Use of femtosecond synchronization system with long-term stability over optical infrastructure

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ABSTRACT
Synchronization systems over optical fibre infrastructure with femtosecond precision in terms of jitter and long-term stability are reviewed and their usage in telecommunications and physics measurements is introduced. The designed electro-optical synchronization system makes use of commercial telecom single-mode optical fibre operating at 1550 nm. It consists of an electro-optical transmitter, located near a low-jitter master radiofrequency oscillator, and an opto-electrical receiver located at a remote location. Both units are connected with a commercial single-mode optical fibre, connected in a loop-back to achieve phase-drift compensation.

Keywords: clock synchronization, time transfer, clock-distribution, femtosecond phenomena, fibre thermal expansion compensation, real-time synchronization system.

1. BASIC SYNCHRONIZATION PARAMETERS
Synchronization is needed in all distributed systems which need synchronized processing. In a distributed network with multiple remote locations, synchronization addresses any distribution of time and frequency. The goal of synchronization is to align the time and frequency of all remote locations which are sometimes spread over a wide area. The facility which implements synchronization over remote locations is called the synchronization network.

The basic elements of the synchronization network are nodes and the communication links interconnecting them. In a synchronization link two different types of nodes need to be used: a transmitter connected to the master clock reference and a receiver located at a remote location.

An optical timing system with precision in the femtosecond range is reviewed in this paper. This work is based on the assumption that the master clock reference provides radiofrequency (RF) signal with high frequency stability. The accuracy demands for synchronization system are coming from the user community. Some of their distributed experiments with high precision requirements are listed in next section.

Synchronization system requirements depend on their applications. There is a big challenge to satisfy all possible usage fields with one universal synchronization system and when talking about system requirements, we must have a well-defined image of system parameters. Sometimes there is confusion due to different engineering aspects. For example, RF engineers speak about the phase noise of an oscillator, where digital-system engineers work with the jitter of a clock.

Characterisation of synchronization system two time interval stabilities is important, as shown in Fig. 1. One is long-term stability which is the gradual change in delay ($\Delta t$) over a period of hours, days or even months. In clock distribution systems the long-term stability is expressed as a comparatively long-term change named drift. Another time interval characterisation is short-term stability. It is a function of noise signals and represents a phase modulation of the output signal. Short-term stability can be specified in the time domain as jitter. Short term stability can also be specified in the frequency domain as phase noise.

![Graph showing long-term and short-term stability of synchronization system](image)

Generally, jitter of periodical synchronization signal presents the time variation of frequency, amplitude or phase which are undesired. Since the master clock reference provides RF signal with stable frequency and...
amplitude, in synchronization system we are only focused on jitter presented as the variation of phase. Jitter is quantified in RMS or peak-to-peak displacement. Jitter can be expressed in terms of spectral density (frequency content). In clock distribution systems the name for phase jitter is usually **timing jitter**. The time variation of periodical synchronization signal in relation to a reference clock source is called **added jitter**. Minimizing the added jitter in synchronization system is key to distributed systems.

**Phase noise** is the frequency domain representation of rapid, short-term, random fluctuations in the phase of a waveform, caused by time domain instabilities – phase jitter. Phase noise is typically expressed in units of dBc/Hz, representing the noise power relative to the carrier contained in a 1 Hz bandwidth centered at a certain offsets from the carrier. Phase noise is sometimes also measured and expressed as a power obtained by integrating noise power over a certain range of offset frequencies. The integrated phase noise (expressed in radians) can be converted to jitter (expressed in seconds)

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\text{Jitter [seconds]} = \frac{\text{PhaseError [radians]}}{\text{Frequency [hertz]}} \quad (1)
\]

**Short time jitter** can be measured with microwave signal source analyzer with integration interval from 10 Hz onwards. Typically integration intervals are from 10 Hz to 10 MHz or from 100 Hz to 10 MHz. **Slow time jitter** or **wander** is slow phase changes in frequency range up to 10 Hz. It defines system long-term stability. It is measured by differential measurements if we are interested only in differential jitter. It is represented in femtoseconds per time period.

2. **NOVEL ULTRAFAST APPLICATIONS AND THEIR REQUIREMENTS**

Synchronization is getting an important issue to **electronic and telecommunication engineering**, due to increased clock frequencies in digital-electronic circuits in connection with achieving higher device or link performances. Higher clock frequencies have commensurately smaller eye openings, and thus impose tighter tolerances on jitter. Clock applications are used in memory interfaces, digital multi-media systems, data communications and wireless base stations. However, in all these areas requirements for a long-term stability are not so severe and a short-term stability is in the range of picoseconds.

Besides telecommunication requirements there are some new scientific applications which require synchronization of multiple remote locations with much higher precision. The majority of physical experiments and measurements require accurate knowledge of time and/or frequency. Physically large experiments and measurements further require accurate mutual synchronization between different parts of the measurement setup. Mutual synchronization is usually achieved with a wire connection (twisted pair, coaxial cable), radio or laser free-space communication and/or using third-party radio-navigation signals, like those provided by the GPS satellites. The described technological approaches no longer satisfy the requirements of modern measurements in particle accelerator facility [4] (especially in a combination with a Free-electron laser) as well as in other particle accelerators, the precise synchronization enables number of instruments in the machine facility to be driven with a low-jitter clock signal. Instruments are significantly better synchronized with each other, and this has a strong impact on a machine performance. In this scientific field, synchronization/clock-distribution requirements for added jitter and long-term stability are also below ten femtoseconds.
3. FUNDAMENTAL DESIGN ISSUES

The main issue which must be taken into consideration when designing the synchronization system is how to transfer timing signals from one node to the other. The way this particular precise synchronization equipment is designed is by using experience from the telecom market. Nevertheless, it can be also applicable in the other areas of science and technology. We must take into account that a timing system is not just all about electronics and optics installed in nodes but it is also the transmission medium between them. In our case, optical fibre infrastructure is used.

Accurate synchronization requires use of higher frequencies in the microwave and optical parts of the frequency spectrum. On the other hand, microwave and optical technologies underwent a substantial development on the telecom market, especially glass optical fibres and the corresponding components in terminal equipment. There have been several proposals in recent professional publications about precise synchronization, time and frequency transfer using optical fibres and corresponding terminal-equipment technology.

Glass optical fibres have many excellent physical properties but also a few drawbacks. A glass optical fibre represents a transmission medium for very high frequencies in the range of a few hundreds THz with a bandwidth of a few tens THz and very low transmission losses at the same time. Unfortunately, fibre itself has also some drawbacks as a transmission medium. It contains chromatic and polarization dispersion, which can limit high-bit-rate communications. When using fibre on long-distance transmission links, at/on high-power working regime, nonlinearities can appear. A fibre is also sensitive to microphonics and other vibrations. Finally, a commercially available fibre does not maintain polarization. Polarization-maintaining fibres are still non-standard components, manufactured in small quantities, expensive and with inferior communication parameters compared to convenient optical fibres. Regarding the polarization-mode dispersion (PMD) in optical fibres, the manufacturing process has made a big step forward, and PMD values can be much below 0.06 ps/√km. Last but not least, we must take into account that fibre has a very high thermal coefficient which affects on an optical-path length.

Regarding wavelength choice, it is important to use standard telecom transmission windows. The most convenient is the third window with the lowest loss and with some chromatic dispersion, which can be even useful for precise system design.

Developing fibre-timing links with either low noise or/and long lengths require measurements and compensation for the changing link delays. These corrections can be applied while post-processing data, or as real-time corrections to the link itself. Since there is great interest in real-time synchronization systems, we are concentrating on actively stabilized systems only.

Demanding measurements are affected by the following disturbing effects: thermal expansion, mechanical expansion and vibrations (microphonics), chromatic dispersion and PMD. A very important technology question is the interface between the synchronization medium and the end user. When choosing synchronization system operating regime we must take into account many design challenges. From the system-regime operation point of view we have three possibilities: optical CW system, pulsed system and CW modulation system.

With optical CW system, which is very narrow band we can face Brillouin scattering inside optical fibre. We must take into account that optical processing components are not available right now or not yet ready for commercialization. From the point of signal to noise ratio direct optical CW system will be the best solution, but today we do not have any technology to make it.

When pulsed system with high-peak power is used as a synchronization signal we face with huge nonlinear effects into optical fibre caused by a nonlinear refractive index and Brillouin or Raman scattering. In fact, the pulse system may work very fine in free-space optical installations, but can encounter several problems in fibre transmission. One of them is chromatic dispersion.

CW-modulation system can be made out of standard telecom components that are mass-volume-produced with certain manufacturing quality control. Drawback of modulation systems with RF clock transmission is higher electrical noise of a photodetector amplifier. The thermal noise is much higher then the quantum noise of a photodiode, mainly due to parasitic capacitance of a photodiode. To improve the short-time jitter as the reason of electrical noise, the flywheel is added.

Optical transmission path has delay variations due to chromatic dispersion, very high thermal coefficient of the fibre refractive index and temperature dependent starching of the fibre. The temperature coefficient of the refractive index ($8 \times 10^{-6}$/°C) is for about one order of magnitude larger than the temperature-expansion coefficient of the glass-fibre length ($7.5 \times 10^{-7}$/°C) [5]. This phenomenon is very high and has to be compensated. We can do compensation by laser-wavelength tuning or thermally adjusting the additional fibre spool. In the case of laser wavelength tuning the idea is to use a fibre chromatic dispersion to compensate for delay variations. By electric-current tuning of DFB laser ±0.1 nm wavelength change can be achieved, since temperature tuning of DFB laser allow ±2.5 nm wavelength change (0.1 nm/K). Compensating the delay-variations by wavelength change is enabling to build fast correction loop, mainly to compensate vibrations and fast temperature changes. While compensations by fibre spool temperature changes are slow and can compensate only long-term variations.
4. RESULTS ON CW MODULATION SYSTEM WITH TEMPERATURE COMPENSATION

Our proposed solution is the compensation of thermal expansion by using the chromatic dispersion in the optical fibre. Together with carefully-designed terminal electronics such a solution allows a synchronization accuracy in the range of a few tens of femtoseconds over a distance of a few hundred meters. An improved version should reach the same accuracy over a distance of a few kilometres with an additional compensation of the PMD. As a final result we expect an accuracy improvement below 10 fs over distances up to 10 km using millimeter-wave or all-optical interfaces. Allowed time deviation can be illustrated with path of 3 μm that light travels through free space in 10 fs, so the allowed jitter is just a few light waves long.

The first prototypes based on CW modulation system was built and tested on the field. The synchronization system makes use of a fibre-length stabilization, which transports a low-jitter microwave signal over a distance of 300 m. It consists of a transmitter, located at the place of the low-jitter master oscillator, and a receiver, located at the remote location. Both units are connected with a pair of optical single-mode fibres.

Short-term and long-term stability was also measured [6]. The RMS added-jitter of the synchronization system is 5 fs integrated from 100 Hz to 10 MHz and 38 fs integrated from 10 Hz to 10 MHz, respectively. The long-term phase stability of the proposed system, relative time difference between the master RF oscillator and the 180 m long compensated fibre link was measured. The master-RF-oscillator signal was compared to the signal transferred over the compensated optical link with an independent phase detector. We obtained a 31.4 fs RMS time drift in a 65-hour period.

5. CONCLUSIONS

An optical timing system with femtoseconds precision depends mainly on the requests coming from the user community and their experiments. Synchronization system over optical fibre infrastructure with femtosecond accuracy in terms of jitter and long-term stability is important for scientific usage in high bit-rate telecommunications, indoor navigation systems, experiments with distributed process control and physics measurements such as radio astronomy and short-pulse free-electron lasers. Using single-mode optical fibres for transmission of synchronization signal, special techniques need to be applied to compensate large-delay variations due to the fibre-temperature coefficient. It is presented that CW-clock transfer is possible over several-hundred-meter long link using commercially-available optical and RF components with an extremely-low added phase-noise and timing jitter, respectively. Group delay of the RF signal in the shown clock-distribution system is stabilized by the wavelength tuning and the chromatic dispersion of the optical fibres in the forward and the backward direction as well as with fibre compensation-spool temperature changes.

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