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A link- and hop-constrained clustering for multi-hop wireless sensor networks

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ABSTRACT

The connectivity of radio frequency (RF) devices is usually limited by their predefined bandwidth. Due to stochastic selection of cluster heads, most wireless sensor networks (WSN) require cluster re-configuration protocols without connection and hop constraints. This paper proposes a connection-constrained real-time power-aware (ccWSN) clustering and routing method for multi-hop WSN with a connection bound for each sensor nodes (SN). Each data packet in the network is given a hop-count denoted as the *deadline* to arrive at base station (BS). ccWSN also controls the diameter of multi-hop clusters so as to derive appropriate clusters size and increase network lifetime. This static clustering method does not require re-configuration which would entail additional energy consumption and time overhead. For each cluster, a set of backup CHs will be selected and serve the cluster as a CH in turn. Simulations result shows that ccWSN increases network lifetime and improves load balance among SNs and CHs.

1. Introduction

In wireless networks, the number of data streams or connectivity of each device is limited by multiple access control (MAC) or physical layer. In a wireless sensor network (WSN), communication nodes are linked by a wireless medium, and problems traditionally associated with wireless channels (e.g. contention and fading) may affect the available number of connections of SNs and network lifetime. These constraints are usually derived from physical or MAC layers in protocol stacks such as IEEE 802.15.4 and 802.15.1, respectively, for ZigBee® and Bluetooth®. For example, the physical layer of ZigBee® allocates a maximum of 16 channels in the 2.4GHz band while Bluetooth® 4.0 provides a maximum of 40 channels and allows a maximum of 7 links for each device. Associated with the designs of MAC layer for sensor networks, ZigBee® and Bluetooth® use time division multiplexing (TDMA) or frequency division multiplexing (FDMA) based protocols. A cluster head (CH) applying TDMA reserves constant time slots for each member node in its cluster. This allows several nodes to share the same frequency channels by dividing the signal into different time slots. Cluster-based sensor networks may produce slot or channel contentions on the CHs in a large-scale single-hop cluster. When a CH runs out its available links it cannot transmit and may thus cause a data overflow in its buffer. In addition to the theoretical bounds, real-life constraints imposed by the application layer (e.g., data packet size or packet inter-arrival time) will usually further reduce available connectivity. Many existing cluster-based protocols fail to consider channel capacity or assume that each node has sufficient bandwidth.

Most WSN applications such as weather monitoring, security and tactical surveillance have time-critical requirements [5–7] and should be designed as real-time tasks for which the execution duration consists of transmission delay and computation time. In large-scale multi-hop WSNs, data transmissions may take considerable amounts of time and should be regarded as part of real-time tasks so as to meet their timely requirements and to obtain valid data. WSN protocol design should consider the transmission delay and connectivity constraints, and their trade-off should be handled properly.

In a large-scale WSN, cluster-based routing protocols [8–15] can localize the routing paths within a cluster and thus reduce transmission delay and routing table in the individual node. They can easily be made scalable and robust to deal with node failures. In addition, cluster-based methods can also localize and balance the transmission load among clusters by conserving bandwidth and carefully determine which nodes make appropriate members. Cluster-based routing reduces energy consumption by applying data fusion (aggregation) in a cluster to decrease the number and size of transmitted packets. Therefore, in a WSN with thousands or ten thousands of SNs, a cluster-based routing protocol achieves transmission efficiency and prolongs network lifetime.

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In cluster-based methods, CHs have to spend more energy on aggregation and forwarding packets, performing route maintenance and routine activities. This additional energy consumption can cause nodes to become depleted much earlier than other sensor nodes. In such a situation, a considerable number of backup CHs can avoid frequent cluster re-configuration and retain cluster optimality. The notion of *center* [1–4,37] in a graph is useful in many applications because placing a shared resource at the center in a geographical region minimizes the response time between resources and facilities. A graphs *median* minimizes the average of the travel distance between resources and facilities so as to reduce average transportation time. However, it is difficult to apply the notions of center or median to an entire network because the locations of base station (BS) is difficult to change with respect to the SNs. The P-center problem [4] proposed by Hakimi [3] involves minimizing the maximum distance between each facility and the P processing resources. P-center problems are NP-hard [1] deterministic algorithms in a given graph. P-median problem [4] minimizes the total travel distance between facilities and P processing resources and is still NP-hard for different values of P [2]. Therefore, frequently cluster re-configuration due to node death can incur excessive computational overhead to find P-center or P-median as the CHs. There should be a simple notion for network initialization to determine the CHs and backup CHs at a suitable location for individual subgraphs (clusters).

On-board communication for RF devices imposes a mandatory energy cost, because the energy consumed to send data grows at least quadratic times as its transmission range [16]. In many previously proposed methods, SNs and CHs apply identical transmission ranges regardless of their distances. Other previous methods assume that each node can transmit data in variable transmission ranges, and usually assume *symmetric* communication. That is, if node u can receive a signal from node v, then node v can also receive a signal from node u. In real WSN applications, most routine work for each node consists of unidirectional transmission to convey sensing data to CHs or BS. Compelling each node having symmetric communication with its neighbors incurs dispensable connectivity and energy consumption for the CHs. Liu and Li [27] discussed the benefits of an *asymmetric* transmission or unidirectional communication model [42] and propose a method that calculates the minimum transmission range while guaranteeing reachability between any two nodes as in their initial topology. They define a directed-graph referred to as *maximum topology* in which each node transmits with maximum transmission power, and propose a distributed topology control method to derive a minimum-power topology that guarantees multi-hop reachability from any source (SN) to any destination (CH or BS) in the directed graph. They noticed that when symmetric links are applied in a network topology, it is difficult to assume the use of variable transmission ranges among its nodes. Their experiments also show that, in a sparse network, the minimum-power topology using asymmetric transmission model can produce a 50% transmission power savings over the maximum topology. In a node-dense network, this method can produce an 80% power savings over the *maximum topology*. Therefore, when an asymmetric model is applied in a WSN, the derived power-aware clustering or routing methods may become more energy-efficient because the SN transmission ranges can be further decreased.

Multi-hop intra-clustering allows nodes to have multiple hops from their CH, and improves scalability in large-scale networks. It also reduces the power consumption of SNs which can choose smaller ranges than in single hop clustering. Therefore, it improves load balance and cluster power consumption, thus prolonging network lifetime. In this paper, the proposed methods provide both inter-cluster and intra-cluster protocols for transmitting real-time packets with respect to their individual hop constraints. All transmitted packets are premised on the basis of meeting their individual deadlines in terms of the number of hops while conveying them as power-efficient as possible. In the assumption of a*symmetric* communications, each node can further decrease its transmission range thus saving more energy. Based on the notion of TTL clustering, the size of each cluster associated with the diameter in terms of hops is controlled at an appropriate level so as to improve network lifetime and meet packet delivery deadlines.

The rest of this paper is organized as follows. Section 2 introduces related works. Section 3 describes the system model and primary assumptions. Section 4 presents the design and analysis of the proposed method. Section 5 derives some properties for clustering and analyzes the proposed algorithms. Section 6 presents experimental results, and Section 7 concludes this study.

2. Related work

2.1. Multi-hop and one-hop WSN protocols

In the literature, most existing protocols choose cluster heads in accordance with various metrics such as residual energy, distance, locations and node densities. Low energy adaptive clustering hierarchy (LEACH) is one of the most popular clustering algorithms for WSNs [26]. It constructs one-hop clusters in accordance with received signal strength and uses the CHs as routers to aggregate and forward data packets to BS in one hop. In LEACH, all CHs are assumed to use a long transmission range so that data packets can reach BS directly from the CHs. Without assuming urgent or timely packets transmission, this is not always a realistic assumption since long range communication is costly and is not deserve to transmit an uncritical packet. Therefore, LEACH is not suitable to be applied in large-area WSN. LEACH-centralized [13] (LEACH-C), is a LEACH variation, which uses a centralized clustering algorithm and the same steady-state protocol as LEACH. It can produce better clusters by distributing the CHs throughout the network. Hybrid energy-efficient distributed clustering (HEED) [23] is a distributed clustering protocol in which CHs are selected from the deployed SNs. HEED considers residual energy and communication cost such as node degree when electing CHs. An SN joins the CH with lower node-degree to distribute the CH load, or joins the one with higher node-degree to create dense clusters. Unlike LEACH, it does not select CHs randomly. Only SNs having high residual energy can become CHs. In HEED, each SN is mapped to exactly one cluster and can directly communicate with its CH.

In the multi-hop clustering protocols, LEACH-L [32] improves the CH selection algorithm of LEACH by using a *distance* factor. It provides one-hop intra-cluster and multi-hop inter-cluster routing protocol and derives optimum hop-counts for inter-cluster communications. This method analyzes the best locations of new CHs elected in each round to optimally distribute communication loading among network nodes. Unequal Cluster-based Routing (UCR) protocol [33] considers the hot spot problem in multi-hop WSNs. It arranges the SNs into clusters of unequal sizes such that the CHs closer to BS have smaller cluster sizes than those farther away. This one-hop intra-cluster and multi-hop inter-cluster protocol can conserve some energy for inter-cluster packet forwarding. Weighted Clustering Algorithm (WCA) [34] is a one-hop intra-cluster and multi-hop inter-cluster protocol that consists of mobile SNs. It selects a CH according to the number of accessible nodes, mobility, transmission power and battery power. To decrease cluster reconfiguration overheads, CH election is only performed in accordance with node mobility and when the current dominant set is incapable of covering all the SNs.

The aforementioned clustering schemes are based on direct communication between a SN and its designated CH. However, multi-hop connectivity within a cluster is required when the sensor's communication range is limited and/or the number of CHs is bounded. Youssef *et al.* proposed the k-hop Overlapping Clustering Algorithm (KOCA) [37], which is an overlapping clustering algorithm for the uniform distribution of sensor nodes. They proved the overlapping