Energy-efficient Unmanned Aerial Vehicle Scanning Approach with Node Clustering in Opportunistic Networks

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***Abstract*—The opportunistic networks are challenging due to their inherent characteristics of intermittent and unreliable communication between nodes. In order to alleviate the communication issues, the unmanned aerial vehicles (UAVs) can be used for delivering packets within the opportunistic networks.**

This paper investigates how to leverage the UAVs in Unmanned Aerial Vehicle aided Opportunistic Networks (UAON). The UAVs are considered responsible for relaying the messages generated by the nodes on the ground. The simulation study is conducted on the real-world datasets of the nodes moving around Orlando and Korea Advanced Institute of Science & Technology (KAIST). Our proposed approach, State-based Campus Routing (SCR) with Density-based spatial clustering of applications with noise (DBSCAN), meander, random, and random spiral scanning approaches, as well as SCR and Epidemic protocols without UAV usage, have been evaluated on both datasets. The simulation metrics included the success rate, the message delay, the number of packets sent, and the distance traveled by the UAVs. SCR with DBSCAN and meander scan approaches were also tested with two UAVs using the Orlando dataset. Furthermore, spiral density and message creation frequency parameters were evaluated for SCR with DBSCAN protocol on North Carolina State University (NCSU) dataset. The simulation results showed improvements in terms of message delay and success rate when the UAVs were used in an opportunistic network setting. The proposed approach showed around 12% less total number of packets sent by the UAVs and the nodes. Similarly, the message delay distributions of the SCR with the DBSCAN achieve 90% of the message delay results, whereas the message delay distributions of random scanning form only 70% in less than an hour.

I. Introduction

Unmanned aerial vehicles (UAV) are used for many applications, including monitoring areas [1], [2] where human intervention is either not possible or practical due to challenging environmental conditions or merely providing network coverage [3]. The UAVs can also be beneficial in opportunistic wireless communications. The opportunistic network is defined as a network of mobile nodes, where the neighbors often change with the mobility of the nodes [4]. In such an environment, the nodes communicate through multiple hops, and communication is not guaranteed or reliable. Due to the inherent characteristics of intermittent communications of the opportunistic networks, the routing can provide more effective ways of information exchange among the nodes.

In this paper, the UAV Aided Opportunistic Network (UAON) assumes to include one or more UAVs. The UAVs aim to use the shortest possible path when communicating with other nodes or with other UAVs for relaying the messages to the destination nodes. Like the mobile nodes on the ground, the UAVs can conserve energy by following optimization strategies on when and how often it should visit specific locations and when to deliver collected messages.

Some of the opportunistic network applications are designed for environments where Internet access is nonexistent or limited since the communication is achieved in an ad hoc manner. The opportunistic network applications allow the system controllers to send messages to some users in a specific place without using location-based data collection or the Internet. In our application case, there is a physical communication between the sender and receiver, and there is no need for GPS data for filtering and communication.

The application case is designed as a flooding example rather than targeting a specific node. Flooding technique focuses on the distribution of the message to the entire network rather than a specific node in mind. If there is a single destination node to receive the message, then the proposed strategy may only focus on intermediary nodes along the route to deliver the message. It may ignore the nodes that are not likely to encounter with the destination node. For the flooding case, every node might be vital if we aim to increase success rates. The success rate is defined as the percentage of the nodes that have a specific message.

In this paper, epidemic routing based approaches with different types of trajectories are tested. There are different shapes of trajectories for the UAVs, while they are patrolling the sky. Experiments are conducted to compare DBSAN, meander, random, and random spiral scan approaches along with State-based Campus Routing (SCR) and epidemic routing with no UAVs. The meander scan technique was included because it scans the whole environment, potentially spending time and energy on empty areas. Random spiral scanning technique is good at scanning some parts of an area but since cruising happens randomly, the UAV may also visit empty areas, wasting time and energy. The proposed technique was compared with the baseline examples of the UAV scanning approaches. The two cases with no UAVs are included in the simulation study to show UAV usage's effectiveness in an opportunistic network.

The contributions of this work are as follows:

- The efficiency of UAV usage in opportunistic networks is examined. The proposed approach is efficient in terms of message delay and success rates for the UAV scanning technique. It uses State-based Campus Routing (SCR) [4] for the nodes.
- The UAV does not require any excessive information exchange between nodes since only the UAV has a location-tracking information such as GPS. The minimal information usage allows us to decrease the communication overhead and make the system more suitable for networks with a larger number of nodes.

The remainder of the paper is organized as follows. Section II reviews the existing work. The application scenario is provided in Section III. The compared approached and the proposed approach are explained in Sections IV and V. The results are presented in Section VI while the paper concludes in Section VII.

II. Related Work

There has been a significant amount of existing literature on opportunistic network routing. Zhou et al. [5] uses UAVs in the crowdsensing domain for task assignment and route planning. Wang and Wu [6] have proposed a solution for a flooding approach using access points and random mobility model for node movements in a delay-tolerant mobile sensor network. Bacanli, Solmaz and Turgut. [4] proposed State-based Campus routing (SCR) in an opportunistic network and compared different routing strategies for different university campus datasets. The simulation study on SCR used encounter dataset, which includes only the encounter times and encounter durations of the nodes.

The disaster management applications can also leverage the usage of the UAVs. Lack of Internet usage in our system can be an expected limitation after an earthquake scenario. Focusing on the disaster scenarios, Zhong et al. [7] examined path assignment for the UAVs in disaster recovery networks. Sudhakar et al. [8] used UAV in forest fire detection and monitoring. Gondaliya and Gondaliya [9] have evaluated delay-tolerant routing strategies in post-disaster scenarios.

The positioning of the UAVs for monitoring and coverage of various networks is crucial for high-quality observation of events. Al-Turjman et al. [10] designed a framework for the optimal placement of the drones to monitor static or mobile targets such that the maximum area coverage is achieved through the minimal number of UAVs. Similarly, Akbas et al. [11] proposed a node positioning algorithm, based on the Valence Shell Electron Pair Repulsion (VSEPR) theory of chemistry, such that multiple UAVs can coordinate and communicate for data collection.

While there are many existing protocols leveraging UAVs within opportunistic networks [12], [13], [14], [15], [16], none of these approaches used a real-world dataset. Ma et al. [13] uses velocity information of the nodes moving in the same direction. Xu and Zhang [17] introduced a routing algorithm, where the UAV travels between three dense groups of nodes. Valentino et al. [15] designed a theoretical model for clusters of the UAVs communicating with each other. In order to implement a more realistic approach, the proposed strategy is simulated on a real-world dataset [18].

Oubbati et al. [19] have incorporated UAVs in vehicular ad hoc networks with synthetically generated vehicle mobility data. In our case, the nodes are mobile, and the users on foot carry the data collection devices. Internet of things applications of the UAVs are also investigated in the literature [20], [21], [22].

Some of the opportunistic networking routing strategies are mainly focused on specific target and destination based scenarios. Therefore, techniques including Spray And Wait [23] or PROPHET [24] are not readily suitable for our application case. Since our application scenario is based on flooding, a flooding based routing strategy is used for the nodes on the ground, namely SCR [4].

III. Application Scenario

A university campus is considered as the opportunistic network environment in this paper. The datasets contain the mobile traces of people walking with a mobile device on the university campus. The mobile devices are assumed to communicate through an ad hoc fashion and the UAV cruises on top of the university campus. The motivation behind adding a UAV into an opportunistic environment allows the nodes on the ground to conserve energy by not heavily engaging in wireless communications. The argument is that it may be easier to charge the UAV battery than drain the batteries of the ground nodes.

The messages are created every hour with the lifetime of the message set to three hours, meaning that the message is broadcast around the whole campus in less than three hours. In order to make the application case more realistic, a one-minute error rate is added. In other words, the messages may be created early or late but do not exceed one minute. Whenever a person encounters with another person, the mobile devices exchange the messages. If a node has a message whose creation time is older than three hours, it keeps the message but does not forward it to other encountered nodes.

The message lengths are 250 characters. Since the message lengths are reasonably small, the nodes and the UAV's memory size are not limited. The proposed strategy uses the same session concept, as stated by Vahdet and Becker [25]. When two nodes encounter each other, one of them, as the initiator sends the protocol message containing the node ID and the list of the message IDs it has, the other node as the replier, replies to that message by sending the list of message IDs for the initiator to send. After receiving this message, the initiator then starts sending the messages one by one. After the message exchange concludes, this process is repeated by switching the roles.

Protocol	Description
Epidemic [25]	This is a baseline approach for opportunistic network routing, proposed by Vahdat and Becker [25], where nodes exchange messages between each other whenever nodes encounter occurs.
Spray and Wait [23]	Spray and Wait strategy, proposed by Spyropoulos et al. [23], covers the application case where each created message has a destination node. Each message creator node sends a predefined number of copies of the message to all encountered nodes. When the creator node finishes sending all the copies, it only sends the message to the actual destination of the message.
PROPHET [24]	Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET) is proposed by Lindgren et al. [24]. The nodes send messages to other nodes based on the encounter history of the receiver node.
PROPHET-CLN [26]	Wang et al. [26] proposed improved PROPHET, called (PROPHET-CLN), which is based on nodes' congestion level. It requires nodes to exchange their encounter histories, similar to its predecessor, resulting in extra communication overhead.
SCR [4]	Bacanli et al. [4] proposed State-based Campus routing (SCR) in an opportunistic network. Nodes exchange messages between each other based on a dynamic probability, and active/passive node states.
SCR with DBCAN	SCR with DBSCAN (density-based spatial clustering of applications with noise) is the proposed approach for the UAV-aided opportunistic networks. The nodes on the ground use SCR routing strategy where one or more UAVs cruise around the environment.

TABLE I
SCANNING ALGORITHMS IN OPPORTUNISTIC NETWORKS

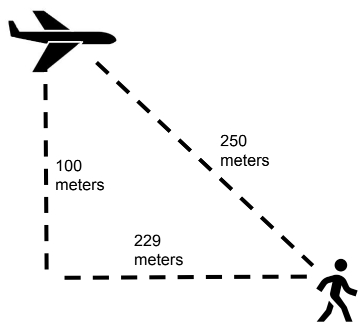

Fig. 1. Maximum communication distance with altitude as 100 meters.

The UAV cruises on top of the campus and collects the messages from the nodes and deliver them back to its encountered nodes. The UAV itself does not create any messages since it is responsible only for delivering the messages created on the ground to as many nodes as possible. The assumed maximum speed of UAV is 33 meters per second, and the maximum cruise time for the UAV is 24 hours (see Bayraktar UAV [27]). The goal was to show that using a UAV for this application case can be better than using no UAV or using the random or the meander scanning approaches. The maximum wireless communication range for the nodes and the UAV is 250 meters that is compatible with an 802.11 wireless communication standard. The assumed altitude of the UAV remains constant at 100 meters while cruising on the map. As the UAV is flying around, the maximum communication distance on the ground is calculated using the Pythagorean theorem. The maximum communication distance is around 229 meters (see Figure 1.)

Several applications within opportunistic networking can leverage UAVs. For instance, the participants of a conference or a meeting taking place at the university campus can send each other messages about the event. Another example could be yellow pages applications where people send messages about items to buy or sell. The application scenarios can be potentially extended to city areas or theme parks since any of these locations become more crowded at different times of the day due to a specific event. Some areas are almost always occupied during certain hours of the day due to regularly scheduled events such as classroom buildings, city offices, and so on—the population density peaks during the weekends or holidays at the theme parks.

An opportunistic networking environment with a UAV and no Internet usage also makes this system functional in cases where the Internet connection is unnecessary. If the nodes are in densely populated environments such as urban areas or special gathering events, the opportunistic network may provide acceptable message delays and high success rates. The proposed system can also be used in situations where the Internet connection is not possible such as in a disaster case scenario. For instance, warning, notification, or information broadcasting after an earthquake or a hurricane can be fulfilled by creating an opportunistic network environment with one or more UAVs.

IV. Compared Approaches

When it comes to forwarding messages, the nodes can only forward the messages in their memory whose expiration time has not yet passed. The nodes first exchange the vector of their message IDs, and this is the only protocol message also stated in the epidemic routing by Vahdet and Becker [25]. For large scale and dense networks, stored and collected information about the neighbor nodes may negatively impact the nodes' processing time and storage space. As a result, an excessive amount of information exchange between the nodes should be avoided to ensure the suitability of the routing strategy for large networks. Exchanging only the actual messages further enhances the privacy and security of the mobile nodes since the encounter history information is not shared between the nodes. Having a less complicated protocol message system also saves memory space for the nodes. For instance, State-based Campus Routing (SCR) uses a small amount of memory for the communicating nodes [4].

The proposed approach, SCR with DBSCAN, is compared with meander, random, random spiral scanning approaches, and SCR and Epidemic protocols without UAV usage in the

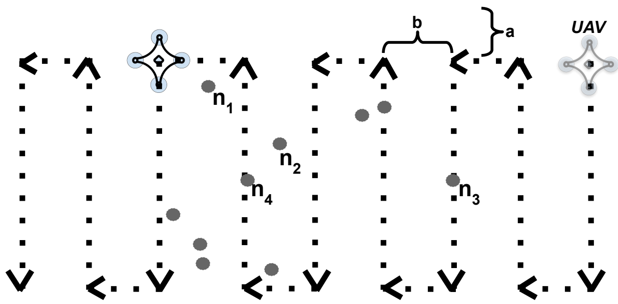

Fig. 2. Meander scan approach.

simulation study. As described in the application scenario, the nodes create and forward messages to each other. Besides the nodes, the UAV scans the environment using different approaches and helps the opportunistic network through message flooding.

In the following, a summary of the compared approaches is provided.

A. Meander scan

The meander scan approach scans the area similar to a meander shape. The density of the path is parameterized with two parameters: a and b. One of the parameters decides the distance between horizontal lines, whereas the other decides the distance between vertical lines. Figure 2 shows the DB-SCAN clustering approach. By adjusting the parameters, more densely or more scarcely scanning paths can be created. The UAV starts from the upper rightmost corner of the area. When the UAV finishes the path, it goes back to its starting point to start scanning again. Both the UAV and the nodes on the ground use Epidemic routing for the meander scan approach.

B. Random scan

This approach scans the area randomly by going to random locations. The UAV takes off from a random location on the map before starting the scanning. Random scanning is an essential technique to scan the map. In this technique, the nodes on the ground and the UAV use epidemic opportunistic routing strategy to communicate with each other.

C. Random spiral scan

The random spiral scan approach scans the area using random spiral paths. Our main objective is to develop a technique for scanning small cluster areas. To serve that purpose, we have used a spiral scanning technique. For the random spiral scanning, the UAV creates a spiral way-point based on parameters *a* and *maximum radius (R)*.

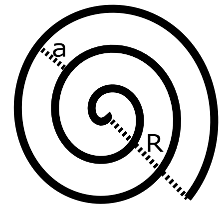

Fig. 3. Spiral parameters.

Figure 3 shows the parameters of a spiral. The distance between two consecutive arcs is a. The maximum displacement that the UAV makes from the initial point is called *maximum radius(R)*. For this specific spiral shown in Figure 3, *R* is triple of a. The spiral we are using in our approaches is the Archimedes spiral. For the random spiral approach, the UAV picks a random location in the area with a random maximum radius(*R*). When the UAV reaches the limits of the area or reaches the maximum spiral radius distance from the starting point, it selects another random location with a random maximum radius. Afterward, it starts scanning as a spiral again. Epidemic routing protocol is used by the UAV and the nodes on the ground as the routing strategy.

The parametric function of the spiral shown in Equation 1 is used to draw the location of a node at each second. The θ is increased, and contiguous locations are created at each second until the distance between first and last projected locations is less than *R*.

$$\begin{aligned} x(\theta) &= a \times \theta \times \cos(\theta) + x_{initial} \\ y(\theta) &= a \times \theta \times \sin(\theta) + y_{initial} \end{aligned} \tag{1}$$

D. State-based Campus Routing (SCR) with no UAV

The SCR [4] is based on the idle and active states of the students in indoor and outdoor places in campus environments. The message transmission procedure (i.e., sessions) resembles the Epidemic routing [25], meaning that the nodes can be either receivers or senders. In this case, only SCR routing for the nodes on the ground is tested, and no UAVs are used. The nodes on the ground follow the SCR approach while sending messages to each other. The parameters of the simulation is set as $\alpha = 0.25, P_{wanted} = 0.99, \lambda = 0.99$.

E. Epidemic routing with no UAV

In this case, only Epidemic routing for the nodes on the ground was tested, and no UAVs were included in the test environment. The nodes on the ground send messages whenever they encounter each other. This approach was added to compare the results with no UAVs, while the success rates and message delay results are still acceptable.

V. SCR WITH DBSCAN

The proposed approach, State-based Campus Routing (SCR) with Density-based spatial clustering of applications with noise (DBSCAN), covers the case where the nodes on the ground are using SCR routing [4] whereas the UAV is scanning the network using DBSCAN.

The DBSCAN is a non-parametric clustering technique. In parametric clustering techniques, the number of expected clusters in a data is given as an input, and the clustering technique gives the set of points for each generated cluster instance. In non-parametric clustering, the number of expected clusters is not provided. Instead, the parameters about the expected cluster properties are given, and the clustering technique outputs the set of points for each generated cluster. For the DBSCAN clustering technique, the minimum number of nodes in a cluster and the maximum distance between cluster centers should be provided as a parameter. With different inputs to those parameters, DBSCAN may output a different number of clusters as the technique applies.

In SCR with DBSCAN, the encounters are tracked by the UAV instead of the nodes. The UAV keeps the records of its encounter history such that it can decide its routing strategy. The encounter history is removed after the completion of the route. Even though the monitoring of the UAV's memory consumption is not within the scope of this research work, the history is still deleted to save the memory space of the UAV. The encounter entries also contain the UAV's location when the UAV encounters a node. Since the maximum communication distance is 250 meters, the UAV can provide approximate location information about the node. The location privacy of the nodes on the ground is preserved by the fact that the UAV does not know the exact location of the nodes.

In the proposed approach, the UAV completes a tour using the meander scan. Based on the encounter data, it creates clusters of nodes with given DBSCAN clustering parameters. The UAV starts a spiral scan for the cluster points. After it finishes the cluster scanning, the UAV sets maximum and minimum x-axis locations to create a frame. The maximum location for the frame is the x coordinate of the farthest node, while the minimum location for the frame is the x coordinate of the closest node. Once the frame limits are created, the UAV travels following the meander scan from the minimum location to the maximum location. Based on that framed scan, the UAV repeats the clustering approach for the encountered nodes. The limits for the frame stays for *framelimit* number of meander scans. In the simulation study, *framelimit* is set to 5. Once the UAV starts a meander scan for the sixth time, the UAV again scans the whole area to set the new frame limits. The motivation behind the framing approach is to consider the changes of the map density. Since the dense locations on the map may change over time, the frame limits are reset once in every *framelimit* times to find the new dense points.

Figure 4 shows the scanning pattern in the environment. n_1 is the maximum point of the frame, whereas n_3 is the minimum point. Once the UAV finishes scanning the whole map, it sets the maximum and minimum points based on n_1 and n_3. After that, based on the encounter history, it has around the n_2 node, the UAV makes a spiral scan around the n_2. The spiral's radius will be half of the maximum distance between the two points in the cluster. Once the spiral scan is finished, all the points in that cluster will be reencountered, considering that their positions stayed within the same cluster group.

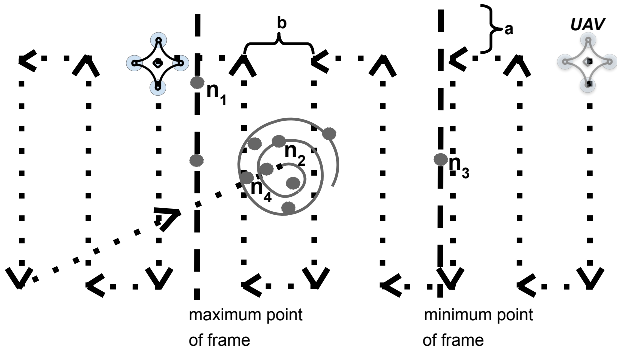

Fig. 4. SCR with DBSCAN clustering approach with framing.

The DBSCAN algorithm requires the maximum distance parameter between two nodes to be 2000 meters. The communication standard used for outdoors is 802.11 WiFi; therefore, the maximum communication distance between nodes was set to 250 meters. In this case, we set the density of the spiral, *a*, parameter to 250 meters, such that the UAV may encounter with the same node once more after the first encounter while making a spiral. Reencountering the node for the second arc of the spiral might help distribute a message inside the spiral area. Let us assume that the UAV gets a message from another node while making the second round. The newly received message can then be forwarded to the node the UAV has encountered during the first round. For instance, n_4 node is encountered twice by the UAV in Figure 4.

In the proposed approach, precisely, a non-parametric clustering technique rather than a parametric one was selected. For a parametric clustering technique (e.g., k-means clustering), constant *number of clusters* parameter could have been examined; however, the parameter would most likely depend on the number of mobile nodes. While we could have used a parametric clustering technique due to the small size network considered in the simulation study, we chose the non-parametric option to emulate a more realistic real-world case scenario with potentially thousands of nodes.

VI. Simulation Study

In this section, the simulation environment, the metrics, and the real-world datasets are described. The remaining of the section includes the simulation results and explanations for each dataset used.

A. Simulation environment and metrics

The simulations for the application scenario was carried out using Java. The simulator, by Bacanli and Turgut [28] is further developed to conduct the evaluation study. The proposed protocol, SCR with DBSCAN, is compared with meander, random, random spiral scanning approaches, as well as SCR and Epidemic protocols with no UAVs.

The simulation metrics include the success rate, message delay, number of packets sent, and the distance traveled by the UAVs. The success rate is defined as the percentage of the nodes that have a specific message. The higher the success rate for a message, the higher the percentage. The message delay is the average delay of a message received by the nodes and the UAVs. The delay term here is defined as the time difference between the packet's creation time and the receiving time of the packet by UAV or node. The total number of packets sent includes the packets sent from the nodes and the UAV. It is important to note that this metric focuses on the sent messages only. As there is a 10% error rate in the system, not all messages are received by the target node at all times. According to the nature of the session system defined by Vahdet and Becker [25], the packets not received by the target are not resent again by the source. The missing message can be possibly sent to the target later from another encountered node. The energy efficiency of a technique should include the number of packets sent by the nodes and the UAV. The distance traveled by the UAV, should also be considered in evaluating the energy efficiency of the approach. The distance traveled by the UAVs is calculated whenever they finish a route between two calculated points and adding them up through the simulation run. The aim is for the UAV to travel the smallest distance possible.

B. Datasets

The dataset by Rhee et al. [18] was used. This dataset included a collection of human mobility traces from five different sites: two university campuses (NCSU and KAIST), New York City, Orlando (Disney World), and North Carolina state fair. The mobility traces from Orlando, KAIST, and NCSU datasets were used in the performance evaluations.

The dataset contains the locations and the times of the nodes calculated by referencing a local point. The location coordinates are in meters. The GPS coordinates of the reference point is unknown. Since the dataset contains the location records taken every 30 seconds, the dataset was extended by filling the location data for the remaining 30 seconds, assuming that the nodes continue to follow a line path at a constant speed.

The dataset contains a different number of nodes on the map at any given time. In other words, not all the nodes may be active at all times. In order to increase the possibility of including all the nodes, the "maximum data collection duration" was considered within the dataset. The active time for each node on the map varies in all three datasets.

Orlando dataset. The mobility traces are collected from smartphones of 11 volunteers who spent their holidays in the Walt Disney World theme parks, which corresponds to the location records of 41 nodes. The maximum data collection duration is 51420 seconds or 14.3 hours. The collection area has the dimensions of 15422 meters by 17934 meters. The Orlando dataset was used to simulate the cases where no UAV and one or two UAVs were leveraged.

KAIST dataset. The mobility trace data is collected from the Korea Advanced Institute of Science and Technology (KAIST) campus in Daejeon, South Korea. This dataset includes the location records of 22 nodes after removing the traces with the collection duration less than 14 hours. The maximum data collection duration is 83970 seconds or 23.3 hours. The collection area has the dimensions of 13227 meters by 19208 meters. The KAIST dataset was used to simulate the cases where no UAV or just one UAV is used.

NCSU dataset. The mobility trace data is collected from North Carolina State University (NCSU) campus with the location records of 35 nodes. The maximum data collection duration is 78090 seconds or 21.7 hours. The collection area has the dimensions of 9713 meters by 14628 meters. The NCSU dataset was used to evaluate the specific metrics of our proposed approach, SCR with DBSCAN.

Dataset property	Orlando	KAIST	NCSU
Number of nodes	41	22	35
Data collection duration (in seconds)	51420	83970	78090
Length of the map (in meters)	17934	19208	14628
Width of the map (in meters)	15422	13227	9713
Data collection frequency (in seconds)	300	300	300

TABLE II
DATASET PROPERTIES

C. Evaluation of approaches on Orlando dataset

We compared SCR with DBSCAN, meander, random spiral, and random scanning approaches on Orlando dataset.

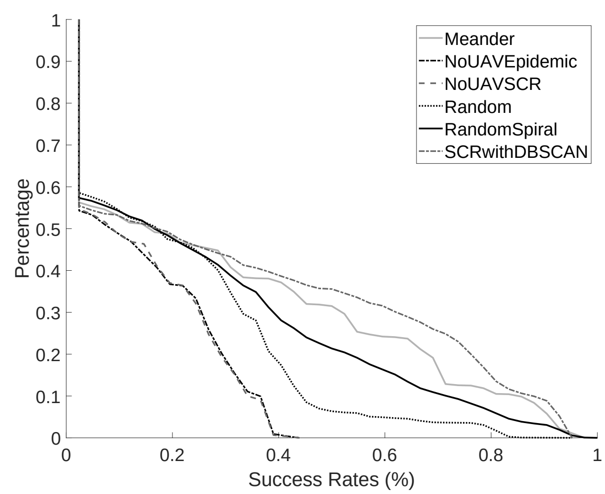

Fig. 5. Complementary cumulative distribution function of success rates on Orlando dataset.

Figure 5 presents the complementary cumulative distribution of success rates in the Orlando dataset. SCR with DBSCAN performs better than the meander and the random scanning techniques for Orlando dataset. The reason behind this result might be that the users might be forming more dense clustered shapes in which the SCR with DBSCAN may visit the clusters of people on the map. The meander scanning approach was better than the random spiral scan. The random spiral scanning technique appears to achieve a higher success rate than a random scanning counterpart. It can be seen that the techniques, including UAV, show better results than the techniques without a UAV.

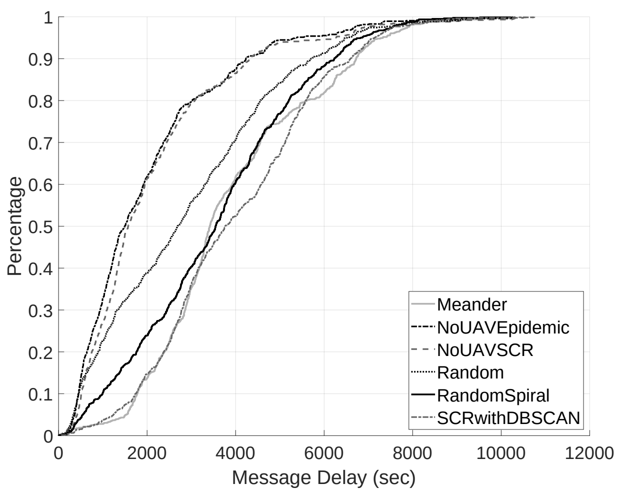

Fig. 6. Cumulative distribution function of message delay on Orlando dataset.

Figure 6 shows the cumulative distribution of success rates in the Orlando dataset. SCR with DBSCAN has similar results with meander, random, and random spiral scanning techniques. It is interesting to note that the random scanning technique performs better in terms of message delay than the success rate metric. Furthermore, SCR and epidemic protocols without UAV also give better message delay results, although their performance on the success rates is not as good.

It is worth to note that checking only the message delay results can be misleading without checking the success rates. Considering a message is transmitted to only one other node in a short time and never transmitted to any other node afterward, the message delay for that message will be small. Since the message is transmitted to only one node in its lifetime, the techniques need to be compared by first checking the success rates. For the techniques with similar success rates, their message delay results can be observed.

Figure 7 presents the number of packets sent in the Orlando dataset. The total number of packets sent by the meander is the highest among all the compared techniques. The number of packets sent by the UAVs in SCR with the DBSCAN approach is almost twice as much as the other techniques, while the total number of packets sent in much less than the meander technique. We can conclude that SCR with DBSCAN is more energy-efficient than other compared approaches in terms of the message delay results in addition to the success rates.

Figure 8 shows the distance traveled by UAV in the Orlando dataset. The total distances traveled by different approaches are similar, except the random spiral scanning approach gives a bit better results. It can be observed that SCR with the

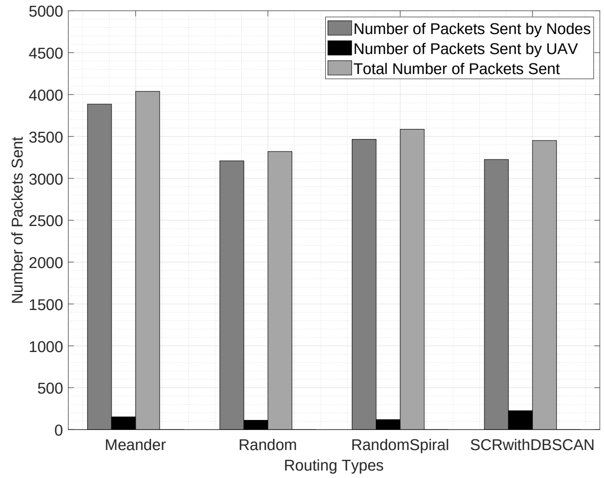

Fig. 7. The number of packets sent on Orlando dataset.

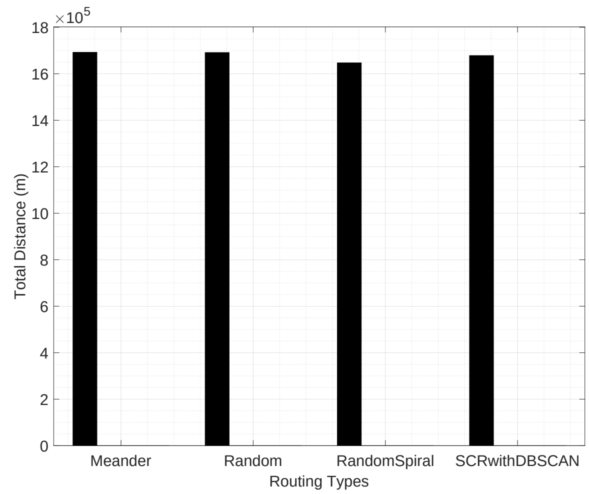

Fig. 8. The distance traveled by UAV on Orlando dataset.

DBSCAN technique is energy efficient as the UAV travels similar distances with the other approaches while sending fewer packets.

D. Evaluation of approaches on KAIST dataset

We compared SCR with DBSCAN, meander, random, and random spiral scanning approaches on the KAIST dataset.

Figure 9 presents the complementary cumulative distribution of success rates in the KAIST dataset. While almost all the techniques performed similarly, the meander scan appears to give higher success rates. The success rate performance of the protocols stays reasonable, acceptable levels, between 0.6 and 0.8, and then makes a sharp decrease. This trend means that not all the nodes remain active on the map at all times, and some nodes get disconnected. Even with these disconnections, nearly 50% of the nodes receive most of the messages under the opportunistic network settings.

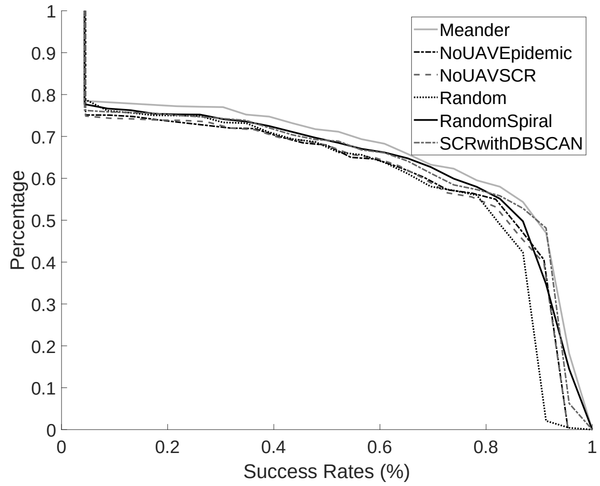

Fig. 9. Complementary Cumulative distribution function of success rates on KAIST dataset.

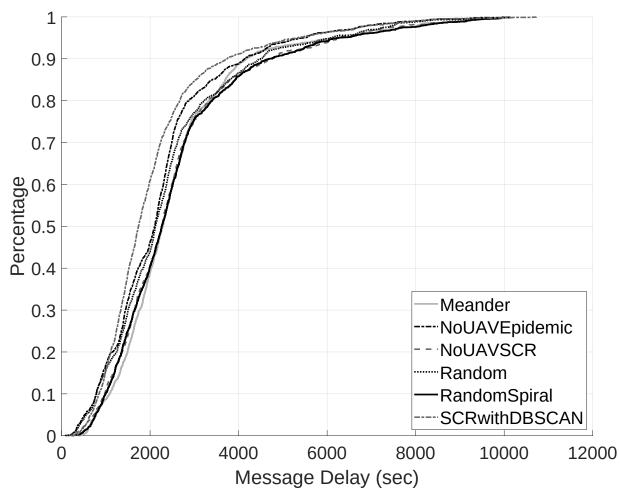

Fig. 10. Cumulative distribution function of message delay on KAIST dataset.

Figure 10 shows the cumulative distribution function of the message delay distribution in the KAIST dataset. The SCR with DBSCAN has lower distribution of message delays than other techniques. The message delay results less than 4000 seconds is around 85% to 95%. These numbers may indicate that the nodes appearing on the map might be forming a connected cluster. It is also possible that some nodes act as gateways between different clusters, extending the connectivity further.

Figure 11 presents the number of packets sent in the KAIST dataset. The compared protocols showed similar trends with the Orlando dataset. The total number of packets sent by the meander is still the highest among all the compared techniques. The number of packets sent by the UAVs in SCR with the DBSCAN approach is almost twice the meander and at least three times more than the random spiral approaches.

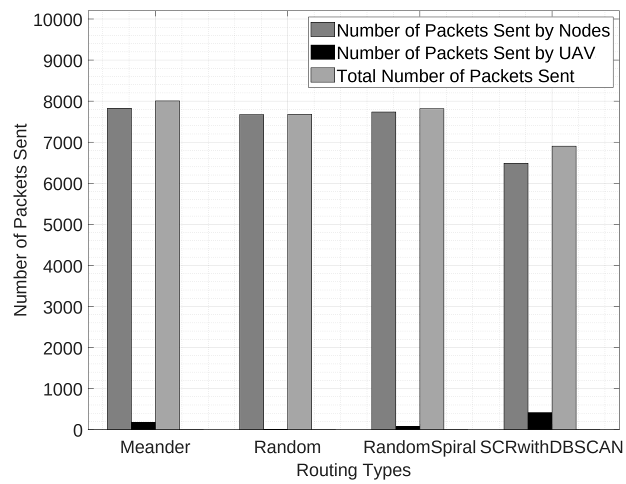

Fig. 11. The number of packets sent on KAIST dataset.

The random and random spiral have almost identical results in terms of number packets sent by the nodes and total packets sent while the SCR with DBSCAN has the lowest number on both counts. We can conclude that SCR with DBSCAN continues to be the most energy-efficient technique.

E. Evaluation of SCR with DBSCAN on NCSU dataset

1) Spiral density (a) value: The spiral density (a) is the distance between the arcs of the spiral. The spiral's density allows the adjustment of the time that a UAV can spend on a cluster. Changing the spiral density plays a vital role in the spiral scanning part of the SCR with DBSCAN protocol in which the UAV makes spiral scans on the cluster of the nodes that DBSCAN has calculated. The denser the density metric becomes, the more frequent the UAV encounters occur with a node in the scanned cluster area.

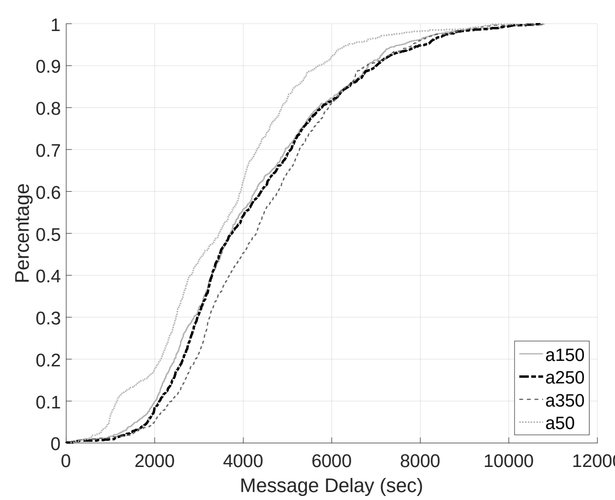

Fig. 12. Cumulative distribution function of message delay of different spiral density values on NCSU dataset.

Figure 12 shows the message delay cumulative distribution graph of the SCR with DBSCAN where the spiral density, a, was evaluated for the values of 50, 150, 250, and 350. The a value of 50 achieves the lowest message delay while the a values of 150 and 250 show similar results. With the a value of 350, the message delay increases. It appears that varying the density of the spiral affects the message delay. As the density value decreases, the spiral route becomes denser. In that case, the UAV would most likely encounter the nodes on that scanning circle more than once.

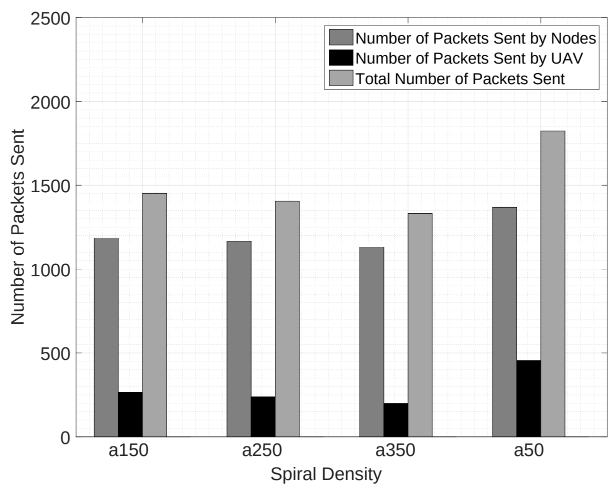

Fig. 13. The number of packets sent for different spiral density values on NCSU dataset.

Figure 13 presents the number of packets sent for SCR with DBSCAN with respect to the a values of 50, 150, 250, and 350. While the number of packets sent by the a value of 350 is the lowest, it incurs the most message delay, as we have seen in Figure 12. Since the message delay for the a values of 150 and 250 were similar, and if the number of messages sent is taken into consideration, the a value of 250 would be the most suitable option.

As the performance results of the message delay and the number of packets sent are evaluated, the spiral density parameter that can balance these two metrics should be identified. Although the a value of 50 has a lower message delay than the a value of 250, it does not contribute to the energy efficiency since it has the highest number of packets sent. The trade-off between the message delay and the number of packets sent can be observed from the results. The spiral density parameter, a, can be easily adjusted to save energy or invest further on the message delay depending on the application needs.

2) Message creation frequency: In the application cases, the messages are created in every 3600 seconds (1 hour) by the nodes. The effects of the message creation frequency were investigated in the simulation study. The approaches evaluated in which the message creation frequencies for the nodes were 1800 seconds (30 minutes) and 7200 (2 hours) seconds.

Figure 14 shows the message creation frequency for the number of packets sent. It is interesting to note that the number of messages is less than half for the frequency of 7200 seconds compared to the 1800 seconds. As expected, it can be concluded that as the message creation frequency decreases, the message traffic becomes less burdensome, and the number of messages sent also decreases.

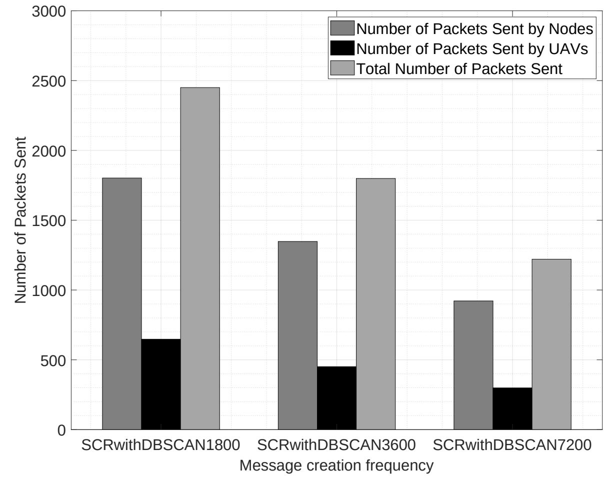

Fig. 14. The number of packets sent for different message creation frequency values on NCSU dataset.

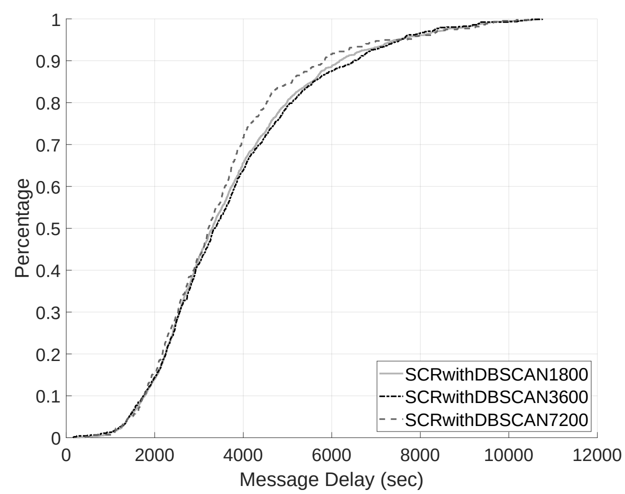

Fig. 15. Cumulative Distribution function of message delay for different message creation frequency values on NCSU dataset.

Figure 15 presents the message delay for the message creation frequency. The message delay for the case where the nodes are sending messages in every hour and every half an hour shows similar results. The message delay gets better when the message creation frequency decreases. When the UAV is cruising around a particular area, the nodes in other areas might be creating messages. This would mean that it may take some time for the UAV to follow up with the newly created messages. If the message creation frequency decrease, the UAV will be less likely to miss these messages.

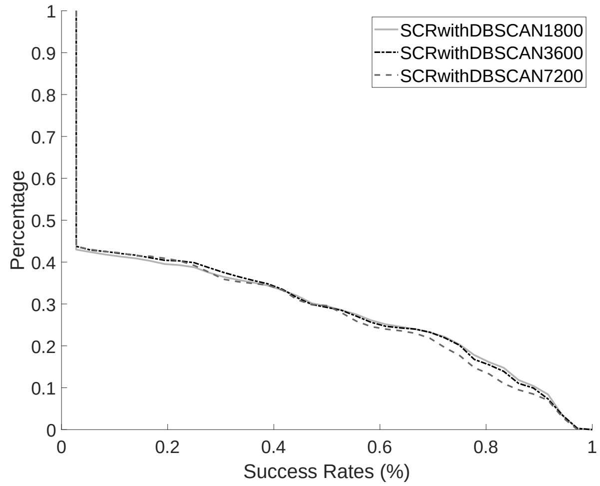

Fig. 16. Complementary Cumulative Distribution function of success rates for different message creation frequency values on NCSU dataset.

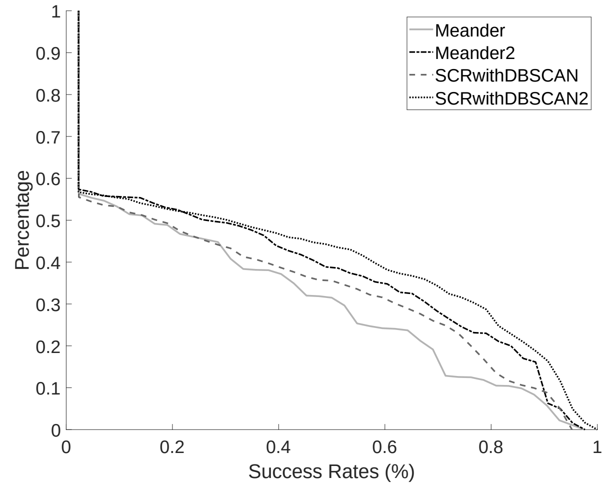

Fig. 17. Complementary Cumulative distribution function of success rates on Orlando dataset with two UAVs in the environment.

Figure 16 shows the success rates of the messages for different message creation frequencies. Based on the result, the success rates do not depend on the message creation frequencies. The reason behind this conclusion is that the message creation frequency does not change the UAV's cruising strategy. The UAV cruise around similar locations in each message creation frequency case; therefore, the success rates are not affected much whether the message creation frequency increases or decreases.

F. Applications with two UAVs

When the protocols with one UAV were evaluated, the meander scan achieved better success rates and the message delay than all the other approaches except SCR with DBSCAN. Since the meander scan was the closest to the proposed approach, the energy efficiency of SCR with DBSCAN with two UAVs were evaluated and compared only with the meander scan.

The meander and SCR with DBSCAN approaches are evaluated with one and two UAVs on the Orlando dataset. For the cases where two UAVs are utilized, one of the UAV starts scanning from the top left corner, and the other UAV starts scanning from the top right corner of the map. The application cases with only one UAV are specified as *SCRwithDBSCAN* and *Meander* while *SCRwithDBSCAN2* and *Meander2* refer to the cases with two UAVs.

Figure 17 presents the complementary cumulative distribution function of the success rates distribution for the cases with one or two UAVs. It can be seen that the success rates increase with two UAVs on both approaches compared to their counterparts with only one UAV utilization. The SCR with DBSCAN approach with two UAVs gives higher success rates than the meander scan with two UAVs. In conclusion, using two UAVs contributes positively to increase the spreading rate of the messages.

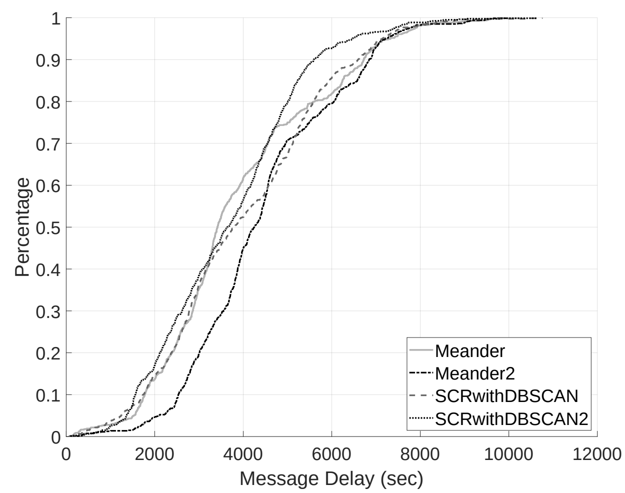

Fig. 18. Cumulative distribution function of message delay on Orlando dataset with two UAVs in the environment.

Figure 18 shows the cumulative distribution function of message delay for the cases with one or two UAVs. The SCR with DBSCAN approach with two UAVs has a lower message delay than the meander scan with two UAVs.

Figure 19 presents the number of packets sent for the cases with one or two UAVs. As expected, for each protocol, the case with two UAVs incur more number of packets sent compared to the case with one UAV usage. The SCR with DBSCAN approach with two UAVs has less number of packets sent than the meander scan with two UAVs, although the difference is small.

The reason for the increased number of packets sent by the nodes comes from the fact that the two UAVs distribute the messages to many different nodes. As the nodes receive new messages, more message exchanges take place during an encounter. Consequently, the increased success rates can be

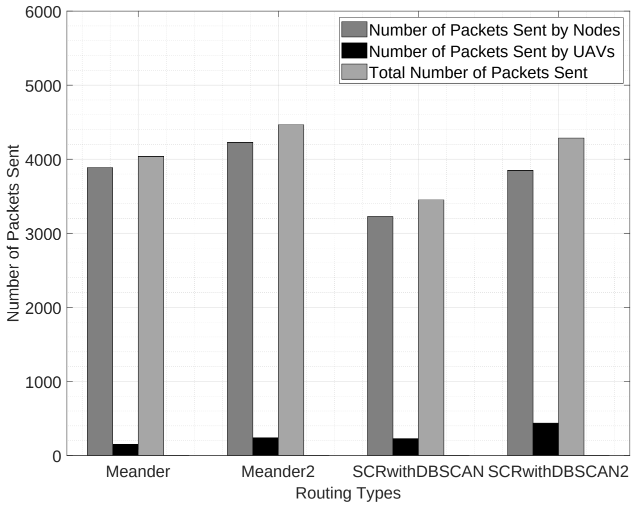

Fig. 19. The number of packets sent for Orlando dataset with two UAVs in the environment.

attributed to the utilization of two UAVs.

The number of packets sent by the UAVs also increases with the increased UAVs. Between the two approaches with two UAVs, SCR with DBSCAN2 has a more increased number of packets sent. Each UAV may acquire messages that the other UAV does not have, causing more new message exchanges. Figure 17 shows an increase in the success rates as expected.

G. *Summary of the results*

The proposed approach was evaluated using the NCSU dataset in terms of spiral density value and message creation frequency. The meander scan was also compared with SCR with DBSCAN approach for two UAVs since the meander scan performed the closest to the proposed approach when there was a single UAV. The a parameter, the spiral density, is tested with different values. The goal was to achieve the best performance in terms of the number of packets sent and message delay. Adjusting the a can be beneficial for trading off between multiple metrics. Changing message creation frequency can also be used similarly. The results show that better message delay results can be achieved if the message frequency is changed every two hours.

Additionally, SCR with DBSCAN and meander scan approaches were evaluated with two UAVs on the Orlando dataset. In terms of the number of UAVs, SCR with DBSCAN using two UAVs outperformed meander scan approach with two UAVs in terms of success rate and message delay metrics.

The SCR with DBSCAN approach gives better results in terms of message delay for KAIST and Orlando datasets. While the SCR with DBSCAN sends a smaller number of packets than the meander scan, it still achieves similar success rates as the meander scan approach. In conclusion, using a UAV was favorable in all the metrics than not using any in an opportunistic environment.

VII. Conclusion

In this paper, State-based Campus Routing (SCR) with Density-based spatial clustering of applications with noise (DBSCAN) protocol with Unmanned Air Vehicles (UAV) in an opportunistic networking was proposed. The proposed approach was evaluated along with meander, random, random spiral scanning techniques, and the SCR and Epidemic protocols without a UAV concerning success rates, message delay, and messages sent. In SCR with the DBSCAN approach, the nodes on the ground are routed through SCR, whereas meander, random, and random spiral scanning techniques use epidemic routing for the ground nodes. KAIST and Orlando datasets were used in our evaluation study.

The future research work may include evaluating additional routing strategies with the proposed approach of SCR with DBSCAN. It would be interesting to see how the message delay and success rate metrics are affected by increasing or decreasing the UAV speed based on different areas.

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