A Distributed Method to Organize Terrestrial Nodes to Facilitate Short Drone Routes in WSNs

Konstantinos Skiadopoulos, Konstantinos Giannakis, Sofia Fanarioti, Konstantinos Oikonomou
Department of Informatics
Ionian University, Corfu, Greece
Email: {kskiad, kgiann, sofiafanar, okon}@ionio.gr

Ioannis Stavrakakis
Department of Informatics & Telecommunications
National and Kapodistrian University of Athens
Athens, Greece
Email: ioannis@di.uoa.gr

***Abstract*—Drones are currently the focus of increased interest for various purposes related to actual applications and communication systems. Although their autonomous capabilities allow them to operate as a distinct network themselves, it is common to use them in combination with traditional communication networks, such as Wireless Sensor Networks (WSN), the Internet of Things applications, etc. Energy constraints and limited automated control of drones are challenging in certain cases, where a network is obligated to operate distributedly with limited control from outside. In this work, a setting involving a ground wireless sensor network and one drone is studied, taking into account the limited energy capabilities of a drone. In particular, the relation between a drone's route (in terms of traveled distance) and the communication cost (in terms of exchanged messages) is addressed, by proposing a novel algorithm that clusters nodes under a simple, cost-effective way. Simulation results depict that sufficient advantage is gained using the proposed solution.**

***Index Terms*—drones, wireless sensor networks, soft geometric random graphs, IoT, communication cost.**

I. Introduction

Information collection (or dissemination) constitutes a vital part of modern systems, especially in the emerging era of the so-called Internet of Things (IoT), as well as for post disaster response, delivering, and monitoring. This point undergoes thorough study within the framework of Wireless Sensor Networks (WSN) [1], [2], where scalability along with overall performance and efficiency are crucial parameters for real-world applications. This is especially true when energy and time constraints are present.

As previously stated, issues regarding the flow of information through communication mechanisms lies in the core of various network systems. The tremendous growth in numbers of access points and devices will naturally cause a thorough revisiting of old solutions and approaches (e.g., [3], [4]), since they will require proper adjustments and reconfiguration. This, also, holds for 5G mobile communications [5].

The rise of the technologies related to Unmanned Aerial Vehicles (UAV), or most commonly known as *drones*, has led to their consideration as potential assets in the direction of enhancing the dynamics of IoT systems [6] like WSNs. Therefore, drones are widely deployed as means of collecting or disseminating information [7], [8]. It is apparent that the use of wireless means of communication provides flexibility and enhanced capabilities for various networking systems. The advent of (relatively) cheap and widely used drones is expected to increase the dimensionality (by adding an extra degree of freedom) of a network, covering scenarios where a aerial assistance may be crucial.

Recent works propose hybrid methods and solutions that combine drones with terrestrial nodes in what seems as a combination of vehicular and mobile networks adding aerial support [6], [9], [10], [8]]. In such network settings, drones undertake either the role of a base station or that of a mobile node [6], [8]. Due to their inherit construction, drones are characterized by energy constraints, which limit their viability and efficiency for real-world applications.

In this work, a specific setting involving a terrestrially deployed wireless sensor network and one drone to collect (or disseminate) information is studied, having in mind the limited capabilities of a drone in terms of energy. More specifically, the relation between a drone's route (in terms of traveled distance) and the communication cost (in terms of exchanged messages, both to transmit sensor data and run the proposed algorithm) is studied and a novel algorithm that groups nodes under a simple, cost-effective way is proposed. Indicative simulation are implemented which reveal that sufficient advantage is gained using the proposed solution. Soft Random Geometric Graphs (SRGG) [11], i.e., an extension of random geometric graphs [12] are used for the simulation part since this particular type of geometric graphs is considered suitable for modeling wireless sensors network topologies [13].

The paper has the following structure: after the introduction in Section I, past related works are discussed is Section II. Section III contains all the needed definitions and assumptions regarding the underlying network model, whereas the detailed algorithm's description lies in Section IV. Simulation results and their depiction are found in Section V and then, Section VI concludes the paper.

II. Past Related Work

Drones and their capabilities either as passive nodes or base stations have drawn the attention of various researchers [14]. Mozaffari et al. [6] discuss the advantages of using drones in the realm of IoT. Bor-Yaliniz et al. consider drones as base stations that undertake duties related to gathering and dissemination of data among the ground nodes, having in mind the decrease of energy cost [8]. It is important to note that the use of drones for monitoring or handling of sensitive situations related to disasters is discussed in various works, such as by Chowdhury et al. in [15], Erdelj et al. in [16], and Scherer et al. in [17].

Several works consider problems related to communication and routing among drones and, in general, nodes moving at high altitude [18], [19], [20]. The aforementioned work deal with networks mainly consisting of drones, like the recent work by Yanmaz et al. in [21]. In the work described in this paper, the underlying scenario involves ground-to-drone communication [10], [7], [6]. The routing for networks of mobile nodes with geographical reference has been extensively studied in literature and various protocols have been proposed [22]. Although geographical routing shares some similarities with the proposed work, the interest here is merely on searching for the appropriate set of nodes that would allow a smaller drone's trajectories.

A similar work with the one presented here is the one of Yang et al. in [10]. In particular, similarly to the motivation behind the proposed algorithm, a drone-based data collection system is described. Their aim is the energy reduction by designing proper routes for the drone that minimize the volume of their emissions (studying circular and straight line routes). In the same manner, Wang et al. address the problem of data collection using drones aiming to plan efficient paths for the drone to minimize their paths [7].

The procedure of calculating the appropriate set of nodes that minimize the communication overhead has attracted a lot of interest. Several authors use techniques based on the construction of dominating sets in order to calculate a network's backbone that would enable data coolection in an efficient manner [23], [24]. Here, a dominating set is not useful, since the drones routes are already defined, but the algorithm's sketch is the calculation of the proper network's nodes subset that will enable the efficient communication between ground nodes and the drone.

III. Network and Problem Definitions

The networks' nodes are supposed to be uniformly distributed on a plain area sized $[0, \ldots, 1] \times [0, \ldots, 1]$ (that is a unit square). Let r be the *euclidean distance* between a certain pair of nodes in the considered network area, r_c be the *connectivity radius* and δ_1 the *1 hop neighbors* of a node. The topology model used is the SRGG model [11] that considers a *connectivity probability* $p(r)$ for any pair of nodes at euclidean distance r given by

$$p(r) = e^{-(r/r_c)^\gamma}, \tag{1}$$

where γ is a constant related to the particular environment. For open area, it has been shown that the best suited value is $\gamma = 2$ [11]. Thus, any pair of nodes at distance r (given a connectivity radius r_c) is connected with probability $p(r)$. It is interesting to see that for large values of γ, e.g., $\gamma \to +\infty$, then if $r \leq r_c$, then $p(r) = 1$ and if $r > r_c$, then $p(r) = 0$, thus SRGG reduces to the well known deterministic random geometric graph model.

The proposed scenario considers the use of a sole drone that is responsible for collecting data from the deployed WSN. The drone moves above the ground nodes in a fixed altitude, thus its connectivity radius covering wirelessly the nodes in the surface is, also, fixed, since nodes' elevation is 0 and there are no obstacles preventing communication. Furthermore, it is assumed that the done follows a predefined trajectory in order to collect the produced data from the whole set of sensor nodes. Since the drones trajectory forms a polygon (see also Fig. 1), only the coordinates of its peak points are necessary for the nodes to calculate the exact route. Thus, they can deterministically calculate if they lie within the scope of the drone's route. Limitations and restrictions imposed by the drone's construction (battery life, broadcast range, etc.) affect the drone's performance.

IV. The Proposed Algorithm

The aim in this work is to decrease the distance traveled by the drone for the collection of data generated and sent within a wireless sensor network. To address this problem, a novel algorithm is proposed that collects the produced data in a set of nodes that are within the communication radius of the drone which flies over in a predefined route.

The proposed algorithm is distributed and its core share similarities with the construction of a minimum connected dominating set [25]. By the time it terminates, the network nodes are painted either "Grey", "Red", or "Black". Each node calculates the best fitted of its δ_1 neighbors to forward the collected data and save it as its own "Red" node. At the end each "Grey" node will forward the collected data to its own "Red" node, whereas each "Red" node collects data from all the *dominated* nodes and forwards them to its "Red" node that has color "Red" or "Black". At the end of the procedure, all the collected information has been gathered on the "Black" nodes and at the time the drone comes over, they forward them.

As has been implied, all network nodes have a *color* variable initially "White". In the beginning, all nodes are aware of the coordinates of a number of points that are the start and the end points of the line segments of the drone's route and all of them are on **State 0**. Each node on **State 0** calculates the distance from the line segments of the drone's route and stores the minimum of them in r_m. Then, it sends r_m to all $\delta_1(u)$. If r_m is within the drone's communication range in relation to the drone's route, it can transmit the collected data directly to the drone when it passes over. In that case it changes the variable *color* to "Black", sends the '*OK*' message to $\delta_1(u)$ (that means its part of the execution of the algorithm is terminated) and changes its **State** to **3**. If r_m is not within the drone's communication range, it changes its **State** to **1**.

Each node on **State 1** waits until it receives the r_m message from all $\delta_1(u)$. Then, it calculates the minimum of them and stores it as variable rn_m. If its own distance from drone's route r_m is smaller than rn_m, then there is no other neighbor

State 0

Data: Start and End points of the line segments of the drone's route.
State 0: The state that all nodes begin with.
`color`: the particular color of a node ▷ Initially white
`red`: the nearest $\delta_1(u)$ to the drone route ▷ Initially None
r_m : The minimum distance from the drone route. ▷ "The node computes the minimum distance from the drone's route."
$r_m \rightarrow \delta_1(u)$ ▷ "The node sends the minimum distance to all $\delta_1(u)$".
if $r_m < r_c$ **then** ▷ "If r_m is in communication range with the drone's route"
    `color` = Black
    $'OK' \rightarrow \delta_1(u)$ ▷ "Sends OK message to $\delta_1(u)$ that means it finished"
    Change **State** to **3**
else
    Change **State** to **1**
end if

node to forward the collected data, so in order to avoid a dead end, it changes its r_m to infinity and transmits the new value of r_m to all $\delta_1(u)$. Otherwise, it stores the node with the minimum distance rn_m to variable *red* and sends '*OK*' message to $\delta_1(u)$. Eventually it is no more at **State 1** and has changed to **State 2**.

State 1

State 1: The node does not have the nearest neighbor to drone route.
while Not received r_m from all $\delta_1(u)$ **do**
    Wait
end while
rn_m = The minimum r_m of all $\delta_1(u)$
if $r_m < rn_m$ **then** ▷ "This node has no direct route to a black node"
    $rm = \infty$
    $r_m \rightarrow \delta_1(u)$
else
    `red` = The nearest neighbor to drone route
    $'OK' \rightarrow \delta_1(u)$ ▷ "Sends OK message to $\delta_1(u)$ that means it finished with commands in **State 1**."
    Change **State** to **2**.
end if

Each node on **State 2** waits until it receives an '*OK*' message from all $\delta_1(u)$. Then, it transmits a '*RED*' message to the node in variable *red*. If its *color* is "White", it changes it to "Grey". Finally, it changes its **State** to **3**.

On receiving a '*RED*' message, a node appends the sender in a *dominated* list and if its *color* is not "Black", it changes to "Red".

To sum up, the proposed distributed algorithm uses the drone's route as input, while after its application, each and

State 2

State 2: The node knows the nearest neighbor to drone route.
while Not received "OK" message from all $\delta_1(u)$ **do**
    Wait
end while
$'RED' \rightarrow$ `red` ▷ "Inform the nearest neighbor to drone route that is the red node for him"
The receiver of a "RED" message :
if $color \neq Black$ **then**
    `color` = Red
    Append sender to `Dominated` list.
end if
if $color = White$ **then**
    `color` = Grey
end if
Change **State** to **3**
State 3: The node finished with the algorithm.

every node has a 1-hop neighbor node to forward the produced data, along with the received data from other nodes in case it dominates to some neighbor nodes. By the time the drone is about to begin its course, all the produced data have been collected to the 'Black' nodes that lie within the drone's transmission range across its route.

V. Simulations

Simulation results presented in this section assume that the area in which the networks are deployed is normalized to a square with sides equal to 1. The number of network nodes is in all cases 1000 and the model used for the construction is SRGG with parameter $\gamma = 2$ that successfully captures the open area environment [11], [13]. A program was developed in Python 3.6.7, using the SciPy and NumPy libraries [26]. Randomness is generated by the random number generator of Scipy (i.e., the Mersenne Twister pseudo-random number generator) using different seeds for each run. Various scenarios are presented in each simulation that correspond to networks with $r_c = 0.070, ..., 0.170$. As r_c increases, the denser the network becomes. When $r_c = 0.070$, the average number of $\delta_1 = 14.476$, while for $r_c = 0.170$, the average number of $\delta_1 = 74.838$. Since the proposed algorithm is based on the exchanged messages between 1-hop neighbors, it is profound that the denser the network the more messages needed.

When such a project is designed, the drone's route length in order to collect the produced data is a crucial factor that must be considered, since most of the currently available drones have strict limits of flying capabilities (need for frequent re-charging, distance-constraint control, etc.). Another important parameter is the energy consumption of each network node, that depends on the number of transmitted messages for the collection of the produced data. In the design phase of such a project, these two issues need to be carefully considered. This is basically an optimization problem. Below are the results of a number of simulations that highlight various aspects of this problem.

Fig. 1 shows the drone's route when the whole network's area must be directly covered for an SRGG topology with $r_c = 0.100$. The distance of each point of the network's area from the drone's route is less than the value of r_c, therefore all nodes are capable to transmit directly to the drone. The circle around the drone's scheme depicts its transmission range.

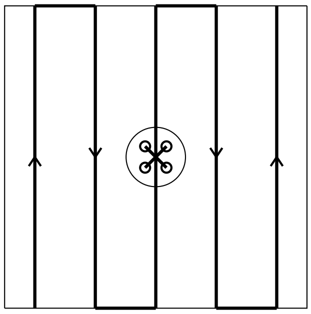

Fig. 1. Drone's route for coverage of the whole network area when $r_c = 0.100$. The circle around the drone's scheme depicts its transmission range in the 2-dimensional space.

Fig. 2 depicts the drone's route length covering the whole area, half, and the quarter of it, as well as the messages needed for the proposed algorithm in each case. For each scenario, the drone's route ends at its starting point. When the drone's route covers directly the whole area (left point on each line), the proposed algorithm is redundant, thus no algorithm messages are exchanged. In this case, the drone's route length is far beyond the maximum flying range of the common available drones, if the side of the network's area is greater than 1km [10], [27].

When the drone's route covers half of the area (middle point on each line) the drone's route length is much smaller and near the the maximum flight distance of the common available drones, if the side of the network's area is above 1km, while the number of needed messages per node is rather small (from 35 messages per node for sparse networks, up to 180 for dense ones). The third point on each line depicts the case in which the drone's route covers directly one forth of the area. In this case, it is clearly observed that with a small increase in the number of messages per node (5 to 30 more messages per node), the drone's route length is reduced almost by half and is within the flight range of many available in the market drones.

Fig. 3 depicts the network coverage and the messages needed by the proposed algorithm when the drone's route is diagonal to the area. The minimum coverage is obtained for $r_c = 0.070$ and the rest points are for $r_c = 0.090, 0.100, 0.105, 0.120, 0.125, 0.170$, accordingly. From this figure, it is clear that for the particular diagonal route of the drone, the coverage and the needed messages of the the proposed algorithm depend on r_c. When r_c is small (meaning that the network is sparse), the number of necessary messages is low and so is the direct drone's coverage. For larger values of r_c (meaning that the networks are denser) the number of necessary messages is increased and the direct drone's coverage is, also, higher.

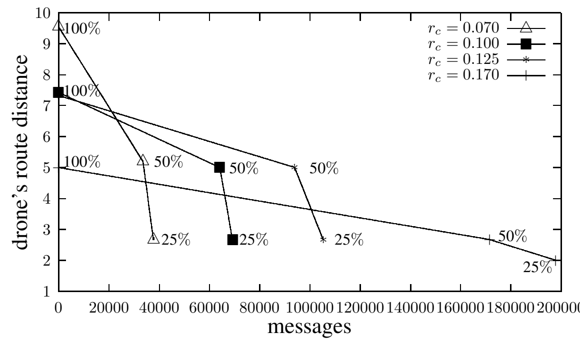

Fig. 2. Networks with 1000 nodes constructed using the SRGG model and $r_c = 0.070, 0.090, 0.100, 0.120$. Three drone's routes that cover the whole network, 1/2, and 1/4 of it. The x axis corresponds to the drone's route length and the y axis to the sum of messages sent under the proposed algorithm.

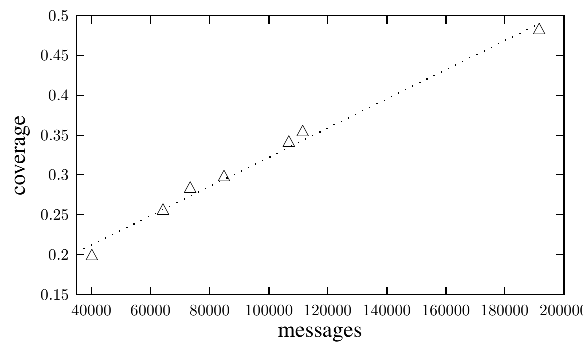

Fig. 3. Networks with 1000 nodes constructed using the SRGG model and $r_c = 0.070, 0.090, 0.100, 0.105, 0.120, 0.125, 0.170$. The drone's route is diagonal to the area where the networks are deployed. The x axis corresponds to the direct drone's coverage and the y axis to the sum of messages sent under the proposed algorithm.

Fig. 4 presents the number of hops needed for data collection per node. Various drone routes that directly cover $90\%, 75\%, 60\%, 50\%, 33\%$ and 25% of the network's area were tested, on networks with 1000 nodes constructed with the SRGG model and $r_c = 0.070$. When the drone covers directly a large portion of the area, the Black nodes that directly communicate with it are the majority and almost all the remaining are 1-hop away. As the directly covered area decreases, the number of the Black nodes, also, decreases and there are nodes 2, 3, 4 and in a case 5-hops away from them. This demonstrates the fact that the proposed algorithm suffices, taking into account that the diameter of the network used in this simulation is 10 hops.

VI. Conclusions and Future Work

In this paper, a novel distributed algorithm for data collection in a wireless sensor network is proposed. A set of nodes that are within the radius of a drone's route is efficiently calculated using a low number of messages. The proposed

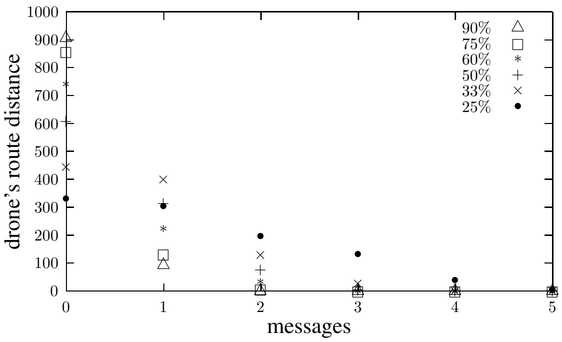

Fig. 4. Network with 1000 nodes constructed with SRGG model and $r_c = 0.070$. Drone's routes that directly cover $90\%, 75\%, 60\%, 50\%, 33\%, 25\%$ of the network's area. The x axis corresponds to the number of hops from drone's route and the y axis the number of nodes. Black nodes are zero hops away from drone's route.

algorithm has a simple implementation and it is shown to consume minimal network resources in terms of messages. This is experimentally observed by simulation results for various scenarios under a predefined setting. It is, thus, proposed that the route of the drone may change in order to consume less energy, whereas the overhead for data collection (or dissemination) remains low. The low number of required messages can be useful in cases where a drone's routes are dynamically altered. Exhaustive simulation results in the future are expected to reveal further advantages of the proposed methodology, for Wireless Sensor Networks and other network environments, like IoT environments, environments with extreme conditions (e.g., for outdoor monitoring), nodes' mobility, etc.

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