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Data Delivery Towards Highly Reliable Mobile AD-HOC Networks

S. Malini Mangai
M.Phil. Research Scholar, Department of Computer Science,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India
G. Karpagam
M.Phil. Research Scholar, Department of Computer Science,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India
K. Saranya
M.Phil. Research Scholar, Department of Computer Science,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India
G. Kesavaraj
Assistant Professor, Department of Computer Science and Applications,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India
S. Mahima
Assistant Professor, Department of Computer Science and Applications,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India
K. S. Saravanan
Assistant Professor, Department of Computer Science and Applications,
Vivekanandha College of Arts and Sciences for Women (Autonomous), Namakkal, Tamil Nadu, India

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 Petal Routing (OPR) protocol which takes advantage of the stateless property of geographic routing and the broadcast nature of wireless medium. In the case of communication hole, a Virtual Destination-based Void Handling (VDVH) scheme is further proposed to work together with OPR. Both theoretical analysis and simulation results show that OPR achieves excellent performance even under high node mobility with acceptable overhead and the new void handling scheme also works well.

Keywords: *Geographic routing, opportunistic forwarding, Petal routing, reliable data delivery, void handling, mobile ad hoc network*

1. Introduction

MOBILE ad hoc networks (MANETs) have gained a great deal of attention because of its significant advantages brought about by multi hop, infrastructure-less transmission. It is expected that future networks will interconnect an even larger number of devices then today, ranging from servers to micro-devices embedded in objects. These devices will provide useful services thanks to the possibility of a networked operation, for example, localization services to support a variety of situation-aware applications. A very significant number of these devices will be carried by users-on-the-move. While a wireless infrastructure could serve to provide a near permanent network access to these devices, structural network dynamics and service demand patterns could impact the main features of the solutions relying on this network.

Traditional topology-based MANET routing protocols (e.g., DSDV, AODV, DSR) 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. One of the main technical drawbacks of these type of networks is that the network tends to change quite often. Nodes may arrive at or depart from the network without notice and direct node-to-node communication may or may not be possible at any given time due to node mobility and changes on the surrounding environment. These characteristics determine a highly dynamic network that makes difficult a reliable forwarding of packets on multi-hop routes over long periods of time. Communications tend to be very unreliable and inefficient, because a route break not only disrupts immediately a communication, but also can introduce additional overhead into the network because of the potential need for retransmissions and re-routing operations.

Geographic routing (GR) uses location information to forward data packets, in a hop-by-hop routing fashion. Directional flooding is used to select next hop forwarder with the minimum duplication and positive progress toward the destination while void handling mechanism is triggered to route around communication voids by increasing the width "w" of the petal. 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

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

- We propose a position-based opportunistic petal 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 Destination-based Void Handling (VDVH) scheme in which the advantages of adjusting the petal width according to the need of nodes for flooding. Thus reducing collision and overheads and 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 based on the petal area.
- The overhead of OPR 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 OPR through extensive simulations and verify that OPR achieves excellent performance in the face of high node mobility while the overhead is acceptable.

2. Related Work

MANETs are subject of intensive research and many works have been devoted to research their properties and operation (1). Some of the principal works that have explicitly addressed MANET reliability, or are in close relation to this discussion, are mentioned below. The list is not intended to be exhaustive, but representative of the related work previously done. A possibility that have been explored by various authors is on the selection of the longest lived links to create stable paths. These works are based on the observation that most randomly moving nodes are likely to drift apart from one another over time (2), so that their main assumption is that a link between two nodes that had survived for a significant long time would be unlikely to change any time soon and so, the link could be classified as stable. In fact, even in static networks wireless links may fail (3; 4; 5). In the *Associativity Based Routing* (ABR) (6), a link lifetime is measured by counting the number of beacons received from neighboring nodes and the links associated with the highest beacon counts are preferred. In the *Signal Stability Adaptive Routing* (SSA) (7), routes are created by giving preference to the selection of strong connected nodes. Nodes are classified as strongly or weakly connected on the basis of their signal strength as measured from beacons, which are exchanged periodically between neighboring nodes. McDonald and Zanti (8) investigated a clustering approach for MANETs and the probability of two nodes remaining within a distance threshold of one another over time. Another possibility for stable routing is to select links based on estimations of the future network state, as done by Su et al. (10; 11) and a previous work (9). In the *Route Lifetime Assessment Based Routing* (RABR), the average change in received signal strength is calculated and used to predict the time when a link would fail (12). A similar approach is used to define link affinity and path stability metrics from the received signal strength (13). A statistical approach was proposed by Gerharz et al. (14; 15) based on observations of link durations for various mobility models. On the other hand, the network availability as a whole can be improved by avoiding routing traffic through nodes with a low remaining energy (16; 17). On the definition of adequate metrics for describing a path reliability or link availability, a probabilistic measure was introduced (18) to help in the selection of stable paths. A prediction-based link availability calculation was also proposed and used to develop a metric for path selection in terms of path reliability (19). An approach to evaluate the signal strength variations between neighbors has also been proposed (20). Most works estimate link lifetimes based on the signal strength of beacon packets or by using the nodes location acquired with a GPS receiver. The beaconing scheme relies on knowledge of a radio propagation model to associate a signal loss to a travelled distance (31). The free space propagation model is commonly used (21) and beacons are transmitted with the highest power level (22). However, the fluctuation in signal strength of the transmitter as perceived by the receiver may not depend only on distance in practice (23). Hence, the distance estimation between transmitter and receiver based solely on signal strength may not be accurate (13). On the other hand, the GPS scheme could produce better distance estimations between nodes (24). However, there are some drawbacks in using GPS receivers. The use of GPS receivers implies an extra power consumption to the nodes and an extra implementation cost, and in some cases the reception of GPS signals may not be possible, for example in some indoor locations or under adverse weather. It is interesting to mention that node localization can also be used to route packets to a given geographic area (25; 26; 27).

3. Opportunistic Petal Routing

3.1. 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. 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. 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.
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.

3.2. Towards Robust Multipath Routing

In this section we present a robust on-demand routing scheme for wireless ad hoc networks that we call Petal Routing. This routing technique utilizes the broadcast nature of wireless networks to combine multiple transmissions from one node to one transmission.
The basic idea is as follows. Given a source and destination, the network carries out constrained flooding to send the packet to the receiver. The flooding is constrained to transmissions within an area that we call a petal and it is determined by the reliability metric, which can be defined on a per transmission basis. The shape of the flooding area is intuitively modeled as a "petal", the two ends of which converge at the source and destination. Since the underlying protocol is flooding, the individual nodes do not need any prior information about their neighbors or maintain any end-to-end paths. Such protocols that do not need neighborhood information are called beaconless protocols. A parameter, called the petal parameter, helps an intermediate node determine whether it is located within the petal or outside.
Before discussing the Petal Routing technique in greater detail, we first state the assumptions and the failure model that are considered.

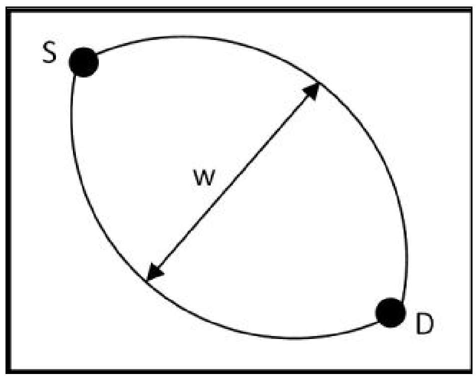

Figure 1: Visualization of Petal

3.3. Assumptions

The Petal Routing methodology uses node locations to minimize the number of individual transmissions in the network. The location of a node determines whether or not it would take part in a certain transmission. It is assumed that a node always knows its current location. In addition to that, the source is expected to know the location of the destination. The (x, y) coordinate of a node is in the form: (longitude, latitude). Other than the source (that knows the location of the destination), no other node knows the location of any other node, other than itself. In addition to that, the nodes in the network need not maintain routes to any other node in the network, or know who their neighbors are. The routing protocol is so designed, that the addressing is using location co-ordinates. A node's latitude and longitude uniquely identifies it. In other words, the geographic location of a node is its address. The source always sends a packet to a location and not to any IP address. We consider this to be an equivalent of the source sending the packet to the node at the location specified.
With regard to nodal density in the network, we assume that the network is reasonably dense. This is pertinent, because we use a multipath routing technique. If no path exists within the area of the petal, then the routing would fail. However, this is a simplifying assumption, and in case of a sparsely populated network, our approach could be used in combination with table-driven approaches to store neighbor information, which can assist in calculating the optimal width of the petal.
In a densely populated wireless network, collisions are an important concern that can lead to poor performance.
MAC layer algorithms for contention resolution in wireless networks have been studied extensively. Moreover, the multi-hop path occurs through a time scale that is more coarse grained, and it does not affect the overall end-to-end performance. We assume that the contention resolution and scheduling issues at the hop time scale are handled by the MAC layer. In the network layer, we provide some heuristic enhancements using back-off time, to reduce the probability of collisions. Node locations are obtained from a positioning system, such as the GPS. In our basic implementation, we assume that the location obtained from the GPS is precise enough for our calculations.
We also assume that the nodes in the network are capable of omni-directional transmission. There are no special requirements on directional transmission for Petal Routing.

3.4. Failure Model

We follow the failure models to test our contribution.
The failure models that have been considered for Petal Routing include both failures from natural disruption as well as failures due to malicious activity. The subsequent sections discuss the failure models that we consider.

3.4.1. No Failure

The case of no failures, all nodes in the network function correctly. All the nodes are able to transmit and receive packets as expected.

We use this model, only to test if our protocol functions correctly in the absence of failures. It is almost impossible to practically realize a reasonably sized model without any failures.

3.4.2. Intermittent Node Failure

This model captures independent node failures. Thus some nodes in the network fail, but there is no pattern by which the nodes fail. Isolated failures occur in reality. Such failures can take place due to energy dissipation or localized environment effects. For instance, if the density of nodes in a certain region in the network is low, then a node in that region would trigger higher physical activity. This would lead to such a node dissipating all its energy, independent of neighboring nodes. Since there are no physical links in wireless net- works, environmental failures do not affect individual links in the network.

3.4.3. Jamming Model

The jamming model captures geographically correlated failures, or patterned failures. Such a failure, affects all wireless links in a circle of radius Rp. The choice of the circle is somewhat arbitrary, but it attempts to model radio wave propagation. In reality, this model can be justified with the fact that environmental effects within a geographic region can cause correlated failures. We use the jamming model in.

We assume that jammers can operate at any location in the network at a given time. The jamming power to signal ratio (JSR) at the receiver determines the degree to which jamming is successful. In general the JSR can be expressed as follows.

$$JSR = \frac{\text{JammingP owerReceived}}{\text{SignalP owerReceived}}$$

$$JSR = \frac{P_J}{P_T} \left(\frac{D_{TR}}{D_{JR}}\right)^n$$

4. Problem Formulation

The problem is to find the most durable path *p** from *s* to *d* for each flow *f*:

$$p^* = \underset{p \in \Pi sd}{\operatorname{argmax}} \Phi p$$

By selecting the most durable paths for the flows, less path repairs would be needed, which implies less protocol overhead and a better use of the nodes' energy.

4.1. Evaluation Under Ideal Conditions

To support the idea, we conducted a simulation study to find out the average route lifetime on a mobile ad hoc network to determine whether there would be any reliability improvement over flooding (calculated as the shortest path) with the use of either the oldest links or the links with the longest residual lifetime metrics. The simulation was done at the topology level and assuming ideal conditions, which imply that links are determined solely based on the distance between nodes and that route calculation can be done with full knowledge of the location of nodes and their mobility patterns. Nodes move according to the random waypoint point (RWP) model without pause times and at a given speed that is randomly selected in the range [1, *S*]. Nodes move on a rectangular field of 400 × 100 units, all with equal wireless coverage of 50 units. For each simulation instance and after a suitable time (2.5 simulated hours) to let the statistical properties of the RWP model emerge, a route is established between two randomly selected nodes. Routes are established with either a hop count, link age, or link residual lifetime criteria.

5. A Distributed Solution: LDR

In a MANET, it is normally impractical to acquire global information about the network state (such as the nodes' location) to drive routing decisions. A distributed algorithm to allow each source independently finds durable paths on demand with only local information. We call the algorithm *Link Durability Routing* (LDR) and has the following properties:

- LDR uses a modified flooding algorithm, but introduces decisions and actions at each iteration based on the residual lifetime of each link as calculated from local information.
- Route selection is distributed and not bounded to the source or destination nodes.
- In case localization becomes available partially to some nodes or not available at all in the network, LDR can continue to work, but it would produce less optimal routes.
- Clock synchronization among nodes is not needed.
- Active paths are periodically monitored by piggybacking information into selected data packets, so that preventive re-routing can occur in addition to reactive re-routing in the case of a route failure.
- The algorithm can be incorporated into existing flooding-based MANET protocols (e.g., AODV (45), DSR (46)). However, we will discuss the algorithm in the context of a independent protocol (LDRP), given that some particular operations available in other protocols are not needed, for example, HELLO beacons for neighbor discovery.
- LDR could also enhance the performance of other location-based protocols.

5.1. Route Setup

As mentioned above, LDR relies on a modified flooding algorithm to discover routes. The standard flooding algorithm is of common use by many on demand ad hoc routing protocols and works as follows. Whenever a new route to a destination is needed, the source broadcasts a route request message. The message indicates the desired destination and a message identifier, in addition to other pieces of information that could be relevant to each particular algorithm.

The identifier and origin addresses of the message allows intermediate nodes to discern new from replicated requests, so that they can select to process only the first arrival of each request. If the node receiving the request if not the destination, the node will append its own address to the packet (and possibly other pieces of information depending on the actual protocol being used) and broadcast again the message without delay.

On the other hand, if the receiving node's address matches the destination of the route request, the node will respond to the source with a reply message that will list the path used by the route request to reach the destination. The message is forwarded along the reversed path. If the destination is reachable, there is a high probability that one of the copies generated by the process will eventually reach the destination. The path produced by the process will tend to the shortest path in number of hops, although, network congestion may induce longer routes.

5.2. Link Selection

To implement a selection mechanism that will discern links based on their residual lifetime to allow setting up durable routes, we introduce a decision mechanism that is executed at each node participating in a route discovery process.

With standard flooding, each node receiving for the first time a route request message broadcast immediately the message to its neighbors. In LDR, a route request in retained at each node for a certain time before doing a new broadcast. By making the retaining time inversely proportional to the durability of the preceding link, LDR can delay the messages traveling on the less desirable routes and favor the best route request replicas (so, those traveling on the most durable links) to reach first the destination. Before the node rebroadcast the request, it will continue processing other route request arrivals sharing the same request identifier. However, each node will at most broadcast one request per route request ID as in the standard flooding algorithm. Since the destination replies only to the first arriving route request, a robust path will be selected for the flow.

5.3. LDR Protocol

Route selection with LDR is distributed by definition and link selection is implicit by introducing a temporal behavior to the way route requests are handled by nodes rather than by defining a spatial selection of the next hop or by explicitly selecting a route among the choices available at the source or destination nodes.

To calculate the durability of a link, a node requires its current location and velocity vector as well as the vectors from the predecessor node. This information can be easily obtained by augmenting route requests with two fields:

- location and
- velocity.

Therefore, in addition to appending its network address, an intermediate node updates these two fields with its own data. Note that these two fields are fixed given that only information from the predecessor is needed and not from the rest of nodes in the path. This procedure allows each intermediate node to obtain fresh information to compute the residual lifetime of links. After the defer time for a new route request is determined, the message is scheduled at a target time for broadcast or to be delivered to upper layers. The target time is the current time plus the calculated defer time. Note that the defer time is a minimum time that the message is forced to wait in a node. The actual residence time in the node could be longer due to other factors that may occur after the target time, such as queue waiting before transmission. A new route request arrival may replace an existing scheduled message transmission whenever the new target time is less than the existing target time. If the target time for a message is reached, the request is considered processed so any further arrival with the same request id will be dropped.

5.4. Maintenance of Route

The route setup phase allows to setup durable paths. However, the residual lifetime of each link on a path is likely to change over time as a consequence of node mobility and changes in the operating environment. To reduce the risk of a route break, active routes are periodically monitored by LDRP. For this purpose, selected data packets are augmented to carry the position and velocity vectors of the predecessor node. On arrival of an augmented data path, the node calculates the new residual lifetime of the preceding link. The link would be assumed to be at risk of failure if its residual lifetime is less than parameter ttb_thr. If so, a *route information* message will be sent to the source to initiate a preventive re-routing action. LDRP limits the creation rate (per flow) of control messages, which include augmented data packets, route requests, and route error messages, to place a cap to the monitoring overhead that could be generated. The inverses of the maximum sending rate limits are defined by rdata_limit, rreq_limit, and route_error_limit.

6. Conclusion

Mobile ad hoc networks can complement existing wireless infrastructure-based networks and bring a plethora of novel services to mobile users. While the lack of need for an existing infrastructure and centralized control, allows MANETs to be quickly created or destroyed as needed, their multihop nature makes them quite sensitive to changes in both the structure of the network and the surrounding environment.

We have discussed reliability issues in MANETs and elaborated on a low-overhead solution to improve the reliability of routes by introducing a mechanism that allows the identification and selection of links with the most availability as measured by their residual lifetime. We have also suggested a realization of the approach whereby the residual lifetime of links are calculated based

on node location. We call the algorithm Link Durability Routing (LDR). In addition to a reliable path establishment, the algorithm takes advantage of existing packet flows to constantly monitor the expected availability of links. By means of the continuous monitoring of active paths, LDR can detect paths at risk of become unavailable and enforce preventive or corrective re-routing.
Finally, we have evaluated LDR in the context of a realistic scenario where node localization is acquired from either a GPS receiver of from tracking sensors. The results suggest that path reliability can be significantly increased with the proposed algorithm as compared to a reference case (AODV). The improvement was particularly noticeable in networks where nodes can move at high speeds. While the GPS-based case performed the best in terms of route reliability, the system based on tracking sensor nodes produced results close to the GPS case. On the downside, the routes produced by the algorithm tend to be longer than the shortest path, which could impact the individual end-to-end latency of packets. However, the overall impact to the flows would be small or even non-existing in most cases given that the higher reliability of paths will reduce the need for packet transmissions as suggested by our relative energy consumption comparison results.

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