UAV as a Data Ferry for a Sparse Adaptive WSN

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***Abstract*—Using UAVs as mobile data ferries can amplify ground network performance by mitigating the impact of horizontal radio pollution on the environment. Designing an energy-efficient UAV communication with a randomly distributed ground sensors via enhancing the ground network structure dependent to the UAV path has been one of the challenges for the UAV-assisted WSN data gathering efforts. This paper aims at developing an approach called 'UAV Fuzzy Travel Path' that supports UAV smooth trajectory planning in gathering data of distributed wireless sensors over a large space. The dynamic orchestration of ground wireless sensors grouping has been considered in this paper for improving the network performance in data collection. This offers a more dynamic and flexible network that interact with the UAV planned path. Preliminary results of testbed simulations reflect that the proposed software define ground network system has presented promising outcomes in terms of network performances such as network latency and packet delivery rate. Further work is required for testing the scheme on a wider range of software defined WSN and UAV flight formations.**

Keywords—Unmanned Aerial Vehicle (UAV), Wireless Sensor Networks (WSN), Fuzzy UAV route, UAV path Planning

I. INTRODUCTION

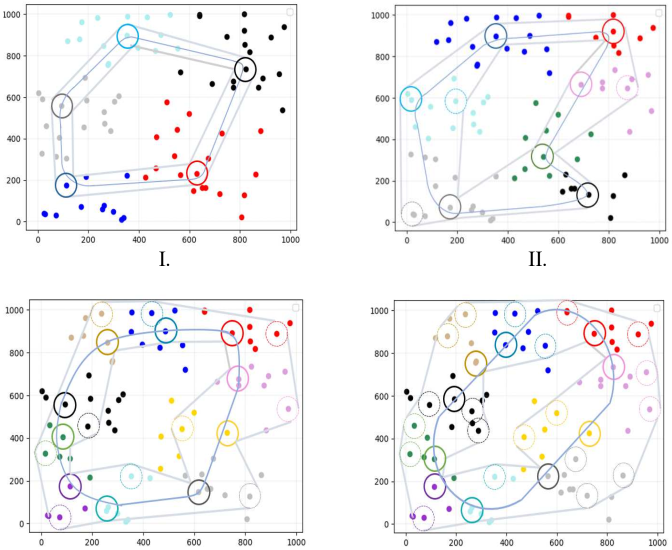
In the last decades, WSNs have witnessed explosive growth among the research hot topics. Radio pollution and energy efficiency are of significant challenges within long range ground network communication. There are various approaches to mitigate the energy usage and radio pollution of ground networks. One solution is through the usage of UAV which offers more flexibility and manoeuvrability in both data capturing and coverage capabilities' used cases. This can significantly reduce the energy consumption of the entire system by timely scheduling the air-to-Ground communication based on the UAV's presence [1]. In this regard, Chiaraviglio, L. et al. [2] have proposed an energy-efficient approach for UAV-aided cellular network used case that provides preferable performances in both throughput maximization and energy optimisation based on realistic scenarios. Considering wireless network energy efficiency and fairness in UAV-enabled data gathering used case, Software-Defined Network (SDN) approach has recently attracted much attention, where the control plane has been separated from the data plane using a central controller such as a cloud computation processor. The control plane carries the logical processes and all relevant decisions regarding managing network structure, while the data plane delivers the packets towards the most appropriate interfaces which is the cloud processing centre. The separation of these two planes allows to route traffic intelligently and optimally reorchestrate the network structures based on the network requirement performances to benefit WSN in terms of network components' energy usages [3]. This paper aims at taking advantage of designing low-complexity and smooth trajectory that enables the UAV to interact with updated SNs representatives through SDN reorchestration process. The main contributions of the paper are summarized as follow. First, we apply the concept of software defined WSN on UAV flight path region called 'UAV Fuzzy Path' considering the ability for dynamic network reorchestration. This offers the flexibility for the UAV path design through the re-election of the gateways within the ground sensor nodes to fit the relaxed path. Next, we utilise a software defined dynamic topology reorchestration process in which the role of network components has been identified based on a proposed fitness model. To facilitate the communication interaction between the UAV and the ground network, an SDN-enabled control/data packet frame has been designed to transfer the control/data plane through both configuration and execution phases. The rest of this paper is organized as follows. In the next section, we discuss previous related works. Section III presents the proposed algorithms. Section IV evaluates the proposed algorithm through extensive simulations. Section V concludes this paper and gives some future work suggestions.

II. RELATED WORK

Numerous studies have dealt with data collection used cases of the UAV from a distributed sensor network where the UAV visits the sensor nodes one by one or through the sensor nodes representatives. The aim is to maximise the network performance by mitigating the risk of high network latency and packet drop rate to identify the shortest UAV path that can serve the maximum data points within the permissible operational link during a limited flight time. To this end, Karunanithy et al. [4] utilised UAV as an intelligent data collector for water irrigation application in which a number of randomly distributed sensor nodes disseminated their data to the UAV based on a suggested UAV-Ground communication structure. To minimise signal attenuation, they proposed a communication transaction diagram in which the UAV initiates the communication by broadcasting a beacon signal to the corresponding SNs. To guarantee that the relevant sensing data packets have been uploaded to the UAV properly, Samir et al. [5] has suggested a novel data collection algorithm from the time constrained IoT devices. However, with rising the number of distributed sensor nodes in the field, the complexity of the system is excessively high that declines the data capturing fairness among the network components. The Software defined Network (SDN) concept has been reflected in multiple applications such as offloading the computation of UAV-assisted vehicles network to execute computationally complex and time-sensitive tasks while at the same time mitigating the risk of higher network latency and packet drop rate [6]. Zhang et al. [7] have also utilised SDN concept at internet of UAVs where the entire network can "forward looking" the uploaded information to potentially idle nodes in order to achieve the optimized system performance [8]. Furthermore, to examine the realistic communication link prior to the real-world implementation testing, there are several methods to virtualise the network behaviour within the cloud [9]. Many researchers now consider WSN virtualization as a key enabling technology in their WSN deployments. Acharyya et al. [10] propose the WSN virtualization unit which utilises Cooja network simulator running the virtual sensor cloud model that supports SDN concept. Al-Hamid et al. [11] suggest the concept of virtualisation for the vehicular network formation and grouping. Moreover, Samir et al. [12] have utilised a novel design for UAV-aided vehicular networks to process fresh information before the carried information loses its value prior to transferring to the UAV. The UAV data gathering method can be enhanced through the analysis of the UAV flight path and the integration with softwarization concept. In our previous work [13], the preliminary idea of fuzzy path approach has been studied. In this paper, the proposed approach considers a geographical grouping structure with one or more representative nodes that can act as ground data collection point(s). Nomination of the active collection points will then be made according to the proposed fitness model design within the cloud. This not only leads to a more efficient and smooth UAV travel planning but can help to route the network traffic fairly. The UAV smooth flight path should be aligned with the updated network structure analysis bringing fairness on the power consumption of gateway capable nodes per round. The scheme has been modelled and tested using Contiki Cooja network simulator.

III. SYSTEM MODEL

UAV based data collection is typically based on either direct communication with individual nodes or through group representative nodes (are referred to as gateways). Based on this arrangement, while the grouping offers more efficient approach for communicating the data, it still restricts the UAV path for collecting the data to limited options once physical topology of each group on ground sensor nodes is set. The question here is, can we relax the options for the UAV path by allowing the gateways to be selected to align with the global data collection path? This allows for the groups topologies to be redefined through software dynamically. Here, the gateways could be software redefined to suite the travel route definition. The above stated concept of creating what we refer to as a 'Fuzzy flight Path' utilizes the capability to software redefine the groups representatives or network topology to align with the UAV flight smooth path. The fuzzy path concept is based on the capability of switching the sensor node from a leaf node functionality to a gateway one. These sensor nodes are referred as gateway-capable nodes. The proposed topology organization eases the UAV path design by bringing the efficient and smooth path within the proposed UAV path fuzzy range and offering the flexibility of adaptive gateway selection closer to the UAV path. An example of smooth UAV path has been shown in Fig.1-IV. The proposed model is highly dependent on the percentage of gateway-capable nodes distribution. As shown in Fig.1 I-IV, the nominated gateways have been represented with solid-line circles for each group while the remining potential gateways have been depicted with dashed-line circles in the network structure.



I.

II.

III.

IV.

Fig.1 the design of fuzzy route and smooth path with various distribution of gateway-capable nodes (from Fig. I to Fig. IV. the distribution of gateway-capable nodes increased)

A. The proposed network communication system

The proposed network communication structure plan is based on dividing the entire system into three main communicating sub-units: Ground Network, Drone, Cloud stations. Ground Network may contain three types of nodes that are identified as three main roles in WSN. These are Leaf, Router and Gateway roles. A given node may have one or more of these roles at the same time. The drone station is the mobile vehicle serves to capture the data from ground and relay it to the cloud over the Internet for real-time post-processing assessments and virtualization of main stations. The network communication messages are split into two main messages: sensing data information messages and control information messages. As the main goal of data acquisition effort is on passing the sensing data information messages, the control information messages have the responsibility to convey the ground network topological configuration data such as election data from the cloud-level to the ground network and assigning the optimal functions to each component of the network in the initial configuration phase. The proposed generic topological arrangement has been depicted in Fig.2. The communication dialogue among the three acting sub-units includes both configuration planning and data collection execution phases. Configuration planning phase aims at:

1. Collecting the control data by the UAV on available gateways and the relevant nodes that can access them and passing the control data to the Cloud.
2. Cloud level analysis of the collected control data and identifying the elected gateways and related network structure and operational parameters.
3. Passing the outcomes of the analysis from cloud to the ground networks within control data information offering the updated ground networks set up.

The data collection execution phase is a subsequent phase running the UAV movement within the designed updated fuzzy route in collecting the ground sensing data.

B. Various roles in the network system

I. Leaf node

These nodes are predefined as leaf nodes prior to the UAV traveling; They are not in direct connection with the UAV either through the control information transmission phase or data gathering phase. Leaf nodes have the key functionality of the data acquisition from connected sensors and passing the sensing data information as well as the critical control information to the upper-level routers or gateways. Leaf nodes also have the capability of being software redefined, both through a given upper-level router or through operational functionalities such as activation or deactivation of a given query or data processing function.

II. Router-Capable node

These nodes have the capability to be software defined as a fully functioned Router node or a reduced functioned Leaf node by the control packets received through the gateway. Once they have been elected as routers, they can transfer the information from other leaf nodes through multi-hop communication protocol to an upper-layer router or active gateway(s). They are assumed not to have direct connectivity with the UAV. Their roles as routers/leaf nodes are assigned by the UAV in the initial configuration phase.

III. Gateway-Capable node

These nodes have the capability to be software defined to act as Gateways, Routers, and/or Leaf nodes. Since they have been distributed in random positions within each group, they can offer different network topologies such as tree or star ones for each group depending on their updated softwarized functionalities. They also define the fuzzy region of the UAV path. Once they have been elected as the Gateways for a given network of sensors, they have been assigned to capture the data information coming from the leaf and router nodes and forward that to the drone in the execution phase. Their roles have been notified by the drone in the configuration phase. In a large-scale distribution of networks, the topological arrangement may consist of more than one node configured as a gateway by the remote cloud server. Although the presence of multiple gateways causes distributed burst of data forwarded to the drone, utilising multiple gateways in a large-scale can help to prevent rapid energy draining of the limited number of gateway-configured nodes, and it improves the reliability by mitigating the risk of the failure of a single gateway. It will also help offering the wider option of UAV fuzzy route where the route can dynamically be changed to suit either the drone flight path or the ground role redistribution in balancing the energy expenditure.

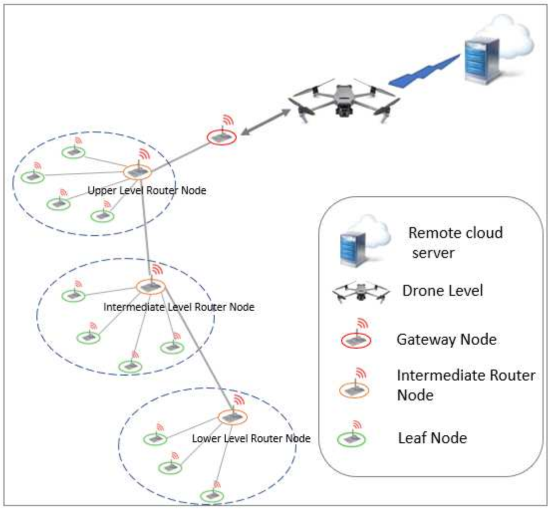


Fig.2 topological arrangement for WSN data gathering

IV. Drone-level

The UAV serves as an access point to the remote cloud server via acting as an upper-level router between the Gateways and the cloud platform (for both upstream flow of control data of the topological setting phase relevant to available regional nodes and the normal operational process of data collection phase and downstream flow of reconfiguration of stations). Once the ground networks are defined, the UAV can resume regular ground sensing data collection.

V. Cloud-level computation

The UAV transfers the status of the ground nodes capability data to the cloud where the decisions for gateway and router elections have been made by utilising a proposed fitness model. Once the decisions have been made, the UAV fuzzy region as well as the elected gateways and routers for each group are assigned to each node's ID within the remote cloud server. Later, the decisions return to the elected routers and gateways as well as their specified leaf-nodes through the notification messages to reorchestrate the ground network configuration. Furthermore, the cloud here is the main station for post-processing of the real-world data information acquired from drone and virtualising the network components and topology.

C. *Communication messages*

The communication among the UAV and ground is based on a set of control/sensing data information messages that needs to be passed over the cloud to either get the network configured during the configuration phase or gather the sensing data through execution phase. The sequence diagram of the messages' transmission within the control and data flow execution phases has been depicted in Fig.3. The communication messages transaction among each network component has been designed as follows:

Once the gateway nodes receive M_{Hello_msg} (message number one in Fig.3) from the UAV, they pass the message to the routers and lower-level leaf nodes to inform about the presence of the UAV. Then the nodes switch their transmitter on to broadcast their initial predefined functionalities (Leaf node, potential router, or potential gateway), along with the sensor's position, the magnitude of $RSSI$ and battery power level which are three criteria on defining the fitness model election over cloud computation (M_{C_UAV} within message number two in Fig. 3). The proposed packet frame format for M_{C_UAV} in UAV-Ground communication is suggested based on Fig. 4. The first message field of the payload within the proposed frame involves the transferring time slot along with the ID of the corresponding Router/Gateway. The next three packet fields involve 'maximum capacity', 'current number of connected nodes' and 'current level' reflecting the updated ground network structure. The 'maximum capacity' packet field places a boundary on the maximum number of supported nodes (leaf or lower-level router nodes) of each router/gateway node. The 'current number of connected nodes' field represents the current number of attached nodes (leaf/lower router nodes) to the router/gateway. The 'current level' message field stands for the level of the corresponding node with respect to the higher-level gateway. Finally, the last three fields consist of the three operational factors associated with gateway/router own data including 'RSSI', 'battery level' and 'relative location' which are the key factors in fitness model decision making. The length of data frame body for M_{C_UAV} is highly dependent on the number of ground networks transferring to the UAV in the initial configuration phase, which is assumed variable here.

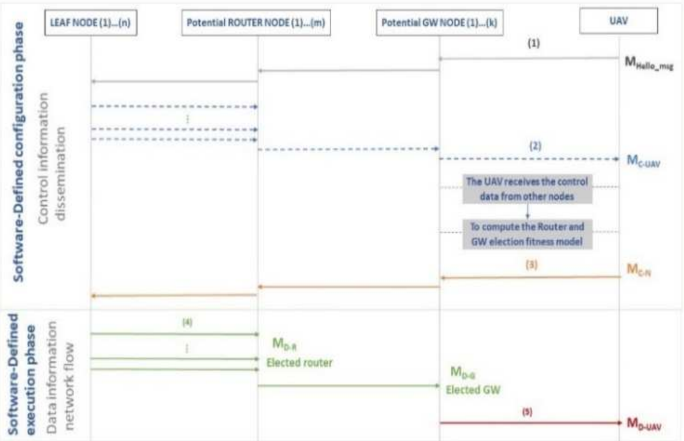


Fig. 3 Sequence diagram illustrating the messages transmission through control and data information dissemination phases

Then, once the election decision has been made within the remote cloud server, the UAV serves to notify the updated elected gateways and routers on their new roles by disseminating M_{C-N} messages (messages number three). The potential routers and gateways that are not selected as router and gateway have been switched over to the role of reduced functioned leaf nodes (M_{C-N} message notifies the updated function definition plus information about the SSID of the lower and upper-level nodes).

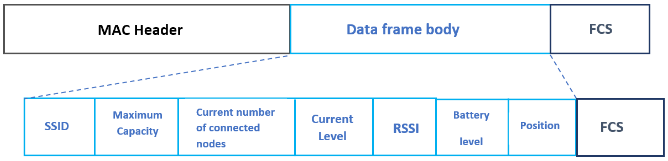


Fig.4 the control packet frame design in configuration phase on UAV-Ground network

The suggested data packet frame for M_{C-N} on notifying on the updated ground functionalities is designed as Fig.5. Besides the 'SSID' segment of transferred packet field in the notification data frame, the 'functionality' packet field represents the updated functionality of the potential node (either Gateway or Router). This packet field consists of 2 octets creating multiple functional messages by utilising a binary code. Furthermore, within the 'SSID Lower-Level' segments, the node IDs of involved leaf nodes or lower routers have been assigned. The 'SSID Higher-Level' packet specifies the ID of a higher-level node either a Gateway or a router. These two segments in the packet frame design reflect the number of updated upper level and lower-level connections per node. These packet frames are relayed to the potential router/gateway nodes in initial configuration phase to redefine the functionality of the potential nodes plus to reorchestrate the entire network structure based on the updated connections among nodes. For assigning the lower-level nodes to the higher-level ones (such as assigning a number of leaf nodes to a specified router), the Euclidean distance among the leaf nodes and the router has been considered for updated groups' formation. The length of data frame body for M_{C-N} is highly dependent on the number of potential routers/gateways distributed in the network, which is considered as variable here.

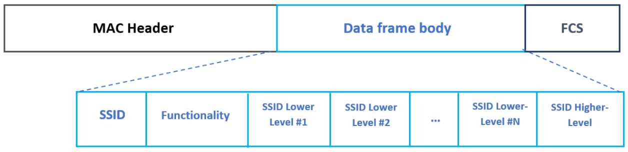


Fig.5 packet frame design for notification messages coming from the UAV to the Ground (Routers and Gateways)

Finally in the software-defined execution phase, once the UAV returns to the elected gateways, the normal flow of sensed data from the leaf nodes relaying to the elected router and gateway (messages number 4) resumes and passes over the UAV (message number 5).

D. Fitness election model

The suggested parameters in the fitness model election process for the involved potential gateways and routers are briefly expressed as: **Link quality based on Radio Signal Strength Intensity (RSSI):** The link quality between a UAV and its neighbour gateways is obtained by using the information of received signal strength indication (RSSI) of received packets. The link quality between UAV and each network component, LQ can be expressed as [6]:

$$LQ_{GWi-UAV} = \left(\sum_{k=1}^{N_{rssi}} \frac{R_k^2}{N_{rssi}} \right) - \left(\sum_{k=1}^{N_{rssi}} \frac{R_k}{N_{rssi}} \right)^2 \qquad (1)$$

Here, N_{rssi} is the total number of RSSI samples received on the UAV from each gateway and R_k is the RSSI value of the k-th sample. Lower the LQ parameter is the higher likelihood of electing as gateway and router node. **Battery power level:** The battery level of each participant router/gateway B_i is another parameter in fitness election model. More the gateway and router participate in the data flow dissemination, the amount of their remained batteries is dropped more. **Fuzzy path distance factor:** The portion of proximity of the UAV smooth path to the gateway-capable nodes d_i is presumed as another factor for gateway/router election process. The intention here is to manipulate the data gathering UAV path to get it closer to the smooth deigned path sequentially which can be done as a part of cloud computation. Consequently, the fitness model for the gateway/router election is mathematically expressed as bellow:

$$W\_election_i = \alpha \times LQ_{GWi-UAV} + \beta \times B_i + \zeta \times d_i \qquad (2)$$

$LQ_{GWi-UAV}$ is the link quality factor of the gateway node ith received on the UAV. B_i is the battery power level of gateway node ith. d_i is the fuzzy path distance factor of gateway node ith. α , β and ζ denote three weights assigned for each of three parameters dependent on the priority of each factor based on the updated network structure.

IV. MODEL TESTING AND EVALUATION

Based on the defined step process of software defined communication system among the network components, the model has been categorized into the proposed major sub processes as following. The preliminary model on ground network has been analysed based on Contiki Cooja network simulator.

A. Software defined configuration phase simulation outcomes

The ground simulation model consists of three groups of nodes (Leaf, Router and Gateway nodes) which are dispersed randomly on the field to pass the control/sensing data information to the UAV and cloud for initial/post processing computations. The communication transactions among one group of sensor nodes considering the initial configuration phase have been illustrated within Fig. 6. The average network latency performance measure has been calculated for each hop by Cooja network simulator. The control packet frame has been defined the same as the proposed packet frame in the last section. As shown in Fig.6, after receiving the M_{Hello_msg} from the UAV on the receiver of each node, the communication transaction is initiated from the leaf nodes to upper levels. In the second round, once the remote server works out on the election of software defined nodes, the UAV returns to inform the elected routers and gateways on their new roles based on the proposed packet frame designed on Fig. 5. On the next round, the network structure is reconfigured based on the new functions allocation and the UAV captures the latest data based on the updated router and gateway node's functionality. Table. 1 has depicted the network performance for the designed configuration phase for one transaction of control data flow.

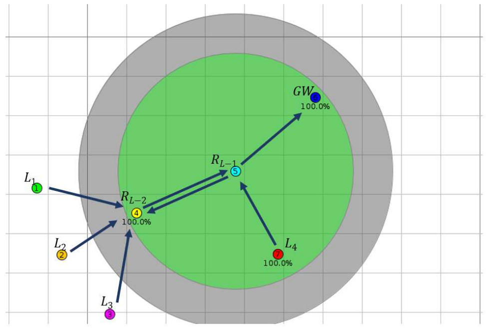


Fig.6 the simulated network architecture for one specified group

Table.1 the network performance for the designed initial configuration phase for one transaction of control data flow

Leaf Node Transmitted Packets	9 Packets			
Router Transmitted Packets	12 Packets + Packets disseminated by other Lower-Level Nodes			
Accumulated Packets Received on GW	33 Packets			
Transmission Rate/Polling Rate (sps)	1 Sample per Second			
Number of Hops	**First Hop Latency**	**Second Hop Latency**	**Third Hop Latency**	**End-to-end Latency**
Average Network Latency (ms)	455	480	535	1520

B. Software defined execution phase simulation outcomes

The air-to-ground communication interaction among the UAV and gateway nodes has been simulated in CupCarbon. It is presumed that the UAV starts its trajectory from a point outside the communication window of gateways and sequentially travels through each gateway's connectivity window and finally departs from the associated window of last gateway. The percentage of the gateway-capable nodes' distribution, D, is scaled up from 5% to 30% of the entire sensor nodes population to evaluate the network communication performance. Furthermore, the impact of UAV velocity on the network efficiency has been assessed. Fig. 7 has indicated the impact of different ranges of UAV speed on the packet delivery ratio starting from $V = 5\ m/s$ to $V = 40\ m/s$. With increasing the UAV speed, the number of dropped packets has been grown, since the UAV has shorter time to communicate with the gateways.

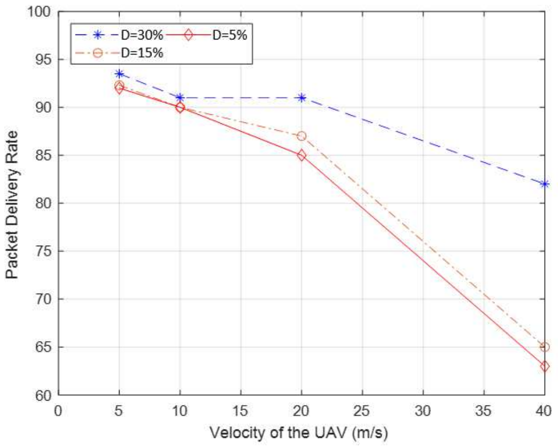


Fig.7 the effect of increasing the speed of the UAV on Packet Delivery Ratio [13]

V. CONCLUSION AND FUTURE WORK

This work introduced a concept that could offer an energy efficient UAV assisted WSN data gathering model. The approach uses software defined network for the distributed sensor networks over large spaces. The dynamic orchestration of the ground network has been contributed by providing flexibility in setting the UAV flight path. This offers potentials for efficient UAV data collection mission in both field coverage and flight energy consumption. The ground network performance has been improved through the WSNs capability for dynamically assigning the data routing nodes based on the UAV trajectory within a region called fuzzy path. For future work, further validation of this concept through fine tuning of the UAV path and WSN dynamics and reducing the overhead required for the dynamic orchestration within various used cases, scales of networks and operation domains will be conducted.

VI. ACKNOWLEDGMENTS

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