SYNCHRONIZATION OF COMPUTERS

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ABSTRACT

In complex systems where processes are controlled with the aid of computers (communications, power industry, transportation, etc.), it is often needed to refer events to one coordinated time scale or at least to time scales which are not divergent. To ensure this, the computers must be synchronized, preferably to the Universal Coordinated Time (UTC), or at least syntonized. This paper presents model equations for syntonization and synchronization of clocks along with measures that allow assessing the synchronization quality (stability and accuracy). Also the difference between clock synchronization and computer synchronization is discussed. The final part of the paper is dedicated to the performance of three UTC dissemination systems which are appropriate for computer synchronization (GPS, long-wave transmissions, and telephone).

INTRODUCTION

Out of all physical magnitudes it is the time which can be measured most accurately and, in addition, which can be easily disseminated. Thus apparently any system based on time and/or frequency measurements can be made very accurate. Time allows to execute commands at proper moments and to assess simultaneity of events. Time gives the events the date. We can consider time a perfect organizer because it allows by means of computers to coordinate the system and, consequently, to make it more effective.

If actions within the system are to be coordinated, the clocks providing time for the computers must be synchronized. The synchronization is based on the time transfer from a master clock to one or more slave clocks. Conceptually it is not important whether the clocks are built in the computers or if they are operating outside the computers. We will introduce the basic concept of clock synchronization and point out the difference between the clock synchronization and computer synchronization.

Suitable measures must be used which would allow to specify requirements on the synchronization and to assess whether these requirements have been fulfilled. We will mention two measures appropriate for this purpose: stability and accuracy.

It is advantageous to synchronize the computer clocks to the Universal Coordinated Time (UTC) [1] because UTC has been adopted as a reference time by many systems and so being synchronized to UTC means being synchronized to all of these systems. In addition, there are a number of UTC dissemination systems which can be readily used for synchronization. In the following text we will illustrate the performance of three systems which are appropriate for this purpose.

SYNCHRONIZATION OF CLOCKS

Consider a model shown in Fig.1. A master clock M is generating time T_M which is physically represented by on-time pulses with corresponding readings. The time information T_M is communicated through a time dissemination system to distant location where is recovered as time information T_M^*.

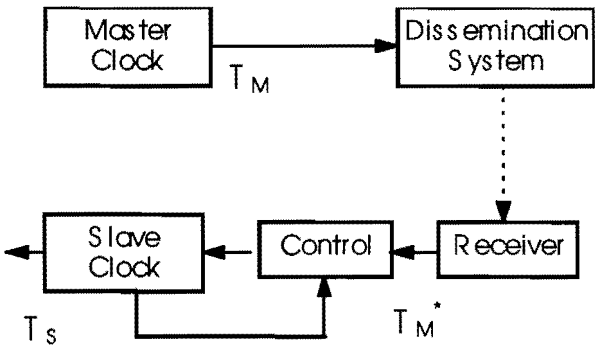

Fig.1. Synchronization of a slave clock.

We can write for the time transfer delay

$$x(t)^* = T_M(t) - T_M(t)^* = D_0 + D(t) \qquad (1)$$

where D_0 is the systematic delay and D(t) represents variations in the delay. D(t) can be assumed a stationary random process with zero mean. The time t which appears in (1) is a coordinated time. T_M^* is delayed against T_M and by convention the difference (1) takes a positive sign that is if a time interval counter is started with T_M and stopped with T_M^*, the display will show a positive number. Obviously, the delay $x(t)^*$ is not directly measurable and can be found only by means of calibration (for example by using a more accurate time transfer).

Assume a free-running slave clock S which provides an independent time scale T_S. The time deviation between the slave and master clocks can be modeled as

$$x_{M,S}(t) = T_M(t) - T_S(t) = \sum_{i=0}^{2} X_i t^i + x_n(t) \qquad (2)$$

where the sum represents systematic components, i.e. initial time deviation (i=0), time drift or frequency offset (i=1), and time acceleration or frequency drift (i=2), and $x_n(t)$ represents the differential phase noise between the clocks.

The relative frequency deviation between the clocks will be

$$y_{M,S}(t) = dx_{M,S}/dt \qquad (3)$$

To synchronize the slave clock S requires to control its frequency and/or time so as to ensure no rate between the time scales T_M and T_S. This is possible by comparing times T_S and T_M^* and by making appropriate corrections through the control system.

Define *relative synchronization* or *syntonization* as the case where

$$\langle x_{M,S}(t) \rangle = C. \qquad (4)$$

The symbol < > indicates time average over an infinite time and C is an arbitrary constant. It is apparent that to satisfy (4) the master and slave clocks must have on average the same frequency (therefore this kind of synchronization is sometimes called *syntonization*).

Define *absolute synchronization* as the case where

$$\langle x_{M,S}(t) \rangle = 0. \qquad (5)$$

Clearly, condition (5) is much stronger than (4) since it implies an accurate estimation of the transfer delay D_0.

When synchronizing an assemble of clocks $S_1, S_2 \ldots S_N$, it is of prime interest to know the differential time between these clocks which is given as

$$x_{j,k}(t) = x_{M,Sj}(t) - x_{M,Sk}(t) \qquad (6)$$

where j,k =1,2 ... N, $j \neq k$. A special case should be noted where $\langle x_{M,Sj}(t) \rangle = \langle x_{M,Sk}(t) \rangle = C$ and therefore $\langle x_{j,k}(t) \rangle = 0$, i.e. the slave clocks are absolutely synchronized with each other but only relatively synchronized with the master.

Assume further that the slave clock maintaining the time scale T_S consists of a generator producing frequency f_C, and a counter of this frequency so that the time tagging of T_S can be assured down to the $1/f_S$ level. The state of the counter is readable on fly and the on-time events are represented by changes in the state of the counter. As we have mentioned previously, it is not important whether the clock is internal or external to the computer. Consider that the computer may be operated as an active clock as depicted in Fig.2.

In the regime of active clock the computer generates pulses at the output port at assigned times according to the clock time T_S (typically, it may be required to generate 1 pps). However, the time T_S is communicated to the output port as a computer time T_C which may be well different from T_S. So we can introduce the difference

$$x_{M,C}(t) = T_M(t) - T_C(t) \qquad (7)$$

and analogously to relations (4) and (5) we can define the conditions for synchronization of computers as $\langle x_{M,C}(t) \rangle = C$ for relative synchronization and $\langle x_{M,C}(t) \rangle = 0$ for absolute synchronization. Evidently, the differential time $T_S - T_C$ is dependent on both hardware and software used in the computer to control the clock.

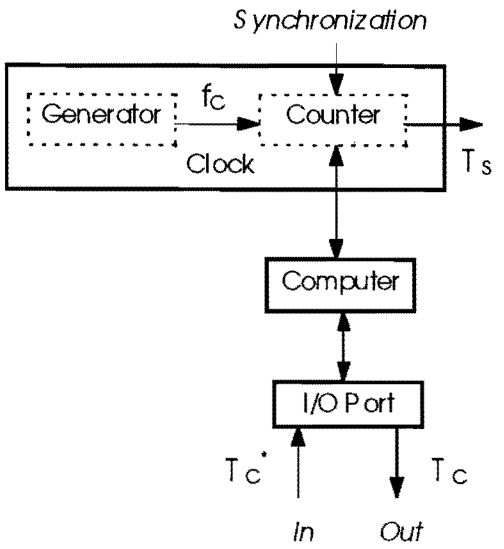

Fig.2 Computer as an active clock representing time T_C

As depicted in Fig.2, the computer is capable to assign time to outside events which are physically represented by pulses applied to the input port. However, if a pulse occurs at time T_S the computer will interpret T_S as T_C^* and T_C^* may be different from T_C.

SYNCHRONIZATION PERFORMANCE

Synchronization *stability* can be specified by the time deviation [2]

$$\mathrm{TDEV}(\tau) = \sqrt{\frac{1}{6}\left\langle\left[\Delta_2 \overline{x}_{M,S}(\tau)\right]^2\right\rangle} \qquad (8)$$

where Δ_2 is the operator of the second difference and $\overline{x}$ is the average over the interval $\tau = n\tau_0$ (n is integer and τ_0 is the basic sampling interval). The TDEV(τ) plot decays as $\tau^{-1/2}$ for white phase noise and TDEV(τ) = constant for flicker phase noise. Thus TDEV(τ) provides information not only on the magnitude of the fluctuations of x(t) but also on their character. In the case of white phase noise TDEV(τ_0) is equal to standard deviation. TDEV(Nτ_0) is the standard deviation of the mean. The larger the averaging interval τ, the longer-term variations (lower frequency components) are characterized. Synchronization stability can be measured by comparing the slave clock against a reference clock which has about the same or better stability than the master clock. One has to distinguish, however, possible perturbing variations due to frequency instability between the master and the reference clocks.

While stability characterizes the synchronization precision, we can also define the synchronization *accuracy*. That may be the deviation

$$\sigma_A(\tau) = \sqrt{\left\langle \overline{x}^2_{M,S}(\tau)\right\rangle} \qquad (9)$$

where the averaging interval τ has the same meaning as in (8). The accuracy in the above sense includes also a constant deviation which has not been corrected for. For $\tau = 0$ (i.e. with no averaging) we have $\overline{x}_{M,S}(\tau) = x_{M,S}(t)$ and $\sigma_A(\tau) = \sigma_A$ will specify the overall accuracy. With increasing the phase noise will be smoothed and $\sigma_A(\tau)$ will reflect only the long-term accuracy. Obviously, $\sigma(\tau) \rightarrow \langle x(t)\rangle$ for $\tau \rightarrow \infty$. For a noiseless process where all systematic changes have been removed, the synchronization will be ideally stable, i.e. TDEV(τ)=0, but it will be inaccurate if $x(t)=C \neq 0$, i.e. giving $\sigma(\tau)=C$. In the case of relative synchronization where C can be arbitrary, accuracy has no meaning.

The problem is that there is no direct access at the location of slave clock to the differential time $x_{M,S} = T_M - T_S$ on which the definition (9) is based. While $x_{M^*,S} = T_M^* - T_S$ can be obtained by direct measurements, the value of $x^* = T_M - T_M^*$ can only be estimated. Obviously, of great importance is the accurate calibration of x^*

PERFORMANCE OF UTC DISSEMINATION SYSTEMS

GLOBAL POSITIONING SYSTEM (GPS)

As for the accuracy the best suited means for the synchronization of clocks is a satellite-based navigation system GPS [3], [4]. The time transmitted from each GPS satellite is derived from on-board atomic clocks and is controlled from the ground so as to maintain the time difference |GPS - UTC(USNO)| < 100 ns (modulo 1 s). Considering that UTC(USNO) is kept against UTC within the limits |UTC(USNO)-UTC| < 100 ns [2], it is apparent that the synchronization accuracy of T_S - UTC via GPS can be readily achieved in the order of hundreds of nanoseconds. Since the above differences are published periodically and the changes in the differences are very slow, post-process corrections can be made to achieve the long-term synchronization accuracy of T_S - UTC bellow 100 ns. A great advantage of GPS is also its global coverage.

A factor limiting the GPS time accuracy for unauthorized users is the intentional degradation of the signal by a so called Selective Availability (SA). The effect of SA on the GPS time transmitted from individual satellites is illustrated in

Fig. 3 showing a plot of the differential time UTC(TP)-GPS[PRN(i)].

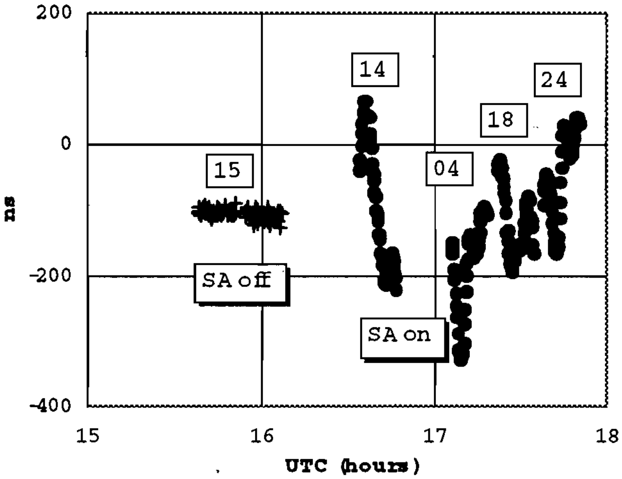

Fig.3. Plot of the differential time UTC(TP)-GPS[PRN(i)].

The symbol UTC(TP) stands for the Czech National Time Scale generated at the IREE, Prague (TP is an abbreviation of *Tempus Pragense*) and GPS[PRN(i)] denotes the GPS time provided by the satellite PRN(i). The measurement was made on MJD 50646 (MJD designates Modified Julian Date). One can clearly seen the worsening of phase variations for the satellites with SA. Each sample in Fig.3 corresponds to a quadratic fit applied to the data measured in 15 s intervals. After corrections have been made for UTC(TP)-UTC = 120 ns (corresponding to MJD 50646), the accuracy σ_A with respect to UTC with SA off (i=15) yields 15 ns while with SA (i=14, 4, 18, 24) 102 ns, 95 ns, 50 ns, and 101 ns for, respectively.

Stability of the differential time UTC(TP)-GPS in terms of TDEV(τ) calculated from 13 minute tracks performed every hour alternatively with nineteen satellites is shown in Fig.4.

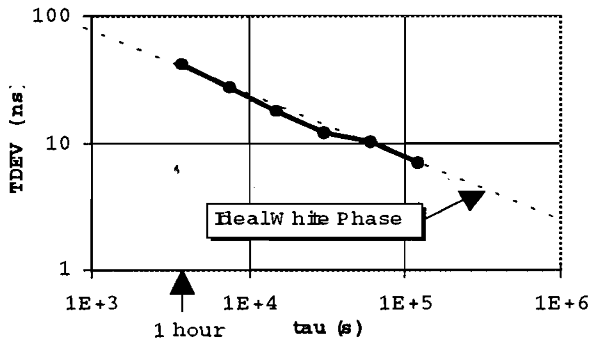

Fig.4. Stability of the differential time UTC(TP)-GPS.

All measurements were performed using an Allen Osborne TTR-6 receiver.

The highest synchronization accuracy between the clocks, i.e. according to relation (6), can be achieved by using the so called GPS common-view time transfer [5]. Using the common-view technique one may obtain $\sigma_A < 10$ ns and TDEV(τ_0 = 1 hour) < 2 ns for distances of several hundred kilometers [6]. Of course, in this case all parameters which have influence on the time transfer (position of the receiver antennas, ionosphere and troposphere refraction, receiver group delay etc.) must be known to a high degree of accuracy. The GPS common-view potentials are illustrated in Fig.5 where the difference between the Czech and Italian time scales, UTC(TP)-UTC(IEN), is plotted for one-week period.

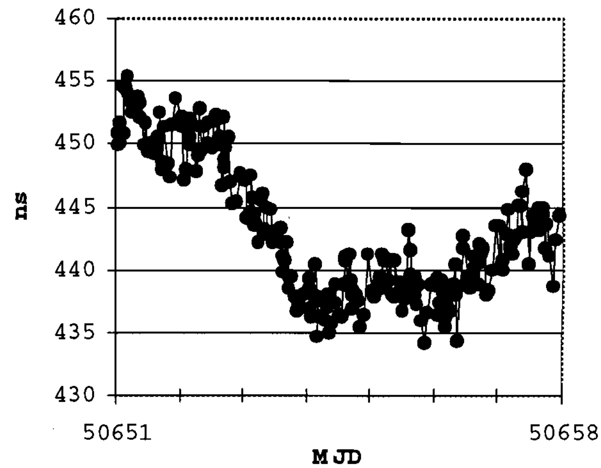

Fig.5. GPS common-view record of UTC(TP)-UTC(IEN).

The value of TDEV(τ_0=1 hour) gives 1.3 ns for the measured interval. The distance between the Czech and Italian laboratories is 768 km. The slow variations are due to frequency instability between the free-running clocks of TP and IEN, and the time drift is caused by the systematic relative frequency offset of about 2 parts in 10^{14}

The above common-view time transfer is primarily used to compare the time (and/or frequency) of high-quality atomic clocks.

Long-wave transmissions (LWT)

Long-wave transmissions such as DCF 77.5 kHz [7] in Europe or WWVB 60 kHz [8] in the U.S. are appropriate for computer synchronization where accuracy of units of milliseconds is needed. Unlike the GPS, the LWT signal coverage is only territorial which, in practice, represents several thousand kilometers from the transmitter depending on the radiated power. The advantage of LWT over GPS is that the antenna may be placed inside the buildings and the receiver is much simpler and therefore cheaper than that of GPS.

The LWT carrier can be used for the relative synchronization (usually a local quartz oscillator is phase-locked to the carrier) while the time marks along with the time code can be used for the absolute synchronization. The variations in the carrier phase depend on the distance from the transmitter, local receiving conditions, and receiver performance. If the signal is not contaminated with a man-made noise, the variations are mainly due to atmospheric noise and the interference between the ground and sky waves. Since the ionosphere moves up with darkness and down with sunlight, the phase of the sky wave is retarded or advanced, respectively. The sky-wave effect increases with the distance from the transmitter. Peak-to-peak variations may reach tens of microseconds at distances of several thousands of kilometers.

The performance of the LWT in distances of several hundred kilometers is illustrated in Fig.6,7 and 8. The results of measurements are shown performed with the DCF77 signal at the IREE, Prague, situated 360 km far from the transmitter (Mainflingen, Germany). The DCF signal field strength at IREE is about 2 mV/m. The receiver used a bandwidth of about 400 Hz and was equipped with a non-coherent automatic gain control.

Fig.6 is a three-day plot of the differential time UTC(TP) - DCF where hourly samples represent one-shot measurements of the carrier zero crossings. The standard deviation gives typically 80 ns during the daytime and about 700 ns at night.

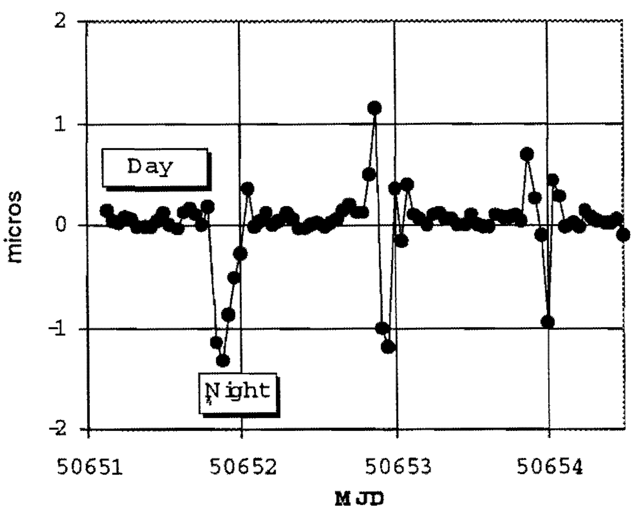

Fig.6. Plot of the differential time UTC(TP)-DCF(Carrier).

Fig.7 shows a two-day plot of the residual differential time UTC(TP)-DCF(Second Marks). Each hourly sample represents a one-shot measurement of the midpoint of the second-mark leading edge. Accuracy calculated from the data in Fig.7 gives $\sigma_A = 50\,\mu$ s (D_o = 2.5 ms has been corrected for).

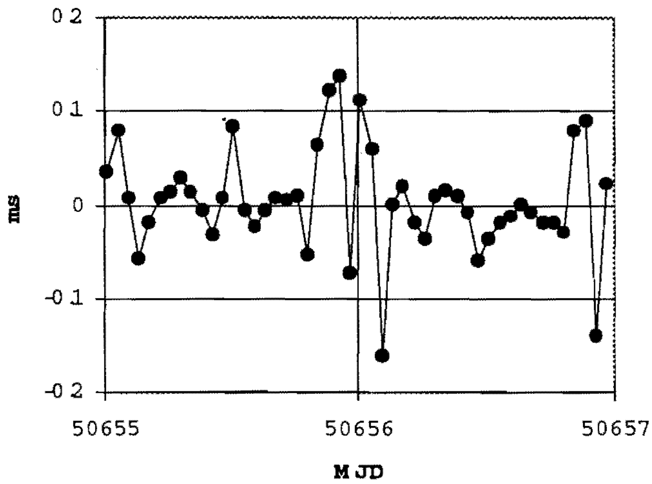

Fig.7. Record of UTC(TP)-DCF(Second Marks).

Fig.8 illustrates the short-term stability in terms of TDEV(τ) of the DCF carrier and the DCF second marks, respectively, as measured against UTC(TP). The values of TDEV for the basic sampling interval τ_o=1s yield 39 ns for the carrier and 26 μs for the second marks. The dashed lines correspond to the ideal white phase noise.

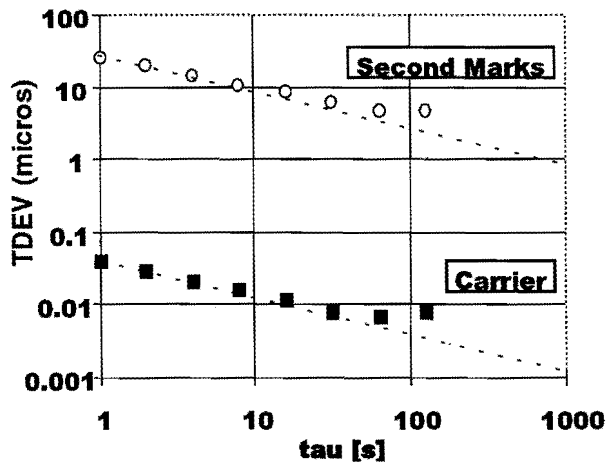

Fig.8. Short-term stability of the DCF signal (carrier and second marks) in terms of TDEV.

Telephone

In several countries [9], [10], [11], a system of time transfer via the telephone lines has been established which enables the user to synchronize his computer to UTC. The time information is generated in a coder located at the country's time center so the on-time marks (characters) at the transmitting site correspond to UTC. The coded signal is transmitted over the telephone line through a standard modem and the same way can be received at the user's site. Thus with the aid of suitable software any clock controlled by the computer can be set to UTC.

The time information transmitted is very rich. The so called „European Code" contains information on year, month, day, hour, minute, second, local-time identification, day-of-weak, weak-of-year, day-of-year, date and time of the next change to and from daylight savings time, UTC (year, month, day, hour, minute), Modified Julian Date (MJD), DUT1 difference, and announcement of leap second.

A simple one-way time transfer, where the on-time marks go only from the time center to the user, provides an accuracy of about 70 ms [10]. The two-way transfer, in which the on-time marks are echoed back to the time center and there the delay in the path can be corrected for, provides an accuracy typically better than 10 ms. Accuracy reaching even 1 ms has been reported in [12]. Measurements of the phase stability of the signal transmitted via a telephone modem have been published in [10] giving TDEV = 3 ms for τ_0 = 0.5 hour. The noise present in the differential time shows a character of white phase noise for averaging intervals up to one-day.

Conclusions

Synchronization of computers is needed in the systems where the computers controlling them should refer events to the same time scale or, at least, to the time scales that have no mutual drift. The time scales are provided by local clocks which are controlled through the computers so to synchronize computers means to synchronize these clocks. Obviously it depends upon the concrete realization of the computer control over the clock (both hardware and software), to what extent the accuracy of clock synchronization is transferred to the accuracy of computer synchronization.

We have mentioned three UTC dissemination systems which are appropriate for the synchronization of computer-controlled clocks. The most accurate is GPS which, in addition, provides global coverage. The receiving conditions are dependent only on adequate antenna placing. Using GPS is very straightforward and, in addition, today market offers a number of GPS driven clocks which can be connected to computers. One can expect that the cost of the GPS clocks will further decrease.

In some regions also LWT can be alternatively used. LWT advantage over GPS is a cheaper clock and the fact that the antenna can be placed inside the buildings. The disadvantage is that the synchronization quality depends upon local receiving conditions which are worse in large distances from the transmitter.

Regarding the telephone, the apparent disadvantage is the need to dial the telephone number to get connected with the source of time information. Thus if the slave clock is not stable enough, too frequent telephone calls may be needed.. So one should use the telephone synchronization in applications where an accuracy on the order of hundreds of milliseconds is required.

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