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Drift estimation using pairwise slope with minimum variance in wireless sensor networks

Kasım Sinan Yıldırım *, Aylin Kantarcı

Department of Computer Engineering, Ege University, İzmir, Turkey

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ABSTRACT

Time synchronization is mandatory for applications and services in wireless sensor networks which demand common notion of time. If synchronization to stable time sources such as Coordinated Universal Time (UTC) is required, employing the method of flooding in order to provide time synchronization becomes crucial. In flooding based time synchronization protocols, current time information of a reference node is periodically flooded into the network. Sensor nodes collect the time information of the reference node and perform least-squares regression in order to estimate the reference time. However, least-squares regression exhibits a poor performance since sensor nodes far away from the reference node collect the time information with large deviations. Due to this fact, the slopes of their least-squares line exhibit large errors and instabilities. As a consequence, the reference time estimates of these nodes also exhibit large errors.

This paper proposes a new slope estimation strategy for linear regression to be used by flooding based time synchronization protocols. The proposed method, namely Pairwise Slope With Minimum Variance (PSMV), calculates the slope of the estimated regression line by considering the pairwise slope between the earliest and the most recently collected data points. The PSMV slope is less affected by the large errors on the received data, i.e. it is more stable, and it is more computationally efficient when compared to the slope of the least-squares line. We incorporated PSMV into two flooding based time synchronization protocols, namely Flooding Time Synchronization Protocol (FTSP) and PulseSync. Experimental results collected from a testbed setup including 20 sensor nodes show that PSMV strategy improves the performance of FTSP by a factor of 4 and preserves the performance of PulseSync in terms of synchronization error with 40% less CPU overhead for linear regression. Our simulations show that these results also hold for networks with larger diameters and densities.

1. Introduction

Wireless sensor networks (WSNs) consist of tiny, cheap and low-power sensor nodes that have the ability of sensing the environment. Each sensor node is equipped with a hardware clock which counts oscillations of a quartz crystal. Due to their low-end crystals, the hardware clocks frequently drift apart which leads to loss of synchronization between the sensor nodes. This situation is problematic for applications and protocols which depend on a synchronized notion of time. For instance, synchronous power on and shutdown of the radios reduce energy consumption where energy is a scarce resource for battery-powered sensor nodes. Such time coordinated actions can be performed if the clocks of the sensors are well synchronized. Thus, time synchronization is mandatory for the correct and efficient operation of the WSNs [1–3].

* Corresponding author.
E-mail addresses: sinan.yildirim@ege.edu.tr (K.S. Yıldırım), aylin.kantarci@ege.edu.tr (A. Kantarcı).

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In the course of time synchronization in WSNs, the hardware clock values of the nodes and the information carried by the synchronization messages are considered to calculate the global (common) time in the network. Most of the time synchronization protocols in the literature [4–8] use least-squares regression in order to establish a linear relationship between the hardware clocks of the nodes and the global clock in the network. Thus, sensor nodes can predict future global clock values without communicating frequently. However, least-squares regression exhibits poor performance if the data points have large errors [9–11]. Such a situation may decrease the performance of time synchronization protocols, especially the ones that use flooding. If synchronization to stable time sources such as Coordinated Universal Time (UTC) time is required, employing the method of flooding in order to provide time synchronization becomes crucial [12].

As an example, in Flooding Time Synchronization Protocol (FTSP) [4] which is the de facto standard time synchronization protocol in WSNs, current time information of a dynamically elected reference node is periodically flooded into the network. Due to the nature of flooding and waiting times at each sensor node, the sensor nodes which are far away from the reference node collect the estimated reference time with large errors, which leads to large errors and instabilities in the slope of their least-squares regression line. As a consequence, the reference time estimates of these nodes which are calculated using least-squares exhibit substantially large synchronization errors when compared to that of nearby nodes to the reference. This situation has a negative impact on the scalability of FTSP.

In this paper, we present a new slope estimation method for linear regression to be used by flooding based time synchronization protocols in WSNs. The proposed method, namely Pairwise Slope With Minimum Variance (PSMV), considers only the pairwise slope between the earliest and the most recently collected data points instead of considering all pairwise slopes as in least-squares. The PSMV slope is less affected by the large errors on the received data, i.e. it is more stable, and it is more computationally efficient when compared to the slope of the least-squares line. For the implementation, we considered two flooding based time synchronization protocols, FTSP and PulseSync [7], and incorporated PSMV into the source code of these protocols. Experimental results collected from a testbed setup including 20 sensor nodes show that PSMV strategy improves the performance of FTSP by a factor of 4 and preserves the performance of PulseSync in terms of synchronization error with 40% less CPU overhead for linear regression. Our simulations show that these results also hold for networks with larger diameters and densities.

The remainder of this paper is organized as follows: Section 2 describes related work on time synchronization. In Section 3, we describe our system model. We present and analyze the packet timestamping mechanism in WSNs and the least-squares method for establishing linear relationship between the clocks of sensor nodes in Section 4 and 5, respectively. The flooding based time synchronization protocols FTSP and PulseSync are analyzed in Section 6. We present and analyze the proposed drift estimation method in Section 7. Implementation details and experimental results are given in Section 8. We also present simulation results for networks with larger diameters and densities in Section 9. Finally, we present our conclusions and discuss future work in Section 10.

2. Related work

Time synchronization protocols for WSNs generally deal with making the clocks of the nodes as close as possible towards the precision requirement of the sensor network. In order minimize energy consumption, they try to establish relationships between the clocks of the nodes and estimate future clock values without communicating frequently. There are a lot of protocol based studies in the literature which use linear regression for the establishment of a linear relationship [13,4,5,7,8,12].

In Reference Broadcast Synchronization (RBS) [13], a sender node transmits a reference packet for its neighbors. The receiver nodes record the time at which they received that packet. Then, the receivers exchange their observations to learn about the clocks of the other nodes. Linear regression is used to compensate the effects of clock drifts. One major problem of RBS is its high message complexity. For a single-hop network of n nodes, $\mathcal{O}(n^2)$ message exchange is required. In addition, it was not designed for large multi-hop networks.

Flooding Time-Synchronization Protocol (FTSP) [4] synchronizes the whole network by electing a leader node based on the smallest node identifier which serves as the source of reference time. Whenever a slave node receives an up-to-date synchronization message, it stores the received clock value of the reference node and uses linear regression in order to establish a linear relationship between its hardware clock and the clock of the reference node. Using this relationship, each sensor node can predict future clock values of the reference node without communicating frequently. The nodes broadcast their predicted clock values of the reference node to their neighbors for the synchronization of the whole network. FTSP is the de facto standard time synchronization protocol in WSNs and it is used as a benchmark by most of the studies in the literature [6–8,12,14].

In Rapid Time Synchronization (RATS) [5], a designated reference node periodically floods its hardware clock value into the network. Each node converts the timestamp of the synchronization messages from the reference node's time base to its local time to calculate the clock offset and uses linear regression to compensate clock drifts. However, RATS cannot maintain network-wide synchronization if the network is partitioned due to a root failure.

PulseSync [7] propagates time information from a reference node as fast as possible. Apart from the *fast flooding* approach, each nodes use a linear regression table to estimate the clock of the reference node. Although this protocol outperforms FTSP drastically, rapid-flooding can also be very slow due to neighborhood contention since nodes cannot propagate their messages until their neighbors have finished their transmissions [15,12].

Temperature Compensated Time Synchronization (TCTS) [8] uses the temperature sensor to calibrate the frequency of the oscillator which is majorly affected by the