Localization and Energy-Efficient Data Routing for Unmanned Aerial Vehicles: Fuzzy-Logic-Based Approach

Fekher Khelifi, Abbas Bradai, Kamal Singh, and Mohamed Atri

Abstract

Localization and energy efficiency is very important for UAVs. In this work, we propose a new mechanism for data routing based on localization in GPS-denied or GPS-challenged areas. The proposed mechanism relies on a weighted centroid localization technique, where the position of unknown UAV nodes are calculated using fuzzy logic. The UAV nodes are organized into clusters. The proposed localization algorithm first localizes the UAVs, then elects the next cluster head in order to minimize the energy consumption of the whole network and consequently increase its lifetime. Evaluation of the proposal shows that it is more efficient than the existing solutions in terms of energy consumption, localization accuracy, localization time, and data transmission.

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Introduction

In recent years, collaborative unmanned aerial vehicles (UAVs) are used in many civilian and military fields such as search and rescue missions, border surveillance, aerial mapping, agricultural imaging, and so on [1]. In this context, growing interest is being paid to the necessity of UAVs' autonomy in terms of navigation as well as in terms of energy, especially when acting in complex environments, both indoors and outdoors. Given a wide and open outdoor area, where the satellite signal is well received, the use of GPS is sufficient to ensure the autonomous safe navigation of the UAV. However, in many scenarios such as urban monitoring in bad weather conditions, the GPS signal could be totally absent (indoors) or insufficient due to different causes such as multipath fading and jamming. In such situations, alternative soft and/or hardware solutions should be proposed in order to ensure reliable positioning for the UAVs [2]. In addition to the positioning autonomy of UAVs, the limited capability of UAVs in terms of computing makes the preservation of energy an important challenge.

In this work, we focus on the scenario of natural disaster, such as Hurricane Katrina in the U.S. Gulf Coast in 2005, which caused a wide communication infrastructure collapse, where much of the backbone network for landlines was flooded out and cell towers were put out of commission. Furthermore, the satellites can also communicate between the ground station and the UAV in mono-UAV systems. For multi-UAV systems, each UAV may communicate with the base station through a satellite. Thus, communications between UAVs can also work in the same way. However, this approach has some weaknesses, such as the high latency of transmission and the cost of launching the satellite. In addition, the UAVs and the control station must be in line of sight of the satellite. Indeed, for certain missions, trees or buildings may act as obstacles and cause communication problems between UAVs and their relay satellites. Moreover, the performance of satellite systems is related to the emission power of ground transmitters, which can be a disadvantage for UAVs that are teamed with low-capacity batteries. In such scenarios, there is an urgent need for a fast deployment of a communication network. Toward this goal, we propose a fully autonomous system based on a fleet of autonomous collaborative UAVS, as illustrated in Fig. 1.

In this context, we propose a new mechanism for routing information based on UAVs' locations. The mechanism is described as follows:

- The locations of unknown UAVs are calculated using fuzzy logic inference depending on the received signal strength indication (RSSI) values between the UAVs and the anchor nodes.
- Additionally, in order to reduce the energy consumption and to extend the network lifetime, we organize the network on a set of clusters, and we introduce a new strategy to select the next-hop cluster head (CH) based on UAVs' locations estimated by the localization algorithm.
- The proposal considers the following parameters: the current CH's energy level at a given moment, the next elected CH's density, the distance between the current and next elected CHs, and the distance between the base station (BS) and the next elected CH.

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Digital Object Identifier: 10.1109/MCOM.2018.1700453

 0163-6804/18/$25.00 © 2018 IEEE

Figure 1. Example of an emergency communication network based on an autonomous decentralized UAVs.

UAV Localization and Data Routing Mechanisms: An Overview

UAV Localization

For localization, both "range-based" and "range-free" algorithms are interesting in solving several requirements related to the criteria of accuracy as well as low cost [3]. Range-based localization techniques are based on measurement of the distance as well as the angle between the directions of reference nodes called anchors. Several technologies [4] allow this measurement using the RSSI, the time of arrival (TOA) [4], the time difference of arrival (TDOA), and the angle of arrival (AOA) .

Trilateration or range-based localization triangulation [3] can be used to calculate node positions. Nevertheless, they may not be applicable in the context of UAVs; Trilateration is costly as it consumes energy, and the accuracy of range-based localization is affected by several parameters such as propagation, humidity, and noise. The above shortcomings can be greatly overcome by using range-free localization. It should be noted that there are two types of nodes. Anchor nodes are the ones whose position, fixed or mobile, is known. Normal nodes are the ones whose positions are unknown. Normal nodes estimate their positions using the information about connectivity and the positions of the anchors. Range-free technique is more beneficial due to the independence of the hardware devices and the distance computing.

Hence, this independence allows for the adoption of different wireless transmission technologies. In the literature, there are many range-free localization methods such as centroid and vision-based [5]. A positioning system based on the RSSI between the safety gauge tags and an interrogation station mounted inside a UAV is proposed in [6]. The localization is based on the weighted mean squares (LMS) algorithm. Another localization approach is proposed by Uluskan *et al.* [3]. Their system finds the position of a signal transmitter by means of a mini UAV (m-UAV) with a sensor node that can record the power of the received signal strength (RSS) and the GPS data. The RSS and GPS data are instantly transferred to the central node to perform real-time positioning and tracking. The use of GPS devices is not a valid solution to some localization problems for many reasons. With the inclusion of a GPS device, the size of the sensor nodes becomes quite large and expensive, which is inconsistent with the wireless sensor node (WSN) requirement that the nodes should be small. Moreover, the estimated distances using the RSSI values are not accurate due to the noisy nature of RSSI. For this reason, we propose a method based on the Sugeno blur system and the measurement of RSSI to calculate the weights of the edges. After calculating the weights of the edges, we use the weighted centroid localization algorithm to estimate the position of the UAVs.

Accurate detection of the transmitter node location permits effective data routing with reduced energy consumption. Localization time is another important parameter to be considered, which is the time taken for network localization.

Information Routing

In the context of localization, the geographic routing protocols are very relevant, which are based on classic routing approaches. If we take the case of multihop hierarchical networking, clustering is used to form clusters. Each member of a cluster communicates with its CH, which is responsible for data aggregation and transfers data using multiple paths to adjacent CHs, which transmit the data ultimately to the BS. Hierarchical routing protocols are more adaptive for conserving energy as compared to flat routing protocols. In addition, multihop routing protocols allow clear minimization of energy as compared to single-hop routing protocols [7]. In the context of UAVs, researchers have tried to tackle related challenges using different approaches such as those based on artificial intelligence, fuzzy logic (FL), and so on. Some studies use FL [8, 9] for CH election and cluster formation. Within this context, our method actually solves these problems as it executes an intelligent node localization algorithm using an intelligent fuzzy logic technique for next-hop CH election. The experimentation results show that the proposed clustering scheme performs better than the existing protocols.

Fuzzy-Logic-Based Localization and Data Routing Mechanism

The data routing mechanism proposed in this article is based on the localization of nodes using weighted centroid localization. This technique uses FL inference based on RSSI values between nodes to compute their locations. Additionally, the measurement of the flow through a wireless channel is used to determine the distance between the anchor and the UAV nodes. The phase of data routing in our mechanism is mainly used to optimize the next-hop CH selection based on the location of nodes. The energy consumption and network lifetime are optimized due to efficient transmission of data. Details are given in the text below.

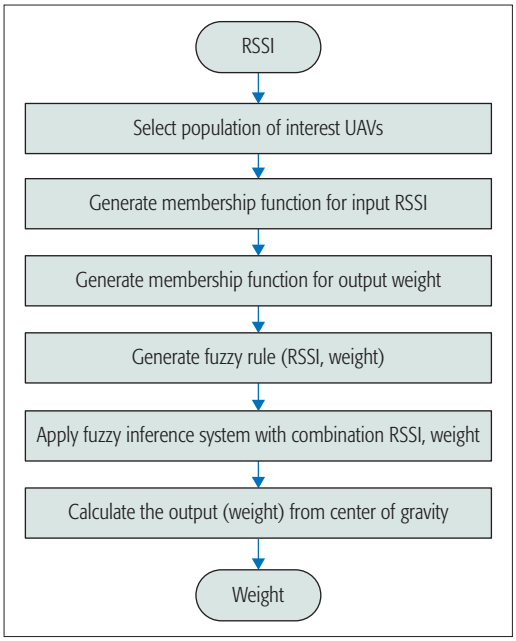

Figure 2. Fuzzy logic for UAV localizations.

Phase 1: Fuzzy-Based Localization Algorithm

As a first step, we propose a range-free UAV localization technique based on fuzzy inference. The RSSI values are used to estimate unknown node positions. There are two main phases in this approach. After initialization, the UAVs follow predefined trajectories to scan the area and receive signals from other UAVs. Once a UAV picks up the signal, the other UAVs are directed to the location of the signal receiving UAVs. Once all UAVs receive the RSSI signal, the distances are calculated using the RSSI values and a signal propagation model for different possible values of transmitter power. Then each UAV estimates its position using the centroid algorithm. Due to the noise characteristics of the RSSI, even after estimating the power of the transmitter and the execution of the localization algorithm, the position of the UAV cannot be determined with great precision. In order to increase the localization accuracy, we propose to estimate the position of UAVs using edge weights. Edge weight estimation is explained in Fig. 2.

The UAVs fly at a fixed altitude according to the UAV positions and the measured distances with respect to the RSSI values. A higher RSSI value means that the anchor is probably close to and must have a higher weight.

The out coming of our solution is that the UAV can be seen as an infinite reference points by measuring the distance estimation thoughts its trajectory (Fig. 3), rather than a standard three points based localization system. The unknown UAV computes its position based on a weighted centroid algorithm.

Phase 2: Data Transmission

Once the location of nodes is estimated using the localization algorithm, the next step is to effectively select the next-hop CH for data transmission with reduced energy consumption. As optimized energy consumption and extended network lifetime is one of the primary objectives, the CH election strategy elects the node with the largest surplus energy in the cluster. This node is elected CH. The main goal is to share the energy dissipation among all cluster members. In the first round, a node with energy higher than a threshold declares itself the CH and disseminates the information to the cluster members. In the second round, the node i with the highest utility function value is elected CH, and the information is disseminated in the cluster. The CH is responsible for data transmission of the collected data from the cluster members to the BS using multihop transmission. This optimizes the energy consumption when the sink node is far away. Selecting yet another next-elected CH for data transmission also greatly impacts the overall energy consumption of the CH.

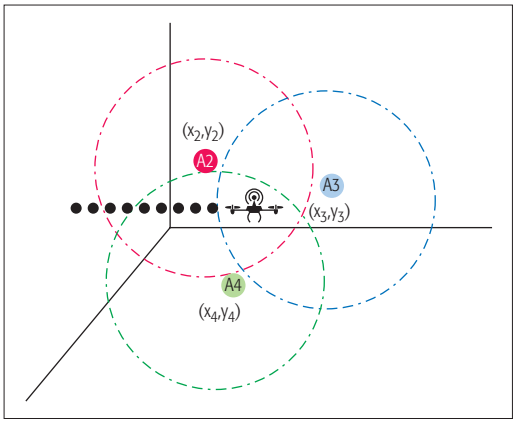

Figure 3. Simple example of the weighted centroid method.

The current CH and its next-elected CH are able to optimize the next elected CH selection to minimize energy dissipation for data transmission to the BS. In a similar way, the next elected CH is selected based on the weighting function, and the data is transmitted using the next elected CH.

We note that the weighting function adopted to select the CH takes into consideration the remaining energy of the CH, the distance between a node i and an adjacent CHj ($d(i,j)$) and the distance between CH and sink node.

Mobility and Communication Model for UAVs

Mobility Model: The high mobility of UAVs can degrade network performance by causing increased end-to-end delay and packet loss. For this, we assume that each aerial node moves independently on a 2D disk with a fixed center and a radius R. Each node rotates around a randomly chosen position with a fixed velocity until it chooses another position. The altitude of each UAV is fixed at random. Once reached, the altitude remains constant until the end of the simulation. The designated area may also be dynamic, and the proposed model may be adapted. The objective was to detect a designated area, while UAVs maintain connectivity to a BS and their neighbors. Three main cases are considered in our mechanism:

1. The UAV is connected to the BS.
2. The UAV is not connected to the BS, but it has at least one neighbor.
3. The UAV has no neighbors at all.

The proposed algorithm is evaluated using MATLAB simulations. The proposed approach is compared to traditional routing approaches. The performance evaluation metrics are accuracy localization, energy consumption, number of transmitted packets, number of dead nodes, and transmission time.

Approaches	Location error (meters)					
	Proposed method		[5]		[11]	
	Max	Min	Max	Min	Max	Min
Simple centroid	1.60	0.18	3.16	0	3.57	0.213
Mamdani fuzzy	1.20	0.15	2.02	0	2.01	0.12
Sugeno fuzzy	0.85	0.05	2.01	0	1.96	0.14

Table 1. Comparison results for different approaches.

In the first two cases, UAVs predict the future positions of their neighbors according to their current directions and eventually adjust their own movements. The direction to take would keep a UAV connected to the best of its neighbors. In the third case, where the UAV has no neighbors, it will keep its current direction until finding another neighbor.

Communication Model: In our system, two types of communication links are necessary: the link between drones (drone-drones) and the communication link between drones and the base station (station-sol) as illustrated in Fig. 1. On the other hand, drones are designed to be used in the most dangerous and hard-to-reach places by humans [10]. It is difficult to have cellular coverage in these places because of the complexity of implementation of fixed relays in these places. In addition, after natural disasters, these infrastructures may be damaged. Therefore, ad hoc networks are well suited for the communications network of a drone's fleet. Indeed, each node communicates directly with its neighbors who are responsible for retransmitting the messages to their destination. Each node is a relay that allows packets to be forwarded to their final destinations. This cooperation allows the nodes to move freely, which can cause frequent and rapid changes in the network topology. A change can cause a link break and at the same time create new links. Thus, in order to cope with the dynamic, frequent, rapid changes in topology, the ad hoc system requires specific communication protocols since it is an autonomous system that has the power to organize automatically. For this reason, we adopt in our solution a new intelligent routing protocol for detecting this sudden change and establishing paths to each destination.

Simulation and Experimental Results

Simulation Setup

The proposed algorithm is evaluated using MATLAB simulations. The proposed approach is compared to traditional routing approaches. The performance evaluation metrics are accurate localization, energy consumption, number of transmitted packets, number of dead nodes, and transmission time. 50 UAVs are randomly deployed in a 20 km^2 area. 100 simulation runs with different random seeds were performed for each result point, and results show the average value obtained from different runs. The values of the main simulation parameters are as follows [7]:

- Number of UAVs: 50
- Number of rounds: 600
- Area size: 20 km^2
- Packet size: 6400 bits
- Electronics energy (Eelec): 50 nJ/bit
- Initial energy of node: 0.5 J

Simulation of RSSI Localization Algorithm

We simulated the RSSI localization mechanism using Matlab 2017. The application layer of the simulation (beaconing, routing, and distance measurement between the unknown UAVs) satisfies the simulation requirements in the article. We assume that the UAVs are organized in a 2D space. During the positioning process, unknown UAVs send a request to the neighbor UAVs in the communication range. After receiving the request, the anchor UAVs periodically send their own identity and location information to other UAVs within their communication radius. The unknown UAV records the RSSI value only from the UAV having the same tag. After receiving several RSSIs from different anchor UAVs, the unknown UAVs classify the RSSIs and select the three closest UAVs.

Accuracy of Localization

For this scenario, 50 UAVs were randomly deployed. For comparison, the simple centroid approach, Mamdani fuzzy approach, and Sugeno fuzzy approach are simulated and compared to the two proposed localization techniques. The localization estimation and localization error results of these methods are shown in Table 1.

Cost of Transmission: Energy Consumption, Overhead, and Network Lifetime

We also compare the cost of transmission with existing routing protocols. One of the main advantages of our localization algorithm is that it allows minimizing the localization error.

The simulation results are presented in Fig. 4. It is shown that our mechanism significantly prolongs the whole network lifetime compared to the well-known BeeCluster protocol [9]. Additionally, it is also shown that with our algorithm the nodes consume less energy as compared to another well-known protocol, Energy-Efficient Multihop Hierarchical Routing (EMHR). These results attest to the better efficiency of our proposal as compared to existing approaches.

Figure 4a shows the consumed energy in our proposed system compared to both BeeCluster and the EMHR protocol.

We note that the energy dissipation of the proposed mechanism is equal to EMHR but lower than BeeCluster. Indeed, we note in Fig. 4a that the energy is consumed uniformly in IMRL. If we look at the last round, IMRL is upto 3.9 J better than BeeCluster. However, it still consumes around 3.5 J more than EMHR.

Figure 4b presents the comparison with respect to the number of transmitted packets to the BS. During 600 rounds, the BS receives more than 39,000 packets with the proposed protocol, called IMRL. However, EMHR transmits 37,100 packets and BeeCluster less than 38,100 packets to the BS.

Discussion

Our contribution has been validated by simulation results. First, considering the localization error results, it is clear that the location accuracy is poor with a simple centroid technique. Second, the intelligent localization algorithm reduces the error in UAV localization, selects the next elected CH using the inference system instead of the weighting function, and minimizes the position

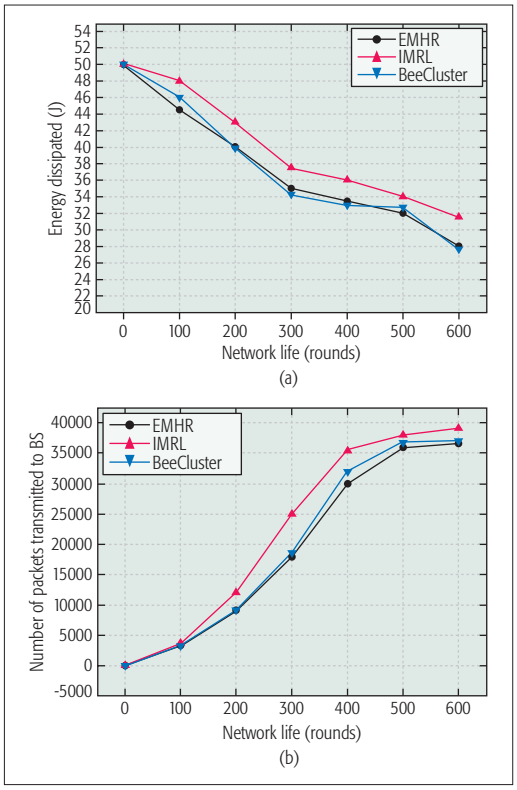

Figure 4. Performance evaluation: a) total energy dissipated; b) total data received by the BS.

error of UAVs. The simulation results show that our approach extends the network lifetime significantly as compared to the BeeCluster protocol. In addition, our simulations show that the nodes consume less energy as compared to the EMHR. The obtained results illustrate the efficiency of our approach when compared to other proposed protocols for similar purposes.

The performance of the proposed algorithm was verified using simulations. However, some open issues will be interesting to study using a real system in the future. The impact of high mobility of drones on the localization and data transmission performance could be interesting. Moreover, in a real system, the control packets can also be lost; additionally, the anchor node positions can be imprecise. This will require adding some robustness to the proposed algorithms. Finally, we considered an outdoor scenario in our simulation. The performance in indoor scenarios will be interesting to study in the future, where radio signal suffers from multiple reflections as well as multipath fading.

Conclusion

In this article, we propose a range-free localization approach for UAVs. A fuzzy inference system was used, which estimated the position of the edge nodes using RSSI information between UAVs and anchor nodes as input. In order to increase the precision of the system, the proposed mechanism uses a weighted centroid localization mechanism to estimate the location of nodes. As a next step, the positions of the nodes are then used for clustering and energy-efficient routing. The proposed system saves about 8 percent of consumed energy as compared to pioneers' protocols. In the future, we will study machine-learning approaches to further improve the performance.

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Some open issues will be interesting to study using a real system in the future. The impact of high mobility of drones on the localization and data transmission performance could be interesting. Moreover, in a real system, the control packets can also be lost; additionally, the anchor node positions can be imprecise. This will require adding some robustness to the proposed algorithms.