WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2012; **12**:1608–1619
Published online 6 December 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/wcm.2333

SPECIAL ISSUE PAPER

Improving routing in networks of Unmanned Aerial Vehicles: Reactive-Greedy-Reactive

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ABSTRACT

Because of their specific characteristics, Unmanned Aeronautical Ad-hoc Networks (UAANETs) can be classified as a special kind of mobile *ad hoc* networks. Because of the high mobility of Unmanned Aerial Vehicles, designing a good routing protocol for UAANETs is challenging. Here, we present a new protocol called Reactive-Greedy-Reactive (RGR) as a promising routing protocol in high mobility and density-variable scenarios. RGR combines features of reactive MANET routing protocols such as Ad-hoc On-demand Distance Vector with geographic routing protocols, exploiting the unique characteristics of UAANETs. In addition to combining reactive and geographic routing, the protocol has a number of features to further improve the overall performance. We present the rationale and design of the protocol, discuss the specific performance improvements in detail and provide extensive simulation results that demonstrate that RGR outperforms purely reactive or geographic routing protocols. The results also demonstrate the impact of the various protocol modifications. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS

Unmanned Aeronautical Ad-hoc Networks (UAANETs); Unmanned Aerial Vehicles (UAVs); routing protocol; Reactive-Greedy-Reactive (RGR) protocol; Greedy Geographic Forwarding (GGF); Ad-hoc On-demand Distance Vector (AODV); mobility prediction; scoped flooding

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1. INTRODUCTION

An Unmanned Aerial Vehicle (UAV) is defined as any aerial vehicle that does not have a human operator onboard. In many state-of-the-art applications, UAVs must cooperate to decrease mission delay and increase reliability. This cooperation, which is accomplished using wireless communication, allows UAVs to share information [1]. These UAVs form an *ad hoc* network, which we referred to as an Unmanned Aeronautical Ad-hoc Network (UAANET) [2]. In UAANETs, the relatively low number of UAVs and their high mobility (causing constant topology changes) challenge network connectivity. Therefore, UAANETs require an efficient networking architecture to combat these limiting topological features. Although many traditional routing protocols have been proposed for MANETs [3–5], their performance will be poor (as we will show later using Ad-hoc On-demand Distance Vector (AODV) as a representative protocol), and they do not exploit the unique features of UAANETs. As a result, it is necessary to develop new efficient routing protocols that perform well in such networks.

We therefore developed a new protocol, called Reactive-Greedy-Reactive (RGR), which combines the advantages of reactive routing and Greedy Geographic Forwarding (GGF). The protocol exploits the fact that UAVs have access to accurate location information for navigation purposes. At the same time, it avoids the need of an independent location service by integrating the propagation of location information into the reactive routing protocol. Furthermore, the reactive and geographic components of the paper can be further improved by exploiting the location information in new ways. In particular, we added scoped route request flooding and mobility prediction to enhance the performance of the core RGR protocol. In addition to the location information, this mechanism takes advantage of the velocity vector of the nodes to predict their current locations. Unlike many other mobile nodes, the trajectories of UAVs are less prone to abrupt changes, so we expect this to lead to very good prediction accuracy.

Mobility prediction then allows the protocol to monitor the status of the reactive routes and select appropriate neighbors during the GGF phase of the protocol. At the same time, two different scoped flooding methods are utilized to reduce the overhead messages generated by the original RGR protocol during the route discovery phase by exploiting location information.

The rest of the paper is organized as follows. Section 2 reviews related work on routing protocols, scoped flooding mechanisms, and mobility prediction mechanisms. In Section 3, we first introduce the core RGR protocol and qualitatively compare it with purely reactive and purely geographic routing protocols. Section 4 introduces the proposed scoped flooding and mobility prediction mechanisms. Section 5 presents the results of a thorough performance evaluation of the proposed protocol and its enhancements via Opnet simulations. Finally, we conclude in Section 6 outlining a number of additional modifications we are currently working on to improve RGR further.

2. BACKGROUND

2.1. Routing in aeronautical networks

In recent years, there has been some attempts to propose routing protocols for aeronautical networks. In [6], a routing mechanism based on the doppler shift of aerial vehicles is proposed for Aeronautical Ad-Hoc Networks (AANETs). When location information is not available, doppler shift is used to estimate the relative velocity of the nodes and to evaluate whether nodes are approaching or receding from each other [7]. These doppler shift values lead to estimated link duration and stability [6]. When location information is available, velocity and current location of the nodes are used as the cost metrics to evaluate link stability [8]. Unlike commercial aircrafts in AANETs, which have transportation applications, UAVs in UAANET are usually used for applications such as searching or tracking. These specific applications typically impose a random nonlinear trajectory on UAVs (e.g. the tracking object could have unpredictable non-linear mobility). Therefore, pseudo-linearity, which results in a specific design strategy in AANETs [8], is not a feasible assumption in UAANETs.

Another category of works on routing protocols for aeronautical networks is to address the intermittent connectivity of the network [9]. A geographical routing algorithm for intermittently connected MANETs is introduced in [10]. The routing algorithm, called LAROD (Location Aware Routing for Opportunistic Delay-tolerant networks), is a geographical beacon-less routing algorithm based on the Store-Carry-Forward principle. The UAV that holds the packet (the custodian) uses greedy packet forwarding when there are other UAVs nearby. The custodian should make sure that the packet has been received by other UAVs. If several nodes in the forwarding area receive the packet, the first expired-timer node is selected as the next forwarder to rebroadcast the packet. Overhearing the transmission by other UAVs, the custodian relinquished the custody of the packet.

2.2. Reactive routing

In reactive routing protocols, a source node finds a route to a destination by flooding route request packets into the network. Because the process is on-demand, the route discovery imposes some latency on the overall performance of the network. Also, the flooding of route requests may cause buffer overflow and network congestion. In this paper, the reactive part of the proposed combined routing is based on AODV [4]. The main reason for choosing AODV is its popularity, although other alternatives besides AODV may be deployed.

2.3. Geographic routing

Geographic routing uses location information rather than network addresses to establish source–destination communication in a MANET environment. Every node in the network is aware of its own location, and location information of neighboring nodes is collected via periodic packet exchanges. Also, a source node knows the location of its destination. For data dissemination, a node uses a greedy forwarding mechanism in which a traditional geometric rule, typically based on the Pythagoras theorem, is employed. The source node sends data packets to the neighbor with minimum distance to the destination [11].

Location services, which is a module to provide location information to nodes in the network, can be classified in three major groups: flooding based, quorum based and home based [12]. A flooding-based service is the traditional one that can be proactive or reactive. In a proactive service, a node disseminates its location periodically. In a reactive service, when a node does not have the updated information of a target, a search message is flooded into the network. Location and mobility information can be used to narrow the scope of flooding. In quorum-based approaches, the destination node sends the location updates, and the source node is responsible for sending search requests. Location updates and search updates are generally sent to two different subsets of network nodes that are respectively called *update quorum* and *search quorum*. These two subsets should be selected such that their intersection is not empty. At the rendezvous points, update and search quorums can provide the location information to the querying nodes. Finally, in the home-based approach, every node has a home region that is known to others, and location updates are proactively sent to the nodes that are in or closest to that region. Other nodes send search messages towards the home region of the destination. If required, the message is redirected from the home region to the current location of the node.

2.4. Reactive-geographic combination

Different versions of combined reactive-geographic routing have already been proposed in the literature for several different purposes. In [13], AODV is used during the connection setup phase, and proactive routing with directional forwarding is used during the data transfer phase. When the authors integrate the characteristics of on-demand and proactive routing, the proposed mechanism provides a better delivery ratio. However, the performance of the protocol in terms of delay is not evaluated. Also, the mobility scenario is not compatible with UAANET missions.

To resolve packet loss issues of geographic routing at the border of voids in mesh networks, a reactive backtracking mechanism is proposed in [14] to inform upstream nodes about blocked sectors. Another combination of reactive and geographic routing protocols can be found in [15]. In that algorithm, the reactive routing mechanism is used to reduce the number of control packets for routing discovery. The proposed method shows an improvement in routing overhead compared with Greedy Perimeter Stateless Routing (GPSR) [11] in sensor networks.

In this work, the RGR mechanism is designed to address high mobility situations in UAANETs. In fact, GGF is used as an alternative of reactive routing for data dissemination. Unlike the previously introduced combinations, in this paper, both the reactive and GGF parts are used for data dissemination. In addition, the reactive part is used for obtaining location information of a destination node without requiring a separate location service in place. Even though the idea of combining reactive mechanism with GGF is proposed in location-aware AODV [16], there have been no realistic performance analysis or simulation results on its performance. In this paper, a detailed description of the algorithm implementation is provided, and its performance in terms of packet delivery ratio (PDR), delay and overhead is experimentally examined.

2.5. Scoped flooding based protocol

Location-Aided Routing (LAR) [17] is one of the most popular proposals to reduce overhead messages in AODV and Dynamic Source Routing (DSR) [4,5]. Because the geographic information of the destination is not directly available in AODV or DSR, LAR utilizes the original AODV or DSR protocol to establish connectivity with the destination node. During this phase, the source node will learn the geographic information of the destination from the route reply message sent by the destination node or by an intermediate node that knows the latest route to the destination. With this location information, LAR does not need to flood the route request packet into the whole network. It confines the flooding of route request (RREQ) packets to the part of the network that approximately contains the destination node. During the route discovery process, every intermediate node will compare its own location information with the specified search area contained in RREQ packet. If it belongs to the search area, this node will rebroadcast the RREQ packet. Otherwise, the RREQ packet will be discarded [18]. When only paths outside the LAR search area are able to reach the destination, LAR will fall back to flooding the RREQs. Under LAR, the geographic information is only utilized to scope the region of the route request message propagation and not used to decide how to forward data packets. In our work, we adopt a similar strategy and will discuss and compare two approaches to defining the search area.

2.6. Mobility prediction based protocol

Different versions of on-demand routing protocols based on mobility prediction [19–22] have already been proposed. Most of these protocols focus on selecting the most stable route from already known backward routes. Those backward routes are set up once the destination node receives the RREQ messages from different neighbor nodes. In [19], Link Expiration Time (LET) between any mobile nodes has been exploited to improve various unicast and multicast routing protocols. By piggybacking location information on control packets, their protocol estimates the LET between any two nodes and appended it to the RREQ message. The intermediate node will broadcast this RREQ message to all neighbors. When receiving RREQ messages, the destination node will learn the LETs of all known links and decide which link has the maximum route expiration time, which is defined as the least of the LET values of one link. Using route expiration time, one can set up a more stable route for data transmission.

The Mobility Prediction algorithm for improving Routing Protocols (MPRP), as proposed in [20], is used to predict link status during the data transfer phase. In this protocol, location information is included in the data packet. During data transmission, an intermediate node can extract the location information of the previous node from the data packet. The node will compare the distance difference between two consecutive received data packets in order to (i) judge when the link will break and (ii) find out unnecessary nodes on the route that are too close to the current node. The closest node should be replaced with a two hop node as new next hop. This mobile prediction method is simple and does not require complicated computation and beacon packets. However, this mechanism must add a prediction table to the on-demand protocol and makes use of a new message called route expired message to feedback the link status to a previous node. In our work, we added a similar capability to RGR yet avoided the need for a new protocol message.

3. REACTIVE-GREEDY-REACTIVE PROTOCOL

The basic idea behind RGR, which has been initially proposed in [23], is to combine a reactive protocol (in this case, AODV) with GGF. In this protocol, if there is no valid route for data packets to be transmitted, the source node of the data packets begins a route discovery process (as in AODV) to find a valid route entry to reach the destination node, flooding RREQ packets into the network. In fact, a reactive route is established when the source node receives the route response (RREP) packet from the destination node. Once the route is established, data packets buffered at the source can be transmitted to the destination. The novelty in RGR is that the location information of the destination node is obtained by every intermediate node as the RREP packet propagates back to the source node. In the route maintenance process, if an intermediate node cannot receive three successive hello messages, the link is considered lost, and the reactive route breaks. RGR invalidates the reactive route and switches to the GGF mode. In this mode, the protocol sends the data packets to the neighbor node that is closest to the destination node (in essence, salvaging it). At the same time, a route error (RERR) packet will be sent back to the precursor node until it reaches the source node. The source node, if it has more data to transmit, initiates a new route discovery process to establish a new reactive route to the destination. Packet forwarding via GGF will continue until the data packet reaches the destination node and is dropped by an intermediate node because of the TTL parameter reaching 0 or until greedy forwarding fails to find a neighbor node closer to the destination. Similar to other geographic routing protocols, RGR keeps track of each neighbor's existence and location by having nodes periodically broadcast hello messages once every second that contain a node's ID and location information. The following subsections briefly describe the different aspects of RGR.

3.1. Control messages

There exist four different types of control messages in RGR: RREQs, RREPs, RERRs, and hello messages. The functionality and propagation of each of these messages in RGR is similar to AODV except for the fact that RREQs, RREPs, and hello messages carry location information. RREQs carry source location information, RREPs carry destination location information, and hello messages carry neighbor's location information. The location information is used to update the node tables in intermediate nodes.

3.2. Node tables

As an important module for routing, the proposed RGR protocol uses two different tables in each individual node: a routing table and a neighbor table. The routing table, indexed with destination IP address, contains information about a specific destination including the destination location acquired during the route discovery process. The neighbor table lists all one-hop neighbors and includes the location information for each neighbor received and updated via periodic hello messages.

3.3. Switching to Greedy Geographic Forwarding

Switching to GGF may take place in intermediate nodes, when the reactive route to a destination breaks. As shown in Algorithm 1, when a data packet arrives, the node checks if there exists a reactive path in its routing table. If the route is already broken (because of neighbor movements), RGR executes another subfunction in which the node tries to geographically forward the packet to the destination. The location information of the destination and neighbor nodes is extracted from the routing table and the neighbor table, respectively.

Algorithm 1 Packet arrival algorithm in Reactive-Greedy-Reactive

```
if This is a control packet then
    Handle it by control packet functions (RREQs, RREPs, RERRs, ...)
else if This is a data packet then
    if There is a valid reactive route then
        Forward the packet on the route
    else if The packet is from the current node (this is a source node) then
        Use RREQ/RREP to find a new path
    else if The packet is forwarded from a neighbor (this is an intermediate node) then
        Switch to Greedy Geographic Forwarding
    else
        Drop the packet (neither reactive nor geographic route is available)
    end if
else
    Drop the unknown packet (neither a data packet nor a control packet)
end if
```

3.4. Handling a received packet

When a node receives a data packet via a greedy geographic forwarder, it checks whether a valid reactive route exists in its routing table. If a reactive route exists and is valid, the packet will be forwarded to the next neighbor on that route. If there is an entry in the routing table pointing at the destination, but the next hop neighbor is not available in the node table, the node will consult the neighbor table to determine the closest neighbor to the destination. If no neighbor node that is closer to the destination can be found, the packet is dropped.

3.5. Destination operation

The destination can receive a packet either on a reactive route or via GGF by a neighbor. The packet received via a reactive route can be from either a source that has a

Table I. Comparing reactive routing, geographic routing, and Reactive-Greedy-Reactive.

Parameter	Reactive routing	Geographic routing	Reactive-Greedy-Reactive
Location service	–	Required	–
Route request	Required	–	Required
Neighbor location	–	Required	Required
Motivation (Application)	Connectivity in MANETs	Scalability in dense MANETs	Handling higher mobility
Control messages	Route establishment/ neighbor discovery	Neighbor discovery	Route establishment/ neighbor discovery
Routing choice made at	Source and intermediate nodes	Intermediate nodes	Source and intermediate nodes
Mobility specifications	Static/low mobility	Low/high mobility	Fairly static to highly mobile

path to the destination or a source without such path. The latter case is only possible when somewhere on the source–destination path, at least one switch from reactive to GGF has occurred. In any case, the destination node delivers the packet to the application when it recognizes itself as the final destination.

3.6. Overview of Reactive-Greedy-Reactive

To summarize, we qualitatively compare the proposed RGR and the reactive and geographic routing protocols as shown in Table I. Unlike geographic routing protocols, an independent location service is not required in RGR because the location information is provided by the reactive RREQ/RREP mechanism. The RGR route discovery process is slightly more complicated and requires the dissemination of location information compared with purely reactive protocols. This somewhat increased overhead is the price that we pay to provide end-to-end connectivity for a density variable highly mobile network architecture without requiring an independent geographic location service. Also, RGR has been designed for networks with a higher relative mobility compared with most MANET scenarios. Therefore, the expectation is to have more route interruptions in the network compared with traditional MANETs. Switching to GGF provides a best-effort alternative in cases that a route interruption occurs.

4. REACTIVE-GREEDY-REACTIVE ENHANCEMENTS

In this section, we discuss two enhancements, namely scoped flooding and mobility prediction, to reduce the overhead and improve the performance of RGR.

4.1. Reactive-Greedy-Reactive with scoped flooding

The original RGR protocol inherited RREQ flooding to the whole network during route discovery process from AODV, optionally using an expanded ring search technique. We call this strategy blind flooding in the remainder of the paper. Although the number of UAVs in the network is relatively small, blind flooding adds high protocol overhead, potentially resulting in buffer overflow and network congestion. To reduce the number of RREQ packets, two different mechanisms of scoped flooding in RGR are discussed in this section and evaluated via simulation later in this work. The first mechanism is as follows. When a route discovery process is initiated for the first time, the source node floods the RREQ packets into the whole network and waits for the RREPs from the destination node. When the RREP packets arrive at the source node, a valid reactive route will be set up, and in the meantime, the location information of the destination node will be learned by the source node. After a short period of time, a new route discovery process may need to be performed for the same destination node because of a route break caused by the highly dynamic topology of our UAANET scenarios. In this case, using the geographic information of the destination learned previously, the source node calculates the distance to reach the destination and includes this information in the RREQ packet (as well as its knowledge of the destination's location). This new request packet is broadcasted to all neighboring nodes. Upon receiving the RREQ packet, a neighbor node extracts the distance value from the RREQ packet and recalculates its own distance to reach the destination node. If this new distance is less than the distance from the RREQ packet, the neighbor node replaces the old value with the new one in the RREQ packet and rebroadcasts the packet to its neighbors. Otherwise, this RREQ packet will be discarded. This process continues until the RREQ packet reaches the destination node, which then replies via an RREP, updating its location information in the process. A source node will wait to receive a route reply to the scoped RREQ. If the geographic information is out of date, this scoped flooding may fail, and the source will issue another RREQ after a predefined timeout, increasing the source–destination distance by a fixed percentage. In our implementation, we used an increase of 20% for each repeated RREQ. The RREQ carries a repetition counter, allowing intermediate nodes to similarly apply an increased distance to the destination with each repetition. In essence, this provides some additional 'slack' in the RREQ propagation. After a specific number of retries, say five, the source node will switch from scoped flooding to blind flooding.

The second mechanism depends on the facts that not only the source node but also other nodes in the network learn the destination location in RGR. When route discovery is initiated the first time, the source node will set the distance to destination to zero and add this to the RREQ packet. Thereafter, the source node broadcasts the RREQ packet to all neighbors. Every neighbor receiving the RREQ packet first checks whether it has geographic information related to the destination node. When a node does not know the destination location, it rebroadcasts the RREQ packet. Otherwise, the intermediate node calculates its own distance to the destination node and compares it with the distance value in the RREQ packet. If the distance value extracted from the RREQ is zero, that is to say, the previous node does not know the destination location, the intermediate node includes the calculated distance into the RREQ packet and rebroadcast it. If the distance value extracted from RREQ is nonzero, the intermediate node compares this distance value with its own distance to the destination as mentioned previously. If the node's distance is less than the distance value from the RREQ, the RREQ distance value will be updated and the RREQ rebroadcasted. Otherwise, the intermediate node drops the RREQ packet. This process is repeated until the RREQ packet reaches the destination. Assuming that no node in the whole network knows the geographic location of the destination, this mechanism degrades to blind flooding. On the other hand, unlike the first idea, we do not necessarily need to resort to blind flooding the first time a route request is issued. If a source node uses inaccurate location information, this version of scoped flooding may fail as well. In this case, a source will re-issue an RREQ with 0 distance after unsuccessfully waiting for an RREQ.

4.2. Reactive-Greedy-Reactive with mobility prediction

According to the RGR protocol, data packets are sent to the destination node once a reactive route is established. During transmission, the intermediate nodes detect the status of the next hop by receiving hello messages. If an intermediate node fails to obtain three consecutive hello messages from the next hop, this intermediate node will then conclude that the link to reach the next hop is broken. At this time, data will be alternatively forwarded by the GGF mechanism. Given that hello messages are broadcasted once every second, this mechanism delays link break discovery by between 2 and 3 s. When a link break takes place, the intermediate node cannot access the current link status immediately and has to wait (in the worst case up to 3 s or three hello intervals) before it can act on it. During this time, the intermediate node still assumes the link is valid and continues to forward data packets through the (falsely) existing reactive route. As a result, these data packets will be lost and cannot be salvaged by the GGF mechanism. Note that we could set the criteria for link breakage to a different number, such as a single missed hello message. Although this would reduce the time it takes to detect an actual link break, it would also lead to many incorrect RERR messages, as hello messages, being broadcasted in the wireless media, could become lost because of interference or collisions. Alternatively, we could reduce the hello interval; but with every node periodically transmitting hello messages, this would increase the protocol message overheads significantly. To solve this problem, the proposed mobility prediction mechanism employs the velocity vector, which is associated with a timestamp, of the next hop node to compute the distance between the current node and the next hop node before forwarding data packets (which is part of the periodic hello message). As soon as the next hop node is out of transmission range, the current transmitting node can immediately respond by invalidating the status of the reactive route and, at the same time, switch to GGF to salvage the data packets that would have been dropped otherwise.

The functionality and propagation of control messages are similar to RGR except that RREQ, RREP, and hello messages carry more information. In the route discovery process, RREQ and RREP messages carry not only the location information of the destination node but also the speed, direction, and timestamp of the precursor node. In the route maintenance process, hello messages periodically broadcast information including location, speed, direction, and timestamp to neighbors. These parameters are extracted from these messages and recorded in every intermediate node.

After the route discovery process, the source node sends buffered data packets to the destination node. Every intermediate node relays data packets one by one. Unlike RGR, the current node, which is about to transmit the packet, first checks the distance to the next node. With the help of equations (1) and (2), the current node estimates the real-time position of the next hop (note that for simplicity, we express this in a 2D coordinate system, but it would be relatively straightforward, although more involved, to express these relations in a 3D coordinate system as well).

$$X_{\text{predict}} = X_{\text{next}} + V\cos(\theta)(\mathit{current\_time} - \mathit{timestamp}) \tag{1}$$

$$Y_{\text{predict}} = Y_{\text{next}} + V\sin(\theta)(\mathit{current\_time} - \mathit{timestamp}) \tag{2}$$

In the previous equations, X_{predict} and Y_{predict} are the X and Y coordinates of the predicted location of the next hop. X_{next} and Y_{next} are the last known location of the next node. The $timestamp$ records the time at which the last known location was recorded. Parameters V and θ represent the speed and the direction of the next hop node, respectively. These necessary parameters are extracted from the routing table maintained in the current node.

When we use equation (3), the current node judges whether the next hop is out of transmission in real time.

$$D_{\text{next}} = \sqrt{(X_{\text{own}} - X_{\text{predict}})^2 + (Y_{\text{own}} - Y_{\text{predict}})^2} \tag{3}$$

In equation (3), D_{next} is the actual distance from the current node to the next hop node. X_{own} and Y_{own} are the current node's location. X_{predict} and Y_{predict} are the X and Y coordinates obtained from equations (1) and (2).

If D_{next} is smaller than the transmission range, the current node continues to transmit data packets to the next hop using the reactive route. However, if the distance is greater than the transmission range (i.e. the next hop in the reactive route is now predicted to be out of range), the current node immediately stops sending data packets over this route and simultaneously switches to GGF to forward data packets. During the GGF phase, the current node obtains the real-time topology of neighbors by exploiting the same mobility prediction method. It then selects the node closest to the destination to greedy forward packets towards it.

Note that mobility prediction requires nodes to be at least approximately time synchronized. If we assume a maximum travel speed of 300 km/h (or equivalently 1080 m/s) for a UAV, clock synchronization errors of 1 ms translate into an error in the predicted location of at most 1.08 m if two UAVs travel in opposite directions, a very small fraction of typical transmission ranges. Such synchronization accuracy is easily achieved with one of the many clock synchronization protocols proposed in the literature [24,25]. In addition, if UAVs obtain their location information for navigation purposes via GPS, all nodes will also be synchronized tightly to a very accurate global reference time, obliviating the need for a separate clock synchronization protocol.

Because GGF is used as a fallback mechanism, the RERR packet does not have to be generated immediately when an intermediate node detects that the link to the next hop node is broken. So we delay the transmission of an RERR message after detecting a link break by 3.5 s, a value that exceeds the longest delay for AODV and original RGR to detect a link break (3 s or alternatively three consecutive hello intervals). A purely reactive routing protocol such as AODV has to re-establish a new route as soon as possible to prevent long gaps in data packet transmissions. During this period, in RGR, data packets can be salvaged via GGF. In fact, a previous study showed that for a small number of hops, GGF has a high success probability to reach the destination [26]. Until a new reactive route is established, an intermediate node can keep on sending data packets to a neighbor node that is closest to the destination node. In highly dynamic topologies, by carefully selecting an appropriate RERR message delay, we expect this to reduce the total number of RREQs initiated by a source without impacting overall protocol performance.

5. EVALUATING REACTIVE-GREEDY-REACTIVE

To evaluate the performance of RGR, we used OPNET Modeler 16.0 [27]. In OPNET, the modular access to different network components makes it possible to design

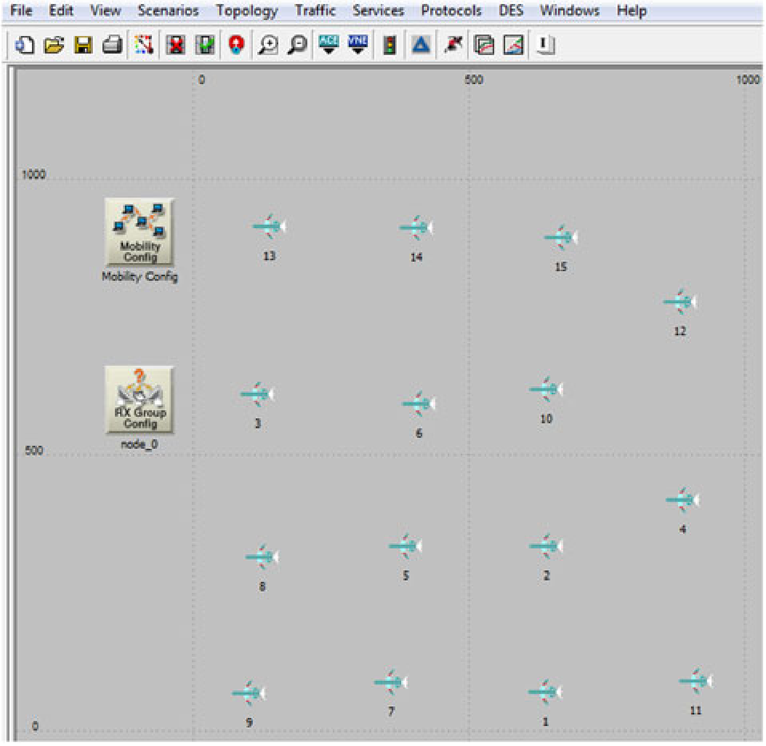

Figure 1. Initial mobility scenario state.

a protocol independent of other modules in the network. The other motivation for using OPNET was that AODV has already been implemented there.

To evaluate the performance of RGR with the proposed enhancements, we set up a specific scenario in which 15 UAVs are distributed randomly in the initial region, as shown in Figure 1. A free path loss propagation model is considered in the simulation. Every UAV in the scenario randomly selects another UAV as a target to send data packets. The packet sizes are drawn from an exponential distribution with mean 1024 bits. The interpacket delays follow an exponential distribution with mean 0.2 s. The reason for this traffic flow structure is that the adaptability of the proposed modified RGR protocol in processing multiflows can be tested. The capability to handle multiflows is an important characteristic of a routing protocol [1]. Thus, this scenario can be considered as a relatively realistic multitraffic flows scenario for UAANETs.

The random waypoint (RWP) model is used to simulate realistic UAV mobility for a search mission. In a search mission, every UAV is looking for an object in a specific area. Because each UAV must move continuously without pause, the pause time in the model for every node is set to 0. To simulate a high-mobility scenario, we choose the speed for every UAV to be uniformly distributed between 50 and 60 m/s [28]. We do not believe that the RWP model is a proper description of UAV mobility, as it allows for very abrupt and sharp changes in a UAV's trajectory, but have not yet completed work on more realistic scenarios. As discussed previously, more realistic UAV trajectories are also more predictable. Therefore, the results presented here underestimate the performance gains that mobility prediction is able to achieve. The transmission range of each UAV is set to 1000 m, and the simulation time is set to 1000 s. In the initial phase (as shown in Figure 1), all UAVs are in each other's vicinity. So, there will be good initial networking performance independent of any routing protocol. As the UAVs gradually spread over the search region during the simulation, the performance in terms of PDR, overhead, and delay will deteriorate and eventually reach a steady-state behavior. It is important to note that we do not force UAVs to be in each other's vicinity. This means that at some point in time, the network can be possibly disconnected as this is the case in realistic UAANET applications. The specific mobility parameters are listed in Table II.

Table II. Mobility parameters of the scenario.

Parameter	Value
Speed	Uniform(50, 60) m/s
Initial region	1×1 km^2
Search size	2×4 km^2
Number of Unmanned Aerial Vehicles	15
Transmission range	1000 m
Simulation time	1000 s

6. SIMULATION RESULTS

For the simulations, 10 different seed values of the pseudorandom number generator are set in OPNET, so that each set of simulation results will be independent. Five protocols – AODV, original RGR, RGR with mobility prediction (MPRGR), RGR with scoped flooding method 1 and mobility prediction (SF1MPRGR) – and RGR with scoped flooding method 2 and mobility prediction (SF2MPRGR) are simulated individually and compared with each other.

In the next figures, the performances of the aforementioned five protocols are compared with each other via the following metrics: PDR, protocol overhead (measured in control packets transmitted per second), and packet end-to-end delay.

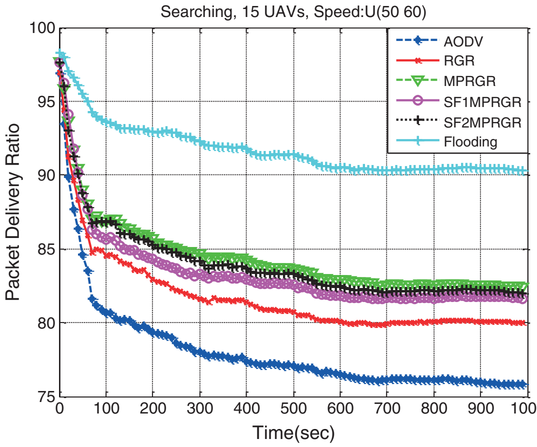

Figure 2. Packet delivery ratio. UAVs, Unmanned Aerial Vehicles; AODV, Ad-hoc On-demand Distance Vector; RGR, Reactive-Greedy-Reactive; MPRGR.

As can be seen from Figure 2, MPRGR has the highest PDR among the five protocols, reaching approximately 83%. The two scoped flooding based protocols have almost similar results, with very little degradation compared with MPRGR. Meanwhile, the original RGR and AODV perform much worse than the other three protocols. Their PDR performance drops to 80% and 76% respectively in steady state. The main reason to explain this difference is that both original RGR and AODV do not have the capacity to check the link status on a reactive route in real time. Detecting the status of a reactive route is delayed by up to three hello intervals. The other three protocols, on the other hand, have the ability to detect the status of the reactive route during data transmission and switch to GGF as soon as a link break takes place. Therefore, packets that are dropped by the original RGR and AODV (as they are transmitted over invalid links) are salvaged by the other three protocols. To establish whether there is further scope for improvement, we also run simulations where we blindly flood the data packets rather than route them. Although this is costly and therefore not recommended in general, it helps us establish an upper bound on the PDR performance of a routing protocol. As the results in Figure 2 show, there is still a nontrivial gap between even our best variant and flooding, indicating that there is further scope for improvement. Some ideas we are currently considering will be discussed at the end of the paper.

From Figure 3, we can see that the two scoped flooding protocols have the lowest protocol overhead, reducing the overhead of MPRGR from almost 21 packets per second to 18 packets per second. The results verify that both scoped flooding mechanisms reduce the amount of RREQs during the simulation by exploiting geographic information successfully. The overhead of MPRGR is about three packets per second lower than the original RGR and about four packets per second for AODV. MPRGR is waiting 3.5 s before sending an RERR back to the source, thus reducing the total number of RREQ. Consequently, the number of RREQs initiated by the source node is decreased resulting in a reduced overhead. Note that a rate of seven control packets per second is a lower bound on the protocol overhead, as AODV and RGR only generate hello messages when nodes are on an active route and there has not been a recent RREQ packet.

All proposed enhancements, in particular scoped flooding and delayed RERR, target a reduction in the protocol control messages other than the periodic hello messages. These therefore form a lower bound on the control message overhead. Intuitively, for 15 nodes and a hello interval of 1 s, we would expect a floor of about 15 hello packets per second, indicating that we have come quite close. However, nodes only generate hello messages when they are on a reactive route and there has not been a recent RREQ packet. Therefore, the actual number of hello messages is much lower, as shown in Figure 3. The number indicates that there is ample scope for further enhancements. It also raises the issue that nodes may not know all neighbors, as those nodes not on an active route will not send hello messages, which does potentially impact GGF negatively.

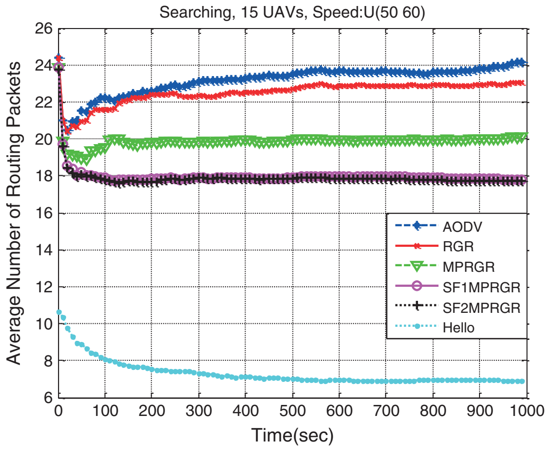

Figure 3. Average routing traffic. UAVs, Unmanned Aerial Vehicles; AODV, Ad-hoc On-demand Distance Vector; RGR, Reactive-Greedy-Reactive; MPRGR.

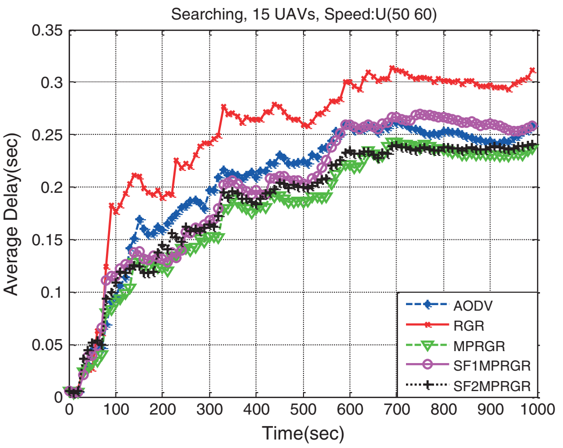

Figure 4. Average packet delay. UAVs, Unmanned Aerial Vehicles; AODV, Ad-hoc On-demand Distance Vector; RGR, Reactive-Greedy-Reactive; MPRGR.

In terms of end-to-end delay, we can see from Figure 4 that the delay for the original RGR is high compared with the other protocols. The original RGR's delay is about 300 ms. Meanwhile, the other four protocols have similar average delay (approximately 250 ms) in steady state. This shows that the improvements in PDR and control message overhead do not come at a cost with respect to delay. Certainly, the reduction in control messages, leading to less overall network traffic, benefits the three new proposed protocol variants. In addition, with delay calculated over all packets that are received, the delay calculated for AODV is somewhat misleading: only those packets that are delivered over the reactive route will be considered. Salvaging packets in general will result in those packets being delivered over more hops, increasing their end-to-end delay. But this (relatively small) incremental latency is a small price to pay for a substantial increase in PDR.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced a new protocol called RGR as a promising routing protocol in high-mobility and density-variable scenarios. RGR combines features of reactive MANET routing protocols such as AODV with geographic routing protocols, exploiting the unique characteristics of UAANETs. In addition to combining reactive and geographic routing, we also presented two enhancements, namely scoped flooding and mobility prediction.

Our simulation results show that scoped flooding and mobility prediction results in significantly higher PDR, lower overhead, and lower end-to-end delay compared with the original RGR and AODV protocols. From these results, we can conclude that it is critical to check the real-time status of the next hop node during the data transfer phase and both scoped flooding mechanisms are effective in suppressing the flooding of RREQ control messages.

For future work, we are currently exploring a range of different issues. First, we have not studied the differences in the two scoped flooding approaches further. As shown by our results, the two approaches perform comparatively, so we plan to conduct further studies with a range of different scenarios to understand the relative strengths and weaknesses of each approach better. Second, we need to explore mobility prediction further. For example, we have not yet systematically studied the prediction errors. As UAVs change direction, past trajectory information will not always allow us to accurately predict current UAV locations. We need to learn the accurate relation between prediction errors and protocol performance. Third, we also need to conclude work on realistic mobility trajectories for UAVs. The RWP model is not suitable for realistic UAV scenarios as it allows nodes to reverse direction by 180°instantaneously. To solve this problem, every UAV should choose the next trajectory destination as a function of its current trajectory, changing speed and or direction within a small range. Fourth, in the GGF phase, the criterion to select the next hop node should not only be based on the closest distance to reach the destination node. It could also include additional parameters, such as link stability, which is decided by how long the next node will stay in the transmission range of the current node, link data rate, and so on. Finally, we also need to study the hello messages in more detail. In fact, sending hello messages is part of the protocol overhead, so the longer the hello interval, the better. On the other hand, timely hello messages are required to update location information in neighboring nodes. Also, with the current protocol only having nodes on the reactive path sending hello messages, GGF may suffer from a lack of neighborhood knowledge. As the simulation results showed, not every node sends hello messages, which is a prerequisite for other nodes learning about them.

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