Network Synchronization
from TDM to IP and Mobile Backhaul Networks

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Summary

Over the last 50 years, network synchronization has been gaining increasing importance in telecommunications. The quality of many services provided by network operators to customers depends on network synchronization performance. Today, even more than in the past, network synchronization is required in fixed and mobile networks (GSM, GPRS, UMTS, LTE), besides in SDH/SONET and ATM transport networks. The migration to the IP packet-switched Next-Generation Network (NGN) poses even more difficult problems of network synchronization at all network levels (access, metro, core) and in particular in backhauling.

Engineers with a solid expertise on network synchronization are not common. The results are quite evident: gross mistakes in system design and management produce quality-of-service degradations that could be avoided.

In this comprehensive tutorial course, participants will learn basic concepts of jitter and justification in PDH and SDH multiplexing; synchronization aspects in SDH/SONET systems; network synchronization requirements and architectures in fixed and mobile networks (2G, 3G, 4G), in PDH and SDH/SONET systems and in ATM transport networks; strategies and issues of synchronization in packet-switched Next-Generation Networks, focusing on mobile backhauling over packet networks and Synchronous Ethernet; standard architectures of synchronization networks; principles of planning, management, protection and performance monitoring in synchronization networks; models and characterization of telecommunications clocks; principles of operation of clocks for synchronization networks; principles of Network Time Protocol (NTP) and Precision Time Protocol (PTP) for time synchronization in packet-switched networks; time and frequency measurement techniques in telecommunications. Throughout all parts of the course, practical issues and applications are emphasized.

The trainer has extensive industrial teaching experience on these topics at international level, in leading industrial companies including equipment manufacturers and telecommunications operators. After having attended this course, participants should be able to avoid mistakes in synchronization network design, planning and operation; diagnose synchronization troubles; intervene appropriately to correct synchronization faults; understand technical documentation from system suppliers; assess actual synchronization requirements for their networks, thus avoiding unnecessary or, on the contrary, insufficient investments.

Overview

Network synchronization deals with the distribution of time and frequency over a network of clocks, including clocks spread over a wide area. 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.

Since the introduction of early digital circuit-switching systems, network synchronization was needed to avoid slips. 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.

Later on, it was been recognized that the importance of network synchronization goes even further: ATM (Asynchronous Transfer Mode) and mobile cellular networks (GSM, GPRS, UMTS, LTE) are striking examples where the availability of network synchronization has been proven to significantly affect the quality of service.

Among quality-of-service degradations due to lack of network synchronization, we may mention slips in digital circuit connections, poor performance in data connections, pointer activity in SDH/SONET networks causing excess jitter on carried bit streams, problems on handover in GSM/GPRS/UMTS mobile cellular networks, poor performance in systems based on TDMA. Some features of CDMA and LTE/Advanced are not even possible, without precise time synchronization.

A striking example of the negative impact of poor network synchronization on the quality of service provided to the final user has been provided by a technical paper reporting experimental results measured in a Vodaphone test plant (by S. Bregni, L. Barbieri, Proc. of IEEE GLOBECOM 2003). 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 becomed unacceptable in the trial.

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 migration of Network Operators to the IP packet-switched Next-Generation Network (NGN) has posed, once again, newer and even more difficult problems of network synchronization at all network levels (access, metro, core) and in particular in backhauling. 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. Since 2004, the ITU-T has been developing a new set of Recommendations, specifically for synchronization over packet-switched networks (beginning with the Rec. G.8261 "Timing and

Synchronization Aspects in Packet Networks"). In 2002, IEEE released a new "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" (IEEE 1588, revised in 2008), which is a good solution for time distribution in mobile backhauling over packet networks. For frequency distribution using physical signals in IP-based networks, the Synchronous Ethernet has been defined by ITU-T and has become a widespread solution.

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. 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 (synchronization in mobile backhauling over packet networks).

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 of Telecommunications Networks at Politecnico di Milano. He was born in Milano, Italy, in 1965. In 1990, he graduated in telecommunications engineering at Politecnico di Milano. Since 1991, 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: Vice-President for Member Relations (2014-2015), Member at Large on the Board of Governors (2010-12, 2013-2015), 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, Symposium Chair in nine other ICC and GLOBECOM conferences, Technical Program CoChair of IEEE LATINCOM 2011, Vice-Chair for the Technical Program of IEEE ENERGYCON 2012, Technical Program Vice-Chair of the IEEE/IFIP 9th Conference on Optical Network Design and Modelling 2005. He is Editor of the IEEE ComSoc Global Communications Newsletter, Associate Editor of the IEEE Communications Surveys and Tutorials Journal and Associate Editor of the HTE Infocommunications 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).

He has extensive experience of academic teaching and professional training at international level. As Distinguished Lecturer of the IEEE Communications Society, in 2003-2009 he gave more than 30 lectures in 14 countries and 29 cities in Mexico, Puerto Rico, El Salvador, Panama, Costa Rica, Guatemala, Ecuador, Peru, Bolivia, Colombia, Malaysia, India, Poland, USA.. Since 1994, he has been teaching technical courses repeatedly in many leading industrial companies in Italy, including telecommunication equipment manufacturers (e.g., Siemens, Nokia Siemens Networks, Italtel, Selex Communications), deployers (e.g., Sirti) and telecommunications operators (e.g., Omnitel/Vodafone, Wind, MCI-Worldcom). He was appointed lecturer in Master courses at Universidad Pontificia Bolivariana, Medellin, Colombia (2013, 2014), at Escuela Superior Politécnica del Litoral (ESPOL), Guayaquil, Ecuador (2011, 2012, 2013, 2014), and at Università della Svizzera Italiana, Lugano, Switzerland (2006, 2007, 2008). As professional trainer, he taught technical courses to engineers and technical personnel of many multinational telecommunications operators in Latin America, Africa, Middle East and Far East.

Proposed Length

This course is proposed with optimal length of **five or four days**.

Who Should Attend?

This course has been designed primarily for the engineers of telecommunications operators, service providers and equipment suppliers. This may include, but not exclusively, system engineers, network planners, designers and engineers in charge of system testing, operation, maintenance and customer support. Also senior personnel with strong practical expertise in this field will discover several enlightening aspects and will benefit from attending it.

The richness and depth of course topics may be adapted to suit the specific interests of the attendees, covering a wide spectrum of practical and theoretical issues in a wide range of applications.

Pre-Requisites for Participants

For best understanding and enjoyment of all topics of this course, a basic knowledge of TDM, PDH, SDH/SONET systems is recommended.

Key Benefits

Network synchronization plays a central role in telecommunications. It determines the quality of most services provided by network operators. Nevertheless, this subject is widely misunderstood.

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.

After having attended this course, participants should:

- ❑ know all fundamental concepts of network synchronization;
- ❑ be capable to avoid mistakes in synchronization network design, planning and operation;
- ❑ be capable to understand technical documentation from equipment and system suppliers;

- be capable of interacting effectively with product managers of equipment and system suppliers, avoiding misunderstandings that may yield additional costs;
- be capable to diagnose synchronization troubles;
- be capable to intervene appropriately to correct synchronization faults;
- possess adequate knowledge to assess actual synchronization requirements for their networks, thus avoiding unnecessary or, on the contrary, insufficient investments.

Outline

- **Basic concepts of synchronization**
  - Synchronization processes in telecommunications
  - Network synchronization
  - Timing signals, jitter and wander

  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. Fundamental concepts and definitions about the timing of digital signals, jitter and wander are introduced.

- **Synchronous and asynchronous digital multiplexing**
  - Digital multiplexing
  - Synchronous digital multiplexing: slip buffering
  - Asynchronous digital multiplexing: bit justification, justification jitter
  - Plesiochronous digital hierarchies (PDH)
  - Synchronous digital hierarchy (SDH) and SONET: frame structures, pointer justification, equipment

  This section reviews basics of synchronous and asynchronous digital multiplexing. Principles of slip buffering and bit justification are outlined. PDH and SDH frames structures are presented. SDH pointer justification mechanism and equipment functions are summarized. Time permitting, numerical exercises on network architectures of practical interest are also proposed, to improve the actual understanding of bit and pointer justification mechanisms among attendees.

- **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

  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 pointer justification. The synchronizer, desynchronizer and pointer processor blocks are introduced. Basics of jitter and wander control and SDH equipment clock specifications are outlined.

- **Evolution of network synchronization requirements and architectures from fixed to mobile communications**
  - Synchronization in analog FDM networks
  - Synchronization and PDH transmission systems
  - Synchronization and circuit digital switching. Slips.

- Network synchronization via PDH links
- Synchronization and SDH/SONET transmission systems
- Synchronization in ATM transport networks
- Synchronization of mobile cellular networks from 2G to 4G

Network synchronization is dealt with from a historical perspective, pointing out its different aspects and how its requirements changed with communication networks. Rationale, architectures and techniques of network synchronization are examined in the cases of FDM, PDH, digital circuit switching, SDH/SONET, ATM and mobile cellular networks, including 2G, 3G and latest 4G systems (LTE-Advanced).

- [ ] **Synchronization networks**
  - Network synchronization strategies
  - ITU-T Recommendations for network synchronization
  - Synchronization network standard architectures (ITU-T/ETSI and ANSI/ATIS)
  - Synchronization network planning
  - Synchronization network management
  - Synchronization network performance monitoring
  - Synchronization network protection: Synchronization Status Messages (SSM)
  - Practical examples of synchronization networks

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, main contents of international standards on telecommunications network synchronization are overviewed. Planning, management, performance monitoring and protection in synchronization networks are discussed. Finally, the architectures of some historical examples of synchronization networks of major operators are outlined.

- [ ] **Principles of Network Time Protocol (NTP) and IEEE1588 Precision Time Protocol (PTP)**
  - Principles of NTP: synchronization strategy, software, algorithms
  - Principles of IEEE 1588 PTP: basic algorithm, architecture and components, performance

NTP is a protocol designed to synchronize the clocks of computers over a network and became the standard protocol for time synchronization of Internet hosts. PTP is an IEEE standard (IEEE 1588) designed to time synchronize clocks with higher precision over local multicast networks. In the section, basic principles of operation of NTP and PTP are briefly reviewed.

- [ ] **Synchronization in IP and mobile backhaul networks**
  - Overview of mobile cellular backhaul technologies
  - Basics of synchronization in packet-switched Next-Generation Networks (NGN)
  - Evolution of international standards on NGN synchronization
  - Packet-based methods for NGN synchronization: adaptive clock recovery (ACR), time stamping, NTP and PTP
  - The IEEE 1588 Telecom Profiles
  - Synchronous Ethernet

This section surveys strategies and architectures of network synchronization in packet-switched Next-Generation Networks, based on IP and Ethernet protocols. An overview of backhaul technologies in mobile networks is provided. After an introduction to NGN synchronization basics, the evolution of international standards on NGN synchronization is presented focusing on ITU-T. Packet-based methods for synchronization in NGN are reviewed, including adaptive clock recovery (CES) and time stamping in one-way and two-way communication (NTP and PTP). Principles and architectures of Synchronous Ethernet are presented.

- [ ] **Models and characterization of clocks in telecommunications**
  - Timing signal model and basic quantities
  - Basic concepts on clock quality: stability and accuracy
  - Autonomous clocks

- Slave clocks: Phase-Locked Loop (PLL) fundamentals
- Clock stability characterization in the frequency domain
- Clock stability characterization in the time domain: Allan variance (AVAR), modified Allan variance (MAVAR), time variance (TVAR), TIErms, Maximum Time Interval Error (MTIE)
- Types of clock noise

This section provides fundamentals of clock modelling and characterization. Basic concepts of time and frequency stability are introduced. Basic quantities for clock stability specification are defined. Both autonomous and slave clocks are treated. The principles of operation of Phase-Locked Loops are summarized. Time permitting, most important mathematical tools for clock stability characterization in both frequency and time domains are detailed (viz. power spectral densities, Allan variances, Maximum Time Interval Error). Common types of clock noise are described.

❑ **Physical principles and technology of clocks**

- Quartz-crystal oscillators
- Atomic frequency standards: caesium-beam, hydrogen-MASER, rubidium
- Global Positioning System (GPS)
- Applications of clocks in synchronization networks

This section overviews the physical principles of operation of clocks used in synchronization networks: in particular quartz oscillators, cesium and rubidium frequency standards. GPS as UTC timing source is also presented.

❑ **Synchronization measurement in telecommunications**

- Basic concepts: RF power spectral density, quantities recommended by IEEE, ITU-T/ETSI standard stability quantities, mean frequency and frequency drift, confidence of estimates, measurement configurations
- Measurement instrumentation
- Direct digital measurement
- Techniques for improving measurement sensitivity: heterodyne, homodyne and multiple-conversion techniques
- Stability measurement on telecommunications clocks
- Practical aspects of synchronization measurements in real systems

This section presents techniques for time and frequency measurement in telecommunications. First, basic concepts are surveyed, including IEEE and ITU-T standard quantities, estimation of frequency offset and linear drift, confidence of Allan variance estimates, measurement configurations and impact of the sampling period. Then, measurement instrumentation, techniques and setups are presented. Peculiar features of time and frequency stability measurement in telecommunications are pointed out. Real results measured on a widely deployed SDH equipment clock and SynchE clocks are also presented to give a practical example.

❑ **Open discussion of practical problems and of customer's network architecture**