Chapter 3.17
Time Synchronization in Wireless Sensor Networks

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ABSTRACT

Time synchronization services are often required to support coordinated operation of the nodes in sensor networking applications, potentially containing hundreds or thousands of elements. The synchronization service must provide application-specific performance (in terms of accuracy and overhead), and must be scalable and robust. For the design of suitable algorithms, the error sources of both the applied synchronization models and the physical devices must be understood and taken into account. In this chapter, various time synchronization models will be introduced, and their potential accuracy and complexity will be shown. The error sources of real devices and communication channels will also be analyzed. Based on the models, several synchronization primitives will be reviewed, and complex synchronization algorithms will be introduced and analyzed.

INTRODUCTION

Sensor networking solutions are used in various data collecting, surveillance, or monitoring applications. Potentially hundreds or thousands of sensors perform distributed measurements and send their collected data to base stations for further processing. Such networks are designed for months or years of autonomous operation.

Time synchronization in wireless sensor networks is one of the most important middleware services. Since sensor networks are closely linked to real physical phenomena, a naturally occurring question from user side is “when did it happen?” Various sensor networking services and protocols also require the knowledge of time, e.g. data

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fusion, calibration, in-network processing, and localization, just to name a few.

Typical tasks and operation modes in sensor networks often require synchronization between nodes. This is especially important when low duty cycle operation is required to conserve energy. Typically, in such networks nodes are in low-power (sleep) mode most of the time, and wake up for short periods, to perform measurements and communication tasks. To minimize the necessary awake interval, nodes must accurately synchronize their wakeup times.

Timing information is also important in data collecting applications, where the required precision depends on the application needs, e.g. acoustic localization or beamforming requires sub-millisecond precision, while in an agricultural monitoring application a few seconds of slip is probably acceptable.

Properties of the wireless communication channel, especially the physical and MAC layers do not enable the use of traditional synchronization methods (e.g. NTP) for fine-grain synchronization needs. Power efficiency and resource constraints in sensor nodes are other driving forces towards special synchronization algorithms tailored for sensor networks.

In this chapter, a model-based approach will be used to introduce and analyze time synchronization algorithms for sensor networks. Apart from the high-level models of the algorithms, the error sources present in wireless networks will also be modeled, and based on these models the most influential solutions will be reviewed. These methods contain several reusable building blocks and ideas that other synchronization schemes and methods use. This chapter is not intended to provide a full overview on all of the available methods but rather focuses on the basic, motivating, and compelling ideas present in the reviewed algorithms, with special emphasis on the constraints and needs arising in sensor networking applications.

TIME AND CLOCKS

Clock Models

A clock can be modeled by the following equation:

$$C\left(t\right) = \frac{1}{f_{nom}} \int_{t_0}^{t} f\left(\tau\right) d\tau + C\left(t_0\right),$$

Where $C(t)$ is the local time shown by the clock at time instant t, f is the instantaneous frequency of the clock's time base and f_{nom} is the nominal time-base frequency. A clock is called accurate if $C(t)=t$. The difference between the clock value and the real time $C(t)-t$ is called clock offset.

Digital clocks use hardware (usually quartz) oscillators as time bases, and digital counters to approximate the integrator. Ideally, the counter $c(t)$ is incremented by one in every $1/f_{nom}$ second, so the local time of a digital clock is

$$C\left(t\right) = \frac{1}{f_{nom}} c(t) + C\left(t_0\right),$$

where $c(t_0)=0$.

The frequency of the clock is $\frac{dC\left(t\right)}{dt}$, which should ideally be exactly one, while the real time-base frequency is $\frac{dc\left(t\right)}{dt}$, which ideally should be equal to f_{nom}. The frequency of real clocks somewhat differs from the nominal frequency. This phenomenon is called drift and defined as

$$\delta\left(t\right) = \frac{dC\left(t\right)}{dt} - 1,$$

or in terms of the time-base frequency

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