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Procedia Computer Science 10 (2012) 535 – 542

Procedia
Computer Science

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The 3rd International Conference on Ambient Systems, Networks and Technologies (ANT)

On the Delay of Reactive-Greedy-Reactive Routing in Unmanned Aeronautical Ad-hoc Networks

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Abstract

Reactive-Greedy-Reactive (RGR) has been proposed as a promising routing protocol in highly mobile density-variable Unmanned Aeronautical Ad-hoc Networks (UAANETs). In RGR, location information of Unmanned Aerial Vehicles (UAVs) as well as reactive end-to-end paths are employed in the routing process. It had already been shown that RGR outperforms existing routing protocols in terms of packet delivery ratio. In this paper, the delay performance of RGR is evaluated and compared against Ad-hoc On-demand Distance Vector (AODV) and Greedy Geographic Forwarding (GGF). We consider extensive simulation scenarios to cover both searching and tracking applications of UAANETs. The results illustrate that when the number of UAVs is high enough in a searching mission to form a connected UAANET, RGR performs well. In sparsely connected searching scenarios or dense tracking scenarios, RGR may also slightly decrease delay compared to traditional reactive routing protocols for similar PDR.

Keywords: Reactive-Greedy-Reactive (RGR), Ad-hoc On-demand Distance Vector (AODV), Greedy Geographic Forwarding (GGF), reactive routing, Unmanned Aerial Vehicle (UAV), Unmanned Aeronautical Ad-hoc Network (UAANET)

1. Introduction

Unmanned Aeronautical Ad-hoc Networks (UAANETs) are formed by several Unmanned Aerial Vehicles (UAVs) communicating with each other during a mission [1, 2]. The relatively low number of UAVs and their high mobility (resulting in frequent topology changes) are challenging characteristics of UAANETs. Because UAVs are equipped with a Global Positioning System (GPS) for acquiring their current geographic information (i.e. coordinates, velocity, etc.), the availability of accurate location information makes it possible to exploit geographic routing mechanisms as a part of the communication protocol for UAANETs [3].

The unique features of UAANETs require a new networking architecture and a different routing design. To that end, Reactive-Greedy-Reactive (RGR) has been proposed as a compatible routing mechanism to

doi:10.1016/j.procs.2012.06.068

satisfy the specific requirements of UAANETs. These specific features and the motivation for the deployment of the RGR protocol are clarified in [4]. The reactive part of RGR is based on the Ad-hoc On-demand Distance Vector (AODV) protocol [5]. In the Greedy Geographic Forwarding (GGF) part of RGR, a node is selected for packet forwarding based on its distance to the destination node [6]. If no closer neighbor node can be found, then a fallback mechanism such as face routing needs to be deployed [7]. Due to the degradation of GGF success probability in sparse scenarios, geographic routing alone is not sufficient in UAANETs [1, 6]. However, it is shown that a combined routing mechanism, such as RGR, can improve packet delivery ratio and delay [8]. In the RGR protocol, a source node establishes a reactive route for data forwarding [4]. In case of a link breakage causing a route interruption, a switch to GGF takes place. The routing process then continues until the data reaches the destination.

Even though RGR routing has already been proposed and is shown to improve packet delivery ratio in an UAANET, its delay performance has not been thoroughly evaluated for different UAANET missions. In this paper, the goal is to implement different mobility scenarios to model searching and tracking missions of an UAANET. Based on these scenarios, we evaluate the delay performance of RGR against AODV and GGF. The goal is to determine the conditions under which RGR improves the total end-to-end delay of the UAANET. As a result of this evaluation, a better estimation of UAANET performance can be achieved which can help in designing routing protocols for delay-critical applications.

The rest of the paper is organized as follows. In Section 2, related background on reactive-geographic combinations are discussed. Section 3 describes the RGR routing protocol. In Section 4, two important UAANET missions are discussed and mobility scenarios based on these missions derived. In Section 5, we present the simulation settings followed by the simulation results in Section 6. Finally, the paper is concluded in Section 7.

2. Background

In recent years, there has been some attempts to propose routing protocols for aeronautical networks. In [9], a routing mechanism based on the doppler shift of aerial vehicles is proposed for Aeronautical Ad-Hoc Networks (AANETs). An algorithm uses position information while the other clusters nodes without knowing position information. 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 [10]. These doppler shift values lead to estimated link duration and stability [9]. When location information is available, velocity and current location of nodes are used as the cost metrics to evaluate link stability [11].

Different versions of combined reactive-geographic routing have already been proposed in the literature [4]. In [12], AODV is used during the connection setup phase and proactive routing with Directional Forwarding (DFR) is used during the data transfer phase. By integrating 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.

In order to resolve packet loss issues of geographic routing at the border of voids in mesh networks, a reactive backtracking mechanism is proposed in [13] to inform upstream nodes about blocked sectors. Another combination of reactive and geographic routing protocols can be found in [14]. 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 to GPSR [15] in sensor networks.

In RGR, GGF is used as an alternative to the reactive routing for data dissemination [1]. Unlike the previously introduced combinations, both the reactive and the GGF parts are used for data dissemination. In addition, the reactive part is used for obtaining the location information of a destination node without requiring a separate location service. In [4], simulation results show that RGR outperforms existing protocols such as AODV in searching UAANET missions in terms packet delivery ratio, yet its overhead is similar to traditional mechanisms. In this paper, we extend the experiments to further investigate the delay performance of RGR in both searching and tracking missions.

3. Reactive-Greedy-Reactive Routing (RGR)

In the route establishment phase of RGR, not only is a reactive route set up, but the geographic location of the destination is also obtained by the source. The data packets use at first the reactive route to forward data. In case a route breaks, a switch to GGF occurs.

There exist four different types of control messages in RGR: route requests (RREQs), route replies (RREPs), route errors (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 [8].

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 (due to neighbor movements), RGR executes another sub-function in which the node tries to geographically forward the packet to the destination. The location information of the destination and neighbor nodes are extracted from the routing table and the neighbor table, respectively.

Algorithm 1 Packet arrival algorithm in RGR

```
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 (i.e. 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
```

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 can be found that is closer to the destination, the packet is dropped. More details about the RGR implementation are available in [8].

4. UAANET Missions

Trajectory design for UAVs is accomplished via the Random Waypoint (RWP) model as a standard mobility model that is modified to represent specific UAANET missions. There are two main missions for an UAANET: searching and tracking. At time 0, the UAVs are all in an initial region, which is a square surface where the UAVs start their mission (analogous to a take off site). In this initial phase, since all the UAVs are in each other's vicinity, we can expect good networking performance, independent of any routing protocol. As time goes on, the UAVs spread over the region, showing a steady-state behaviour in terms of delivery ratio and overhead [8]. Given the speed of UAVs, the size of the deployment area, and the number of UAVs in the network, [16], any independent random mobility may divide the UAANET into several temporary partitions.

4.1. Searching Missions

In order to model a search mission of an UAANET, a square area is considered. The assumption in a search mission is that every UAV is looking at different places to find the desired object. Therefore, the RWP can model the mobility of each UAV, especially when they move independently. In such a case, a node chooses a destination and speed, and then moves from its current location at that speed towards the destination. A node then remains at that location for *pause time* seconds and the process repeats. We consider a continuous flight mission in which the UAVs never come to a rest, which is why *pause time* is set to 0. Also, the mission starts at time t=0 sec and ends at t=1000 sec, which is the end of the simulation. The mobility characteristics for searching missions are summarized in Table 1. Please note that UAVs are spreading out all over the region independently to look for the object. As a rsult, the independent random mobility may divide the UAANET into several partitions.

Based on the mobility parameters described in Table 1, we defined three different UAV scenarios. The first scenario models a low speed searching UAANET in which the UAV velocity is changing based on a uniform distribution in the $[10, 20]$ m/s interval. In the medium velocity model, UAVs uniformly select a velocity in the $[30, 40]$ m/s interval, and finally our high speed scenario has UAV speeds uniformly distributed between $[50, 60]$ m/s. Please note that these ranges of speeds are typical values for a UAANET including medium size UAVs [16].

4.2. Tracking Missions

For modelling a flock of UAVs participating in a tracking mission, another modification of the RWP can be used in OPNET. In this model, called flocking UAANET, all UAVs are moving towards a target region. This target region is a 2000 × 2000 m square, which is 125 km away from the origin (where the UAVs start their mission). The region is considered 125 km away to make sure that the implemented scenario correctly models the tracking mission. If the region is somewhere closer, the UAVs would possibly reach there before the simulation ends, which is not desirable for modelling a tracking mission. In this model, all UAVs travel towards the region while showing randomness in their trajectories. The details of the mobility parameters for an UAANET in a tracking mission are summarized in Table 1.

Table 1: Mobility parameters for searching and tracking missions of UAANETs

Parameter	**Searching Mission**	**Tracking Mission**
Mobility Model	Random Waypoint	Modified Random Waypoint
Low Speed Scenario	Uniform(10, 20) m/s	Uniform(17, 20) m/s
Medium Speed Scenario	Uniform(30, 40) m/s	Uniform(36, 40) m/s
High Speed Scenario	Uniform(50, 60) m/s	Uniform(55, 60) m/s
Size	25 km^2	Not Available
End Region	Not Available	125 km away from Origin
Size of End Region	Not Available	4 km^2
Initial Region	1×1 km square with a vertex on (0, 0)	1×1 km square with a vertex on (0, 0)
Number of UAVs	10, 20	10, 20
Pause Time	0	0
Start Time	0	0
Stop Time	1000 sec	1000 sec

In a tracking mission, UAVs' speeds are changing based on a uniform distribution in the range of [17, 20] m/s, [36, 40] m/s, and [55, 60] m/s for low speed, medium speed, and high speed scenarios respectively [16]. Compared to a search mission, the uniform intervals for the velocities are smaller. The reason for such a selection is that in a tracking mission, UAVs are assumed to follow a target on the ground, therefore they would have smaller deviations in their speeds and directions. In other words, the target would cause the UAVs to have more correlated mobility vectors. In OPNET, we model this phenomenon by a smaller uniform interval for the velocity vectors. The other fact is that as the target moves faster, we expect to have more deviation in UAV mobility. Hence, we increase the uniform interval width from 3 for low speed scenarios to 4 and 5 for medium and high speed scenarios respectively. We only consider 10 UAVs in tracking mission.

5. Simulation Settings

In order to evaluate the delay performance, the RGR protocol was implemented in OPNET Modeler 16 [17]. In OPNET, the modular access to different network components makes it possible to design a protocol independent of other modules in the network. The other motivation for using OPNET was that AODV and GGF have already been implemented thus making it easier to compare. The propagation model considered in our simulations is a free space path loss, which models the propagation as a disc around the transmitter. MAC layer specifications are based on 802.11 standard and similar to the values of [4, 18]. The transmission range is set to 1000 m. AODV parameters and their values are listed in Table 2, and are based on the standard definition in [5]. It is worth-noting that we considered the same settings for RGR.

Table 2: AODV/RGR configurations

Parameter	Value
Active Route Timeout	5 sec
Hello Interval	Uniform (1, 1.1)
Allowed Hello Loss	3
Net Diameter	35
Node Traversal Time	0.04 sec
Route Error Rate Limit	10 pkts/sec
TTL Start	1
TTL Increment	2
TTL Threshold	7
Timeout Buffer	2

In the simulations, two UAVs are elected as head UAVs. They communicate with each other bi-directionally. The communicated traffic among these two nodes is higher than other nodes in the network. Every other nodes in the network has uni-directional flows towards each of these nodes. The reason for considering such a structure for traffic flows is two-fold. First, it will help to have more simulation data to depict more accurate figures. Second, we can test the adaptability of the proposed RGR protocol in dealing with multi-flows in the network. One important feature of a routing protocol is the ability to handle multi-flows. Different protocols may impose different routing delays, and processing time in intermediate nodes. In order to have a meaningful comparison of the protocols, assuming such an environment is necessary. Thus, unlike many literature available on the topic which only consider a very limited number of flows, we test the protocols in a more realistic scenario assuming several flows in the network. The traffic parameters in the network are listed in Table 3.

Table 3: Traffic parameters

Parameter	Searching scenario
Start Time	0 sec
Packet Inter-arrival Time (head UAVs)	Exponential (0.05 sec)
Packet Inter-arrival Time (other nodes)	Exponential (0.2 sec)
Packet Size	Exponential (1024) bits
Stop Time	1000 sec

6. Simulation Results

In order to measure delay, 10 independant scenarios are generated in OPNET. Each of those scenarios is generated using a different seed of the pseudo-noise sequence generator available in the OPNET core. We consider the same number of seeds for each routing protocol to gather several sets of pseudo-independent results. We evaluate the delay of those packets that are successfully delivered to the destination. Delay in the past 10 sec for a seed i is called $D^i(t)$. By averaging $D^i(t)$ over all 10 simulation runs, we have:

$$D_{avg}(t) = \frac{1}{10 \cdot t} \sum_{x=1}^{t/10} \sum_{i=1}^{10} D^i(10 \cdot x) \qquad t = 10 \ldots, 1000 \tag{1}$$

where $D_{avg}(t)$ is the average delay for the interval $[0, t]$, and $D^i(x)$ is the delay imposed by the protocol using the seed i during the time interval $[x - 10, x]$.

In [4], the performance of RGR is compared to GGF and AODV with and without local repair in terms of packet delivery ratio and overhead. It is shown that due to the fact that RGR employs a GGF alternative, we can expect that a part of the packets are recovered, resulting in a better packet delivery ratio in the long term. Also due to the high relative mobility in the network, some local repair attempts and repaired routes may fail again, which causes RGR to show an improvement compared to AODV with local repair.

In this paper, we specifically focus on the delay performance of RGR compared to AODV and GGF. For that purpose, we consider the two different applications of UAANETs discussed earlier: searching and tracking. The level of confidence for all the figures is 95%, shown by error bars in the figures.

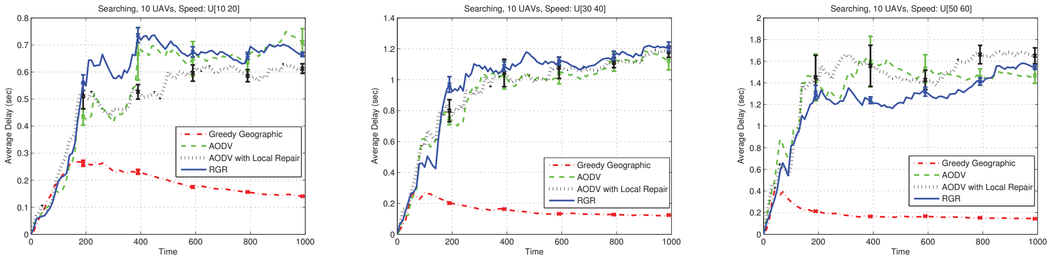
An interesting characteristic of RGR is that the global repair process takes place at the same time that GGF is trying to deliver the packets. As a result, we can see an improvement in RGR delay compared to AODV without local repair. Also, the delay improvement of RGR compared to AODV with local repair is based on the fact that the imposed delay (queueing and processing) in intermediate nodes for the GGF part of RGR is smaller than the RREQ/RREP process available in AODV with local repair.

The first major observation, which is also valid for all the figures in this paper, is that the delay performance of GGF is much lower than all other protocols. In [8], it is shown that even though GGF has a lower delay, its PDR is also much lower. The main reason is that GGF can provide end-to-end connectivity only if an end-to-end greedy geographic path can be found. In UAANETs, due to the sparse nature of the network, such a greedy path is not always available, therefore many packets would be dropped in intermediate nodes. But if a packet can reach its destination, its end-to-end delay is lower. In this paper, we keep GGF as the base case for packets that do not need salvaging. Other protocols deliver a significant number of packets after a route breaks, which increases the latency. In AODV, packets are buffered either in source node (for global repair) or in intermediate nodes (for local repairs), which imposes higher delays in either of these cases. In RGR, the GGF process is deployed to salvages the packets, while building a new global route.

Figures 1a, 1b, and 1c depict the delay performance of RGR, AODV (with and without local repair), and GGF in a search mission, covering a 25 km^2 area with 10 UAVs. In Figure 1a, for low-speed UAVs, the average delay of RGR is worse than the two flavours of AODV. The reason is that due to sparsity in the network (10 UAVs in 25 km^2), many unsuccessful switches to GGF take place. As the network topology changes faster when UAVs travel at higher speeds (Figure 1c), we see that RGR performs slightly better compared to AODV with and without local repairs.

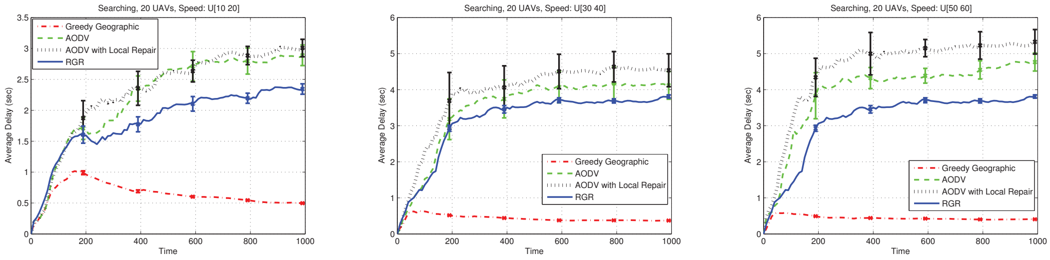
Next we increase the number of UAVs to 20 in a searching mission in the same area of 25 km^2. We expect to have less and less network disconnectivities. In such scenarios, the reactive route breakage most probably can be bypassed by switching to GGF. Also, due to the nature of GGF, its smaller delay cause an overall improvement in the RGR delay compared to the other alternatives. Figures 2a, 2b, and 2c illustrate that for low, medium and also high speed scenarios, RGR outperforms both versions of AODV.

Another observation from the figures so far is that the latency curve is an increasing function in the beginning. The reason is that in the initial phase, all the nodes are close to each other and the paths are usually short. As a result, the delay is very small at the beginning and increases after the UAANET goes into its steady state mobility. Based on the 95% confidence intervals, there is not a statistically significant



(a) Low speed scenario (b) Medium speed scenario (c) High speed scenarioe

Fig. 1: Average delay for 10 searching UAVs in a 25 km^2 region

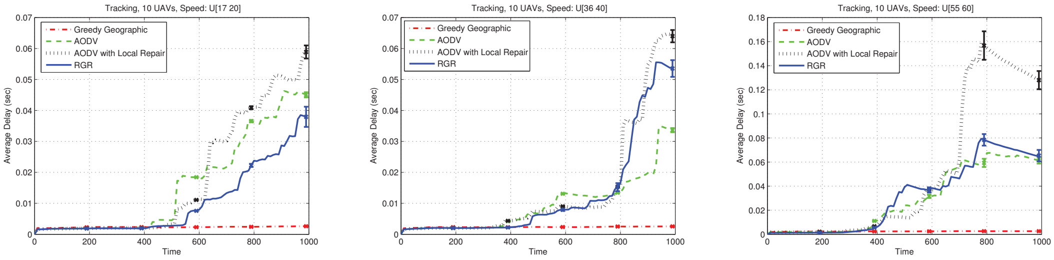


(a) Low speed scenario (b) Medium speed scenario (c) High speed scenario

Fig. 2: Average delay for 20 searching UAVs in a 25 km^2 region

difference between RGR and AODV for searching scenarios including 10 UAVs. On the other hand, for searching UAANET including 20 UAVs, it is shown that RGR improvement is statistically significant.

In tracking missions, the UAANET scenario is denser due to the fact that all the nodes are following an object and stay in each others vicinity most of the time. Figures 3a, 3b, and 3c represent the delay performance of RGR versus AODV (with and without local repair) and GGF in low-speed, medium-speed, and high-speed tracking scenarios respectively. RGR delay in tracking scenarios is similar to AODV without local repair. The reason for this phenomenon is that due to the density of the network, the RGR mechanism is more likely to salvage the packets in case of a route breakage in intermediate nodes. In tracking scenarios, AODV with local repair is not a promising solution compared to AODV without local repair and RGR.



(a) Low speed scenario (b) Medium speed scenario (c) High speed scenario

Fig. 3: Average delay for 10 tracking UAVs

7. Conclusion and Future Work

RGR has already been proposed as a combination of reactive and geographic routing protocols to improve the packet delivery ratio of an UAANET in searching missions [4]. In this paper, the lack of RGR delay performance analysis in tracking and searching scenarios is addressed. The goal was to understand the delay behaviour of RGR in different scenarios. It is shown that in searching scenarios with higher mobility, RGR provides lower packet latencies, yet its delay in tracking missions is comparable with the different flavours of AODV. For tracking mission, however, the delay performance of RGR is comparable with AODV without local repair. The results illustrate that switching to GGF is useful in relatively connected searching scenarios but not for highly dense tracking missions or very sparse searching missions.

One possible idea for future research is to use trajectory information (speed and direction of UAVs) as well as the freshness of the location information to further improve the overall performance (packet delivery ratio, latency, and overhead) of the RGR protocol. Another direction of future work is to analytically derive upper and lower performance bounds for RGR and compare them with the simulation results.

Acknowledgement

The work reported herein was supported by Defence Research and Development Canada (DRDC).

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