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Poster Abstract: AGRO - Optimal Routing with Low Latency and Energy Consumption in Wireless Sensor Networks with Aerial Relay Nodes

Jin Zhang, Kai Li, Andreas Reinhardt, Salil S. Kanhere
School of Computer Science and Engineering
The University of New South Wales, Sydney, Australia
Email: {jinzhang, kail, andreasr, salilk}@cse.unsw.edu.au

***Abstract*—Energy efficiency is always a challenge in Wireless Sensor Networks (WSNs). Unmanned Aerial Vehicles (UAVs) can relay the data to a remote base station, which can help save energy for the ground sensors in the WSN. However, the aerial link in a UAV network is not always connected due to the movement of UAVs. As a result, routing data in the UAV network causes significant delay. To achieve maximum throughput with lowest latency and energy consumption, we propose an Air-Ground Routing Optimization (AGRO) which selects the optimum routing paths from all possible Air-Air, Air-Ground, Ground-Air or Ground-Ground links at each hop.**

I. Introduction

Wireless sensors are often deployed in a large area or in harsh environments for disaster recovery, environmental monitoring or target-tracking. In these scenarios, sensors transmit their data to the base station in multiple hops. In order to achieve energy efficiency in WSNs, UAVs equipped with flight control systems and radio transmitters have been used to relay data for the ground sensor nodes [1], [2]. UAVs significantly prolong the lifetime of the WSN since they have large radio coverage and their battery can be recharged conveniently. A UAV collects the data from the ground sensors and acts as a relay node in a multi-hop aerial network as shown in Figure 1. We assume the WSN on the ground is connected. Hence, the routing latency in the WSN is negligible compared to the UAV network.

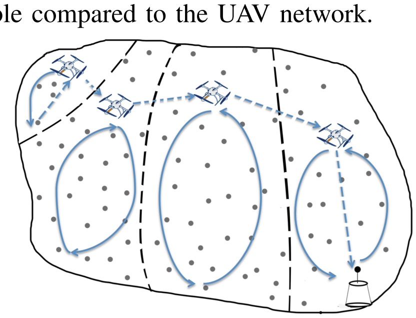

Figure 1: The structure of a UAV-WSN system. Each UAV covers a part of ground area.

However, incorporating UAVs in WSNs presents several non-trivial challenges on data routing. Usually, the UAV network is not always connected in the UAV-WSN system. Since the transmission power of ground sensors is low, UAVs need to move in different areas separately so as to cover all ground sensors. Therefore, if a ground sensor node only chooses the UAV as the next hop but it is not in the radio coverage of the UAV, it has to buffer its data and wait for the UAV for a long time to relay the data to the base station.

To address these issues, in this preliminary work, we propose AGRO which finds a route to the base station by selecting either Air-Air, Air-Ground, Ground-Air or Ground-Ground link at each hop so that more data is received with low latency and energy consumption of the ground sensor nodes, considering the network that includes both static ground sensors and mobile UAVs.

II. Problem Statement and AGRO

The total number of ground sensor nodes is n and we have m UAVs in the air ($n > m$). Given a combination of Air-Air, Air-Ground, Ground-Air, Ground-Ground links, the routing problem in the UAV-WSN system is how to find an optimal path so that the data reception at the base station is maximized during a data collection time while the energy consumption and routing latency are both upper bounded. We assume the ground sensor nodes are the only data sources and UAVs only relay data. UAVs move at constant speed following predefined trajectories. Specifically, the connectivity between two UAVs depends on their trajectories, which means the link is connected only when one UAV flies into the radio range of the other. We define the initial energy of a ground sensor node i as E_i^0 and the data generation rate of the ground sensor node i as λ_i. In order to prevent a ground sensor node from completely depleting its battery, we assume that it powers down if its residual energy goes below a certain threshold $E_{td} > 0$. The energy consumption of the ground sensor node i on routing path $\mathcal{P}$ is defined as $\check{E}_i(\mathcal{P})$. We assume both UAV and base station have unlimited energy. $\check{E}_i(\mathcal{P})$ contains the energy consumption on transmitting packets to the neighbor i'' and receiving packets from its neighbor i'. Hence,

$$\check{E}_i(\mathcal{P}) = (P_{(receiving)ii'} + P_{(sending)ii''}) \cdot T_i(\mathcal{P}) \qquad (1)$$

$T_i(\mathcal{P})$ is the time for the ground sensor node i to transmit and receive data packets on the routing path $\mathcal{P}$. We define the number of ground sensor nodes on the routing path in the WSN is $n(P_g)$ and the energy consumption of the path $\mathcal{P}_g$ is $\Sigma_{i=1}^{n(\mathcal{P}_g)} \breve{E}_i(\mathcal{P}_g)$.

We define the waiting time of neighbor node j' for UAV j in aerial routing path $\mathcal{P}_a$ to cover its own area as $\tau_{jj'}(\mathcal{P}_a)$. As a result, the maximum waiting time for ground sensor node i is $\Sigma_{j=1}^{m(\mathcal{P}_a)} \tau_{jj'}(\mathcal{P}_a)$.

Objective Maximize $\Sigma_{i=1}^{n(\mathcal{P})}(\lambda_i \cdot T_i(\mathcal{P}))$

Constraints

- $\Sigma_{i=1}^{n(\mathcal{P})} \breve{E}_i(\mathcal{P}) \leq \Sigma_{i=1}^{n(\mathcal{P}_g)} \breve{E}_i(\mathcal{P}_g)$
- $E_i^0 - \Sigma_{i=1}^{n(\mathcal{P})} \breve{E}_i(\mathcal{P}) \geq E_{td}$
- $\Sigma_{k=1}^{n(\mathcal{P})} \Sigma_{i=1}^{k} \tau_{ik}(\mathcal{P}) \leq \Sigma_{j=1}^{m(\mathcal{P}_a)} \tau_{jj'}(\mathcal{P}_a)$

The proposed optimization is modeled as a linear programming problem and can be solved in linear time. In AGRO, the optimal routing path $\mathcal{P}$ is calculated at the base station. Since the flight trajectory of UAV is fixed and known, $\mathcal{P}$ can be pre-calculated. The routing path $\mathcal{P}$ indicates the next-hop link in the routing table locally stored at each node. AGRO makes use of routing tables to select the next-hop link so that the packet can be transmitted.

III. Performance Estimation

Based on the setting in a real-world application [3] where the authors use the UAV to monitor the bio-geophysical properties of the vines in a vineyard, we define the following parameters for the energy consumption and latency estimation:

- 11 ground sensor nodes deployed in a 200m x 300m area shown in Figure 2. The area is divided to 3 subareas equally so that 3 UAVs can cover the whole area shown in Figure 3.
- Velocity of UAV is $2.4m/s$ and one round flight time of a UAV to cover its area is $T_u = 5mins$.
- The size of one data packet is 32 bytes and total data payload of one ground sensor node is 1MB.

Firstly, we estimate the upper bound of energy consumption. If the source node sends data to the base station and there are 11 hops on the ground, the energy consumption of 10 relay ground sensor nodes on the routing path is $\breve{e} * \frac{1024^2}{32} * 10 = 49.152J$ [4]. $\breve{e}$ is the energy consumption on receiving and transmitting one data packet. Secondly, we estimate the upper delay bound as follows. In the worst case, a ground sensor node at the left bottom corner of the subarea A generates data when *UAV-1* just flies past. In this case, the ground sensor node needs to wait $2 * T_u$ to route data to *UAV-1*. The total delay is $2 * T_u + T_u + T_u = 20mins$. Based on the estimated energy consumption and time delay, there exists an optimal routing path that contains both air and ground links to achieve lower latency and more energy efficiency. For example, in Figure 2, *UAV-1* and *UAV-2* save the energy for the ground sensor node $S3$ since they relay the data from $S2$. In Figure 3, UAVs cause the latency on the data routing if they are selected as next hop.

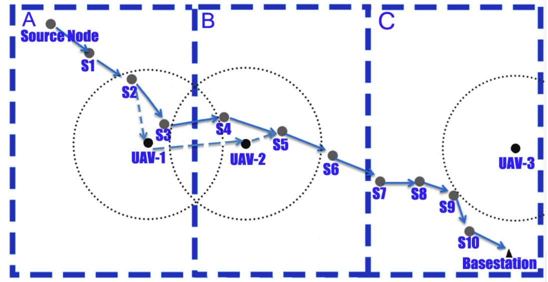

Figure 2: Estimating the upper bound of energy consumption of the ground WSN

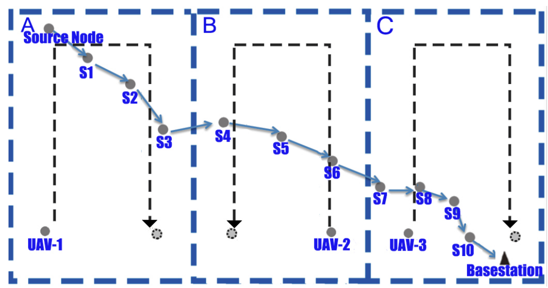

Figure 3: Estimating the upper bound of latency introduced by UAVs

IV. Conclusion

The work presented in this paper focuses on the energy efficiency and routing latency problem in a WSN-UAV system. Previously UAVs were assumed to cause much routing delay to WSNs. We have thus presented AGRO that significantly reduces the energy consumption of ground sensor nodes while guaranteeing low latency, by flexibly selecting a combination of Air-Air, Air-Ground, Ground-Air or Ground-Ground link at each hop. We will implement the linear solution as well as heuristics for the analysis of data reception, energy efficiency and latency in our future work.

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