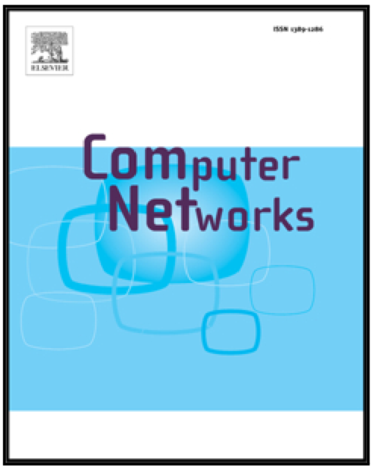

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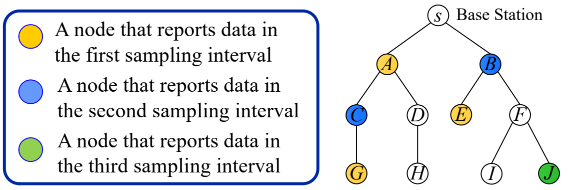

Fig. 1. An example to illustrate the dynamic traffic pattern.

I. INTRODUCTION

Sensor networks are usually distributed in the physical world to monitor the changes of the environmental phenomenon. Sensor nodes are capable of sampling the local phenomena and communicating with neighboring nodes through radios. The data acquired by different nodes are periodically collected by the base station for further analysis. This is known as *continuous data collection* which extracts abundant information of the operational field but is prohibitively expensive. Since the sensor nodes are battery-powered devices, the rapid depletion of sensor energy would break the entire network into partitions. It is essential to conserve sensor energy to extend the network lifetime for continuous data collection [1]–[3]. Following common practices [4]–[6], the *network lifetime* is by definition the time elapsed before the first sensor node dies.

The routing structures determine the number of packets received and transmitted by different sensor nodes and thus directly influence their energy consumptions. It is important to design energy efficient routing structures that can steer the network traffic away from the exhausted sensor nodes to prolong the network lifetime. On the other hand, collisions are a major barrier to energy conservation in sensor data collection. In this paper, we consider a network that uses Time Division Multiple Access (TDMA) [7] as the MAC protocol. For illustration purpose, we define the *sampling interval* as the period that a sensor node gets data samples [8], and the *traffic pattern* as the set of nodes that report to the base station at each sampling interval [9].

Most existing routing approaches [4], [5], [10]–[13] are designed for a given static network traffic pattern in which each node generates a fixed amount of data to transport to the base station at each sampling interval. In continuous data collection, due to the exploitation of the energy conservation strategies [8], [14], [15] that trade the data accuracy for energy efficiency, the network traffic pattern often exhibits the dynamically changing characteristics. Also, due to the nature of condition-based monitoring, data are sent to the base station only when certain predefined conditions are satisfied. For instance, in GreenOrbs project [16] deployed to monitor the concentrations of carbon dioxide in the forest atmosphere, only spikes of the carbon density need to be reported to the sink. In the example network shown in Fig. 1, the set of nodes reporting to the base station at the 1st, 2nd, and 3rd sampling intervals are $\{A, E, G\}$, $\{B, C\}$ and $\{J\}$, respectively. The change of the network traffic pattern is not known a priori to any node in the network as well as the base station. The dynamic traffic pattern makes the design of the energy efficient routing structures a challenging task.

In this paper, we investigate efficient routing structures to extend the network lifetime for continuous data collection with dynamic traffic patterns. We focus on construct a DAG (Directed Acyclic Graph) in which each node can have multiple parents and multiple children [4]–[6]. DAG achieves better spatial load balancing by distributing the traffic load across different routes in the network.

Our major contributions can be summarized as follows. To find the lifetime-optimal DAG routing structure, we devise a mixed integer programming formulation and a greedy algorithm, from which the optimal and near-optimal solutions are obtained. We have proposed two methods to make use of the DAG routing structure for data collection. The first method factors the DAG into several trees and picks up one tree for routing at each sampling interval. The second method builds a transmission schedule on the DAG and the schedule is directly utilized for data gathering. We have developed a simulator to evaluate the performance of the proposed methods using real-world data traces. The simulation results have demonstrated that: (1) the greedy algorithm produces similar network lifetimes to the optimal method with much shorter computational times; (2) both of the two DAG-based methods outperform constructing a single routing tree for data collection; and (3) compared with the first method, the DAG-based scheduling better adapts to the fluctuations in the network traffic pattern and is more effective in extending the network lifetime for continuous data collection.

The rest of the paper is organized as follows. Section II illustrates the prior works. Section III presents the system model. Section IV investigates the construction of the lifetime-optimal DAG structures. The using of the DAG is illustrated in Section V. The experimental evaluation is given in Section

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