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A Complementary Void Handling Mechanism Based on Virtual Destination for Highly Dynamic Mobile Ad-Hoc Networks

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Abstract—This paper addresses the problem of delivering data packets for highly dynamic mobile ad hoc networks in a reliable and timely manner. Most existing ad hoc routing protocols are susceptible to node mobility, especially for large-scale networks. Driven by this issue, we propose an efficient Position-based Opportunistic Routing (POR) protocol which takes advantage of the stateless property of geographic routing and the broadcast nature of wireless medium. When a data packet is sent out, some of the neighbor nodes that have overheard the transmission will serve as forwarding candidates, and take turn to forward the packet if it is not relayed by the specific best forwarder within a certain period of time. By utilizing such in-the-air backup, communication is maintained without being interrupted. The additional latency incurred by local route recovery is greatly reduced and the duplicate relaying caused by packet reroute is also decreased. In the case of communication hole, a Virtual Destiny-based Void Handling (VDVH) scheme is further proposed to work together with POR. Both theoretical analysis and simulation results show that POR achieves excellent performance even under high node mobility with acceptable overhead and the new void handling scheme also works well.

Index Terms— Position-based Opportunistic Routing, local route recovery, Virtual Destiny-based Void Handling.

1. INTRODUCTION

Mobile ad- hoc networks (MANETs) have gained a great deal of attention because of its significant advantages brought about by multihop, infrastructure-less transmission. However, due to the error prone wireless channel and the dynamic network topology, reliable data delivery in MANETs, especially in challenged environments with high mobility remains an issue. Traditional topology-based MANET routing protocols (e.g., DSDV, AODV, DSR [1]) are quite susceptible to node mobility. One of the main reasons is due to the predetermination of an end-to-end route before data transmission. Owing to the constantly and even fast changing network topology, it is very difficult to maintain a deterministic route. The discovery and recovery procedures are also time and energy consuming. Once the path breaks, data packets will get lost or be delayed for a long time until the reconstruction of the route, causing transmission interruption.Geographic routing (GR) [2] uses location information to forward data packets, in a hop-by-hop routing fashion. Greedy forwarding is used to select next hop forwarder with the largest positive progress toward the destination while void handling mechanism is triggered to route around communication voids [3]. No end-to-end routes need to be maintained, leading to GR's high efficiency and scalability. However, GR is very sensitive to the inaccuracy of location information [4]. In the operation of greedy forwarding, the neighbor which is relatively far away from the sender is chosen as the next hop. If the node moves out of the sender's coverage area, the transmission will fail. In GPSR [5] (a very famous geographic routing protocol), the MAC-layer failure feedback is used to offer the packet another chance to reroute. However, our simulation reveals that it is still incapable of keeping up with the performance when node mobility increases.

In fact, due to the broadcast nature of the wireless medium, a single packet transmission will lead to multiple reception. If such transmission is used as backup, the robustness of the routing protocol can be significantly enhanced. The concept of such multicast-like routing strategy has already been demonstrated in opportunistic routing ([6], [7], [8]). However, most of them use link-state-style topology database to select and prioritize the forwarding candidates. In order to acquire the internodes loss rates, periodic network-wide measurement is required, which is impractical for mobile environment. As mentioned in [9], the batching used in these protocols also tends to delay packets and is not preferred for many delay sensitive applications. Recently, location-aided opportunistic routing has been proposed [10] which directly uses location information to guide packet forwarding. However, just like the other opportunistic routing protocols, it is still designed for static mesh networks and focuses on network throughput while the robustness brought upon by opportunistic forwarding has not been well exploited In this paper, a novel Position-based Opportunistic Routing (POR) protocol is proposed, in which several forwarding candidates cache the packet that has been received using MAC interception. If the best forwarder does not forward the packet in certain time slots, suboptimal candidates will take turn to forward the packet according to a locally formed order. In this way, as long as one of the candidates succeeds in receiving and forwarding the packet, the data transmission will not be interrupted. Potential multipath are exploited on the fly on a per- packet basis, leading to POR's excellent robustness.

The main contributions of this paper can be summarized as follows:

We propose a position-based opportunistic routing mechanism which can be deployed without complex modification to MAC protocol and achieve multiple reception without losing the benefit of collision avoidance provided by 802.11.The concept of in-the-air backup significantly enhances the robustness of the routing protocol and reduces the latency and duplicate forwarding caused by local route repair . In the case of communication hole, we propose a Virtual Destiny-based Void Handling (VDVH) scheme in which the advantages of greedy forwarding (e.g., large progress per hop) and opportunistic routing can still be achieved while handling communication voids. . We analyze the effect of node mobility on packet delivery and explain the improvement brought about by the participation of forwarding candidates. . The overhead of POR with focus on buffer usage and bandwidth consumption due to forwarding candidates' duplicate relaying is also discussed. Through analysis, we conclude that due to the selection of forwarding area and the properly designed duplication limitation scheme, POR's performance gain can be achieved at little overhead cost. . Finally, we evaluate the performance of POR through extensive simulations and verify that POR achieves excellent performance in the face of high node mobility while the overhead is acceptable. The rest of this paper is organized as follows: we present the protocol design of POR and complementary mechanisms in Section 2. VDVH is depicted in Section 3.

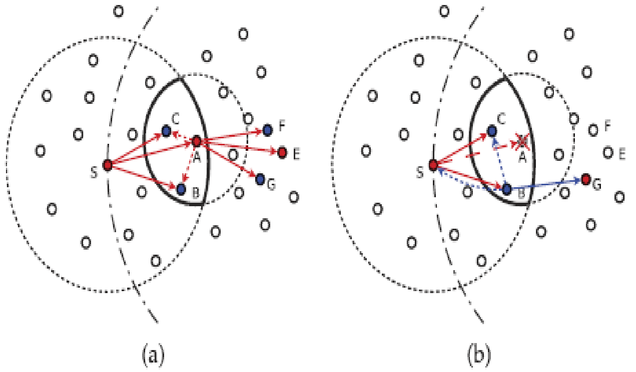
2. POSITION-BASED OPPORTUNISTIC ROUTING

2.1 Overview

The design of POR is based on geographic routing and opportunistic forwarding. The nodes are assumed to be aware of their own location and the positions of their direct neighbors. Neighborhood location information can be exchanged using one-hop beacon or piggyback in the data packet's header. While for the position of the destination, we assume that a location registration and lookup service which maps node addresses to locations is available just as in [5]. It could be realized using many kinds of location service ([11], [12]). In our scenario, some efficient and reliable way is also available. For example, the location of the destination could be transmitted by low bit rate but long range radios, which can be implemented as periodic beacon, as well as by replies when requested by the source.

When a source node wants to transmit a packet, it gets the location of the destination first and then attaches it to the packet header. Due to the destination node's movement, the multihop path may diverge from the true location of the final destination and a packet would be dropped even if it has already been delivered into the neighborhood of the destination. To deal with such issue, additional check for the destination node is introduced. At each hop, the node that forwards the packet will check its neighbor list to see whether the destination is within its transmission range. If yes, the packet will be directly forwarded to the destination, similar to the destination location prediction scheme described in [4]. By performing such identification check before greedy forwarding based on location information, the effect of the path divergence can be very much alleviated. In conventional opportunistic forwarding, to have a packet received by multiple candidates, either IP broadcast or an integration of routing and MAC protocol is adopted. The former is susceptible to MAC collision because of the lack of collision avoidance support for broadcast packet in current 802.11, while the latter requires complex coordination and is not easy to be implemented. In POR, we use similar scheme as the MAC multicast mode described in [13]. The packet is transmitted as unicast (the best forwarder which makes the largest positive progress toward the destination is set as the next hop) in IP layer and multiple receptions are achieved using MAC interception. The use of RTS/CTS/DATA/ACK significantly reduces the collision and all the nodes within the transmission range of the sender can eavesdrop on the packet successfully with higher probability due to medium reservation. The basic routing scenario of POR can be simply illustrated in Fig. 1.

In normal situation without link break, the packet is forwarded by the next hop node (e.g., nodes A, E) and the forwarding candidates (e.g., nodes B, C; nodes F, G) will be suppressed (i.e., the same packet in the Packet List will be dropped) by the next hop node's transmission. In case node A fails to deliver the packet (e.g., node A has moved out and cannot receive the packet), node B, the forwarding candidate with the highest priority, will relay the packet and suppress the lower priority candidate's forwarding (e.g., node C) as well as node S. By using the feedback from MAC layer, node S will remove node A from the neighbor list and select a new next hop node for the subsequent packets. The packets in the interface queue taking node A as the next hop will be given a second chance to reroute. For the packet pulled back from the MAC layer, it will not be rerouted as long as node S overhears node B's forwarding.



(a) (b)

Fig. 1. (a) The operation of POR in normal situation. (b) The operation of POR when the next hop fails to receive the packet.

TABLE 1
Forwarding Table in POR

(src_ip, dst_ip)	next_hop	candidate_list
(N1, N11)	N4	N5, N6
(N2, N12)	N7	N8, N5
. . .	. . .	. . .

Every node maintains a forwarding table for the packets of each flow (identified as source-destination pair) that it has sent or forwarded. Before calculating a new forwarder list, it looks up the forwarding table, an example is illustrated in Table 1, to check if a valid item for that destination is still available. The forwarding table is constructed during data packet transmissions and its maintenance is much easier than a routing table. It can be seen as a trade-off between efficiency and scalability. As the establishment of the forwarding table only depends on local information, it takes much less time to be constructed. Therefore, we can set an expire time on the items maintained to keep the table relatively small. In other words, the table records only the current active flows, while in conventional protocols, a decrease in the route expire time would require far more resources to rebuild.

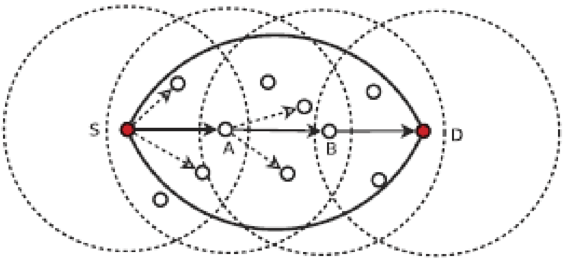


Fig. 2. Duplicate relaying is limited in the region enclosed by the bold curve.

2.2 MAC Modification and Complementary Techniques

We leverage on the broadcast nature of 802.11 MAC: all nodes within the coverage of the sender would receive the signal. However, its RTS/CTS/DATA/ACK mechanism is only designed for unicast. It simply sends out data for all broadcast packets with CSMA. Therefore, packet loss due to collisions would dominate the performance of multicast-like routing protocols. Here, we did some alteration on the packet transmission scenario. In the network layer, we just send the packet via unicast, to the best node which is elected by greedy forwarding as the next hop. In this way, we make full utilization of the collision avoidance supported by 802.11 MAC. While on the receiver side, we do some modification of the MAC-layer address filter: even when the data packet's next hop is not the receiver, it is also delivered to the upper layer but with some hint set in the packet header indicating that this packet is overheard. It is then further processed by POR. Hence, the benefit of both broadcast and unicast (MAC support) can be achieved.

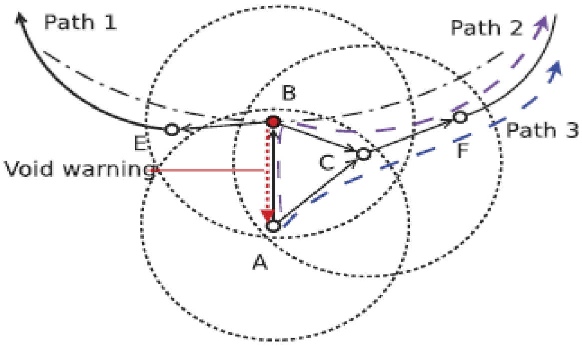


Fig 3.potential path around the void

3. VIRTUAL DESTINY-BASED VOID HANDLING

In order to enhance the robustness of POR in the network where nodes are not uniformly distributed and large holes may exist, a complementary void handling mechanism based on virtual destination is proposed. 3.1 Trigger Node The first question is at which node should packet forwarding switch from greedy mode to void handling mode. In many existing geographic routing protocols, the mode change happens at the void node, e.g., Node B in Fig. 3. Then, Path 1 (A-B-E-_ _ _) and/or Path 2 (A-B-C-F-_ _ _) (in some cases, only Path 1 is available if Node C is outside Node B's transmission range) can be used to route around the communication hole. From Fig. 3, it is obvious that Path 3 (A-C-F-_ _ _) is better than Path 2. If the mode switch is done at Node A, Path 3 will be tried instead of Path 2 while Path 1 still gets the chance to be used. A message called void warning, which is actually the data packet returned from Node B to Node A with some flag set in the packet header, is introduced to trigger the void handling mode. As soon as the void warning is received, Node A (referred to as trigger node) will switch the packet delivery from greedy mode to void handling mode and reclose better next hops to forward the packet. Of course, if the void node happens to be the source node, packet forwarding mode will be set as void handling at that node without other choice (i.e., in this case, the source node is the trigger node).

Virtual Destiny

To handle communication voids, almost all existing mechanisms try to find a route around. During the void handling process, the advantage of greedy forwarding cannot be achieved as the path that is used to go around the hole is usually not optimal (e.g., with more hops compared to the possible optimal path). More importantly, the robustness of multicast-style routing cannot be exploited. In order to enable opportunistic forwarding in void handling, which means even in dealing with voids, we can still transmit the packet in an opportunistic routing like fashion, virtual destination is introduced, as the temporary target that the packets are forwarded to. Virtual destinations are located at the circumference with the trigger node as center (Fig. 4), but the radius of the circle is set as a value that is large enough (e.g., the network diameter). They are used to guide the direction of packet delivery during void handling. Compared to the real destination D, a virtual destination (e.g., D0 left and D0 right) has a certain degree of offset simulation) in Fig. 4. With the help of the virtual destination, the potential forwarding area is significantly extended. Strictly speaking, our mechanism cannot handle all kinds of communication

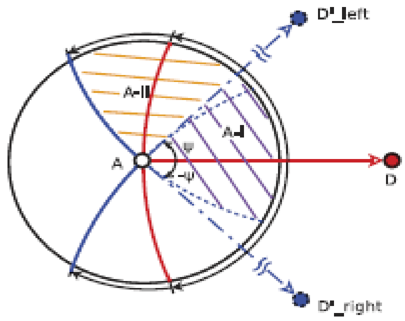


Fig. 4. Potential forwarding area is extended with virtual destination.

voids, since not all the neighbors of the current node are covered. However, for most situations, it is effective. For those communication holes with very strange shape, a reposition scheme has been proposed [15] to smooth the edge of the hole. Given the work that has been done in [15], VDVH thus still has the potential to deal with all kinds of communication voids. Fig. 5 shows an example in which VDVH achieves the optimal path of seven hops while GPSR undergoes a much longer route of 15 hops.

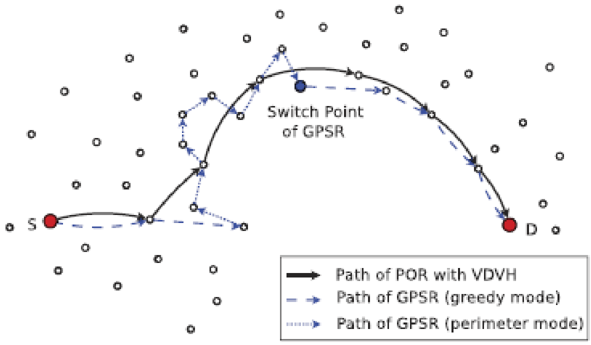


Fig. 5. The paths exploited by VDVH and GPSR.

If a forwarding candidate receives a packet that is being delivered or has been delivered in void handling mode, it will record a reverse entry. Once the packet reaches the destination, a path acknowledgment will be sent along the reverse path to inform the trigger node.Then, the trigger node will give up trying the other direction. For the same flow, the path acknowledgment will be periodically sent (not on per-packet basis; otherwise, there will be too many control messages). If there is another trigger node upstream, the path acknowledgment will be further delivered to that node, and so on. On the other hand, if a packet that is forwarded in void handling mode cannot go any further or the number of hops traversed exceeds a certain threshold but it is still being delivered in void handling mode, a DISRUPT control packet will be sent back to the trigger node as reverse suppression. Once the trigger node receives the message, it will stop trying that direction.

4. ANALYSIS

In this section, theoretical analysis on the robustness of POR will be conducted. The overhead inclusive of memory consumption and duplicate relaying will also be discussed. Since our focus lies on the effect of node mobility, an ideal wireless channel is assumed in the following part and the unit disc graph model will be used by default: a link between two nodes exists if and only if the distance between them is less than a certain threshold. When two nodes are located inside each others' coverage range (R), bidirectional data transmission between them can be achieved without failure.Robustness versus Mobility Owing to node mobility, it is impossible that the location information of a node's neighbors which is maintained through beacon exchange is always up to date. Therefore, an error disc bðx; reÞ corresponding to each neighbor exists from the current node's perspective, with x as the latest obtained coordinate of the neighbor. The radius of the error disc re is the maximum deviation from x and the value of revaries with the elapsed time, t, since the last update and is defined as follows:

Here, we only consider the forwarding failure caused by node mobility while the effect of the unreliable wireless link has not be taken into consideration. We believe that in the light traffic case with retransmission scheme implemented in the MAC layer, node mobility should be the main factor resulting in the packet forwarding failure.

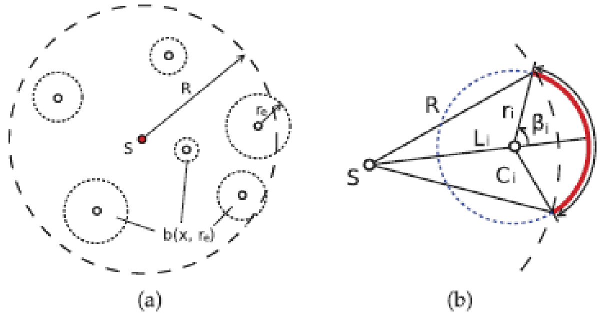


Fig. 6. (a) Network model. (b) Out of range caused by node's movement.

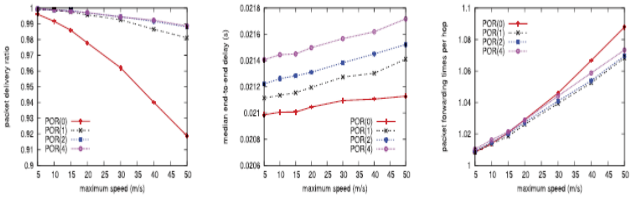
4.1 Forwarding Candidate Number Evaluation

We first evaluate the effect of the number of forwarding candidates (i.e., N) on POR's performance. Generally, larger value of N will result in higher robustness as more nodes serve as backups. However, it also means more memory resources need to be consumed and a higher percentage of duplicate relaying. In addition, the increase in the number of forwarding candidates will also enlarge the packet header, thus introducing more overhead. Therefore, a trade-off between the robustness and the required resource exists, in which the number of forwarding candidates plays an important role.

The network topology used in our simulation is illustrated in Fig. 11: 80 nodes are deployed in a rectangular area of size 1;200 m 800 m. The source (S) and the destination (D) are fixed at the two ends to create a long enough end-to-end path length (5 hops), while the remaining 78 mobile nodes move according to the RWP model that we have described. A CBR flow is injected into the network at a rate of 10 packets per second (i.e., 20 Kbps), starting at 170 s and ending at 870 s. We vary the value of N from 0 to 4 and measure the packet delivery ratio, the median end-to-end delay, and the packet forwarding times per hop.

The simulation results, averaged over 10 independent runs, are shown in Fig.7. From Fig. 7a, we can see that though more forwarding candidates yield a higher packet delivery ratio, only the involvement of the first forwarding candidate achieves the most significant performance gain, while the improvement becomes less and less observable when N continues to increase, which is consistent with our theoretical analysis presented in Section 4.1. Note that in the operation of routing protocols when link break happens, some recovery scheme (e.g., packet rerouting) will be triggered to salvage the packet. Hence, the simulated delivery ratio tends to be higher than the analytical one, especially for the protocol without forwarding candidates (i.e., POR(0)). On the other hand, the measured result should be lower than the analytical one due to the impact of wireless interference on the contrary.

These two factors, together with ignoring the change of the path length (as mentioned in footnote 6), contribute to the difference between the simulated delivery ratio and the analytical delivery ratio. Fig. 12b shows that the median end-to-end delay grows more or less linearly with the number of forwarding candidates. The reason is due to the increased packet size as the IP addresses of the forwarding candidates are attached to the packet header. Pertaining to duplicate relaying (Fig. 7c), we can see that the involvement of forwarding candidates reduces the value of FTH instead of introducing more duplication, especially when the node mobility is high, as shown in Section 4. Note that the calculation of FTH also takes the wasted forwarding of lost packets into consideration. Thus, the improvement in packet delivery ratio also contributes to the reduction of FTH. When more candidates



(a) Packet delivery ratio. (b) Median end-to-end delay. (c) FTH.

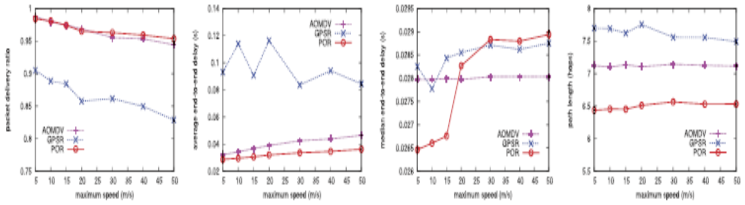
Fig.7. Forwarding candidate number evaluation.

4.2 ENHANCEMENT

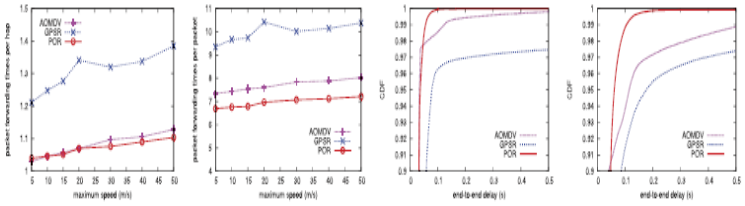
To enhance a system's robustness, the most straightforward method is to provide some degree of redundancy. According to the degree of redundancy, existing robust routing protocols for MANETs can be classified into two categories. One uses the end-to-end redundancy, e.g., multipath routing, while the other leverages on the hop-by-hop redundancy which takes advantage of the broadcast nature of wireless medium and transmits the packets in an opportunistic or cooperative way. Our scheme falls into the second category.

Multipath routing, which is typically proposed to increase the reliability of data transmission [22] in wireless ad hoc networks, allows the establishment of multiple paths between the source and the destination.

Existing multipath routing protocols are broadly classified into the following three types: 1) using alternate paths as backup (e.g., [20], [23], [24]); 2) packet replication along multiple paths (e.g., [13], [25]); and 3) split, multipath delivery, and reconstruction using some coding. However, as discussed in, it may be difficult to find suitable number of independent paths. More importantly, in the face of high node mobility, all paths may be broken with considerably high probability due to constantly changing topology, especially when the end-to-end path length is long, making multipath routing still incapable of providing satisfactory performance. In recent years, wireless broadcast is widely exploited to improve the performance of wireless communication. The concept of opportunistic forwarding, which was used to increase the network throughput ([6], [7]), also shows its great power in enhancing the reliability of data delivery.



(a) Packet delivery ratio. (b) Average end-to-end delay. (c) Median end-to-end delay. (d) Path length.



(e) FTH. (f) FTP. (g) CDF (max-speed: 5m/s). (h) CDF (max-speed: 50m/s).

Fig. 8. Simulation results: with communication hole.

5. CONCLUSION

In this paper, we address the problem of reliable data delivery in highly dynamic mobile ad hoc networks. Constantly changing network topology makes conventional ad hoc routing protocols incapable of providing satisfactory performance. In the face of frequent link break due to node mobility, substantial data packets would either get lost, or experience long latency before restoration of connectivity. Inspired by opportunistic routing, we propose a novel MANET routing protocol POR which takes advantage of the stateless property of geographic routing and broadcast nature of wireless medium. Besides selecting the next hop, several forwarding candidates are also explicitly specified in case of link break. Leveraging on such natural backup in the air, broken route can be recovered in a timely manner. The efficacy of the involvement of forwarding candidates against node mobility, as well as the overhead due to opportunistic forwarding is analyzed. Through simulation, we further confirm the effectiveness and efficiency of POR: high packet delivery ratio is achieved while the delay and duplication are the lowest.

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