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### Authors

Garcia-Luna-Aceves, J.J.

Wang, Y.

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# Minimizing Routing Overhead With Two-Hop Coordinate Awareness in Ad Hoc Networks

Yali Wang, J.J. Garcia-Luna-Aceves

ylwang,jj@soe.ucsc.edu

Computer Engineering Department,  
University of California, Santa Cruz  
Santa Cruz, CA 95064, USA

**Abstract**—We introduce ORTHCA (On-demand Routing with Two Hop Coordinates Awareness) a method for minimizing the dissemination of route requests in mobile ad hoc networks (MANET). The selection of relaying nodes is implemented by first computing the best two-hop relay nodes  $R_2(u)$  whose Euclidean Distance to four polar points are the shortest among all two-hop neighbors  $\mathcal{N}_2(u)$ , and then determining one-hop relay nodes  $R_1(u)$  connecting with  $R_2(u)$ . This process is iterated by each member of  $R_2(u)$ . We prove that all nodes in a connected MANET are covered in the dissemination of route requests using this procedure, and that  $|R_1(u) + R_2(u)| \leq 16$ , which constitutes complexity  $O(1)$ , regardless of the density of the network. ORTHCA is compared with representative routing protocols, namely AODV, OLSR, LAR, and THP. The simulation results show that ORTHCA reduces the routing load and improves packet delivery ratios, outperforming the other four routing protocols.

## I. INTRODUCTION

Proactive routing protocols (e.g., OLSR [1], WRP [2]) require that all network nodes receive signaling packets with updates to the state of links of distances to destinations, so that correct routes to destinations can be established at each node. On the other hand, on-demand routing protocols (e.g., AODV [3], DSR [4], NSR [5]) require that route requests reach all nodes in the network, so that it can be ensured that either the destination or a relay with a route to it answers a given route request. Consequently, flooding or network-wide dissemination of signaling packets constitutes an integral component of many routing protocols designed for mobile ad hoc networks (MANET), and it could be argued that any solution to the routing problem in MANETs that relies on destination-based routing tables requires some signaling packets to traverse the entire network, even if this involves changing the content of the signaling packets on a hop by hop basis.

It has been shown that, in order to make MANETs scale with the number of nodes, its signaling must avoid or reduce the amount of broadcast traffic required to maintain control information or disseminate data [6]. Section II summarizes the prior work aimed at making the flooding or network-wide dissemination of route signaling packets more efficient. What is interesting about this prior work is that the number of neighbors forwarding the signaling packets transmitted by a given node increases as the size of the node neighborhood increases. Hence, the number of neighbors that must relay signaling packets for any given node is  $O(|\mathcal{N}(j)|)$  where  $|\mathcal{N}(j)|$  is the cardinality of the set of neighbors of a node  $j$ .

We introduce ORTHCA (On-demand Routing with Two-Hop Coordinate Awareness), the first routing scheme to utilize the geographical locations of two hop neighbors to ensure that the number of neighbors that need to relay signaling packets at each hop is  $O(1)$ , regardless of the density of the network.

Section III presents the process used in ORTHCA to select the nodes that should relay signaling packets. ORTHCA assumes that each node knows its own geographical coordinates by GPS, and each node communicates its node identifier (ID) and geographical coordinates to its neighbors periodically. Accordingly, each node learns the geographical locations of all its own neighbors. A node determines its one- and two-hop forwarders among all neighbors, which are those neighbors that are closest to the four polar points of the network (North, South, East, West) within the transmission range of the node. The node also adds secondary forwarders as needed, such that the entire connected network is covered. When a node relays a route request, it asks its forwarders to forward the route request if they do not have a route to the intended destination.

Section IV proves the correctness of ORTHCA and

that the complexity of the maximum number of relay nodes needed at each hop to cover the entire network is  $O(1)$ , regardless of the number of neighbors of a node. Section V presents the results of simulation experiments based on MANETs of 200 and 250 nodes used to compare ORTHCA with AODV, OLSR, Location-Aided Routing (LAR) [7], and Three-hop Horizon Pruning (THP) [8]. The results of these simulations show that ORTHCA incurs the smallest routing load among all protocols while attaining average delays and packet delivery ratios that are comparable to or better than those obtained with the other four routing protocols. Section VI presents our conclusions.

## II. RELATED WORK

The prior work aimed at reducing the overhead incurred in on-demand or proactive maintenance of destination-based routing tables in MANETs includes hierarchical routing, substituting flooding of signaling packets with depth-first search mechanisms, targeting the dissemination of signaling packets based on known prior locations of destinations, and reducing the number of nodes that must ensure that signaling packets reach all nodes.

With hierarchical routing (e.g., [9]–[12]), groups of destinations are aggregated into clusters or other structures in a way that the number of entities for which routing-table entries must be maintained is reduced. However, the use of routing hierarchies still requires the dissemination of signaling packets within clusters and across clusters.

There have been only a few attempts to solve the problems incurred with flooding by using depth first search (DFS) instead of breadth first search (BFS) or flooding. These approaches have focused on the use of *random walks* [13], [14] in which a route request starts at the source and travels along a single path found by consecutive random next-hop choices in search for the destination. The limitation of these approaches is that the communication complexity incurred in reaching destinations when packets have to traverse random walks may be comparable to that of flooding, but with much longer delays.

Approaches based on DFS and BFS that have improved over random walks in the past use geo-location information for the routing of packets. Starting with the first proposals on geographical routing (e.g., Greedy Perimeter Stateless Routing (GPSR) [15]), they have assumed that the sources know the geographical coordinates of the destinations, or at least regions where the

destinations may be located. Cartesian Routing [16] uses latitude and longitude address to determine the position of route relative to that of the destination. GeoGRID is an extension of GRID [17] in which a forwarding zone is composed of multiple two-dimensional logical grids. Two types of GeoGRID are proposed; a flooding-based GeoGRID restricts the gateway nodes within forwarding zone to forward the geocast packets, and a ticket-based GeoGRID restricts the gateways nodes to be only those holding tickets evenly distributed by the source to rebroadcast the geocast packets. GeoTORA [18] is an extension of TORA that floods geocast packets to a geocast group. In Distance Routing Effect Algorithm for Mobility (DREAM) [19], each node periodically broadcasts location information about its own position to maintain routing tables and uses this information to transmit data packets.

Many approaches have been proposed that take advantage of knowledge regarding the geographical locations of destinations to make route signaling more efficient. Location-Aided Routing (LAR) [7] and GeoCast [20] are two examples of this approach. In particular, in LAR, after a source finds the geo-location of a destination by means of the flooding of a route request without any sense of direction, the source or relays are able to direct subsequent route requests towards the previously known location of the destination. Location-Based Multicast (LBM) protocol [21] reduces flooding by using an extension of LAR; a node can forward a packet to a forwarding zone, or to the nodes within a distance to the center of a geocast region. It is important to note that, as the density of the network increases (i.e., the average number of nodes in the neighborhood of any one node), the number of nodes that must relay signaling information with or without a sense of direction increases.

Several approaches have been proposed and implemented attempting to reduce the number of nodes that need to relay signaling packets in a network while still ensuring that all network nodes are able to receive such packets. These approaches (e.g., [1], [8], [22]–[24]) use different algorithms that in essence establish connected dominating sets dynamically. The strength of these schemes is that they succeed in reducing the number of nodes that must relay signaling packets in a MANET. However, the number of relays that must forward a signaling packet transmitted by a given node grows with the density of the network.

All of the above schemes are such that the number of nodes that must relay signaling packets must increase as

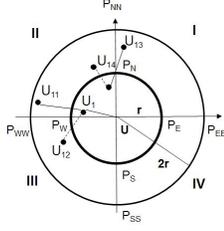


Fig. 1. Information at node  $u$

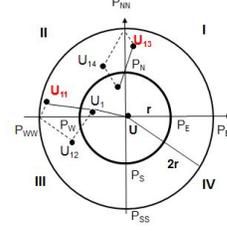


Fig. 2. Select two hop forwarders

the density of the network increases. To the best of our knowledge, only one prior scheme (ORCA [25]) allows route requests to propagate to all nodes in the network while having a maximum number of relays at each hop, independently of the density of the network.

TABLE I  
NOTATION

$u$	a node
$r$	Transmission radius
$(x_u, y_u)$	Coordinates of $u$
$d(u_1, u_2)$	Distance between $u_1$ and $u_2$
$P_1(u), P_2(u)$	Set of four poles of $u$ located within $r, 2r$
$\mathcal{N}_1(u), \mathcal{N}_2(u)$	Set of 1-, 2-hop neighbors of $u$
$R_1(u), R_2(u)$	Set of 1-, 2-hop relay nodes of $u$
$ R_1(u) ,  R_2(u) $	The cardinality of $R_1(u), R_2(u)$

### III. ORTHCA

The goal of ORTHCA is to attain full coverage of all nodes in the MANET while requiring only a constant number of neighbors to forward a signaling packet, independently of the total number of neighbors. The operation of ORTHCA makes the following assumptions: (a) all nodes have the same transmission range  $r$ , (b) nodes are half duplex and share a single broadcast channel, (c) the MANET in which ORTHCA operates is connected, (d) each node is capable to know its own geographical location with GPS [26] and has a unique node identifier, and (e) no two nodes have the exact same geographical location. Table I summarizes the nomenclature we use in the description of ORTHCA.

#### A. Selecting Relay Nodes

Figure 1 illustrates the information used in ORTHCA by a given node  $u$ . To simplify the description of ORTHCA, the one- and two-hop neighbors of a node are enumerated with subscripts. The first number in the subscript is used to enumerate one-hop neighbors, and the second is used for two-hop neighbors. For instance,

$u_1 \in \mathcal{N}_1(u)$  is located inside transmission range  $r$  and  $u_{11} \in \mathcal{N}_2(u)$  is between  $(r, 2r)$ . Each node  $u$  transmits a HELLO message to all its neighbors  $\mathcal{N}_1(u)$  periodically. Node  $u$  states its node ID and geographical coordinates in its HELLO messages. In addition, it includes the identifier and geographical coordinates of all its one-hop neighbors in its HELLO messages. Thus, each node  $u$  obtains information about nodes one and two hops away  $\mathcal{N}_2(u)$ . As shown in Figure 1,  $u$  defines four polar positions  $\{P_1(u), P_2(u)\}$  along four axis directions on the plane (i.e., *North, East, South* and *West*).

$$\begin{cases} P_1(u) = \{P_N(u), P_E(u), P_S(u), P_W(u)\} \\ P_2(u) = \{P_{NN}(u), P_{EE}(u), P_{SS}(u), P_{WW}(u)\} \end{cases}$$

To explicitly define the polar positions, node  $u$  follows the diameter rule of a circle:

$$\begin{cases} P_E : (x_u + r, y_u), P_{EE} : (x_u + 2r, y_u) \\ P_S : (x_u, y_u - r), P_{SS} : (x_u, y_u - 2r) \\ P_W : (x_u - r, y_u), P_{WW} : (x_u - 2r, y_u) \\ P_N : (x_u, y_u + r), P_{NN} : (x_u, y_u + 2r) \end{cases}$$

Selecting relay nodes is divided into three stages. First, node  $u$  determines the set of two-hop forwarders denoted by  $R_2(u)$ . All members in  $R_2(u)$  must satisfy with the rule of being the closest to one of four poles  $P_2(u)$ :

$$\forall u_{ii} \in \mathcal{N}_2(u), \exists u_{jj} \in \mathcal{N}_2(u),$$

$$\begin{cases} d(u_{jj}, P_2(u)) = \min\{d(u_{ii}, P_2(u))\} \\ R_2(u) = R_2(u) + \{u_{jj}\} \end{cases}$$

Second, node  $u$  determines the set of one hop forwarders denoted by  $R_1(u)$ . All members in  $R_1(u)$  must satisfy with the rule of being the closest to one of  $R_2(u)$  such as:

$$\forall u_i \in \mathcal{N}_1(u), \exists u_j \in (\mathcal{N}_1(u), \mathcal{N}_1(R_2(u)))$$

$$\begin{cases} d(u_j, R_2(u)) = \min\{d(u_i, R_2(u))\} \\ R_1(u) = R_1(u) + \{u_j\} \end{cases}$$

Third, if after both  $R_1(u)$  and  $R_2(u)$  are selected and not all neighbors are covered to receive route requests, supplemental forwarders are added. To ensure complete

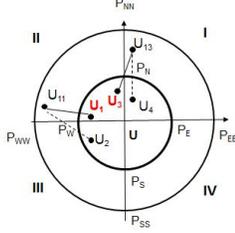


Fig. 3. Select one hop forwarders

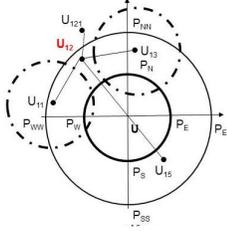


Fig. 4. Select additional two hop forwarders

full coverage of all in the two-hop neighborhood, the following conditions must be satisfied:

$$\begin{aligned} & \forall u_{ii} \in \mathcal{N}_2(u), \exists u_{jj} \in \mathcal{N}_2(u) \\ & \left\{ \begin{array}{l} \forall v_{ii} \in R_2(u), d(u_{jj}, v_{ii}) > r \\ R_2(u) = R_2(u) + \{u_{jj}\} \end{array} \right. \\ & \forall u_i \in \mathcal{N}_1(u), \exists u_j \in \mathcal{N}_1(u) \\ & \left\{ \begin{array}{l} \forall v_i \in R_1(u), d(u_j, v_i) > r \\ R_1(u) = R_1(u) + \{u_j\} \end{array} \right. \end{aligned}$$

Node  $u$  repeats this computation procedure until no neighbor satisfies with all equations listed as above. Figures 2 to 5 illustrate the selection process.

### B. Propagation of Signaling Packets by Relay Nodes

ORTHCA requires the list of relays to be included in the header of a signaling packet that is to be flooded in

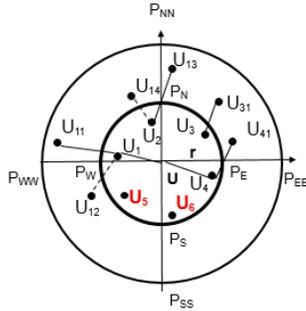


Fig. 5. Select additional one hop forwarders

the network. All nodes in the one-hop neighborhood of a node  $u$  receive the broadcast signaling packet, and the nodes that are not listed in the relay list of the packet header process the packet but do not forward it; only the nodes in the relay list forward the packet using their own relays, which they compute using the ORTHCA relay selection procedure.

When a source  $s$  has data to send to an intended destination for which it does not have a valid route, it proceeds with a route discovery process similar to most on-demand routing protocols. Node  $s$  broadcasts a route request (RREQ) to establish a valid route by flooding the RREQ throughout the network in order to find the destination or a node with a valid route to the destination. As in prior on-demand routing protocols, the RREQ specifies the source, the intended destination, a sequence number used to prevent replicas of the RREQ to be transmitted, and the list of relays for the packet. The same mechanisms used in prior on-demand routing protocols for the processing of RREQs apply to ORTHCA. Any node receiving the RREQ may send a route reply (RREP) if it has a valid route to the destination; however, only the nodes listed in the relay list of the RREQ can propagate the RREQ.

The handling of RREPs in ORTHCA is the same as in AODV and similar on-demand routing protocols, and the same applies to the processing of route errors (RERR) sent by a node  $n$  to the source  $s$  of a data packet when  $n$  is asked to forward a data packet for which it has lost its valid route.

### C. Example

To simplify our description, only some quadrants are presented. For the rest of quadrants the same is rule followed. In Figure 1,  $u$  defines  $P_2(u) = \{P_{NN}(u), P_{EE}(u), P_{SS}(u), P_{WW}(u)\}$ . In Figures 2, 3, and 4, given  $(u_1, u_2, u_3, u_4) \in \mathcal{N}_1(u)$ ,  $(u_{11}, u_{12}, u_{13}, u_{14}, u_{15}) \in \mathcal{N}_2(u)$  from HELLO messages,  $u$  gets the coordinates information of  $\mathcal{N}_1(u)$  and  $\mathcal{N}_2(u)$ .

In Figure 2,  $u$  computes  $R_2(u)$

$$\left\{ \begin{array}{l} d(u_{11}, P_{WW}) < d(u_{12}, P_{WW}) \Rightarrow u_{11} \in R_2(u) \\ d(u_{13}, P_{NN}) < d(u_{14}, P_{NN}) \Rightarrow u_{13} \in R_2(u) \end{array} \right.$$

In Figure 3,  $u$  computes  $R_1(u)$

$$\left\{ \begin{array}{l} d(u_1, u_{11}) < d(u_2, u_{11}) \Rightarrow u_1 \in R_1(u) \\ d(u_3, u_{13}) < d(u_4, u_{13}) \Rightarrow u_3 \in R_1(u) \end{array} \right.$$

In Figure 4,  $u$  computes additional forwarders needed.

$$\left\{ \begin{array}{l} d(u_{12}, u_{11}) > r \\ d(u_{12}, u_{13}) > r \\ d(u_{12}, u_{15}) > r \\ R_2(u) = R_2(u) + \{u_{12}\} \\ d(u_5, \{u_1, u_2, u_3, u_4\}) > r \\ d(u_6, \{u_1, u_2, u_3, u_4, u_5\}) > r \\ R_1(u) = R_1(u) + \{u_5, u_6\} \end{array} \right.$$

$$R(u) = \{R_1(u) + R_2(u)\}$$

The pseudocode of the simple relay-selection procedure in ORTHCA that we have just described is presented below using the nomenclature stated in Table I. The algorithm consists of three procedures: *Select2hopRelay*, *Select1hopRelay*, *AddRelayNode*.

**Algorithm :** COMPUTERELAYSET( $u$ )

```

 $R_1(u), R_2(u) \leftarrow \emptyset$ 
SELECT2HOPRELAY( $u$ )
SELECT1HOPRELAY( $u$ )
ADDERELAYNODE( $u$ )
procedure SELECT2HOPRELAY( $u$ )
   $MIN = \infty$ 
  for  $i \leftarrow 1$  to 4
    for  $k \leftarrow 1$  to  $|\mathcal{N}_2^k(u)|$ 
      do do do
        if  $\mathcal{N}_2^k(u) \notin R_2(u)$ 
          if  $d(P_2^i, \mathcal{N}_2^k(u)) < MIN$ 
            then  $\{MIN \leftarrow d(P_2^i, \mathcal{N}_2^k(u))$ 
               $m \leftarrow \mathcal{N}_2^k(u)$ 
            if  $d(P_2^i, \mathcal{N}_2^k(u)) = MIN$ 
              then  $\{$ 
                if  $\mathcal{N}_2^k(u) < m$ 
                  then  $m \leftarrow \mathcal{N}_2^k(u)$ 
               $\}$ 
             $R_2(u) \leftarrow R_2(u) + \{m\}$ 

```

```

procedure SELECT1HOPRELAY( $u$ )
   $MIN = \infty$ 
  for  $i \leftarrow 1$  to 4
    for  $k \leftarrow 1$  to  $|\mathcal{N}_1^k(u)|$ 
      do do do
        if  $\mathcal{N}_1^k(u) \in \mathcal{N}_1(R_2(u))$ 
          if  $d(P_1^i, \mathcal{N}_1^k(u)) < MIN$ 
            then  $\{MIN \leftarrow d(P_1^i, \mathcal{N}_1^k(u))$ 
               $m \leftarrow \mathcal{N}_1^k(u)$ 
            if  $d(P_1^i, \mathcal{N}_1^k(u)) = MIN$ 
              then  $\{$ 
                if  $\mathcal{N}_1^k(u) < m$ 
                  then  $m \leftarrow \mathcal{N}_1^k(u)$ 
               $\}$ 
             $R_1(u) \leftarrow R_1(u) + \{m\}$ 

```

```

procedure ADDERELAYNODE( $u$ )
  for  $k \leftarrow 1$  to  $|\mathcal{N}_2^k(u)|$ 
     $c \leftarrow 0$ 
    for  $j \leftarrow 1$  to  $|R_2(u)|$ 
      do do
        if  $d(\mathcal{N}_2^k(u), R_2^j(u)) > r$ 
          then  $c \leftarrow c + 1$ 
        else break
      if  $c = |R_2(u)|$ 
        then  $R_2(u) \leftarrow R_2(u) + \{\mathcal{N}_2^k(u)\}$ 
  for  $k \leftarrow 1$  to  $|\mathcal{N}_1^k(u)|$ 
     $c \leftarrow 0$ 
    for  $j \leftarrow 1$  to  $|R_1(u)|$ 
      do do
        if  $d(\mathcal{N}_1^k(u), R_1^j(u)) > r$ 
          then  $c \leftarrow c + 1$ 
        else break
      if  $c = |R_1(u)|$ 
        then  $R_1(u) \leftarrow R_1(u) + \{\mathcal{N}_1^k(u)\}$ 
   $R(u) \leftarrow R_1(u) + R_2(u)$ 

```

**output** ( $R(u)$ )

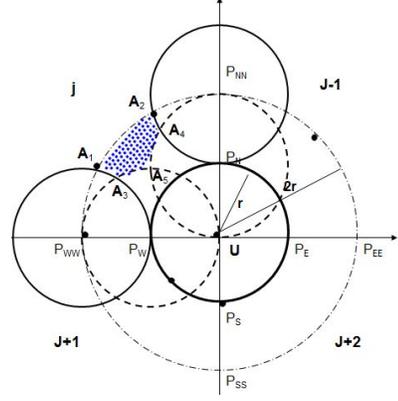


Fig. 6. The number of forwarders in quadrant  $j$

#### IV. ORTHCA CORRECTNESS

For ORTHCA to work correctly, it must ensure that a flooded signaling packet covers all network nodes in the absence of packet losses due to multiple access interference (MAI) [?], and it must require a *constant and fixed* maximum number of relays per node independently of number of two-hop neighbors per node. The following theorems demonstrate that ORTHCA is correct using the nomenclature stated in Table I.

We address the full coverage of a *connected undirected* graph  $G = (V, E)$ , where  $V$  is the set of network nodes and  $E$  is the set of edges, by stating that any  $k$ -hop neighbors of source  $s$  are reachable from  $s$  for an arbitrary number of hops  $k$ . The plane is divided into four quadrants by the reference axis in a Cartesian coordinate system, denoted by  $j$  in Table I, at most two relays can be selected in each quadrant.

The proof for ORTHCA relies on the correctness proof of ORCA [25], for which the the following statements have been shown to be true for a given any node  $u \in G$ :

- All  $k$ -hop neighbors  $\mathcal{N}_k(u)$  are reachable and each node is fully covered in connected MANETs
- Node  $u$  can have at most two polar relay nodes in any one quadrant
- Node  $u$  cannot have two adjacent quadrants with two polar relay nodes each
- Node  $u$  cannot have any additional relay node in a quadrant for which it has any polar relay nodes
- Node  $u$  can have at most two relay nodes in a quadrant of transmission range  $r$
- $\forall u \in G, |R_1(u)| \leq 6$ .
- **if**  $|R_1^j(u)| = 2$ , **then**  $|R_1^{j-1}(u)| \leq 1$  and  $|R_1^{j+1}(u)| \leq 1$

*Theorem 1:* Given a connected undirected graph  $G(V, E)$ ,  $\forall u \in V$ , in any one quadrant  $j$ ,  $(|R_1^j(u)| + |R_2^j(u)|) \leq 6$ .  $\square$

*Proof:* As stated above, within transmission range  $r$ ,  $|R_1^j(u)| \leq 2$ , as shown in Figure 6. For simplicity and without loss of generality, we only present the quadrant  $j$  and in all other quadrants, it follow same proof because of symmetric property.

Based on the selection process, selecting the two-hop relay set  $R_2^j(u)$  in the  $j$  quadrant can initially give at most two forwarders, because there are at most two polars from  $P_2(u)$  in quadrant  $j$ . Thus, we have that  $|R_2^j(u)| \leq 2$ .

As Figure 6 shows, five vertices  $A_1, A_2, A_3, A_4, A_5$  define a shaded intersection zone  $\Delta$ , which is uncovered by  $\{R_1^j(u), R_2^j(u)\}$ . This zone has the greatest area as the worst case, because each vertex  $A_i$  is intersected by two circles with the farthest polar origins. Any other cases of intersection result in a smaller-area zone. Compute the location of  $A_i$  and the distances of every two vertices, then using transmission range  $r$  and rules to determine the number of additional forwarders for full coverage in quadrant  $j$ .

$$\begin{cases} x^2 + y^2 = 4r^2 \\ (x + 2r)^2 + y^2 = r^2 \end{cases}$$

$$\implies A_1(-\sqrt{3}r, r)$$

$$\begin{cases} x^2 + y^2 = 4r^2 \\ x^2 + (y - 2r)^2 = r^2 \end{cases}$$

$$\implies A_2(-r, \sqrt{3}r) \implies d(A_1, A_2) = 1.035r > r.$$

Iterating this computation all distances between two vertices are obtained.  $d(A_1, A_2)$  is the longest such distance, and all of the other distances are shorter than  $r$ . Thus, at most two additional forwarders are needed. Therefore the upper bound is  $|R_1^j(u)| + |R_2^j(u)| \leq 2 + 2 + 2 = 6$   $\blacksquare$

*Lemma 1:* Given a connected undirected graph  $G(V, E)$ , for  $\forall u \in V$ , if  $(|R_1^j(u)| + |R_2^j(u)|) \leq 6$ , then

$$\begin{cases} |R_1^{j-1}(u)| + |R_2^{j-1}(u)| \leq 4 \\ |R_1^{j+1}(u)| + |R_2^{j+1}(u)| \leq 4 \\ |R_1^{j+2}(u)| + |R_2^{j+2}(u)| \leq 2 \end{cases}$$

*Proof:*  $\{j-1, j, j+1, j+2\}$  are four adjacent distinct symmetric quadrants along the direction of counter-clockwise. We only need to consider the worst

case to prove the upper bound because any other cases are equal or better. The upper bound of one-hop and two-hop forwarders is six for a quadrant, for instance,  $|R_1^{j+1}(u)| + |R_2^{j+1}(u)| \leq 6$ . However, it still includes redundant forwarders and should be eliminated.

Let us take  $j$ 's adjacent quadrant  $j+1$  as an example.  $P_{WW}(u)$  is a shared polar intersected by quadrants  $j$  and  $j+1$ , that implies at least two forwarders were counted already by previous selection process in quadrant  $j$ . Therefore,  $|R_1^{j+1}(u)| + |R_2^{j+1}(u)| \leq 4$ . Because of the symmetry of quadrants,  $|R_1^{j-1}(u)| + |R_2^{j-1}(u)| \leq 4$ . In quadrant  $j+2$ , because in all other three quadrants, four forwarders were already covered, then  $|R_1^{j+2}(u)| + |R_2^{j+2}(u)| \leq 2$ . Hence the result is true.  $\blacksquare$

*Theorem 2:* Given a connected undirected graph  $G = (V, E)$ ,  $\forall u \in V$ ,  $\max(\min(|R_1(u)| + |R_2(u)|)) \leq 16$  within transmission range of  $2r$ . The order of message complexity at each hop is  $O(C) \asymp O(1)$ .

*Proof:* This theorem represents that the maximal cardinality of the minimal required one- and two-hop forwarders of any node  $u$  is six. By the sum of all upper bounds of forwarders in all quadrants, we obtain:

$$|R_1(u)| = \sum_{j=I}^{IV} |R_1^j(u)|, |R_2(u)| = \sum_{j=I}^{IV} |R_2^j(u)|$$

Therefore we have

$$\begin{aligned} & |R_1(u)| + |R_2(u)| \\ &= \sum_{j=I}^{IV} (|R_1^j(u)| + |R_2^j(u)|) \leq 6 + 4 + 4 + 2 = 16 \\ &\implies O(|R_1(u)| + |R_2(u)|) = O(C) \asymp O(1). \end{aligned} \quad \blacksquare$$

## V. PERFORMANCE COMPARISON

### A. Scenarios and Metrics

We conducted discrete-event simulations using the Qualnet Simulator [27]. In the scenarios we used, 200 and 250 nodes were deployed randomly in a rectangular-shaped area of  $1200 \times 300 \text{ m}^2$  and  $1500 \times 400 \text{ m}^2$ , respectively, to have similar densities. Nodes move with speeds randomly chosen between 1m/s and 20m/s, according to the random way-point (RWP) mobility model. The simulation time is 900 seconds, and pause time varies from 100 seconds to 900 seconds, by increment of 100 seconds. Nine seeds were used for each simulation run. Data transmission is constant bit rate (CBR), and the duration of data flows is exponentially distributed with the mean value of 100 seconds. Different percentages of flows to total number of nodes were used from 40% to

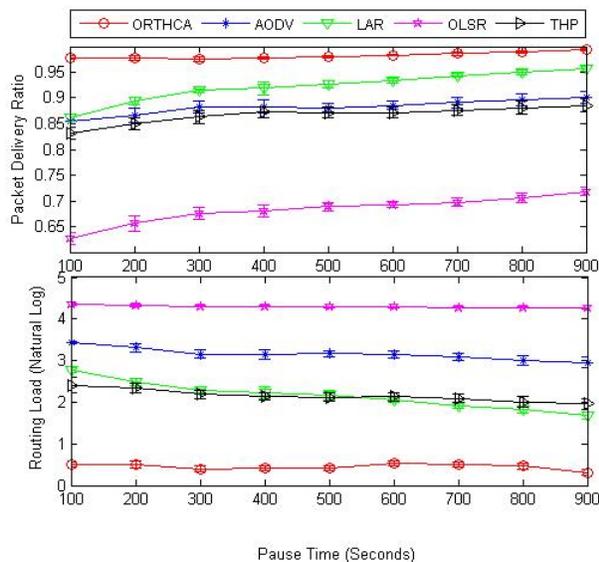


Fig. 7. PDR & Routing Load (200 nodes 200 flows)

100%. A data packet is of size 512 bytes. The two-ray signal propagation model is used, which is common for open space scenarios. At the physical layer, we use the IEEE 802.11 protocol operating with a data transmission rate of 2M bit/s. The radio range is 250m. At the MAC layer, we use the IEEE 802.11 DCF protocol. Finally, at the transport layer, we use the UDP protocol. The collected data shows that guarantee 95% confidence interval of the mean value.

We simulated five routing protocols, ORTHCA, AODV, LAR, OLSR, and THP. Three performance metrics were used to compare the performance of the routing protocols. *Packet Delivery Ratio* is the ratio of the total number of received data packets by all destination sides to the total number of the transmitted packets by all source sides. *Routing Load* is the ratio of the total number of routing messages(RREQ, RREP and RRER) to good received data packets, which implies the average network routing load per good data packet. *Average Delay* is the average latency including routing delay, data transmission period and retransmission period per good received data packet.

## B. Performance Results

Figure 7 and Figure 8 show the packet delivery ratios attained by the five protocols we compared.

ORTHCA attains the highest or second highest packet delivery ratio in both scenarios. This performance is

the result of the bandwidth savings attained in ORTHCA from reducing the overhead incurred in flooding signaling packets. The fact that ORTHCA attains high packet delivery ratios is an indication that it covers all network nodes when RREQs are sent to find routes to destinations.

LAR attains better packet delivery ratios than ORTHCA at low mobility, and is worse than ORTHCA when node mobility is high. This performance of LAR is the result of its use of previously-known geographical coordinates of destinations to direct the propagation of RREQs; hence, if node mobility is low, directing RREQs is effective, but as nodes move more and more, the location information used in LAR becomes out of date more quickly.

THP attains much lower packet delivery ratios than ORTHCA and LAR, and the reasons for this performance appear to be that too few relays are used in THP to forward RREQs, and the two-hop information exchanged among nodes becomes outdated with node mobility, which leads to unsuccessful RREQ attempts.

OLSR shows the worst packet delivery ratios, because of the large amount of signaling packets it requires. AODV performs better than OLSR in this regard, but is worse than ORTHCA and LAR, which is a consequence of the larger amount of signaling traffic it incurs.

Figure 7 and Figure 8 show the routing load incurred by each routing protocol we simulated. OLSR requires the most control overhead in both scenarios, due to routinely flooding topological information through multipoint relays. AODV consumes the second largest load, which is the result of flooding RREQs when new routes need to be established or broken routes need to be re-established. THP incurs a smaller overhead than OLSR and AODV thanks to its use of fewer relays of signaling packets than those used in AODV. In all cases, ORTHCA incurs the smallest signaling overhead, which results from its use of a constant number of relay nodes per node, independently of how many neighbors a node has.

Figure 9 shows the average delays experienced by packets delivered using each of the five routing protocols. ORTHCA attains the smallest delays for 200 nodes, and is as good as THP and AODV for 250 nodes. However, it is important to note that both THP and AODV deliver much fewer packets than ORTHCA does. OLSR incurs higher delays than ORTHCA, THP and AODV due to its higher signaling overhead, which leaves less bandwidth for data traffic. LAR performs poorly at high mobility, because the previously-known location information it

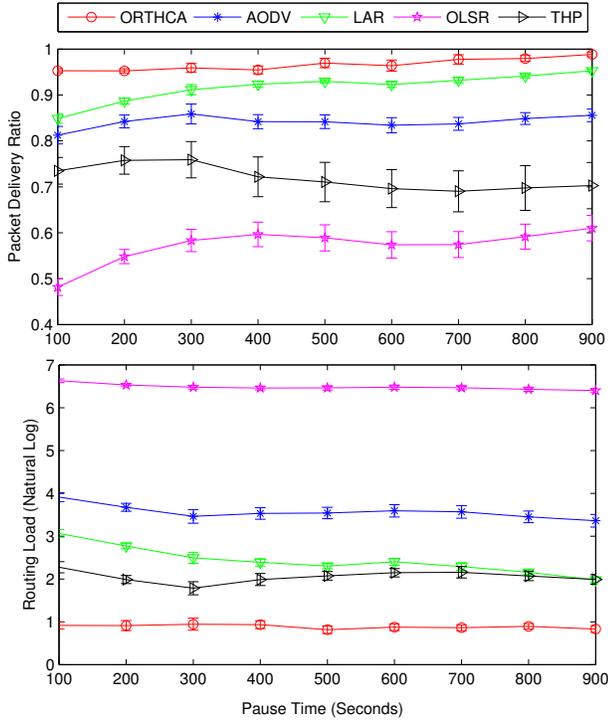


Fig. 8. PDR & Routing Load (250 nodes 100 flows)

uses to direct RREQs becomes obsolete.

## VI. CONCLUSION

This paper introduced ORTHCA, an innovative routing approach for exploiting two hop neighbors locations to broaden routing efficiency and limit the number of relay neighbors in MANETs. ORTHCA is the first two hop routing protocol in which a signaling packet is forwarded by a maximum constant number of relay neighbors per node, independently of the number of neighbors that the node has.

Under the assumption that wireless transmission ranges for all nodes consists of circles of radius  $r$ , we proved that the relaying of a given signaling packet in ORTHCA covers all network nodes in the absence on multiple access interference, and that at most six relays per node are needed to flood a signaling packet independently of the neighborhood size.

Simulation results were presented with the comparison of the performance of ORTHCA and four other routing protocols, namely OLSR, AODV, THP and LAR, which

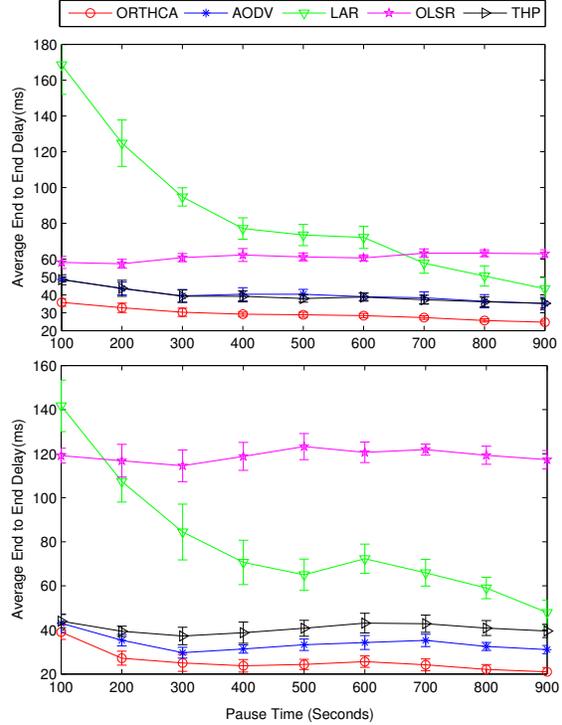


Fig. 9. Average Delay (200 nodes 200 flows)

are representatives of routing approaches for on-demand and proactive routing. OLSR uses multipoint relays to reduce its signaling overhead, THP defines subsets of one-hop neighbors that cover all two-hop neighbors to serve as relays, and LAR uses previously-known locations of destinations to direct route requests when routes to those destinations are broken. The simulation results show that ORTHCA performs better than the other four protocols overall, and that its selection of relay nodes is such that all network nodes tend to be reached by flooded signaling packets.

## VII. ACKNOWLEDGMENTS

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