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C-Sync: Counter-based synchronization for duty-cycled wireless sensor networks

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ABSTRACT

Different variants of synchronous duty-cycle MAC protocols have been designed for wireless sensor networks to reduce energy consumption. However, the synchronization process of these protocols remains a significant contributor to the energy consumption. In this paper, a new energy-efficient synchronization algorithm referred to as C-Sync is proposed. C-Sync reduces energy consumption by adaptively regulating the synchronization traffic and synchronization wakeup period based on the changing network neighborhood conditions through counter-based and exponential-smoothing algorithms. Extensive simulations of multi-hop multi-neighborhood network scenarios are performed using ns-2. We compare C-Sync with the fixed periodic synchronization (F-Sync) algorithm and the 1-Sync algorithm and show that C-Sync outperforms F-Sync and 1-Sync in energy-efficiency over a wide range of node densities, drift rates and duty cycles.

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1. Introduction

A typical wireless sensor network (WSN) generates very light traffic and sensor nodes spend most of the time listening to the radio channel and idling. This idle listening is the dominant source of energy consumption in WSNs.

Duty-cycling is a mechanism where sensor nodes alternate between active and sleep periods. This is a common approach used in the MAC layer to reduce idling time and consequently reduce energy consumption. Sensor nodes in duty-cycle networks schedule the transmission and reception of data during active periods, and switch the radios off completely during sleep periods to conserve energy. Huang et al. [1] and Ahmad et al. [2] provide comprehensive reviews of duty-cycle MAC protocols for WSNs. In addition, energy-efficient solutions in Network, Transport and Application layers are also discussed in [3].

There are two main categories of duty-cycle MAC protocols. The synchronous approach makes use of a MAC layer synchronization algorithm to synchronize sensor nodes in the same neighborhood so that they can wake up at the same time to exchange sensor data. On the other hand, the asynchronous or preamble sampling approach does not use a synchronization algorithm, but places the burden of data delivery on the senders. When a sensor node has data to send, it has to first transmit a preamble that is longer than the sleep period of the receiver so that the receiver will be able to detect the preamble. Once the preamble is detected, the receiver will stay awake to receive the data.

The seminal synchronous duty-cycle MAC protocol S-MAC [4] further divides the active periods into SYNC and DATA windows. During SYNC windows, sensor nodes broadcast synchronization (*sync*) packets periodically to synchronize the clocks of the neighboring nodes. During DATA windows, sensor nodes send out data packets from the higher layers based on some contention mechanisms to avoid collisions. Later developments of synchronous MAC protocols such as DW-MAC [5], AS-MAC [6], SEA-MAC [7] and LO-MAC [8] focus on improving the energy efficiency, throughput and delay performances by implementing changes in the scheduling and transmission of data packets, leaving the synchronization algorithm largely unchanged.

The synchronization algorithm adopted by the above synchronous MAC protocols is based on a fixed, periodic synchronization packet broadcast algorithm (F-Sync) [9] by the sensor nodes in SYNC windows. This algorithm works fine when the network is sparse. When the network is dense, however, too many sync packets are generated and transmitted in the network, causing collisions and increasing energy consumption unnecessarily. The energy consumption for the synchronization process in SYNC windows is not insignificant. For many of the synchronous MAC protocols implemented, the duration of the SYNC window is about one-third of the entire active period. It is therefore worthwhile to examine the synchronisation process of duty-cycle MAC in more detail.

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In this paper, we present a new, counter-based synchronization algorithm (C-Sync) that works in the framework of synchronous MAC protocols. C-Sync reduces energy consumption and improves the effectiveness of the synchronization process by adaptively switching off the radio, as well as reducing unnecessary *sync* packet transmission when the network density is high. It also enables the sensor nodes to wake up more frequently to receive *sync* packets when the network density is low. Extensive simulations are conducted for multi-hop multi-neighborhood grid networks with different densities for performance evaluation. Effects of drift and duty-cycling on both the energy and data performance are also studied.

The contributions of this work can be summarized as follows:

- We introduced and developed a new synchronization algorithm that is adaptive to a wide range of network densities. This algorithm effectively reduces congestions and collisions in the network when *sync* traffic is high and maintains synchronization performance when *sync* traffic is low. In a large multi-hop WSN, different neighborhoods have different densities; an adaptive synchronization algorithm will enable the MAC protocol to deliver a better energy performance.
- End-to-end multi-hop network simulations are performed against sensor nodes with different duty cycles, network densities and clock drifts to analyze the sensitivity and stability of the synchronization algorithms. Both energy and data performance are evaluated and analyzed.
- Although we implemented the C-Sync algorithm with S-MAC, it is also compatible with other synchronous duty-cycle MAC protocols such as DW-MAC, AS-MAC, etc.

The rest of this paper is organized as follows: Section 2 discusses the related work of the synchronization algorithms proposed for duty-cycle WSN. Section 3 discusses the synchronization process in a duty-cycle WSN and the effects of different network conditions. Section 4 describes the design of the proposed C-Sync algorithm, detailing the sync transmission and reception processes. In Section 5, the performances of C-Sync are evaluated based on the simulation results, including a comparison with F-Sync and 1-Sync. Finally, Section 6 concludes the paper.

2. Related work

Time synchronization in WSNs can be achieved by exchanging timing messages among the sensor nodes. There are, broadly categorized, three approaches for time synchronization in WSNs. They are the sender-receiver synchronization, the one-way message dissemination (or unidirectional reference broadcast) and the receiver-receiver synchronization [10]. In the unidirectional reference broadcast approach [11,12], a single-message broadcast carrying reference clock signal is used to achieve local synchronization with the participating nodes in the sender neighborhood. On the other hand, both sender-receiver [13,14] and receiver-receiver [15,16] synchronizations use multiple message exchanges to achieve pair-wise synchronization with high accuracy. A comprehensive comparison and review of different synchronization algorithms in WSNs can be found in [17].

The listen period in synchronous duty-cycle MAC protocols is much longer than the clock drift. As such, a much looser synchronisation among neighboring nodes is required compared with TDMA schemes with very short timeslots [9]. In addition, as the frame structure of synchronous duty-cycle MAC provides only small time windows for exchanging timing messages, single-message unidirectional broadcast is the most appropriate and energy efficient among the three approaches for synchronizing sleep/wakeup schedules of the sensor nodes.

F-Sync was proposed in [9] together with S-MAC protocol and has since been the default synchronization algorithm used in the synchronous MAC protocols that were developed later. As the neighboring nodes need to coordinate their sleep/wakeup schedules, and the clock for each sensor node drifts independently from one another, the drifts can cause data loss if the clocks are left unsynchronized. Using the F-Sync algorithm, each sensor node broadcasts a *sync* packet periodically to update the neighbors on its sleep/wakeup schedule to prevent long-term phase offset.

Intelligent Network Synchronization (INS) [18] attempts to improve the energy efficiency in the synchronization process by exploiting the periodic nature of *sync* packet transmission in F-Sync. In the INS networks, each node maintains a counter for each of its neighbors. Each counter is increased by one after every cycle. When a node receives a *sync* packet from a neighbor, the corresponding counter will be reset to zero. By examining the list of its counters, the node is able to determine whether there will be a *sync* packet arriving in the current SYNC window. If any of the counter value is greater than or equal to the synchronization period, the node wakes up in the current window as it is expecting a *sync* packet to arrive. It will otherwise go to sleep to conserve energy. INS was simulated and evaluated over a linear and a sparse grid network with good energy performance. However, in a dense network where collisions frequently occur, the periodicity of *sync* packets from each neighbor cannot be guaranteed and INS faces the similar energy inefficiencies as F-Sync [19].

The 1-Sync algorithm proposed in [19] puts a sensor node to sleep after it receives a valid *sync* packet in the current synchronization period, which is independent of network neighborhood density. Similar to both F-Sync and INS, a sensor node using 1-Sync schedules a *sync* packet periodically. After a *sync* packet is sent, the sensor node stays awake during the subsequent SYNC windows and waits for a valid *sync* packet from its neighbors. Once a valid packet is received, the node goes into a synchronized state and will go to sleep in the subsequent SYNC windows to conserve energy. The sensor node will only turn its radio on when it is ready to transmit its *sync* packet, and the cycle repeats. 1-Sync is shown to be more energy efficient than F-Sync and INS in single neighborhood networks of wide density ranges. However, the performances of these synchronization algorithms under multi-hop multi-neighborhood networks in the presence of hidden terminals are not studied.

3. Synchronization in duty-cycle MAC networks

3.1. Overview

The basic operation of common listen/sleep periods in synchronous duty-cycle MAC protocols requires a network-wide synchronization mechanism to synchronize the local clocks of the sensor nodes within the same neighborhood. Beacons or *sync* packets must be received regularly within a specific interval before the local clock drifts out of synchronization.

The design goal of the proposed synchronization algorithm design is to offer energy consumption efficiency while providing good data performance, including packet delivery ratio and end-to-end packet delay across a wide range of multi-hop WSNs. In this paper, we will study the performances of the proposed algorithm against F-Sync and 1-Sync algorithms in WSNs with different network densities, clock drifts and duty cycles. We will also compare the robustness and stability of these three synchronisation algorithms by examining individual node energy performance under a wide range of network scenarios.

Since the original S-MAC and many of the synchronous duty-cycle MAC family have implemented F-Sync for synchronization, it

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