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A mathematical formulation to optimize UAV trajectories for WSN data collection

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Abstract—This paper deals with the trajectory definition problem for a fleet of mobile collectors moving over a Wireless Sensor Network (WSN). The mobile collectors are tasked to roam the network deployment area and visit the sensors in order to hastily offload the data. In order to guarantee the system's feasibility, several operational constraints are taken into account. The problem addressed is a particular instance of the Split Delivery Vehicle Routing Problem. A mixed integer programming is proposed with the aim of determining the optimal trajectory to visit the sensors that have data to deliver with a correct timeliness. The problem faces two different decisions: the routing and the scheduling ones. Preliminary computational results are carried out on instances based on a real-life scenario with the aim of validating the proposed model in terms of efficiency and effectiveness.

I. INTRODUCTION

In presence of non-negligible amounts of data to transfer, the majority of routing protocols for Wireless Sensor Network (WSN) are outperformed by data-muling approaches [1], [2]. In this challenging scenario, it is more feasible to have a robotic mobile collector roaming the deployment field of a WSN rather than leaving the network transfer all the data to a common sink, either mobile or not [3]. It is neither straightforward, however, which visiting strategy to employ, nor how to drive the collectors on the field.

If we suppose a WSN in a challenged environment (industrial/remote/hazardous area), the nodes of this network need to offload a considerable amount of data to a remote station, it is more feasible to send a fleet of *Mobile Collectors* (MCs) to fetch it rather than sending it through the network via WSN routing. In this specific operational environment, using Unmanned Air Vehicles (UAVs) as devices for carrying the MCs is a common choice in recent scientific literature [4], [5], [6].

However, two important questions arise: (i) what is the order of visit for the MCs in order to minimize the traveled distance and (ii) how much time the MCs can spend to download data in order to maintain feasibility in terms of energy consumption.

We assume that each MC has a limited time to perform its tasks: start its route, download data and move to a collection area. In addition, each node can be visited by more than one MC, thus the decision is which nodes the MC has to visit, in

what order, and how much data each MC has to upload from each of them. It follows that the scenario considered belongs to the class of *routing and scheduling* problem.

Our contribution is to formulate the problem providing a mathematical model in order to obtain optimal routes and scheduling for a given fleet of MCs in a WSN.

The paper is organized as follows. Section II presents the set of related literature on this subject. Section III is devoted to the formal definition of the problem along with the mathematical formulation. Section IV concludes the paper.

II. RELATED WORKS

The discovery of routes and energy distribution are some of the issues addressed by researchers [7], [8]. Two main research lines have been investigated in WSN. In the first one, we can envision the mobile sinks traveling the network and visit a subset of its nodes. In the second approach, nodes track the sinks and then route their data directly to them [3].

There are different works that leverage the use of mobile entities for information gathering and delivering. Data Mules [9], [10] and Message Ferries [11], [12] propose the use of mobile elements to transport large quantities of offloaded data using mobile nodes with enhanced capabilities in respect to the rest of the network. Regarding this issue, in the following we describe a set of works that employ controlled mobility for network enhancement.

In [13] a mobile sink uses a set of phased arrays antennas to pinpoint the locations of nodes that respond to certain criteria when traveling across a predefined path. Instead, in [14] a group of mobile sinks is instructed on the paths they have to travel to achieve an improvement in the network-wide lifetime using a dedicated framework. The set of movements is the result of either a mathematical optimization or distributed and centralized heuristics.

Our work is instead different, as we propose a mathematical formulation for sinks movement that collect network information within a time constrained environment. Indeed, we consider a simple energy consumption model that can be expressed in terms of temporal permanence in the general network area of the mobile sinks. The aim is to collect data, guaranteeing energy feasibility of the system. In addition, we

introduce the possibility of split the upload to several MCs for each node of the WSN.

The problem addressed is known in the logistic field as the Split Delivery Vehicle Routing Problem (SDVRP). In its original formulation, a fleet of trucks has to visit a subset of customers with an associated set of demands. All the customers have to be served. More than one truck can visit the same customer and each truck delivers/picks-up a portion of the demand associated with the customer. Several operational constraints can be considered, such as, the duration of the trip performed by each truck. In our context, the trucks are the MCs, the customers are the nodes of the WSN, the demand is the data to upload and the duration of the trip is the permanence time of each MC in the system.

The scientific literature gave great attention to the optimization of the SDVRP due to its practical importance [15], [16], [17], [18]. For more details and references up to 2012, the reader is referred to [19].

In addition, it is proven that a particular instance of the SDVRP, that is, the Vehicle Routing Problem (VRP) belongs to the NP-hard class of complexity [20].

III. PROBLEM DEFINITION

The working scenario is composed by a WSN where it is implemented a *location service* as the one of [1] and [2].

In detail, we suppose that the underlying sensor network has already selected local cluster-heads, named *Data-Spots*, that aggregate data from their cluster's nodes. The location service is responsible for advertising the positions of the cluster-heads to the whole network.

Using the system, after being connected to one of the network nodes, it is assumed that each MC gets periodical updates about the position (relative or absolute) of the Data-Spots.

In this way we formulate a visiting problem where the MCs need to get in the vicinity of the Data-Spots and retrieve the aggregated data. To retrieve the data, the MCs have to get into range of the Data-Spots. Each Data-Spot can upload only a limited quantity of data.

A. The Model

The problem is formulated on a complete graph $\mathcal{D}(\mathcal{V}, \mathcal{A})$. The set \mathcal{V} of vertexes is composed by the set of available Data-Spots \mathcal{N} and by the source node (entrance point) s and the target node (exit point) d , that is, $\mathcal{V} = \mathcal{N} \cup \{s, t\}$. The set \mathcal{A} contains all arcs $(i, j), i, j \in \mathcal{V}$. The distance d_{ij} between node i and node j is associated with each arc $(i, j) \in \mathcal{A}$.

Each node $j \in \mathcal{N}$ is represented as a circle that identifies the coverage area. Ideally, communications between nodes become more difficult as the signal power decreases moving away from the center of the circle. Furthermore, we consider the centers of the circles to identify the position of the Data-Spots.

We assume that the position of each Data-Spot $j \in \mathcal{N}$ is known in advance by previous advertisement (see [2]).

A certain amount of data to upload D_{up}^j is associated with each Data-Spot $j \in \mathcal{N}$.

Let U be the set of available MCs. An entry point s^u and an exit point d^u are associated with each MC $u \in U$. In this respect, the set of nodes is defined as $\mathcal{V} = \mathcal{N} \cup \{\cup_{u \in U} s_u\} \cup \{\cup_{u \in U} d_u\}$. A maximum permanence time T_{esc}^u is associated with each MC $u \in U$. In particular, the time to move among the served Data-Spots and the time to download possibly a portion of data D_{up}^j , for all served Data-Spots j must be less than or equal to $T_{esc}^u, \forall u \in U$. The constraint on the time can be viewed as a simplified model of the energy consumption. Imposing the time limit T_{esc}^u , we guarantee, in the limit of the simple energy consumption model used, that the energy spent by the MC does not exceed the initial available energy. It is assumed that the MCs traverse each arc $(i, j) \in \mathcal{A}$ with a velocity v_{max} .

A bandwidth B_j^u is assigned to each MC $u \in U$ by each Data-Spot $j \in \mathcal{N}$.

We envision a scenario where more than one MC $u \in U$ is able to download simultaneously data from the same Data-Spot $j \in \mathcal{N}$. In this respect, a maximum number of simultaneously connected MCs n_j^{max} is associated with each Data-Spot $j \in \mathcal{N}$. In addition, we admit that a MC can wait for a certain amount of time, named a_u , before to download data from a sensor $j \in \mathcal{N}$ in the case the sensor j is fully occupied. We consider a discretized time horizon T . Thus, the number of MCs connected to each Data-Spot $j \in \mathcal{N}$ have to be less than or equal to n_j^{max} for each instant time $t \in T$.

Starting from the own position $s_u, \forall u \in U$, the MCs have to collect all data available from each Data-Spot $j \in \mathcal{N}$ and to move to the position d_u guaranteeing the permanence time constraints and minimizing the total distance traveled.

The solution obtained represents a path from s_u to d_u for each MC $u \in U$, with a given sequence of served Data-Spots. It is worth noting that paths associated with different MCs can share, possibly, one or more served Data-Spots, because these last ones allow more than one MC to download the data. Indeed, since the MCs have a limited permanence time, the cooperation among them is mandatory to ensure the energy feasibility of the system and to achieve the goal of downloading all data from each Data-Spot.

Let $x_{ij}^u, \forall (i, j) \in \mathcal{A}, u \in U$ be the flow variables that take value 1 if the corresponding arc $(i, j) \in \mathcal{A}$ is traversed by the MC u , 0 otherwise. With each node $j \in \mathcal{V}$ and MC $u \in U$ are associated the variables t_j^u and T_j^u that represent the time the MC $u \in U$ is connected to the node $j \in \mathcal{V}$ and the arrival time of MC u to node j , respectively. We assume that $t_{s_u}^u = t_{d_u}^u = T_{s_u}^u = 0$. Let a_j^u be continuous variables indicating the waiting time of MC $u \in U$ at Data-Spot $j \in \mathcal{N}$.

Let $n(j, t)$ be a function that defines the number of MCs connected to Data-Spot $j \in \mathcal{N}$ at instant time t .

From a mathematical stand point, the problem can be formulated as follows.

$$\min z(x) = \sum_{(i,j) \in \mathcal{A}} \sum_{u \in U} d_{ij} x_{ij}^u \quad (1)$$

s.t.

$$\sum_{\{j:(i,j) \in \mathcal{A}\}} x_{ij}^u - \sum_{\{j:(j,i) \in \mathcal{A}\}} x_{ji}^u = \begin{cases} 1 & \text{if } i = s_u \\ -1 & \text{if } i = d_u \\ 0 & \text{otherwise} \end{cases}, \quad \forall i \in \mathcal{V}, u \in U \quad (2)$$

$$\sum_{j \in \mathcal{N}} \sum_{u \in U} x_{ij}^u \geq 1, \quad \forall i \in \mathcal{N} \quad (3)$$

$$T_j^u \geq T_i^u + t_i^u + \frac{d_{ij}}{v_{max}} - M(1 - x_{ij}^u), \quad \forall (i,j) \in \mathcal{A}, u \in U \quad (4)$$

$$T_j^u \leq T_i^u + t_i^u + \frac{d_{ij}}{v_{max}} + a_j^u + M(1 - x_{ij}^u), \quad \forall (i,j) \in \mathcal{A}, u \in U \quad (5)$$

$$t_j^u \leq T_{esc}^u \sum_{(i,j) \in \mathcal{A}} x_{ij}^u, \quad \forall j \in \mathcal{N}, u \in U \quad (6)$$

$$t_j^u \geq \epsilon + \left(\sum_{(i,j) \in \mathcal{A}} x_{ij}^u - 1 \right), \quad \forall j \in \mathcal{N}, u \in U \quad (7)$$

$$\sum_{(i,j) \in \mathcal{A}} \frac{d_{ij}}{v_{max}} x_{ij}^u + \sum_{j \in \mathcal{N}} t_j^u \leq T_{esc}^u, \quad \forall u \in U \quad (8)$$

$$\sum_{u \in U} B_j^u t_j^u = D_{up}^j, \quad \forall j \in \mathcal{N} \quad (9)$$

$$n(j,t) \leq n_j^{max}, \quad \forall j \in \mathcal{N}, t \in T \quad (10)$$

$$x_{ij}^u \in \{0,1\}, \quad \forall (i,j) \in \mathcal{A}, u \in U; 0 \leq a_j^u \leq a_u, t_j^u, T_j^u \geq 0, \quad \forall j \in \mathcal{N}, u \in U \quad (11)$$

Equations (2) represent the flow constraints and (3) impose that all Data-Spots are visited at least once. Conditions (4) and (5) define the arrival time T_j^u of MC $u \in U$ to node $j \in \mathcal{V}$. The constant M is a sufficiently large number. A valid upper bound on M is the maximum time in which the MC $u \in U$ can stay in the network, that is, $M = T_{esc}^u$. Constraints (6) and (7) impose the connection time t_j^u to be equal to zero if the Data-Spot $j \in \mathcal{N}$ is not visited by the MC $u \in U$ and if Data-Spot $j \in \mathcal{N}$ is visited by the MC $u \in U$, then the latter have to connect to the former, respectively, where $\epsilon \ll 1$ is a positive real number. Conditions (8) are the time constraints related to the maximum permanence in the system of MC $u \in U$. Constraints (9) guarantee that all data available to each Data-Spot $j \in \mathcal{N}$ is downloaded. Constraints (10) impose a maximum number of MCs connected to Data-Spot $j \in \mathcal{N}$ for each instant time $t \in T$. Conditions (11) define the domain of the decision variables.

In order to define function $n(j,t)$, let n_u^t be a binary variable that assumes value equal to 1 if MC $u \in U$ is connected to Data-Spot $j \in \mathcal{N}$ at instant time t . Thus, we have

$$n(j,t) = \sum_{u \in U} n_u^t, \quad \forall j \in \mathcal{N}, t \in T. \quad (12)$$

An MC $u \in U$ is connected to a Data-Spot $j \in \mathcal{N}$ at instant time t if $T_j^u \leq t \leq T_j^u + t_j^u$. In order to identify whether an MC $u \in U$ is connected to a Data-Spot $j \in \mathcal{N}$ at instant time t , we define four integer variables, named $y_{j,h}^{u,t}$, $h = 1, \dots, 4, \forall u \in U, j \in \mathcal{N}, t \in T$ with the following meaning:

- 1) $y_{j,1}^{u,t}$ is equal to one if $T_j^u > t$, zero or one otherwise;
- 2) $y_{j,2}^{u,t}$ is equal to one if $T_j^u + t_j^u < t$, zero or one otherwise;

- 3) $y_{j,3}^{u,t}$ is equal to one if $T_j^u \leq t$, zero or one otherwise;
- 4) $y_{j,4}^{u,t}$ is equal to one if $T_j^u + t_j^u \geq t$, zero or one otherwise.

In order to accomplish the aforementioned conditions, the following equations are defined

$$T_j^u - t \leq M y_{j,1}^{u,t}, \quad \forall j \in \mathcal{N}, u \in U, t \in T \quad (13)$$

$$t - (T_j^u + \bar{t}_j^u) \leq M y_{j,2}^{u,t}, \quad \forall j \in \mathcal{N}, u \in U, t \in T \quad (14)$$

$$T_j^u - t - 1 \geq -M y_{j,3}^{u,t}, \quad \forall j \in \mathcal{N}, u \in U, t \in T \quad (15)$$

$$T_j^u + \bar{t}_j^u - t + 1 \leq M y_{j,4}^{u,t}, \quad \forall j \in \mathcal{N}, u \in U, t \in T \quad (16)$$

$$y_{j,1}^{u,t} + y_{j,2}^{u,t} + y_{j,3}^{u,t} + y_{j,4}^{u,t} = 2, \quad \forall j \in \mathcal{N}, u \in U, t \in T \quad (17)$$

It is worth noting that an MC $u \in U$ is connected to a Data-Spot $j \in \mathcal{N}$ at the instant time t if $y_{j,3}^{u,t} = y_{j,4}^{u,t} = 1$, see conditions 3) and 4). Variables $y_{j,3}^{u,t}$ and $y_{j,4}^{u,t}$ are used to define variable n_u^t as follows

$$n_u^t = y_{j,3}^{u,t} + y_{j,4}^{u,t} - 1, \quad \forall j \in \mathcal{N}, u \in U, t \in T. \quad (18)$$

In order to validate the proposed model in a reasonable (limited) amount of time, we consider a simplified scenario where five Data-Spots are randomly deployed in a square $200 \times 200 \text{ m}^2$. Each Data-Spot has a download buffer of 9.5 MB. We consider three MCs with a maximum speed set to 15 m/s. We assume that each Data-Spot $j \in \mathcal{N}$ assign a bandwidth of 19 Mb/s to each MC, considering a stationary close-range TCP connection; we set the maximum allowed permanence time T_{esc}^u to 17, 15, and 86 seconds for the three MCs, respectively; we assume that the three MCs start their route at time zero. The waiting time a_j^u is assumed to be 2 seconds for all the considered MCs and Data-Spots.

The aim of this example is to make a sensitivity analysis on the value of the objective function and on the makespan (ms), varying the value of n_j^{max} . We highlight that the ms is the higher arrival time among all MCs, i.e., $ms = \max_{u \in U} T_{du}^u$.

Tables I and II report the arrival time T_j^u and the connection time t_j^u for each MC $u = 1, 2, 3$ and Data-Spots j . We report the time the MCs reach the exit point under column d_u . The empty entries mean that the corresponding MC u is not connected to the related Data-Spot. In the last two rows of Tables I and II we report the total traveled distance $z(x)$ and the makespan ms with n_j^{max} set to one and two, respectively.

For the instance with $n_j^{max} = 1$, see Table I, MCs $u = 1$ and $u = 2$ visit one Data-Spot, that is, 5 and 3, respectively. We observe that both MCs are connected to the visited Data-Spots for a time interval equal to 1. Thus, only a portion of the data is downloaded from both Data-Spots 3 and 5. The MC $u = 3$ visits all Data-Spots in the order $\langle 1, 2, 3, 5, 4 \rangle$ and downloads all data from 1, 2, 4 and the remaining portion of data available to Data-Spots 3 and 5. It is worth observing that, since $n_j^{max} = 1$, then no overlap between $u = 1$ and $u = 3$ exists when both MCs visit Data-Spot 5. The same observation is valid for Data-Spot 3. The total traveled distance is 777 and the makespan is 43.19.

| | | Data-Spots | | | | | d_u |
|---------|--------------------|------------|-------|-------|-------|-------|-------|
| | | 1 | 2 | 3 | 4 | 5 | |
| $u = 1$ | T_i^u t_i^u | | | | | 8.66 | 14.92 |
| $u = 2$ | T_i^u t_i^u | | | 6.66 | | | 13.66 |
| $u = 3$ | T_i^u t_i^u | 3.4 | 11.86 | 19.06 | 47.66 | 27.66 | 43.19 |
| $z(x)$ | 777 | 4 | 4 | 3 | 4 | 3 | |
| ms | 43.19 | | | | | | |

Table I
RESULTS WITH $n_j^{max} = 1, \forall j \in \mathcal{N}$.

| | | Data-Spots | | | | | d_u |
|---------|--------------------|------------|------|-------|-------|-------|-------|
| | | 1 | 2 | 3 | 4 | 5 | |
| $u = 1$ | T_i^u t_i^u | 3.46 | | | | | 11.72 |
| $u = 2$ | T_i^u t_i^u | 3.46 | | | | | 13.59 |
| $u = 3$ | T_i^u t_i^u | | 7.73 | 14.93 | 36.53 | 25.73 | 42.06 |
| $z(x)$ | 754 | | 4 | 4 | 4 | 4 | |
| ms | 42.06 | | | | | | |

Table II
RESULTS WITH $n_j^{max} = 2, \forall j \in \mathcal{N}$.

For the instance with $n_j^{max} = 2$, we obtain a different solution in terms of both routing, i.e., sequence of visited Data-Spots and scheduling, i.e., arrival time of the MCs to each Data-Spot. In particular, both MCs $u = 1$ and $u = 2$ visit Data-Spot 1 and download simultaneously the data available. Indeed, the arrival time to Data-Spot 1 is equal to 3.46 for both $u = 1$ and $u = 2$. The two MCs download all data from Data-Spot 1. The MC $u = 3$ visits the remaining Data-Spots in the order $\langle 2, 3, 5, 4 \rangle$. The total traveled distance is 754 and the makespan is 42.06.

Comparing the two solutions, it is clear the benefit of allowing parallel visit to the same Data-Spot. Indeed, the total travelled distance with $n_j^{max} = 2$ is reduced of about 3% with respect to that obtained with $n_j^{max} = 1$. The same reduction is observed for the value of the makespan.

IV. CONCLUSIONS

In this paper we present a problem of efficiently driving a set of flying mobile collectors in a Wireless Sensor Network. The problem is formulated as a mixed integer linear program. The mathematical formulation is tested considering a low complex example with the aim of validating the proposed formulation. However, there is still considerable work that can be done on the subject. In order of priority, we plan to introduce a meta-heuristic to drive the MCs using only locally-available information, then producing a refined version of the model and its implementation, in order to attain results for extended sets of inputs. Furthermore, we plan to leverage the use of real

UAVs to perform a set of live experiments with real Wireless Sensor Network deployments.

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