Trajectory and Buffer Aware Message Forwarding for Multiple Cooperating UAVs in Message Ferry Networks

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Abstract. This paper presents a Trajectory and Buffer Aware message Forwarding (TaBAF) scheme in message ferry networks with multiple mobility-controlled UAVs. UAVs are basically message ferries with an on-the-fly mobility decision maker to deliver messages between isolated nodes. Besides, UAVs forward messages opportunistically when they visit each other on-the-air. UAVs have only local observation in our network model and do a signaling with each other when they fly into the radio transmission range of each other. The signaling information are the next node that a UAV will visit and its buffer state. TaBAF applies this information in its message forwarding decision and forwards a message to a neighbor UAV if it can deliver the message earlier. The results show that the TaBAF in message ferry networks outperforms pure message ferry approaches and existing message forwarding schemes in terms of end to end message latency. We showed that the TaBAF decreases the average traveling delay of messages in UAVs and this is the reason for its performance improvement. Moreover, TaBAF decreases average flied distance of each UAV in the network by efficient message forwarding.

Keywords: Trajectory aware · Message forwarding · UAV
Message ferry

1 Introduction

In disaster scenarios or sparse sensor networks, message delivery is a challenging task due to disconnections in the network and isolation of wireless nodes. Delay Tolerant Network (DTN) routing approaches can be applied for message delivery in such scenarios. However, if nodes are stationary, messages cannot be delivered to their destinations. Unmanned Aerial Vehicles (UAVs) can be employed in such networks as message ferry nodes to make data communication possible. A UAV, as a message ferry, is responsible to travel among disconnected nodes and deliver their messages.

One of the main properties of a UAV that distinguishes it from other types of wireless nodes is its mobility that be controlled. The flight path of a UAV

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can be planned in advanced (offline path planning) or the UAV can decide it on-the-fly and autonomously. Controlling the mobility of a UAV in a message ferry network improves dramatically the performance of message delivery [1]. Moreover, by employing multiple cooperating UAVs, the latency of message delivery is decreased more [2]. Some challenges are emerged in multi UAV networks such as the coordination of UAVs and collision avoidance between them [4], but UAVs can build an ad hoc network on-the-air and cooperate in message delivery with multi hop communication. In this case, a UAV is not only a message ferry but also it acts as a router to forward messages.

In this paper a Trajectory and Buffer Aware message Forwarding (TaBAF) scheme for multiple cooperating UAVs in message ferry networks is proposed where UAVs act basically as message ferries but they forward messages opportunistically to each other to accelerate message delivery in the network. UAVs decide about their mobility on-the-fly based on their local observations from the state of network [2] and are coordinated applying stigmergy [3]. To cooperate in message delivery, UAVs do a signaling on-the-air when they fly close to each other. The signaling information are the next node that a UAV is flying towards it and the state of its message buffer. The received signaling information from neighbor UAVs are applied in a UAV for its message forwarding decision. TaBAF in a UAV forwards a message to a neighbor if the neighbor UAV can deliver the message earlier.

The results show that TaBAF in message ferry networks with multiple UAVs outperforms pure message ferry approaches which UAVs do not forward messages and existing message forwarding schemes. Trajectory and buffer aware message forwarding between UAVs decreases end to end message delivery latency in a network by decreasing message traveling delay in buffer of UAVs. Moreover, TaBAF decreases the average flied distance for each UAV in the network by efficient message forwarding between UAVs. Average flied distance is the cost for each UAV. To the best of our knowledge, this is the first work that applies trajectory and buffer aware message forwarding in multi UAV based message ferry networks.

The remainder of this paper is organized as follows: we discuss existing work in Sect. 2. In Sect. 3, the network model is described. The on-the-fly next node decision maker in UAVs is presented in Sect. 4. Section 5 introduces signaling between UAVs and nodes. In Sect. 6, we present our trajectory and buffer aware message forwarding scheme. Simulation study and performance evaluations are in Sect. 7. Finally, we conclude the paper in Sect. 8.

2 Related Work

The message ferrying approach was proposed in [5] to deliver messages in disconnected networks. They controlled the mobility a ferry node by an offline path planning. The path planning was same as the solution of Traveling Salesman Problem (TSP) which the main objective is to visit all nodes in the shortest path. [7] is another single ferry approach where a ferry node has a full observation over the network. In [1], authors proposed an on-the-fly decision maker in a ferry with local observations. They showed that an on-the-fly decision making outperforms offline path planning approaches in networks with asymmetric traffic load.

The latency of message delivery increases in large and highly loaded networks with a single ferry. To overcome the limitation of single ferry networks, several architectures for multi ferry networks was proposed in [8]. Ferries mobility decision, coordination and cooperation of ferries were out of the scope of this work. In [9], authors proposed a multi ferry approach with local observations in ferries. The mobility decision in ferries was based on the mobility of nodes. An on-the-fly decision making for multi ferry networks was proposed in [2] that ferries decide the next node to visit on-the-fly after visiting a node and exchanging data and control messages. Ferries have only local observations in their assumptions. Therefore, the coordination of ferries was done applying a stigmergic communication among ferries by leaving traces in nodes. Exiting multi ferry works are pure message ferry networks where the possibility of message forwarding among ferries is neglected.

As mentioned in Introduction, UAVs are mobility controlled wireless nodes which can be considered as a realization of message ferries. In multi ferry networks, message forwarding among UAVs is possible and UAVs are not only message ferries but also routers that can forward messages.

A hybrid DTN/geographical routing approach for multi UAV networks has been proposed in [10] that the message forwarding decision is made based on an estimation about the future location of UAVs. They apply the speed and mobility direction of UAVs in their estimations. Moreover, they assume a long range communication in UAVs that provides a full observation of the network in each UAV. Their message forwarding scheme cannot be applied in networks with local observations in UAVs. The authors in [11] also proposed a geographical routing protocol that estimates a UAV link life time using the mobility direction and speed of a UAV. The mobility of UAVs are not controlled in this work and UAVs are used as opportunistic relays.

Existing work are either pure message ferry networks without any message forwarding between ferries or consider a full observation in UAVs. A message forwarding scheme for multiple cooperating UAVs with an on-the-fly mobility decision making which each UAV has only a local observation in message ferry networks is required.

3 Network Model

3.1 Assumptions

In our network model, wireless nodes (N) are of two types; regular nodes ($R \subset N$) and UAVs that can act as data ferries or routers ($F \subset N$). From now on, we call regular nodes only ‘nodes’. Nodes are stationary and isolated. Therefore, no direct communication between any pair of nodes is possible. The location of nodes is given to UAVs. Nodes are producer (generator) and consumer (receiver) of messages. They generate messages with a variable rate. UAVs are wireless nodes that act basically as message ferries with controlled mobility. They can forward messages between each other, either. UAVs only carry messages or forward them and do not generate any message. UAVs always travel with a constant velocity. Moreover, we assume an unlimited buffer size in UAVs and nodes.

To model opportunistic visits of UAVs on-the-air for message forwarding, we assume a constant radio transmission range for UAVs such that they can communicate if they come into the range of each other. Moreover, the required time for a UAV to travel among nodes is much longer than the required message transmission time (T_{tx}) between wireless nodes. Thus, we neglect T_{tx}.

$$T_{travel}(i, j \in R) \gg T_{tx} \tag{1}$$

In our network model, there is no direct communication among all UAVs while their radio transmission range is limited. UAVs can only communicate when they are in the radio transmission range of each other. Therefore, A UAV has no global knowledge about the network and can only observe the network locally when it visits a node or another UAV. During a UAV visit to a node or another UAV, several steps occurs sequentially that will be described in the next section.

3.2 Steps of a UAV Visit

In our multi UAV based message ferry network, UAVs travel between nodes and when they visit a node or another UAV several steps are triggered and run as follows:

1. Exchange control information (signaling)
2. Exchange data messages
   (a) If the UAV visits a node, it collects all messages from the node's buffer and delivers all messages for which the current node is the destination
   (b) If the UAV visits another UAV, it decides to forward all or part of its buffered messages based on the received signaling information
3. Decide the next node to visit using the on-the-fly decision maker in the UAV
4. Travel to the next (decided) node

In the next sections, we describe steps in more details.

4 On-the-Fly Next Node Decision Maker in UAVs

To control the mobility of UAVs, an on-the-fly decision maker similar to [2] is applied. The main goal of the decision maker is to make on-the-fly decisions in a UAV about the next node to visit. The decision maker works only based on the local observations of a UAV and the history of nodes that a UAV keeps in its memory. Each UAV applies a *Score* function for its mobility decision. A score is calculated in a UAV for each node r and a node with the maximum $Score(r)$ value is selected as the next node to visit. The *Score* for each node r is calculated as follows:

$$Score(r) = \frac{mb(r) + hist(r)}{d(c, r)} \tag{2}$$

where $mb(r)$ is a function that returns a normalized value based on the number of waiting messages in the UAV buffer for the destination r. The second function is based on the history of nodes in the UAV. Each UAV keeps the history of its last visit time to all nodes and applies it in its decision maker. $hist(r)$ returns a normalized value for the node r based on the last visit time of a UAV to the node r. The function $hist(r)$ returns a bigger value for a node r which has been visited a long time ago than a node which has been visited recently. This function avoids any visit starvation in nodes and frequent visits of the node in a short time window. $d(c, r)$ in *Score* function is the distance between the current node c that the UAV is visiting and a candidate next node r.

5 Exchange of Control Information

In the proposed multi UAV based message ferry network in this paper, a UAV signals some control information with nodes or other UAVs in the network when it visits them. Signaling information are different in a visit of a UAV to a node or to another UAV. The signaling information are applied later in the mobility decision maker of the UAV and its message forwarding decision.

5.1 Signaling Between UAV and Node for Stigmergic Coordination of UAVs

As mentioned in Sect. 4, to avoid frequent visits of UAVs to a node and visit starvation in nodes, each UAV keeps a history of its last visit time to all nodes. Same as UAVs, each node keeps a history table that contains the last visit time of all other nodes. As the nodes are stationary in our network, the history information is about the visits of UAVs to nodes. During a UAV visit to a node, the UAV and the node exchange their last visit time history table and update their tables with more up-to-date information.

As UAVs have not a long range communication in our network, they cannot signal this information directly to each other. Therefore, UAVs are coordinated using a stigmergic communication in a form of an indirect signaling. Indirect signaling among UAVs is formed when each UAV does a signaling with nodes. In other words, a UAV leaves traces in nodes (environment) and take existing traces from them. A node acts as a relay for UAVs to exchange their control information.

5.2 Signaling Between UAVs

Another type of signaling occurs in a UAV visit to another UAV on-the-air when two UAVs fly into the radio transmission range of each other. There are two types of information in this signaling that are applied in the message forwarding decision of UAVs and are as follows:

1. The mobility decision of UAV: It is the output of the on-the-fly next node decision maker in the UAV.
2. State of message buffer in UAV: It is the number of buffered messages for each destination in a UAV and reflects future nodes that the UAV will visit.

6 Trajectory and Buffer Aware Message Forwarding

In our network, multiple UAVs are employed as message ferries to deliver messages between disconnected nodes. Besides, there is a possibility for message forwarding between UAVs if they visit each other on-the-air. Therefore, UAVs are not only message ferries but also flying wireless routers. Different metrics can be applied in message forwarding decision between two visiting UAVs. In this paper, we propose a trajectory and buffer aware message forwarding scheme that UAVs exploit the signaling information that they exchange with each other (see Sect. 5.2). The message forwarding decision is done in each UAV during an on-the-air visit to a neighbor UAV in two steps as follows:

1. In the first step, each UAV uses the trajectory information of neighbor UAVs that it has received during signaling. The trajectory information is the next node that the on-the-fly decision maker in Sect. 4 has decided for a UAV. The UAV forwards all message for which the neighbor UAV is flying directly towards the destination of messages. In case which both UAVs fly to the same destination, the UAV forwards messages if the neighbor UAV is closer to the destination. After forwarding messages to a neighbor UAV, if the UAV has not any message to deliver to its next visiting node, it runs the on-the-fly next node decision maker and may change its trajectory.
2. In the second step, the UAV applies both trajectory and buffer information of the neighbor UAV to forward more messages. In the first step, the UAV forwards all messages which the neighbor UAV will fly directly to their destination. In this step, the UAV may forward more messages even if the neighbor UAV will not fly directly to the destination of messages but the trajectory and buffer state of the neighbor UAV meet two conditions as follows:
   (a) The first condition is based on the traveling direction of UAVs. The first condition is met, if a UAV is going to fly away from the destination of a message while the neighbor UAV will fly to a node that is closer to the destination of message.
   (b) A UAV forwards a message to a neighbor UAV if the first condition is met and only if the neighbor UAV has messages in its buffer to the same destination of the message. If the both conditions are met for more than one neighbor UAV, the message is forwarded to the neighbor with highest number of buffered messages with the same destination address.

As all UAVs apply the on-the-fly decision maker in Sect. 5 for the next node to visit and the decision maker applies $mb(r)$ and $distance(c, r)$ functions in its decision function, the neighbor UAV will visit the destination of a message earlier than the UAV that has buffered the message if both conditions (a and b) are met.

7 Simulation Study

In this section, we evaluate and study the performance of proposed message forwarding scheme in multi UAV based message ferry networks. To do this, we developed a Python based simulator.

We simulate message ferry networks with 10 nodes where nodes are placed randomly with a uniform distribution. The position of a node is limited to a $1000 \times 1000\,\text{m}^2$ area. Message generation in nodes has a variable rate. It starts at $t = 0$ and runs for 1000 s. Then, the simulation is continued till delivery of all messages. The traffic load in the network is asymmetric. Message generation rate in nodes can be classified into four classes which are very high rate (20% nodes), high rate (20% of nodes), normal rate (50% of nodes) and no message generation (10% of nodes) with mean inter-message arrival time of 1 s, 3 s, 5 s, ∞, respectively. Moreover, UAVs start their travel from different nodes with a constant velocity of 5 m/s and their radio transmission range is assumed 10 m. We run the simulation 10 times for each algorithm. In each run the topology of the network, i.e. the placement of nodes is different. We compare the proposed trajectory and buffer aware message forwarding scheme with a pure message ferrying approach and three other message forwarding schemes in multi UAV based message ferry networks. Different message delivery approaches in our comparisons are as follows:

1. Pure Message Ferry (Pure MF) [2,3]: It is a pure message ferry approach for multi UAV networks where UAVs are only ferries and there is no message forwarding between them.
2. Greedy forwarding (GF) [6]: It is a multi UAV based message ferry network where the message forwarding between UAVs is enabled. A UAV forwards a message to its neighbor UAV if the neighbor is closer to the destination of message.
3. Mobility Direction based Forwarding (MDF) [10,11]: In MDF message forwarding between UAVs in a message ferry network is done based on the mobility direction of UAVs.
4. Trajectory Aware Forwarding (TAF): It is a message forwarding scheme that is proposed in this paper for multi UAV based message ferry networks and will be used in our comparisons. The message forwarding decision in TAF is done only based on the trajectory information of a neighbor UAV that has been received during signaling. Trajectory information is the next node that the UAV will visit. TAF has only the step 1 in message forwarding which was mentioned in Sect. 6.

5. Trajectory and Buffer Aware Forwarding (TaBAF): TaBAF is our proposed message forwarding scheme in this paper which considers trajectory and buffer information of UAVs to forward messages.

The mobility decision in UAVs for all 5 approaches are made based on the on-the-fly next node decision maker in Sect. 4. In Pure MF, there is no singling between UAVs. In GF and MDF, UAVs exchange only their position information and mobility direction. Signaling between UAVs in TAF and TaBAF is same as Sect. 5.2.

Figure 1 shows the end to end latency of messages in five different approaches. The end to end latency of a message refers to the time difference between a message generation in its source and the delivery of message at its destination. The results show that enabling message forwarding between UAVs decreases end to end delay of message delivery in a message ferry network. TaBAF outperforms all approaches. TAF has the closest results to TaBAF, but TaBAF decreases maximum message delay and dispersion of delays. TaBAF forwards a message if the neighbor UAV will deliver the message earlier even if it will not fly directly to the destination of the message. TAF forwards messages only if the neighbor UAV will fly directly to the destination of messages and looses the opportunity of earlier delivery of some messages by neighbor UAVs. MDF and GF are better than Pure MF but median for delays, maximum delay and dispersion of delays are worst than TaBAF and TAF. In GF, a message is forwarded to a neighbor UAV which is closer to the destination of the message but it is flying away from the destination. MDF considers only the mobility direction and a message may be forwarded between several UAVs without considering the final destination of UAVs. MDF applies the short term mobility information of UAVs in its decision which causes inefficient decisions.

The end to end message latency consists of two components. Message waiting delay is the waiting time of a message in a node buffer till its collection by a UAV- $delay_{wait}$ and message traveling delay is the time that a message travels in a UAV after its collection from the source node till delivery to the destination- $delay_{travel}$.

$$Delay_{e2e} = delay_{wait} + delay_{travel} \tag{3}$$

In Figs. 2 and 3, we show the impact of different approaches on the average message traveling and waiting delay employing 1 to 7 UAVs. It can be seen that different message delivery schemes have not any impact on the average message waiting delay. Message waiting delay decreases by increasing number of UAVs in all approaches. On the other hand, message forwarding impacts mostly on the average message traveling delay. Message traveling delay decreases slightly by increasing number of UAVs in Pure MF. Increasing number of UAVs impacts message traveling delay dramatically if message forwarding between UAVs is enabled like MDF, GF, TAF and TaBAF. TaBAF has the least message traveling delay because a UAV forwards messages to a neighbor if the neighbor can deliver them earlier even if the neighbor will not fly directly to the destination of messages. This strategy decreases the average message traveling delay in the

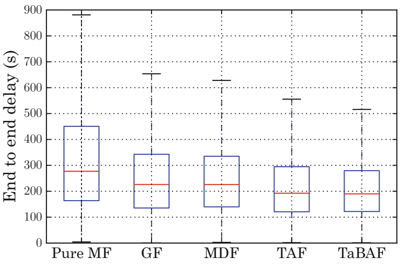

Fig. 1. Average end to end delay of messages.

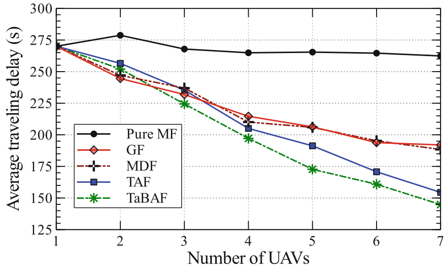

Fig. 2. Average traveling delay of messages in the buffer of a UAV.

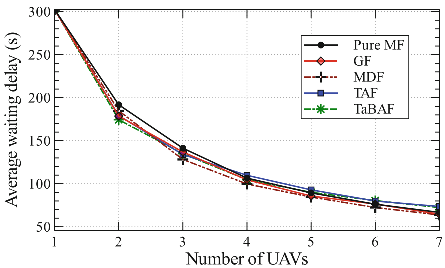

Fig. 3. Average waiting delay of messages in the buffer of a node.

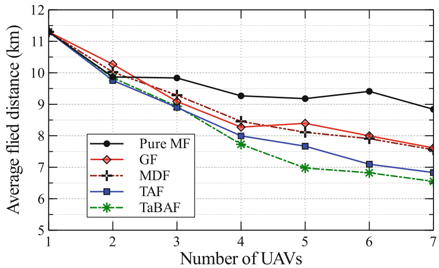

Fig. 4. Average flied distance of a UAV to finish its mission.

network. As mentioned before, TAF takes into account only the next node of a neighbor UAV and does not forward messages if the neighbor UAV will not fly to the destination of messages directly. For this reason, some messages may not be forwarded and have to travel longer in the UAV. MDF and GF show similar average message traveling delay. MDF and GF do not choose the best neighbor UAV which can deliver a message earlier and this causes longer message traveling delays comparing with TAF and TaBAF.

Figure 4 illustrates the average flied distance of each UAV in the network to deliver all generated message (message generation runs for 1000 s). The flied distance of a UAV is the cost that each UAV pays to deliver messages. By applying message forwarding between UAVs in a message ferry network, the cost decreases. However, the cost in TAF and TaBAF is less than GF and MDF due to the efficient message forwarding decisions which avoid message forwarding to a neighbor UAV if a UAV itself can deliver messages earlier. However, the flied distance of a UAV is less in all approaches which apply message forwarding between UAVs than a pure message ferrying.

8 Conclusion

In this paper, we proposed a trajectory and buffer aware message forwarding scheme for multi UAV based messages ferry networks where UAVs cooperate in message delivery by forwarding messages between each other. We introduced an exchange of trajectory and buffer state information between UAVs in form of a signaling when they visit each other on-the-air. Our proposed message forwarding scheme in a UAV exploits signaling information and forwards a message to a neighbor UAV if it can deliver the message earlier. By efficient message forwarding, we decreased end to end message delay in message ferry networks and average flied distance of each UAV which is the cost for a UAV to deliver messages. Moreover, a UAV may replicate messages in nodes or other UAVs to accelerate message delivery. This is our future work.

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