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Recent Advances in Clock Synchronization for Packet-Switched Networks

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Contents

Recent Advances in Clock Synchronization for Packet-Switched Networks

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ABSTRACT

Clock synchronization is a mechanism for providing a standard time to various devices across a network. This monograph provides a comprehensive overview of recent developments for clock synchronization protocols built on two-way message exchanges. Several clock synchronization protocols are available in the literature for distributing time from high-cost, high-stability clocks (termed masters) to low-cost, low-stability clocks (termed slaves) via an interconnecting network. A number of clock synchronization protocols are built on two-way message exchanges. These include the timing protocol for sensor networks (TPSN), lightweight time synchronization (LTS) protocol, tiny-sync and mini-sync, network time protocol (NTP) and the IEEE 1588 precision time protocol (PTP). The messages traveling between the master and slave nodes can encounter several intermediate switches and routers, accumulating delays at each node. The main factors contributing to the overall delay are the fixed propagation and processing delays at the intermediate nodes along the network path between the master and slave, as well as the stochastic queuing delays at

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each such node. Popular probability density function (pdf) models for modeling the stochastic delays include Gaussian, exponential, gamma, Weibull, and log-normal. Although these pdf models for the stochastic queuing delays apply to several scenarios, they might not be suitable in specific scenarios such as cellular base station synchronization using mobile backhaul networks and IEEE 1588 in 4G Long Term Evolution (LTE) networks. Further, there could be possibly unknown asymmetries between the fixed path delays in the forward master-to-slave path and the reverse slave-to-master path. These unknown asymmetries could arise from various sources, including delay attacks or incorrect modeling. In this monograph, we present recent developments for clock synchronization protocols built on the two-way message exchange. After an introduction to the basic concepts and mathematical models, the optimum estimators are presented for estimating the clock skew and offset that are applicable for any pdf model of the stochastic delays. Robust algorithms that can also handle unknown path asymmetries are presented next. The focus is on techniques that consider practical, relevant measurement models in order to guide the reader from physical observations to the actual synchronization of the clocks at the slave and master.

1

Introduction

The proper functioning of a distributed network is critically dependent on the availability of a standard reference time for the various devices in the network. These devices, typically at different geospatial locations, usually perform timekeeping locally using clock hardware that exploits the periodicity of certain physical phenomena, such as the mechanical resonance of vibrating crystals (in low-cost quartz crystal oscillators), or electromagnetic transitions within cesium or rubidium atoms (available in expensive atomic clocks). However, such timekeeping techniques are subject to errors that can accumulate over large time scales. Further, the cost, size, and complexity of timekeeping hardware are typically proportional to clock stability. As a result, there are often scenarios where it is impractical to locally maintain the clock hardware required to achieve the desired level of stability due to space or budget constraints.

Clock synchronization is a mechanism for providing a standard reference time to various devices across a distributed network. It is critical in modern computer networks because every aspect of managing, securing, planning, and debugging a network involves determining when particular events happen. Time provides the standard frame of reference for the various devices on the network. A few key areas where time-synchronized information can directly affect network operations are:

1. *Network Fault Diagnosis and Recovery*: Information regarding key network events are usually stored in switches, routers, and other dedicated devices. In case of a network fault or crash, the proper sequence of events can be established, and the root cause can be quickly identified, only if the timestamps associated with the recorded events are synchronized.
2. *File Timestamps*: In a distributed file-sharing system, a master file is maintained by a Network File Sharing (NFS) server for use by remote clients. NFS is network time-dependent. Thus, when presented with duplicate versions of the file, it saves the latest copy. However, if a client is not synchronized to the network and produces a timestamp for a remotely accessed file with a time earlier than the file maintained on the server, the client file, along with any changes, are discarded [65].
3. *Services:* Several user services, including billing and financial services, require highly accurate timestamps.
4. *Miscellaneous:* Many localization, security, and tracking protocols in distributed networks also demand the devices to timestamp their messages and events [74].

One of the most popular mechanisms for achieving standard time across a network is to use the Global Positioning System (GPS) [51, 63]. Each GPS satellite contains multiple atomic clocks that contribute accurate time data to the GPS signals. GPS receivers decode these signals, effectively synchronizing each receiver to the atomic clocks. Although GPS-based timing is very accurate, it may not be feasible to equip every device in a network with a GPS receiver. Further, GPS-based time synchronization requires line-of-sight between the network device and the GPS satellite, a condition that might not be possible for some devices in the network. GPS spoofing is also a serious concern [36, 45, 60, 61].

A popular alternative to GPS-based timing is network time distribution. Here the time from a high-cost, high-stability clock (termed master) is distributed to low-cost, low-stability clocks (termed slaves) via an interconnecting network. Several clock synchronization protocols based on network time distribution are available in the literature. For instance, the network time protocol (NTP) [52] and the IEEE 1588 precision time protocol (PTP) [32] are widely used in IP networks, while protocols such as the timing protocol for sensor networks (TPSN) [20], lightweight time synchronization protocol (LTS) [70], tiny-sync and mini-sync [62], and reference broadcast time synchronization (RBS) protocol [10] are used in wireless sensor networks. Network time distribution is often more cost-effective than GPS-based timing, as it does not require any dedicated hardware and can often make use of the existing network resources for synchronizing devices across the network.

Though the time synchronization protocols for network time distribution differ from each other in many aspects, a fundamental mechanism common to a number of clock synchronization protocols including TPSN [20], LTS [70], tiny-sync and mini-sync [62], and PTP [32], is the two-way message exchange. This refers to the exchange of messages between a pair of nodes to achieve clock synchronization. During a two-way message exchange, a slave node exchanges a series of synchronization packets with a master node over an interconnecting network and collects timestamps corresponding to the departure and arrival times of these packets. The slave then attempts to utilize these timestamps to correct its clock. However, as with any packet-switched network, the exchanged packets experience difficult to predict (stochastic) delays as they traverse the network. These stochastic delays experienced by packets can significantly degrade the performance of various clock synchronization protocols. In this monograph, we present some recent developments to combat the degrading effects of stochastic delays for clock synchronization protocols based on two-way message exchange.

While the techniques presented in the monograph apply to many applications and any clock synchronization protocol based on two-way message exchanges, we mainly discuss the applications of our results in the context of IEEE 1588 PTP applied to telecommunication networks. IEEE 1588 PTP [32] is a popular time synchronization protocol used in a number of scenarios, including electrical grid networks [18], cellular base station synchronization in 4G Long Term Evolution (LTE) [24, 25], substation communication networks [33] and industrial control [29]. It is cost-effective and offers accuracy comparable to GPS-based timing. Emerging technologies such as fog computing and industrial Internet of Things (IIoT) networks have identified the IEEE 802.1Q amendment for Time-Sensitive Networking (TSN) as the standard for time-predictable networking [46]. TSN employs PTP to provide a global notion of time over the local area network.

Packet-based time synchronization techniques based on PTP [32] are being increasingly considered as a viable alternative to GPS-based time synchronization as a means to provide sub microsecond-level synchronization between the cellular base stations in 4G LTE mobile networks [24, 25, 28, 55, 56, 73]. Further, PTP has been explored as a possible cost effective solution for synchronizing base stations in 5G new radio (NR) cellular networks [26, 27]. Such a high degree of synchronization accuracy between the cellular base stations ($<1.5\ \mu$s) is necessary for 4G LTE/5G NR cellular networks to enable seamless handovers between cell towers, reduce inter-cell interference, and enable the use of MIMO techniques to improve capacity [2, 26, 27].

Packet-based synchronization based on PTP is often more cost-effective than GPS-based time synchronization as it can utilize the existing mobile backhaul network infrastructure that is used to interconnect cell towers. However, since backhaul networks are typically leased from commercial internet service providers (ISPs), mobile network operators must share their use with other commercial and residential users. Background traffic generated by these users often results in sizeable random network delays that hinder packet-based synchronization. Overcoming this problem is key to the adoption of packet-based synchronization schemes in mobile backhaul networks, especially given that the synchronization accuracy requirements are only expected to grow more stringent in the future.

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