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An energy-efficient QoS routing for wireless sensor networks using self-stabilizing algorithm

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ABSTRACT

Transmission delays caused by wireless multi-hop communications usually hamper the time-sensitive applications on wireless sensor networks (WSNs). In this paper, transmission delay of data packets is quantified as the number of hops from a sensor to base station (BS), and a tolerable delay (TD) of each packet denotes the initial value of aging tag (*AT*) to present their QoS metric. On the basis of predictability of TDMA schedule, we propose a self-stabilizing hop-constrained energy-efficient (SHE) protocol for constructing minimum energy networks for hard real-time routing. The protocol first constructs ad hoc multi-hop paths within a cluster while controlling the number of nodes in the cluster so as to meet the TD of data packets from member nodes to their *CH*. An adaptive routing protocol is then proposed to convey aggregate data packets from *CHs* to BSs in different routes depending on their current *AT* values, thus meeting their QoS requirements while prolonging the network lifetime.

1. Introduction

Wireless sensor networks (WSN) consist of a large number of sensor nodes (SNs) which are capable of sensing, gathering, processing and transmitting data. SNs collect data on the target environment, and send the data to base station (BS) using wireless transmission techniques [5,6]. WSNs have been widely applied to industrial, military and civilian applications such as industrial plant management, motor/engine monitoring, target tracking, surveillance, health care system management and geographic information analysis, etc. [1–4].

In WSN applications [7,8], data transmission delay is a problem in multi-hop WSN networks. Many such applications entail time-critical requirements [2–4] such as weather monitoring, security and tactical surveillance, and are usually performed by time-sensitive tasks with bounded delay or deadline. WSN applications are also increasingly used to monitor the physical condition of aged people and hospitalized patients [7,8]. In multi-hop wireless ad-hoc sensor networks, transmission delays dominate over processing delays [7,9,10], and the effective control of transmission delays is needed to perform time-sensitive applications in such networks. We propose a self-stabilizing hop-constrained energy-efficient (SHE) protocol that uses a tolerable delay (TD) for hard real-time transmission in terms of the number of hops for packets in the network layer. This notion provides good compatibility and a metric for the application of a variety of WSN architectures.

Many researchers have investigated the transmission delay with respect to MAC layer [9,10,13,14] using traditional real-time scheduling for packet schedules on end-to-end packet delivery. Based on MAC layer protocols such as CSMA and TDMA, many energy-efficient and higher-throughput methods are proposed [7,13–15,41,42,52,53], a few of which focused on network layer in terms of quality of service (QoS) for WSN routing. For example, Souil et al. [41] propose an adaptive MAC protocol called AMPH with QoS for heterogeneous WSNs. AMPH provides heterogeneous traffic using traffic prioritization and increases channel utilization based on its hybrid and adaptive natures. Yigitel et al. [42] propose a QoS-aware MAC protocol called Diff–MAC with for wireless

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multimedia sensor networks (WMSNs). Diff–MAC integrates existing QoS features and provides service differentiation and QoS provisioning to transmit heterogeneous traffic to meet the requirements of different traffic classes. Other protocols such as hexagonal topology [7,16,17] have been proposed for wireless networks based on MAC layer protocols. The protocols consider multi-hop transmission from SNs to BS while each cluster head (*CH*) contains only single hop to its SN members. In the structure discussed in [7,18], the topological control attempts to achieve specific connectivity among the nodes, and the deployments of SNs are determined manually. Their data packets are routed through pre-determined paths. Recently, there are some network layer and clustering protocols with QoS for WSN [34–36,43,44,47]. Tang and Li [43] propose a QoS routing protocol with optimal energy allocation for cluster based linear WSN topology. Each cluster has a *CH* modeled by single server fixed rate (SSFR) with finite capacity and different data arrival rate in accordance with the traffic from other clusters. Nazir and Hasbullah [44] propose an energy-aware QoS routing protocol called EEQR for cluster-based WSNs. EEQR provides QoS service for transmitting packets in accordance with network traffic including bandwidth and delay constraints, and uses different forwarding strategies. In [47], Ye et al. propose a redeployment method to solve energy balanced problem among mobile heterogeneous SNs and *CH*s in WSNs. This method with virtual force model can also improve the QoS of the deployment.

In a large-scale WSN, a cluster-based routing protocol [19–26] reduces energy consumption by performing data aggregation and fusion within a cluster, thus improving network lifetime and reducing network congestion. Moreover, clustering reduces channel contention, resulting in higher network throughput under heavy loads. In addition to supporting network scalability, clustering reduces the routing table kept in each SN [27]. Most cluster-based routing protocols in the literature determine the *CH*s stochastically and hamper the maximum network life time. In this paper, the transmission of each data packet is regarded as the hard real-time transmission with a predefined tolerable delay (TD). We aim to design a clustering method and a routing protocol to meet the hop constrains or hard deadlines of each data packet arriving at BS and improve both network and coverage lifetime.

In a distributed system with arbitrary states, a self-stabilizing algorithm can lead the system to a legitimate state and keeps the system in the legitimate state unless the system meets a subsequent transient fault [29,30,45,46]. Many studies regarding self-stabilizing algorithms have adopted Dijkstra's central demon model [31] or Burns' distributed model [32]. In a large-scale WSN, inter-cluster routing will substantially affect the lifetime of *CH*s. When the *CH*s located further from the BS submit their aggregate data directly to the BS, it will drain their batteries quickly and thus bring forward the time to cluster re-configuration. The proposed distributed self-stabilizing algorithm enables each *CH* to concurrently contact its adjacent *CH*s to construct time- and energy-efficient routes to the BS.

Radio transmission energy is critical to energy efficiency in WSNs, because the energy grows at least quadratically with the transmission range [16]. Some existing WSN protocols use identical or maximum transmission power to send data packets regardless of node distances. Many off-the-shelf low-power RF transceiver designs such as CC2420 and CC1000 [28,40] are programmed to a maximum of 31 different power levels, and have been implemented in ZigBee systems, PC peripherals, home/building automation and consumer electronics. These designs also benefit multi-hop cluster for power saving because the transmission ranges shorter than those in single-hop methods can be selected, and thus reduce the number of required clusters and prolong network lifetime.

The rest of this paper is organized as follows: Section 2 introduces existing methods that are related to this work. Section 3 describes the network model including system assumptions, QoS metrics and packet format. Section 4 describes the power model and outlines the proposed clustering and routing protocols. The protocols are also explained by examples. The performance evaluations given in Section 5 include time complexity analysis and simulations comparing to the existing methods. Finally, Section 6 concludes the paper.

2. Related work

Low-energy adaptive clustering hierarchy (LEACH) [23] is a distributed cluster-based routing protocol in which a large number of SNs are divided into several clusters. For each cluster, an SN is selected as a *CH* determined according to a given probability. LEACH-C [24] providing for the same steady-state phase as LEACH is a centralized deterministic clustering approach. It outperforms LEACH by dispersing the *CH*s throughout the network. In the set-up phase of LEACH-C, additional information such as location and residual energy are sent to the BS which computes ideal clustering decisions. Another noteworthy clustering protocol, called hybrid energy-efficient distributed clustering (HEED) [11], considers the residual energy of each SN and determines a good distribution of the *CH*s in the sensing area. In literature, some network layer clustering protocols with QoS for WSN [34–36,48–50] have been proposed. Diaz et al. [50] propose an ad hoc cluster-based protocol for logical sensor network topology to provide QoS-based multimedia streams. The QoS parameters such as packet loss, jitter, delay, bandwidths and multimedia properties are used for end-to-end transmissions. They also derive the maximum diameter for individual clusters, which is suitable for different types of multimedia streams. Atto and Guy [49] propose a power-aware cross-layer based protocol to provide QoS for wireless video sensor networks. The protocol keeps a high capture rate for some sensor nodes in the security applications in order to make better decisions to signal other nodes to move their status. Suganthe and Balasubramanie [48] propose a network layer protocol for mobile ad hoc networks which transmit data using message ferries and gateways. This protocol improves transmission rate and decreases communication overhead based on message ferrying scheme.

The chain-based technique is suitable for reducing the energy consumption in WSN. In the chain-based protocol, all of the SNs are interconnected into a chain, and a chain head will gather the data packets forwarded by the SNs along the chain. Power-efficient gathering in SN information systems (PEGASIS) is proposed to create a chain structure in WSN