

TECHNICAL OVERVIEW

Delivering accurate time through the network is a crucial part of today's Telecom infrastructure. IEEE 1588, commonly known as Precision Time Protocol (PTP), is rapidly becoming the principal protocol to precisely transport time, phase and frequency over packet networks. This Technical Overview discusses how time is distributed over the network, how Time Error affects network performance, and methods to mitigate Time Error to ensure accurate timing and synchronization throughout the network.



Time and Time Error

A Guide to Network Synchronization



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1. What is Time?

Time is a fundamental physical dimension – the fourth dimension of “space-time” – which allows for the ordering of events from past to present to future. In electronic systems, it allows us to sequence events into a series of steps, or to share resources between multiple devices or functions. In order to do this, we need the ability to measure time.

1.1 Time and Frequency

In order to measure time, we need some concept of a fixed period of time. Typically this is provided by a regularly repeating event of constant period. This provides the concept of “frequency”. Historically, the solar day was used as the principal measure of the passage of time. Early societies also needed the ability to break the day up into fractional quantities. For example, the Egyptians used 10 hours of daylight, plus two hours of twilight at either end of the day. This definition had the problem that the length of the hour varied with the seasons, and later systems fixed this by counting in 24 equal divisions from noon to noon.

There are several physical events that exhibit a more or less constant frequency; repeating astronomical cycles such as the day, year, lunar month; and physical events such as the motion of a pendulum, and the resonance of a quartz crystal or a Caesium atom. These have all been used to measure the passage of time in some form or other.

1.2 Relative Nature of Time

While time itself is a fundamental physical dimension, the measurement of time is relative. We need to know the “epoch” or start time of the measurement, and the rate of advancement. For example, different calendars use different starting events to determine dates; the Romans counted years from the founding of Rome, the Gregorian calendar dates from the presumed birth of Christ, and the Islamic calendar counts lunar months from the date of the Hijra.

The rate of advancement is determined by counting equal lengths of time from the start event. In the current physical system, this length of time is the second. This is a fairly arbitrary length of time, but has the advantage that it is used by virtually all societies in the world today, and is accurately defined. Originally defined as a fraction of the period of the earth’s rotation, the current SI unit of the second is defined as:

“The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom in its ground state at a temperature of 0 K”

The current civil and legal time standard is UTC (Coordinated Universal Time), which is based on the Gregorian calendar epoch, and advances at a rate in step with TAI (International Atomic Time). It differs from TAI by a number of seconds, introduced to compensate for the fact that the earth’s rotation is slowing down relative to the oscillations of a Caesium atom.

This provides a framework for ordering events occurring at different places. In the case of mobile telecoms, these events might be the start of a transmission frame at two or more basestations. With a common time reference, these frames can be co-ordinated such that they don’t overlap, causing transmission errors.

2. Time Distribution

With a common time reference established, it is then necessary to know how this time reference can be distributed. This allows the measurement of time at different physical places.

2.1 Rate and Set

A clock or time measuring device is normally adjusted for rate (such that its indicated time advances correctly), and then set to match a reference clock. It will then advance in step with the reference clock, in so far as its rate is accurate. For example, a watch may be adjusted to advance at the correct rate, then set to match a clock of presumed higher accuracy. Later observation of the time indicated by the watch may be different to that of the clock because of an inaccuracy in either the rate adjustment and/or the original setting; this is *time error*, relative to the reference clock.

2.2 Time Messages

One way of measuring time at different locations is to physically transport a clock between the two locations, and adjust a local clock there to match the transported clock. This gives a notion of slave clocks, i.e. a clock that is adjusted to match another clock, known as the master clock. It also produces the concept of hierarchy.

Another method is to send a message containing the time from one place to another. In order for this to be useful, it is also necessary to know how long the message takes to arrive. For example, if I send a letter saying “The time is now 12 noon precisely”, that information is useless to the receiver unless they know exactly how long the letter took to arrive. The recipient can then adjust their clock to match the time indicated in the letter, plus the delivery time.

One method of estimating the delivery time is to send a return message. This allows the “round trip time” to be measured. Provided the original and returned message have the same delay, that delay can then be estimated as half the round trip time. This is the method used by network time distribution protocols such as Network Time Protocol (NTP) or Precision Time Protocol (PTP)

Another method is by knowledge of distance between the sender and receiver, and the speed of the message. GPS time systems use this, knowing the time of sending of the message, the position of the satellite at that time, and the position on the ground of the observer. The delay can then be estimated from knowledge of the speed of radio waves through the atmosphere.

2.3 Network Protocols

Network time distribution protocols such as NTP (Network Time Protocol, defined in RFC5905) and PTP (Precision Time Protocol, defined in IEEE1588-2008) use the exchange of timed messages to communicate time from a master node to a number of slave nodes.

PTP uses the following four basic messages, shown pictorially in Figure 1. NTP uses the same principles, although the message exchange protocol is different.

- SYNC message

A message transmitted at a regular rate from the master to all slaves. Contains a timestamp t_1 , identifying the time of message transmission from the master measured in nanoseconds from a known point in time known as the "epoch". Most PTP systems use the time: 00.00.00, 1 January 1970 as the epoch.

The arrival time of the SYNC message at the slave is denoted t_2 .

- FOLLOW_UP message

A message transmitted after each SYNC message, containing a more precise version of the timestamp t_1 , obtained by measuring the exact time of transmission at the physical layer. Some PTP clocks are capable of modifying the timestamp in the SYNC message "on-the-fly" as it is transmitted, and therefore do not need to transmit the FOLLOW_UP message. Such clocks are called "one-step clocks". Clocks that need to use the FOLLOW_UP message are called "two-step clocks".

- DELAY_REQ message

(Delay Request) A message from the slave to the master, requesting that the master inform the slave of the precise time of arrival of the message at the master. This is used to calculate the round-trip time of the master-slave route.

The transmission time of the DELAY_REQ message is denoted t_3 .

- DELAY_RESP message

(Delay Response) A message from the master to a specific slave in response to the DELAY_REQ, containing the time of arrival, t_4 , of the DELAY_REQ message at the master.

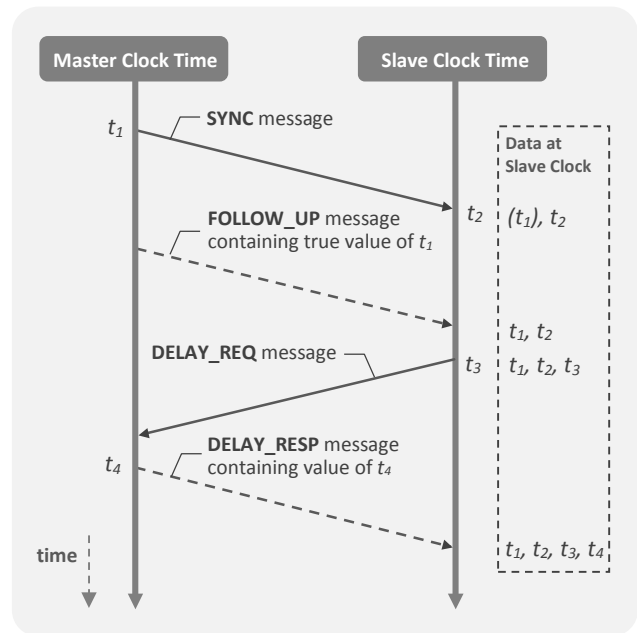


Figure 1: PTP Message Exchange

The messages yield four timestamps (t_1 , t_2 , t_3 and t_4) as shown in Figure 1. From these it is possible to calculate the round trip time for messages from the master to the slave, and back to the master (assuming that the slave clock is advancing at a similar rate to the master). The time offset is then estimated using the assumption that the one-way network delay is half the round trip delay, and used to correct the slave timebase to align to the master.

$$\text{Round trip delay} = (t_2 - t_1) + (t_4 - t_3)$$

$$\text{One-way delay estimate} = \frac{\text{round trip delay}}{2}$$

$$= \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$$

$$\text{Slave time offset estimate} = t_2 - (t_1 + \text{one-way delay})$$

$$= \frac{(t_2 - t_1) - (t_4 - t_3)}{2}$$

Note that if the forward and reverse paths are of different lengths, then this will introduce an error into the time offset estimate. There is no information within the PTP protocol itself which allows the offset to be corrected for this asymmetry, although the slave may be able to make use of other information available to infer the size of the offset. This is a major issue with packet time protocols, and is discussed in more detail in the next section.

3. Time Error

Time error is a measure of the difference between the time, relative to the epoch, reported by a local clock and a reference clock. It is only ever relative; time error has no meaning without a comparison to a reference. The time error may vary, and can be expressed as a function of time. For example, if the rate of a clock is wrong, the time error will gradually increase over time, as demonstrated by a watch that needs adjusting every few days as it gets progressively more out of time. It may also vary with temperature changes and other random effects.

3.1 Constant and Dynamic Time Error

ITU-T Recommendation G.810 describes a mathematical model of time error¹ between two clocks using the following equation:

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

where:

$x(t)$ is the time error function (the difference in time between the slave and the reference clock)

x_0 is the constant time error (i.e. the time offset, or “DC level” of the function)

$y_0 - y_{0,ref}$ is the fractional frequency offset between the two clocks

$D - D_{ref}$ is the difference in drift between the two clocks (i.e. the rate of change of frequency)

$\varphi(t) - \varphi_{ref}(t)$ is the random phase deviation component (i.e. the dynamic time error)

For a clock that is frequency or phase locked to the reference, the fractional frequency offset between the two clocks and the drift become zero and there are basically two components, the constant time error (cTE) and the dynamic time error (dTE):

$$\begin{aligned} x(t) &= x_0 + \frac{\varphi(t) - \varphi_{ref}(t)}{2\pi\nu_{nom}} \\ &= cTE + dTE \end{aligned}$$

This is shown in Figure 2. The constant time error, cTE is the mean level of the time error function, or the offset. The dynamic time error, dTE is the amplitude of the function. The maximum absolute time error, max|TE|, is the largest difference between the time of the two clocks, i.e. the largest distance from zero, whether positive or negative.

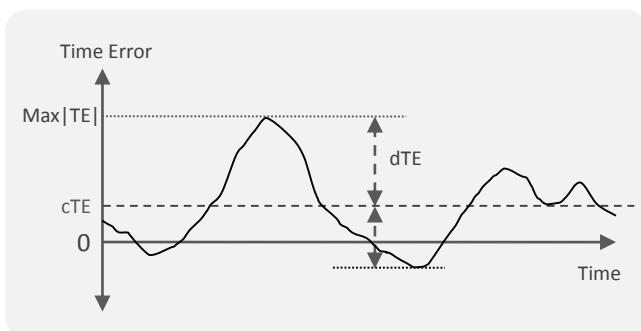


Figure 2: Constant and Dynamic Time Error (cTE and dTE)

3.2 Comparison with Time Interval Error

Time error is sometimes confused with Time Interval Error (TIE). The difference is that time error is the difference in time relative to the epoch, whereas TIE is a measure of the change in time error over an observation interval. In effect, this is a measurement of the phase change between the two clocks. TIE and the related metric MTIE (Maximum Time Interval Error) is used to characterise phase wander in frequency clocks.

TIE is conventionally set to zero at the start of the measurement, and the subsequent change in phase between the two clocks at different observation intervals is plotted. No epoch is required to measure TIE; the epoch is essentially the start time of the measurement. If we were to plot the TIE of the same clock shown in Figure 2, the shape of the graph would be the same, but the function would have the value zero at the start time of the measurement. This is shown in Figure 3:

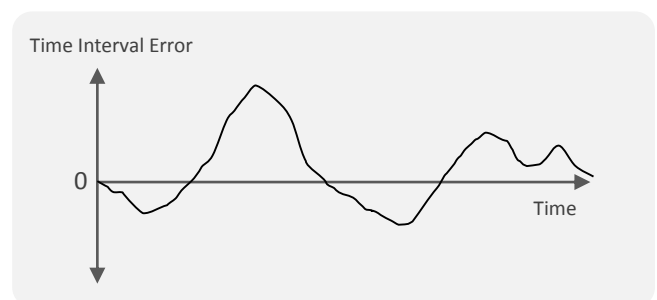


Figure 3: Time Interval Error

The maximum time interval error (MTIE) is the maximum change of TIE recorded over an interval. This is often used to define a limit on the maximum phase change of a frequency clock signal. For a time clock, MTIE can be used to define a limit on the dynamic portion of the time error. The MTIE value is equivalent to the peak-to-peak value of the dTE. For example, the dTE of a Primary Reference Time Clock (PRTC) is limited by an MTIE mask, shown in Figure 4

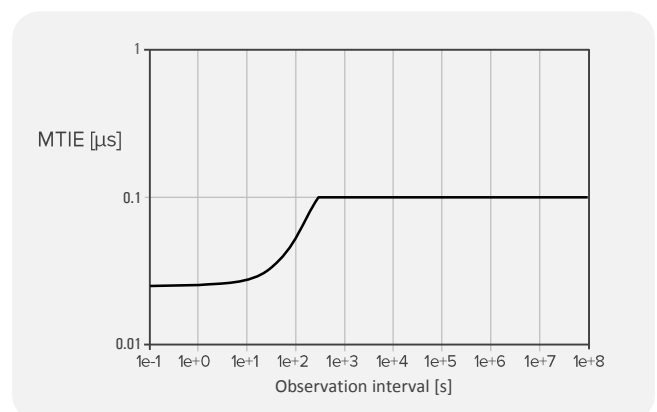


Figure 4: MTIE Limit for a PRTC
(Figure 1 from G.8272)

¹ITU-T Recommendation G.810, Appendix I (August 1996)

3.3 Characterisation of Time Clocks

In general, performance limits for time clocks are specified in three key parameters:

- **Max|TEI**
the maximum difference between the time of the clock and that of the reference.
Limits are usually specified in fractions of a second.
- **cTE**
the mean time error of the clock.
Limits are usually specified in fractions of a second.
- **dTE**
the change of time error of the clock.
Limits are usually specified using MTIE and TDEV masks.

Sometimes all three limits are specified, but often just two, the **max|TEI** and **dTE** are specified. For example, the PRTC specified in G.8272 only has specifications for **max|TEI** and **dTE**. The **Max|TEI** is the sum of the **dTE** and **cTE**, so a value for **cTE** is implied. However, some manufacturers may trade off lower **dTE** for higher **cTE** and still fit within the overall **max|TEI** figure.

4. Sources of Time Error

Time error may arise in several ways. For example, there may be an error in setting the time, which will persist until the next time the clock is set. If the clock is regularly set and re-set, this will be perceived as a random error, changing at the update rate.

An error in the rate will cause a gradual increase in time error, as the clock gets progressively more out of time with the reference. For a clock with a constant frequency offset and regular corrections, the time error function will exhibit a sawtooth shape, as the adjustments snap the clock back to the correct time. Temperature variations and aging in oscillators may cause the rate to change with time, causing wander in the time error.

4.1 Errors in Network Time Distribution

Packet network protocols such as NTP and PTP can contribute to both constant and dynamic time error. Constant time error (**cTE**) arises if the forward network delay is different from the reverse network delay. This is because there is no direct way to measure the delay from one place to another without an independent reference. In packet protocols, the network delay is estimated as half the round-trip delay. If this is not true, there will be an error in the time offset calculation, causing a corresponding error in setting the time of the slave clock.

The difference between the forward and reverse network delay is known as “asymmetry”. There are three main causes of asymmetry in a packet network:

- **Node asymmetry:**
the delay through each network node (e.g. switch or router) may not be equal in each direction
- **Link asymmetry:**
the delay through the links between nodes may not be equal. This may be caused by fibers or cables of different lengths, or by operating at different wavelengths over the same fiber
- **Route asymmetry:**
packet routing protocols do not guarantee that the packets will take the same route in each direction

As discussed earlier, neither NTP nor PTP directly address the issue of asymmetry, since there is no way to detect or measure asymmetry from the timestamps themselves. Constant time error due to asymmetry will remain undetected unless measured by an independent reference. However, if an external measurement of asymmetry can be made, then this measurement may be used as a correction factor when calculating the time offset of the clock.

Dynamic time error is caused by the fact that each packet takes a different length of time to travel through the network. This is known as packet delay variation, or PDV. The principal cause of PDV is queuing in each switch or router on the path, e.g. while waiting for other packets to be transmitted. Queuing can be reduced by setting timing packets to the highest priority, but can't be eliminated.

Another cause of dynamic time error is the local oscillator in the clocks. Fluctuations in frequency due to temperature variations or aging cause the clock to run fast or slow, creating a time error from the reference. This is corrected when the clock is adjusted, but the stability of the oscillator is still an important factor in the accuracy of a slave clock.

Timestamp quantisation may also affect the accuracy of the timestamps themselves, causing jitter in both position and time. This is described in more detail in section 6.2. Much of this error can be removed using a low-pass filter, but some will remain

Each of these issues cause errors both in the setting of time at a clock, and in the distribution of time from that clock to another clock. In a chain of packet clocks, the error in recovering the time and passing it down the chain causes a build-up in time error through the chain.

4.2 Mitigation of Time Error

Packet protocols for time distribution include a number of ways to reduce time error. NTP describes an algorithm for filtering the timestamp values to reduce the impact of the PDV on the dynamic time error². The algorithm is based on nearly 30 years of experience of operating NTP over the internet since the protocol was first published in 1985.

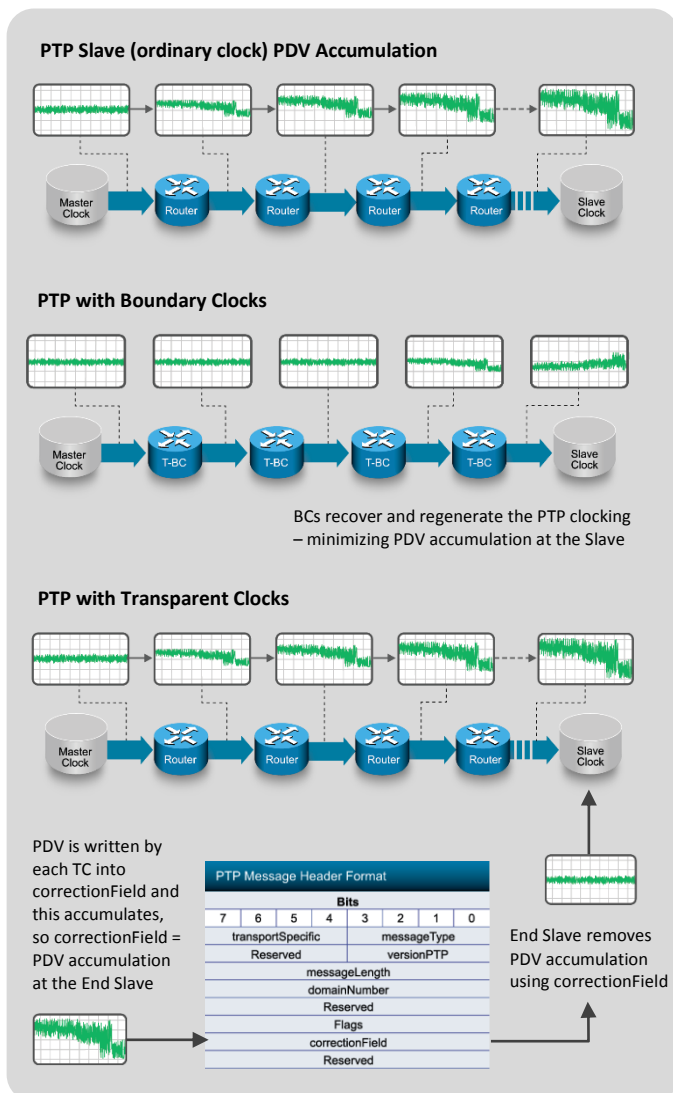
PTP doesn't describe an algorithm, which is left up to the implementer. It does describe two different methods of reducing the impact of PDV, both of which involve modifying the switches or routers on the path between the master and the slave:

- **Boundary Clocks (BC)**

terminates the PTP flow at each BC-capable switch or router, synchronising its local clock to the PTP master. The clock then re-generates the PTP messages to send to downstream devices.

- **Transparent Clocks (TC)**

measures the time taken by the packet to pass through a switch or router, and adds it to a correction field in the packet. The slave device then has a record of the delay for each TC-capable switch or router in the path.



It should be noted that both of these devices may be imperfect and introduce some time error of their own. This "noise" is generally less than that caused by the PDV, but the characterisation of such clocks is an important part of assessing their suitability for meeting the target accuracy of the overall system.

The ITU is in the process of defining two "profiles" for the distribution of time across the network using PTP. The first is for the case where every node in the path between the master and the slave contains a BC. This is termed "full timing support". The second is where there may be a mixture of ordinary switches and routers, and "PTP aware" devices, containing a BC or TC. This is known as "partial timing support".

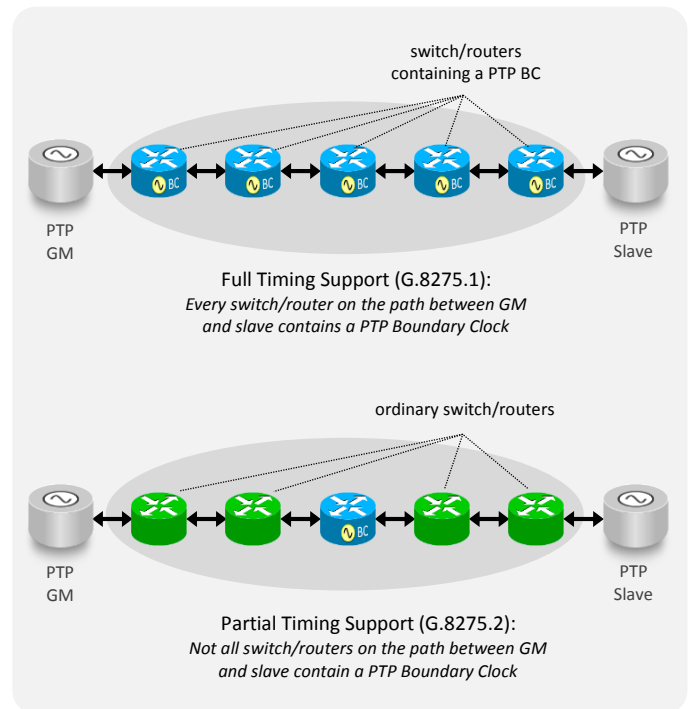


Figure 5: Full and Partial Timing Support

² RFC5905, Section 10 (IETF, published June 2010)

5. Time Error Budget (G.8271.1)

G.8271.1 defines a reference model for the deployment of PTP to a mobile basestation, or other similar application requiring precise time. Two separate deployment cases are described, to cover the cases of integrated or distributed basestation architectures. The reference model is shown in Figure 6:

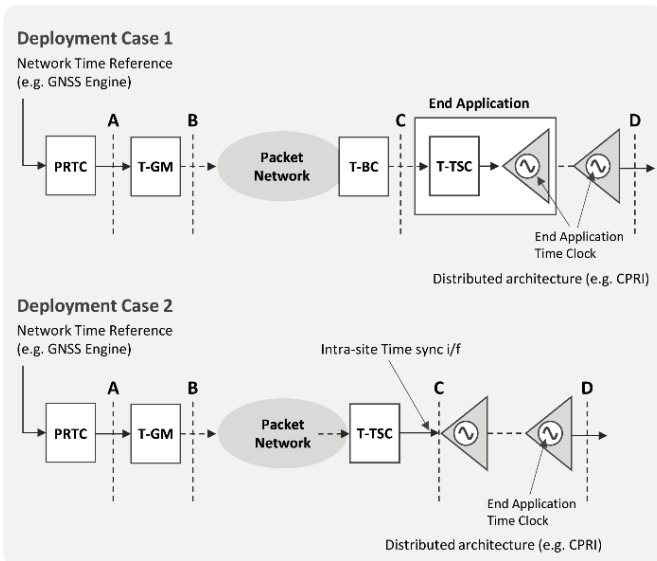


Figure 6: G.8271.1 Network Reference Model
(Figure 1 from G.8271.1)

The model defines four different reference points, allowing limits on the amount of time error to be defined at each of the reference points. The four reference points are:

- A:** Time accuracy and stability at output of PRTC
- B:** Packet timing interface at output of PTP T-GM (Telecom Grandmaster)
- C:** Budget at the output of the network
- D:** End application requirements (e.g. air interface time/frequency spec.)

For mobile basestations requiring better than $1.5\mu\text{s}$ accuracy, G.8271.1 defines an example budget for the network as shown in Figure 7. This breaks the budget down into the constant and dynamic time error contributions for each part of the network, based on the use of full timing support (i.e. boundary clocks at every node in the network between the T-GM and T-TSC (Telecom Time Slave Clock).

The budget shown in Figure 7 only covers the case of full timing support. A separate budget for partial timing support is to be developed.

- Reference points A, B:
The maximum time error at the output of the PRTC and T-GM is defined to be $\pm 100\text{ns}$ from the reference (e.g. UTC). This limit includes both constant and dynamic time error. No separate limit is defined at reference point B, since in most implementations, the PRTC and the T-GM are integrated into the same piece of equipment.
- Reference point C:
Here the limit is broken into both constant and dynamic portions. Each network node is allowed to contribute up to 50ns constant time error. Up to ten BCs are allowed, with an eleventh node allocated for the slave clock. The dynamic time error portion is 200ns for the whole network. Simulations on the use of BCs at every node show that this is well within the capability.
- Reference point D:
 150ns of error is allocated for the end application (i.e. the basestation itself, since the $1.5\mu\text{s}$ requirement is at the radio interface of the basestation). A further 250ns is allocated for short-term holdover, necessary when switching between alternate grandmasters.

The approach provides a building-block methodology that can be used in any full timing support network design. It shows how the performance required by the end application can be sub-divided and assigned to the various network components. This allows the network designer to use the specified performance of each BC along with the known topology characteristics of their network to determine suitable networks to support the end application.

One key point to note is that the budget for cTE is considerably larger than that for dTE. Of the $1.1\mu\text{s}$ allocated to the network (measured at reference point C), 800ns is for constant time error, 200ns for dynamic time error, with the last 100ns (for the PRTC) undefined. This is because with 10 nodes constant time error builds up rapidly, even with relatively small budgets allocated for equipment or links.

Secondly, cTE is not filtered out by the clocks along the path, therefore it increases linearly through the network with the number of nodes and links. This is not true for dTE, which if uncorrelated, builds logarithmically. Therefore, cTE grows very quickly as the number of nodes increases.

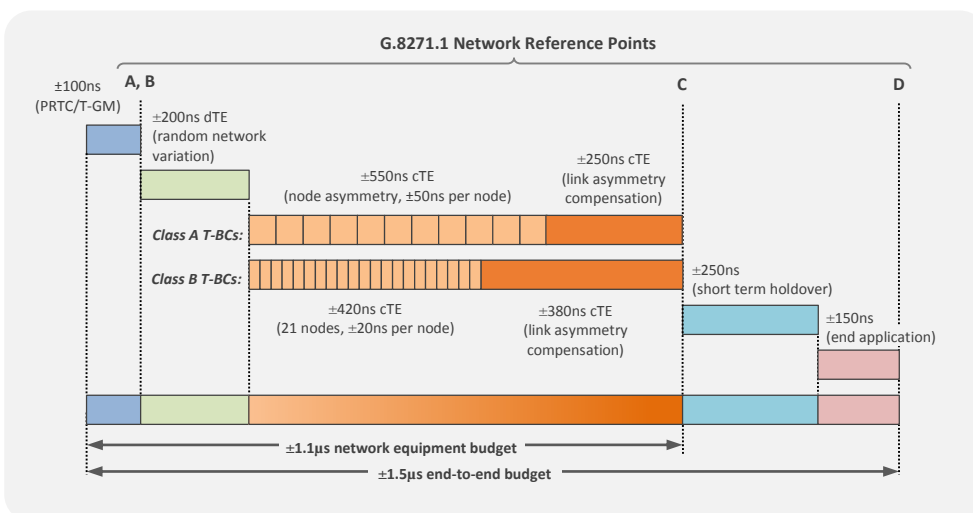


Figure 7: G.8271.1 Time Error Budget

6. Measuring Time Error

As noted earlier, time measurement is always relative to a reference clock, because the reference clock provides the epoch for the measurement. A Primary Reference Time Clock (PRTC) provides a reference time accurate to within 100ns of UTC. In the field, the PRTC itself is most commonly a GPS receiver, reconstructing time from the satellite messages.

In a lab setting, a time clock driven from a local stable frequency reference could be used (e.g. a Caesium or Rubidium oscillator), since it may not be necessary to reference back to UTC for lab measurements.

6.1 Measuring Time Error on a Packet Interface

At a packet time interface, the time offset of the slave clock is given by a calculation involving four timestamps, two from the slave and two from the master. Any errors in those timestamps will cause an error in the time offset calculation. When characterizing the noise generation of packet clocks, the trick is to separate the master's contribution to time error from the slave's contribution.

A master port can be tested by connecting the master directly to a test device through a calibrated connection. This is shown in Figure 8.

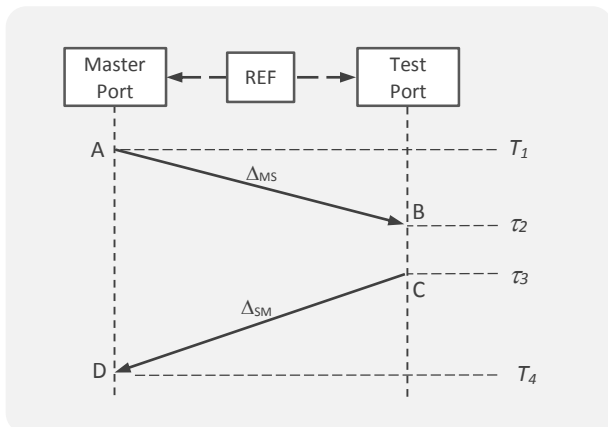


Figure 8: Test configuration for a Packet Master Port
(Figure A.1.1 from G.8273)

- Timestamp T_1 represents the time the SYNC message left the master port
- Timestamp T_2 represents the time the SYNC message arrives at the test port
- Timestamp T_3 represents the time the DELAY_REQUEST message leaves the test port
- Timestamp T_4 represents the time the DELAY_REQUEST message arrives at the master port
- Δ_{MS} represents the cable delay from master to test port
- Δ_{SM} represents the cable delay from test to master port

The error in the SYNC message timestamp, TE_1 , is given by
 $TE_1 = T_1 + \Delta_{MS} - T_2$

The error in the DELAY_REQUEST message arrival time, TE_4 , is given by $TE_4 = T_4 - \Delta_{SM} - T_3$

If the cable delays, Δ_{MS} and Δ_{SM} are equal (symmetrical), the contribution of the master port to the overall time error in the time offset calculation is given by $TE_{master} = (TE_1 + TE_4)/2$

This is known as the two way time error.

6.2 Timestamp Jitter

Figure 9 shows how the layers interact in an Ethernet interface. In most designs, the timestamps are actually struck at the MAC/PHY interface, rather than the Medium Dependent Interface (MDI). This allows different PHY devices to be used to connect to the medium itself, whether copper or fiber.

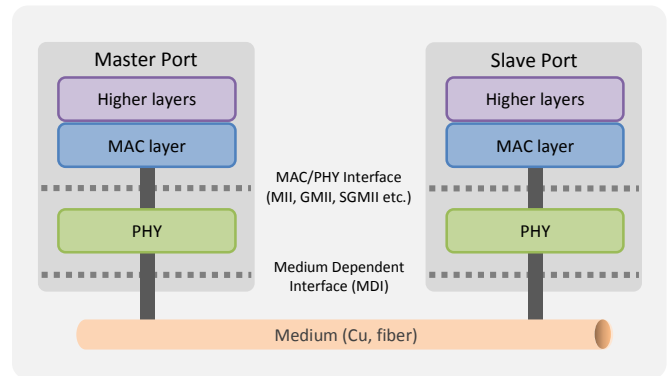


Figure 9: Ethernet Interfaces

For a packet exiting the port, the timestamp may contain some quantization due to the rate of the clock controlling the timestamp counter. For example, if the timestamp counter increments at 250MHz, the resolution will be 4ns, resulting in a potential quantization error of up to 4ns. This will appear as jitter on the timestamp.

Secondly, the MAC/PHY interface is not the actual output interface of the port. The timestamp must be adjusted to take into account the delay through the PHY component. This will be different depending on the type of PHY and the rate of the interface (e.g. 100M, 1G, 10G). If the PHY delay is not constant, this may cause further jitter on the timestamp itself, relative to the actual exit time of the packet.

The delay through the medium may also experience change. Temperature changes in the cable may cause length changes and consequently, the delay may change. Underground or undersea fibers are typically less vulnerable to environmental factors, largely because they are less exposed to the sun.

Finally, on reception, the PHY must receive the incoming bit stream, recover the clock and reconstruct the data to be presented on the digital MAC/PHY interface. Since Ethernet allows the physical layer clock frequency to have a tolerance of up to 100ppm, the PHY must compensate for a potential rate difference with its own internal clock of up to 200ppm.

This is done by buffering the incoming bit stream before presenting it on the MAC/PHY interface. For a 1G interface, IEEE 802.3 specifies that each new packet must start on a 16-bit boundary, hence this rate adaption can cause up to 16ns of jitter in the arrival time of a packet at the MAC/PHY interface. For a 100M interface, the quantization is on 8-bit boundaries, or 80ns, while for a 10G interface, it is on 32-bit boundaries, or 3.2ns of jitter.

These jitter components may be filtered over many packets to reduce the impact on the overall time error. Since the jitter is likely to be high frequency in nature, a cut-off frequency of around $\frac{1}{10}$ to $\frac{1}{100}$ of the packet rate should be sufficient to smooth it out. As an example, the full timing support profile being defined in G.8275.1 specifies a packet rate of 16Hz, with a filter bandwidth of 0.1Hz in each boundary clock.

6.3 Constant Time Error

Of more concern than the jitter is the possible generation of constant time error due to asymmetry in the forward and reverse delays. 10G and 100G PHY interfaces involve adaptive digital signal processing on reception to reconstruct the signal from the medium. The processing delay is dependent on the length of the line and the quality of the signal received. It is therefore possible for the processing delay in the forward direction to be different to that on the receive direction, especially if the wavelength used is different. This asymmetric delay creates a constant time error that must be measured and compensated for. This is more likely to be a problem in the field, with long fiber runs, than in the lab with short cables.

Secondly the fiber length itself may be different in each direction. Even if the same fiber is used, the transmit and receive wavelengths will be different resulting in a different propagation delay through the fiber. In a lab situation, these differences can be reduced by keeping the fiber lengths short, and calibrating the delays.

The cTE is measured by taking the mean of the time error function over a period. The exact period over which the function should be averaged to evaluate the cTE is not defined, although in practice a good value is achieved within 100 to 1000s. G.8260 suggests averaging over a period based on the minimum value of the TDEV function, which may be suitable for a post-processed measurement, but cannot be used for a real-time assessment.

6.4 Dynamic Time Error

Dynamic time error, dTE, is assessed by measuring the Time Interval Error (TIE) of the time error function. This represents the change in time error over the period of the measurement. The TIE is evaluated by computing the MTIE and TDEV metrics, and comparing them to pre-determined masks, e.g. those specified in G.8272 for the PRTC. Suitable masks for the BC and slave functions have yet to be defined by the ITU.

6.5 Maximum Absolute Time Error

The maximum absolute time error, max|TEI, is assessed by measuring the maximum distance of the time error function from the reference time. This value may be positive or negative, hence the use of the absolute value operator. For example, the max|TEI of a PRTC is defined in G.8272 to be 100ns, i.e. the time of the PRTC is permitted to be between -100 and +100ns of the reference time.

7. Summary

While time itself is a fundamental physical dimension, having a common idea of what time it is requires reference to a known epoch, or reference point. When making measurements of time, this means that a reference clock is always required. There is no such thing as a referenceless measurement of time or time error.

For normal everyday use, our clocks and watches are set with reference to the time reported by radio, TV or our telephones. These in turn are referenced back to UTC, the universal time standard agreed. For field measurements, UTC is again a useful reference, both for test equipment and network infrastructure, as it provides a common reference available at each location. The most common way of accessing UTC in the field is to use GPS.

In the lab, a "local time standard" may often be sufficient, with an epoch at the start of the measurement itself. UTC reference through GPS may not be required since all devices may be connected to the local reference. A stable frequency (e.g. a Caesium or Rubidium clock) should be used to avoid measurement errors caused by wander in the frequency reference itself.



Calnex Solutions Ltd
Oracle Campus
Linlithgow
West Lothian EH49 7LR
United Kingdom

tel: +44 (0) 1506 671 416
email: info@calnexsol.com

calnexsol.com

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