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Towards minimum-delay and energy-efficient flooding in low-duty-cycle wireless sensor networks

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ABSTRACT

Wireless sensor networks (WSNs) play a very important role in realizing Internet of Things (IoT). In many WSN applications, flooding is a fundamental network service for remote network configuration, diagnosis or disseminating code updates. Despite a plethora of research on flooding problem in the literature, there has been very limited research on flooding tree construction in asynchronous low-duty-cycle WSNs. In this paper, we focus our investigation on minimum-delay and energy-efficient flooding tree construction considering the duty-cycle operation and unreliable wireless links. We show the existence of the latency-energy trade-off in flooding. We formulate the problem as a undetermined-delay-constrained minimum spanning tree (UDC-MST) problem, where the delay constraint is known a *posteriori*. Due to the NP-completeness of the UDC-MST problem, we design a distributed Minimum-Delay Energy-efficient flooding Tree (MDET) algorithm to construct an energy optimal tree with flooding delay bounding. Through extensive simulations, we demonstrate that MDET achieves a comparable delivery latency with the minimum-delay flooding, and incurs only 10% more transmission cost than the lower bound, which yields a good balance between flooding delay and energy efficiency.

1. Introduction

Wireless sensor networks (WSNs) are important elements for realizing the Internet of Things (IoT), which are composed of tiny wireless sensing devices equipped with data processing and communication capabilities [1]. WSNs offer several advantages over traditional wired industrial monitoring and control systems including extended network coverage, easy and fast installation, resilience against single node failure and cost effective maintenance. On the contrary, traditional wired sensing and automation systems normally require expensive communication cables to be installed and regularly maintained [2]. In many WSN applications, *e.g.*, factory automation, industrial process monitoring and control, and plant monitoring, flooding is a fundamental network service for remote network configuration, diagnosis or disseminating code updates. The development of effective flooding protocol is hence a key research topic in this area. During flooding (or network wide broadcasting), messages from a root node are disseminated to the whole network via multi-hop communication. Since sensor nodes are usually energy constrained for WSN sustainable monitoring and surveillance applications, they normally operate at a very-low-duty-cycle (*e.g.*, 1% or less) to ensure the service continuity [3].

Existing flooding protocols [4] utilize the broadcast nature of radio transmission to improve the delivery ratio and reduce transmission redundancy, *i.e.*, a single transmission can be heard by multiple neighbors within the sender's radio range. However, in an asynchronous low-duty-cycle WSN, neighboring nodes do not always wake up at the same time. Flooding is essentially achieved through a number of unicasts [3,5], and thus more transmissions are required to ensure the flooding coverage than conventional wireless networks.

On the other hand, sensor nodes are subject to radio frequency interference. For example in harsh industrial environments, highly caustic or corrosive environments, high humidity levels, vibrations,

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dirt and dust, or other conditions challenge network performance [6]. As a result, wireless links can be highly unreliable. Considering the unreliable wireless links especially for low-power embedded devices, to forward a packet reliably, it is likely multiple retransmissions are needed for an individual receiver to successfully receive a packet. In addition, flooding in low-duty-cycle WSNs suffers from a long sleep latency problem, where the sleep latency refers to the time that a sender spends on waiting for the receiver to wake up. Since each node only stays in active state for a very short period in each working cycle, a sender needs to wait for a long time until the receiver wakes up again and the interval between consecutive retransmissions is very large. Such an operation, poses new challenges for flooding protocol design on energy efficiency and latency.

Tree-based topology has been considered as an effective way to achieve efficient flooding in WSNs [3]. In low-duty-cycle WSNs, tree-based flooding tree aligns nodes' active slots for sending and receiving, which reduces idle-listening time. Compared with the asynchronous flooding without a tree structure. it avoids the sender sending probes for a long period that exceeds the sleeping period of the receiver. In addition, tree-based topology facilitates the reliable flooding, *e.g.*, a parent node takes charge of the forwarding task to its children nodes. Such a flooding tree is usually constructed after the initial node deployment and re-constructed locally when the topology changes. A tree structure is time efficient if each node receives a flooding packet with minimum delay. However, it may not be energy optimal in terms of the total transmission cost for flooding a packet (*i.e.*, there exists a latency-energy trade-off). In this paper, we study the problem of routing tree construction for minimum delay and energy efficient flooding in asynchronous low-duty-cycle WSNs with unreliable wireless links. The contributions from this work are summarized as follows:

- We show the existence of flooding latency-energy trade-off in asynchronous low-duty-cycle WSNs. Then, we formulate the minimum-delay and energy-efficient flooding problem as a undetermined-delay-constrained minimum spanning tree (UDC-MST) problem in low-duty-cycle WSNs, which is proven to be NP-complete.
- We present a distributed Minimum-Delay Energy-efficient flooding Tree (MDET) algorithm to construct an energy optimal tree with flooding delay bounding. The main idea is to first construct an ETX (Expected Transmission Count)-based shortest path tree, and then locally improve the energy optimality with delay constraint, by allowing a node to select its parent node with the best link quality while ensuring the network's loop-free property.
- To demonstrate the efficacy of MDET, we compare its performance with four different flooding tree construction methods. Evaluation results show that MDET achieves a comparable delivery latency with the minimum-delay flooding, only incurs 10% more transmission cost than the lower bound, and significantly outperforms the other baseline flooding tree structures.

The outline of the paper is as follows. Section 2 surveys the related work. Section 3 presents the network model. Section 4 elaborates the design of MDET protocol in detail. Section 5 provides the simulation results. Finally, conclusions are drawn in Section 6.

2. Related work

WSNs play a very important role in realizing IoT [7]. Typically, a WSN is composed of a large number of sensor nodes to measure physical phenomena. It provides valuable information to enable a wide range of applications, including smart battlefield, healthcare, environment and habitat monitoring, home automation, and traffic control, fault diagnosis and prediction, and process control in industrial environments. In recent years, many research efforts have studied different enabling technologies that facilitate WSNs for real-world applications. TI's SensorTag provides a solution for the quick and efficient deployment of industrial sensor arrays that can be used for monitoring industrial equipment [8]. Rockwell have applied wireless sensors across the factory to synchronize production, link machines to smartphones to remotely monitor manufacturing processes, and to smart electricity grids to reduce energy costs [9]. Anastasi et al. [10] presented an adaptive staggered sleep protocol in WSNs. The proposed scheme dynamically adjusts the wakeup/sleep activities of sensor nodes based on the traffic pattern and the operating conditions experienced by nodes, achieving both low power consumption and delivery latency.

Since collecting data at a base station is a common requirement of WSN applications, many data gathering trees have been proposed in the literature [11–14]. Different from the data collection, flooding is another fundamental network service in WSNs, such as code update [15–18], remote network configuration and query [19], which has been extensively studied in the literature [20–22]. Construction of energy-efficient flooding and multicast trees in conventional wireless networks have been extensively investigated [4,23], which mainly takes advantage of the broadcast nature of wireless communication to improve the energy efficiency. Shen et al. [24] designed of a network-coding based multipacket flooding protocol that provides efficient and reliable message dissemination service for WSNs with unreliable and correlated links.

Recently, flooding in low-duty-cycle WSNs with unreliable links has attracted much attention in the wireless sensor network research community [3,5,25–29]. According to the radio duty-cycling model, flooding in low-duty-cycle WSNs can be generally classified into two categories: synchronous or asynchronous flooding. In synchronous flooding, for reducing energy consumption and sleep latency, a flooding tree synchronize nodes that have the same parent to wake up simultaneously to receive broadcast packets, by utilizing the wireless broadcast advantage. In asynchronous flooding, nodes set their own sleep/wakeup schedules independently.

In [3], Guo et al. proposed an energy optimal tree-based opportunistic flooding for asynchronous low-duty-cycle WSNs. Based on the delay distribution along the flooding tree, it makes a probabilistic forwarding decision at each sender, so that a packet always travels along a statistically minimum delay and energy efficient routing path. ADB [30] is another for asynchronous flooding protocol in duty-cycled WSNs. By introducing the transmission task delegation, ADB is able to avoid transmissions over poor links, thus reducing energy cost during flooding over unreliable wireless links. Lai et al. proposed an asynchronous and multihop broadcasting protocol in [31], which reduces redundant transmission via delivery deferring and online forwarder selection. The authors in [26] extended the dynamic switch-based forwarding [32] to the flooding scenario. Xu et al. [33,34] provided an adaptive control on the tradeoff between delay and energy efficiency for broadcasting in low-duty-cycle WSNs, by allowing receivers to defer their wake-up time slots to opportunistically overhear the broadcasting messages sent by their neighbors. Chen et al. [35] investigated the minimum active time slot augmentation for delay-bounded multicast problem in duty-cycled WSNs, which can be applied for the broadcasting communication scenario.

Recent advance in physical-layer concurrent transmission allows multiple senders transmit the same packet simultaneously and the constructively synchronized transmissions can be decoded at individual receivers. Glossy [22] exploits concurrent transmissions over interference for reliable flooding in WSNs, which removes unnecessary channel contention and improves the flooding performance. Cao et al. [36] presented a distributed concurrent broadcast layer for Low-Power-Listening (LPL) flooding in asyn-