GEOGRAPHIC ON-DEMAND DISJOINT MULTIPATH ROUTING IN WIRELESS AD HOC NETWORKS

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ABSTRACT

Multipath routing in ad hoc networks is a challenging problem. In this paper, we present a new approach to the problem of finding multiple disjoint paths (both edge-disjoint and node-disjoint) in ad hoc networks. Most existing multipath routing protocols are based on AODV or DSR and compute multiple paths with a single route discovery process via a network-wide flooding, which takes a substantial amount of network bandwidth. When node's geographic information is available, routing discovery flooding can be substituted by unicasts and then the routing overhead can be reduced. We propose a Geography based Ad hoc On demand Disjoint Multipath (GAODM) routing protocol in wireless ad hoc networks. Our protocol combines the idea behind the distributed push-relabel algorithm in a flow network with nodes' geographic information in the ad hoc networks. Instead of a blind flooding, an informed and independent unicast decision is made by each node so that the traffic flow for the route discovery is efficiently directed towards the destination. We compare our protocols with AODV and AOMDV. The simulation result shows that 1) GAODM has better ability of finding more disjoint paths than AOMDV, especially when nodes are further apart; 2) GAODM finds shorter paths (in terms of hop count) than AODV and AOMDV due to the use of nodes' geographic information; 3) GAODM incurs much less route discovery overhead than AODV and AOMDV because of the substitution of unicasts for blind flooding.

I. INTRODUCTION

Wireless ad hoc networks are characterized by multi-hop wireless links with limited bandwidth and dynamically varying network topology. Design of efficient routing protocols in such networks is a challenging issue. Numerous routing approaches have been proposed for wireless ad hoc networks. On-demand routing protocols, such as Ad hoc On-Demand Distance Vector (AODV) [16], [17] and Dynamic Source Routing (DSR) [7], discover routes via a flooding technique, where the source (or any node seeking the route) floods the entire network with a query packet in search of a route to the destination. Flooding takes up a substantial amount of network bandwidth, which is at a premium in wireless networks. Efficient control of frequent network-wide flooding is thus important for the efficient performance of on-demand protocols. Two main methods have been seen to reduce the flooding overhead. One is directed to limit the flood within a small region of the network or substitute the flooding by unicast using geographic routing when node's position information is available. Such methods includes LAR [9], FACE [2], GPSR [8] and GOAFR+ [10], in which node spatial positions are essential to the method. The other method is to find multiple routes between source and destination from a single query. Usually a multipath route discovery consumes more energy than a single path route discovery, because some nodes need to rebroadcast Route Request (RREQ) packets more than once, such as SMR [12], or some intermediate nodes need to send Route Reply (RREP) packets to the source, such as AOMDV [14]. However, due to the availability of multiple paths, when one path is broken, alternate path(s) can be used to maintain the communication between the source and destination without initializing a new route discovery flooding. Therefore, the overall routing overhead can be reduced.Several multipath routing protocols in ad hoc networks have been proposed. AODV-BR [11] and braided multipath routing [6] aim to find partially disjoint paths, while SMR and AOMDV target to find edge-disjoint paths. Some node-disjoint multipath routing protocols are proposed in [13], [22].

In this paper, we incorporate node's geographic information into multipath routing and propose a Geography based Ad hoc On demand Disjoint Multipath (GAODM) routing protocol in wireless ad hoc networks. We consider the routing task, in which data packets are to be sent from a source to a destination in a relatively static but highly error-prone wireless ad hoc network (e.g., a sensor network [1]). We present a theoretical foundation for disjoint-path (both edge-disjoint and node-disjoint) routing in wireless ad hoc networks. We demonstrate that the problem of finding disjoint paths between the source and destination in an ad hoc network is equivalent to the flow assignment problem in a flow network. We then propose our GAODM routing

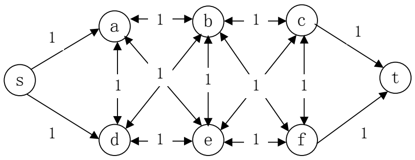


Fig. 1. An Ad hoc network mapping to a flow network for disjoint-path routing

protocol which is based on the push-relabel algorithm in a flow network. We find that by incorporating geographic information, our GAODM routing protocol can find paths with better quality while incurring less routing overhead.

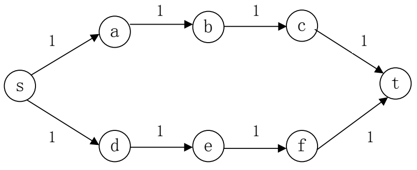
The paper proceeds as follows. In section II, We briefly give a theoretical framework of finding k disjoint path in ad hoc networks. In section III, our disjoint-path routing algorithm based on the push-relabel algorithm combining geographic routing method is presented. Section IV summarizes the simulation results and conclusions are drawn in section V.

II. THEORETICAL FRAMEWORK

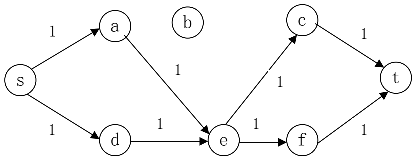
An ad hoc network with a communication pair (s,t) can be viewed as a flow network in Fig.1, in which all the directed edges from s is outgoing, all the directed edges to t is incoming and other edges between any two neighbors are bidirectional. Assuming each edge in the flow network has capacity one, the problem of finding k disjoint paths between source node s and sink node t in the ad hoc network is equivalent to finding a flow with value k in the corresponding flow network. Fig.2 gives the example of finding 2 node-disjoint and edge-disjoint paths.

Algorithms, such as Ford-Fulkerson and Push-relabel algorithms [5], have been proposed to find a maximum flow in flow networks. Ford-Fulkerson algorithm needs to have the global knowledge of the network which is not suitable for ad hoc networks. Push-relabel algorithm is a distributed algorithm which only needs each node having the knowledge of its neighbors and is more desirable for us to implement in ad hoc networks.

The push-relabel algorithm involves recursive processes in order to find the maximum flow, which is not desirable in an ad hoc network and the complexity of push-relabel algorithm is $O(V^2E)$. So when we apply it to a practical ad hoc network for disjoint-path routing, we need to do some modification. First, the algorithm is for finding maximum flow in a flow network. While in an ad hoc network, we usually need to find m disjoint paths (e.g. in [14], m is set to be 3), and m may be less than the value of maximum flow in the corresponding unit capacity flow networks. Second, an intermediate node should decide which neighbor it should push the flow to in the flow network, which is just like an intermediate node should decide which neighbor node it should forward the RREQ packet to in the ad hoc network. There are several criterions, such as forward the packet to the neighbor which is nearest to the destination [8], or which is more energy efficient to forward the packet [19]. In this paper, the criterion is the Euclidian distance between a node and the destination, that is, the intermediate node will forward the packet (i.e., push the flow) to the neighbor that has shortest Euclidian distance to the destination.



(a)



(b)

Fig. 2. (a)A flow assignment with value 2 $\Longleftrightarrow$ 2 node-disjoint paths (b)A flow assignment with value 2 $\Longleftrightarrow$ 2 edge-disjoint paths

III. GEOGRAPHIC DISJOINT-PATH ROUTING

In this paper, we assume $a)$ that each network node is informed about its own and about its neighbor's positions and $b)$ that the source of a message knows the position of the destination. The location of nodes may be available directly by communicating with a satellite, using GPS (Global Positioning System), if nodes are equipped with a small low power GPS receiver [20]. Alternatively, relative coordinates of neighboring nodes can be obtained by exchanging distance information between neighbors [3]. Some sensor self-positioning systems [4], [18] can also be used to obtain node's position information. Similarly the location of the destination could be learned via an overlay (e.g. peer-to-peer [21]) information system. We present the node location by a (x,y) coordinate pair. Following the thinking of push-relabel algorithm, we propose geographic disjoint-path routing to find disjoint paths between a communication pair (s,t). Similar to ad hoc routing protocols [14], [17], the RREQ and RREP packets are used in the routing discovery phase. We discuss both node-disjoint-path routing and edge-disjoint-path routing.

A. Geographic Node-disjoint-path Routing

For our geographic disjoint-path routing protocol, each node maintains a list of its neighbors and their location.

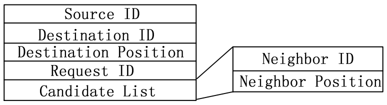
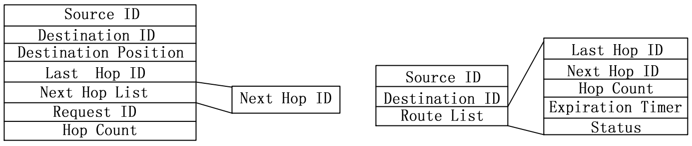


Fig. 3. Structure of candidate neighbor table entry in GAODM



(a) (b)

Fig. 4. (a) Format of RREQ packet in GAODM (b) Structure of routing table entry in GAODM

For nodes involving in a route discovery phase, a Candidate Neighbor Table (CNT) (as shown in Fig.3) is created, where *source ID*, *Destination ID*, and *Request ID* collectively identify a particular route discovery[1], while *Candidate List (CL)* indicates the neighbors a particular RREQ can be sent to. CL is initially set to include all its neighbors and is updated as described below. The RREQ packet format is shown in Fig.4 (a), where the *Next Hop List (NHL)* indicates the neighbor(s) that are expected to receive or forward the RREQ.

When a source node, s, wants to communicate with a destination node, t, it calculates the Euclidean distances between each neighbor and the destination, selects k ($k \leq$ the number of neighbors) neighbors nearest to the destination, records the IDs of the k neighbors into the Next Hop List in the RREQ packet and broadcasts the RREQ packet.

When an intermediate node receives or overhears a RREQ packet from one of its neighbors, it first checks in the corresponding CNT for that route discovery and deletes from the CL the neighbor from which it receives the RREQ. It also deletes from its CL node(s) listed in the NHL of the RREQ packet[2] except that node is the destination node. If the intermediate node is expected to forward the RREQ[3], its CL is not empty, and it has not forwarded the particular RREQ before, the node identifies the neighbor that is nearest to the destination in its CL, updates NHL field with the neighbor's ID, and sends the RREQ to the neighbor. It then deletes the neighbor from its CL and adds an entry into the routing table (as shown in Fig.4 (b)). Notice that the *Last Hop ID* field records the ID of the neighbor from which the RREQ is received and the *Next Hop ID* fields records the ID of the neighbor to which the RREQ is forwarded. At the stage, the *Status* field is set to $Invalid$.

Following this procedure, when the destination is in a node's neighborhood, the node just sends the RREQ to the destination, because the destination is the nearest node to itself. When an intermediate node that receives an RREQ can not forward it further because the CL is empty or the node has already forwarded the RREQ, the node just discards the RREQ.

When the destination node, t, receives a RREQ from its neighbor, it sends a RREP back to this neighbor. When the neighbor receives the RREP, it updates the corresponding entry in its routing table with the field $Status = Valid$, then forwards the RREP packet to the node corresponding to the Last Hop ID in the entry. The intermediate node forwards the RREP back to s along the reverse path it travelled before in this way.

The feature of our geographic node-disjoint multipath routing is that every node except source s and destination t involving in the routing discovery phase just forwards the RREQ once to its neighbor that neither received nor forwarded the RREQ packet before. The criterion for choosing which neighbor the RREQ is forwarded to is the distance between the neighbor and the destination. The greedy forwarding method is used such that the RREQ is sent to the candidate neighbor that is nearest to the destination. Each node on the paths has only one ingress edge and one egress edge, so the paths are node-disjoint.

It is possible that we may not find k node-disjoint paths when some RREQ(s) is (are) dropped under certain circumstances. For example, in Fig.2(b), if node a did not overhear that d has sent a RREQ packet to e, it may sends the RREQ to e because e is nearest to t in its CL. Since e has forwarded the RREQ before, it will drop this RREQ packet. The number of paths found by our protocol might be smaller than k.[4]

B. Geographic Edge-disjoint-path Routing

The difference between our edge-disjoint-path routing and node-disjoint one lies in the processing of duplicate RREQ packets. In the node-disjoint routing, duplicate RREQ packets are simply dropped in order to maintain the node disjointness. While in the edge-disjoint routing, when an intermediate node receives another RREQ(s) from a different neighbor, it may forward the RREQ(s) packets

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[1] Use of these fields is similar to AODV.

[2] A RREQ packet sent from the source may have multiple entries in the NHL field. RREQ packets from intermediate nodes only have one entry in the NHL field.

[3] is in the NHL list

[4] Some remedial mechanisms might be implemented if the purpose is to maximize the number of disjoint paths. For example, if a overhears the transmission of e and notices that it is not the *Last Hop* of e, it may pick another *Next Hop* if its CL is not empty. Or, an error message can be initiated by e and sent to a indicating the confliction.

further if its CL is not empty. The CL updating method and forwarding criterion are the same as the geographic node-disjoint-path routing. But the neighbor node of the destination only forwards the first RREQ to the destination and will discard the following RREQ it receives. It may also happen that some intermediate node can not forward the RREQ further because $CL = \emptyset$ or the hop count the RREQ travelled exceeds the TTL of the RREQ. In this situation, the RREQ is also discarded and will not arrive at the destination. For those RREQs reaching the destination, they travelled along different links, because when a node sends a RREQ to a neighbor, it will eliminate that neighbor from the CL, then when it forwards another RREQ, it will not send the RREQ to the same neighbor. According to the routing discovery procedure, the number of ingress edges is equal to the number of egress edges for an intermediate node, and one edge is only belong to one path. So the paths are edge-disjoint.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of GAODM and compare it with both single path routing protocol, AODV [17], and Ad-hoc on-demand multipath distance vector routing protocol, AOMDV [14]. AOMDV is based on AODV and the multiple paths are computed distributively and independently at each hop. AOMDV propagates the RREQ messages the same way as the basic AODV - only the first received RREQ is further rebroadcasted. For the duplicate RREQs, instead of simply ignoring them, AOMDV examines the path information contained in the message for potential alternate reverse path which preserves loop-freedom and link-disjointness among other paths back to the source. For each new alternate path found, the intermediate node generates a RREP message and sends it back to the source along the reverse path if it knows a forward path that has not been used in any previous RREPs for this RREQ. The destination node replies to every RREQ it receives.

Since this paper focuses on the ability and efficiency of finding disjoint paths using our geographic routing protocol, we evaluate the following performance metrics:

1) Average number of paths found per route discovery
2) Probability of finding at least m path(s)
3) Average number of hop count per path
4) RREQ packets sent per route discovery
5) RREP packets sent per route discovery

Metrics $1) - 3)$ are used to evaluate the ability of finding multipaths, and parameters 4)-5) is used to evaluate the efficiency of our protocol.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Network Size	$250m * 250m$
Number of nodes	$50, 100, 150, 200$
Simulation time	$20sec$
Node placement	uniform
Node mobility	None
Node transmission range	$70m$
Channel capacity	$2Mbps$
MAC protocol	IEEE 802.11

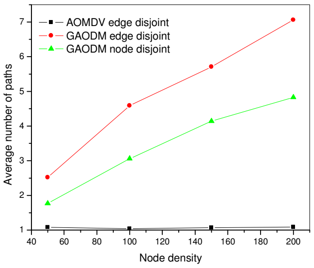

Fig. 5. The average number of paths found vs. node density

The simulation of the protocol has been implemented in GloMoSim network simulator [23]. The various simulation parameters are shown in Table I. The results are averaged over 100 simulation runs with different random seeds. The traffic load used in all the simulations was Constant Bit Rate (CBR) data session between a pair of source and destination nodes. Each data session consists of 100 packets of 521 bytes sent at a rate of 10 packets per second. We define the node distance as $Ceiling(Dist(s,t)/r)$, where $Ceiling()$ indicates the ceiling function, $Dist(s,t)$ is the Euclidian distance between the source and the destination and r is the radio transmission range. So the node distance is the ideal shortest hop count between two nodes. Each node has the same radio transmission range. Given network size $(250m \times 250m)$ and node transmission range $(70m)$, the largest distance between two nodes is $250\sqrt{2}/70 \approx 5$. For AODV, AOMDV and our protocols, $TTL = 8$, which indicates the largest hop count the RREQ can travel. The variant parameter k of our protocol was set approximately to half of the average node degree of the network (i.e., number of neighbors each node has). The density of the network is varied by deploying different number of nodes in the network. The number of nodes varies from 50, 100, 150 to 200, the corresponding average node degree is 8, 18, 28, 36 respectively. So k is set to 5, 10, 15, 20 respectively. The communication pair with node distance $= 5$ was selected to evaluate GAODM, AODV and AOMDV under different node density. The performance comparison between edge-disjoint GAODM and AOMDV is also presented with different node distance and node number $= 100$.

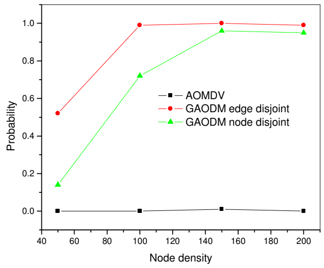

Fig. 6. The probability of finding at least 3 paths vs. node density

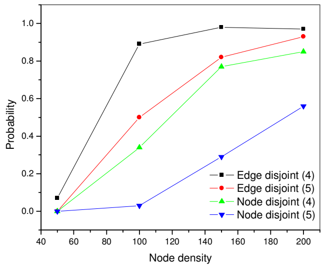

Fig. 7. The probability of finding at least 4 and 5 paths vs. node density by GAODM

A. *Ability of Finding Disjoint Paths*

Fig.5 shows the average path number found by GAODM and AOMDV. GAODM shows much higher ability to find disjoint paths than AOMDV. Actually, few multipaths can be found by AOMDV when the node distance is larger than 2 (as show in Fig.9). Similar results have been reported in a mobile environment in [15]. It is not surprising that more edge disjoint paths are found than node disjoint paths. Because for edge-disjoint-path routing, when an intermediate node receives duplicate RREQs, it will forward it further when $CL \neq \emptyset$. But for node-disjoint-path routing, the intermediate node will discard the duplicate RREQs even if $CL \neq \emptyset$. The RREQ packet is more likely to be dropped by using GAODM node-disjoint-path routing than edge-disjoint-path routing. The simulation result also shows that the higher the node density, the more disjoint paths found by GAODM. In contrast, AOMDV finds very few disjoint paths even in very dense networks.

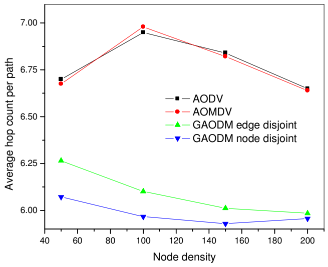

Fig. 8. The hop count vs. node density

Fig.6 shows the probability of finding at least 3 disjoint paths. We observed that GAODM has much better ability in path finding than AOMDV. AOMDV can hardly find 3 disjoint paths, while GAODM finds at least 3 disjoint paths with very high probability. Similarly, Fig.7 shows the probability of finding at least 4 and 5 paths. Again, we observed that GAODM is able to find both edge-disjoint and node-disjoint paths with high probability. This probability becomes almost certain (close to 1) when the network is dense enough.

Fig.8 shows the average hop count per path found by the routing protocols. It is an indicator of the quality of the paths. An interesting observation is that the average hop count per path found by GAODM is smaller than that found by AODV and AOMDV. It seems doubtable at first thought but it can be explained as follows. For AODV and AOMDV, RREQs are *flooded*, usually the neighbor first receiving the RREQ rebroadcasts the packet. The neighbor receiving the RREQ first is more likely to be the node close to the sending node, but may not be the one nearest to the destination. This mechanism tends to pick the lowest latency path under medium access control effects but may not find the minimum-hop path. However, for GAODM, RREQs are forwarded by *unicast*, every RREQ is forwarded to a node as near as possible to the destination, so it's more possible to find minimum-hop path when node distribution is uniform. Another observation is that the average hop count of edge-disjoint paths is larger than node-disjoint paths. This is attributed to the difference between node-disjoint-path routing and edge-disjoint-path routing. For edge-disjoint-path routing, an intermediate node receiving a duplicate RREQ packet may resend the packet to another neighbor that is not nearest to the destination, since it has sent the first received RREQ packet to the neighbor that is nearest to the destination in its CL. This may cause the packet travel a longer path to get to the destination. When the node density becomes higher the difference between the average hop count of edge-disjoint paths and node-disjoint becomes smaller. Because even an intermediate node resends the duplicate RREQ packet to its neighbor that is not nearest to the destination in its neighborhood, it is more likely that the other node is also close enough to the destination that the difference is not enough to cause an additional hop. When node density is higher, the neighborhood size of a node is larger, then the difference between the distance from the nodes to the destination becomes smaller. The average hop counts per path found by AODV and AOMDV are nearly the same.

Fig.9 and Fig.10 plot the path finding ability as a function of node distance. It further shows the superior performance of GAODM over AOMDV. The average number of edge-

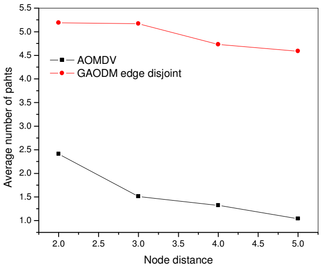

Fig. 9. The average number of edge-disjoint paths found vs. node distance

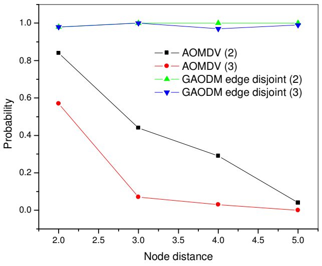

Fig. 10. The probability of finding at least 2 and 3 paths vs. node distance

disjoint paths found by GAODM is much larger than that found by AOMDV, especially when node distance is larger than 2. When node distance $= 5$, the average number of paths found by AOMDV drops to 1.04, but remains 4.59 for GAODM. The probability of finding 2 and 3 edge-disjoint paths drops very quickly for AOMDV, but nearly remains the same at a high level (0.97 in our simulations) for GAODM.

B. Routing Overhead

For GAODM, in the routing discovery phase, the propagation of RREQs is by unicast rather than flooding. Assume we find m ($m \leq k$) disjoint paths, destination will send m RREPs. For one route discovery which finds m disjoint paths, it needs to send at most $k*(TTL-1)+1$ RREQs and $\sum_{i=1}^{m} HC_i$ RREPs, where HC_i is the hop count of the ith path been found. For flooding based routing protocol, such as AODV, it needs to send at most n RREQs and i RREPs, where n is the number of nodes in the network and i is the hop count of the path found. The RREQs sent by GAODM could be larger than n for edge-disjoint-path routing since the itermediate node may send duplicate RREQ packets, but never larger than n for node-disjoint-path routing. In a large scale network, it should be much less than n.

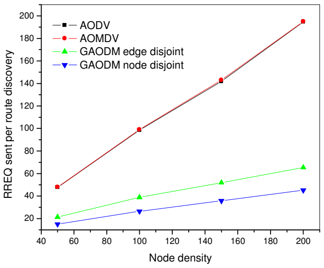

Fig. 11. RREQ packets sent vs. node density

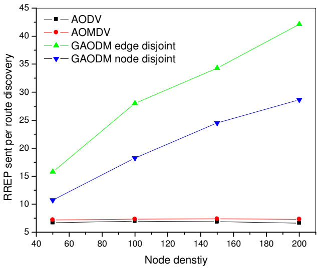

Fig. 12. RREP packets sent vs. node density

Fig.11 shows that GAODM sends much less RREQ packets than AODV and AOMDV per route discovery. Since AOMDV follows the same rule as AODV on flooding the RREQ packets, they send the same number of RREQs, which nearly flood the whole network. The advantage of GAODM becomes more obvious when the number of nodes in the network becomes larger. Since GAODM sends RREQs as near as possible to the destination, and such mechanism implicitly constraints the RREQs in a zone between source and destination. More RREQ packets are sent by edge-disjoint routing than node-disjoint routing. Because more edge-disjoint paths are found than node-disjoint paths and the average hop count per path of edge-disjoint paths is larger than that of node-disjoint, so there exist more links of edge-disjoint paths than node-disjoint paths, which implies that more RREQs are sent by edge-disjoint path routing than node-disjoint path routing. We also can explain this result from the difference of RREQ forwarding rules between edge-disjoint routing and node-disjoint routing that edge-disjoint routing may send duplicate RREQs but node-disjoint routing just discards duplicate RREQs.

More RREP packets are sent by GAODM than by AODV and AOMDV, because more paths are found by GAODM than by AODV and AOMDV. The number of RREPs sent is equal to the total number of links of the paths found. More links exist for edge-disjoint paths than node-disjoint paths as explained before, so more RREP packets sent by edge-disjoint path routing. Although more RREP packets are sent by GAODM, we can find that the overall route discovery overhead (RREQ packets + RREP packets) for GAODM is still much less than that for AODV and AOMDV by observing Fig.11 and Fig.12.

V. CONCLUSIONS

In this paper, we present a theoretical foundation for disjoint-path (both edge-disjoint and node-disjoint) routing in wireless ad hoc networks. As we demonstrated, the problem of finding disjoint paths between a source and destination pair in wireless ad hoc networks is equivalent to the flow assignment problem in a flow network. In particular, finding k disjoint paths in an ad hoc network is equivalent to finding a flow assignment of value k in a corresponding unit-capacity flow network. Following the idea of push-relabel algorithm, we propose the Geography based Ad hoc On Demand Disjoint Multipath (GAODM) routing protocol to find disjoint paths between a communication pair in wireless ad hoc networks. We compare our protocols with AODV and AOMDV by simulation, and find that 1) the ability of finding disjoint paths of GAODM is much higher than AOMDV and it has more advantage when node distance is larger than 2. The higher the node density the higher the ability of finding disjoint paths for GAODM; 2) the average hop count per path found by GAODM is smaller than that found by AODV and AOMDV, which is another advantage by using our geographic multipath routing; 3)The routing overhead is much less by using GAODM than by using AODV and AOMDV.

The multiple paths found by GAODM is related to the network density and the variant parameter k. In this paper, we set k to be half of the neighborhood size of the network. Intuitively, more disjoint paths may be found when k is larger, but there would be a limit for k beyond that no more disjoint path can be found. This parameter gives us an option to control the routing overhead and makes GAODM scalable. How to set k optimally and how to enhance the probability of finding node-disjoint paths and the performance of GAODM under the condition of node mobility and different failure patten is our future work.

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