EDAL: An Energy-Efficient, Delay-Aware, and Lifetime-Balancing Data Collection Protocol for Heterogeneous Wireless Sensor Networks

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***Abstract*—Our work in this paper stems from our insight that recent research efforts on open vehicle routing (OVR) problems, an active area in operations research, are based on similar assumptions and constraints compared to sensor networks. Therefore, it may be feasible that we could adapt these techniques in such a way that they will provide valuable solutions to certain tricky problems in the wireless sensor network (WSN) domain. To demonstrate that this approach is feasible, we develop one data collection protocol called EDAL, which stands for Energy-efficient Delay-aware Lifetime-balancing data collection. The algorithm design of EDAL leverages one result from OVR to prove that the problem formulation is inherently NP-hard. Therefore, we proposed both a centralized heuristic to reduce its computational overhead and a distributed heuristic to make the algorithm scalable for large-scale network operations. We also develop EDAL to be closely integrated with compressive sensing, an emerging technique that promises considerable reduction in total traffic cost for collecting sensor readings under loose delay bounds. Finally, we systematically evaluate EDAL to compare its performance to related protocols in both simulations and a hardware testbed.**

***Index Terms*—Data collection, energy efficiency, heuristic algorithms, routing protocols, wireless sensor networks.**

I. Introduction

In RECENT years, wireless sensor networks (WSNs) have emerged as a new category of networking systems with limited computing, communication, and storage resources. A WSN consists of nodes deployed to sense physical or environmental conditions for a wide range of applications, such as environment monitoring [1], scientific observation [2], emergency detection [3], field surveillance [4], and structure monitoring [5]. In these applications, prolonging the lifetime of WSN and guaranteeing packet delivery delays are critical for achieving acceptable quality of service.

Many sensing applications share in common that their source nodes deliver packets to sink nodes via multiple hops, leading to the problem on how to find routes that enable all packets to be delivered in required time frames, while simultaneously taking into account factors such as energy efficiency and load balancing. Many previous research efforts have tried to achieve tradeoffs in terms of delay, energy cost, and load balancing for such data collection tasks [6], [7]. Our key motivation for this work stems from the insight that recent research efforts on open vehicle routing (OVR) problems are usually based on similar assumptions and constraints compared to sensor networks [8]–[10]. Specifically, in OVR research on goods transportation, the objective is to spread the goods to customers in finite time with the minimal amount of transportation cost. One may wonder, naturally, if we treat packet delays as delivery time of goods, and energy cost as delivery cost of goods, it may be possible to exploit research results in one domain to stimulate the other.

Motivated by this observation, our work in this paper develops EDAL, an *E*nergy-efficient *D*elay-*A*ware *L*ifetime-balancing data collection protocol. Specifically, EDAL is formulated by treating energy cost in transmitting packets in WSNs in a similar way as delivery cost of goods in OVR and by treating packet latencies similar to delivery deadlines. We then prove that the problem addressed by EDAL is NP-hard. To reduce its computational overhead, we introduce both a centralized metaheuristic based on tabu search [11], and a distributed heuristic based on ant colony gossiping, to obtain approximate solutions. Our algorithm designs also take into account load balancing of individual nodes to maximize the system lifetime. Finally, we integrate our algorithm with compressive sensing, which helps reduce the amount of traffic generated in the network. We evaluate both approaches using large-scale simulations with NS-3 [12] as well as a small-scale hardware testbed and present the evaluation results.

As an extension to our conference paper [13], which only considered the case of homogeneous sensor network deployments, as reflected by its evaluation that focused on delay and energy efficiency, in this paper, we systematically address the very different research challenges of heterogeneous sensor networks to significantly strengthen our design. More specifically, our major contributions in this journal paper are as follows.

- We extend the data collection protocol called EDAL [13], which employs the techniques developed for OVR in operations research to find the minimum cost routes to deliver

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