Position-based Routing in Flying Ad Hoc Networks

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Abstract—**In recent years the interest in Flying Ad Hoc Networks (FANETs) to solve military and civil tasks increased significantly. Due to FANETs being comprised of highly mobile Unmanned Aerial Vehicles, the development of generally efficient routing algorithms proves to be considerably complex. This paper compiles a survey on routing protocols using position information in the routing process. Position-based routing protocols follow two main concepts, reactive and greedy-based. When comparing two algorithms, each following one of these concepts, different strengths and weaknesses become apparent, resulting in different ideal areas of application.**

Index Terms—**FANET, position-based, routing, protocol, UAV, ad hoc network, MUDOR, GPMOR**

1. Introduction

With increased interest in using cooperating groups of Unmanned Aerial Vehicles (UAVs) to solve civil and military tasks, the concept of Flying Ad Hoc Networks (FANETs) was introduced to connect the individual UAVs as a mesh network. The existing FANET routing protocols follow two main strategies using either topology or position information in the routing process. This paper introduces position-based routing protocols for FANETs. It starts with outlining the reasons for the considerable difficulties in designing adequate routing algorithms, the specific characteristics, in Section 2. Subsequently, Section 3 outlines the two main approaches of position-based routing protocols, namely reactive and greedy-based. Thereafter, both Section 5 and Section 6 present one algorithm following each of these two approaches. This paper concludes with a comparison and assessment of the two presented algorithms in Section 7.

2. Characteristics of FANETs

FANETs consist of multiple highly mobile UAVs. This results in a specific set of characteristics, outlined and explained here:

Network topology: As the nodes of FANETs consist of individual UAVs, they possess a high degree of freedom in both speed and direction of movement. This results in a significantly reduced longevity of the network topology, especially when compared to ground-based networks [1], [2].

Node density: As UAVs do not require supporting infrastructure and are less likely disturbed by obstacles due to being located in the air, the relative node density can be assumed to be sparse [2].

Radio propagation model: Due to the high distances between nodes compared to the strength of the radio transmitters, FANETs usually require a free Line-of-Sight (LoS) between nodes. As FANETs are located in the air, they have a high likelihood of fulfilling this requirement [1].

Power sparsity: The availability of power to the routing protocol is highly dependent on the size of the used UAVs. For large UAVs the power required for routing calculations is insignificant compared to the power required for movement. For smaller UAVs the power capacity can be limited [1], [2].

3. Reactive and Greedy Routing Protocols

Position-based routing protocols in FANETs are generally separated into two distinct groups. Both of them are outlined here:

Reactive: In routing protocols using a reactive approach, the path discovery process is started on demand for every packet by flooding the network with a Route Request (RREQ) for a routing target. This is answered by a Route Reply (RREP) when the target was found. In comparison to proactively managing a routing table, this comes with a significantly reduced network overhead but usually increases the end-to-end delay. Compared to purely topology-based reactive routing protocols, the additional position information can be used to flood the network in a more controlled approach, reducing overall network overhead [1], [3].

Greedy: Greedy position-based routing protocols forward packets in the target direction without previously calculating a complete path to the target node either in a proactive or reactive manner [2], [3].

4. Related Work

Development of FANET routing protocols is a highly active field of research and as such a variety of related work is available. This paper provides an introduction to the topic of position-based routing algorithms by describing and comparing two algorithms, following fundamentally different approaches, in-depth. By contrast, Oubbati et al. [4] compile a more general, higher-level survey of position-based FANET routing protocols. Oubbati et al. [2], Lakew et al. [3], Sang et al. [5], and Perez et al. [6] compile generally broad surveys on routing

doi: 10.2313/NET-2022-07-1_04

algorithms in FANETs. All of them reflect on different types of routing algorithms while dedicating chapters of their work to position-based routing algorithms. Oubbati et al. [2] should be highlighted in this context due to being extraordinarily extensive even compared to the other papers providing a general overview.

5. MUltipath DOppler Routing (MUDOR)

MUltipath DOppler Routing (MUDOR) is a reactive position-based routing protocol proposed by Sakhaee et al. [7] for FANETs. The main feature separating MUDOR from other reactive routing protocols is the incorporation of the relative node mobility to increase link stability and reduce the flooding overhead. The relative mobility of nodes is measured through observing the doppler shift of the received signals. MUDOR is partly based on Dynamic Source Routing (DSR) [8]. An optional Quality of Service (QoS) extension for MUDOR, proposed by Sakhee et al. [9], offers improved control over the required route performance. This section is based on the original MUDOR algorithm as proposed by Sakhaee et al. [7].

5.1. Physical Background

The doppler effect describes a perceived shift in frequency between the sender of a wave compared to the observer. As the velocity of UAVs is small compared to the speed of light [2], according to Rosen et al. [10] the aforementioned frequency shift can be approximated by:

$$\frac{f_o}{f_s} = 1 + \frac{v}{c} \tag{1}$$

With f_s being the frequency at the sending node and f_o being the frequency observed by the observing node. As f_s is standardized across all nodes, c is known and f_o is observed, the relative velocity v between sender and receiver can be calculated by solving Equation (1) for v:

$$v = c \cdot (\frac{f_o}{f_s} - 1) \tag{2}$$

Nodes approaching each other have a negative relative velocity and show a statistically higher link stability compared to receding nodes as they are longer in each others vicinity. Therefore, smaller values are superior. MUDOR introduces the Doppler Value (DV) metric representing the cost of each link based on this relative velocity. The DV is just the relative velocity calculated according to Equation (2) and weighted by -1 for approaching nodes and $+2$ for receding nodes:

$$DV = \begin{cases} -v, & v < 0 \text{ (nodes approaching)} \\ +2v, & v > 0 \text{ (nodes receding)} \end{cases} \tag{3}$$

5.2. Different Roles of Node

The MUDOR routing protocol differentiates between two different roles of nodes: requesting and receiving nodes. Each of the following sections describes one of them, with the role of the receiving node being subdivided in receiving Route Requests (RREQs) and Route Replys (RREPs). Roles are not node exclusive, therefore one node can have multiple roles.

TABLE 1: Format of a MUDOR RREQ as described by Sakhee et al. [7].

Name	Description
Request Id	Request identifier
Target Id	Target packet identifier
Hop Count	Hop counts until request termination
Packet Doppler Value	Largest doppler value on route
Route Addresses	Cumulated node addresses on route

5.2.1. Requesting Node.

The communication process starts by the source node flooding its neighborhood with RREQs. The format of a RREQ is outlined in Table 1. Similar to other reactive routing protocols, a MUDOR RREQ possesses a maximum hop count field containing the maximum future hop counts until request termination, a unique request identifier, and a route addresses field cumulating the addresses of the previously visited nodes. Differences to other routing protocols occur in the target id and Packet Doppler Value (PDV) fields. Contrary to other routing protocols, the target of a MUDOR RREQ is a specific data packet, containing arbitrary data, instead of a node. The target id field contains the respective identifier of the target packet. The PDV field contains the largest DV observed during a node hop on the current route.

5.2.2. Receiving Node (RREQ).

Each node possesses a request table containing all previously forwarded RREQ ids and the Minimum Doppler Value (MDV) of the specific requests. If a node receives a request, it compares the RREQ PDV with the observed DV in the last hop. The larger of the two values is then written into the PDV field of the RREQ. The following process differs depending on whether the node offers the requested data packet and if it has already forwarded the received RREQ.

Node offers the requested data packet: The node sends a RREP back to the last sending node. The RREP contains the same fields as the RREQ except for the target id and hop count fields which are omitted in the RREP.

Node has not already forwarded the RREQ: The node creates an entry in its request table containing the request id and the current RREQ PDV. Then it apprehends its address to the RREQ route addresses, decrements the RREQ hop count and forwards the RREQ to all neighboring nodes.

Node has already forwarded the RREQ: The node compares the current RREQ PDV with the PDV of the specific RREQ in its routing table. If the RREQ PDV is larger than the PDV in the route request table, the node has already forwarded the same RREQ on a superior route and the RREQ is dropped. If the current RREQ PDV is lower than the PDV in the request table, the newly discovered route is superior and the request table entry is overwritten with the RREQ PDV. Then the node apprehends its address to the RREQ, decrements the RREQ hop count and forwards the RREQ to all neighboring nodes. This measure enables the system to discover multiple routes leading through the same node while simultaneously reducing the overhead significantly compared to having a hard boundary of RREQs with the same id being forwarded by each node.

5.2.3. Receiving Node (RREP). The RREQ PDV is updated, as described in the previous paragraph, by comparing the RREQ PDV with the observed DV in the last hop and writing the larger value in the RREQ PDV field. The following process differs depending on whether the receiving node is also the requesting node:

Node is not requesting node: The RREP is forwarded by backtracking the route addresses in the corresponding RREQ field.

Node is requesting node: The node waits a configurable amount of time collecting incoming RREPs and ordering them by their PDV. Then it selects the path with the smallest PDV for packet transmission. If a selected path fails, MUDOR selects the path with the next smaller PDV. This is the multipath approach of MUDOR offering built-in failure recovery.

6. Geographic Position Mobility Oriented Routing (GPMOR)

Geographic Position Mobility Oriented Routing (GPMOR) is a greedy position-based routing protocol for FANETs proposed by Lin et al. [11]. This section is a summary of GPMOR as described in [11].

As outlined in Section 2, FANETs are a highly dynamic environment. Due to the high degree of mobility, a connection of two nodes can be interrupted during a packet broadcast even if they were initially sufficiently close. As the sender might not be able to detect such a loss of connection, this might lead to a significant amount of packet loss. GPMOR introduces an algorithm using the stored position and movement information to predict the future movement of potential relay nodes. Then, a node with a low probability of the described packet loss scenario is selected as the next relay node.

6.1. Mathematical Background

To predict the future velocity V_n and direction of neighboring nodes d_n, Lin et al. [11] use the following Gauss-Markov mobility model:

$$\begin{aligned} V_n &= \alpha V_{n-1} + (1-\alpha)\bar{V} + \sqrt{(1-\alpha^2)}V_{x_{n-1}} \\ d_n &= \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)}d_{x_{n-1}} \end{aligned} \tag{4}$$

with $\bar{V}$ and $\bar{d}$ being historical averages of V and d respectively. $V_{x_{n-1}}$ and $d_{x_{n-1}}$ are random variables from a Gaussian distribution introducing noise into the prediction equations. The tuning parameter α can be adjusted depending on the movement model, with $\alpha = 1$ representing no change of movement in the given time period.

The predicted values are then used by Lin et al. [11] to calculate the new position of the specific node after a time period ΔT:

$$\begin{aligned} x^{'} &= x + s_x \Delta T \\ y^{'} &= x + s_y \Delta T \end{aligned} \tag{5}$$

with x and y being the node coordinates and s_x and s_y being the velocity components in the respective dimensions calculated from V_n and d_n.

Lin et al. [11] then use the predicted node position to calculate the future euclidean distance between a relay node r and the destination node d:

$$\Delta d^{'} = \sqrt{(x_r^{\prime} - x_d^{\prime})^2 + (y_r^{\prime} - y_d^{\prime})^2} \tag{6}$$

If $\Delta d^{'}$ is below the range threshold R of node r, r will be able to send messages to the destination d after the ΔT used for the prediction calculation.

To decide which node the data packet is forwarded to if more than one node fulfills the $\Delta d^{'} \leq R$ prerequisite, the Metric To Connect (MTC) value is calculated:

$$\begin{aligned} \Delta x &= x_r^{'} - x_d^{'} & a &= (\Delta s_x^2 + \Delta s_y^2) \cdot R^2 \\ \Delta y &= y_r^{'} - y_d^{'} & b &= (\Delta s_x \Delta y - \Delta s_y \Delta x)^2 \\ \Delta s_y &= s_{ry} - s_{dy} & c &= \Delta s_x \Delta x + \Delta s_y \Delta y \\ \Delta s_x &= s_{rx} - s_{dx} & & \end{aligned}$$

$$MTC = \begin{cases} \frac{c-\sqrt{a-b}}{a}, & 0 < \Delta d \leq R \\ \frac{\sqrt{a-b}-c}{a}, & R < \Delta d \end{cases} \tag{7}$$

Source: [11]

The MTC value indicates the mobility relationship between nodes. In the first case $0 < \Delta d \leq R$, the nodes r and d are in range both before and after the prediction. This implies a strong correlation in movement and the assigned value is negative to display this condition. In the second case $R < \Delta d$, r and d are only in range in the predicted time step but not before. This signals a possible next hop but shows a historically worse movement corelation as compared to the first case, the assigned value is positive. In both cases the assigned absolute value is relative to the distance between nodes.

The outlined equations are only defined in a two-dimensional scenario, limiting the application area of GPMOR significantly.

6.2. Algorithm

The node discovery process works proactively by each node regularly sending HELLO messages to nearby nodes. These messages contain position and velocity information and are used by each node to maintain a node table. Any sent data packets contain the identifier of the destination node. Each intermittent node transmits the data packet to the best node according to the information in its node table. The algorithm terminates when the destination node is reached. The next hop is selected as follows:

1) The current source node calculates the immediate position of destination and neighboring nodes according to Equations (4) and (5).
2) The distance between destination node and all neighboring nodes is calculated according to Equation (6).
3) Now there are three distinct possibilities depending on how many neighboring nodes fulfill the $\Delta d^{'} \leq R$ condition:

   No node: The neighbors of the current source node are not directly in range of the destination node. An additional relay node is necessary. The neighbor with the smallest $\Delta d^{'}$ is selected.

   One node: This node will be in range of the destination node after ΔT. It is selected as next hop.

Multiple nodes: The MTC value between the affected neighboring nodes and the target node is calculated according to Equation (7). The node with the lowest MTC value is selected as next hop.

4) The next hop calculation algorithm is terminated and the packet is forwarded to the selected node. The selected node is the source node in the next iteration.

GPMOR only considers the currently best next relay node without considering the global situation with potential local but not global optima. This approach is considered greedy.

7. Comparison and Discussion

As MUDOR and GPMOR follow fundamentally different architectures, they also show significantly different characteristics. Table 2 shows an overview of these differences.

TABLE 2: Characteristics of MUDOR and GPMOR.

	TD	NO	BR	SPAR	SCAL
MUDOR	-	+	+	+	+
GPMOR	+	-	-	-	-

+: superior -: inferior

Transmitting delay (TD): Due to its greedy approach GPMOR has no notable transmitting delay as transmission starts instantly. By contrast, MUDOR has to calculate at least one complete route to the target node before being able to start transmission, leading to a significant transmission delay.

Network overhead (NO): As GPMOR has a reactive-based routing approach, exchanging the available network nodes regularly, it has a notably larger network overhead as compared to MUDOR.

Bandwith requirements (BR): As a consequence of its larger network overhead, GPMOR requires significantly more bandwidth as compared to MUDOR.

Network sparsity (SPAR): Due to its greedy approach a GPMOR RREQ can be stuck in a local but not global optimum. Currently GPMOR does not have any failure recovery strategy for this problem and therefore needs a sufficiently dense and convex network to avoid the occurrence of this problem. By contrast, MUDOR is not affected by sparse networks.

Scalabilty (SCAL): Due to its fundamentally proactive approach GPMOR has to manage a node table containing all available nodes in the network. This leads to a significantly worse scaling, especially concerning memory requirements compared to MUDOR which does not have to manage a similar node table.

The outlined significantly different characteristics also lead to different ideal areas of application. To have sufficient doppler shift to be able to avoid significant measurement errors, MUDOR is ideal for networks of fast and linear moving nodes such as larger scale fixed wing UAVs. Xi et al. [12] show that MUDOR does also work with slower moving ground-based nodes but the performance compared to other routing protocols increases with node speed. GPMOR needs a sufficiently dense network that does not violate its size boundaries. Compared to MUDOR it is superior in end to end delay. Therefore, it is optimally suited for dense networks of smaller scale UAVs such as grid focused search and rescue operations which also profit from its excellent end to end delay enabling in-person operation if necessary.

8. Conclusion and Future Work

The unique characteristics of FANETs pose a significant challenge for routing algorithms. This paper introduces a promising approach to solve this challenge, position-based routing protocols. These protocols can be categorized into two main strategies, reactive and greedy-based. A presentation and subsequent comparison of two algorithms following these strategies, MUDOR and GPMOR, shows distinct strengths and weaknesses. This results in complementary ideal areas of application with MUDOR showing superior characteristics for networks of fast moving fixed wing UAVs and GPMOR for dense networks of small scale UAVs.

Future work on the presented GPMOR algorithm could include a more sophisticated movement prediction model allowing the prediction of non-linear and three-dimensional movement. Additionally, the introduction of a route request failure recovery strategy is necessary to overcome the problem of a route request being stuck in a local but not global optimum.

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