Course

Synchronization of Telecommunications Networks

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Introduction to the Subject

Network synchronization deals with the distribution of time and frequency over a network of clocks, including clocks spread over a wide area. The goal is to align the time and frequency scales of all the clocks, by using the communications capacity of links between nodes.

A synchronization network is the facility that implements network synchronization. The basic elements of a synchronization network are nodes (autonomous and slave clocks) and communication links interconnecting them. Since the '70s and '80s, most telecommunications operators have set up synchronization networks to synchronize their switching and transmission equipment.

Over this time, network synchronization has been gaining increasing importance in telecommunications. As a matter of fact, the quality of many services offered by network operators to their customers depends on network synchronization performance [1][2].

Since the introduction of early digital switching systems, network synchronization was needed to avoid slips in circuit-switched voice and data networks. The deployment of SDH (Synchronous Digital Hierarchy)/SONET networks imposed new and more complex requirements on the quality of synchronization systems. To study those new problems, international standard bodies established specific work groups, which culminated in the '90s with the release of a new series of ITU-T Recommendations on synchronization of digital networks (ITU-T Recs. G.810, G.811, G.812 and G.813), as well as their counterparts released by ATIS and Telcordia (e.g. GR-1244) in the USA and by ETSI in Europe.

More recently, it has been recognized that the importance of network synchronization goes even further: 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 significantly affect the quality of service [3].

Traditionally, synchronization has been distributed to telecommunications network nodes using circuit-switched links in Time Division Multiplexing (TDM). In particular, E1 and DS1 circuits have been most commonly used, respectively over European and North-American standard PDH (Plesiochronous Digital Hierarchy) systems.

The recent migration of Network Operators to the packet-switched Next-Generation Network (NGN) once again poses newer and even more difficult problems of network synchronization. Today, as fixed and mobile operators migrate to NGN infrastructures based on IP packet switching, Ethernet transport is becoming increasingly common. This trend is driven by the prospect of lower operations costs and by the convergence between fixed and mobile services. However, migrating trunk lines to IP/Ethernet transport poses significant technical challenges, especially for circuit emulation and synchronization of network elements.

Therefore, the network evolution towards IP packet switching has led to increased interest on the part of communications engineers in synchronization distribution using packet-based methods. After a few years of declining research, considerable new investigation activity on network synchronization has restarted in both industry and academia.

International standard bodies have also resumed significant levels of activity on this subject. Since 2004, the ITU-T has been developing a new set of Recommendations, specifically for synchronization on packet-switched networks beginning with the ITU-T Rec. G.8261/Y.1361. In 2002, IEEE released a new "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" (IEEE 1588, revised in 2008).

At this point, it is worth pointing out that the traditional model, in which synchronization distribution is engineered carefully for optimal performance and survivability, may give way to scenarios in which there is greater expectation of automatic, self-configured operation while still maintaining adequate synchronization quality. This consideration widens the scope of interest in synchronization beyond specialists, reaching the wider audience of telecommunications engineers in general. An example is the distribution of synchronization to next-generation wireless base-stations, which are connected to the core network only via packet-switched networks, but still require highly accurate synchronization to meet standard quality-of-service expectations.

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 is Associate Professor at Politecnico di Milano, where he teaches telecommunications networks and transmission networks. He was born in Milano, Italy, in 1965. In 1990, he graduated in telecommunications engineering at Politecnico di Milano. Since 1991 and for several years, he worked in industry on SDH systems and synchronization networks, first with SIRTI S.p.A (1991-1993) and then with CEFRIEL consortium (1994-1999). In 1999, he joined Politecnico di Milano as tenured Assistant Professor.

He has been Senior Member of the IEEE since 1999. Since 2004, he has been Distinguished Lecturer of the IEEE Communications Society, where he holds or has held the following official positions: Member at Large on the Board of Governors (2010-12), Director of Education (2008-11), Chair of the Transmission, Access and Optical Systems (TAOS) Technical Committee (2008-2010; Vice-Chair 2002-2003, 2006-2007; Secretary 2004-2005) and Member at Large of the Globecom/ICC Technical Content (GITC) committee (2007-2010). He is or has been Technical Program Vice-Chair of IEEE GLOBECOM 2012, Symposia Chair of GLOBECOM 2009 and Symposium Chair in eight other ICC and GLOBECOM conferences. He is Editor of the IEEE ComSoc Global Communications Newsletter and Associate Editor of the IEEE Communications Surveys and Tutorials Journal. He was tutorial lecturer in four IEEE conferences ICC and GLOBECOM. He served on ETSI and ITU-T committees on digital network synchronization.

He is author of about 80 technical papers, mostly in IEEE conferences and journals, and of the two books *Synchronization of Digital Telecommunications Networks* (Chichester, UK: John Wiley &

Sons, 2002; translated and published to Russian by MIR Publishers, Moskow, 2003) and *Sistemi di trasmissione PDH e SDH - Multiplazione* (PDH and SDH Transmission Systems – Multiplexing. Milano, Italy: McGraw-Hill, 2004).

Besides his academic activities, he has extensive industrial teaching experience, also at international level. Since 1994, he has been teaching his technical courses repeatedly in many leading industrial companies, including telecommunication equipment manufacturers (e.g., Siemens, Nokia Siemens Networks, Italtel, Selex Communications), deployers (e.g., Sirti) and telecommunications operators (e.g., Omnitel/Vodafone, the Italian GSM operator Wind, MCI-Worldcom). Technical personnel of several other telecommunications operators in Latin America, Middle East and Far East has attended his courses fruitfully.

Proposed Length

This course is proposed with optimal length **three or four days**, assuming that participants have basic knowledge of digital telecommunications and of PDH and SDH/SONET multiplexing.

Intended Audience

This course has been designed primarily for the technical personnel of telecommunications operators, service providers and equipment manufacturers. This may include, but not exclusively, system engineers, network planners, designers and engineers in charge of system testing, operation, maintenance and customer support.

Not only practitioners or new-to-the job should attend this course, but also senior personnel with expertise in the field will discover several enlightening aspects and will benefit from attending it. The richness and depth of course topics cover a wide spectrum of practical and theoretical issues in a wide range of applications.

Requirements

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

Key Benefits of Attending This Course

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

Quality of service degradations due to some synchronization problem look of mysterious origin for almost everybody but the (good) synchronization engineer. As a result, gross mistakes in system design produce quality-of-service degradations that unfortunately, due to ignorance, are often deemed unavoidable.

The various reasons, for which these networks require good synchronization, are well known and are summarized in [2]. Moreover, a striking example of the negative impact of poor network synchronization on the quality of service provided to the final user is provided by paper [3], which reports experimental results measured in a Vodaphone test plant. This study points out how the GSM quality of service, as perceived by the user, is negatively affected when the GSM base stations are not synchronized: the Mean Opinion Score of a high percentage of calls undergoing handover may become unacceptable.

Also in IP networks and NGN, synchronization plays a key role. Since 2004, the ITU-T has been developing a new set of Recommendations, specifically for synchronization on packet-switched networks (for example, ITU-T Rec. G.8261/Y.1361 "Timing and Synchronization Aspects in Packet Networks"). Let us also notice the Network Time Protocol for time distribution in the Internet.

Therefore, all telecommunications engineers dealing with transport and switching network design, planning, operation and maintenance will benefit from attending this course. In particular, telecommunications operators handling SDH/SONET transport networks, ATM networks, fixed and mobile (GSM, GPRS, UMTS) telephone networks may be identified as the primary target audience of this course. All technical personnel of such companies, involved in the technical management of networks and systems, should possess the knowledge provided in this course.

After having attended this course, participants should be able to:

- know all main aspects related to synchronization of telecommunications networks;
- avoid mistakes in synchronization network design, planning and operation;
- diagnose synchronization troubles;
- intervene appropriately to correct synchronization faults;
- understand technical documentation from equipment and system suppliers;
- interact effectively with product managers of equipment and system suppliers, avoiding misunderstandings that may yield additional costs;
- possess adequate knowledge to assess actual synchronization requirements for their networks, thus avoiding unnecessary or, on the contrary, insufficient investments.

Scope and Objectives

This tutorial provides a broad overview on several topics that are not addressed in literature, neither provided in competing courses. In particular, the participants will learn:

- bit and byte justification techniques used in PDH and SDH multiplexing;
- basic concepts such as jitter and wander;
- synchronization aspects in SDH/SONET networks;
- network synchronization requirements and architectures in fixed and mobile telephone networks;
- network synchronization requirements and architectures in PDH, SDH/SONET and ATM;
- strategies and issues of synchronization in Next-Generation Networks;
- strategies and standard architectures of synchronization networks;
- principles of synchronization network planning, management, protection and performance monitoring;
- models and characterization of telecommunications clocks;
- principles of operation of clocks for synchronization networks;

- principles of Network Time Protocol (NTP);
- time and frequency measurement techniques in telecommunications.

Throughout all parts of this course, practical aspects are emphasized.

Outline

- **Introduction: synchronization processes in telecommunications**
  - carrier synchronization
  - symbol synchronization
  - frame synchronization
  - bit synchronization
  - packet synchronization
  - network synchronization
  - multimedia synchronization
  - synchronization of real-time clocks
- **Basic concepts about timing of digital signals**
  - chronosignals
  - timing relationships between digital signals
  - jitter and wander
- **Synchronous and asynchronous digital multiplexing**
  - taxonomy of multiplexing techniques
  - primary PCM multiplex
  - synchronous digital multiplexing: slip buffering
  - asynchronous digital multiplexing: bit justification, justification jitter
  - plesiochronous digital hierarchies (PDH)
  - synchronous digital hierarchy (SDH) and SONET
- **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
  - jitter and wander control in PDH/SDH networks
  - SDH equipment clock
- **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
- **Synchronization in Next-Generation Networks**
  - issues and strategies
  - ITU-T standards

- architectures and methods for synchronization over packet networks

- **Synchronization networks**
  - network synchronization strategies
  - ITU-T Recommendations relevant to network synchronization
  - synchronization network standard architectures (ITU-T/ETSI and ANSI)
  - synchronization network planning, management and performance monitoring
  - synchronization network protection: Synchronization Status Messages (SSM)
  - examples of synchronization networks
  - clocks in synchronization networks: quartz and atomic clocks, GPS

- **Principles of Network Time Protocol (NTP) and Precision Time Protocol (PTP)**
  - principles of NTP
  - principles of IEEE 1588 PTP

- **Models and characterization of telecommunications clocks**
  - chronosignal model and basic quantities
  - basic concepts on clock quality: stability and accuracy
  - autonomous clocks
  - slave clocks
    - Phase-Locked Loop (PLL)
    - PLL linear model
    - second-order PLL
    - PLL performance with internal noise sources
    - PLL operation limits and modes
  - clock stability characterization in the frequency domain
    - power spectral densities
  - clock stability characterization in the time domain
    - instantaneous frequency $y(t)$
    - classical variance of $y(t)$
    - M-samples variance of $y(t)$
    - Allan variance (AVAR)
    - modified Allan variance (MAVAR)
    - time variance (TVAR)
    - root mean square value of Time Interval Error (TIErms)
    - Maximum Time Interval Error (MTIE)
  - noise types found in experimental results
    - power-law noise
    - periodic noise
    - background white noise due to trigger and quantization error

- **Physical principles and technology of clocks**
  - quartz clocks
  - atomic frequency standards: caesium beam, hydrogen MASER, rubidium, Global Positioning System (GPS)
  - clocks in synchronization networks

- **Time and frequency measurement techniques in telecommunications**
  - fundamentals
    - RF power spectral density of the chronosignal
    - quantities recommended by IEEE for frequency stability measurement
    - standard stability quantities defined by ITU-T and ETSI, estimators
    - time-domain and frequency-domain measures
    - estimating the mean frequency and frequency drift

   - confidence of the Allan variance estimate
   - distinguishing the variances of the clock under test and of the reference clock
   - measurement configurations and stability quantities
   - impact of the sampling period on stability quantities
- measurement instrumentation
- direct digital measurement
- techniques for improving measurement sensitivity: heterodyne, homodyne and multiple-conversion techniques
- stability measurement on telecommunications clocks
- examples of measurement results on a SDH equipment clock

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, "A Historical Perspective on Network Synchronization", *IEEE Communications Magazine*, Vol. 36, No. 6, June 1998.

[3] Stefano Bregni, Lucia Barbieri, "Experimental Evaluation of the Impact of Network Frequency Synchronization on GSM Quality of Service During Handover", *Proc. of IEEE GLOBECOM 2003*, S. Francisco, CA, USA 1-5 December 2003.

[4] 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.

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