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Research article

A proportional integral estimator-based clock synchronization protocol for wireless sensor networks

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ABSTRACT

Clock synchronization is an issue of vital importance in applications of WSNs. This paper proposes a proportional integral estimator-based protocol (EBP) to achieve clock synchronization for wireless sensor networks. As each local clock skew gradually drifts, synchronization accuracy will decline over time. Compared with existing consensus-based approaches, the proposed synchronization protocol improves synchronization accuracy under time-varying clock skews. Moreover, by restricting synchronization error of clock skew into a relative small quantity, it could reduce periodic re-synchronization frequencies. At last, a pseudo-synchronous implementation for skew compensation is introduced as synchronous protocol is unrealistic in practice. Numerical simulations are shown to illustrate the performance of the proposed protocol.

1. Introduction

Recent years have witnessed great advancement in smaller, cheaper and low-power sensors which are capable of sensing, collecting, processing data and communication through wireless channel [1]. Sensor networks are mainly used for data fusion [2], which highlights the necessity for a synchronized clock of time among sensors, that is, all local sensors should share the same global reference time. For example, in distributed data fusion process, sensor readings and time-stamps are grouped into packages and then pass along to their neighbours so that fusion of such information will be used to calculate a precise estimate. Indeed, the fusion of individual sensor readings is meaningful only with packets that are time-stamped by each sensor's local clock. High accuracy of local clocks is also essential for energy-saving purposes [3], as sensor nodes need to spend most of the time in the sleeping mode with only occasional interactions with neighbouring nodes. Furthermore, most common services in WSN, including coordination, communication, object tracking or distributed logging also depend on the existence of global time [4,5].

To develop successful clock synchronization protocols for WSNs, several issues need to be considered carefully. First, WSNs have wide deployment of sensors which increase the complexity of the network. This leads to scalability requirements for the synchronization protocols. Additionally, wireless communication is unreliable and may suffer from severe interference. Hence the synchronization protocol need to enhance the robustness in order to avoid node failures and packet losses. Furthermore, the energy conservation becomes a significant concern due to the fact that the smaller size sensors are almost battery-based with limited power supply. To avoid this restriction, it is required to optimize energy use in software levels. Effective protocol with low overhead in both communication and computation still remains to be studied further.

There are two kinds of clock synchronization protocols: structure-based and distributed. In structure-based protocols a hierarchical topology is created within the WSNs. Initially, one node is chosen to be the root node which is treated as the global clock reference, then a spanning tree based on this root node is created. Afterwards, each node synchronizes both its clock skew and its offset with respect to its parent node. Typical examples are listed as follows. Timing-sync Protocol for Sensor Networks (TPSN) [6] establishes a hierarchical structure in the network and then a pairwise synchronization is performed to construct a global timescale throughout the network. Flooding Time Synchronization Protocol (FTSP) [7] initially elects the root of the network which maintains the global time and all other nodes synchronize their clocks to that of the root with periodic flooding packets. Reference Broadcast Synchronization (RBS) [8] is proposed as one-hop time synchronization, where a node is selected as reference node and then broadcasts a sequence of synchronization messages to other receivers in order to estimate both clock skew and offset of local clocks relative to each other. Sari et al. [9] further apply the joint

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maximum likelihood (JML) estimator of clock offset and skew under exponential noise model in RBS protocol. Besides, [10] develops a receiver-only synchronization which can synchronize a series of sensor nodes by receiving time stamps of pair-wise references while it could reduce the energy consumption of the whole network. To deal with a time-varying nature of the clock offset, a novel Bayesian approach to the clock offset estimation is proposed in [11]. In most cases, structure-based protocols suffer from computational overhead if a new root needs to be elected under the circumstance of dynamic changes of communication topology. To our best knowledge, they do not satisfactorily handle node failures or packet losses.

Confronted with the above problems, distributed protocols have been proposed for time synchronization in WSNs. These protocols work in a distributed way and do not require a specific tree topology or a root node, thus have the advantages of being scalable and robust to node failure and packet losses. Typical examples include [12–19]. Among distributed protocols consensus-based ones serve as the most popular designing methods. Existing consensus-based algorithms can be classified into two main categories according to their ways of implementation, synchronous [20,21] and asynchronous protocols, also known as gossip [22]. For asynchronous protocols, Schenato proposed an Average TimeSync (ATS) protocol [23] which is based on a cascade of two consensus algorithms to make all the nodes converge to a virtual reference clock by tuning compensation parameters for each node. CCS [24] reduces the clock errors between nodes whose locations are geographically close and achieves long lasting synchronization by converging all nodes to a common skew. He proposed a novel maximum time synchronization algorithm (MTS) [25,26], for delay-free case and a weighted maximum time synchronization algorithm for random delay case. Other work includes [27], etc. For synchronous implementation, see [28–31]. Initially, synchronous implementation seems unrealistic as it requires each node to update its information simultaneously, which implicitly requires a common clock, which contradicts the fact that they do not share a common global clock. Carli et al. [29] proposed a synchronization algorithm that is based on a proportional–integral (PI) consensus-based controller. A similar approach, based on the second-order consensus algorithm, has been proposed in [30] to deal with the synchronization of networks of non-identical double integrators. Based on [30], Carli and Zampieri [31] further develop a pseudo-synchronous implementation way for synchronous protocols and it is proved to have the same performance. Since then researchers can focus on designing synchronous synchronization protocols but implementing them using a pseudo-synchronous implementation.

In this paper, we consider a distributed approach and develop a proportional–integral estimator-based protocol (EBP) for clock synchronization over WSNs. As each local clock skew may experience slow drift due to external environmental conditions such as ambient temperature or battery voltage and on oscillator aging, even if all clocks are perfectly synchronized at a certain time instant, they will slowly diverge from each other. In the case of slow changes of clock skews, tracking is a preferable choice. Compared with the existing protocols, the concrete technical merits of the proposed algorithm can be summarized as follows:

1. Theoretical contribution to tackle with clock synchronization time-varying clock skew. Most existing synchronization algorithms either ignore the drifted clock skew or ideally assume the change of clock skew as a zero-mean noise [32]. Ahmad [11] proposed a novel Bayesian approach to deal with time-varying clock offset estimation by using a factor graph representation of the posterior density but only in scenarios of pairwise synchronization. In spite of realizing convergence of clock parameters, they fail to take time-varying clock skew into consideration when giving their theoretical analysis. We aim to develop a consensus-based synchronization protocol which could theoretically prove the convergent result under time-varying clock skew. The proposed protocol generally assumes that each physical clock skew has a relatively small change bounded by a constant quantity. By applying EBP, the synchronization error of virtual clock skews can be bounded by a relative small steady state error bound when physical clock skews are gradually changing within certain limits.
2. Higher synchronization accuracy under time-varying clock skew. Our work focuses on improving synchronization accuracy. The comparison between other two consensus-based algorithms indicates that the proposed algorithm could gain better synchronization accuracy especially under time-varying clock skew.

The proposed protocol also deals with random delay case and shows that the convergence of virtual clock skew is in mean square sense. After the clock skew compensation, an asynchronous clock offset compensation protocol is presented. Inspired by [31], a pseudo-synchronous implementation for EBP is presented as synchronous implementation for clock skew compensation is unrealistic in practice. Moreover, as pseudo-synchronous implementation requires no simultaneous action of each sensor node at a global time instant, EBP with a pseudo-synchronous implementation could support both half-duplex and full-duplex systems.

The remainder of this paper is organized as follows. In Section 2, the wireless sensor network model and a time-varying clock skew model for WSNs are introduced as the preliminary knowledge. Section 3 introduces the proportional integral estimator-based protocol. Filtering-based algorithms under both delay-free and random delay cases are presented. Then a proportional integral estimator-based protocol including both clock skew and offset compensation is proposed, where the convergent results are shown in the main theorem and other two corollaries. In Section 4, analysis of pseudo-synchronous implementation is presented for handling the unrealistic synchronous implementation. Simulation results are shown in Section 5. Conclusion of our work and several open problems are given in Section 6. The proof of main theorem is in Appendix.

2. Preliminaries

This section introduces some notations, preliminaries of graph theory, wireless sensor network model and a time-varying clock skew model.

2.1. Notations

$\mathbb{R}$ denotes the set of real numbers and $\mathbb{R}^+$ denotes the set of positive real numbers. $\mathbf{1}$ represents n-dimensional vector of ones while $\mathbf{0}$ represents vector of zeros with an appropriate dimension. $\mathbb{R}^n$ represents an n-dimensional vector while $\mathbb{R}^{n\times n}$ denotes an $n_* n$ square matrix composed of real numbers. I^n indicates identity matrix with order n while $\mathbb{O}^n$ indicates zero matrix with order n. $\mathbb{Z}$ denotes the set of nonnegative integer numbers.

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