an error is flagged. The following equations are used to calculate angle to send and what state to store in each packet (all angle values are between $0°$ and $360°$):

$$Dev\ Angle\ \theta = min(+\frac{\tau * \phi}{4},\ 2 * (\tau * m)), m\ positive \quad (1)$$

$$Dev\ Angle\ \theta = max(-\frac{\tau * \phi}{4},\ 2 * (\tau * m)), m\ negative \quad (2)$$

$$Desired\ Angle\ \alpha = \gamma + \pi - \theta \quad (3)$$

$$Multiplier\ m = \frac{(\beta - \alpha)}{\tau} \quad (4)$$

At each hop, the node unpacks the multiplier from the packet header and calculates a desired angle to send out based on (3). It then searches through its neighbors which have corresponding transceiver angles and finds one with the closest angle to the desired angle. When one is found, a new multiplier is calculated based on (4) and stored into the forwarding packet header before the packet is sent out. The process is repeated until the packet arrives at the destination.

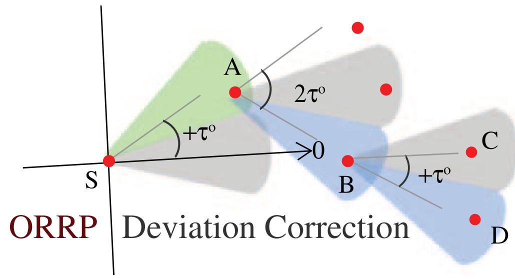

Fig. 4. Basic deviation correction example with Multiplier Angle Method

An example of our proposed *multiplier angle method* for deviation correction is shown in Figure 4. Node S is sending packets along the line. Because it has no nodes along the line in range of its transceivers, S opts to send to node A which is at a transceiver angle of τ from the desired angle α and encode multiplier m of one into the packet header. When node A receives S's packet, it calculates the desired outgoing interface based on (3) and as a result, sends to Node B while encoding a multiplier m of zero because there is no deviation from desired angle and found angle. The rest is self explanatory.

Potential problems may arise if the problem is cascading: node A wishing to send in the correcting direction but has no neighbors in that direction. So, we continue with the original method of choosing a neighbor closest to the deviation angle and sending it. However, ORRP still maintains the multiplier angle method and corrects large deviations with larger forwarding angles. In dense networks, there should be no issues obtaining proper nodes to forward in a straight line.

4) Sparse Networks: Although the concept of ORRP centers around sending packets in four orthogonal directions, it easily adapts to sparse network cases as ORRP merely seeks for rendezvous points between source and destination probe packets. ORRP works based on the assumption that source's and destination's "probe packets" will eventually intersect at a point. That intersection point, however, need not necessarily be along the orthogonal paths. If in the process of sending out RREQ packets, a path is navigated in a curve-like fashion (as opposed to a straight line) due to lack of nodes, which intersects with a node that knows the path to the destination, then a path from source to rendezvous node to destination can easily be built.

Figure 5 illustrates using ORRP's *multiplier angle method* of deviation calculation to navigate around an area devoid of nodes (only one direction is shown). Assuming that node R contains a path to S's intended destination, S's RREQ packets can traverse the perimeter of the void until it reaches node R. Calculations for each step of the way are shown and derived according to (1)-(4). Figure 6 shows a complete path selection from source to destination given a sparse network and no nodes at intersection points.

The multiplier angle method (MAM) differs from GPSR's perimeter routing and many other face routing techniques in

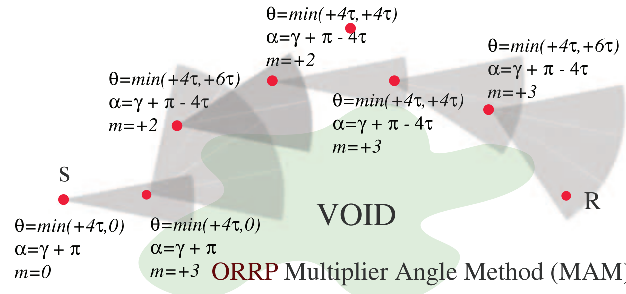

Fig. 5. Multiplier angle method to traverse voids in sparse networks

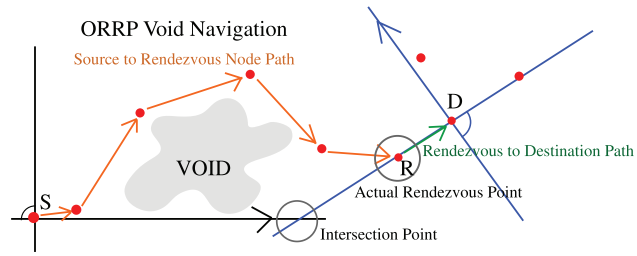

Fig. 6. Traversing voids in sparse networks with differing intersection points

several ways. Firstly, because ORRP seeks only intersections with rendezvous nodes that contain a path to the destination, it is not trying to reach a specific node (assuming that rendezvous nodes will successfully deliver to destination). This allows for much higher flexibility and less stringent requirements for path selection. Secondly, MAM is an inherent nature of ORRP and *not* a special case that switches on and off like GPSR's perimeter routing. Additionally, GPSR's packets maintain additional states such as the node it entered the perimeter routing, points on the coordinate space, and destination information whereas ORRP's MAM requires only one state updated at each node. This additional fact makes MAM much more unstructured and requires much less information.

5) Perimeter Nodes: The multiplier angle method allows for state information to be propagated along the network perimeter as long as its send angle is within $\pm\frac{\pi}{2}$ of the desired direction. While this prevents packets from traversing back on itself, it is important to set a TTL on ORRP announcement and RREQ packets to ensure that perimeter nodes do not get saturated with state information. Section III describes simulation results on how TTL affects reachability, path length, and state maintenance.

6) MAC Layer Issues: [23] bring up several concerns with the nature of directional antenna's asymetric gain resulting in collisions and hidden terminal problems. The main result show that straight line routes are inefficient because of higher interference in the direction of ongoing communications. [24] propose several MAC level solutions to the problem without taking obscure paths to avoid hidden terminal problems and because ORRP focuses more on the routing layer, we do not feel these MAC layer issues are a problem.

III. Theoretical Analysis

As mentioned in the introduction, ORRP provides connectivity with less information at the cost of suboptimal path selection. In this section, we will examine metrics of *reachability* and *average state complexity* with growth of network under a set of conditions and topologies while also observing *path stretch* to determine how much inefficiency in path selection we are trading off to utilize ORRP. Specifically, we will address the following questions for each metric:

1) *Reachability:* Are there certain conditions in which ORRP cannot successfully deliver a packet? What is the upper bound on the source-destination reachability in ORRP?
2) *State Complexity:* How much state information does each node on average need to maintain and how does this compare with other protocols in terms of scalability?
3) *Path Stretch:* How inefficient is ORRP path selection compared to shortest path. Are these results an acceptable tradeoffs for connectivity?

A. Reachability Upper Bound Analysis

Given a Euclidian area over which nodes are scattered, a source-destination pair cannot reach each other using ORRP under conditions where all rendezvous points are outside the boundaries of the area. In order to determine ORRP's reachability upper bound, it is important to isolate cases where ORRP will fail based on source and destination location and orientation. Assuming a Euclidean 2-D rectangular topology $0 < y < b$ and $0 < x < a$ with nodes randomly oriented with "north" between $0°$ and $90°$, we claim that an upper bound in packet delivery success utilizing ORRP is 99.4%.

The general idea behind obtaining the reachability upper bound is to find intersections between orthogonal lines between the source and destination. In cases where all the intersections lie outside of the rectangular area for a particular source and destination oriented in a certain way, ORRP fails to find a path. Notice that this analysis assumes that ORRP probe packets do not travel along perimeters of the Euclidian area under consideration and therefore inspects a worst-case upper bound on reachability. By using very simple techniques (see Sections II-B.3 and II-B.5), it is possible to achieve 100% reachability in ORRP.

Our analysis begins with randomly selecting two source and destination pairs along with random orientations. We then formulate the equations of the orthogonal lines generated by these two nodes and randomly selected orientations and find their intersection points. If at least one of these intersection points lies in the boundaries of the topology, then we consider that particular source-destination pair as reachable. By iterating through all possible orientations for each possible source-destination pairs, we find a percentage of the total combinations that provide reachability vs. the total paths chosen. Because different Euclidian area shapes will no doubt yield different reachability requirements, we calculated the reachability probability for various area shapes by using Matlab. We refer the reader to Appendix for detailed description of our reachability analysis.

Figure 7 shows the varying degree of reachability depending on the topology shape. As can be seen, topologies that spread nodes in single direction such as a rectangle or ellipse with one of the sides much greater than the other yield poor results for reachability due to the fact that ORRP intersections often fall outside of the topology area more easily under those situations. While at first this seems rather disappointing, it is important to note that random topologies rarely fall into a rectangle with one side much longer than the other and even so, ORRP's MAM enables rough forwarding along perimeters to find intersection points, significantly enhancing reach.

TABLE I
COMPARISON OF AVERAGE STATE INFORMATION

	GPSR	DSDV	XYLS	ORRP
Node State	O(1)	O(n^2)	O($n^{3/2}$)	O($n^{3/2}$)
Reachability	High	High	100%	High (99%)
Name Res.	O(n log n)	O(1)	O(1)	O(1)
Invariants	Geography	None	Global Comp.	Local Comp.

B. State Information Maintained at Each Node

One of the major hindrances to network scalability is the amount of state information each node is required to maintain. In completely proactive routing protocols, nodes trade routing tables and other information on a regular basis to keep routes up to date. While this helps maintain connectivity even in highly mobile environments, maintaining such a vast amount of state information at each node requires extensive coordination and information transfer resulting in networks that scale poorly. Because ORRP only forwards routing announcements in orthogonal directions and only nodes along those lines maintain state information about the node sending announcements, it is expected that ORRP will incur less overhead in state maintenance. We ran matlab simulations for a square topology of nodes and calculated the total number of state information each node maintained with respect to the total number of nodes in the system. Because the granularity in our simulation was one, we were able to calculate the total number of state information maintained by iterating through each possible node and orientation combination and taking the average of the distance of the orthogonal lines to the borders of the topologies. This was used to calculate average total state maintained at each node. Our results showed that with rectangular and circular topologies, state scales on the order of $N^{3/2}$ with N being the number of nodes.

Table I shows the ORRP's state information maintenance compared to other protocols. Compared to GPSR with location mapping factored in, ORRP requires more state information to be maintained at each node but requires much less structure and global information to be shared. Looking at the opposite extreme, DSDV provides full connectivity and optimal path selection at the cost of a scalability. In comparison to XYLS [21], ORRP uses less information while achieving virtually similar reachability performance.

C. Average Path Stretch

Because ORRP trades off suboptimal paths for connectivity under less information, it is important to see what conditions lead to unacceptable path choices and how much sub-

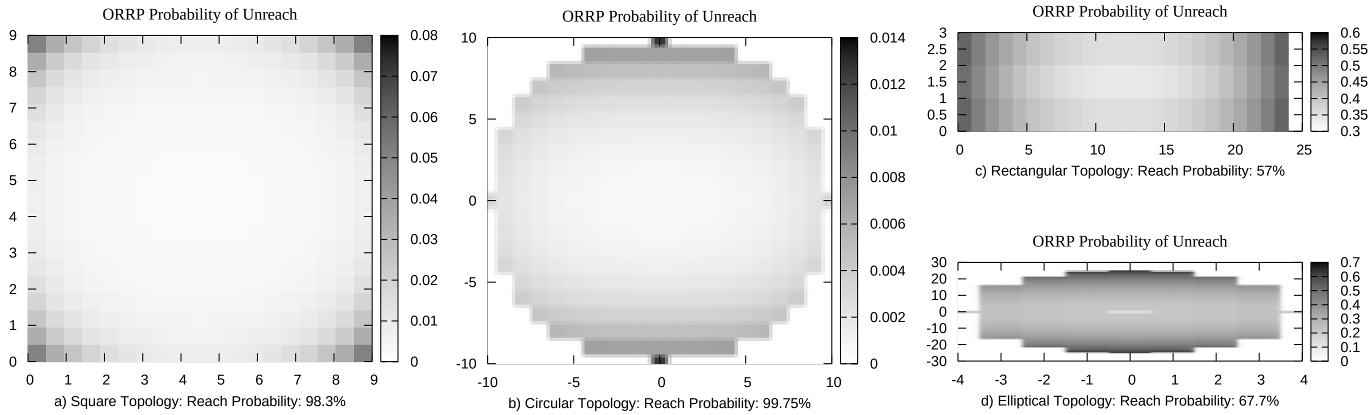

Fig. 7. ORRP Reachability for Various Topology Areas: Nodes in darker regions are less reachable. The strength of the darkness of a point shows the probability that a node located on that point will be unreachable by any other node on the area. It can be seen that topology corners and edges suffer from the highest probability of unreach.

optimality we are trading off for connectivity in an unstructured manner. We begin first by attempting to analyze and understand what kind of stretch values we should expect and then move onto matlab and NS2 [18] simulations for more realistic values.

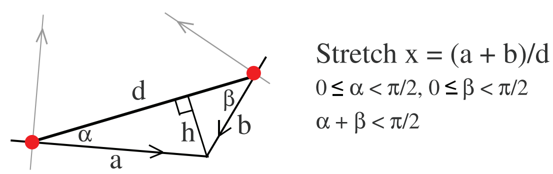

Fig. 8. Average stretch (ORRP Path/Shortest Path) between two nodes

Suppose two nodes are trying to communicate with each other using ORRP as shown in figure 8 where d is the path length between the two points and a and b are the lengths of the two piece ORRP Path (souce-to-rendezvous node and rendezvous node-to-destination). Because there can theoretically be two interception points between the pair of orthogonal lines resonating from the two nodes, path selection is based on the shorter of the two paths. The conditions listed in figure 8 bound the selection to the minimum ORRP Path. Stretch is defined as the path selected (in this case, $a+b$) vs. the shortest path (d). Due to the nature of orthogonal lines, α and β are between 0 and $\pi/2$ and because there is an equal probability for each node to be oriented in a certain manner, α and β are uniformly distributed.

$$h = b\sin\beta = a\sin\alpha \tag{5}$$

$$d = b\cos\beta + a\cos\alpha \tag{6}$$

$$x = \frac{a+b}{d} = \frac{\sin\alpha + \sin\beta}{\sin(\alpha+\beta)} \tag{7}$$

Equations 5 and 6 come from basic trigonometry. Equation 7 represents the stretch x in terms of two uniformly distributed angles α and β. We know that the *probability density function* of a random variable that is uniformly distributed is merely one over the interval resulting in *pdf* of α and β to be $\frac{1}{\frac{\pi}{2}}$ and $\frac{1}{\frac{\pi}{2}-\alpha}$ respectively to satisfy the conditions listed in figure 8. The minimum stretch possible is merely the shortest path and therefore, one. The maximum stretch occurs when both α and β are at $\pi/4$ and $x = \sqrt{2} = 1.414$. As a result we expect the mean of the stretch to be somewhere between 1 and 1.414.

$$E[X] = \int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}-\alpha} \frac{\sin\alpha + \sin\beta}{\sin(\alpha+\beta)} \left(\frac{1}{\frac{\pi}{2}-\alpha}\right)\left(\frac{1}{\frac{\pi}{2}}\right) d\beta d\alpha \tag{8}$$

$$E[X] = 1.125$$

Equation 8 gives the expected value of the random variable X with respect to the two uniformly distributed angles α and β. Integrating the values over the chosen intervals yields a mean of 1.125 for the ORRP path stretch in *unbounded regions* (12.5% path stretch). Although not quite exactly shortest path, we can see that the stretch is still very low and in most cases, acceptable. Similar analysis leads to a variance of 0.0106 and therefore we can expect most of the path selections to be relatively close to shortest path.

Using Matlab, we created several topologies and iterated through every possible source-destination pair along with every possible orientation for each node. We then built paths (distances) from the source to rendezvous node to destination and compared with the shortest path. If no rendezvous nodes were found within the boundaries of the topology, a path length of the perimeter of the topology was used in calculations, as this is the worst possible path length if packets are routed along perimeter.

Figure 9 shows evaluated topologies along with ORRP path to shortest path ratios for nodes in each region. As expected, the rectangular topology yielded the highest path discrepancy with an average path stretch of 3.24. This is most likely due to the fact that in the reachability evaluations as shown in Figure 7, the rectangular shape had the highest amount of unreachability resulting in the perimeter case needing to be invoked the most. As for why the highest path discrepancy appeared in the middle of the rectangle, it is due to the fact that nodes in the middle allow for the longest ORRP paths, reaching the left and right edges while the shortest path is extremely short (the middle to anywhere else directly is short).

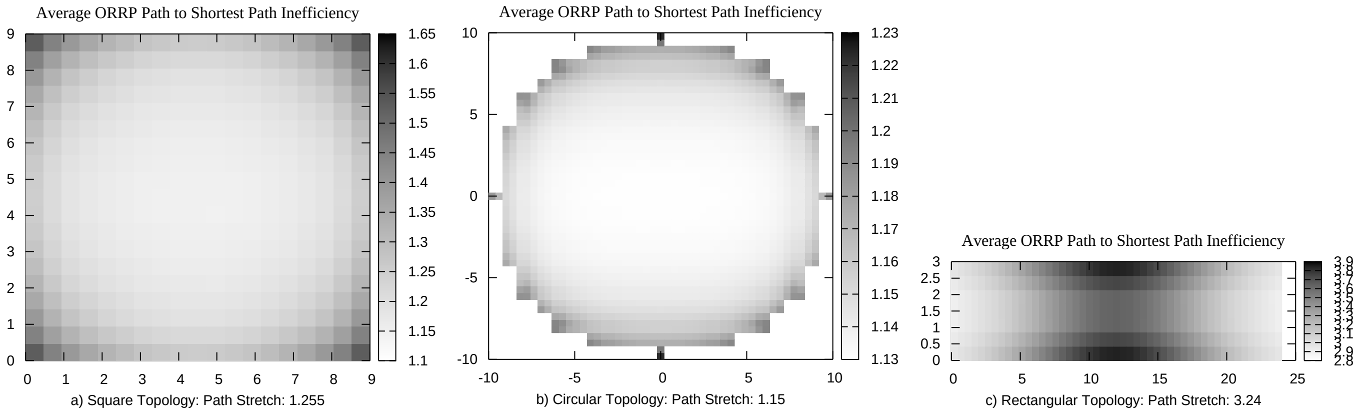

Fig. 9. ORRP Path vs. Shortest Path Ratio: A node in darker regions have higher likelihood of having longer paths to a destination on the area. Topology corners and edges suffer from the higher stretch in symmetric topologies.

The results from the other topologies are also consistent with expectations in that the circular topology, with the greatest reach probability, yielded the smallest average path stretch.

IV. Packetized Simulation and Evaluation

In this section, we will evaluate the metrics of *reachability*, *state maintenance*, and *path stretch* listed above under conditions of varying *number of interfaces*, and *TTL values*. Unless otherwise noted, all simulations were performed using Network Simulator [18].

A. Affect of Control Packet TTL on Varying Network Densities

MAM attempts to minimize deviations in path. In sparse networks, however, announcement packets scheduled for orthogonal directions might initially be sent through the same path due to lack of neighbor options. In traditional routing announcements, one of these packets would be dropped to minimize overhead. In ORRP, however, there is a potential for the packets to "split" to different paths as neighbor density increases. ORRP limits a continual flood of announcement and RREQ packets through packet TTL. While in many cases, packet drops would occur at the network perimeter due to ORRP's MAM forwarding conditions, TTL plays an important role in amount of state needed to be maintained at each node.

The simulations were performed in NS2 [18] in a 300x300m sized network with each node averaging 5 neighbors and having an antenna range of 60m. Interfaces were setup so that they were all aligned equally spaced radially from a single point (the node) with the transmission and receive angle for each interface equal. Adding all the transmission angles together provided for omnidirectional coverage. For example, a node with 36 interfaces would have a transmit/receive and interface separation angle of 10°. In the same way, a node with 4 interfaces would have a transmit/receive and interface separation angle of 90°.

Figure 10 shows the affect of TTL on the reachability, total states maintained, and average path length. Our results showed that varying the number of interfaces did not affect the outcome of the TTL study under average density conditions. We have also run extensive simulations on the affect of the number of interfaces on each of the metrics stated above under various network densities. Results from those simulations (which are beyond the scope of this paper) showed that under sparse network conditions, number of interfaces has a greater affect on the reachability, average states maintained, and path stretch.

Results from our TTL simulations show that as the TTL is increased, a steady increase in reachability and number of states maintained network-wide occurs and reaches a saturation point. This is to be expected because since the network size and transmission range of the nodes dictate that almost all nodes should be able to be reached within 5-6 hops. Even for a TTL of two which should result in paths of 4 hops (2 hops from source to rendezvous node, 2 hops from rendezvous node to destination), much of the network would be reachable. Our simulations showed this as even with a TTL of 2, 95% of the network was reachable. Saturation is reached as the MAM takes over and prevents additional forwarding along the perimeter which is consistent with our results.

B. State Information Maintained

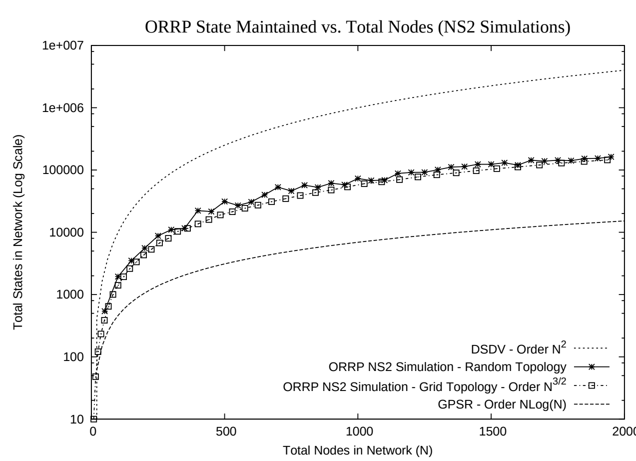

Fig. 11. NS2: ORRP Total State Maintained vs. Total Nodes in Network

ORRP was run in with grid and random topologies for several numbers of nodes and the total state maintained

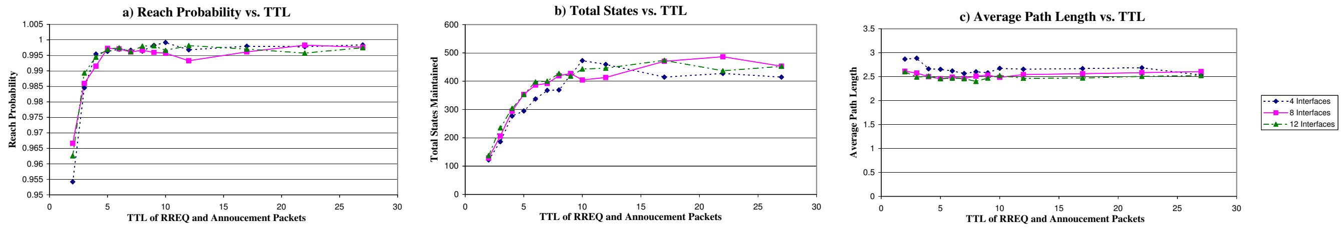

Fig. 10. ORRP reachability, total states maintained, and average path length vs. control packet TTL for various number of interfaces. Increasing TTL up to a certain point does not affect reach probability, states maintained, and average path length.

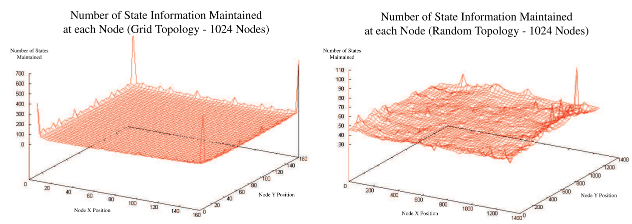

Fig. 12. NS2: State Maintained in Network Topology. ORRP states are evenly distributed throughout the network.

throughout the network tracked. Figure 11 shows the total number of states maintained vs the total number of nodes in both grid and random topologies. Lines fitted to both plots show an order $N^{3/2}$ maintenance of state at each node.

To understand the distribution of where on the topology nodes generally kept more state, a 1024 node scenario was run in grid and random topologies and the number of states kept at each node averaged over 10 trials. Figure 12 shows that edge nodes in both grid and random topologies maintained more state than usual. This is expected as perimeter nodes often bear the brunt of deviated routes. One interesting thing to note is that the amount of state information kept at each node is relatively consistent throughout the entire network. This finding is important because it shows that ORRP is highly distributed and that no single point of failure will drastically affect the network unlike Hierarchical routing where if cluster heads go down, a large network disruption occurs.

V. Future Work and Conclusion

In this paper, we presented Orthogonal Rendezvous Routing Protocol (ORRP), an unstructured forwarding paradigm based on directional communication methods and rendezvous abstractions. By taking intersection of orthogonal lines originating from source and destination, packets from the source are forwarded to rendezvous nodes which in turn hand them over to the destination providing simplified routing. We have shown that ORRP provides connectivity under lessened global information (close to 98% reachability in most general cases), utilizes the medium more efficiently (due to directionality of communications), and state-scales on order $N^{3/2}$ at the cost of roughly 1.12 times the shortest path length. In addition, simulations performed on random topologies show that state information is distributed rather evenly throughout the system and as a result, no single point of failure is evident.

ORRP's benefits all stem from using lines to find intersection points between source and destination. Routing protocols that rely on localization schemes and/or flooding of the network with control packets often find themselves limited in scaling potential due to the amount of information needing to be disseminated throughout the network. ORRP provides highly scalability routing under relaxed and unstructured global information for wireless networks with directional communications support.

While we have only considered ORRP in the context of static wireless mesh networks, there are several directions for future work. Firstly, it would be interesting to investigate how ORRP fits into a context of a hybrid network network containing nodes with both directional antennas and omnidirectional antennas. Another area of consideration is mobility and how to prevent routing loops and provide error correction.

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APPENDIX

In this appendix, we outline our approach for calculating ORRP's reachability probability for a rectangular topology area. Similar approaches were taken to obtain the results for circular and elliptical topologies shown in Figure 7.

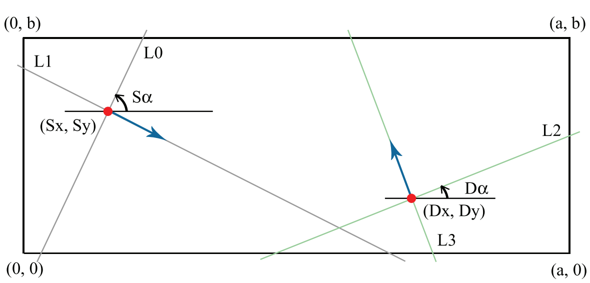

Fig. 13. ORRP unreachability probability calculation

Given a Euclidean 2-D rectangular topology area defined by coordinate ranges $0 < y < b$ and $0 < x < a$, we assume that the nodes are randomly oriented with local "north" between 0° and 90°. Our goal is to find probability that a randomly selected source-destination pair on this rectangular area will not be able to reach each other, or vice versa.

We first find the conditional probability that, given a particular source point in the area, that source point will not be reachable by any other point in the area. Given a source located at (S_x, S_y) and oriented in S_α such that $S_\alpha \leq 90°$, $S_x \leq a$ and $S_y \leq b$ (node is without the bounds of the topology), we assume that L_0 and L_1 are orthogonal lines that intersect source S with one line oriented in the direction S_α. Now, suppose that the source S wishes to send to a destination node D located at $D = (D_x, D_y)$ with D_α such that $0 \leq D_\alpha \leq 90°$, $D_x \leq a$, $D_y \leq b$ and L_2 and L_3 are orthogonal that intersect at D with one oriented in the direction D_α. We need to analytically construct the condition that the source S will be unreachable by any destination D. To do so:

Step 1: We formulate the slopes (m) and the equations for the four lines L_0, L_1, L_2, and L_3. As an example, for line L_0, we formulate as follows:

$$\begin{aligned} L_0 : m_0 &= tan(S_\alpha) \\ y_0(x) &= x_i tan(S_\alpha) + S_y - tan(S_\alpha) \times S_x \end{aligned} \tag{9}$$

Step 2: We determine four possible intersection points (excluding the source point S and the destination point D) among the lines L_0, L_1, L_2, and L_3:

$$\begin{aligned} &L_2 \ and \ L_0 : \ (x_{20}, y_{20}) \ s.t. \ y_0(x_{20}) = y_2(x_{20}) \\ &L_2 \ and \ L_1 : \ (x_{21}, y_{21}) \ s.t. \ y_1(x_{21}) = y_2(x_{21}) \\ &L_3 \ and \ L_0 : \ (x_{30}, y_{30}) \ s.t. \ y_0(x_{30}) = y_3(x_{30}) \\ &L_3 \ and \ L_1 : \ (x_{31}, y_{31}) \ s.t. \ y_1(x_{31}) = y_3(x_{31}) \end{aligned}$$

Step 3: We finally formulate the analytical unreachability conditions as that all four of the intersection points must *NOT* be in the topology rectangular area. Thus, constraints for intersection points for unreachability can be written as:

$$NOT\big(0 \leq x_{20} \leq a \ AND \ 0 \leq y_{20} \leq b\big) \tag{10}$$
$$NOT\big(0 \leq x_{21} \leq a \ AND \ 0 \leq y_{21} \leq b\big) \tag{11}$$
$$NOT\big(0 \leq x_{30} \leq a \ AND \ 0 \leq y_{30} \leq b\big) \tag{12}$$
$$NOT\big(0 \leq x_{31} \leq a \ AND \ 0 \leq y_{31} \leq b\big) \tag{13}$$

To numerically calculate unreachability probability, we first obtain the intersection point coordinates in terms of S_x, S_y, S_α, D_x, D_y, and D_α by using the line equations in the intersection point equalities (e.g. in (9)). For example, x_{20} and y_{20} can be derived as follows:

$$\begin{aligned} &y_0(x_{20}) = y_2(x_{20}) \\ &x_{20} tan(S_\alpha) + S_y - tan(S_\alpha) \times S_x \\ &\quad = x_{20} tan(D_\alpha) + D_y - tan(D_\alpha) \times D_x \end{aligned}$$

$$x_{20} = \frac{D_y - D_x tan(D_\alpha) - S_y + S_x tan(S_\alpha)}{tan(S_\alpha - tan(D_\alpha)} \tag{14}$$

$$\begin{aligned} y_{20} = &\frac{D_y - D_x tan(D_\alpha) - S_y + S_x tan(S_\alpha)}{tan(S_\alpha) - tan(D_\alpha)} \\ &\times tan(S_\alpha) + S_y - S_x tan(S_\alpha) \end{aligned} \tag{15}$$

Then, we calculate the intersection point coordinates for all possible values of S_x and D_x between 0 and a, S_y and D_y between 0 and b, and S_α and D_α between 0° and 90°, while checking the unreachability constraints (10)-(13). By running through all possibilities, we calculate the ratio of the number of S-D pairs satisfying the unreachability constraints and the total possible number of S-D pairs, which is the unreachability probability.