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SERIES G: TRANSMISSION SYSTEMS AND MEDIA

Digital transmission systems – Digital networks – Design objectives for digital networks

Definitions and terminology for synchronization networks

ITU-T Recommendation G.810

(Previously CCITT Recommendation)

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
INTERNATIONAL ANALOGUE CARRIER SYSTEM	
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA CHARACTERISTICS	
DIGITAL TRANSMISSION SYSTEMS	
TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
General aspects	G.800–G.809
Design objectives for digital networks	**G.810–G.819**
Quality and availability targets	G.820–G.829
Network capabilities and functions	G.830–G.839
SDH network characteristics	G.840–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999

For further details, please refer to ITU-T List of Recommendations.

ITU-T RECOMMENDATION G.810

DEFINITIONS AND TERMINOLOGY FOR SYNCHRONIZATION NETWORKS

Summary

This Recommendation provides definitions and abbreviations used in timing and synchronization Recommendations.

Source

ITU-T Recommendation G.810 was revised by ITU-T Study Group 13 (1993-1996) and was approved under the WTSC Resolution No. 1 procedure on the 27th of August 1996.

Keywords

Clock Performance, Jitter Performance, SDH, Synchronization network, Wander Performance.

FOREWORD

ITU (International Telecommunication Union) is the United Nations Specialized Agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of the ITU. The ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Conference (WTSC), which meets every four years, establishes the topics for study by the ITU-T Study Groups which, in their turn, produce Recommendations on these topics.

The approval of Recommendations by the Members of the ITU-T is covered by the procedure laid down in WTSC Resolution No. 1 (Helsinki, March 1-12, 1993).

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

CONTENTS

Recommendation G.810

DEFINITIONS AND TERMINOLOGY FOR SYNCHRONIZATION NETWORKS

(Melbourne, 1980; revised in 1996)

1 Scope

This Recommendation provides definitions and abbreviations used in timing and synchronization Recommendations. It also provides background information on the need to limit phase variation and the impairments on digital systems.

2 References

The following Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. All Recommendations are subject to revision; all users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published.

[1] ITU-T Recommendation G.707 (1996), *Network node interface for the Synchronous Digital Hierarchy (SDH).*

[2] CCITT Recommendation G.811 (1988), *Timing requirements at the outputs of primary reference clocks suitable for plesiochronous operation of international digital links*.

[3] CCITT Recommendation G.812 (1988), *Timing requirements at the outputs of slave clocks suitable for plesiochronous operation of international digital links*.

[4] ITU-T Recommendation G.813 (1996), *Timing characteristics for SDH equipment slave clocks (SEC).*

[5] CCITT Recommendation G.822 (1988), *Controlled slip rate objectives on an international digital connection*.

[6] ITU-T Recommendation G.823 (1993), *The control of jitter and wander within digital networks which are based on the 2048 kbit/s hierarchy*.

[7] ITU-T Recommendation G.824 (1993), *The control of jitter and wander within digital networks which are based on the 1544 kbit/s hierarchy*.

[8] ITU-T Recommendation G.825 (1993), *The control of jitter and wander within digital networks which are based on the Synchronous Digital Hierarchy (SDH).*

3 Abbreviations

For the purposes of timing and synchronization Recommendations, the following abbreviations apply:

ADEV Allan Deviation

AIS Alarm Indication Signal

AP Access Point

CUT Clock Under Test

FFM Flicker Frequency Modulation

FPM Flicker Phase Modulation

MC	Master Clock
MDEV	Modified Allan Deviation
MRTIE	Maximum Relative Time Interval Error
MST	Multiplex Section Terminal
MTIE	Maximum Time Interval Error
NE	Network Element
PDH	Plesiochronous Digital Hierarchy
PRC	Primary Reference Clock
PSTN	Public Switched Telephone Network
RWFM	Random Walk Frequency Modulation
SASE	Stand Alone Synchronization Equipment
SC	Slave Clock
SDH	Synchronous Digital Hierarchy
SE	Synchronization Element
SEC	SDH Equipment Clock
SETS	SDH Equipment Timing Source
STM	Synchronous Transport Module
SSU	Synchronization Supply Unit
TDEV	Time Deviation
TIE	Time Interval Error
TIErms	root mean square Time Interval Error
TVAR	Time Variance
UI	Unit Interval
UIp-p	Unit Interval peak-to-peak
UTC	Coordinated Universal Time
WFM	White Frequency Modulation
WPM	White Phase Modulation

4 Definitions

For the purposes of timing and synchronization Recommendations, the following definitions apply.

4.1 General definitions

4.1.1 alignment jitter: The short-term variations between the optimum sampling instants of a digital signal and sampling clock derived from it.

4.1.2 bilateral: A synchronization link where the corrective action to maintain locking is active at both ends of the link.

4.1.3 frequency departure: An underlying offset in the long-term frequency of a timing signal from its ideal frequency.

4.1.4 network synchronization: A generic concept that depicts the way of distributing a common time and/or frequency to all elements in a network.

4.1.5 single ended synchronization: A method of synchronizing a specified synchronization node with respect to another synchronization node, in which synchronization information at the specified node is derived from the phase difference between the local clock and the incoming digital signal from the other node.

4.1.6 synchronization chain: An active interconnection of synchronization nodes and links.

4.1.7 synchronization reference chain: A specific synchronization chain to form the basis for simulations of jitter and wander in the synchronization network.

4.1.8 slip: The repetition or deletion of a block of bits in a synchronous or plesiochronous bit stream due to a discrepancy in the read and write rates at a buffer.

4.1.9 standard frequency: A frequency with a known relationship to a frequency standard.

4.1.10 time: Time is used to specify an instant (time of the day) or as a measure of time interval.

NOTE – The words time or timing, when used to describe synchronization networks, usually refer to the frequency signals used for synchronization or measurement.

4.1.11 time scale: A system of unambiguous ordering of events.

NOTE – This could be a succession of equal time intervals, with accurate references of the limits of these time intervals, which follow each other without any interruption since a well-defined origin. A time scale allows to date any event. For example, calendars are time scales. A frequency signal is not a time scale (every period is not marked and dated). For this reason "UTC frequency" must be used instead of "UTC".

4.1.12 (timing) jitter: The short-term variations of the significant instants of a timing signal from their ideal positions in time (where short-term implies that these variations are of frequency greater than or equal to 10 Hz).

4.1.13 unilateral: A synchronization link where the corrective action to maintain locking is only active at one end of the link.

4.1.14 UTC: The time scale, maintained by the *Bureau International des Poids et Mesures (BIPM*) and the International Earth Rotation Service (IERS), which forms the basis of a coordinated dissemination of standard frequencies and time signal.

NOTE – The reference frequency for network synchronization is the frequency which generates the UTC time scale. It is therefore preferable to use the words "UTC frequency" instead of "UTC".

4.1.15 wander: The long-term variations of the significant instants of a digital signal from their ideal position in time (where long-term implies that these variations are of frequency less than 10 Hz).

NOTE – For the purposes of this Recommendation and related Recommendations, this definition does not include wander caused by frequency offsets and drifts.

4.2 Definitions related to clock equipments

4.2.1 clock: An equipment that provides a timing signal.

NOTE – The word "clock" generally means, when used for synchronization networks, the generator of the frequencies which will be used to synchronize the network.

4.2.2 frequency standard: A generator, the output of which is used as a frequency reference.

4.2.3 master clock: A generator which generates an accurate frequency signal for the control of other generators.

4.2.4 node clock: A clock distributing synchronization to one or more synchronized equipment.

4.2.5 primary reference clock (PRC): A reference frequency standard that provides a reference frequency signal compliant with Recommendation G.811.

4.2.6 slave clock: A clock whose timing output is phase-locked to a reference timing signal received from a higher quality clock.

4.2.7 stand alone synchronization equipment (SASE): The stand alone implementation of the logical SSU function, which incorporates its own management function.

4.2.8 synchronization supply unit (SSU): A logical function for frequency reference selection, processing and distribution, having the frequency characteristics given in Recommendation G.812.

4.3 Definitions related to synchronization networks

4.3.1 asynchronous mode: A mode where clocks are intended to operate in free running mode.

4.3.2 local node: A synchronous network node which interfaces directly with customer equipment.

4.3.3 master slave mode: A mode where a designated master clock is used as a frequency standard which is disseminated to all other clocks which are slaved to the master clock.

4.3.4 mutually synchronized mode: A mode where all clocks exert a degree of control on each other.

4.3.5 plesiochronous mode: A mode where the essential characteristic of time scales or signals such that their corresponding significant instants occur at nominally the same rate, any variation in rate being constrained within specified limits.

4.3.6 pseudo-synchronous mode: A mode where all clocks have a long-term frequency accuracy compliant with a primary reference clock as specified in Recommendation G.811 under normal operating conditions. Not all clocks in the network will have timing traceable to the same PRC.

4.3.7 synchronization element: A clock providing timing services to connected network elements. This would include clocks conforming to Recommendations G.811, G.812 and G.813.

4.3.8 synchronization link: A link between two synchronization nodes over which synchronization is transmitted.

4.3.9 synchronous network: A network where all clocks have the same long-term accuracy under normal operating conditions.

4.3.10 synchronization network: A network to provide reference timing signals. In general, the structure of a synchronization network comprises synchronization network nodes connected by synchronization links.

4.3.11 synchronization network node: A group of equipment in a single physical location which is directly timed by a node clock.

NOTE – A physical location may contain more than one synchronization network node.

4.3.12 synchronization sink: The destination of timing in a synchronization trail.

4.3.13 synchronization source: The source of timing in a synchronization trail.

4.3.14 synchronization traceability: A series of synchronization elements and synchronization trails, normally within a single SDH or PDH equipment domain.

4.3.15 synchronization trail: The complete connectivity between synchronization element and a network element, or between two synchronization elements.

4.3.16 transit node: A synchronous network node which interfaces with other nodes and does not directly interface with customer equipment.

4.4 Definitions related to clock modes of operation (applicable to slave clocks)

4.4.1 free running mode: An operating condition of a clock, the output signal of which is strongly influenced by the oscillating element and not controlled by servo phase-locking techniques. In this mode the clock has never had a network reference input, or the clock has lost external reference and has no access to stored data, that could be acquired from a previously connected external reference. Free-run begins when the clock output no longer reflects the influence of a connected external reference, or transition from it. Free-run terminates when the clock output has achieved lock to an external reference.

4.4.2 holdover mode: An operating condition of a clock which has lost its controlling reference input and is using stored data, acquired while in locked operation, to control its output. The stored data are used to control phase and frequency variations, allowing the locked condition to be reproduced within specifications. Holdover begins when the clock output no longer reflects the influence of a connected external reference, or transition from it. Holdover terminates when the output of the clock reverts to locked mode condition.

4.4.3 ideal operation: This category of operation reflects the performance of a clock under conditions in which there are no impairments on the input reference timing signal.

4.4.4 locked mode: An operating condition of a slave clock in which the output signal is controlled by an external input reference such that the clock's output signal has the same long-term average frequency as the input reference, and the time error function between output and input is bounded. Locked mode is the expected mode of operation of a slave clock.

4.4.5 stressed operation: This category of operation reflects the actual performance of a clock considering the impact of real operating (stressed) conditions. Stressed conditions include the effects of jitter, protection switching activity and the loss of the input reference timing signal.

4.5 Definitions related to clock characterization

4.5.1 ageing: The systematic change in frequency of an oscillator with time.

NOTE – It is the frequency drift when factors external to the oscillator (environment, power supply, temperature, etc.) are kept constant. An ageing value should always be specified together with the corresponding duration.

4.5.2 fractional frequency deviation: The difference between the actual frequency of a signal and a specified nominal frequency, divided by the nominal frequency. Mathematically, the fractional frequency deviation $y(t)$ can be expressed as:

$$y(t) = \frac{\nu(t) - \nu_{\text{nom}}}{\nu_{\text{nom}}}$$

4.5.3 frequency accuracy: The maximum magnitude of the fractional frequency deviation for a specified time period.

NOTE – The frequency accuracy includes the initial frequency offset and any ageing and environmental effect.

4.5.4 frequency drift: The rate of change of the fractional frequency deviation from a specified nominal value, caused by ageing and external effects (radiation, pressure, temperature, humidity, power supply, load, etc.).

NOTES

1 The external factors should always be clearly indicated.

2 The frequency drift includes not only the linear frequency drift rate but also any other higher order frequency drift.

4.5.5 frequency stability: The spontaneous and/or environmentally caused frequency change within a given time interval.

NOTE – It is generally distinguished between systematic effects such as frequency drift effects (caused by radiations, pressure, temperature, humidity, power supply, charge, ageing, etc.) and stochastic frequency fluctuations which are typically characterized in time domain (special variances have been developed for the characterization of these fluctuations, such as Allan variance, modified Allan variance and Time variance) and/or frequency domain (one-sided spectral densities).

4.5.6 hold-in range: The largest offset between a slave clock's reference frequency and a specified nominal frequency, within which the slave clock maintains lock as the frequency varies arbitrarily slowly over the frequency range.

4.5.7 pull-in range: The largest offset between a slave clock's reference frequency and a specified nominal frequency, within which the slave clock will achieve locked mode.

4.5.8 pull-out range: The offset between a slave clock's reference frequency and a specified nominal frequency, within which the slave clock stays in the locked mode and outside of which the slave clock cannot maintain locked mode, irrespective of the rate of the frequency change.

4.5.9 timing signal: A nominally periodic signal, generated by a clock, used to control the timing of operations in digital equipments and networks. Due to unavoidable disturbances, such as oscillator phase fluctuations, actual timing signals are pseudo-periodic ones, i.e. time intervals between successive equal phase instants show slight variations. Mathematically a timing signal $s(t)$ is represented by:

$$s(t) = A \cdot \sin\left[\Phi(t)\right]$$

where:

A is a constant amplitude coefficient, and

$\Phi(t)$ is the total instantaneous phase (modelled as reported in Appendix I).

4.5.10 reference timing signal: A timing signal of specified performance that can be used as a timing source for a slave clock.

4.5.11 measurement reference timing signal: A timing signal of specified performance used as a time base for clock characterization measurements. The basic assumption is that its performance must be significantly better than the clock under test with respect to the parameter being tested, in order to prevent the test results being compromised. The performance parameters of the frequency standard must be stated with all test results.

4.5.12 time function: The time of a clock is the measure of ideal time t as provided by that clock. Mathematically the Time function $\mathrm{T}(t)$ generated by a clock is defined as:

$$\mathrm{T}(t) = \frac{\Phi(t)}{2\pi\nu_{\mathrm{nom}}}$$

where:

$\Phi(t)$ is the total instantaneous phase of the timing signal at the clock output; and

ν_{nom} is the nominal frequency of the clock.

4.5.13 time error function: The time error of a clock, with respect to a frequency standard, is the difference between the time of that clock and the frequency standard one. Mathematically, the Time Error function $x(t)$ between a clock generating time $\mathrm{T}(t)$ and a reference clock generating time $\mathrm{T}_{\mathrm{ref}}(t)$ is defined as:

$$x(t) = \mathrm{T}(t) - \mathrm{T}_{\mathrm{ref}}(t)$$

At a purely abstract level of definition, the frequency standard can be thought of as ideal (i.e. $\mathrm{T}_{\mathrm{ref}}(t) = t$ can be assumed); since ideal time is not available for measurement purposes, ideal time error is of no practical interest.

Time error is the basic function whereby many different stability parameters (such as MTIE, TIErms, Allan variance, etc.) can be calculated: since continuous knowledge of the function $x(t)$ is not practically attainable, sequences of equally spaced samples $x_i = x(t_0 + i\tau_0)$ are used for this purpose.

Based on a suitable model of timing signals, a corresponding time error model can be derived, as reported in Appendix I.

4.5.14 time interval error function: The difference between the measure of a time interval as provided by a clock and the measure of that same time interval as provided by a reference clock. Mathematically, the Time Interval Error function $\mathrm{TIE}(t;\tau)$ can be expressed as:

$$\mathrm{TIE}(t;\tau) = [\mathrm{T}(t+\tau) - \mathrm{T}(t)] - [\mathrm{T}_{\mathrm{ref}}(t+\tau) - \mathrm{T}_{\mathrm{ref}}(t)] = x(t+\tau) - x(t)\,,$$

where τ is the time interval, usually called *observation interval*.

4.5.15 maximum time interval error (MTIE): The maximum peak-to-peak delay variation of a given timing signal with respect to an ideal timing signal within an observation time ($\tau = n\tau_0$) for all observation times of that length within the measurement period (T). It is estimated using the following formula:

$$\mathrm{MTIE}(n\tau_0) \cong \max_{1 \le k \le N-n} \left[\max_{k \le i \le k+n} x_i - \min_{k \le i \le k+n} x_i \right], \qquad n = 1,2,\ldots, N-1$$

4.5.16 maximum relative time interval error (MRTIE): The maximum peak-to-peak delay variation of an output timing signal with respect to a given input timing signal within an observation time ($\tau = n\tau_0$) for all observation times of that length within the measurement period (T).

4.5.17 time deviation (TDEV or σ_x): A measure of the expected time variation of a signal as a function of integration time. TDEV can also provide information about the spectral content of the phase (or time) noise of a signal. TDEV is in units of time. Based on the sequence of time error samples, TDEV is estimated using the following calculation:

$$\mathrm{TDEV}(n\tau_0) \cong \sqrt{\frac{1}{6n^2(N-3n+1)} \sum_{j=1}^{N-3n+1} \left[\sum_{i=j}^{n+j-1} \left(x_{i+2n} - 2x_{i+n} + x_i \right) \right]^2}\,, \qquad n = 1, 2, \ldots, \text{integer part} \left(\frac{N}{3} \right)$$

where:

x_i are time error samples;

N is the total number of samples;

τ_0 is the time error sampling interval;

τ is the integration time, the independent variable of TDEV;

n is the number of sampling intervals within the integration time τ.

Thus the integration time τ equals $n\tau_0$. Appendix II gives technical information on the TDEV parameter.

NOTE – In some cases systematic effects such as phase or frequency quantization steps can mask noise components. See also the pros and cons subclause II.3.

4.5.18 time variance (TVAR or σ_x^2): The square of the time deviation.

4.5.19 phase transient: Perturbations in phase of limited duration.

4.6 SDH specific definitions

4.6.1 SDH equipment clock (SEC): The logical function representing the equipment clock of a SDH network element having the timing characteristics given in Recommendation G.813.

4.6.2 SDH equipment timing source (SETS): The logical function representing all synchronization related functions to be considered in an SDH network element.

4.6.3 synchronization node: A synchronization node consists of an SSU and all co-located SECs directly synchronized from that SSU.

4.6.4 synchronization status message: A coding of the reference level of the timing source as specified in Recommendation G.707.

5 Description of phase variation components

Phase variation is commonly separated into three components: jitter, wander and effects of frequency offsets and drifts. In addition, phase discontinuities due to transient disturbances such as network re-routing, automatic protection switching, etc., may also be a source of phase variation.

6 Impairments caused by phase variation

6.1 Types of impairments

6.1.1 Errors

Errors may occur at points of signal regeneration as a result of timing signals being displaced from their optimum positions in time.

6.1.2 Degradation of digitally encoded analogue information

Degradation of digitally encoded analogue information may occur as a result of phase variation of the reconstructed samples in the digital to analogue conversion device at the end of the connection. This may have significant impact on digitally encoded video signals.

6.1.3 Slips

Slips arise as a result of the inability of an equipment buffer store (and/or other mechanisms) to accommodate differences between the phases and/or frequencies of the incoming and outgoing signals in cases where the timing of the outgoing signal is not derived from that of the incoming signal. Slips may be controlled or uncontrolled depending on the slip control strategy.

6.2 Control of impairments

6.2.1 Errors

The intent of both network and equipment jitter specifications is to ensure that jitter has no impact on the error performance of the network.

6.2.2 Degradation of digitally encoded analogue signals

The intent of jitter specifications is to provide sufficient information to enable equipment designers to accommodate the expected levels of phase variation without incurring unacceptable degradations.

6.2.3 Slips

Slips may occur in asynchronous multiplexes and various synchronous equipments. Given the specified levels of phase variation, slip occurrences may be minimised in asynchronous muldexes by appropriate choice of justification and muldex buffer capacity within. For synchronous equipments, slip occurrences may be minimised by appropriate choice of buffer capacity as well as rigorous specification of clock performance.

It should be noted that it is impossible to eliminate slips when there is a frequency difference between the incoming and outgoing timing signals. Controlled slip performance objectives for an international connection are given in Recommendation G.822.

Various forms of aligning equipment may be used to minimise the impact of slips. The following two forms of aligning equipment are suitable for the termination of digital signals:

– frame aligner;
– time slot aligner.

6.2.3.1 Frame aligner

Where a frame aligner is used, a slip will consist of the insertion or removal of a consecutive set of digits amounting to a frame. In the case of frame structures defined in Recommendation G.704 the slip can consist of one complete frame. It is of importance that the maximum and mean delays introduced by the frame aligner should be as small as possible in order to minimize delay. It is also of importance that, after the frame aligner has produced a slip, it should be capable of absorbing substantial further changes in the arrival time of the frame alignment signals before a further slip is necessary.

6.2.3.2 Time slot aligner

Where a slot aligner is used, a slip will consist of the insertion or removal of eight consecutive digit positions of a channel time slot in one or more 64 kbit/s channel. Because slips may occur on different channels at different times, special control arrangements will be necessary in switches if octet sequence integrity of multiple time slot services is to be maintained.

7 Purpose of phase variation specifications

7.1 Jitter

Network node interface jitter requirements given in Recommendations G.823, G.824 and G.825 fall into two basic categories:

– specification of the maximum permissible jitter at the output of hierarchical interfaces;
– sinusoidal jitter stress test specifications to ensure the input ports can accommodate expected levels of network jitter.

Additional jitter requirements for individual equipments may be found in the appropriate equipment Recommendations.

7.2 Wander

Relevant wander requirements fall into the following categories:

i) maximum permissible wander at the output of synchronization network nodes;

ii) stress tests to ensure that synchronous equipment input ports can accommodate expected levels of network wander;

iii) wander specifications for primary reference and slave clocks may include:

   a) intrinsic output wander under locked conditions;

   b) intrinsic output wander under free-running conditions;

   c) output wander under stress test conditions;

   d) wander transfer characteristic.

The existing requirements for the primary and slave clocks are given in Recommendations G.811, G.812 and G.813.

The purpose of these Recommendations is not only to provide limits for the allowance wander accumulation along the transmission paths but also for the wander accumulation along the synchronization distribution paths arising from cascaded clocks.

8 Structure of synchronization networks

8.1 Synchronization modes

International networks usually work in the plesiochronous mode one with another.

The synchronization of national networks may be of the following types:

– fully synchronized, controlled by one or several primary reference clocks;

– fully plesiochronous;

– mixed, in which synchronized sub-networks are controlled by one or several primary reference clocks functioning plesiochronously one with another.

8.2 Synchronization networks

There are two fundamental methods of synchronizing nodal clocks:

– master-slave synchronization;

– mutual synchronization.

The master-slave synchronization system has a single primary reference clock to which all other clocks are phase-locked. Synchronization is achieved by conveying the timing signal from one clock to the next clock. Hierarchies of clocks can be established with some clocks being slaved from higher order clocks and in turn acting as master clocks for lower order clocks.

In a mutual synchronization system, all clocks are interconnected; there is no underlying hierarchical structure or unique primary reference clock.

Some practical synchronization strategies combine master-slave and mutual synchronization techniques.

9 Measurement configurations

When measuring the performance of clocks, the measurement configuration will influence the test results. Consequently all synchronization and timing Recommendations should specify one of the following measurement configurations.

9.1 Synchronized clock measurement configuration

When the two timing signals involved in the measurement of time error are traceable to a common master clock, the measurement configuration is referred to as synchronized clock configuration. Two cases of practical interest where this configuration applies are shown in Figure 1. The time error measured in synchronized clock configuration is unaffected by frequency offset and drift of the common master clock, as shown in Appendix I. Stability parameters calculated from such time error values reflect only internal phase noise of clocks involved in the measurement.

9.2 Independent clock measurement configuration

Any situation where there is no common master clock controlling the timing signals between which the time error is measured is referred to as independent clock configuration. Examples where this configuration applies are shown in Figure 2. The time error measured in independent clock configuration, besides being dependent on internal clock noises, is affected by any frequency offset or frequency drift of the clocks involved in the measurement.

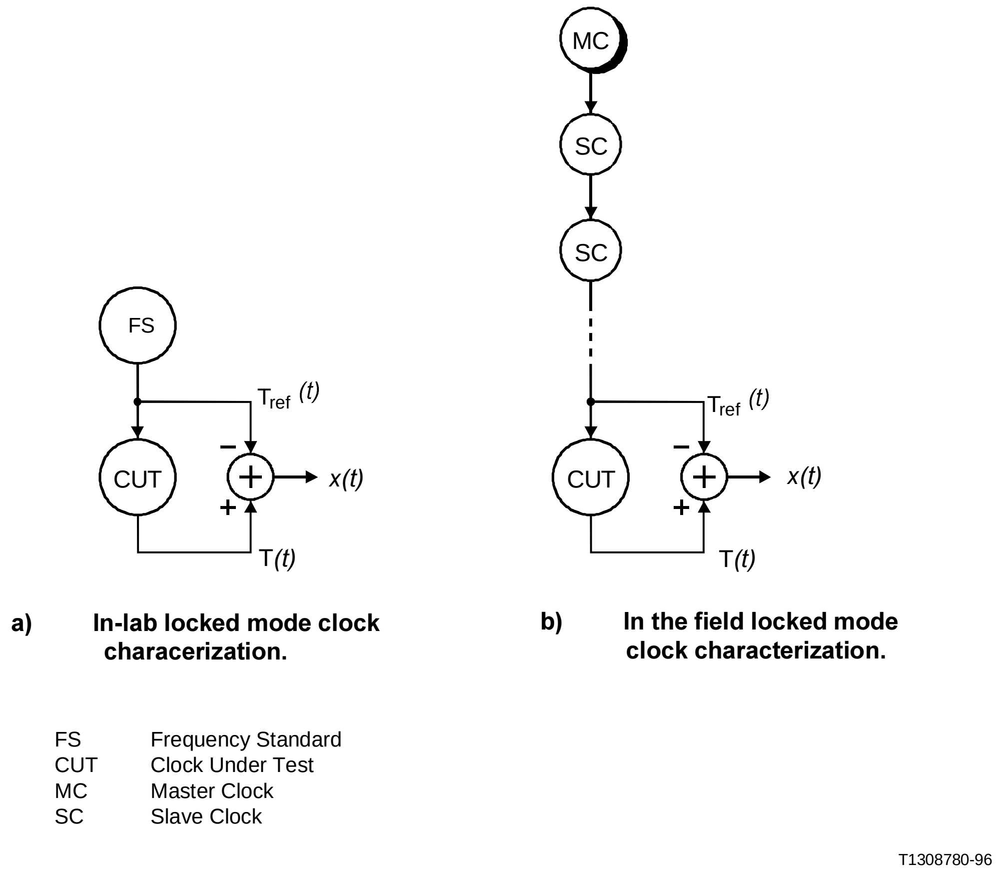


FIGURE 1/G.810

Examples of time error measurement in synchronized clock configuration

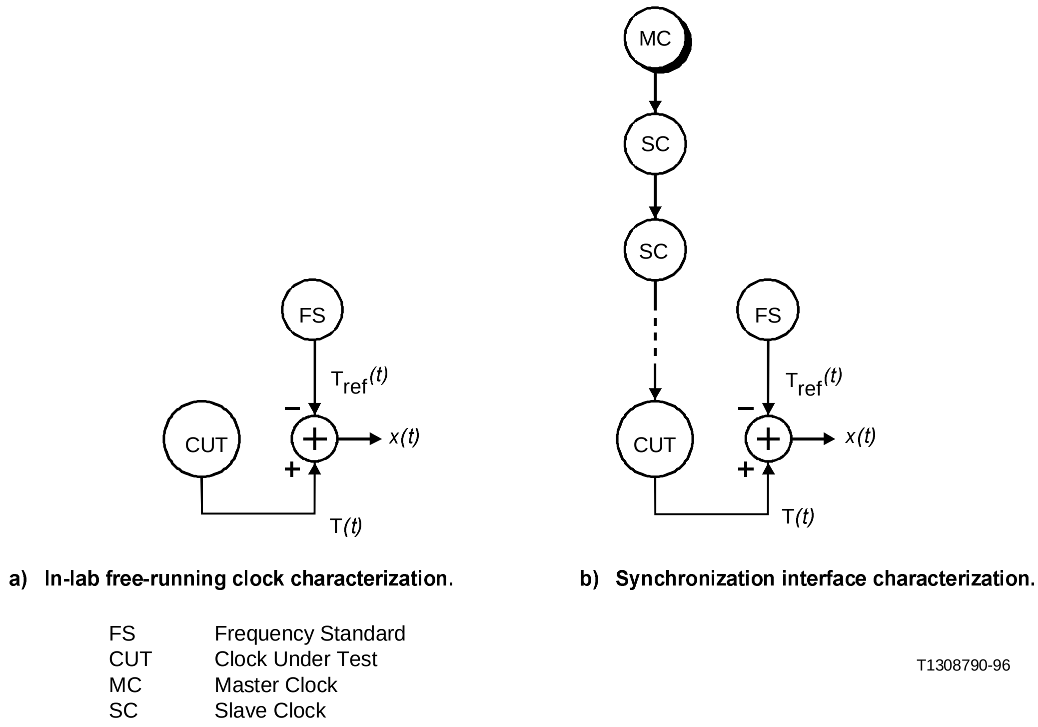


FIGURE 2/G.810

Examples of time error measurement in independent clock configuration

Appendix I
Mathematical models of timing signals

I.1 Total instantaneous phase model of an ideal timing signal

The total phase $\Phi_{id}(t)$ of an ideal timing signal is modelled as follows:

$$\Phi_{id}(t) = 2\pi\nu_{nom}t$$

where:

ν_{nom} is called *nominal frequency*.

I.2 Total instantaneous phase model of actual timing signals

In actual timing signals $\Phi(t)$ is modelled as:

$$\Phi(t) = \Phi_0 + 2\pi\nu_{nom}(1 + y_0)t + \pi D\nu_{nom}t^2 + \varphi(t)$$

where:

Φ_0 is the initial phase offset, y_0 is the fractional frequency offset from the nominal value ν_{nom} (mainly due to finite frequency settability of the clock);

D is the linear fractional frequency drift rate (basically representing oscillator aging effects);

$\varphi(t)$ is the random phase deviation component.

I.3 Time error model

Based on the definition of time error and the above model of $\Phi(t)$, the following model for $x(t)$ results:

$$x(t) = x_0 + \left(y_0 - y_{0,\mathrm{ref}}\right)t + \frac{D - D_{\mathrm{ref}}}{2}t^2 + \frac{\varphi(t) - \varphi_{\mathrm{ref}}(t)}{2\pi\nu_{\mathrm{nom}}}$$

NOTE – Some authors denote by $x(t)$ the random noise component only (i.e. the last term in the above equation), while here $x(t)$ represents the whole time error (i.e. also deterministic components, if any, are included in $x(t)$, as shown in the above model).

Assuming that for the measurement of $x(t)$ the independent clock configuration applies and that the reference clock is properly chosen (i.e. all its degradation sources – $y_{0,\mathrm{ref}}$, D_{ref} and $\varphi_{\mathrm{ref}}(t)$ – are negligible as compared to those of the clock under test), the $x(t)$ model reduces to:

$$x(t) = x_0 + y_0 t + \frac{D}{2}t^2 + \frac{\varphi(t)}{2\pi\nu_{\mathrm{nom}}}$$

When the synchronized clock configuration applies and all slave clocks involved in the distribution of timing (including the clock under test) are operating in locked mode, $y_{0,\mathrm{ref}} = y_0$ and $D_{\mathrm{ref}} = D$ can be assumed; the $x(t)$ model then reduces to:

$$x(t) = x_0 + \frac{\varphi(t) - \varphi_{\mathrm{ref}}(t)}{2\pi\nu_{\mathrm{nom}}}$$

Appendix II

Definitions and properties of frequency and time stability quantities

At present, five quantities are considered of interest in standardization bodies for characterization of time stability:

– the Allan Deviation (ADEV);

– the Modified ADEV (MDEV);

– the Time Deviation (TDEV);

– the root mean square of Time Interval Error (TIErms);

– the Maximum Time Interval Error (MTIE).

In subclauses II.1 to II.5, the various stability quantities are characterized according to the above scheme.

– the formal definition in terms of the Time Error function $x(t)$;

– the estimator expression in terms of a sampled version of $x(t)$, i.e. in terms of the sequence of N values $x_i = x(i\tau_0)$, where τ_0 is the sampling period and $i = 1,2,\ldots, N$;

– the integral time-domain/frequency-domain relationship between the power spectral density $S_\varphi(f)$ of the random phase deviation $\varphi(t)$ affecting a timing signal and the considered quantity;

– the quantity behaviour when the timing signal is affected by noise of the most common types, namely, White Phase Modulation (WPM), Flicker PM (FPM), White Frequency Modulation (WFM), Flicker FM (FFM) and Random Walk FM (RWFM);

– the quantity behaviour when the timing signal is affected by frequency offset and drift;

– pros and cons, as well as technical information on the measurement set-up and on the usefulness in designing synchronization networks.

As far as the formal definitions of ADEV and MDEV in terms of $x(t)$ are concerned, it must be pointed out that the $x(t)$ function takes into account random noise effects only, while here, for practical reasons and without loss of generality, it is assumed that $x(t)$ includes also deterministic components, if any.

II.1 Allan deviation (ADEV)

In the following $x(t)$ is the time error function, $\{x_i = x(i\tau_0),\ i=1,2,...,N\}$ is a sequence of N equally spaced samples of $x(t)$, τ_0 is the sampling period and $\tau = n\tau_0$ is the observation interval.

Definition

The Allan deviation ADEV(τ) is defined as:

$$\mathrm{ADEV}(\tau) = \sqrt{\frac{1}{2\tau^2}\left\langle \left[x(t+2\tau) - 2x(t+\tau) + x(t)\right]^2 \right\rangle}$$

where the angle brackets denote an ensemble average. For power law noise types, the result is the same if the ensemble average is replaced by an infinite time average, provided the square of the second difference is taken prior to the infinite time average.

Estimator formula

ADEV($n\tau_0$) can be estimated by:

$$\mathrm{ADEV}(n\tau_0) \cong \sqrt{\frac{1}{2n^2\tau_0^2(N-2n)} \sum_{i=1}^{N-2n} \left(x_{i+2n} - 2x_{i+n} + x_i\right)^2} \quad , \quad n = 1, 2, ..., \text{integer part} \left(\frac{N-1}{2}\right)$$

Integral frequency-domain/time-domain relationship

The Allan deviation of a timing signal is related to the power spectral density $S_\varphi(f)$ of its random phase deviation $\varphi(t)$ by the following integral relationship:

$$\mathrm{ADEV}(\tau) = \sqrt{\frac{2}{\left(\pi\nu_{\mathrm{nom}}\tau\right)^2} \int_0^{f_h} S_\varphi(f) \sin^4(\pi\tau f)\, \mathrm{d}f}$$

where ν_{nom} is the nominal frequency of the timing signal and f_h is the measurement system bandwidth. The above relationship holds under the assumption that no deterministic component affects the time error data used to compute ADEV(τ).

Noise performance

The ADEV(τ) converges for all the major noise types affecting actual timing signals. In Table II.1, the characteristic slopes of ADEV(τ), for different noise types, are reported. The ADEV(τ) does not allow to discriminate between WPM and FPM noises.

TABLE II.1/G.810

Noise process	Slope of ADEV(τ)
WPM	τ^{-1}
FPM	τ^{-1}
WFM	$\tau^{-1/2}$
FFM	τ^{0}
RWFM	$\tau^{1/2}$

Frequency offset and drift

Any constant frequency offset of a timing signal, relative to the reference clock, has no influence on ADEV(τ).

For observation intervals τ where a linear frequency drift dominates, the ADEV(τ) behaves as τ.

Pros and cons

The behaviour of ADEV(τ) is substantially independent of sampling period τ_0.

ADEV gives more information on the clock noise than MTIE, but it is not suited for buffer characterization.

ADEV is sensitive to systematic effects, which might mask noise components; Adequate filtering must be done on the measured signal before processing ADEV calculation. Diurnal wander is an example of systematic effect.

ADEV result coming out of network measurement could be heavily influenced by systematic effects.

II.2 Modified Allan deviation (MDEV)

In the following $x(t)$ is the time error function, $\{x_i=x(i\tau_0),\ i=1,2,...,N\}$ is a sequence of N equally spaced samples of $x(t)$, τ_0 is the sampling period and $\tau=n\tau_0$ is the observation interval.

Definition

The Modified Allan deviation MDEV($n\tau_0$) is defined as:

$$\mathrm{MDEV}(n\tau_0)=\sqrt{\frac{1}{2(n\tau_0)^2}\left\langle\left[\frac{1}{n}\sum_{i=1}^{n}\left(x_{i+2n}-2x_{i+n}+x_i\right)\right]^2\right\rangle}$$

where the angle brackets denote an ensemble average. For power law noise types, the result is the same if the ensemble average is replaced by an infinite time average, provided the square of the second difference averaged over $n\tau_0$ is taken prior to the infinite time average.

Estimator formula

MDEV($n\tau_0$) may be estimated by:

$$\mathrm{MDEV}(n\tau_0)\cong\sqrt{\frac{1}{2n^4\tau_0^2(N-3n+1)}\sum_{j=1}^{N-3n+1}\left[\sum_{i=j}^{n+j-1}\left(x_{i+2n}-2x_{i+n}+x_i\right)\right]^2}\ ,\qquad n=1,2,...,\text{integer part}\left(\frac{N}{3}\right)$$

Integral frequency-domain/time-domain relationship

The modified Allan deviation of a timing signal is related to the power spectral density $S_\varphi(f)$ of its random phase deviation $\varphi(t)$ by the following integral relationship:

$$\mathrm{MDEV}(n\tau_0) = \sqrt{\frac{2}{\left(\pi \nu_{\mathrm{nom}} n^2 \tau_0\right)^2} \int_0^{f_\mathrm{h}} S_\varphi(f) \frac{\sin^6(\pi n \tau_0 f)}{\sin^2(\pi \tau_0 f)} \mathrm{d}f}$$

where ν_{nom} is the nominal frequency of the timing signal and f_h is the measurement system bandwidth. The above relationship holds under the assumption that no deterministic component affects the time error data used to compute MDEV($n\tau_0$).

Noise performance

The MDEV(τ) converges for all the major noise types affecting actual timing signals. In Table II.2, the characteristic slopes of MDEV(τ), for different noise types, are reported, showing that MDEV(τ) allows to discriminate all the five types of noise.

TABLE II.2/G.810

Noise process	Slope of MDEV(τ)
WPM	$\tau^{-3/2}$
FPM	τ^{-1}
WFM	$\tau^{-1/22}$
FFM	τ^{0}
RWFM	$\tau^{1/2}$

Frequency offset and drift

Any constant frequency offset of a timing signal, relative to the reference clock, has no influence on MDEV(τ).

For observation intervals τ where a linear frequency drift dominates, the MDEV(τ) behaves as τ.

Pros and cons

For observation intervals where the WPM noise dominates, the behaviour of MDEV(τ) significantly depends on sampling period τ_0.

MDEV gives more information on the clock noise than MTIE, but it is not suited for buffer characterization.

MDEV is sensitive to systematic effects which might mask noise components; Adequate filtering must be done on the measured signal before processing MDEV calculation. Diurnal wander is an example of systematic effect.

MDEV result coming out of network measurement could be heavily influenced by systematic effects.

II.3 Time deviation (TDEV)

In the following $x(t)$ is the time error function, $\{x_i=x(i\ \tau_0),\ i=1,2,...,N\}$ is a sequence of N equally spaced samples of $x(t)$, τ_0 is the sampling period and $\tau=n\tau_0$ is the observation interval.

Definition

The Time deviation TDEV($n\tau_0$) is defined as:

$$\mathrm{TDEV}(n\tau_0) = \sqrt{\frac{1}{6n^2}\left\langle\left[\sum_{i=1}^{n}\left(x_{i+2n} - 2x_{i+n} + x_i\right)\right]^2\right\rangle} = \frac{n\tau_0}{\sqrt{3}}\mathrm{MDEV}(n\tau_0)$$

where the angle brackets denote an ensemble average. For power law noise types, the result is the same if the ensemble average is replaced by an infinite time average, provided the square of the second difference averaged over $n\tau_0$ is taken prior to the infinite time average.

Estimator formula

TDEV($n\tau_0$) may be estimated by:

$$\mathrm{TDEV}(n\tau_0) \cong \sqrt{\frac{1}{6n^2(N-3n+1)}\sum_{j=1}^{N-3n+1}\left[\sum_{i=j}^{n+j-1}\left(x_{i+2n} - 2x_{i+n} + x_i\right)\right]^2} \quad , \quad n = 1, 2, ..., \text{integer part}\left(\frac{N}{3}\right)$$

Integral frequency-domain/time-domain relationship

The Time deviation of a timing signal is related to the power spectral density $S_\varphi(f)$ of its random phase deviation $\varphi(t)$ by the following integral relationship:

$$\mathrm{TDEV}(\tau) = \sqrt{\frac{2}{3(\pi\nu_{\mathrm{nom}}n)^2}\int_0^{f_\mathrm{h}} S_\varphi(f)\,\frac{\sin^6(\pi n\tau_0 f)}{\sin^2(\pi\tau_0 f)}\,\mathrm{d}f}$$

where ν_{nom} is the nominal frequency of the timing signal and f_h is the measurement system bandwidth. The above relationship holds under the assumption that no deterministic components affects the time error data used to compute TDEV($n\tau_0$).

Noise performance

The TDEV(τ) converges for all the major noise types affecting actual timing signals. In Table II.3, the characteristic slopes of TDEV(τ), for different noise types, are reported. The TDEV(τ) allows to discriminate between WPM and FPM noises.

TABLE II.3/G.810

Noise process	Slope of TDEV(τ)
WPM	$\tau^{-1/2}$
FPM	τ^{0}
WFM	$\tau^{1/2}$
FFM	τ
RWFM	$\tau^{3/2}$

Frequency offset and drift

Any constant frequency offset of a timing signal, relative to the reference clock, has no influence on TDEV(τ).

For observation intervals τ where a linear frequency drift dominates, the TDEV(τ) behaves as τ^2.

Pros and cons

For observation intervals where the WPM noise dominates, the behaviour of TDEV(τ) significantly depends on sampling period τ_0.

TDEV gives more information on the clock noise than MTIE, but it is not suited for buffer characterization.

TDEV is sensitive to systematic effects, which might mask noise components; Adequate filtering must be done on the measured signal before processing TDEV calculation. Diurnal wander is an example of systematic effect.

TDEV result coming out of network measurement could be heavily influenced by systematic effects.

II.4 Root mean square Time Interval Error (TIErms)

In the following $x(t)$ is the time error function, $\{x_i = x(i\tau_0),\ i = 1,2,...,N\}$ is a sequence of N equally spaced samples of $x(t)$, τ_0 is the sampling period and $\tau = n\tau_0$ is the observation interval.

Definition

The root mean square time interval error TIErms(τ) is defined as:

$$\mathrm{TIErms}(\tau) = \sqrt{\left\langle \left[x(t+\tau) - x(t) \right]^2 \right\rangle}$$

where the angle brackets denote an ensemble average. For noise types where the spectrum of the TIE values obeys a power law with an exponent of –1 or less, the replacement of the ensemble average by an infinite time average results in an expression that diverges.

Estimator formula

TIErms($n\tau_0$) can be estimated by:

$$\mathrm{TIErms}(n\tau_0) \cong \sqrt{\frac{1}{N-n} \sum_{i=1}^{N-n} \left(x_{i+n} - x_i \right)^2}\ , \qquad n = 1, 2, ..., N\text{–}1$$

For noise types where the spectrum of the TIE values obeys a power law with an exponent of –1 or less, the estimator formula diverges.

Integral frequency-domain/time-domain relationship

The root mean square time interval error of a timing signal is related to the power spectral density $S_\varphi(f)$ of its random phase deviation $\varphi(t)$ by the following integral relationship:

$$\mathrm{TIErms}(\tau) = \sqrt{\frac{1}{(\nu_{\mathrm{nom}}\pi)^2} \int_0^{f_{\mathrm{h}}} S_\varphi(f) \sin^2(\pi\tau f)\, \mathrm{d} f}$$

where ν_{nom} is the nominal frequency of the timing signal and f_{h} is the measurement system bandwidth. The above relationship holds under the assumption that no deterministic components affects the time error data used to compute TIErms(τ).

Noise performance

The TIErms(τ) does not theoretically converge in the presence of FFM and RWFM noises. In Table II.4, the characteristic slopes of TIErms(τ), for different noise types, are reported.

TABLE II.4/G.810

Noise process	Slope of TIErms(τ)
WPM	τ^0
FPM	τ^0
WFM	$\tau^{1/2}$

Frequency offset and drift

For observation intervals τ where a constant frequency offset dominates, the TIErms(τ) behaves as τ.

For observation intervals τ where a linear frequency drift dominates, the TIErms(τ) does not theoretically converge to a finite value. From the measurement viewpoint this circumstance is expected to cause increasing value of estimated TIErms(τ) as the number N of x_i samples, and hence the total averaging time is increased.

Pros and cons

The behaviour of TIErms(τ) is substantially independent of sampling period τ_0.

II.5 Maximum Time Interval Error (MTIE)

In the following $x(t)$ is the time error function, $\{x_i = x(i\tau_0),\ i = 1,2,...,N\}$ is a sequence of N equally spaced samples of $x(t)$, τ_0 is the sampling period and $\tau = n\tau_0$ is the observation interval.

Definition

The maximum time interval error MTIE(τ) is defined as a specified percentile, β, of the random variable:

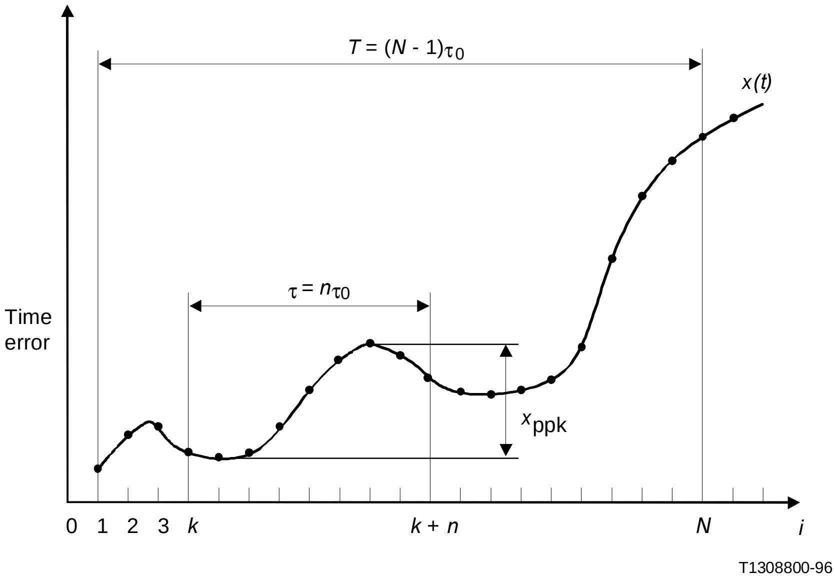
$$X = \max_{0 \le t_0 \le T-\tau}\left(\max_{t_0 \le t \le t_0+\tau}\left[x(t)\right] - \min_{t_0 \le t \le t_0+\tau}\left[x(t)\right]\right)$$

Estimator formula

MTIE($n\tau_0$) can be estimated by:

$$\mathrm{MTIE}(n\tau_0) \cong \max_{1 \le k \le N-n}\left(\max_{k \le i \le k+n} x(i) - \min_{k \le i \le k+n} x(i)\right), \quad n = 1, 2, ..., N-1$$

The above is a point estimate, and is obtained for measurements over a single measurement period (see Figure II.1).



where:

τ_0	is the sample period;
τ	is the observation time;
T	is the measurement period;
x_i	is the i-th time error sample;
x_{ppk}	is the peak-to-peak x_i within k-th observation;
MTIE(τ)	is the maximum x_{pp} for all observations of length τ within T.

FIGURE II.1/G.810

Estimates of MTIE (for specified T, τ and β), and their respective degrees of statistical confidence, may be obtained from measured data if measurements are made for multiple measurement periods. Let X_1, X_2,...X_M be a set of independent measurement samples of MTIE, for an interval of length τ, for M measurement periods each of length T. Assume that the samples have been put in ascending order, i.e. $X_1 \le X_2 \le \ldots \le X_M$. Let x_β be the β the percentile of the random variable X. Then a confidence interval for x_β, expressed as the probability that x_β falls between the samples X_r and X_s (with $r<s$), is given by:

$$P\left\{X_r \le x_\beta \le X_s\right\} = \sum_{k=r}^{s-1} \frac{M!}{k!(M-k)!} \beta^k (1-\beta)^{M-k}$$

where P{˙} denotes probability.

Frequency offset and drift

For observation intervals τ where a constant frequency offset dominates, the MTIE(τ) behaves as τ.

For observation intervals τ where a linear frequency drift dominates, the MTIE(τ) is not theoretically bounded. From the measurement viewpoint this circumstance is expected to cause increasing value of estimated MTIE(τ) as the total observation time, (i.e. the length N of the x_i data) is increased.

Pros and cons

The behaviour of MTIE(τ) is substantially independent of sampling period τ_0.

MTIE (and MRTIE) is well-suited for characterization of buffer size.

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