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Opportunistic Communications in WSN Using UAV

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***Abstract*—This paper studies the opportunistic routing (OR) in unmanned aerial vehicle (UAV) assisted wireless sensor networks (WSNs). We consider the scenario where a UAV collects data from randomly deployed mobile sensors that are moving with different velocities along a predefined route. Due to the dynamic topology, mobile sensors have different opportunities to communicate with the UAV. This paper proposes the All Neighbors Opportunistic Routing (*ANOR*) and Highest Velocity Opportunistic Routing (*HVOR*) protocols. In essence, ANOR forwards packets to all neighbors and HVOR forwards them to one neighbor with highest velocity. *HVOR* is a new OR protocol which dynamically selects route on a pre-transmission basis in multi-hop network. *HVOR* helps the sensor which has little opportunity to communicate with the UAV to determine which sensor, among all the sensors that are within its range, is the forwarder. The selected node forwards the packet. As a result, in each hop, the packet moves to the sensor that has higher opportunity to communicate with the UAV. In addition, we focus on various performance metrics, including Packets Delivery Ratio (*PDR*), Routing Overhead Ratio (*ROR*), Average Latency (*AL*) and Average Hop Count (*AHC*), to evaluate the proposed algorithms and compare them with a Direct Communication (*DC*) protocol. Through extensive simulations, we have shown that both *HVOR* and *ANOR* algorithms work better than *DC*. Moreover, the *HVOR* algorithm outperforms the other two algorithms in terms of the average overhead.**

***Index Terms*—Wireless sensor networks, unmanned aerial vehicles, mobility, opportunistic routing protocols**

I. Introduction

Unmanned aerial vehicle (UAV) assisted wireless sensor networks (WSNs) are becoming a new attractive communication paradigm in monitoring environmental factors (such as temperature, pressure moisture etc.) and military surveillance tasks. Data collection, in this context, has to be performed on dynamic and disruption tolerant network.

Opportunistic Routing (OR) protocol is essential to the performance and reliability of wireless networks ([1], [2]). OR protocols are different from traditional protocols since they take advantage of the broadcasting nature of WSNs when forwarding packets and selecting routes which can be managed well with unpredictable and unreliable wireless links. They can strengthen the transmission links through combining multiple weak links and enhance the throughput by applying opportunistic transmissions.

One of the major challenges in OR is the maximizing transmission without re-transmissions or incurring significant coordination overhead. Therefore, it is crucial for OR to support diverse traffic patterns, such as multiple simultaneous flows, and achieve significant performance gain in real wireless networks.

In our work, we introduce two new OR protocols, *ANOR* protocol in which the source node will share its traffic to all the neighbors that are within its range and *HVOR* protocol where the source node sends packets to a single node that has the highest speed. *HVOR* dynamically chooses route and determines which sensor is the forwarder and build the connection. The proposed algorithms are compared with *DC* algorithm in terms of delay, overhead and delivery ratio.

The reminder of this paper is organized as follows: Section II introduces the related work. Section III shows an overview on the problem and discusses the motivation of this paper. The new OR mechanisms along with the performance metrics are also discussed in this section. Section IV presents an evaluation to compare the new OR protocols with the *DC* algorithm. Section V concludes this paper.

II. Related Works

Number of researches have been done on OR protocols in wireless networks ([1], [2], [3], [5], [6], [7], [8]). Biswas et al., propose the Extremely Opportunistic Routing (ExOR) [3], which is the most basic one that practically applies the OR into wireless networks. The ExOR arranges the collected packets into different sets with each set has 10 to 100 packets after assignments. Each packet records the potential forwarders ID and selects the forwarding nodes list prioritized according to the ETX [4] mechanism which gives higher priority to the shorter distance (from source node to destination node). Only the ones that have higher priority are listed in the forwarder queue.

ExOR is the first to implement OR in wireless sensor networks, it enhances the performance of the routing. However, it still has a problem on packet re-transmission because it never responds to the nodes that are without transmission time which may causes packet duplication. Minimum Transmission Scheme (MTS) [5] is proposed to minimizes the expected transmission rate. In MTS, the nodes with lower priority can always hear the broadcast of the ones that have higher priority. Based on ExOR, MTS gives fewer transmissions than the ETX.

Energy Efficient Opportunistic Routing (EEOR) [6] selects the forwarder list through the minimum energy consumption metric while broadcasting in the wireless network. EEOR shows an expected calculation for each source node and then

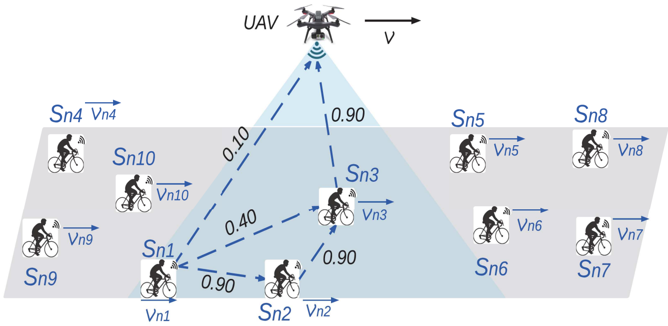


Fig. 1. Scenario with data collection by UAV from mobile WSN.

selects the forwarder list. If a node is selected, its expected cost should less than the ones in the prefixed forwarder list. This mechanism helps the system to achieve the minimum expected consumption. In total energy consumption, the EEOR performs better than ExOR because its cost metrics. Factually, the time consumed by EEOR on sending and receiving data is also less than that of ExOR. Therefore, the EEOR performs better than ExOR in terms of the packets delivery ratio and overhead ratio.

Another energy saving protocol, Energy Saving via Opportunistic Routing (ENS-OR) [8], is proposed to use virtual energy efficient node (EEN) which is obtained from real node through relay function based on residual energy. The nodes that are selected in the forwarder list queue up according to their residual energy and their distance from EEN.

Geographic Random Forwarding (GeRaF) [7] is an opportunistic routing based on geographic location. The source node broadcasts data with its position and destination information. The nodes in the transmission range that receive such information are prioritized to work as forwarders. Then, the selected node relays packets to broadcasting address which also including the information of sender and destination. Thus, GeRaF provides a geographic route without maintaining routing table.

In our scenario, the UAV flies at a given height and speed to collect data from a group of mobile sensors that are moving at the same direction with different velocities. In a previous work [9], we proposed four direct communication algorithms *DC* to collect data from a mobile on-ground WSN. The objective was to maximize the number of collected packets. However, the proposed algorithms only collect data from the nodes that are within the communication range of the UAV. It is unfair to the nodes that are deployed in the same network but have no opportunity to communicate with the UAV.

In this work, we introduce opportunistic communication algorithms (*ANOR* and *HVOR*) for multi-hop wireless sensor networks. In both *ANOR* and *HVOR*, the source nodes that are out of the range of the UAV could send packets through forwarders that are near them. In *ANOR* algorithm, the source nodes transmit packets to the neighbors that are within its range, and in *HVOR*, they only send packets to the one that have the highest velocity. Through simulations and performance metrics, we evaluate the proposed algorithms and compare them with the direct communication scheme.

TABLE I
PARAMETERS

Parameters	Descriptions
r	The communication range of UAV and sensors;
v	The velocity of the UAV;
v_i	The velocity of the mobile sensor S_i ($S_i \in \mathbb{S}$);
h	The fly height of the UAV;
α	The time slot duration;
N	The number of mobile sensors;
N_{ts}	The number of time slots;
P_d	The total number of packets delivered;
P_g	The total number of packets that are generated in time T;
P_r	The total number of relayed packets;
S_{pk}	The packet size;
$Dr(j,i)$	The data rate of sensor S_i ($i \in \mathbb{N}$) in time slot t_j;
$T_{cdt}(i)$	The contact duration time of sensor S_i ($i \in \mathbb{N}$) when it is within the communication range of the UAV;
$d(U, S_i)$	The distance between the UAV and the sensor S_i ($i \in \mathbb{N}$);
$d(S_k, S_i)$	The distance between the sensor S_k and S_i ($k, i \in \mathbb{N}$);
$S(x_{it_k}, y_{it_k})$	The coordinates of sensor S_i ($i \in \mathbb{N}$) in time slot t_k ($t_k \in \mathbb{T}$).

III. System Preliminaries

A. Overview

For the purpose to establish an intuitive understanding for why there might be room for improvement of opportunistic routing in multi-hop WSN using UAV, it is helpful for this paper to introduce the simple scenario in Figure 1. In this scenario, the UAV flying at given height and speed to collect data from sensor nodes that are moving along a predefined path at the same direction as UAV. As the network topology is changing under the mobility of the UAV and the nodes, each sensor has limited opportunities to communicate with the UAV.

Suppose there are a number of mobile nodes, such as S_{n1}, S_{n2}, S_{n3} in figure 1, within the communication range of the UAV in a given moment and S_{n1} wants to transmit its data to the UAV. It can be seen from figure 1 that there is a certain number of different possible routes for S_{n1} to send its packets to the UAV. S_{n1} could directly transmits data to the UAV in one-hop but with low transmission rate. In this situation, S_{n1} has to send each packet many times to avoid packet losses. S_{n1} could also use 2-hop or 3-hop routes through S_{n2} and S_{n3}. However, S_{n1} also needs to re-transmit each packets many times since there are multiple hops.

In fact, each particular route has its own limitation performance on the table. When S_{n1} uses the 3-hop route by sending packets to S_{n2}, S_{n3} and the UAV receives data at the same time. Thus, it is useless for S_{n2} to work as the forwarder and forward such data to S_{n3}. If S_{n1} tries to send its data to the UAV in one-hop, the UAV may lose most of the transmitted data but the S_{n2} and S_{n3} hear it in many cases. Hence, it

TABLE II
DATA RATE

Level	Distance	Data rate
1	(0,20] m	$250Kbps$
2	(20,50] m	$19.2Kbps$
3	(50,80] m	$9.6Kbps$
4	(80,100] m	$4.8Kbps$

would be better for either of them to forward the data to the UAV than S_{n1} to send directly. One of the contributions of our proposed *HVOR* protocol is to take advantage of these opportunities to enhance the network performance.

Furthermore, this paper applies a discrete-time system where the total duration (the same as the UAV flying time) T is divided into N_{ts} time slots and each time unit has a duration of α. The relationship between them can be written as $N_{ts} = \lfloor \frac{T}{\alpha} \rfloor$. The time slots along the path are indexed as $1, 2, \cdots, N_{ts}$, and the set of time slots is denoted by $\mathbb{T} = \{t_1, t_2, \cdots, t_{N_{ts}}\}$. Others, the set of sensors is denoted by $\mathbb{S} = \{S_i | i \in \mathbb{N}\}$ ($\mathbb{N} = \{1, 2, \cdots, N\}$), and their velocities set is referred to as $\mathbb{V} = \{v_i | v_i \leq v, i \in \mathbb{N}\}$. The flying time T is determined by the UAV velocity and the path length.

B. Sensors Mobility

From figure 1 we can see that both the UAV and the sensors are moving, the network topology is changing dynamically along time. Thereby, the nodes have limited contact duration time when they are within the transmission range of the UAV. The relative moving distance between the node S_i ($S_i \in \mathbb{S}$) and the UAV in time slot t_k ($t_k \in \mathbb{T}$) is denoted as $d_k(U, S_i)$. Then, the Contact Duration time (*CDT*) between S_i and UAV, denoted by T_{icdt}, is defined as in equation (1). The parameters that are used in this work are defined in Table I.

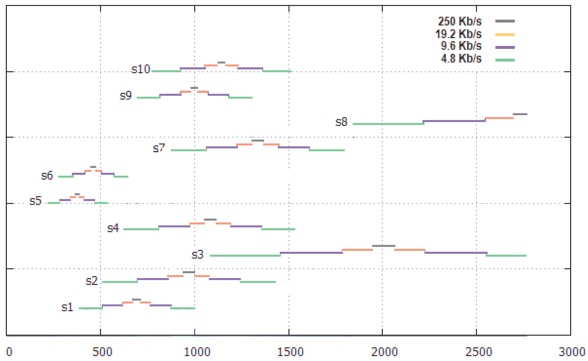
$$T_{icdt} = \frac{d_k(U, S_i)}{v - v_i}. \quad (1)$$

The data-rate between the UAV and nodes depends on the relative distance between them and the relative distance is changing over the time, thereby the data rate is varying with the movement of the network also. Thus, it is unreasonable for the system to use a constant transmission rate among different nodes and different time slots. Here, we adopt a multiple data rate mechanism, which uses 4-pairwise communication parameters setting [10]. The transmission parameters and the corresponding distances are detailed in Table II.

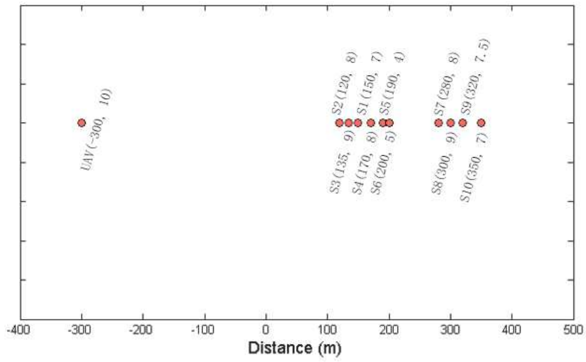
C. Simple Example

From equation (1) we notice that it is unreasonable for the network to select forwarders according to the distance between source node and the destination node in such scenario because T_{icdt} depends not only on the relative distance but also on the relative velocity. Take the simple scenario, which is illustrated in figure 2, for example to show the impact of different parameters.

The contact duration time of each mobile node can be seen from figure 2(a) and the node information are detailed in figure



(a) The contact duration time of each node.



(b) Node information.

Fig. 2. An simple example.

2(b). From figure 2(a) and 2(b), we can conclude that the sensor that has the longest contact duration (S_3) and the one that has the shortest contact duration (S_5) have the highest speed (9 ms^{-1}) and lowest speed (4 ms^{-1}) respectively. From figure 2, we can also notice that, even if the node S_8 is deployed far away from the UAV at the beginning, it still has longer contact duration than S_1 which is deployed near the UAV at the beginning.

However, when the speed of a sensor is almost the same as the UAV, it is possible that the UAV will never achieve the range of the sensor during the duration T when it is deployed far away from the UAV at the beginning. Here, we only consider the speed of the UAV is twice that of the sensors. Thus, the velocity has a significant impact on the *CDT*, and the original position has small impact on it. The *CDT* directly affects the opportunity of the source node to communicate with the UAV. That's why this paper selects the one that has the highest velocity to serve as a forwarder.

D. Opportunistic Routing Algorithms

In this section, we discuss the problem of time slot allocation for UAV connection to the mobile sensors with the highest data rate to communicate with the UAV. Also to allocate the time slot for the communication between sensors and their neighbors. In this work, we proposed *ANOR* and *HVOR* algorithms:

Algorithm 1 HVOR Algorithm

Input: N, V, α, r, h, T, N_{ts}, L, $Width$, $Dr(N_{ts}, N)$ and $N_s(N)$.
Output: R_d, R_0, *AL* and *AHC*.
N_s = 0; j = 1;
while $j < N_{ts}$ **do**
    $T = (j-1) * \alpha$;
    Refreshment of the network:
    for $i = 1 \rightarrow N$ **do**
        Calculate: $S(x_i, y_i)$ and $d(U, S_i)$;
        if $d(U, S_i) <= r$ **then**
            Calculate $Tcdt(j, i)$ and $Dr(j, i)$;
        end if
    end for
    $A = \{S_i \mid S_i \in S$, $Dr(j, i)$ is the maximum$\}$;
    $B = \{S_i \mid S_i \in A$, $Tcdt(j, i)$ is the minimum$\}$;
    t_j allocated to S_{i_0}, ($S_{i_0} \in B$);
    $N_s = N_s + 1$;
    for $i = 1 \rightarrow N$ **do**
        for $i = k \rightarrow N$ **do**
            Calculate: $S(x_i, y_i)$, $S(x_k, y_k)$, $d(S_k, S_i)$ and $d(S_k, U)$;
            if $d(S_k, S_i) < r$ and $d(S_k, U) > r$ **then**
                Calculate $C = \{S_{k0} \mid S_{k0} \in S$, v_{k0} is the minimum $\}$;
            end if
        end for
        In t_j, S_i communicates with S_{k0};
    end for
    j = j + 1;
end while
Calculate: R_d, R_0, *AL* and *AHC*;
End of algorithm.

- **ANOR Algorithm**. The source nodes create routes with all the neighbor nodes that are within its communication range and relay packets to them.
- **HVOR Algorithm**. The source nodes build connections with the one that has the highest velocity among its neighbors. As it is shown before, the one that has the highest velocity has longer contact duration time with the UAV than other nodes, which means it has more opportunities to communicate with the destination.
- **DC Algorithm**. In this situation, the source nodes directly communicate with the UAV when they are within the range of the UAV. Here, we adopt the *DR/CDT* algorithm [9], which gives high priority to the nodes that have the highest data rate first and then gives the priority to the ones that have the lowest contact duration time when the sensors have the same highest date rate. As presented in [9], it is proved by simulation results that *DR/CDT* is an efficient direct communication algorithm.

Here, we present the *HVOR* algorithm for multi-hop data collection problem in Algorithm 1.

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
r	100 m	h	15 m
v	10 ms^{-1}	T	300 s
α	0.2117 s	S_{pk}	127 $Bytes$
$Path$	100 $m\times$ 3000 m	V	(0,5] ms^{-1}

IV. EVALUATION AND SIMULATION RESULTS

This part presents the implementation details. Here, we focus on the performance metrics including packets delivery ratio, routing overhead ratio, average latency and average hop count.

A. Performance Metrics

The performance metrics used to evaluate the proposed algorithms are described as follows:

1) Packets Delivery Ratio (PDR): The packet delivery ratio measures the percentage of the number of packets received out of the number of data packets generated.

P_d is the total number of packets delivered, P_g is the total number of packets that are generated by the sensor network. The *PDR* of the system is computed in equation (2).

$$R_d = P_d/P_g. \tag{2}$$

2) Routing Overhead Ratio (ROR): The *ROR* of the system is the ratio of the total number of packets delivered over the total number of relayed packets during the simulation time T.

P_r is the total number of relayed packets. The *ROR* of the network is given in equation (3).

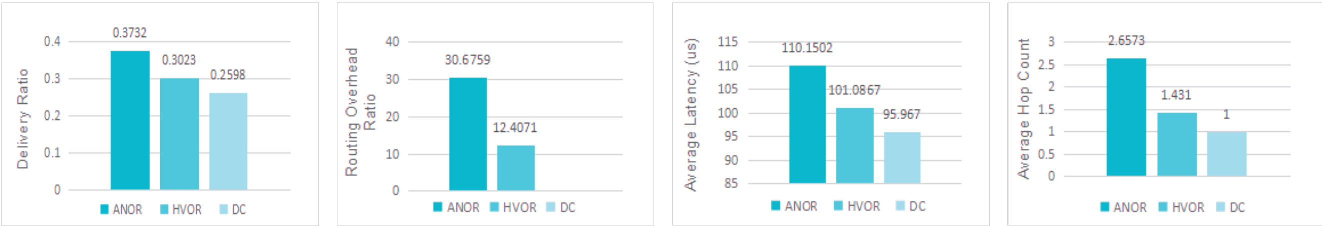
$$R_o = P_d/P_r. \tag{3}$$

3) Average Latency (AL): The *AL* metric measures the average time that the network takes for all the delivered packets to be routed from the source nodes to the UAV. The lower the *AL* is, the better performance the application has.

4) Average Hop Count (AHC): We introduce this metric to measure the average number of hops of each packet used from the source node to the UAV. The hop count metric [12] of a packet generated by a source node (S_i) and delivered to the destination node (UAV) can be defined as the number of intermediate devices (such as routes) through which the packets should pass between the S_i and the UAV and each route along the data path constitutes a hop. In our scenario, the larger the value of *AHC*, the more opportunities for the mobile nodes to transmit packets to the UAV.

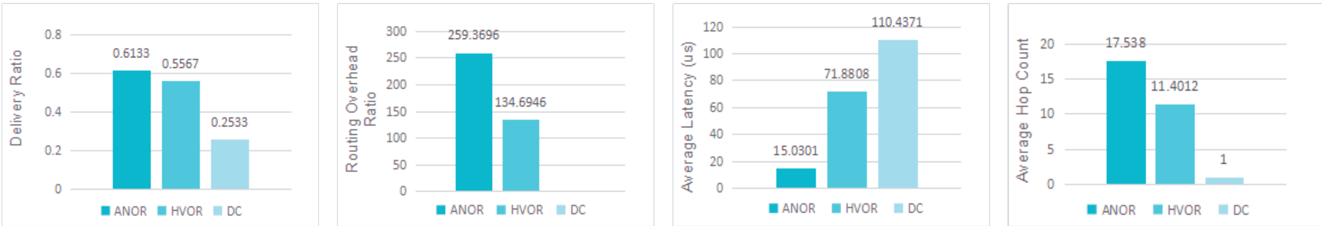
B. Simulation Setup

This paper studies the scenario as illustrated in figure 1, the UAV and the sensors moving in the same direction along a predefined $Path$. The UAV flies at a height (h) with constant speed (v), 200 mobile sensors are randomly deployed on the path and moving with constant but different speeds v_i (v_i ¡ v). The simulation time is T. The duration of time slot is the same definition as in [9]. The simulation parameters are given in Table III.



(a) Packets delivery ratio (*PDR*) (b) Routing overhead ratio (*ROR*) (c) Average Latency (*AL*) (d) Average Hop Count (*AHC*)

Fig. 3. Comparison of *HVOR, ANOR* and *DC*, with continuous generation.



(a) Packets delivery ratio (*PDR*) (b) Routing overhead ratio (*ROR*) (c) Average Latency (*AL*) (d) Average Hop Count (*AHC*)

Fig. 4. Comparison of *HVOR, ANOR* and *DC*, with random generation.

C. Simulation Results and Discussion

This paper uses the Opportunistic Network Environment (ONE) simulator [11], which is an extensible tool for evaluating Delay-Tolerant Networking (DTN) protocols and applications under different types of mobility patterns.

The following simulations use two different event generators: (*i*) Periodically generation traffics (PGT), in which, all the mobile sensors will continuously generate packets per second. (*ii*) Randomly generation traffics (RGT), in which, only one packet will be generated from a random sensor in one second. The PGTs are usually applied in some monitoring applications which need to share the monitoring data once in a while. And RGTs are mostly used in some scenarios such as disaster rescue. In such applications, a session is initiated when the nature disaster occurs and a rescue work is triggered.

1) Periodically generation traffics (PGT): Figure 3 shows the simulation results when each sensor generates one packet per second. So, for 300 seconds of simulation, we have a total of 60.000 packets generated. From the figure, we notice that when the number of connections between sensors increases, all the metrics increase.

In figure 3 we notice more connections between sensors are created, more packets are relayed and delivered (figure 3(a)), thereby more sensors have the opportunity to send packets to the UAV. In figure 3(c), we can see that the average latency also increases as the number of connections increases. This is because more connections help more packets to be delivered. In addition, all delivered packets that have the larger *AHC* (*AHC* ¿ 1) in this scenario, also have a larger latency value.

From figure 3(b), we also notice that when sensor nodes relay their packets to all neighbors that are within its range (*ANOR* algorithm), there is a significant growth of the overload ratio and this is not recommended in any network. The difference between the other metrics obtained for each metric (*AL* and *AHC*) is not as significant as the difference on the overhead ratio.

2) Randomly generation traffics (RGT): Figure 4 shows the simulation results in RGT case. In this scenario, the system only have one packet generated per second by a random sensor node. Hence, in 300 seconds of simulation, we will have a total of 300 packets generated.

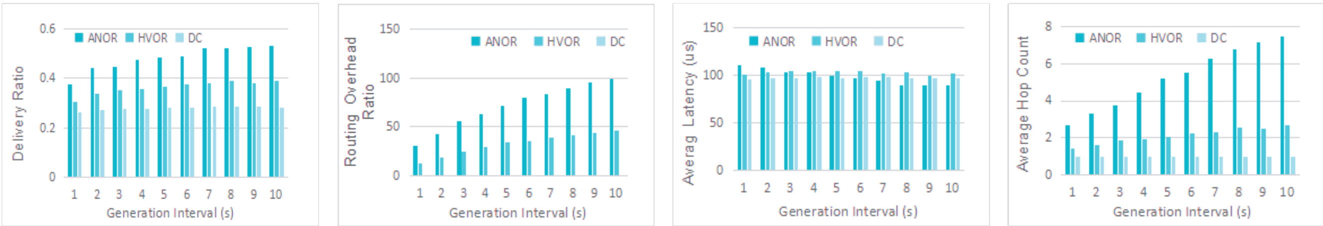
We notice that when the number of connections between sensors increases, all the metrics increase excepting the average latency (figure 4(c)). The explanation of this phenomenon is that the network only have a small amount of packets. Thus, they will be delivered faster when there are more connections between the sensors. If there is no connections (*DC* case) between nodes, the generated packets will wait in the sensors queue until the sensors are within the communication range of the UAV.

From figure 4(c), we also notice that the overhead has greater values than in the figure 3(c). This is because, in this scenario, the number of created messages is significantly less than the number of relayed messages.

Compare the results of *HVOR* and *ANOR* schemes with the results of *DC* algorithm, it is also obvious that, multi-hop transmissions in such scenario perform better than (*DR/CDT*) direct transmission.

3) The impact of traffic load with PGT: Factually, the above simulations apply a very high generation metric (the sensor nodes generate one packet per second) when it tends to be low in practical applications.

In this subsection, we study the impact of the traffic load on the proposed performance metrics. We increase the interval



(a) Packets delivery ratio (*PDR*) (b) Routing overhead ratio (*ROR*) (c) Average Latency (*AL*) (d) Average Hop Count (*AHC*)

Fig. 5. The impact of traffic load on the *HVOR, ANOR* and *DC* protocols.

of one second to see how the metrics (*ROR, AL* and *AHC*) will change. Taking the traffic load value '5' in figure 5 for example, the '5' means that each sensor will generate one packet every five seconds.

From figure 5(a), we can see that the delivery ratio tends to increase when there are less packets in the network. We also notice that the more connections, the more visible increase.

We can conclude from figure 5(b) that the routing overhead ratio increases as the the generation interval increases. The longer the generation interval, the more relayed packets, the higher routing overhead ratio. From figure 5(d) we find that the *AHC* has the same evolution as the overhead ratio. This is because of the relayed packets, less packets generated, more relayed packets.

Figure 5(c) presents the evolution of the average latency. Here, we can see an interesting combination of the above scenarios latency results. We notice that the more packets generated, the greater the latency is. This is because there are more connections for flooding. However, when sensors generate less packets, the average value tends to decrease because the number of connections increases. Thats why for the first simulations, when the interval of generated packets is shorter than 5 seconds, *ANOR* metric has the highest latency, and then when the interval between generated packets increases, directly communication has the highest latency and *ANOR* metric has the lowest latency.

Consequently, we can conclude that when sensors generate more packets, the latency increases when the number of connections increases, but when the sensors generate less packets, the latency decreases when the connections number decreases. The *HVOR* algorithm refers to multi-hop WSN outperforms the other two schemes in terms of the evaluated performance metrics.

V. Conclusion

In this paper, we presented *ANOR* and *HVOR* mechanisms. They are opportunistic routing schemes that dynamically select forwarder in UAV-assisted WSN. We apply the performance metrics, including Packets Delivery Ratio, Routing Overhead Ratio, Average Latency and Average Hop Count, to evaluate the proposed algorithms and compare them with Direct Communication algorithm. Results from simulation show that the multi-hop transmissions are better than direct communications. By having flooding in the on-ground sensor network, we maximize the number of collected packets and also the opportunities for each sensor to send at least one packet to the UAV. But also, taking into account the overhead average value, we can conclude that *HVOR* algorithm is a better choice for a multi-hop transmission in a UAV-assisted WSN application.

Since the proposed algorithms are concentrated on the opportunity to communicate with the UAV, we are planning to develop a performance metric to evaluate the packet queue size along with the transmission capacity between the sensors that have high speeds and the UAV.

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