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无线传感器网络同步技术

Synchronization in Wireless Sensor Networks

(China Edition)

Erchin Serpedin
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内 容 简 介

无线传感器网络在民用与军用设备中有着广泛的应用。微传感器以无线互联的形式完成高度分散系统中的感应、计算、通信以及控制等工作。本书介绍了无线传感器网络部署中的一项最关键的技术：同步技术。本书概述了无线传感器网络中的时钟同步协议，着重讲解了导出高效时钟补偿评估方法以及运行评估指标等技术手段。本书适合电子信息专业、计算机专业的高年级本科生、研究生以及相关研究人员阅读。

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《国外电子信息精品著作》序

20世纪90年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近30本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是2005年后出版的，力求“层次高、内

容新、参考性强”。在内容和形式上都体现了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王越

中国科学院院士

中国工程院院士

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PREFACE

The clock or time synchronization problem in wireless sensor networks (WSNs) requires a procedure for providing a common notion of time across the nodes of WSNs. In general, clock synchronization is viewed as a critical factor in maintaining the good functioning of WSNs due mainly to their decentralized organization and timing uncertainties caused by the imperfections in hardware oscillators and message delays at the physical and medium access control (MAC) layers. In addition, synchronization of the nodes of wireless sensor networks is crucial for implementing fundamental operations such as power management, transmission scheduling, data fusion, localization and tracking, and security protocols to name only a few applications.

The aim of this book is to provide an introduction to the clock synchronization problem of WSNs from a statistical signal processing viewpoint. Therefore, most of the topics presented in this book deal with building efficient clock offset estimation algorithms and performance benchmarks for general synchronization approaches that rely on sender–receiver and receiver–receiver timing packet exchange mechanisms. A summary of the key features of the most representative protocols proposed for clock synchronization of WSNs is also presented, together with some interesting open research problems.

Synchronization of WSNs is currently a very active research field with a large number of results and very diverse contributions coming from an equally diverse body of researchers: computer scientists, electrical engineers, mathematicians, statisticians, etc. Despite the deployed efforts, the general problem of building efficient global synchronization protocols for large-scale wireless sensor networks is still open and the proposed results are still introduced in a quite ad-hoc manner, lacking comprehensive design and optimization studies to assess and improve their performance in a systematic fashion. Although herein we will not solve these general and very important problems, this book assumes the modest task of building efficient synchronization algorithms and performance benchmarks for simple sender–receiver and receiver–receiver timing packet exchange based synchronization protocols. Despite its unambitious goal, this book will be of interest to all practitioners who are looking for techniques to improve the performance of existing protocols such as network time protocol (NTP), time protocol for synchronization of sensor networks (TPSN), reference broadcast synchronization (RBS), pairwise broadcast synchronization (PBS), etc., and to develop novel synchronization protocols.

This book consists of 15 chapters. Chapter 1 is a short introduction to the time synchronization problem, its history, and importance. Chapter 2 presents the main constraints that must be taken into account when designing time synchronization protocols for WSNs. Chapter 3 focuses on the most representative synchronization protocols for wireless sensor networks by outlining their main features, while Chapter 4 discusses three general packet-based synchronization approaches for WSNs. Chapters 5–14 propose a variety of statistical signal processing algorithms for improved estimation of clock phase offsets and assessing performance benchmarks. A series of novel results, extensions, and interesting relationships between different estimation schemes are reported. At first, the emphasis is put on developing efficient clock offset estimators for the general scenarios when the network delays are normally or exponentially distributed. However, observing the facts that the distribution of network delays in general cannot be predicted accurately, and that the estimators reported in the literature are not robust with respect to the unknown possibly time-varying distribution of network delays, we address in Chapter 14 the problem of building clock offset estimators that are robust to the distribution of network delays. Finally, Chapter 15 concludes this book with some open research problems.

This work would have not been possible without the support and encouragement of Dr. Bruce Suter from Air Force Research Laboratory (AFRL), Rome, NY, and the help of our students. Our heartfelt thanks go to Bruce, and to our families and students (Dr. Kyoung-Lae Noh, Dr. Jangsub Kim, Dr. Yik-Chung Wu, Mr. Ilkay Sari, Mr. Jaehan Lee, and Mr. Sabit Ekin). Despite our efforts to contain all sources of errors and misunderstandings, we believe that inconsistencies and errors might show up. Therefore, we are asking our readers kindly to email us their feedback to: eserpedin@gmail.com. Any feedback is welcome to improve this work. This book webpage will be maintained at http://www.ece.tamu.edu/~serpedin/.

CONTENTS

Chapter 1

INTRODUCTION

1.1 Wireless Sensor Networks

With the help of technological advances in micro-electro-mechanical systems (MEMS) and wireless communications, low-cost, low-power, and multi-functional wireless sensing devices have been developed. When these devices are deployed over a wide geographical region, they can collect information about the environment and efficiently collaborate to process such information by forming a distributed communication network, called a *wireless sensor network* (WSN), as illustrated in Figure 1.1. A WSN is a special case of an ad-hoc wireless network, and assumes a multi-hop communication framework with no common infrastructure, where the sensors spontaneously cooperate to deliver information by forwarding packets from a source to a destination. The number of practical applications involving WSNs keeps growing rapidly, and WSNs have been regarded as providing the fundamental infrastructure for future communications due to a variety of promising potential applications: monitoring the health status of humans, animals, plants, and the environment; control and instrumentation of industrial machines and home appliances; homeland security; detection of chemical and biological threats and leaks, etc. [2], [14], [75], [100].

When designing sensor networks, there are a number of important factors to be considered such as tolerance to node failures, scalability, dynamic network topology, hardware constraints, production cost, and power consumption [2]. In general, the lifetime of a sensor network is proportional to that of a battery since the sensor nodes are usually inaccessible after deployment. Moreover, due to the space limitations and other practical constraints in sensor nodes, power is a scarce resource for practical WSNs. For these reasons, energy efficiency in general has top priority when designing WSNs out of all the above mentioned design considerations. Data

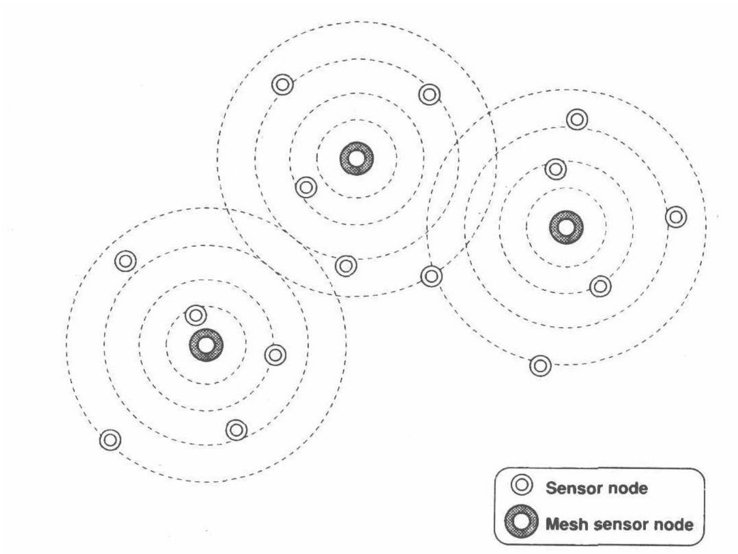

Figure 1.1: A wireless sensor network.

communication is one of the most significant operations in WSNs and requires a huge portion of the overall energy consumption. Indeed, the energy required for data communication is far greater than the energy required for data processing in a sensor node [75].

1.2 Time Synchronization

In distributed systems, maintaining the logical clocks of the computers in such a way that they are never too far apart is one of the most complex problems of computer engineering. Whether disciplining computer clocks with the devices synchronized to a global positioning system (GPS) satellite or a network time protocol (NTP) [62] time server over the Internet, it is possible to equip some primary time servers to synchronize a much larger number of secondary servers and clients connected through a common infrastructure. In order to do this, a distributed network clock synchronization protocol is required through which a server clock can be read, the readings to other clients can be transmitted, and each client clock can be adjusted as required. In such a distributed synchronization approach, the participating devices exchange timing information with their chosen reference at regular intervals and adjust their logical clocks accordingly.

A computer clock in general has two components, namely a frequency source and a means of accumulating timing events (consisting of a clock interrupt mechanism and a counter implemented in software). The implementation of the computer clock in the operating system and the programming interface differ between operating systems and hardware platforms. However, the basic sources of timing errors are an uncompensated quartz crystal oscillator and the clock interrupts it generates. Theoretically, two clocks would remain synchronized if their offsets were set equal and their frequency sources run at the same rate. However, in practice clocks are set with limited precision and the frequency sources run at slightly different rates. In addition, the frequency of a crystal oscillator varies due to the initial manufacturing tolerance, aging, temperature, pressure, and other factors. Because of these inherent instabilities, distributed clocks must regularly be synchronized.

1.3 Importance of Time Synchronization

Time synchronization is a procedure for providing a common notion of time across a distributed system. It is crucial for WSNs when performing a number of fundamental operations, such as:

- *Data fusion* Data merging is a major operation in all distributed networks for processing and integrating the collected data in a meaningful way, and it requires some or all nodes in the network to share a common timescale.
- *Power management* Energy efficiency is a key factor when designing WSNs since sensors are usually left unattended without maintenance and battery replacement for their lifetimes after deployment. Most energy-saving operations strongly depend on time synchronization. For instance, duty cycling (sleep and wake-up modes control) helps the nodes to save huge energy resources by spending minimal power during the sleep mode. Thus, network-wide synchronization is essential for efficient duty cycling and its performance is proportional to the synchronization accuracy.
- *Transmission scheduling* Many scheduling protocols require time synchronization. For example, the time division multiple access (TDMA) scheme, one of the most popular communications schemes for distributed networks, is only applicable to a synchronized network.
- *Miscellaneous* Many localization, security, and tracking protocols also demand the nodes to timestamp their messages and sensing events.

Therefore, time synchronization is one of the most important research challenges in the design of energy-efficient WSNs.

1.4 History of Clock Synchronization

Many time synchronization protocols for maintaining synchronization of physical clocks over computer networks have been designed over the past few decades. The pioneering work in this area was the remote clock reading method proposed by Cristian, which handles unbounded message delays between processes [16]. In this algorithm, a time request is sent to the remote process and after receiving the response, the host process calculates the round-trip time as the difference between the transmission and reception times. The main feature of this algorithm relies on the fact that performing a large number of request/response experiments will make it more likely that at least one trial will not encounter random delays. Logically, the chosen trial is the one with the least round-trip delay.

The standard for time synchronization in the Internet, the network time protocol (NTP), was developed by Mills [62] (also see [61]). NTP is a protocol for synchronizing the clocks of computer systems over packet-switched, variable-latency data networks. It is a layered client–server architecture based on user datagram protocol (UDP) message passing, which synchronizes computer clocks in a hierarchical way. The main attractive features of NTP are its scalability, robustness to failure, self-configuration in large multi-hop networks, and ubiquitous deployment. NTP's sender–receiver synchronization architecture is now widely accepted in designing time synchronization algorithms and relies on the same two-way timing message exchange mechanism targeted in most of this book.

The time transmission protocol (TTP), which is used by a node to communicate the time of its clock to a target node, was introduced in [7]. The target node estimates the time in the source node by using the message timestamps and message delay statistics without any feedback response or pairwise synchronization. The exploitation of the inherent properties of the broadcast media, where a node sends timing beacons to all the nodes within a single broadcast domain, was first introduced in the CesiumSpray system [97]. Later, one of the most popular clock synchronization protocols in wireless sensor networks, the reference broadcast synchronization (RBS) [22], was proposed based on the same idea, but allowing an extension of the protocol to multiple domains. The RBS protocol will be discussed in detail in Chapter 3. For ad-hoc communication networks, the time synchronization protocol [79] is one of the pioneering contributions. This protocol is based on generating timestamps to record the time at which an event of interest occurred. The timestamps are updated by each node using its local clock and the time transformation method, in which the final timestamp is expressed in terms of an interval with a lower bound and an upper bound. Clock synchronization in WSNs is an entirely new area of research due to the fact that the above general synchronization protocols present a number of challenges when applied to WSNs. This is because of the unique nature of sensor networks: limited power resources, wireless channel conditions, and dynamic topology caused by node mobility and failure. Therefore, different types of synchronization schemes have to be designed explicitly for WSN applications to cope with these challenges. References [23], [24], [80], [81], [82], [84], [88], [89], [91] are excellent surveys of research in this area.

The main protocols put forward for clock synchronization to cope with the above mentioned requirements in WSNs are described next. RBS [22] is based on the post-facto receiver–receiver synchronization approach. In RBS, a reference broadcast message is sent by a node to two or more neighboring nodes which record their own local clocks at the reception of broadcasted message. After collecting a few readings, the nodes exchange their observations and a linear regression approach is used to estimate their relative clock offset and skew. The timing synch protocol for sensor networks (TPSN) [29] is a conventional sender–receiver protocol which assumes two operational stages: the level discovery phase followed by the synchronization phase. During the level discovery phase, the WSN is organized in the form of a spanning tree, and global synchronization is achieved by enabling each node to be synchronized with its parent (the node located in the adjacent upper level) by means of a two-way message exchange mechanism through adjusting only its clock offset. Because TPSN and NTP share the same signaling mechanism, one might interpret TPSN as an extension of NTP to WSNs.

The timing synchronization protocol for high latency acoustic networks (TSHL) [93] combines both of these approaches, namely the receiver–receiver (RBS) and sender–receiver (TPSN), in two stages. The first stage in TSHL is similar to RBS while the second stage is similar to TPSN. TSHL is particularly suitable for networks involving large message delays, e.g., underwater acoustic networks. The flooding time synchronization protocol (FTSP) [58] also combines the two approaches in the sense that the beacon node sends its timestamps within the reference broadcast messages. The delay measurement time synchronization (DMTS) protocol for WSNs [74] is an energy-efficient protocol which avoids estimating the round-trip time unlike NTP or TPSN, synchronizes the sender and multiple receivers at the same time, and requires a smaller number of message transfers than RBS. Among other non-probabilistic approaches, the tiny–mini-synchronization protocols [86] provide good synchronization accuracy in WSNs while using a deterministic protocol with minimal computational and storage complexity.

The Time Diffusion Protocol (TDP) proposed in [90] achieves a network-wide time equilibrium by using an iterative, weighted averaging technique based on a diffusion of messages involving all the nodes in the synchronization process. Also, the asynchronous diffusion protocol (ADP) [53] uses a diffusion strategy similar to TDP, but the network nodes execute the protocol and correct their clocks asynchronously with respect to each other.

Suggesting a probabilistic approach to tackle the clock synchronization problem in WSNs, PalChaudhuri *et al.* [69] extended the results from RBS by providing probabilistic bounds on the accuracy of clock synchronization. Valuable research was carried out by Abdel-Ghaffar [1] who adopted the probabilistic approach. He presented a detailed analysis of clock offset estimation assuming a symmetric exponential model for network delays. It was implicitly argued in [1] that for known fixed delay and exponential delay parameters, the maximum likelihood estimator of the clock offset does not exist because the likelihood function does not possess a unique maximum with respect to the clock offset. However, it was proved by Jeske in [41] that for an unknown fixed delay, irrespective of the exponential delay parameter being known or unknown, the MLE of the clock offset does exist and coincides with a previously proposed estimator by Paxson in [71] and [72].

The research presented in this book advances the results for the clock synchronization problem for WSNs by adopting a probabilistic approach and applying techniques from statistical signal processing and estimation theory. The next section lists the major topics in the book. Some very interesting results for this problem were derived in [27], which showed that for the synchronization problem consisting of estimating all the unknown parameters, i.e., skews and offsets of all the clocks as well as the delays of all the communication links, even in the presence of noiseless communication of messages, the estimation of all the unknown parameters is impossible.

1.5 OUTLINE

The topics covered in this book are summarized as follows.

In Chapter 2, the general clock model for time synchronization is first introduced and analyzed. The most important features that have to be considered when designing time synchronization protocols for WSNs are presented. In addition, the different delay components that are present in the timing message delivery are categorized. In Chapter 3 we categorize and survey the existing time synchronization protocols for WSNs, focusing mainly on the signal processing aspects. In addition, in Chapter 3 we describe the importance and effectiveness of adaptive time synchronization schemes, and introduce some important adaptive synchronization protocols as well. In Chapter 4 three general and fundamentally different time synchronization approaches are presented, based on packet synchronization, namely,