Time transfer: from GNSS to WHITE RABBIT

After a short introduction on definition and characterization of oscillators and clocks, and a short description of synchronization principles, mainly one way, multiple one way and dual way, we review the main synchronization techniques that may be used between distant emitter / receiver. We classify these technologies in microwave and wireless (UWB, eLORAN, LORA, pseudolite-based, GNSS …) and fiber-based (SDH event timing, amplitude modulation, NTP, PTP, White Rabbit,…), and we try to describe main advantages / disadvantages of each.

1.1 General and basic definitions of time and frequency

Oscillators and clocks: An oscillator provides a periodic signal of known duration. This periodic signal is used to make a "clock" by counting the number of "known periodic duration event", from a predefined "time origin".

Then a clock is made of four elements:

- a periodic oscillator, providing known cycle duration,
- a mean to count the number of periods,
- a mean to re initiate the counting,
- a definition of time origin.

After an elapsed time "*x*", the local time is defined by:

$$Time(x) = T_0 + N_C \cdot T_P$$

Where: Nc is the number of events, Tp is the event period, and T_o is the counting origin.

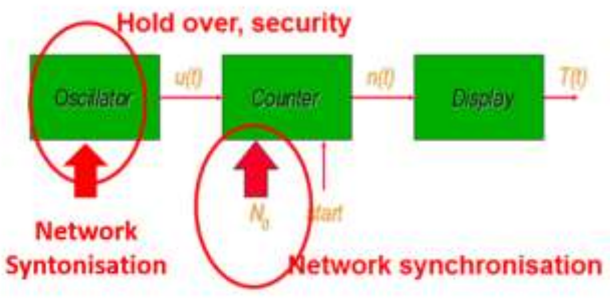


Figure 1:clock contributors

Erreur ! Source du renvoi introuvable. describes the role of each contributor- the local oscillator must be "syntonised" (running at same frequency as reference clock) to adjust Tp (period) value. The local oscillator intrinsic frequency stability (vs ageing or environmental perturbations) play a key role in "hold over", maintaining the "accuracy" of the clock when operating on its own. Counter N_C is supposed to be exact (who knows..?). Network syntonisation (F) and synchronization (t) are the management tool providing information *to* the clock (f steering, set T_0), and getting information *from* the clock (status, health check, etc.).

1.2 Oscillator characterization

The clock oscillator is the critical device. An ideal oscillator signal is defined by the periodic output voltage of the oscillator as:

$$V_{ideal}(t) = A_0 \sin [2\pi\nu_0 t + \phi_0]$$

In real oscillators, both amplitude and phase may vary with time, giving the real output voltage as:

$$V_{osc}(t) = A(t) \sin [2\pi\nu_0 t + \phi(t)]$$

As described in the document "***Time & Frequency : basics***" in this web site, all fluctuations are the same physical perturbation applied on the real signal. It is our own decision to identify and characterize these perturbations in terms of frequency, phase or phase-time fluctuations…For example, we can derive from preceding equation the "Instantaneous frequency" $\nu_{osc}(t)$ of the oscillator :

$$\nu_{osc}(t) = \nu_0 + (2\pi)^{-1} d\phi(t)/dt$$

General characterization of clocks and oscillators will describe drifts and noises of frequency $\nu_{osc}(t)$ and phase fluctuation $d\phi(t)/dt$ (Stability, instability).

The frequency accuracy of a signal will be defined from comparison to an ideal source by a systematic bias (ε) and the frequency fluctuation, varying with time, $y(t)= (\nu_{osc}(t) - \nu_0)/\nu_0$.

Then one have:

$$\vartheta_{osc}(t) = \vartheta_0.(1 + \epsilon + y(t)$$

Introducing the "in-accuracy" ε of the oscillator compared to a reference one, and y(t) being the relative frequency fluctuation, which will be characterize using statistical tool (power spectrum of frequency fluctuation, variance, averaging filtering,…).

The clock behavior extracted from the oscillator behavior, when assuming that a local oscillator frequency may suffer from a linear frequency drift and from random noise instability is described by:

$$x(t) = x_0 + y_0\, t + \frac{D}{2} t^2 + \frac{\phi(t)}{2\pi\nu_0} + \int S_p(t)\, P(t)\, dt \qquad [1]$$

Where x_o is the initial clock setting error, y_o the initial frequency offset, D the linear frequency drift, $\phi(t)$ the noisy instability of the frequency behavior, and $S_p(t)$ and P(t) describe the impact on frequency of a perturbation P(t) affecting the running frequency by the sensitivity $S_p(t)$. (t) indicates that both perturbation and sensitivity may vary with time.

Statistics and noise analysis in clocks and oscillators will attempt to describe the statistical behavior of fluctuations in time domain and in frequency domain:

- on $\nu_{osc}(t)$ and $d\phi(t)/dt$: phase noise spectrum, Allan deviation
- on x(t) : TIE (Time Interval Error), MTIE (Maximum Time Interval Error), …

Fluctuations might be analyzed in terms of fluctuation spectrum of frequency and they "averaged", while uncertainty refers to systematics biases which do not average.

Accuracy and stability are graphically described by the well known graph, from J.Vig:

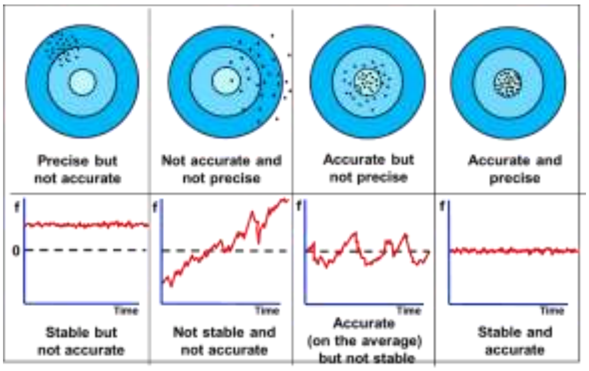


Figure 2: instability, precision and stability

We define “syntonization” when aligning frequency of a device to the frequency of another device, and “synchronization” when adjusting the clocking signals of a device on the clocking signal of a reference clock.

The reader (thanks to you !) must pay attention that all the exact meaning (and the way to use) of the words “accuracy”, “precision”, “stability”, “instabilities”… obey to very strict definitions provided by the metrology institutions. The words and their definition used in the time and frequency domain are described in ***VIM: International vocabulary of metrology,*** and ***GUM: Guide to the Expression of Uncertainty in Measurement*** (both available on BIPM web site).

The following table summarizes the main definitions of noise and instabilities characterized in time and frequency domains in oscillators and clocks, and the main relationships to convert from one domain to another (as they represent the same physical phenomenon) by:

$$\nu(t) = \nu_0 + \frac{1}{2\pi}\frac{d\phi(t)}{dt} = \text{"instantaneous" frequency;} \quad \phi(t) = \phi_0 + \int_0^t 2\pi[\nu(t') - \nu_0]dt'$$

$$y(t) = \frac{\nu(t) - \nu_0}{\nu_0} = \frac{\dot{\phi}(t)}{2\pi\nu_0} = \text{normalized frequency;} \quad \phi_{RMS}^2 = \int S_\phi(f)dt$$

$$S_\phi(f) = \frac{\phi_{RMS}^2}{BW} = \left(\frac{\nu_0}{f}\right)^2 S_y(f); \qquad \mathscr{L}(f) = 1/2\ S_\phi(f),\ \text{per IEEE Standard 1139} - 1988$$

$$\sigma_y^2(\tau) = 1/2 < (\bar{y}_{k+1} - \bar{y}_k)^2 > = \frac{2}{(\pi\nu_0\tau)^2}\int_0^\infty S_\phi(f)\sin^4(\pi f\tau)\,df$$

The five common power-law noise processes in precision oscillators are:

$$S_y(f) = \underset{\text{(White PM)}}{h_2 f^2} + \underset{\text{(Flicker PM)}}{h_1 f} + \underset{\text{(White FM)}}{h_0} + \underset{\text{(Flicker FM)}}{h_{-1} f^{-1}} + \underset{\text{(Random-walk FM)}}{h_{-2} f^{-2}}$$

$$\text{Time deviation} = x(t) = \int_0^t y(t')dt' = \frac{\phi(t)}{2\pi\nu}$$

The following graph depicts the physical behavior of oscillator frequency and clock using such oscillator, affected by bias, drift and noise:

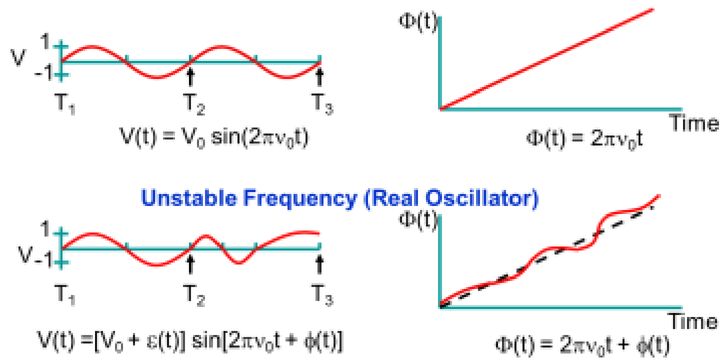


Figure 3: oscillator instability and clock impact

The most commonly used definitions of characterization of noise behavior are given by:

- Two-sample deviation, also called "Allan deviation" : $\sigma_y(\tau)$
- Spectral density of phase deviations : $S_\phi(f)$
- Spectral density of fractional frequency deviations : $S_y(f)$
- Phase noise : $\mathcal{L}(f)$

1.3 Time transfer and synchronization process

There are different techniques and options to provide time transfer (synchronization) or frequency transfer. There are a lot of work about frequency transfer, or more precisely, on frequency stability transfer, the main topic being frequency comparison between distant clocks (1000's km) , each clock being "un-transportable" (such as primary optical clocks in time laboratories such as SYRTE, PTP, INRIM, NPL, NIST,…)

These frequency comparison might be based on TW**S**FTT, two way **s**atellite Frequency and Time Transfer, or TW**F**FTT over **f**iber.(see work by LPL Laboratoire Physique des Lasers, leaded by Anne Amy Klein, and SYRTE, project Refimeve, providing frequency comparison over fiber using the Renater infrastructure).

In this presentation and in this web site, we are focusing on raising bridges between Industrial world and academic world. That means that we are focused on technologies that might have an industrial application, and on improvement/technology request coming from industrial application (ie the market) and raised to the academic.

On my opinion, and we can see many examples around us and in this web site, there are tremendous need in "Time Transfer" , synchronization, in many (more and more) systems of our daily lives. See time requirements in fix line and wireless telecom, see requirements in smart grid synchronization energy distribution network, see security issues in GNSS receivers, see timing requirements in banking system,… Accuracy ranges from some **ms** to some **ns**, but the key issue, disregarding the target accuracy, is the availability, integrity and security of the synchronization signal to be used.

These are the reasons why I am mainly focusing on time transfer in this document, and in my web site…

1.3.1 Generalities

One key issue we need to keep in mind while dealing with time transfer / synchronization is the velocity versus distance impact. Light travelling in a fiber or in free space is limited by the speed of light (~$3*10^8$ m/s). That means:

- ***distance between the emitter and the receiver has key role in synchronization process (1ns is equivalent to ~30 cm),***
- There are two options to achieve distant synchronisation: ***either the distance is known (within the requested system time accuracy)*** *and the system computes time of flight from distance * velocity to deduct time offset from in/out data,* ***or the time transfer process allows computing the time of flight*** *(requiring two-way communications).*

1.3.2 One-way time transfer

In a one-way process, a time stamped event is sent from a master (emitter) to a slave (receiver). The receiver must decode the data and provide the timing of the "event" in its own time scale. The time offset between sender and receiver are the algebraic sum of ***time scale offset and time of flight***.

The distance between emitter and receiver must be precisely known, to remove the time of flight from the total time offset. The internal time stamping process must be "known" and "stable" within system tolerance.

$D_{AB} = V * \delta t$, V is the velocity of traveling wave (light velocity in air RF)

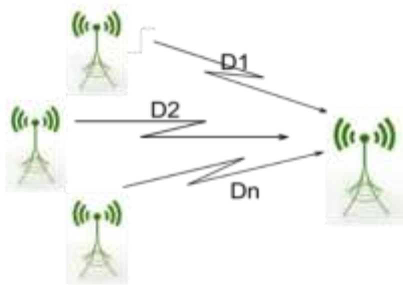
Accuracy relays on "time stamp process" (i.e., the time resolution of the time stamping operation, time stamp can be software or hardware defined). ***"Electrical" or "propagation" distance between sender and receiver must be known within 30 cm to achieve 1 ns accuracy***. The time of HW and SW internal electrical processing (between the physical layer and the high OSI layer), in sender and receiver, should be also taken into account. Furthermore, there is no information directly available on the status of receiver known by sender, and vice versa.

This is the synchronization scheme used by long wave RF signal emissions, such as DCF77 (Germany) and France Inter (France), based on amplitude and carrier phase modulation, sent from a single emitter, located close to Frankfort for the German one, and close to Bourges for the French one.

1.3.3 Multiple one-way time transfer

This is the technology used in most of GNSS timing and positioning messages broadcast or in ground-based pseudolite system based (such as LOCATA), or in eLORAN, using high power low frequency (100 kHz) to allow ships to position on sea close to the coast. It is a multiple "one way", providing enough data from all emitters (i.e., satellites position and onboard local time at time of broadcast in GNSS, local position and local time in ground based beacons) to the receiver, to allow the receiver to compute accurately its position and its local time.

Distance from emitter to (common) receiver is unknown, local time at receiver is unknown, while emitter position and local time at emitter are known at time of emission:



Pseudo distance are computed from

$$D_1 = (T_{1,s} - T_r) * c$$

$$D_2 = (T_{2,s} - T_r) * c$$

$$D_n = (T_{n,s} - T_r) * c$$

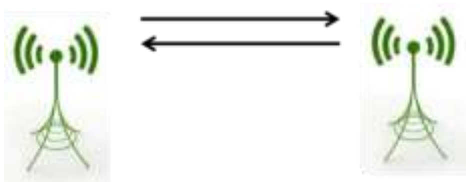
The subscripts ***r*** and ***s*** refer to receiver and sender (sender number from 1 to n), respectively. Assuming that all emitters operate in a common time scale, we can define the user clock offset as $Dt_{loc} = (T_r - T_r')$ versus the system time scale, and the distance between each emitter and the receiver can be defined by the geometric vector:

$$Di = \sqrt{(\mathbf{X_i} - \mathbf{X_r})^2 + (\mathbf{Y_i} - \mathbf{Y_r})^2 + (\mathbf{Z_i} - \mathbf{Z_r})^2}$$

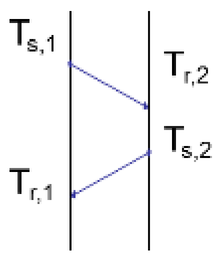
As the satellite (or pseudolite) coordinates are known at the time of emission, one can determine simultaneously the local position and the local time of the receiver.

1.3.4 Two-way time transfer

Two-way time transfer is a forth and back process between a sender (master) and a receiver (slave). Such round trip eliminates the need of accurate positioning identification.



Both sender and receiver may have access to the determination of the total "time distance" between both. The following picture gives the main time identification of a two-way process. In this figure, we denote the time scale with $T_{x,y}$, where subscript $x \in \{s, r\}$ is used to denote send data (s) or receive (r) data, and subscript $y \in \{1,2\}$ refers to master time scale (1) or slave time scale (2).



A physical event is sent at time $T_{s,1}$, in master time scale, and received at time $T_{r,2}$ in receiver time scale. This signal is acknowledged and the slave sends back at time $T_{s,2}$ (in slave time scale) a clocking signal to master, and master receives this signal at time $T_{r,1}$ in master time scale.

We cannot say anything, so far, about $T_{r,2}$ vs $T_{s,1}$, or about $T_{s,2}$ and $T_{r,1}$, as they are defined is different (so far not yet synchronized!) time scale, but we can use $T_{r,1}$ and $T_{s,1}$ on one hand and $T_{s,2}$ and $T_{r,2}$ on the other hand , as they are defined in the master time scale or slave time scale.

If we define : δt_{12} as the time of flight from master to slave, δt_{21} the time of flight from slave to master, and Δ the clock offset between master and slave then we have :

$$T_{r,2} = T_{s,1} + \delta t_{12}$$

$$T_{r,1} = T_{s,2} + \delta t_{21}$$

$$T_{r,2}' = T_{r,2} + \Delta$$

$$T_{s,2}' = T_{s,2} + \Delta$$

The comma " ' " indicates time at slave given in the master time scale

Assuming that $\delta t_{21} = \delta t_{12,}$ which means the time of flight master to slave is equal to the time of flight slave to master (symmetry assumption), then we have

$$T_{r,1} - T_{s,1} = 2 * \delta + (T_{s,2} - T_{r,2})$$

$$\delta t = \frac{(T_{r,1} - T_{s,1}) - (T_{s,2} - T_{r,2})}{2}$$

$$T'_{r,2} = T_{r,2} + \Delta = T_{s,2} + \delta \qquad \textbf{[2]}$$

$$\Delta = \frac{(T_{r,1} + T_{s,1}) - (T_{s,2} + T_{r,2})}{2}$$

Terms in bracket can be computed, as they are referred in the same time scales. A two-way time transfer process thus gives access both to time of flight and clock offset and allows a slave to offset its local time scale to synchronize itself on the master time scale, namely after checking some "Quality of Service (QoS)" information.

The performance limits are given by:

- ***Symmetry assumption*** (*main limit of such process in wired lines)***,*** usually valid for wireless terrestrial communications if the same antennas are used at both end to receive and transmit (reciprocity theorem), partially valid on fiber-based telecom network because of traffic asymmetry, but not necessarily valid for satellite-based two-way techniques due to the Earth rotation (Sagnac delay) and satellite displacement).
- Availability of statistics on δt and Δ to improve the time transfer accuracy.
- Time stamping precision (Hardware HW, Software SW, ...).

The two-way time transfer process is used for instance in:

- Two-way time transfer via Satellite (TWSTT), on point-to-point, to compare and synchronize high performance primary clocks, between main "primary clocks laboratories" METAS, NIST, PTB, NPL, SYRTE, etc.
- NTP (Network Time Protocol) process, commonly used in computer network synchronization. NTP limits are inherently in the ms range due to poor time stamp (software time stamp).

- PTP (Precision Time Protocol) process, which is more and more used in telecom infrastructure, standardized under IEEE 1588. Very similar to NTP, it offers a better accuracy, down to the μs, because of a ”physical low OSI layer” time stamp process.
- Two-way time transfer range determination systems, e.g., for local positioning systems.
- PTP WHITE RABBIT, operating over fiber (there are work to reduce the requested band width to allow PTP operating over wireless in the IMS band), able to synchronize clocks within some pico-second over long distance, if careful management of wavelengths and calibration is properly applied.

2 Microwave and Fiber-based time transfer technologies

2.1 Introduction

As we can anticipate, there are multiple techniques and technologies applicable to perform time-transfer. Only a few of them will be good enough in terms of performances and costs, for commercial use…

We will compare ground wireless over medium/long distances (GNSS, pseudolites based – LOCATA, LORAN and eLORAN, e.g., and short distance (LORA, Ultra-Wide Band – UWB,..) and fiber-based technologies (SDH time tamp, dedicated time stamp, protocol-based fiber-based , such as NTP, PTP) and finally WHITE RABBIT

2.2 Microwave / wireless media

2.2.1 Microwave propagation

Wireless propagation point to point, electromagnetic waves, like light waves, radio waves are affected by propagation impact of the support media : mainly absorption, reflection on solid (generation of indirect path) , refraction, diffraction, but also impact on polarization and scattering. In GNSS , a special case but well disseminated, ionospheric and tropospheric effects have a significant impact, and measurement (when using di-frequency receivers) or models (in single frequency receivers) need to be used to correct propagation time (and exact distance) from velocity iono- and tropo- impact.

Propagation perturbations are *time variant* due to environment changes: either we have real time estimation or we have accurate enough model to perform statistical correction .

Main impact on ground will be originated by the motion of the receiver (doppler and near/far effect).

Two main parameters are important in wireless links for time synchronization applications: the *signal attenuation* (which limits the distance between receiver and emitter) and the *propagation delay which is key for accuracy determination.*

Friis’ free space link equation gives the received power (P_r) as a function of the transmitted one (P_t), the transmitter and receiver antenna gains (G_t and G_r), the signal wavelength ($\lambda = c/f$), and the distance between the transmitter and receiver (d) as:

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{\left(4\pi \cdot d\right)^2}$$

P_r/P_t is called path loss, and the exponent d^2 applies to free space, without any multipath or obstructions between transmitter and receiver.

In real propagation condition, such as GNSS signal reflexion on buildings, the propagation medium leads to the reception of multiple time-delayed versions of the transmitted signal. The signal attenuation then goes with d^n with $n > 2$. This factor is called the *path loss exponent* and its value depends on the environment (Botteron 2008).

Table 1: path loss exponent for different environments [Botteron2008]

Path Loss Exponents for Different Environments:	
Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building LOS	1.6 to 1.8
In building obstructed	4 to 6
In factories obstructed	2 to 3

Attenuation of signals received from various (at least three) base station is one of the possible tool to determine position of a mobile receiver in wireless telephony, 3G 4G,…

Moreover, signal attenuation also changes with weather conditions over carrier frequency as shown below:

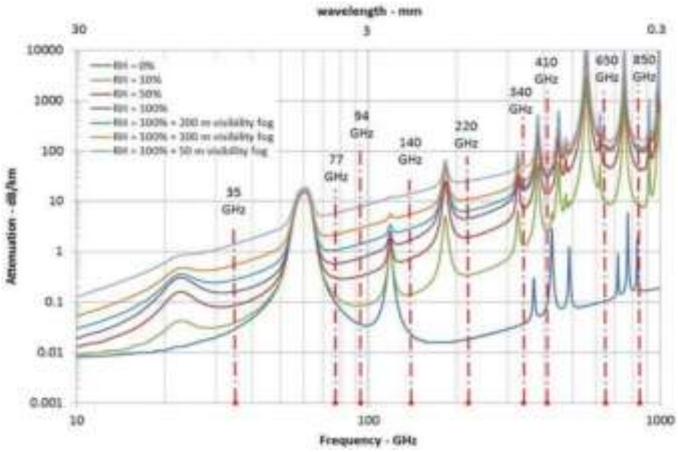


***Figure 4:Absorption peaks are related to Oxygen and water atomic bounds in atmosphere*.**

In real world, the propagation delay can vary locally, and exhibit rapid local variation (propagation noise) affecting amplitude, phase and polarization, called small-scale fading. These fluctuations are generated by interferences between multi-path waves (Botteron 2012)

This spread effect may impact the synchronization accuracy. The actual delay must be estimated to correct the time stamp with the actual time of arrival, but this delay fluctuates with time and need to be estimated in real-time. In GSM systems the channel is sounded by means of training sequences.

Some experiments have been performed for mobile communication systems. For *cellular communication in urban area* delay spread is reported around *0.3µs per 1km*.

We can find in microwave propagation literature, *that, operating at constant power in order to be compliant with the regulations, the lower is the frequency the higher is the received power.*

Some other effects may impact propagation delay. Waves propagation at low frequencies (KHz to some MHz), will be guided between the earth's surface and the layer of the ionosphere. Such wave propagates, with less attenuation, over-the-horizon and over obstacles like mountain, and they can be received at long distance from emitter.

Such guided trajectory of long-waves is impossible to predict because it changes with environment and ionosphere conditions (weather, altitude, electromagnetic behavior,…), then the time of flight cannot be accurately determined.

At higher frequencies (Very-High Frequency - VHF, microwaves and beyond) the propagation is line-of-sight therefore is almost straight line, and waves cannot travel over the horizon or behind obstacles. In line-of-sight, the delay path estimation is more accurate.

The estimation of the propagation delay is typically performed in the digital signal processing domain by using an estimator which on the average yields the true delay value.

From estimation theory, the Cramer-Rao Lower Bound (CRLB) provides a lower bound on the estimator's variance, valid for any unbiased estimator.

The estimation of propagation delay can be done using estimation tools developed for radar systems. The round trip delay τ_0 from the transmitter to the target and back is related to the range R as $\tau_0 = 2R/c$, where *c* is the speed of propagation. In the case of White Gaussian Noise the variance of the propagation delay can be estimated by :

$$\mathrm{var}(\hat{\tau}_0) \geq \frac{1}{SNR \cdot B}$$

Where SNR is the signal-to-noise ratio and B is bandwidth. Then :

- the larger the bandwidth the lower the variance.
- *ns delay accuracy is achievable with a signal bandwidth of 2 MHz (such as GPS L1 C/A)*.
- *0.1ns delay accuracy might be obtained for a 20MHz signal (such as the military GPS P(Y) or the new GPS civil signal L1 C or Galileo E1).*

Based on the preceding, we can review some potential performances of various wireless system, on short distance or medium range distance.

2.2.2 Ultra-wideband (UWB) technology

Ultra-wideband (UWB) systems are very high frequency short distance communication system.

UWB operates in the 3.1-10.6 GHz. UWB communication works by sharing the already-occupied spectrum by using the overlay principle, the transmitted power density of UWB radios is quite limited (below -41.3 dBm/MHz) in order not to cause interference to the other users. Finally, the standard states that the signal bandwidth (-10 dB) must be greater than 20% or greater than 500 MHz.

There are two main categories of UWB devices: *pulsed radio*, where very short pulses occupy the UWB bandwidth, and orthogonal frequency-division multiplexing (*OFDM*)-radios, which aggregate at least 500 MHz of narrow-band carriers to access the UWB spectrum under the designated rules.

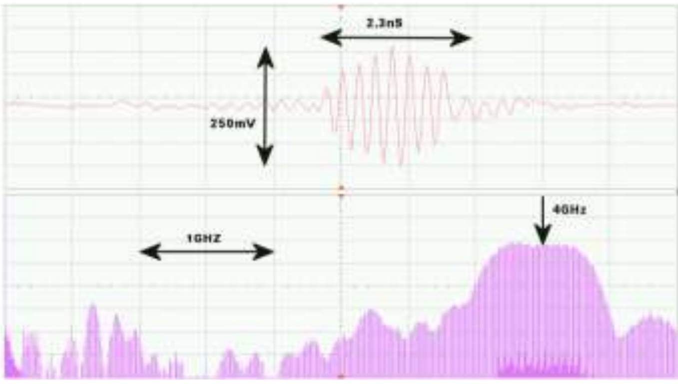


Figure 5:Measured UWB signals (time and frequency domains) generated with a pulse radio developed by EPFL-ESPLAB [Robert-EPFL 2010].

Due to its wide bandwidth, UWB may provide high time resolution, down to the sub-ns level.

UWB system can isolate the individual multipath signals from the received direct line-of-sight signal. This ability makes UWB an interesting technology for indoor positioning and time-synchronization systems. Moreover, for data rates smaller than the signal bandwidth a large processing gain can be obtained. Therefore, UWB systems can be designed to be robust against intentional and non-intentional interferences including multiuser access, narrowband and wideband systems, and jammers. This enables the use of UWB for synchronization applications where multipath would otherwise significantly affect accuracy.

In indoor environment, EPFL ESPLAB using their impulse-based UWB system developed in the laboratory, have demonstrated a 2-D positioning accuracy on the order of 2.4 cm 67% of the time and 4.9 cm 95% of the time, which corresponds to a ***1-sigma time-accuracy on the order of 50 ps***!

The main drawback of UWB technology is the limited range (***tens to one hundred of meters***) due to the spectrum regulation. the maximum allowed power density of -41.3 dBm/MHz corresponds to a maximum transmitted power of 75 µW for an UWB signal of 1 GHz bandwidth!

This makes UWB systems a **suitable technology** for positioning **or time synchronization over distances lower than hundred of meters, mainly indoor**.

2.2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a method of encoding digital data on multiple carrier frequencies. OFDM has developed into a popular scheme for wideband digital communication, whether wireless or wired.

It is used in applications such as *digital television (DVB)* and *audio broadcasting (DAB)*, *DSL (Digital Subscriber Line) Internet access*, *wireless networks (WLAN)*, and *4G mobile communications (LTE)*.

Multiple wavelength allows to drastically enhance link throughput. A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying).

The low symbol rate makes the use of a guard interval between symbols affordable, reducing inter-symbol interference (ISI) and utilize echoes and time-spreading to achieve a diversity gain, i.e. a signal-to-noise ratio improvement.

Due to the guard interval, OFDM based systems are quite robust against imperfect symbol-timing, but for synchronization/positioning this timing offset directly results in an estimation error.

The symbol-timing calculation can be accurately estimated, **in the range of tens of nanoseconds** by implementing different metrics, based on CIR, in the software defined radio that demodulates the OFDM signal [Sajadi2009].

OFDM modulation offers intrinsic accurate mechanism for the estimation of the *channel time delay spread and the maximum excess delay*, allowing accurate time synchronization.

2.2.4 Single-carrier narrowband & spread spectrum

Single carrier narrow band and single carrier spread spectrum are well known techniques for communications.

Narrow band is not suitable for time transfer (while perfect for low noise / narrow band communication) , bandwidth is too narrow, rate is too low, and spectral efficiency too poor (1bit/Hz), to support time transfer or positioning.

Spread spectrum single carrier microwave uses a bandwidth far wider than the one required by signal. Spectral efficiency is huge, allowing multiple users without significant interferences. SS signals are pseudorandom signals that exhibit a noise-like property (orthogonality) that is exploited in the digital correlation at the receiver side in order to separate the signals and reduce the noise bandwidth.

Spread Spectrum techniques are suitable for mobile communications because they are resistant to fading, and signals are resistant to interference, to jamming and are inherently secure.

Single carrier spread spectrum is at the base of many popular systems such as ZigBee (DSSS), Bluetooth (FHSS) and also GNSS systems.

In a GNSS receiver processing the CDMA signal coming from a given GNSS satellite, there are typically two tracking loops:, first, a phase-locked-loop (PLL) for tracking the carrier phase, and then a delay–locked-loop (DLL) for tracking the code phase. Both loops outputs can be used to estimate the range between the receiver and the satellite.

There are multiple broadcast protocols, such as **RBS -** Reference Broadcast Synchronization**,** utilizing receiver to receiver synchronization, or such as **TPSN -** Timing-sync Protocol for Sensor Networks: implementing a sender to receiver synchronization, or **FTSP -** Flooding Time Synchronization Protocol, again a sender to receiver synchronization protocol.

These protocols allow point to point (neighbors) synchronization in the range of some 10’s μs.

PTP - Precision Time Protocol**,** widely used in fix line and base station synchronization, is also implemented in wide band / high frequency communications protocols. The IEEE 802.15.4/ZigBee network (2.4GHz, DSSS) was used for the precision time protocol in LR-WPAN's (Low-Rate Wireless Personal Area Network). The PTP system for LR-WPAN consists of the master node and slave nodes. Their time synchronization for offset and drift correction is established by message exchange. The hardware-assistant time stamp enables high precision.

in Low-Rate Wireless Personal area Network (LR-WPAN) time synchronization within 1 μs microsecond , and in *LR-WPAN on a static link , PTP was reported within ~9 ns of average accuracy and ~42.5ns of standard deviation*.

2.2.5 The LORAN & eLORAN status.

LORAN (**LO**ng **RA**nge **N**avigation) is a terrestrial 2-D radio navigation system which enables ships and aircraft to determine their position and speed from low frequency radio signals transmitted by fixed land based radio beacons, using a receiver unit. The most recent version of LORAN in use is eLORAN, replacing the previous LORAN-C, which operates in the low frequency (LF) portion of the radio spectrum from 90 to 110 kHz. Many nations have used or are still using the system, including the United States, Canada, Japan, and several European countries. Main advantage is its inherent difficulty to be disrupted.

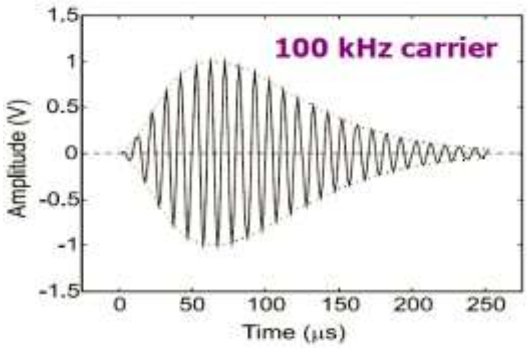


Figure 6: Pulsed signal of e-Loran with carrier frequency of 100 kHz

Technology wise, Loran uses a modulation of a low frequency / long wavelength RF signal (frequency on the order of 100 kHz). Using a high power emission, eLORAN is difficult to jam. Furthermore, the locations of antennas are known and stable. In the US, there was a trend to dismount Loran-C in 2000, then a trend to deploy eLoran. Some other countries are also highly supporting redeployment of eLORAN, mostly to remove sensitivity to GPS vulnerabilities.
Accuracy of time synchronization through eLORAN is claimed to be typically +/- 100 ns, which could be accurate enough for most time-dependent infrastructure.

Such a system would provide a navigation and timing signal comparable with GNSS and complementary to GNSS. One study of the Institute for Defense Analyses (IDA) concluded that: *"eLoran is the only cost-effective backup for national needs; it is completely interoperable with and independent of GPS, with different propagation and failure mechanisms, plus significantly superior robustness to radio frequency interference and jamming. It is a seamless backup, and its use will deter threats to U.S. national and economic security by disrupting (jamming) of GPS reception"* [GPS World 2013].

The eLORAN antennas are disseminated over Europe, covering mainly coastal segments, There are only 9 transmitters in Northern Europe (Denmark, France, Germany, Norway and UK)- A second one was installed in UK, allowing eLoran to cover all the country. There are two sites in France (Lassay and Soustons) - covering mainly the Atlantic and channel coasts. All Europe is not fully covered by eLORAN. France and Norway are (?) on the way to switch off their stations, provoking a real difficulty in Atlantic and Channel ship positioning. Nevertheless, there are some attempts to consider eLoran as potential back-up timing network, mainly in UK (General Lighthouse Authorities). Other countries are supporting eLoran as GNSS back up, such as South Korea (nationwide coverage), China (6 sites) and Russia (14 antennas).

Figure 7:eLoran transmitters in Europe – BREST (DCNS, now Naval Group, is the control center)

In US, a report was asked in 2000 under the target of switching off Loran-C by 2008. However, the report concludes that eLoran (which is significantly different from Loran-C) satisfy all the US requirements -NPA, HEA, timing/frequency and could mitigate the operational of GPS disruption and confirm that eLoran is the best available backup provider to GPS as reference source for precise time synchronization and frequency control. Rather than spending $146M to dismount Loran-C infrastructure, # $300M non-recurrent and $37M/y recurring were allocated to develop eLoran.

There were till recently activities supported by Harris and UrsaNav to support test by US coast Guard. By June 2017 there were some tests between eLoran sites in US, Havre, Montana; George, Washington and Fallon, Nevada (all in north West). The company Continental Electric, Texas, has developed a new eLoran transmit method, requiring low-frequency antennas significantly lower in height than conventional antennas. In France, LORAN 'control is still under discussion. We need to mention some developments. In Denmark, eDLORAN, enhanced differential Loran, provides 5m accuracy (15 ns..!). eLoran is considered as the only available e-navigation back up to GNSS, and the remaining sole obstacle, in Europe, is the lack of political agreement between European countries, mainly because the control institution are different country to country (Lighthouse, Fisheries, Army,…)…

Actual trend is promoting eLoran switch off in western Europe, because of the "crazy" decision from France and Norway to switch off their antennas. If it goes that way, it may happen that US stop eLoran too. It is a pity to see a system claimed as the sole GNSS backup available to disappear…. Once again, in my opinion, Galileo is not a GPS back up, and Galileo is not more secure than GPS. Both are vulnerable, and a ***backup is mandatory to operate critical infrastructures***…eLoran might be one of these

2.2.6 Pseudotite-based positioning system

Basic idea is to deploy on ground a set of synchronized pseudo satellites (pseudolite), at known position, disseminating RF signals (CDMA like , similar to GNSS) to mobile receivers. It works, like GNNS, as a multiple one-way system, providing position and timing. Locata is one company providing such systems (www.locata.com).

From this network of synchronized ground-based transceivers, Locata-Lites, a transmit positioning signals is broadcasted that can be tracked by ad hoc receivers. These transceivers can operate autonomously, using the network time reference of any third party time reference, such as GNSS – to support positioning, navigation and timing (PNT).

Locata's positioning technology solution is a possible option to replace GNSS (e.g. for indoor or limited field of operation applications) or to provide a highly secured positioning system, such as military field, operating totally autonomous, and, being much higher RF power than GNSS, more jamming-resistant or spoofing resistant.

LocataNet, as a time-synchronous system, *allows point positioning with cm-level accuracy using carrier phase measurements.*

The second generation of Locata incorporates a proprietary signal transmission structure that operates in the ISM band (2.4-2.4835 GHz). Within the ISM band the LocataLite design allows the transmission of two frequencies, each modulated with two spatially-diverse Pseudo Random Noise (PRN) codes, similar to those as used in GNSS.

In order to avoid near-far issues, Locata employs a pulsed CDMA (time-hopped CDMA – TH/CDMA) architecture, i.e., a gated version of a continuous CDMA signal. This allows a TDMA scheme to be employed, using a multi-slot frame, where each LocataLite is assigned a single slot for transmission. This slot allocation is based on pseudorandom gating sequence and repeats every 200 frames, where each frame is 1 ms long, and contains 10 slots of 0.1 ms. Moreover, LocataLites operating in a given LocataNet are divided on a geographic basis, into subnets of up to 10 LocataLites each [Locata ICD 2011]. The timeslots within each frame are assigned on a non-overlapping basis to each of the LocataLites within a subnet. Each LocataLite employs two transmit antennas, with each antenna transmitting at each of the two carrier frequencies. This allows LocataLites to track four signals.

This new Locata signal structure enables:

- Capability for on-the-fly ambiguity resolution using dual-frequency measurements.
- multipath mitigation on pseudo range measurements due to the higher 10 MHz chipping rate, and less carrier phase multipath than GPS/GNSS due to the higher frequency used.
- Transmit power of up to 10 watt giving line-of-sight range of up to 100 km. Longer distances could be enabled by using higher-powered amplifiers.

The latter Locata claim entails a **nano-second level synchronization of all transmitters in the positioning network**. To do this the LocataLite transceiver use a patented mechanism, named TimeLoc, to synchronize the signals transmitted by LocataLites. This internal correction process is accurate to the millimeter level.

A LocataNet covering 1,350 square miles (3,500 square kms) was deployed at White Sands (USA). The USAF and the 746th Test Squadron (see GNSS vulnerabilities page on this site) proved that a LocataNet can accurately position USAF aircraft over a large area. Locata delivered accurate independent positioning as good as 2.5 inches (6cm) horizontally and 6 inches (15 cm) vertically for aircraft flying at a distance of 30 miles (50km) at up to 350 mph (550 km/hr) at 25,000 feet. Also, Locata demonstrated reaching more than 50 km of coverage by increasing the power level from 100 mW up to 10 W and using some customized quadrifilar helix antennas. Moreover, Locata signals could be acquired and tracked by aircraft at distances of up to 100 km using high-power amplifiers.

In 2013, a study performed by the University of New South Wales in Australia characterized the time transfer capabilities of Locata, by performing two independent research experiments. In a first experiment, Locata network was locked to external GPS time, across a 73 km transmission distance, and the mean and standard deviation of time difference were -5ns and 4.2 ns, respectively., while standard deviation of frequency difference was 1.03 ppb. In a second experiment, Locata being locked on internal relative time transfer, over a 56 km transmission distance, mean and standard deviation of time difference were 5.9ns and 300 ps, respectively, while standard deviation of frequency difference was 0.07 ppb. Then we can conclude that pseudolite-based system may allow ***to achieve ns wireless synchronization over large distances*****.**

2.2.7 Long range wave system

Many countries have deployed long range wave system, mainly for positioning. Similar to e.LORAN, they take benefit from ***high power (some KW)*** which make the system difficult to be jammed, allows indoor penetration, and provides wide coverage, etc…They are mostly using amplitude modulation to offer ms accuracy, and complemented with carrier phase to improve performance down to some microsecond.

In Europe, there are DCF 77 (DCF network) broadcasting from Germany and France Inter (from France). Similar systems do exist in other countries, such as JJY (Japan), CHU (Canada) and WWVB (USA).

DCF 77: is a long range wave emitted (F # 77-5 kHz) from south of Germany, j operated by PTB. It covers an area greater than 1500 km, i.e., most part of Europe [online: www.dcf77.de]. The original DCF 77 is an amplitude modulation, ***providing ms level synchronization capability*** and a phase modulation was added recently.

- DCF77 carrier frequency relative uncertainty is 2×10^{-12} over 24-hour and 2×10^{-13} over 100 days, with a ***deviation in phase with respect to UTC < 5.5 ± 0.3 µs***.
- It operates free access, and use very simple code.

France Inter: is emitted from center of France (Bourges) at a frequency of # 162 kHz. It is not free access and uses a more complex code scheme. Receivers are expensive, there are only 2 manufacturers. Maintenance of the service provided by France Inter is regularly questioned.

- the time transfer limits are ***in the range of ms for amplitude modulation***;
- ***carrier phase information improves the resolution down to some*** μs.

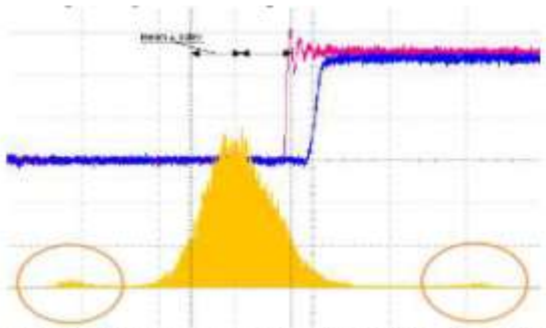
2.2.8 Point-to-Point microwave links

Point-to-Point static links at microwave frequencies can benefit of the high antenna gain (parabolic antenna) therefore they are widely used for wireless link up to few hundred kilometers. Relative wide bandwidth available on microwave bands, the data-rates achievable are high-enough to operate as fiber optic cable replacement, or last mile.. Most of them are IP based, limiting the synchronization capabilities compared to analog link. In the § PTP and PTP-WR, we will see the role of syntonised frequencies (SyncE over fiber), top-down syntonisation, and the role of dual way PTP message exchange in synchronization process. PTP-White Rabbit require dual way IP signals (PTP format) and dual way syntonisation (D.DMTD between phases of incoming/outgoing 125 MHz signal is used for interpolation and final accurate timing). From commercial products available and current activities, we can anticipate that microwave link, properly configured, might be able to support PTP, while it will be more difficult to support White Rabbit. Furthermore, the bandwidth of PTP-White

Rabbit on fiber is very wide (1 GHz). Getting this signal on wireless link will raise a need of wide RF band width, not compatible with the standards of the ISM band , for example. One option is there to try to reduce the required bandwidth of PTP-WR signals, to allow carrying these signals over an ISM band compatible RF link. Such development are under work at university of Granada (Pr Javier Diaz, www.ugr.es/~jda/)

The key configuration parameters are the modulation scheme (x-PSK, X-QAM data rate, PTP is 1 166 bytes process) low latency, low jitter , frequency/time selective channel. FDD or TDD time and frequency spectrum allocation, and half duplex / full duplex bandwidth….. A main configuration issue is the SyncE-like behavior, ie the frequency transfer form fiber to microwave and vice versa

Some commercial products, such as Cambium PtP 650 radio devices, provides specific configuration TC, Transparent clock, SyncE(one way), PTP and TDD compliance. it is IP based for data-rates up to 1.4Gbps, bandwidth @ frequency carrier. It's available for the ISM bands at 5.8GHz and 24GHz; highest frequency enables highest data-rate. Accurate PTP-SyncE time transfer (1 σ 6.6 ns) has been achieved with such microwave link, shown below, allowing the application of such link as point to point time dissemination:



PTP over TDD - TC enabled: <delay> 50.5 ns – std dev 6.6 ns
red curve: master pps –blue: slave pps - green: pps delay – yellow: histogram

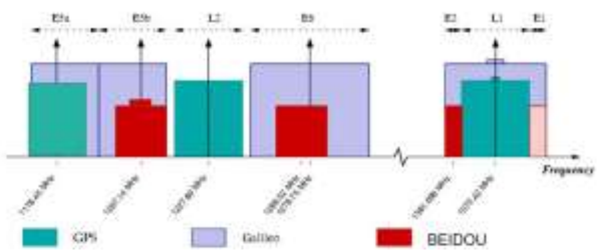
Figure 8: PTP-SyncE over TDD – TC enhabled microwave link

2.2.9 GNSS timing and TWSTT (Two way Satelllite time transfer)

GNSS is probably the widest time and localization provider, mainly over direct link (time generated from GNSS signal) or over indirect time comparison (double difference between userA vs GNSS versus userB vs GNSS gives userA versus userB).

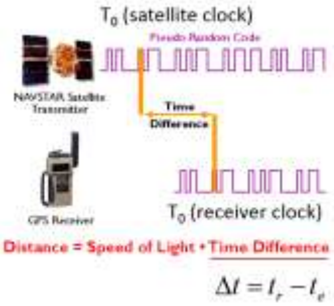
GNSS are constellation of MEO (Medium earth orbit, typ. GPS 20'000 km, Galileo 23'000 km) satellites (# 25-30 for each GPS, Galileo or Glonass constellation).

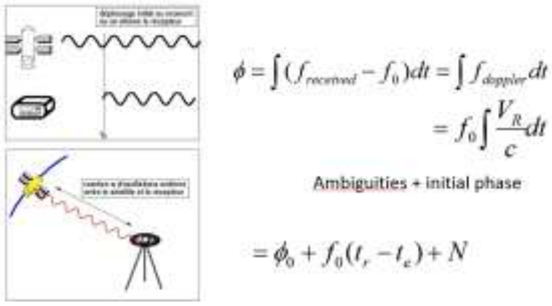
Each satellite circles the earth twice a day, and broadcast coded information, on 1, 2 or 3 frequencies,



carrying each individual position and local timing over PRN – pseudo random- codes. Relativistic impact on onboard satellite clocks -38.6 μs par day faster-, is onboard frequency corrected.

On ground receivers collect simultaneously information sent by various satellites. Calculation of individual distances receiver-satellites(s) - time of flight is # 66 ms-, including GNSS code identification and carrier phase measurement, ephemerides and clocks data, ionospheric delays impact -either measured on 2 frequencies receivers, or modeled in single frequency receivers-, tropospheric delay -modeled-, …, allow calculation of precise localization and timing at receiver level.

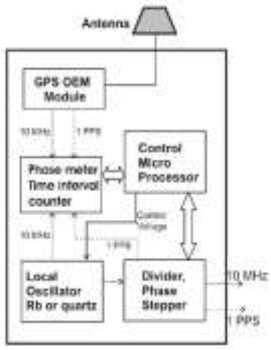




GNSS timing might be acquired through single frequency receivers or dual frequency receivers (eliminate some ionospheric effect).

GNSS and related TWSTT, Two Way Satellite Time Transfer is used for scientific purpose, mainly to perform (high stability)-frequency signal comparison over long distance. Main application is to operate the clock comparison of TAI the time scale calculated by BIPM from two hundreds atomic clocks over 50 laboratories and countries, and comparison between high end primary clocks - optical, the future SI standard for the second-, etc…

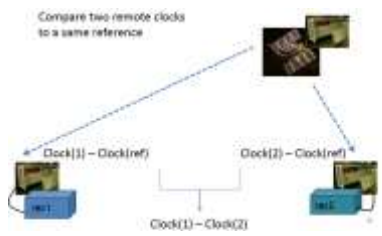
Basic GNSS timing operates through a direct reading by a local receiver of some (ideally at least four) satellites signals. Receiver identify individual satellites through correlators and resolves the pseudo range equations once satellites are identified and selected. In general, the GNSS signal is used to steer a high performance oscillator (Rb or D.OCXO, Double Oven Xtal Oscillator) in timing receiver. TCXOs are widely used in commercial localization receivers (cars,…).



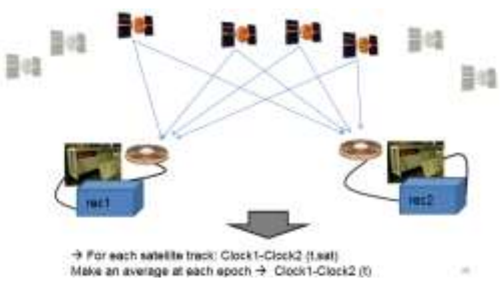
More accurate GNSS time transfer operates by a double difference. The contribution of GNSS bias or instabilities is eliminated through:

(ClockA-GNSS)–(ClockB–GNSS) = ClockA-ClockB

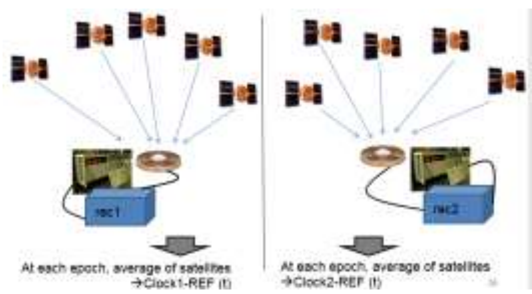
It is then possible to streer clock A on value of clock B (*or vice versa if you wish..)* without contribution of satellite clock



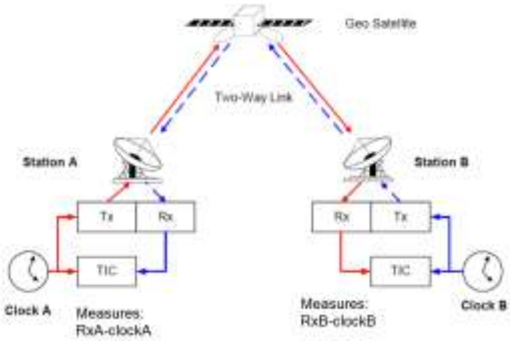
A further more sophisticated system is to apply the “common view” or “all in View” to achieve better time transfer:



In first case, clocks average individual biases, while the second compare each clock to the average sat timing t.REF



Geostationary satellites and some other transponders onboard telecom satellites, may support TWSTT, Two way Satellite Time Transfer. By design, TWSTT performs a quasi-perfect cancelation of the medium effects on propagation, as both uplink and down links, between clockA and satellite, and between clock B and satellite, are running same distance (ideal with geostationary satellites) in same media (apart from chromatic effect – uplink and downlink frequencies are slightly different-, from small variation of real position during data exchange, etc…). This technique, due to its very high renting cost of communication channels, is used only for scientific applications.



The most accurate time transfer over GNSS uses the PPP technique, Precise Point Positionning, determining position of one clock (fix station), making use of code data and carrier phase data, refining data though a signal modeling (body tide, diurnal, semi-diurnal, ocean effects, satellite elevation impact,…., reserved for scientific or institutional purposes

Commercial purpose of GNSS is to provide localization for vehicles (cars, ships, train, planes,..) and disseminate time to users, either individuals or infrastructure (fixline and wireless Telecom, Transportation , energy,) banking system etc…

Most of commercial receivers use single frequency (dual civilian frequencies soon) and simple oscillators (TCXO in car localization). Hold over in case of GNSS signal natural disruption (urban canyon, tunnel, forest,..) are provided by embedded Inertial navigation unit, using MEMS level gyrometers and accelerometers. In timing domain, “hold over”, to protect reception from accidental GNSS signal disruption, is provided by the use of high stability oscillators (DOCXO, Rb) able to provide ageing drift les than 1.10^{-11} per day (1 µs / day following Eq.1) . In real application, redundant GNNS channels are implemented (with automatic switching of both active channels when needed), and third party timing might be also embedded on same shelf (SDH E1 or SONET T1 reference, DCF,…), in redundant dual power shelf.

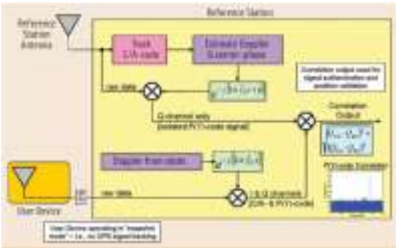
Classical commercial receivers allow frequency steering within 10^{-12} after one day lock, and allow to provide +/- 100 ns – 6 sigma- stability of pps output.

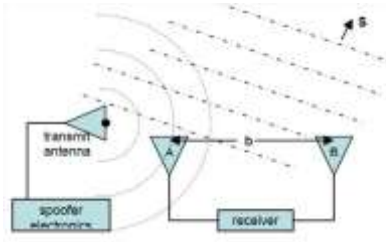
The more sophisticated the receiver is (multiple frequency, all in View, Common view, PPP,…) the better the timing accuracy and stability, down to ns level for best receivers. TWSTT are able to reach some ps level timing performance and some 10^{-16} in relative frequency variation comparison.

Since 2001 and the so called “Volpe record” (see link on this webpage) it is acknowledged that receivers, due the very low power signal received at antenna), are the weak point of the GNSS time transfer. There multiple examples of jamming, spoofing, signal disruption recorded during the last 10 years (thre events of perturbation of GNSS receivers at national level in South Korea, jamming by truck drivers or taxi drivers close to many airports ,..), spoofing of drone receivers or ship receivers, feeding the local receivers by fake signals and corrupting the computed localization and local timing,..Texas university shows that a low cost spoofer can take control of a super yatch I Ionian sea… Furthermore, GPS is physically steered to UTC, but this is not binding by law, and can by interrupted by political decision. GPS signals (Galileo ?) might be switched off over specific region of the earth (replacing the former added noise “Selective Availability” in place up to May 2000).

Hardware and software enhancement of GNSS receivers addresses some of the vulnerabilities, such as beam forming antenna, allowing to point only in direction of satellites, whose positions are extracted from stored ephemerides compared to calculated position – within certain limits- , software signal processing , identifying line of sight from reflected signals, authentication, cross-check against internal/external metrics, predictable characteristics of navigation or timing signals, direction -of-arrival, uses of hidden GPS attributes linked to each satellite, cross-compared between receivers,…, data processing compared between receivers (joint processing), code related data processing, L1 L2 common code sequence,…, correlation between recorded raw data by distant receivers.

Back in 2009, data processing of correlated signal between distant receivers (1 user, 1 reference which should be trusted and access protected, hopefully redundant,…) was proposed: and many other anti-spoofing process have been proposed, from machine learning to multi-antenna receiver against GPS spoofer.





Antenna diversity geometry for a single satellite and point transmitter

Since some years, UAV navigation system and navigation and timing systems in critical infrastructure must be certified “spoof-resistant”, and institutions (see university of Texas) propose Spoofing test battery, to be executed for receiver certification. For example, tests performed by Spectracom on three different GPS chip receivers against spoofing attack , on spoofing impact on time and position, show that these receivers can be spoofed up to 500ns in time, 600m in position after half a minute or 1 minute spoofing. Department of Homeland Security, in the US, is now asking GPS receivers used in critical infrastructure to be harden

Even if HW and SW integrity check have improved security, and despite the wide usage of GNSS, it is now obvious that infrastructure and public use of timing signals require an additional time dissemination signal to provide counter measure to GNSS signals and secure time reading.

Candidates for being wide scale GNSS back up must provide -legal-UTC driven accurate signal (less than 100 ns to fit all Telecom and infrastructure requirements) and might be RF or microwave (eLoran, Long range wave -DCF-,..) of fiber based (PTP White Rabbit).

2.3 Wired communication and time transfer protocols

Various configuration over existing networks or available fibers have been made. There are two main categories, those using SDH networks (time stamp of special event in SDH frame) or those using IP-based protocols .

2.3.1 Sub µs time transfer protocol over fiber

Various attempts have been done on how to use available fibers. Single optical wavelength or multiple wavelengths have been tested. SDH configured fiber or Amplitude modulation on dark fiber was also tested by various authors.

The time transfer concept relays on:

- Definition of "TIC" - Time Interval Counter (time stamp event)
- The propagation media
- The network support
- The overall stability of the transfer media (temperature, …)

Three major attempts have been made to deploy synchronization techniques:

1. One supported by a Swedish Group (Prof. Hedevkvist): their latest technology uses the existing frame header A1 A2 A3 existing in SONET and SDH frame, as the TIC signal on 10 Gbits Ethernet link [Ebenhag2011].
2. One supported by a Polish group, uses a dedicated modulation on a dark channel or a dark fiber [Sliwczynsk2013].
3. One supported by a team from Czech Republic (Prof Smotlacha), is using a very simple modulation on dark channel [Smotlacha2012].

On the first technique [Ebenhag2011], taking note that the A1 A2 A3 header (STM 64 frame header) are the same in SDH and SONET frame, one "time stamp" the crossing A1 A2 on both direction on long distance network, one have to take into account the constrain on symmetric amplification on optical fiber, typically every 100 km on optical fiber and also the constrain of time bridge of every router. Dual way symmetric amplification at layer 0 of OSI signal structure is a common item in many fiber-based synchronization schemes.

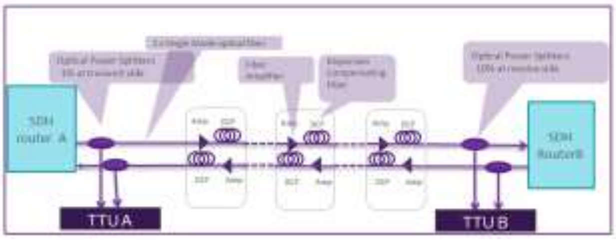


Figure 9: Time transfer over SDH network: line amplification and TTU Time Tansfer Unit interfaces

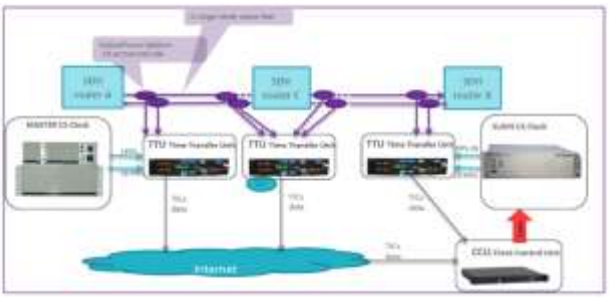


Figure 10:Time transfer over SDH equipped fiber: showing TTU bridging over SDH routers

Time transfer method using passive listening and detection of SDH frame headers in fiber-optical networks [Ebenhag2011] has been tested at USNO, through a basic test set up:

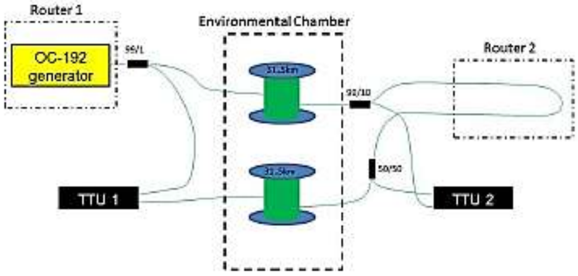


Figure 11:Experimental set up for evaluation of time transfer over SDH fiber

At the first router, a splitter provided a 1% tap to the transmit port of the first TTU box. The return signal from the second router went directly to the receive port of the first TTU box. At the second router, a 10% splitter provided the signal to the receive port of the second TTU box. When an A1A2 recognition pulse was generated, the time difference between it and the 1PPS from the local oscillator was recorded. A stability analysis of the phase data shows that the Allan deviation integrates down as 5e-10/τ.

The results of the baseline test of the TTU boxes. The blue data corresponds to the round trip delay in a controlled environment. The red data, offset by 5 ns, is the post-processed data. Despite some spikes which must be resolved, ***a 5 ns level performance of the TTU is shown.***

Influence of fiber network (temperature impact on fiber, TTU to be implemented to bridge on every IP router, are not considered in this measurement which aims to qualify the TTU unit by itself.

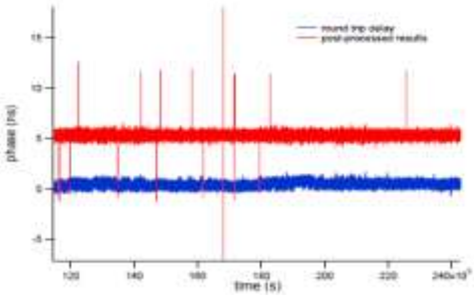


Figure 12: comparison time transfer raw data and post-processed data (offset 5 ns for clarity)

The advantages of this technology are the use of passive "un-occupied" SDH channel. The Time Transfer Unit (TTU) hardware is rather simple. The most critical point will remain the temperature effect on fiber (velocity, amplitude, noise).

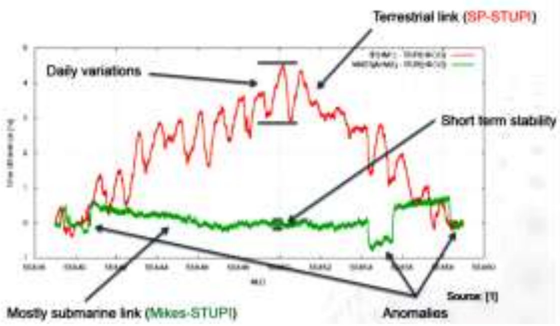


Figure 13: Time transfer over SDH fibers – Comparison between undersea fiber (green) and terrestrial fiber (red). Air fiber exhibits day/night temperature effect on propagation

In conclusion, this technique may provide

- a time transfer accuracy of ***~5 ns over a “on air fiber” over 500 km***,
- a time transfer accuracy close to ***1 ns when using undersea fiber between the same cities*** (benefit from thermal stabilization of the link)

On the second experiment [Sliwczynsk2013], stabilization of propagation delay through a round trip analysis and by the use of delay line on both directions to adjust propagation delay is implemented, as well as bidirectional symmetric fiber optic amplifiers. The basis is an amplitude modulation on dark fiber /channel, and the time stamp event «TIC» is the 10 MHz phase at pps crossing.

It requires active stabilization of propagation delay (round trip) and specific bisectional fiber optic amplifiers :

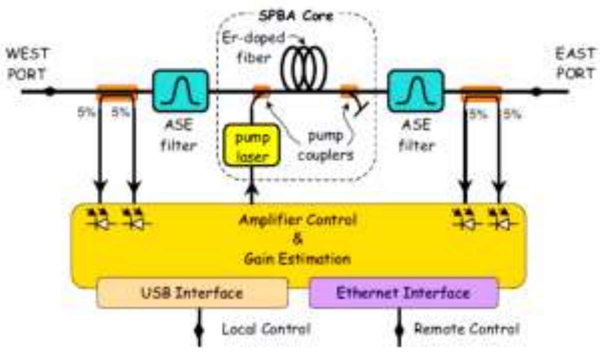


Figure 14: *single path bidirectional optical line amplifier [Sliwzczynski2012]*

The drawing of time transfer interface configuration is shown below without optical amplifier. It can be used this way on short distance (less than 70 km) without optical amplifiers.

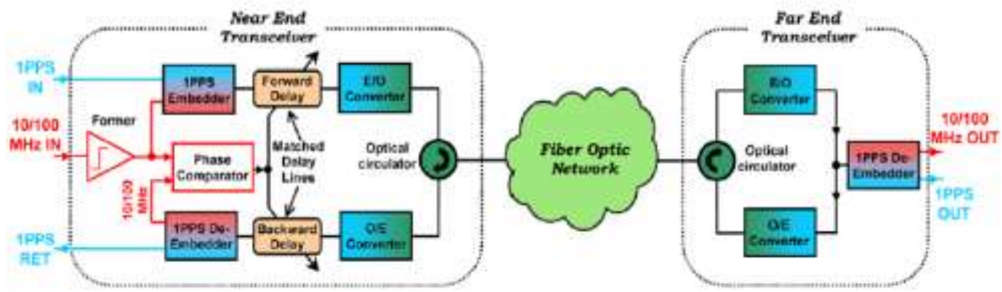


Figure 15:round trip delay stabilization, showing the two optical links and the SAW delay line used to electronically adjust propagation delay between forward and reverse link

This technique shows time deviation *as low as 1 ps over 70 km distance* and provide delay instability for 480 km long link with optical fibers spooled in the laboratory of some 10’s of ns.

Finally, on the third experiment [Smotlacha2012], amplitude modulation on a dark channel of a DWDM network is used to transfer timing information. The team has tested their technology on medium range distance (200 km), and they report performances in the range of ***some tens of ns***. Advantage is a low cost interface for amplitude modulation, drawback is the renting cost of dark channel.

One advantage of these technologies is to re-use existing fiber network, even SDH configured, the Drawback is the need of optical amplifiers (that will be the case for all optical biber-based system) and the need of dedicated high cost interfaces in/out

2.3.2 High performance frequency and time transfer over fiber

In order to cover the global requirement of the project, one must be able to offer a "GNSS independent" time reference, down to the end user. This time reference must be accurate, secure, manageable…

There is actually huge demand of high accuracy time transfer with sub-µs capability, but there are only few technologies available. We have reviewed here some of these.

There are mainly two areas in clock and clock comparison over fiber:

- One is developed for scientific purpose (high performance frequency -stability- comparison between T&F institutes)
- One deal with commercial application of time dissemination, targeting µs and ns time dissemination resolution, mainly for operation of critical infrastructure

Time and frequency laboratories are working on Frequency comparison, accuracy and stability, between primary clocks (optical sources), un-transportable. Most actives institutions are PTB (Germany), METAS (Switzerland), Syrte (France), NPL (UK), INRIM (Italy), NIST (US), MNI (Australia), NIM (China), etc…

There is a strong competition between these laboratories to demonstrate the "best" atomic oscillator and the best clock…, and they need to establish tools and processes to compare such accurate frequencies and clocks.

These laboratories are mainly involved in the definition of very high performance Atomic oscillators (Cesium Fountain, optical lattice clocks (Sr or others..) , trapped Ions (Al, Yt,..) , Cold atoms clocks, ..) to contribute to a significant improvement in their clock accuracies, and then a more precise and accurate definition of the local time (UTC(k)), and finally to get a significant improvement in the definition of UTC. For such applications, there are some techniques being developed, on a point to point basis, to be able to perform frequency stability comparison down to the 10^{-16} / 10^{-18}.

In order to take benefit of such "scientific oscillators", laboratories must be able to compare frequency and time. The most commonly used tool is "Two way Satellite Time and Frequency transfer" (TWSTFT), which resolution can be as low as 1ns, even 100 ps under proper conditions. Geostationary satellites or GPS "common view" are used to perform such comparisons.

Such configuration requires highly sophisticated end-to-end equipment, and has high costs (requires access to a satellite channel). Despite its high accuracy, such technique is restricted to special case of primary clock comparison, to build the coordinate time scale UTC.

Time & Frequency primary laboratories are also working on high resolution time and frequency transfer over optical fiber. PTB (Germany) Syrte/laboratoire physique des laser (France), Utinam/Femto-ST (France), are developing techniques "over fiber" to transfer frequency stability over long distances. See the European project called "Refimeve+" targeting the deployment of a fiber based frequency stability comparison tool between many European countries.

The project Refimeve+ is led by Laboratoire de Physique des Lasers (CNRS/ Université Paris Nord). REFIMEVE+ – REseau FIbré MEtrologique à Vocation Européenne+ – is based on the technology developed by LPL and SYRTE for the ultra-stable frequency transfer over long- haul fibers on a public network. It was experimentally demonstrated on a span from Villetaneuse (close to Paris) to Reims that the clock signal can be transmitted, throughout the ***Internet academic network RENATER*** over 540km, with an «reproducing» frequency accuracy of **$2x10^{-19}$** after one day of measurement.

This result paves the way to clocks comparison at a continental scale, with clocks which accuracy is as low as a few 10^{-16} and will reach in a near future 10^{-17}. This is an alternative tool to GPS that is now a limitation factor for the remote comparison between ultra-stable modern clocks. The project aims at broadcasting the clock signal to 21 Labs located all over France, making a wide usage of the optical link technique, and thanks to partnership with RENATER and private companies, Muquans, Syrlinks, ..

REFIMEVE+ is part of the international JRP NEAT FT project which aim is to interconnect though optical fibers, T&F laboratories in France, Germany, UK, Italy, Finland, Sweden, Czech Republic…

2.3.3 NTP : Network Time protocol operation

NTP was originally introduced by university of Delaware in the late 70's, to provide time to computer networks. It is a master-slave process, based on a software time stamp, in band client-server. It is internationally normalized under RFC 1305 (version 3) and RFC 5905 (version 4 under discussion).

Different variant have been introduced (client/server, active/passive, unicast/multicast, broadcast,..) static / dynamic addresses, to allow multicast and link multiple servers to multiple clients. NTP security is acknowledged as being too poor, and NTP protocol allows wide corruption schemes. NTP servers are regularly used to reflect and amplify spoofed UDP packets towards the target of DDoS attacks. Security being an issue, NTPs was introduced, mainly in the banking system , to reinforce security.. Security is not yet satisfactory, and accuracy is still not compliant to critical infrastructure requirements. Public keying cryptography is applied to improve security, such as MD5 encrypted keys

- ***Accuracy of NTP is typically ms level sur la couche internet, et 0.2 ms en réseau local***
- By using hardware time stamp in master and slave, ***some NTP protocol can reach 0.1 ms range of accuracy***

Originally deployed in computer network and industrial applications, NTP was also used in 2G base station wireless telecom network, mainly on Ericson 2G BS (Base Station). The idea was to use ***ms*** time resolution to tune the carrier frequency at BS. The frequency requirement at BS in 2G network was +/- 5.10^{-8}.

The first part of Eq [1] shows that a $1{\cdot}10^{-8}$ frequency offset brings 1 ***ms*** offset after one day. By synchronizing within 1 ms on a regular basis, using a properly working NTP link, it is possible to steer the BS frequency within the 10^{-8} range. Such technique is not any more usable in 3G / 4G / LTE, because of the time requirement for LTE services (1.5 μs for standard features, 1 μs for MBMS (Multimedia Multicast Broadcast Services) and/or LTE TDD technologies (~ 1 μs), and now less than 1 μs in last issue LTE and 5G or for wireless aggregation.

2.3.4 PTP : Precision Time Protocol

PTP protocols are IP based, widely used in Telecom (Mobile base station synchronization), in smart Grid (PMUs timing reference),. It is a client/server technology, known as IEEE 1588 [Weibel2006], and internationally acknowledged as a power tool to spread some μs accuracy among local access networks, such as metro network of 3G, 4G and LTE base stations. Experimentally, PTP over telecom networks suffers from traffic asymmetry variation, destroying the symmetrical assumption of time of flight (eq [2]). SyncE was introduced to support better PTP efficiency by taking care of syntonisation.

PTP Time transfer protocol operates between a Grand master and a slave, connected through the IP network. It is based on a two way time transfer, time stamping time of departure and time of arrival in both time scale to determine time of flight and time offset between both master and slave time scale.

Like any two way time transfer protocol, PTP is a master-slave concept described on the following picture.

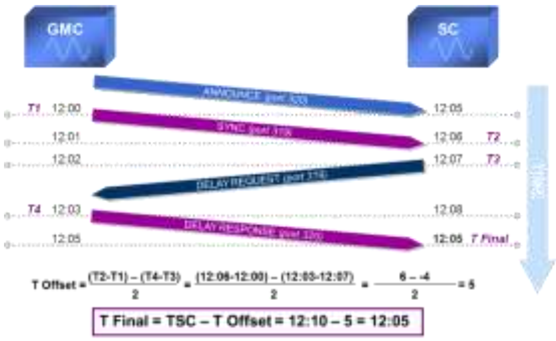


Figure 16: PTP time transfer protocol between grandmaster and slave clocks

The key advantage versus NTP is the "physical time stamp", embarked in the PTP frame when the PTP message crosses the lowest OSI level, when entering the physical media. That eliminates most of the internal processing delay contribution in the time stamp process.

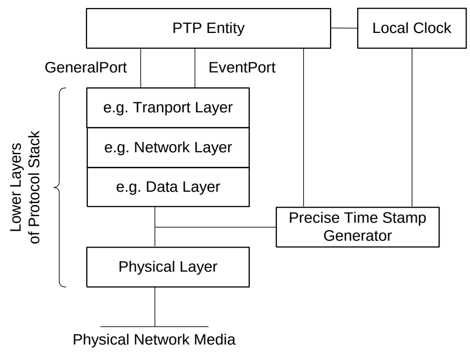
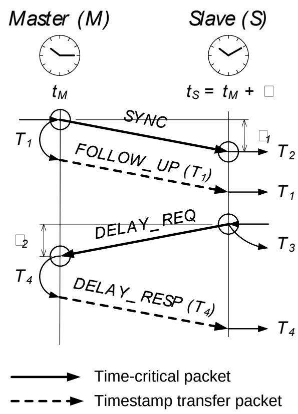


Figure 17:PTP layered architectur

The PTP working scheme is



Assuming uplink and downlink are symmetrical, on have T2 - T1 = T4 – T3

Time offset between slave and master is

$$\bar{q} = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

and the operation will implies :

- Multiple offset q(t) leads to frequency offset and drift
- Once q and q(t) estimated, one can adjust local time offset
- PDV : packet delay deviation
- **Statistics over Lucky packet**
    - Minimum delays
    - Statistics over “minimum delay population”
    - Wander resistant

Synchronous Ethernet provide synchronization operates through the following scheme:

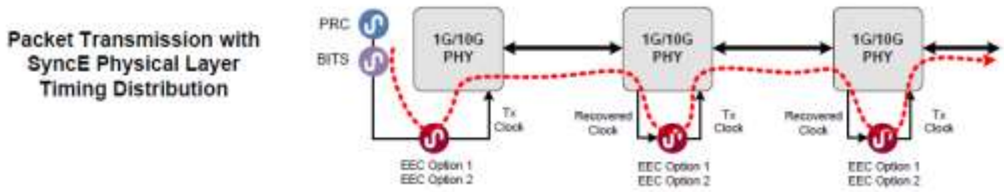


Figure 18: Synchronous Ethernet M/S operation

- SyncE master / SyncE slave (clock recovery)
- Syntonization on the lowest layer (independent of the network load)
- PLL active even without data (Idle pattern forms 125MHz square signal)
- No time or phase synchronization
- Synchronous Ethernet allows to “syntonize” Network Element in daisy chain >> all NE must be SyncE compliant

PTP for wireless network requires PTP transparent router

- Transparent or boundary clocks in network
- Highly sensitive of numbers of hop / «delays»
- Highly sensitive to trafic asymetry variation
- **>> PTP over SyncE networks reduce these traffic generated limits**

PTP WHITE RABBIT requires PTP compliant network and dual way syntonisation, allowing the use of D.DMTD to fine tune the timming transfer accuracy between master and slave.

PTP over wireline or wireless networks requires security and PTP-SyncE compliant nodes, to provide accuracy and security to non telecom users (smart grid, infrastructure, etc…)
Questions remain of potential behavior in real world, including long distance fiber, and yet to identify constraints on the fiber and the fiber interfaces. Special attentions are driven by fiber optic behavior (amplitude attenuation, requiring regularly spaced proper amplification, temperature stability and temperature impact compensation in optical fiber, etc…).

PTP packets are exchanged between Master and Slave. Various approaches have been deployed to select the so called “lucky packet”, i.e. the fastest packet travelling. The target is to remove data traffic contribution to take into account only the network delay contribution. The fastest packets are supposed to travel without congestion or delay due to data traffic. Those fastest packets are supposed to represent the “close to minimum” limit of time of flight, issued only by network. Delay asymmetry and delay asymmetry variation are “poison” to PTP process.

Dialog between Master and Slaves, is limited by the data rate and the number of slaves to be addressed from the master, then the number of slaves supported by a single Gran master takes into account the number of request, speed of data transfer (8-16-32 or 64 kbit/s).

High-end Gran Master can support up to 1000 slaves @ 128 messages/s, the carrier media can be an electrical interface (100 Mbits/s, 1Gbits/s) or an optical (1/10 GBits/s). Network variant use “sync Ethernet” technology, meaning that network is physically “frequency syntonised” which improves PTP time transfer.

Regarding network constraint when planning PTP deployment, one must pay attention that “tracking all and any” unexpected delays, drives the need of “PTP transparent” router and switches. Most of the last Cisco router generations are PTP compliant. PTP can be deployed on Telecom network, assuming that traffic load remain below certain limit of capacity occupation, to avoid additional delays. PTP , as any IP based message, suffers from delay in network propagation (PDV), affecting its intrincic performance. Telecom deployed PTP and SyncE, SyncE taking care of the master/slave syntonisation, PTP being used only for timing.

- ***PTP time transfer, mainly on SyncE infrastructure, can reach 1 μs***

2.3.5 Telecom applications of NTP and PTP

As Time Division Multiplexing (TDM) lines are replaced at cell sites, alternative modes of delivering synchronization are required. The focus has shifted to packet based sync distribution technologies such as precision timing protocol (PTP) and network timing protocol (NTP).

Synchronous Ethernet (SyncE) is also a rapidly emerging technology that can frequency lock an Ethernet network just like a SONET/SDH network. SyncE will allow an IP network to be “syntonised”, drastically improving the stability of the PTP “synchronization” process applied through such network.

As mobile networks increasingly deploy PTP as the network transitions to Ethernet, PTP is rapidly becoming the industry’s technology of choice for synchronization transfer supporting both frequency and phase required for LTE deployments.

2.3.6 WHITE RABBIT

The **White Rabbit** is protocol based operating on low layers of the OSI map (Gigabit Ethernet over fiber) using deterministic IEEE 1588 protocol, SyncE (layer 1 syntonization) and phase interpolation using D.DMTD, Digital Dual Mixer Time Difference. Optical links are managed, in terms of wavelength and clink calibration. White Rabbit is a concept developed by CERN people. More details on technology, HW and SW may be find on CERN White Rabbit web page.

The white rabbit precision time protocol is described by the following design sheme:

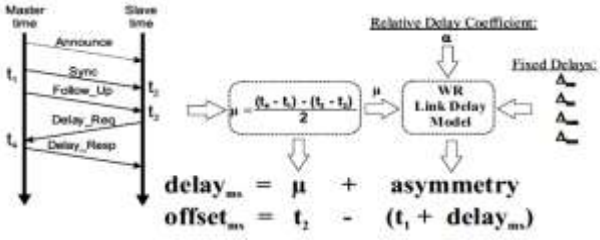
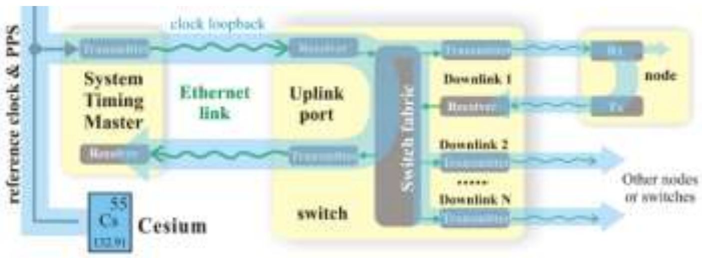
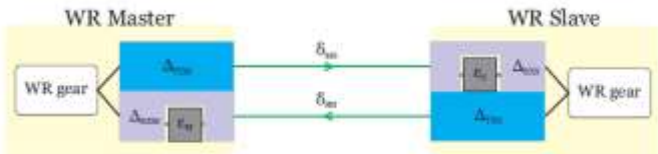


Figure 19:white rabbit precision time protocol extension.

Thanks to SyncE, all WR receivers use the same physical layer clock, digital clock is embedded in Ethernet carrier, and phase detection allows sub ns delay.



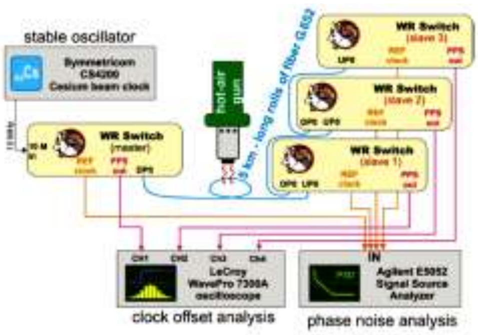
Link must be accurately modeled, and calibration properly performed to identify the link model values Δ_{TXM} Δ_{RXM} Δ_{TXS} Δ_{RXS} and α.



Introducing physical delays observed on fibers, usually not taken into account in classical PTP, and using SyncE as a common physical layer clock, providing phase measurement to improve PTP capability (namely by proper asymmetry identification).

White Rabbit is described as the best accurate implementation of PTP worldwide, and WR is proposed as part of the evolution towards PTPv3 "high accuracy" profile.

Through the test set up shown here,



CERN team was able to perform high accuracy time transfer measurement as shown in that demonstrates a ***sub ns capability within an isolated network***.

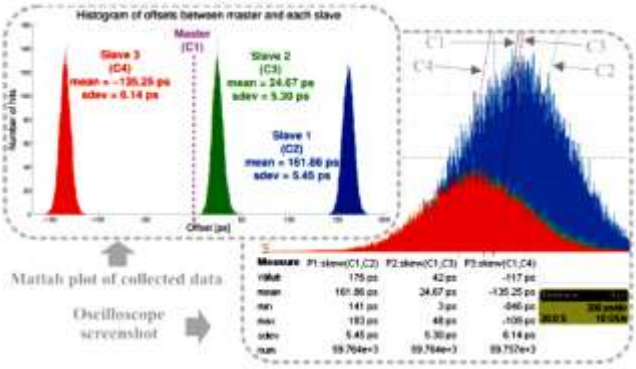


Figure 20: White Rabbit time transfer performance over three hops

White Rabbit is now entering the industrial world. There are now some manufacturers of Gran Master PTP-WR, slaves-WR, and dual way symmetric optical amplifiers requested every 100's km over fiber www.OPNT.nl, . Deployment and calibration processes are now well mastered It has been approved by Vodafone to address issue if synchronization of RAN Radio Access Network (TALGRASS-OPNT) , for frequency aggregation , it has been proven over long distances (MIKES) and proven for metrology application. Number of projects in various time and frequency application are currently underwork.

CONCLUSION

Telecom networks are demanding highly accurate timing, evolving from 1.5 ms for the current LTE requirements down to +/- 65 ot +/- 130 ns for 5G or aggregation radio access network (see time requirements in fixline and mobile telecom networks) . New requirements in transportation , energy distribution (see page Renewable energy and smart Grid) and the requested accuracy and security in critical infrastructure synchronization, are all raising demands on accuracy and security:

The actual solutions are

- **GPS receivers**: accurate to 100ns, known to be vulnerable. high performance 'flywheel' oscillator provides short-term stability and holdover (moving outside 100ns level)
- **IEEE 1588-2008** (IEEE 1588v2 or PTPv2): accurate to 1000 ns, sensitive to network traffic, cumulative jitter / nb Hops; SyncE requested - fails to address new requirements
- **Assisted Partial Timing Support -APTS (GPS/PTPv2/SyncE)**: autocontrol, removes the full on-path PTP requirement, combine good and bad, GPS receivers vulnerable
- **PTP-WHITE RABBIT,** providing sun ns accuracy on multiple fiber configuration (free channel, alien wavelength on operating network, management channel).

On security, it is widely acknowledged that GNSS vulnerabilities are a main concern. Software and hardware GNSS improvements , such as beam forming antennas, use of local high performance clocks (CSAC or equivalent), ephemerid simulation, software analysis and path mitigation, spoofing and jamming detection, signal analysis, …., are improving security, without providing a total guarantee of signal integrity. Spoofer and jammer are more and more elaborated and efficient, and many infrastructure cannot relay only on GNSS, even a so-called secured one. General IP based cyber security, with classical attack such MiM, man in the middle, and others, are a main concern in connected infrastructure.

Banking systems are also highly demanding, either on accuracy (sub micro second) or on security. There again, GNSS based solution cannot be accepted as a sole source.

In this paper, we have reviewed many and main technologies to perform time transfer and synchronize distant clocks, within sun microsecond accuracy, to fit the most important commercial application requirements, and able to provide the requested security.

GNSS based system are widely used, and despite their vulnerabilities, the question is not to put all gnss receivers in the bin.. The question is tom provide alternative timing sources, able to support dense networks such as telecom, smart grid PMUs time reference, banking and infrastructure, to provide a counter measure to GNSS and an GNSS-independent jamming or spoofing tracker. Imagine someone have a GNSS and a fiber-based timing sources. If both agrees, within network limit, life is good.. If they both disagree, one may have a tool to analyze the situation, first raising an alarm. At the end of the day, fiber based will be easiest to check, and probably the link to select.

On my opinion, PTP-White Rabbit is the sole and most promising technique, once properly deployed in secure network, to synchronize distant clocks and infrastructure networks.

Tribute of this section to N Dimarq, E Rubiola, P Defraigne, A.Bauch, A.Michaud, CERN team an many others…