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Energy efficient data collection in sink-centric wireless sensor networks: A cluster-ring approach☆

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ABSTRACT

Sink-centric traffic pattern is common in wireless sensor networks (WSN), which typically causes higher energy consumption of the sensor nodes near the sink node (called 'hot spot' problem). Clustering combined with careful traffic flow control can alleviate a hot spot by dispersing the energy burden concentration. Existing clustering schemes treat each clusters as an entity for energy efficiency optimization. We propose to group a set of clusters into 'cluster-rings', which is a chain of clusters that are equal distance away from the sink, and conduct energy efficiency optimization at the cluster-ring level. More specifically, we first present a novel method to compose a cluster structure. Next, we present an algorithm that gradually optimizes the traffic flow control at the cluster-ring level by using a multi-agent reinforcement learning technique. Then, we present an algorithm that makes cluster-level traffic routing decision on the basis of cluster-ring level traffic flow control results. Via simulations, it is shown that the proposed scheme result near-optimal performance and can adapt to dynamic changes of network-wide traffic generation.

1. Introduction

Internet of Things (IoT) sheds new light on the research of Wireless Sensor Networks (WSN) by expanding the notion of sensor node to include home appliances, surveillance devices, etc. Many IoT applications require continuous or periodic collection of sensing data in order to obtain a holistic view of network. For example, continuous data collection enables pre-cautioning for environment pollution tracking scheme in [18]. Traffic surveillance CCTV [16], pollution detector [15], fire detector [17], and video sensing [19], and agricultural sensing [20] are other examples.

Due to the high cost of cellular communication, multi-hop communication by using short range radio is still a preferable solution, particularly for the large scale WSN. The 'cost' means not only the financial one but also the energy resources that is usually limited in WSN. As the network size is increasing, the entire size of collected data and number of node grows geometrically. This makes it harder to handle the limited energy resource of sensor nodes than the case of smaller network. Moreover, in multi-hop WSN, generated sensing data is often relayed to the sink node by multi-hop manner to get the holistic view of network. If the battery of a sensor node is depleted, not only its sensing operation but also data relaying is interrupted. By progression of energy depletion of sensor nodes, some node permanently loses all routes to the sink node, which is well-known as a network partitioning [12,13]. In particular, the sensor nodes near the sink node are inevitably suffering for the high energy consumption in this sink-centric traffic pattern, which is known as 'hot spot' problem. As the network size is increasing, this hot spot problem is exacerbated by the rapid increase of relayed data. To sustain the operation of network as long as possible, it is crucial to mitigate the hot spot problem.

In this paper, we suggest a solution to prevent network partitioning in a view of network organization and routing of data. We start from the idea that the circularly symmetric network is easy to be abstracted in a view of routing optimization. If the network is already formed circular-symmetrically, the energy consumption of network also can be easily controlled to be circular-symmetric, which gives a good abstraction rather than each area has different energy consumptions. By this idea, we first present an algorithm to compose a circular-symmetric cluster structure. For the given size of clusters, this algorithm gradually forms a cluster structure without requiring any location information of sensor nodes. We then present a pair of algorithms to decide traffic routing over the composed cluster structure. Existing cluster routing schemes commonly treat a cluster as the basic unit of the routing decision. In contrast, we group the clusters that is located with the same

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distance from the sink are equal. Since we already formed the network circularly symmetric, the grouped clusters form a doughnut-shaped 'ring' of clusters. We call this group as 'cluster-ring' or 'ring' in this paper. If we assume that all clusters in the same cluster-ring does same actions for data relaying, the energy consumption pattern also becomes circularly symmetric. In other words, all clusters at the same distance from the sink node should have identical energy consumption.[1] We divide the entire network into the set of cluster-rings.

With this abstraction, we convert the routing problem into two sub problems: (i) the decision of the amount of data flow between cluster-rings, and (ii) the decision of traffic relaying between clusters. Once we solve first sub problem, we solve the second problem on the basis of the solution of the first sub problem. The main benefit of the two-level approach is the scalability. If the number of clusters is very large, existing schemes that make routing decisions at the level of individual cluster will become quickly infeasible. By grouping the clusters into the 'cluster-ring', the computational complexity can be significantly reduced.

For the ring-level routing (1st sub problem), we present an algorithm that yields energy-efficient strategy by using the reinforcement learning technique [7]. For the cluster-level routing (2nd sub problem), we present an algorithm for choosing the relay nodes for inter-cluster communication. The energy cost metric proposed in [8] is used to in this algorithm. Our two-level routing algorithms adapt to the dynamic changes of network topology and traffic pattern. The simulation results indicate that our scheme produces near optimal performance.

The rest of paper is organized as follows. Section 2 describes the related works. The network model and assumptions are presented in Section 3. In Section 4, we suggest a method to compose a cluster-ringed network. In Section 5, we formulate the problem in linear programming and propose a method that adaptively decides data flow between cluster-rings. Section 6 presents a cluster-level routing algorithm. The simulation results are shown in Section 7. Section 8 concludes the paper.

2. Related work

Energy-efficient routing for WSN has been extensively studied, mostly focusing on balancing the energy consumption of sensor nodes [23,24]. Existing schemes oftentimes assume static traffic generation pattern and rely on the optimization solutions. In [4], a routing algorithm that maximizes energy efficiency based on Pareto optimality is proposed. This scheme is suitable for the case that the link configuration and traffic generation pattern can be probabilistically characterized. In [3], energy-efficiency is pursued in conjunction with geographic routing. However, geographic information of sensor nodes is not readily available in practice yet. In [21], energy-efficiency is considered for real-time WSN applications with QoS requirements. The scheme maximizes energy efficiency and also meets QoS requirements by differentiating service delays and data redundancy. Node mobility is also exploited in conjunction with energy efficient routing for extending WSN lifetime [22,25,26]. This approach is to overcome the hot spot problem near the sink nodes by migrating the sink nodes. In [2], two multi-hop routing algorithms are combined. One algorithm is to reduce the total power consumption of the network and the other is to decrease the volume of data flow by data aggregation.

In this paper, we consider the clustering technique and the group of clusters as a network design. Some representing survey works [31–33] provide a comprehensive aspect of traditional and current clustering methods. In the clustering structure [6,11], multiple sensor nodes are grouped to form a cluster. There exist many studies for composing the clustering structure. In [9] clustering is done on the basis of the artificial bee colony algorithm which simulates the intelligent foraging behavior of honey bee swarms. In [6], a distributed algorithm that determines cluster size by the hop distance to the sink node is proposed. This algorithm achieves energy balancing by controlling probability that a node becomes a cluster head. In [1], the clusters are formed in a pie shape and Voronoi clusters that utilizes Voronoi tessellation based on the cluster head. In [29,34,36], a ring-based topology is used for load balancing. In [35], the cluster size and the density of cluster head in the cluster is chosen to maximize the network lifetime. In [27], the distance among the cluster head is adaptively adjusted according to the distance to the base station. In [28], an unequal clustering and gradient-based routing is proposed. Each sensor node's gradient value keeps its minimum hop count to the sink and that of its cluster head decides the size of a cluster. The direction of descending gradient leads the route of data. One goal of clustering is scalability of network management, by dividing intra-cluster data collection and inter-cluster data forwarding. This division is beneficial from the perspective of energy efficiency as well. Unfortunately, most of above works have not considered the scalability well. The shortest path routing with multi-hop forwarding is not enough to overcome the hot spot problem. In this paper, we combine the design of clustering with the energy efficient routing while securing the scalability as well as relieving the hot spot problem.

3. Network model

While the proposed scheme can be applied to generic configurations, we make some assumptions on the network topology for the ease of presentation. That is, we assume that the network has a circular shape and the sink node locates at the center. Each sensor periodically generates sensing data at a certain rate while different sensor nodes may produce data at different rates. We consider a sink-centric traffic pattern, meaning that all the sensing data are forwarded to the (single) sink node.

The cluster structure that our scheme uses has the following properties. In each cluster, there exists a 'cluster head' (CH), which is responsible of forming a cluster and choosing a relay node and a data collection node. The 'relay node' receives other clusters' forwarding data and forwards to the other relay node. It piggybacks the collected data of its own cluster. A 'data collection node' collects the data generated by all the sensor nodes in the cluster. The same node may function as a relay node and data collection node. The relay nodes and data collection nodes are periodically rotated, so that the energy consumption of each node in a cluster is balanced. We define a 'cluster-ring' (or 'ring' in short) as a group of clusters that are included in the area of a concentric circle with the sink node at the center. The clusters within the inner-most circle form the '1st cluster-ring'. The clusters that are adjacent to the 1st cluster-ring form the 2nd cluster-ring, i.e., the 2nd ring encircles the 1st ring. Therefore, all cluster-rings except the 1st ring have a doughnut shape. This encircling relationship between cluster-rings is continued until the entire network is covered by cluster-rings. An illustrative example of the cluster ring is given in Fig. 1. The dot at the center of the network represents the sink node and the dots in the middle of each cluster represent the cluster heads.

In the proposed scheme, the energy consumption of the clusters in the same cluster-ring is equally balanced. The energy consumption of sensor nodes within a cluster is also balanced by rotating the role of relay node and data collection node. Since the energy consumption of all clusters in the same cluster-ring is equalized and that of each node in a cluster is identical, the lifetime of all

[1] Our scheme may be applied to a WSN with non-circular shape topology. The concept of cluster-ring can be extended to a group of cluster chain that does not necessarily form a ring shape.

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