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Fairness-Aware UAV-Assisted Data Collection in Mobile Wireless Sensor Networks

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***Abstract*—In this paper, we study data collection in mobile wireless sensor networks (WSNs) assisted by unmanned aerial vehicle (UAV). We focus on randomly deployed mobile sensors along a predefined path with different but constant velocities, and a flying UAV in different heights to collect data from the mobile sensors. As the network topology is changing under the mobility of the UAV and the sensor nodes, the design of efficient data collection protocols is a major concern. In this paper, we propose four data collection algorithms taking into account the multi-data-rate transmissions (DR) and the contact duration time (CDT) between the sensors and the UAV. Besides, we propose a fairness metric to evaluate the algorithms. Through extensive simulations, we examine the effectiveness of the proposed algorithms under different configurations and show how the algorithm combining DR and CDT outperforms the others in terms of number of collected packets and weighted fairness.**

***Index Terms*—Wireless sensor networks, Unmanned aerial vehicles, Mobility, Data Collection, Fairness**

I. INTRODUCTION

UAV applications have gained more and more interest due to the need of sensing in the regions where there is no need to human interactions or that are dangerous for human operators (e.g. wilderness search and rescue [1]). Sink mobility in WSNs has been extensively studied ([2]–[6], [9]–[12]), and data collection protocols play a critical role in ensuring low packet loss rate, low communication latency, and high throughput. Traditional data collection schemes assume that nodes are deployed statically (e.g. [3], [6], [10]), and most of them are considered in WSNs with mobile sensors only [4] or with flying UAV only [5]. Indeed, the combination of UAVs and mobile sensors have board applications such as detecting on maritime or rescuing in wilderness where the targets are moving. However, the data collection issues combining UAVs and mobile sensors were not covered in the literature. This is the emphasis of this paper.

The existing data collection protocols are mainly based on traditional mobile sinks that they are usually moving on the ground with lower speeds and static sensors. However, the scenario studied in this paper considers the UAVs that differ with mobile sinks as they fly at given heights and speeds, and the sensor nodes are moving also. Thus, the network topology is rapidly changing. Hence, there have been some limitations if existing data collection protocols are fully applied in this scenario. One common weakness is the very short contact duration time which rises a limited collection. Thus, maximizing the received data from the dynamic network becomes the primary issue.

Moreover, most of existing data collection protocols aim to improve various performance metrics of static networks. Wei et. al [5] apply multi-UAVs to collect data from static sensors with the objective to minimize the average sensing time of each sensor. Ren et. al [12] use a mobile sink and multi-data-rate schemes to maximize data collection on static nodes. They divide the collecting time into equal time slots and allocate them according to the data rate of the covered sensors. Indeed, the data collection maximization has two meanings: maximizing the use of time slots and maximizing the number of sensors that transmit at least one packet during the collecting time.

This paper concentrates on the data collection issues of UAV-assisted mobile WSNs. Considering that the curve trajectory can be decomposed into multiple linear motion trajectories, and the distance between UAV and interesting areas can be maintained by changing the flying height, this paper will study the basic unit of motion. That is the UAV and mobile sensors are moving along a predefined linear path with different velocities. The sensors are deployed on mobile vehicles, such as bicycles, which are used in our simulations. The simultaneous movement of UAV and bicycles greatly degrades the dynamic performance of the system. To overcome the dynamics of the network topology, our schemes refresh the network information through time. Our main contributions are summarized as follows:

- We proposed a UAV-assited scheme to collect data from mobile sensors that are randomly deployed in an interesting area.
- We study the impact of UAV velocity, flying height, sensors density and velocities, and then mathematically formulate the data collection problem into the optimization with the objective of maximizing the number of collected packets and the number of sensors that successfully send at least one packet.
- To solve the problem, we combine the multi-data-rate schemes and the contact duration time to provide four algorithms: DR, CDT, DR/CDT and CDT/DR.
- Furthermore, we define a weighted fairness metric (weighted fairness regarding the collected packets and regarding the number of allocated time slots) to evaluate the fairness of the four algorithms.

- Through extensive simulations, we examine the effectiveness of the proposed algorithms under different configurations and show how the algorithm combining DR and CDT outperforms the others regarding the number of collected packets and the weighted fairness.

The reminder of this paper is organized as follows: In the next section, we discuss previous related work. Section III presents the system model and the proposed data collection algorithms. Data collection, weighted fairness, and relevant simulations are formulated, in Section IV. Section V concludes this paper and gives some future work suggestions.

II. RELATED WORKS

In traditional WSN architectures, sensors are considered to be static and battery powered. Thus, energy consumption of sensors is the most precious resource. Data collection in these static networks, is based on multi-hop data propagation. The neighbor nodes to the static sink, relay data from the nodes that are far away from the sink. The existing of the relay nodes directly results in a fast death of the network because the relay nodes lose energy faster and die faster than the other nodes. Then the MSKs (mobile sinks) are introduced to reduce and balance energy consumption by traveling among the whole interesting area.

The main role of MSKs is to gather data from static sensor nodes. MSKs could be classified into mobile collectors and mobile relay nodes, according to its role in WSNs. Maximum Amount Shortest Path (MASP) [10] was proposed for a dynamic network with MSK as a mobile collector in the sensing path. MASP scheme divided the sensing path into two parts: MCA (Multi hop Communication Area) and DCA (Direct Communication Area). One part is for communicating directly, and another one is for sub-sink. The MSK identifies the static nodes that are within its communication range: either sub-sinks or communicating static nodes and the MSK collects data only from sub-sinks. Jain et. al [6] provide a data collection algorithm that apply the middle node as a relay node, in their three tier scenario. The upper node is the destination node. The relay node is responsible for collecting information from the lower node and forward them. However, they are mostly concentrate on static networks.

UAVs have been widely used in many fields (military, commercial and civilian activities) as MSKs. The main functionalities of UAVs are maintaining connectivity, localization, and data collection. Maintaining connectivity is the essential functionality of UAVs, especially when UAVs are applied in harsh terrains (e.g. snow mountains, highly dense forest, vast and hot desert, etc.) [11] where it is difficult for the normal MSKs to operate. Kuiper et. al [7] combine position scheme and beacon-less strategy to maintain the intermittent connections in ad hoc networks. Localization was committed as an important functionality of UAVs in tracking or monitoring applications [9]. Typically, localization is carried out after the deployment of sensor nodes and the traditional techniques are based on the use of GPSs. The UAVs are equipped with GPSs and fly over the sensing area to estimate the geographical position of nodes [8]. Data collection is the crucial functionality of UAVs because the limited buffer space of sensor nodes may result in the data loss if the nodes have to wait for a long time to communicate.

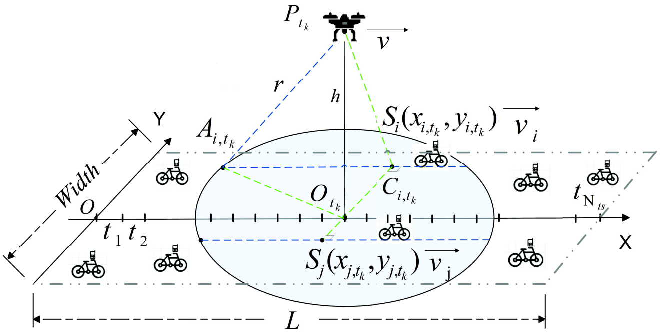


Fig. 1. An illustration of time slots covered by sensors S_i and S_j.

Based on UAV-assisted WSNs, some researches have been done on data collection. Wei et. al [5] applied multi-UAVs and proposed IBA-IP (Iterative Balanced Assignment with Integer Programming) algorithm to collect data from static sensors. They apply Genetic Algorithm (GA) to facilitate the WSN to deploy the UAVs and evaluate the connectivity of UAVs. They object to minimize the average upload time cost of all the sensors. However, in some special applications (e.g. wilderness search and rescue [1]), the importance of maximizing the collected data from the sensing area is no less than to minimize the average upload time. Ren [12] provide a mechanism for this maximization problem.

Generally, they are committed to collecting data from static networks. This paper takes into account the multi-data-rate scheme and the contact duration time to maximize the number of collected packets from mobile sensors and share the communication opportunity with the UAV as fair as possible. Indeed, if the local time slot is allocated to the one that has the highest data rate or the one that has the lowest contact duration time, it can maximize data collection during the collecting time. Focused on data collection in high mobility, we provide four algorithms based on two factors and define the weighted fairness metric to evaluate the four algorithms.

III. UAV-ASSISTED DATA COLLECTION

A. System Model

This paper considers a UAV-assisted mobile sensor network which has N mobile bicycles equipped with N mobile sensors. $S = \{S_1, S_2, \cdots, S_N\}$ is a set of mobile sensors. Bicycles are deployed along a predefined path (Figure 1). The UAV is flying along this path with a velocity v to collect data from the mobile sensors. The sensor S_i has the velocity v_i, and $V = \{v_1, v_2, \cdots, v_N\}$ is the set of sensors velocities. Finally, $S_i(x_{i,t_k}, y_{i,t_k})$ is the coordinate of S_i in time slot t_k, and its corresponding initial position is $S_i(x_{i0}, y_{i0})$.

Given the path length L, the total flying time T of the UAV is determined by the UAV and the bicycles velocities.

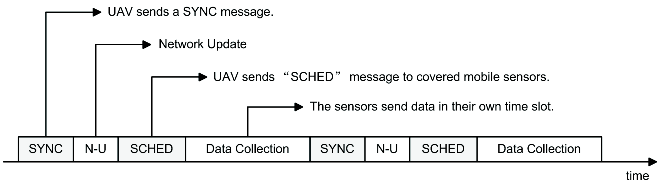


Fig. 2. The procedure of allocating.

Moreover, we consider a discrete-time system where the total flying time is divided into N_{ts} time slots with each lasting α time units: $N_{ts} = \lfloor \frac{T}{\alpha} \rfloor$. Assume that the time slots along the path are indexed as $t_1, t_2, \cdots, t_{N_{ts}}$ (Figure 1).

According to Figure 1, the mobile sensors that are covered by the UAV and deployed nearly (e.g. S_i and S_j.) share some time slots at which both of them can transfer their data to the UAV. In other words, multiple sensors that are sharing the same time-slot compete for it to communicate. Hence, how to allocate N_{ts} time slots to the optimal mobile sensors so as to maximize the data collection is a challenging task. One of our contributions is to provide allocation algorithm so that each time slot is allocated to one mobile sensor only with the objective to maximize the amount of the collected data by the UAV.

B. Data Collection Protocols Using UAV

Here, we present a distributed solution for the data collection maximization problem as follows. The collecting time T is divided into N_{ts} time slots. As it is shown in Figure 2, at the beginning of every time slot, UAV sends a *SYNC* message to tell the mobile sensors that UAV is coming. Then, the UAV updates the network. The new comers in current coverage send *JOIN* messages including their coordinates and velocities to the UAV. The UAV detects whether the mobile sensors are within its communication range or not according to the *JOIN* information, and then calculates the contact duration time, data rate, and potential time slots for each mobile sensor that are within its coverage. According to the time slot allocation algorithms that we proposed in III-E, the UAV provides a scheduling for the covered sensors, and broadcasts them a *SCHED* message which contain the assignments of the time-slots. Having received the *SCHED* message, every sensor transmits its data in its own time slots.

However, it is inappropriate to calculate the time of the UAV sends the *SYNC* and *SCHED* to covered sensors and updating network time because of the high mobility of the network and the number of new coming sensors is unpredictable. We will study the problem in the future, and this paper will pay full attention on data collection part.

C. Multi-rate Mechanism

The communication performance is affected by path loss, interference, and shadowing, etc. The data-rate depends on the distance between the sensors and the UAV, which leads to have different data rates in different time slots for the sensors. In fact, the data-rate is changing with the moving of UAV and mobile sensors even in the same time slot. Hereby, we use the mean data-rate in current time slot. $Dr_{ji} \propto \frac{1}{d_j(U,S_i)}$, is determined by the distance between UAV and S_i in time slot t_j. This paper adopts a 4-pairwise communication parameters setting, where the transmission parameters and corresponding distances are: $250Kbps$ when $r \in (0, 20]m$, $19.2Kbps$ when $r \in (20, 50]m$, $9.6Kbps$ when $r \in (50, 120]m$, and $4.8Kbps$ when $r \in (120, 200]m$ [12].

TABLE I
PARAMETERS

Parameters	**Descriptions**
r	The communication range of the UAV and the mobile sensors;
v	The velocity of the UAV;
v_i	The velocity of the mobile sensor S_i $(i = 1 \rightarrow N)$;
h	The height of the UAV;
α	The duration time of one time slot;
N_s	The number of sensors that send at least one packet in time T;
S_{pk}	The packet size that the mobile sensor send to the UAV;
$Dr(j, i)$	The data rate between sensor S_i $(i = 1 \rightarrow N)$ and the UAV within time slot t_j $(j = 1 \rightarrow N_{ts})$;
$T_{cdt}(i)$	The contact duration time of sensor S_i $(i = 1 \rightarrow N)$ when it is within the communication range of the UAV;
$w(i)$	The weight of contact duration time of sensor S_i $(i = 1 \rightarrow N)$;
$N_{pk}(i)$	The number of packets that the UAV has collected from sensor S_i $(i = 1 \rightarrow N)$ in time T;
$N_{ts}(i)$	The number of time slots that sensor S_i $(i = 1 \rightarrow N)$ was allocated in time T;
$d_k(U, S_i)$	The distance between UAV and sensor S_i $(i = 1 \rightarrow N)$ in time slot t_k $(k = 1 \rightarrow N_{ts})$;
$Tcdt(j, i)$	The contact duration time of sensor S_i $(i = 1 \rightarrow N)$ within time slot t_j $(j = 1 \rightarrow N_{ts})$;
$Npk(j, i)$	The number of packets that the UAV has collected from sensor S_i $(i = 1 \rightarrow N)$ within time slot t_j $(j = 1 \rightarrow N_{ts})$;
$Ntss(j, i)$	$Ntss(j, i)$ = 1 means that time slot t_j is allocated to sensor S_i;
$S_i(x_{it_k}, y_{it_k})$	The coordinates of sensor S_i $(i = 1 \rightarrow N)$ in time slot t_k.

D. Contact Duration Time Calculation

During the collecting time, mobile sensors have the opportunity to communicate with the UAV when it is within their communication range. Thus, every mobile node has limited contact duration time because of the network dynamicity. Considering the scenario illustrated in Figure 1, for example, to show the calculation of the contact duration time.

This paper assumes that the UAV and mobile sensors are equipped with the same communication technology. (e.g. ZigBee/IEEE-802.15.4, etc.). Consequently, when the UAV is within the mobile sensors communication range, the mobile sensors are also within the UAV range. We also assume that the velocity of UAV is not smaller than the mobile sensors velocities. The parameters that are used in this paper as defined in Table I.

In Figure 1, $O_{t_k}C_{it_k} = y_{i0}$, $O_{t_k}P_{t_k} = h$, $P_{t_k}A_{it_k} = r$, the relative distance between S_i and UAV in time slot t_k is: $d_k(U, S_i) = \sqrt{r^2 - h^2 - (y_{i0})^2} - x_{it_k} + x_{t_k}$. Thus, we can get the contact duration time of S_i from equation (1),

$$T_{icdt} = \frac{d_k(U, S_i)}{v - v_i}, i = 1, 2, \cdots, N . \tag{1}$$

E. Time Slots Allocation Algorithms

The data collection problem is to maximize the number of collected packets by the UAV through allocating the N_{ts}

Algorithm 1 DR/CDT Algorithm

```
Initialization: $N$, $V$, $\alpha$, $v$, $r$, $h$, $T$, $N_{ts}$, $L$, $Width$, $w(N)$, $Tcdt(N_{ts}, N)$, $T_{cdt}(N)$, $Dr(N_{ts}, N)$, $Npk(N_{ts}, N)$, $N_{pk}(N)$, $Ntss(N_{ts}, N)$ and $N_{ts}(N)$.
$N_s$ = 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 $S_{i_0}$, $(S_{i_0} \in B)$;
    $N_s = N_s + 1$;
    Calculate: $Npk(j, i_0)$, $Ntss(j, i_0)$;
    j = j + 1;
end while
for $i = 1 \rightarrow N$ do
    Calculate: $N_{pk}(i)$, $N_{ts}(i)$, $T_{cdt}(i)$ and $w(i)$;
end for
Calculate: $WF_{pk}$ and $WF_{ts}$;
End of algorithm.
```

time slots to individual mobile sensors under the multi-data-rate mechanism. Hence, we consider two factors: the first is allocating the time slot to the sensor that has the highest data rate to maximize its usage. the second is trying to allocate the time slot to the one that has the lowest contact duration time so as to collect data from mobile sensors as much as possible. Here, we proposed four algorithms:

- DR Algorithm. It gives high priority to the sensor that has the highest data rate.
- CDT Algorithm. It gives high priority to the sensor that has the lowest contact duration time.
- DR/CDT Algorithm. It gives high priority to the sensors that have the highest data rate first and then gives the priority to the sensors that have the lowest contact duration time for the sensors that have the same date rate.
- CDT/DR Algorithm. It gives high priority to the sensors that have the lowest contact duration time first and then gives the priority to the sensors that have the highest data rate for the sensors that have the same contact duration time.

In Algorithm 1, we present the DR/CDT algorithm for data collection maximization problem.

IV. PERFORMANCE EVALUATION

The purpose of our simulations is to evaluate the effectiveness of our design. In order to establish whether the proposed algorithms really has a positive impact on the data collection process, we opted to study its performance in terms of number of collected packets and fairness. In this study, we have not studied the energy efficiency of the algorithms. Moreover, even if the sensor nodes are assumed to be mostly-on during the data collection phase (i.e., when they are within the range of the UAV), we can easily claim that sensors save energy by going to sleep mode when they are out of the range.

A. Collecting Packets

In this paper, allocating the N_{ts} time slots to individual mobile sensors under multi-rate mechanism is equivalent to maximizing the usage of time slots, that's the generalized assignment problem (GAP) [13].

Given N_{ts} time slots, N mobile sensors, and a predefined path L. Each time slot t_j, there are N_{tj} mobile sensors, potentially available for the allocation of the time slot t_j, where Dr_{ji} is the average data rate of mobile sensor S_i if it does transmit its packets at time slot t_j. Let,

$$Ntss(j, i) = \begin{cases} 1 & if\ t_j\ is\ allocated\ to\ S_i\,, \\ 0 & otherwise. \end{cases}$$

The data collection maximization problem is to maximize P (equation 2),

$$P = \sum_{i=1}^{N} \sum_{j=1}^{N_{ts}} Ntss(j, i) \cdot Dr_{ji} \cdot \alpha\,. \tag{2}$$

B. Weighted Fairness

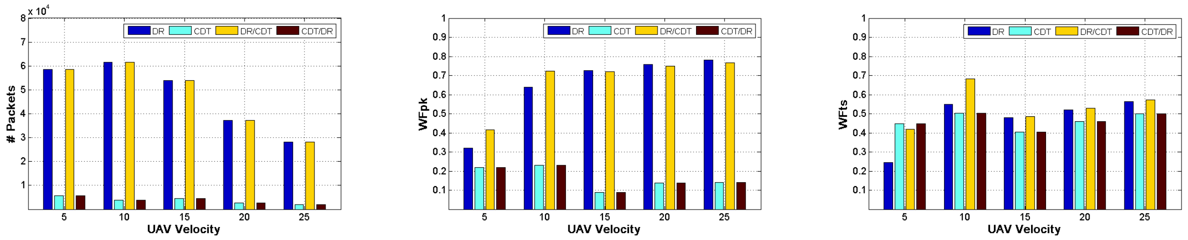
Fairness is a key question under high mobility context. Indeed, each mobile sensor should communicate in all available time slots to take full advantage of the data collection from the entire network. Meanwhile, some mobile sensors share some time slots at which they could communicate with UAV. However, the UAV can communicate with only one sensor in any given time slot otherwise a collision occurs. Thus, fairness plays a key role in evaluating the four algorithms.

In the design of fairness, we only take into account the mobile sensors that have successfully transmitted at least one packet during the collection time. In this scenario, the sensor nodes are moving and are randomly deployed, and, therefore, they may have different contact duration times and the number of sent packets should be proportional to the contact duration time of every node. Therefore, weighted fairness regarding the contact duration time is required when evaluating the fairness of the proposed algorithms. For sensor S_i, $w_i = \frac{T_{cdt}(i)}{T}$, we define the weighted fairness as follows,

$$WF_{pk} = \frac{(\sum_{i=1}^{N} N_{pk}(i) \cdot w(i))^2}{N_s \cdot \sum_{i=1}^{N} (N_{pk}(i) \cdot w(i))^2}\,, \tag{3}$$

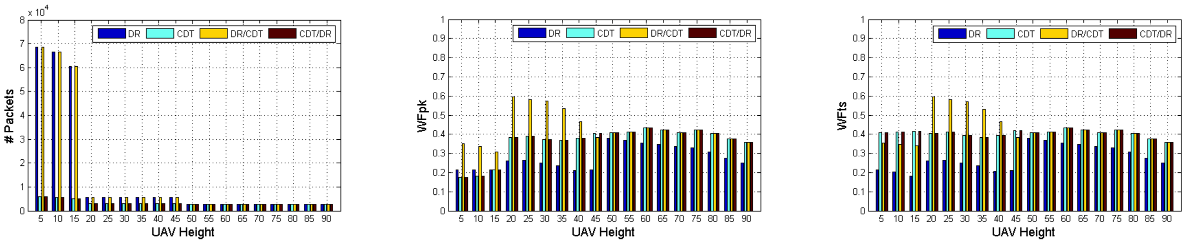
$$WF_{ts} = \frac{(\sum_{i=1}^{N} N_{ts}(i) \cdot w(i))^2}{N_s \cdot \sum_{i=1}^{N} (N_{ts}(i) \cdot w(i))^2}\,. \tag{4}$$

WF_{pk} evaluates the fairness that every mobile sensor transmitted packets during the collecting time. The larger value of WF_{pk}, the greater value of fairness for mobile sensors that transmit at least one packet. WF_{pk} = 1 means they send the same number of packets during time T. WF_{ts} evaluates the opportunity that every mobile sensor had to communicate. The larger value of WF_{ts}, the greater value of fairness for mobile sensors that transmit at least one packet. WF_{ts} = 1 means the N_s mobile sensors were allocated with the same number of time slots.



(a) #Packets (b) WF_{pk} (c) WF_{ts}

Fig. 3. The impact of UAV velocity on #Packets, WF_{pk} and WF_{ts}.



(a) #Packets (b) WF_{pk} (c) WF_{ts}

Fig. 4. The impact of UAV height on #Packets, WF_{pk} and WF_{ts}.

C. Simulation Results and Discussion

The following simulations conduct with UAV and sensors moved within a predefined path. This paper consider the main criteria, UAV velocity and height, sensors mobility and density, which have impacts on data collection. The simulation parameters applied in this paper are presented in Table II. The time slot is considered as the time that the mobile sensor need to successfully send one packet with the lowest data rate (4.8 Kb/s). Hence, $\alpha = t_{pk} = \frac{S_{pk}}{D_r}$. The other parameters for each simulations will be described in detail in the following parts.

TABLE II
SIMULATION PARAMETERS

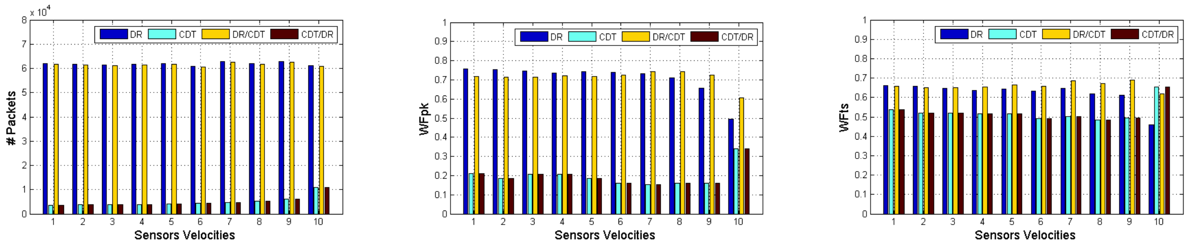
Parameter	Value	Parameter	Value
r	100 m	Path	10 m × 3000 m
α	0.2117 s	Packet_Size	127 $Bytes$

The purpose of our simulations is to evaluate the effectiveness of our design in terms of number of collected packets and weighted fairness. Under all these simulation settings, we collected and averaged the results of 30 simulation runs. The simulations are implemented on MATLAB, and the results are endorsed by NS3 simulations.

1) The impact of UAV's velocity: In this scenario, the UAV flies at 15 m, and its velocity varies from 5 ms^{-1} to 25 ms^{-1} considering the upper-bound. Meanwhile, sensors velocities can not be greater than the minimum speed of UAV. Thus, this simulation varies their velocities from 0 ms^{-1} to 5 ms^{-1}.

Figure 3(a) shows that DR and DR/CDT algorithms have absolute advantages on data collection compared with CDT and CDT/DR algorithms. The number of collected packets by DR and DR/CDT is increasing as the UAV speed increases till 10 ms^{-1}. Beyond 10 ms^{-1}, the number of collected packets is decreasing as UAV speed increases. Indeed, when the UAV velocity is closely to the sensors velocities, the UAV will miss many sensors that are deployed faraway from the beginning where the UAV flies. Thus, the larger the UAV velocity is, the more opportunity the UAV has. In contrast, if the UAV velocity is much faster than sensors speeds, the contact duration time will be very short between them, then the collected value decreases as UAV velocity increases. The number of collected packets by CDT and CDT/DR algorithms are steadily down as UAV velocity climbs because CDT and CDT/DR algorithms give priorities to the contact duration time which steadily decreases as UAV velocity increases.

Figure 3 (b) and (c) demonstrate that both DR and DR/CDT algorithms work better than CDT and CDT/DR algorithms. From Figure 3 (b), we can see that the WF_{pk} has grown steadily, and achieved its maximum when the UAV flies at 25 ms^{-1}. Indeed, almost all sensors have a tiny chance to send data when they have a huge gap velocity between them. This is also shown in Figure 3 (c). The main difference is



(a) #Packets

(b) WF_{pk}

(c) WF_{ts}

Fig. 5. The impact of sensors mobility on #Packets, WF_{pk} and WF_{ts}.

that the WF_{ts} of DR/CDT algorithm has the optimal value when the UAV flies at 10 ms^{-1}. This is consistent with the Figure 3 (a). Figure 3 (a), (b) and (c) show that the UAV has the optimal velocity (10 ms^{-1}). We will apply it in the following simulations.

2) The impact of UAV's height: In this scenario, the UAV flies at a constant velocity (10 ms^{-1}) and its height varies from 5 m to 90 m. 200 bicycles are carried with mobile sensors deployed at the predefined path and moving with constant but different velocities. Their velocities vary from 1 ms^{-1} to 10 ms^{-1}. Figure 4 (a) shows the number of collected packets of the four algorithms. The collected value follows a step-like curve as the height increases because of our multi-rate mechanism. The contact duration time gives a slight effect on the number of collected packets when the UAV's height exceeds 20 m while the data rate has a continuous impacting on the collected value till 50 m especially when the height is smaller than 20 m. From Figure 4 (a) and (b), it is clear that DR and DR/CDT algorithms always work better than CDT and CDT/DR algorithms.

In Figure 4 (b) and (c), both WF_{pk} and WF_{ts} are presented in a step curve which match with our multi-data-rate schemes. DR/CDT algorithm has a significant impact on these two weighted fairness in the second level. The CDT algorithm presents continuous trend in different levels because the contact duration time is decreasing as the height is increasing under the same network topology. DR/CDT algorithm as a whole is the one that works better between the four algorithms.

In Figure 4 (a), we set the height of the UAV at 15 m in order to fully take into account the impact of other parameters.

3) The impact of sensors mobility: This simulation considering the above two simulations results, the UAV is flying at constant height (15 m) and velocity (10 ms^{-1}), 200 bicycles with mobile sensors are deployed in a predefined path. We divide the bicycles velocities into ten levels. Take the velocity '5' in Figure 5, for example, this means that all the bicycles velocities are within [4, 5] ms^{-1}.

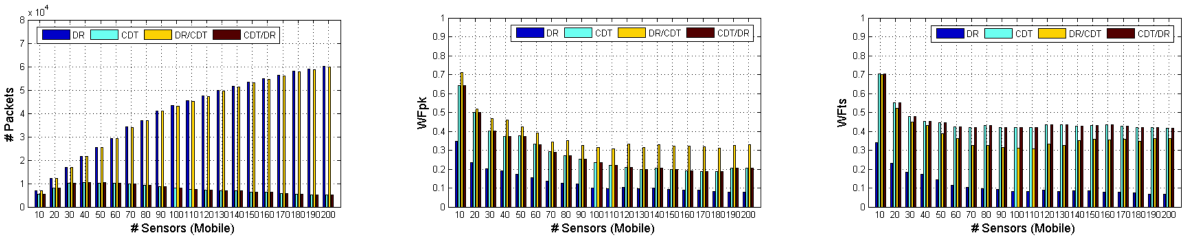
From Figure 5 (a), (b) and (c), we can conclude that DR and DR/CDT algorithms work well on data collection. Indeed, their number of collected packets and their weighted fairness are better than those of the CDT and the CDT/DR algorithms. We can see from Figure 5 that the #Packets, WF_{pk} and WF_{ts} are not changing dramatically as the speed increases. Thus, sensors velocities have a small effect on the four algorithms. Meanwhile, the higher the sensor velocities, the better the DR/CDT works, except the special case, sensors velocities within [9, 10] ms^{-1}. None algorithm keeps continuous trend because almost all sensors velocities are near the UAV velocity, their data rate and contact duration time are quite near.

4) The impact of density: Here, we consider two scenarios, the mobile case and the static one. The same parts of the two scenarios are UAV's height (15 m) and velocity (10 ms^{-1}), the bicycles equipped with sensors are deployed on a given path and the number of mobile sensors varies from 10 to 200. The only difference between them is mobile sensors velocities, varying from 1 ms^{-1} to 10 ms^{-1} for mobile case and 0 ms^{-1} for static case.

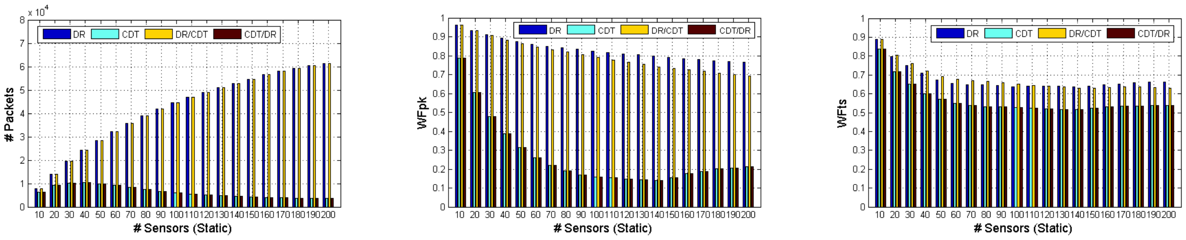
Figure 6 (a) and (d) show the number of packets collected by DR and DR/CDT algorithms. As we can see, the gap between the DR, DR/CDT and CDT, CDT/DR algorithms is increasing as the density increases. Moreover, both DR and DR/CDT algorithms work very well on the maximizing problem. Figure 6 (a) and (d) demonstrate that the density has a slight impact on CDT and CDT/DR algorithms because of its small gap between different levels. The DR/CDT algorithm shows high scalability in terms of sensors density.

Figure 6 (c) and (f) show that the weighted fairness in terms of allocated time slots is slowly decreasing as density increases and has small fluctuations when the number of sensors exceeds 120 in mobile case.

From Figure 6 (b) and (e), the weighted fairness with reference to sent packets is decreasing as density increasing. Moreover, WF_{pk} values of CDT and CDT/DR algorithms decreasing when #Sensors $<$ 140, and increasing when #Sensors $>$ 140 mobile sensors in the static case. It can be seen from Figure 6 (e) that the density is responsible for the changement trend. When the #Sensors $<$ 140, the higher is the density the deployed sensors, the higher is the number of sensor that competes for transmitting in one time slot. When #Sensors $>$ 140, there are too many sensors, competing for communication, so that almost all sensors within the communication range have a small opportunity to transmit.



(a) #Packets (Mobile) (b) WF_{pk} (Mobile) (c) WF_{ts} (Mobile)



(d) #Packets (Static) (e) WF_{pk} (Static) (f) WF_{ts} (Static)

Fig. 6. The impact of sensors density on #Packets, WF_{pk} and WF_{ts}.

However, the mobile case presents a different situation because of the mobility of the sensor nodes.

In mobile case, the DR/CDT algorithm shows an absolute advantage in terms of WF_{pk} for each density. Additionally, WF_{ts} of the DR/CDT algorithm is almost two times larger than that of the DR algorithm.

V. CONCLUSION

In this paper, we studied how to collect data through a UAV-assisted mobile sensor network. This scheme can overcome the limitations of the traditional data collection methods where the generated packets are forwarded to the base station hop by hop. We presented four data collection algorithms taking into account the multi data-rate transmissions (DR) and the contact duration time (CDT) between the sensors and the UAV. We also proposed a weighted fairness metric calculation to evaluate the algorithms. We examined the performance of the algorithms under different conditions and demonstrated how the algorithm that combine DR and CDT outperforms the others in in terms of the number of collected packets and the weighted fairness.

Since all the algorithms are centralized due to the use of a single UAV, we are planning to design efficient distributed algorithms based on a set of UAVs. Indeed, it will be interesting to see whether a group of UAVs can enhance the data collection process and guarantee low latencies.

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