IEEE Communications Society
Distinguished Lecturers Program

Synchronization of Digital Telecommunications Networks

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Abstract

Network synchronization has gained increasing importance in telecommunications throughout the last thirty years: digital switching, SDH/SONET, ATM, CDMA, GSM and UMTS are striking examples where network synchronization has been proven to affect quality of service.

In this tutorial lecture, synchronization processes at different levels in telecommunications are first reviewed and fundamental definitions about timing of digital signals, jitter and wander are introduced. Major topics of this tutorial are: timing aspects in SDH/SONET networks; architectures and requirements for timing transfer in PDH, SDH/SONET, ATM and fixed/mobile telephone networks; strategies, standards, architectures and clocks for synchronization networks; basic principles of Network Time Protocol.

Introduction to the Subject

Network synchronization deals with the distribution of time and frequency over a network of clocks, even spread over a wide area. The goal is to align (i.e., *synchronize*) the time and frequency scales of all the clocks, by using the communications capacity of links among them (e.g. copper cables, fiber optics, radio links).

Network synchronization has gained increasing importance in telecommunications throughout the last thirty years, especially since transmission and switching turned digital. Actually, the quality of most services offered by network operators to their customers is affected by network synchronization performance.

Digital switching equipment requires synchronization to avoid slips at input elastic stores. Plain telephone conversations are not affected much by synchronization slips, but circuit switched data services are indeed. Therefore, the deployment of circuit-switched data networks and of ISDN yielded first the need of more stringent synchronization requirements.

Network synchronization became a thorny matter for telecommunications operators with the deployment of SDH (Synchronous Digital Hierarchy)/SONET networks, which pose new and more complex requirements on the stability of synchronization systems.

More recently, it has been also recognized that the importance of network synchronization goes way farther than SDH/SONET needs. ATM (Asynchronous Transfer Mode) and cellular mobile telephone networks (GSM – Global System for Mobility -, GPRS – Global Packet Radio Services -, UMTS – Universal Mobile Telecommunications Services) are two striking examples where the availability of network synchronization references has been proven to affect quality of service.

A different kind of network synchronization is the distribution of a reference *absolute* time (for instance, the national standard time) to equipment real-time clocks, mainly to the purposes of network management (*synchronization of real-time clocks*). For example, the Network Time Protocol (NTP) is used to synchronize real-time clocks of Internet routers and hosts via a hierarchy of time servers and clients. Accuracy within few milliseconds (deviation from the standard absolute time) can be achieved, although the timing information is exchanged through normal UDP packets affected by extremely variable delay.

A synchronization network is the facility implementing network synchronization. Basic elements of a synchronization network are nodes (autonomous and slave clocks) and communication links interconnecting them. Most modern telecommunications operators have set up synchronization networks to synchronize their switching and transmission equipment.

It is maybe needless to say that quality of service degradations due to some synchronization problem look always sudden, unexpected and of mysterious origin for almost everybody but the (good) synchronization engineer. Rather surprisingly, engineers with a solid expertise on the above mentioned topics are not common. The results are quite evident: gross mistakes in system design and management produce quality-of-service degradations that unfortunately, due to ignorance, are often deemed unavoidable.

Biography of the Lecturer

Stefano Bregni was born in Milano, Italy, in 1965. He received his *Dr. Ing.* degree in Telecommunications Engineering from Politecnico di Milano.

In 1991 he joined SIRTI S.p.A., where he was involved in SDH transmission systems testing and in network synchronization issues, with special regard to clock stability measurement. From 1994 to 1999, he was with CEFRIEL (consortium of private companies with Politecnico di Milano) as head of the Transmission Systems Dept. He is Associate Professor at Politecnico di Milano (tenured Asst. Prof. since 1999), Dept. of Electronics and Information, where he teaches telecommunications networks and transmission networks.

He has been Senior Member of IEEE since 1999. He is Distinguished Lecturer of the IEEE Communications Society, having been Expert Lecturer from 1999 to 2003. He is vice-chair of the Transmission, Access and Optical Systems Committee of the IEEE Communications Society. He is co-chair or vice-chair of a few symposia in IEEE conferences (viz. ICC2004, GLOBECOM2005, ICC2006, ICC2007). He has been member of the Technical Program Committees (TPC) of several IEEE conferences, including ICC and GLOBECOM.

He served on ETSI and ITU-T committees on digital network synchronization. He is author of the book *"Synchronization of Digital Telecommunications Networks"*, John Wiley & Sons, Inc. [1]. He is author or co-author of about twenty papers in this field, mostly published on IEEE Conferences and Journals. He was Guest Editor of the "*Focus on Synchronization of Digital Networks*" on the European Transactions on Telecommunications Journal. He is author of the article *"Clocks in*

Telecommunications" included in the *Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons, 1999 and then included also in the *Survey of Instrumentation and Measurement*, Editor S. Dyer, New York, USA, John Wiley & Sons, 2001. He was lecturer of the tutorial *"Synchronization of Digital Telecommunications Networks"* at IEEE ICC 2000 (New Orleans, LA, USA 18-22 June 2000), IEEE GLOBECOM 2002 (Taipei, Taiwan, 17-21 Nov. 2002), IEEE GLOBECOM 2003 (S. Francisco, CA, USA, Dec. 2003) and IEEE GLOBECOM 2005 (St. Louis, MO, USA, Dec. 2005).

Intended Audience and Motivation

Network synchronization plays a central role in digital telecommunications. Nevertheless, this subject is widely misunderstood. Neither it may be said that such knowledge is common among telecommunications engineers. Actually, it is not easy to find in literature detailed information on several network synchronization issues (with the exception of book [1]).

Therefore, all telecommunications system engineers dealing with transmission equipment and system testing, as well as with network design, operation and maintenance would benefit from attending this tutorial. In particular, those dealing with SDH/SONET transmission, fixed/mobile telephone digital switching and ATM may be identified as the target audience of the tutorial proposed.

In conclusion, researchers and designers interested to the topics above, both in academia and in industry, will find this tutorial a unique and exciting opportunity for an overview on topics not commonly addressed in literature.

For best understanding and enjoyment of some topics of this tutorial, basic knowledge of SDH/SONET and digital multiplexing is recommended.

Scope and Objectives

This tutorial provides a quick but broad overview on several topics that are not commonly addressed in literature. It does not go deep into details of special topics, but rather aims at making the audience aware of the main concepts and issues in synchronization of digital telecommunications networks. In particular, the participants will learn:

- that the word "synchronization" is used in several contexts in telecommunications, addressing a wide spectrum of different timing issues;
- basic concepts such as jitter and timing relationships between timing signals;
- timing aspects in SDH/SONET networks, such as the main causes of jitter in SDH/SONET networks and what are synchronizers, desynchronizers and pointer processors;
- how network synchronization issues evolved with the telephone networks, beginning from old FDM networks up to the latest technologies, through PDH, SDH/SONET, ATM and mobile telephone cellular networks;
- strategies and standard architectures for synchronization distribution;
- principles of operation of clocks for synchronization networks;
- principles of Network Time Protocol (NTP).

Prior History of This Lecture

Prior versions of this lecture were given as full-day or half-day tutorials in IEEE conferences:

- ❑ GLOBECOM 2005 (St. Louis, MO, USA, Nov. 2005)
- ❑ GLOBECOM 2003 (S. Francisco, CA, USA, Dec. 2003);
- ❑ GLOBECOM 2002 (Taipei, Taiwan, 17-21 Nov. 2002);
- ❑ ICC 2000 (New Orleans, LA, USA 18-22 June 2000).

The tutorial at ICC2000 was attended by about 20 people. The tutorial at GLOBECOM 2002 was ranked as the second best rated in the Tutorial Quality Evaluation report, based on the evaluation forms filled-in by attendees, with overall performance 3.60 (1: poor - 4: excellent; source: Globecom 2002 Wrap-Up Report by the Conference Organizing Committee).

Various reduced versions of this lecture, depending on the audience and local requests, were given during the Distinguished Lecturer Tours of October 2003 (Mexico, Costa Rica, El Salvador and Guatemala), November 2004 (Dallas, Tulsa and St. Louis, USA), April 2005 (Puerto Rico, Mexico), June 2005 (Poznan, Poland).

Lecture Length

This lecture is proposed with length half day. Three or four hours will be sufficient to overview all program topics. A reduced program is also available for shorter lectures of about one or one and half hour, according to the requests of the inviting Chapter.

Lecture Outline

The outline below is proposed for a half-day lecture.

❑ **Introduction: synchronization processes in telecommunications**

The word "synchronization" is used in several contexts in telecommunications, addressing a wide spectrum of different timing issues. Carrier and symbol synchronization, frame synchronization, bit synchronization, packet synchronization, network synchronization, multimedia synchronization and synchronization of real-time clocks are briefly reviewed.

❑ **Basic concepts about timing of digital signals**

- chronosignals
- timing relationships between digital signals
- jitter and wander

Some fundamental concepts and definitions about the timing of digital signals (e.g., the definitions of synchronous, mesochronous, plesiochronous and heterochronous digital signals) and about jitter and wander are introduced.

❑ **Timing aspects in SDH/SONET networks**

- Causes of jitter and wander in a SDH/SONET transmission chain
- Synchronization processes along a SDH transmission chain
- SDH/SONET synchronizer and desynchronizer
- SDH/SONET pointer processor

This section reviews the main causes of jitter and wander in a SDH/SONET transmission chain: environmental conditions, digital signal regeneration, overhead and stuffing bits in the mapping *structures of tributaries into STM frames, bit justification and – over all - pointer justification. Moreover, the synchronizer, desynchronizer and pointer processor blocks are introduced.*

- **A historical perspective on network synchronization**
  - synchronization in analog FDM networks
  - synchronization and PDH digital transmission
  - synchronization and digital switching
  - impact of slips on digital services
  - synchronization of digital switching exchanges via PDH links
  - synchronization and SDH/SONET digital transmission
  - synchronization in ATM transport networks
  - synchronization of mobile telephone cellular networks

Network synchronization is dealt with from a historical perspective, pointing out its different aspects and how network synchronization issues evolved with the telephone networks, beginning from old FDM networks up to the latest technologies, through PDH, SDH/SONET, ATM and mobile telephone cellular networks. For each case, rationale, architectures and techniques for timing transfer are reviewed.

- **Synchronization networks**
  - network synchronization strategies
  - ITU-T Recommendations relevant to network synchronization
  - synchronization network standard architectures
  - synchronization network planning, management and protection
  - clocks in synchronization networks: quartz and atomic clocks, GPS

Synchronization networks are the facilities implementing the distribution of synchronization signals to the nodes of telecommunications networks. First, different strategies to synchronize the nodes of a network (full-plesiochronous network, master-slave synchronization, mutual synchronization, etc.) are reviewed. Then, the ITU-T Recs. relevant to synchronization network architectures and performance are cited. Some details on the planning, management and protection of synchronization networks are briefly discussed. Finally, the timing sources used in synchronization networks are presented: quartz and atomic clocks and GPS.

- **Network Time Protocol (NTP) principles**

The Network Time Protocol (NTP) is used to synchronize real-time clocks of Internet routers and hosts via a hierarchy of time servers and clients. The principles of operation of this protocol are reviewed, in order to show an example of how synchronization of network clocks to an absolute time can be achieved by exchanging messages affected by random delays on a packet-switched network.

- **Conclusions and topics for further study**

Major References

[1] Stefano Bregni, *"Synchronization of Digital Telecommunications Networks*", Chichester, UK, John Wiley & Sons, March 2002, 430 pages, ISBN: 0-471-61550-1. Translated also to Russian: “Синхронизация цифровых сетей связи” (*"Sincronizazia zifrovih sotoi sviasi"*), Moscow, Russia, MIR Publishers, 2003, ISBN: 5-03-003588-5.

[2] Stefano Bregni, "Clocks in Telecommunications", in *Encyclopedia of Electrical and Electronics Engineering*, Vol. 3 of 24, pp. 497-511, Editor John G. Webster, New York, USA, John Wiley & Sons, 1999. Included also in *Survey of Instrumentation and Measurement*, pp. 743-757, Editor S. Dyer, New York, USA, John Wiley & Sons, 2001. ISBN # 0-471-39484X.

[3] Stefano Bregni, "A Historical Perspective on Network Synchronization", *IEEE Communications Magazine*, Vol. 36, No. 6, June 1998.

[4] Stefano Bregni , "Clock Stability Characterization and Measurement in Telecommunications", *IEEE Transactions on Instrumentation and Measurement*, Vol. 46, No. 6, Dec. 1997, pp. 1284-1294.