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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 synchronized. The synchronization is based on transfer from a master clock to one or more slave clocks. Conceptually it is not important whether the clock is in the computers or if they are operating outside them. 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 requirements on the synchronization and to assess whether requirements have been fulfilled. We will mention the most appropriate for this purpose: stability and accuracy.

It is advantageous to synchronize the computer clocks with the Universal Coordinated Time (UTC) [1] because UTC has been adopted as a reference time by many systems and synchronizing to UTC means being synchronized to UTC 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 UTC systems which are appropriate for this purpose.

SYNCHRONIZATION OF CLOCKS

Consider a model shown in Fig.1. A master generating time $T_M$ which is physically represented on-time pulses with corresponding reading $T_M$. The slave clock receives the pulses and, after a delay $T_{D}$ the time $T_{S}$ is given. The difference $T_{S} - T_{M}$ is the time error of the slave clock. The synchronization of the slave clock requires the error signal $T_{E}$ which is calculated as

$$T_{E} = T_{M} - T_{S} = T_{M} - (T_{M} + T_{D}) = -T_{D}$$

The delay $T_{D}$ can be determined by measuring the time difference between the pulses at the master and slave clocks. The synchronization is achieved by adjusting the slave clock so that $T_{E}$ is zero.

$$T_{S} = T_{M} + T_{D} = T_{M}$$

The accuracy of the synchronization depends on the accuracy of the delay measurement $T_{D}$. The delay can be measured using a variety of methods, such as delay lines, electronic circuits, or software algorithms. The accuracy of the delay measurement determines the accuracy of the synchronization.
Fig. 1. Synchronization of a slave clock.

We can write for the time transfer delay

\[ x(t)^* = T_M(t) - T_M(t)^* = D_0 + D(t) \]  

(1)

where \( D_0 \) is the systematic delay and \( D(t) \) represents variations in the delay. \( D(t) \) can be assumed as 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

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

(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

\[ y_{M,S}(t) = dx_{M,S}/dt \]  

(3)

To synchronize the slave clock \( S \) requires to control its frequency with

\[ x_M(t) = T_M(t) - T_S(t) \]  

(4)

and analogously to relations (3) and (4)

\[ x_{M,S}(t) = \langle x_{M,S}(t) \rangle = C. \]

The symbol < > indicates time average over a finite period and \( C \) is an arbitrary constant. It is apparent that the master and slave clocks must have an average frequency (therefore this kind of synchronization is called syntonization).

Define absolute synchronization as the case

\[ \langle x_{M,S}(t) \rangle = 0. \]

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

When synchronizing an assembly of clocks of prime interest to know the differential time between clocks which is given as

\[ x_{j,k}(t) = x_{M,S_j}(t) - x_{M,S_k}(t) \]  

(6)

where \( j,k = 1,2 \ldots N, j \neq k \). A special case should be noted where \( \langle x_{M,S_j}(t) \rangle = \langle x_{M,S_k}(t) \rangle = C \) 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 clock.

Assume further that the slave clock maintains its scale \( T_s \) consists of a generator producing frequency \( f_s \) and a counter of this frequency so that the time tag can be assured down to the \( 1/f_s \) level. The state of the scale is readable on fly and the on-time events are relative changes in the state of the counter. As we have seen previously, it is not important whether the clock is internal or external to the computer. Consider that the counter may be operated as an active clock as depicted in Fig 1.

In the regime of active clock the computer generates at the output port at assigned times according to the time \( T_s \) (typically, it may be required to generate shorter times). However, the time \( T_s \) is communicated to the output computer time \( T_C \) which may be well different. We can introduce the difference

\[ x_{M,C}(t) = T_M(t) - T_C(t) \]  

(7)
Synchronization Performance

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

\[ \text{TDEV}(\tau) = \sqrt{\frac{1}{6} \left( \Delta_2 x_{M,S}(\tau) \right)^2} \]  (8)

where \( \Delta_2 \) is the operator of the second difference and \( x \) is the average over the interval \( \tau = n \tau_o \) (n is integer and \( \tau_o \) is the basic sampling interval). The TDEV(\( \tau \)) plot decays as \( \tau^{-12} \) for white phase noise and \( \text{TDEV}(\tau) \) = constant for flicker phase noise. Thus TDEV(\( \tau \)) 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 \( \text{TDEV}(\tau) \) is equal to standard deviation. \( \text{TDEV}(N \tau_o) \) is the standard deviation of the mean. The larger the averaging interval \( \tau \), the longer-term variations (lower frequency components) are characterized. Synchronization stability can be measured by comparing the precision, we can also define the synchronization deviation

\[ \sigma(\tau) = \sqrt{\left( x_{M,S}(\tau) - x_{M}(\tau) \right)^2} \]  (9)

where the averaging interval \( \tau \) has the same meaning as in (8). The accuracy in the above sense includes also the deviation which has not been corrected for. For \( \tau \rightarrow \infty \) (with no averaging) we have \( x_{M,S}(\tau) = x_{M}(\tau) \) and \( \sigma(\tau) \) will specify the overall accuracy. With increasing noise level, the noise will be smoothed and \( \sigma(\tau) \) will reflect only the short-term accuracy. Obviously, \( \sigma(\tau) \rightarrow \infty(t) \) for \( \tau \rightarrow 0 \), giving \( \sigma(\tau) = 0 \). In the case of relative synchronization, \( \sigma(\tau) = 0 \) can be arbitrary, accuracy has no meaning.

The problem is that there is no direct access at the level 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 only be estimated. Obviously, of great importance is the accurate calibration of \( x \).

Performance of UTC Dissemination

Global Positioning System (GPS)

As for the accuracy the best suited means for synchronization of clocks is a satellite-based system GPS [3], [4]. The time transmitted from a satellite is derived from on-board atomic clocks and controlled from the ground so as to maintain the primary difference \( |\text{GPS} - \text{UTC(USNO)}| < 100 \text{ ns} \) (mean). Considering that UTC(USNO) is kept against the international time scale (ITM) the limits \( |\text{UTC(USNO)} - \text{UTC}| < 100 \text{ ns} \) [2], it follows that the synchronization accuracy of \( T_s \), the GPS time, can be readily achieved in the order of the number of nanoseconds. Since the above differences are published periodically, very small changes in the differences are very slow, possible small corrections can be made to achieve the synchronization accuracy of \( T_s - \text{UTC} \) bellow \( 100 \text{ ns} \) (max.).
Fig. 3 showing a plot of the differential time UTC(TP)-GPS[PRN(i)].

All measurements were performed using an AIT TTR-6 receiver.

The highest synchronization accuracy between clocks, i.e. according to relation (6), can be achieved by using the so called GPS common-view time (CVT). Using the common-view technique one can achieve $\sigma_A < 10$ ns and $\text{TDEV}(\tau_\text{o}=1 \text{ hour}) < 2 \text{ ns}$ for several hundred kilometers [6]. Of course, in all cases parameters which have influence on the time (position of the receiver antennas, ionosphere, troposphere refraction, receiver group delay) are well 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(IEN), is plotted for one-week period.

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 Pragensis) 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 see 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 $\sigma_A$ 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($\tau$) calculated from 13 minute tracks performed every hour alternatively with nineteen satellites is shown in Fig.4.

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

The value of TDEV($\tau_\text{o}=1 \text{ hour}$) gives 1 ns measured interval. The distance between the Czech and Italian laboratories is 768 km. The slow variations and instability between the free-running Czech and Italian laboratories are very well known, and the time drift is caused by the systematic 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-precision clocks.

LONG-WAVE TRANSMISSIONS (IWT)
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.7 shows a two-day plot of the residual difference UTC(TP) - DCF(Second Marks). Each hourly sample is a one-shot measurement of the midpoint of the sky- and leading edge. Accuracy calculated from the data is

\[ \sigma_A = 50 \mu s \] (\( D_o = 2.5 \) ms has been corrected for).

![Fig.7. Record of UTC(TP)-DCF(Second Marks)](image)

Fig.8 illustrates the short-term stability in TDEV(\( \tau \)) of the DCF carrier and the DCF second marks, as measured against UTC(TP). The TDEV for the basic sampling interval \( \tau_0 = 1 \) s yields 18 ns for the carrier and 26 \( \mu s \) for the second marks. These correspond to the ideal white phase noise.
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-week, week-of-year, day-of-year, date and time of the next change to and from daylight savings time, UTC (year, hour, minute), Modified Julian Date (MJD), DUT and announcement of leap second.

A simple one-way time transfer, where the only way to go only from the time center to the user, provides delays of about 70 ms [10]. The two-way transfer, in which time marks are echoed back to the time center and delay in the path can be corrected for, provides typically better than 10 ms. Accuracy reaching even been published in [12]. Measurements of the phase of the signal transmitted via a telephone modem published in [10] giving TDEV = 3 ms for τ₀. The noise present in the differential time shows a long term of white phase noise for averaging intervals up to

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 clocks which can be connected to computers. One can be sure that the cost of the GPS clocks will further decrease.

In some regions also LWT can be alternative. LWT advantage over GPS is a cheaper clock and the fact that the antenna can be placed inside the building. Disadvantage is that the synchronization quality is dependent upon local receiving conditions which are worst distances from the transmitter.

Regarding the telephone, the apparent disadvantage is the need to dial the telephone number to get connected. Source of time information. Thus if the slave clock is not enough, too frequent telephone calls may be needed. If you should use the telephone synchronization in any application an accuracy on the order of hundreds of milliseconds
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