Study on the Network Architectures for Message Ferry Networks with Multiple UAVs

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***Abstract*—In networks with disconnected and stationary wireless nodes, a "message ferry" is employed to make the communication possible. The message ferry node travels among isolated nodes in the network and delivers their messages. A UAV with a communication interface is the realization of a message ferry node. It flies between nodes and exchanges their messages. This paper presents a study on the performance of different network architectures for message ferry networks with multiple UAVs. The architectures are explained and compared in terms of the average delay of message delivery considering different scenarios. The considered scenarios are networks with different number of nodes, different number of ferry UAVs and different traffic models. The results show that the best architecture to apply in message ferry networks with multiple UAVs depends on the traffic model and the size of network w.r.t. the number of nodes and ferries.**

I. Introduction

Wireless nodes have limited radio transmission ranges. They are disconnected when their distances are further than the transmission range. Sparse sensor networks, where sensor nodes are placed in vast areas like forests or mountains to measure and send data, are examples for such a situation. Another example is a disaster scenario with isolated wireless nodes, where nodes need to communicate and the network infrastructure is collapsed. Delay Tolerant Networks (DTNs) routing protocols employ the store-carry-forward mechanism to overcome the disconnection of nodes and deliver their messages. However, this mechanism fails in networks with stationary nodes. A message ferry network is the solution for such a problem. A mobile node is employed as a message ferry to travel among isolated and disconnected wireless nodes and deliver their messages.

Unmanned Aerial Vehicles (UAVs) can be employed in message ferry networks as message ferries. They fly among isolated wireless nodes, collect and deliver their messages. The mobility of a message ferry impacts on the performance of message delivery in message ferry networks. Employing a UAV as a message ferry in disconnected networks makes the data communication possible. Furthermore, controlling the mobility of a message ferry UAV improves the delivery delay of messages [1]. The mobility of a UAV can be controlled by a given flight path (offline path planning) or the UAV can decide it on-the-fly. In large networks w.r.t. the number of nodes, employing a single UAV as a message ferry causes long delays in delivery of messages while the speed of a UAV is limited. Therefore, employing more UAVs can decrease the latency of message delivery.

The problem of path planning for a single message ferry UAV and multiple message ferry UAVs can be modeled as the Traveling Salesman Problem (TSP) and its variant the multiple TSP (mTSP), respectively. In the TSP, the objective is to find the shortest path for a salesman to visit all the given cities only once. The solution finds the optimal sequence of cities to be visited by the salesman. In the mTSP, there are multiple salesmen. The cities must be visited only once and the total traveled distance of all salesmen must be minimum. The solution for the mTSP assigns a subset of cities to a salesman and defines the sequence of assigned cities to visit. The TSP is NP-complete which cannot be solved in polynomial time. The mTSP is more complex than TSP and NP-hardl. Therefore, heuristic methods should be applied to approximate the optimal solution for these problems.

This paper presents different architectures for message ferry networks with multiple UAVs, which act as message ferries, and compares them considering different scenarios. In comparisons, the average delay of messages applying the network architectures is calculated. In the compared architectures, the TSP and mTSP are utilized to model the UAVs path planing problem and the genetic algorithm is used to approximate the optimal path planning solution. As this paper focuses on the performance of networks architectures, the genetic algorithm for the path planning is not discussed here. An architecture for a message ferry network defines the message delivery approach between nodes which can be done with a single hop, multi hop or through relaying. The architectures are compared in scenarios with different number of nodes, different number of message ferry UAVs and different traffic models in multi ferry networks. The results show

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that the best architecture to apply depends on the traffic model and the size of the network with respect to the number of nodes and ferries.

The remainder of this paper is organized as follows: existing work is explained in Section 2. In Section 3, we describe the network model. Multi ferry network architectures are introduced and discussed in Section 4. Section 5 is the simulation study and comparison of different network architectures. Finally, we conclude the paper in Section 6.

II. Related Work

In [2] and [3] offline path planning was applied to control the mobility of a ferry in single ferry networks. They modeled the problem as TSP and found the route with minimum traveled distance for the message ferry.

To overcome limitations of a single ferry network in large and highly loaded networks, different architecture were proposed in [4] to establish a multi ferry network. However, they did not study on message ferry networks with optimized path planning for message ferries and different traffic models.

As mentioned earlier in this paper, the problem of path planning for multiple message ferries can be modeled as mTSP. Several works were proposed to solve the mTSP which optimize the total traveled distance of salesmen [5], [6], [7]. However, they did not consider a communication network and did not evaluate the different message delivery approaches in terms of the message delivery delay.

The authors in [8] and [9] proposed solutions for path planning of multiple mobile data collectors. However, their work is limited to networks where all sensor nodes generate messages only to a sink node and their optimization goal is to minimize the traveled distance of the mobile collectors. Moreover, they did not study on possible network architectures.

On-the-fly decision making for the mobility of ferries was proposed in [1], [10], [11], [12], [13]. With on-the-fly decision making for mobility of ferries, there is no predefined path for ferries and they decide the next node to visit during their flight.

There is no work in the literature that studies different message delivery approaches (architectures) in multi ferry networks where the path is optimally planned for ferries and all nodes need to exchange messages.

III. Network Model

In our work, the network is modeled as follows: wireless nodes (W) are of two types; isolated wireless nodes ($N \subset W$) and UAVs which act as message ferries ($F \subset W$). From now on, we call isolated wireless nodes only 'nodes' and message ferry UAVs only 'ferries'.

Nodes are stationary and isolated. They are not able to communicate while they are located far from each other. Message ferry UAVs are the only mobile nodes in the network. The geographical position of nodes are known and given to the ferries. Ferries travel among nodes, collect, deliver or forward messages. The flight path of UAVs is planned offline to improve the performance of message delivery in the message ferry network. The TSP and mTSP are applied to model the ferries path planning problem and they are solved using the genetic algorithm in [5] as a heuristic to approximate the optimal solution. As the main objective of this paper is the comparison of different message ferry network architectures, the path planning is not discussed here.

Ferries do not generate any message and only carry the generated messages in nodes. The message generation only occurs in nodes. We assume two traffic models in our studies. In one of the models, nodes generate messages only to a sink node. Another model is a general traffic model where each node can generate messages to any other node in the network including the sink node.

As the size of message ferry networks are large and distances between nodes are long, several assumptions are done in this paper to compare different multi ferry network architectures. The assumptions are as follows:

- The radio transmission range for nodes and ferries is considered as zero while the travel distance of ferries between nodes is much longer than their radio transmission ranges. Therefore, it can be neglected ($tx_{range} = 0$).
- The transmission delay is also much shorter than the travel delay of ferries. Therefore, the transmission delay can also be neglected ($D_{tx} = 0$).
- The buffer size is also considered as unlimited in both nodes and ferries for the simplicity.

IV. Multi-Ferry Network Architectures

In this section, three different network architectures for message ferry networks with multiple UAVs are explained.

A. Single route for multiple ferries

In this type of multi ferry networks, an optimal path is planned for all ferries in the network. The path planning is done by modeling the problem as the TSP. Then, the path is planned in such a way which the length of path is minimum and all nodes are visited only once. Having the planned path, all ferries follow the same path but start their tour in different times. In a simple case, ferries can keep an equal distance from each other to start their tour. In this architecture, all ferries start and finish their tour from a sink node (or depot). At the end of a tour, the ferry starts again a new tour following the planned path. The following relation shows the distance between ferries.

$$Distance = \frac{len(Tour)}{|F|} \tag{1}$$

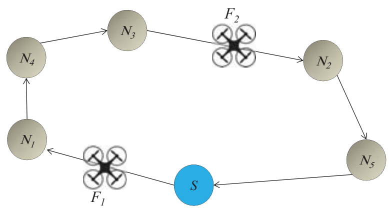

Fig. 1. The SRMF architecture with two UAVs as message ferries

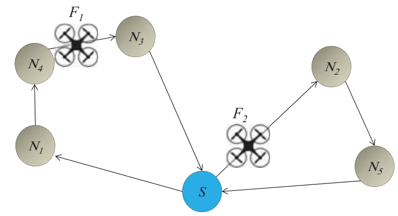

Fig. 2. The MRMF architecture with two UAVs as messages ferries and two clusters

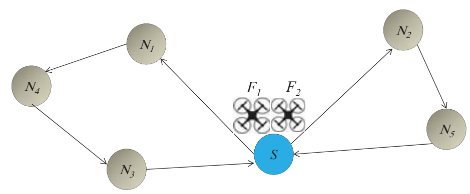

Fig. 3. The MRMF-R architecture with two UAVs as message ferries and the sink node location for rendezvous

where $|F|$ is the number of ferries in the message ferry network. The time difference (TD) between two consequent ferries is as follows:

$$TD = \frac{Distance}{v} \tag{2}$$

where v is the velocity of ferries. Each ferry starts its tour from the sink node TD time unit (seconds) after the last ferry. In this architecture, each messages is collected by a ferry node and is delivered by the same ferry. This means, there is no message forwarding between ferries or message relaying through nodes. Figure 1 shows the Single Route for Multiple Ferries (SRMF) with two ferries.

B. Multiple routes for multiple ferries

To plan the path for multiple ferries, the problem is modeled as the mTSP. In mTSP, each salesman visits a subset of nodes. The constraint in this problem is same as TSP which each city must be visited only once. The goal of optimization is also to find a solution which the sum of all traveled distances by salesmen is minimum. For a message ferry network with multiple message ferries, each message ferry starts and finishes its tour from a sink node. Each ferry visits only a subset of nodes. We call the subset of nodes a "cluster". The sink node is employed as a relay to forward messages among clusters. Therefore, a message may be carried by more than one ferry if the source and destination of a message are not in the same cluster. In this case, the message is collected by a ferry in the source cluster and is delivered to the sink. It waits in the sink node to be collected and delivered by the second ferry in the destination cluster. Figure 2 shows the Multiple Routes for Multiple Ferries (MRMF) with two ferries and two clusters.

C. Multiple routes for multiple ferries with a rendezvous

In both SRMF and MRMF architectures, ferries start and finish their tours from the sink node. At the end of each tour, a ferry starts immediately a new tour without any stop (waiting). In the SRMF, a message is delivered by the ferry which has collected the message and in the MRMF the message is relayed by the sink node between clusters. In Multiple Routes for Multiple Ferries with a Rendezvous (MRMF-R), the problem is modeled as mTSP same as MRMF. In MRMF-R, ferries make a rendezvous on-the-air to exchange (forward) their messages if messages should travel from one cluster to another cluster (source and destination of a message are in different clusters). Therefore, all ferries wait in a predefined location to visit each other and exchange messages if needed. When the rendezvous is done, ferries start again a new tour to visit the nodes in the assigned cluster. The ferry with longest tour has no waiting for the rendezvous and the ferry with the shortest tour has the longest waiting time. As the ferries start and finish their tour from the sink node, the rendezvous can take place in the location of sink node. Figure 3 shows the MRMF-R architecture with two ferries and two clusters. The ferry F_1 has a longer tour than F_2. Therefore, F_2 must wait at the location of sink node to visit F_1 each time it finishes its tour.

V. Simulation Study

To compare different architectures for message ferry networks with multiple ferry UAVs, we implemented a simulation model in Python. The comparisons between existing architectures take place considering different scenarios as follows:

1) Average delay of message delivery in different network architectures with constant number of nodes and increasing number of ferry UAVs
2) Average delay of message delivery in different network architectures with constant number of ferry UAVs and increasing number of nodes

3) Performance of different network architectures with different traffic models

Two different traffic models are considered in our study. In both models, the message generation rates in nodes are constant and traffic flows are as follow:

1) All2sink model: All nodes may generate messages only for the sink node. In this model, nodes generate messages to a sink node (as the destination of messages) as follows: 20%: 1 msg/s; 60%: 5msg/s and 20%: 10 msg/s.
2) All2all model: Each node may generate messages to any other node in the network including the sink node. The nodes generate messages to the sink node with rates same as the previous model and generate messages to each other with following rates: 60%: 0 msg/s; 10%: 5 msg/s, 10%: 10 msg/s, 10%: 50 msg/s and 10%: 100 msgs/s .

We run the simulation 40 times for each architecture and configuration. In each simulation run, the nodes were placed randomly with a uniform distribution. All ferry UAVs start and finish their tour in a sink node. Ferry UAVs fly always with a constant speed of 1 m/s.

To solve the TSP and mTSP, the genetic algorithm is applied to find the shortest tour to visit all nodes once in the SRMF architecture and to minimize the total travel distance of all ferry UAVs in MRMF and MRMF-R architectures. Figure 4 shows the average delay of message delivery for the SRMF, MRMF and MRMF-R architectures considering the all2sink traffic model in networks with 20 nodes and 2 to 10 ferries. For the all2sink traffic model, MRMF shows the best performance while it assigns a subset of nodes to each ferry and the ferry travels between the assigned cluster and the sink node. For the all2sink model, this is an ideal case while all nodes generate messages to the sink node. SRMF is the worst architecture for this traffic model. In SRMF, each ferry must visit all nodes in the network. Thus, it must finish its tour to travel back to the sink node and deliver the messages. In this architecture, messages to the sink node must travel for a long time in a ferry. In MRMF-R, a ferry visits a subset of nodes and travels back to the sink. However, a ferry must wait in the location of sink node for the rendezvous to visit other ferries and exchange message. For this traffic model, the rendezvous is useless while all message should be delivered to the sink.

Figure 5 illustrates the average delay of message delivery considering the all2all traffic model. For this traffic model, MRMF-R and MRMF show similar performance with less number of ferries. With increasing number of ferries, MRMF is a better architecture while it does not impose extra delay for messages which the source and destination are inside one cluster. SRMF is still the worst approach due to the long travel delay of messages.

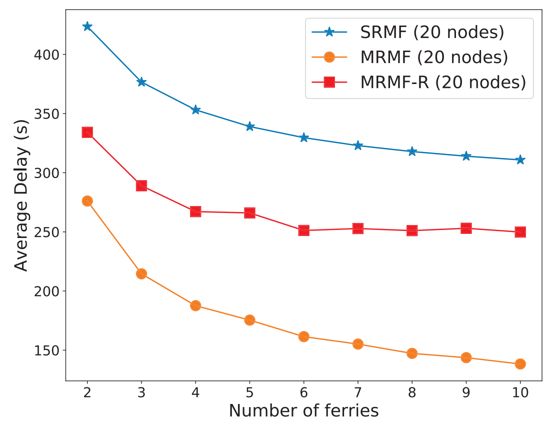

Fig. 4. Comparison of different network architectures with increasing number of ferries considering all2sink traffic model

In the next study, we evaluate the performance of network architectures with increasing number of nodes having limited number of ferries in the network considering the mentioned traffic models. Figure 6 shows the average delay for the all2sink model in networks with different number of nodes. As it is seen, MRMF is still the best approach while ferries only visit a subset of nodes and travel back to the sink. SRMF is better than MRMF-R for small networks. However, when the number of nodes increases, the tour time of ferries increases. This imposes long delivery delay in SRMF. It is seen that in networks with more than 15 nodes, the MRMF-R is a better approach than SRMF.

Figure 7 compares the multi ferry network architectures with different number of nodes considering the all2all traffic model. For this traffic model, in networks with less number of nodes, the SRMF is the best approach while it may deliver messages between nodes without relaying them through the sink node and the tour time for the ferries is not long due to the number of nodes. Thus, messages to the sink node will not experience long delays in SRMF. However, the MRMF and MRMF-R are better architectures in networks with higher number of nodes while the tour time of ferries increases in SRMF.

VI. Conclusion

In this paper, different network architectures for messages ferry networks, where UAVs are employed as message ferries, were studied. The studies on the network architectures were done considering different number of nodes, ferries and different traffic models. The results show that the single Route for Multiple Ferries (SRMF) works good if small number of nodes exchange messages employing a limited number of ferries. In other cases, Multi Route for Multiple Ferries (MRMF) is most of the times best approach. The MRMF with Rendezvous

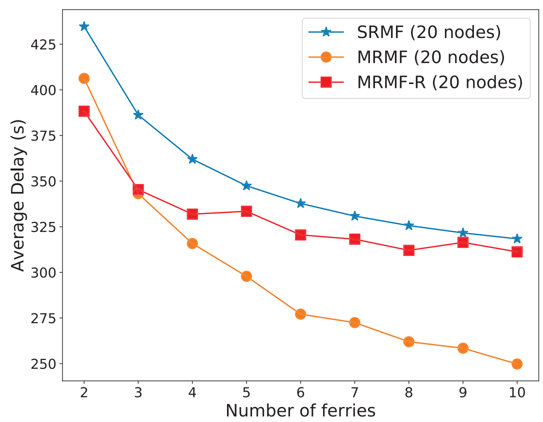

Fig. 5. Comparison of different network architectures with increasing number of ferries considering all2all traffic model

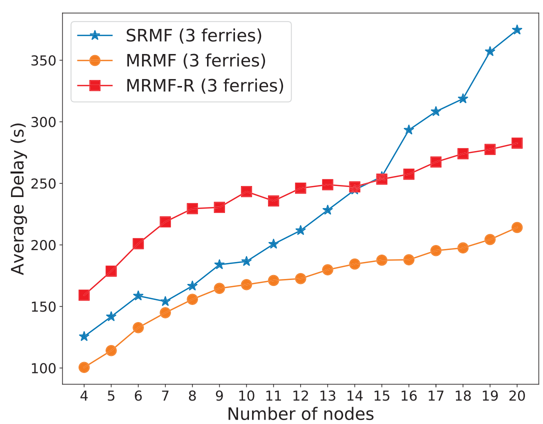

Fig. 6. Comparison of different network architectures with increasing number of nodes considering all2sink traffic model

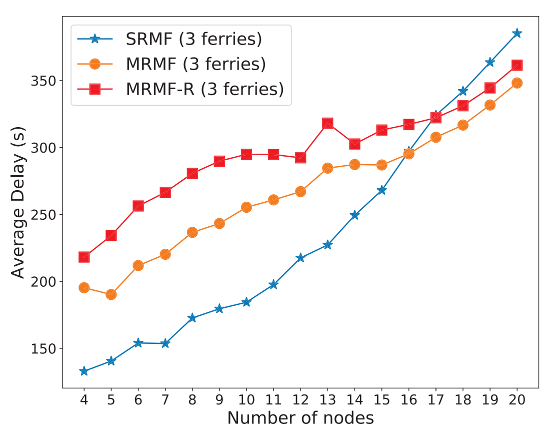

Fig. 7. Comparison of different network architectures with increasing number of nodes considering all2all traffic model

(MRMF-R) imposes extra delay in delivery of messages and is usually worse than MRMF. Therefore, it can be concluded that relaying messages through the sink node is a better approach than a rendezvous of UAVs to forward (exchange) messages. The lesson that we learned through our study is that the best architecture to apply in multi ferry networks depends on the traffic model and size of the network with respect to the number of nodes and ferries.

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