White Paper

Introduction to Timing and Synchronisation

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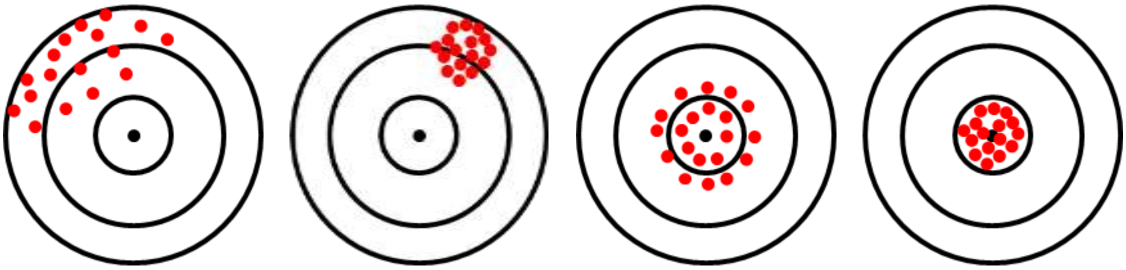
Timing dependent applications rely on their clocks being correct within the set tolerances required by that technology. In order to achieve this, timing is transferred between clocks using various methods that enable time or frequency, phase or time of the required quality to be available to the application. The activity of transferring time between clocks is known as ***synchronisation***.

Timing and synchronisation quality can be described by two factors: accuracy and stability. Accuracy is the measure of how closely the clock compares to a reference or target value; this can be a global standard for time such as UTC or a desired frequency such as 10MHz; stability is the measure of the variance of the clock when observed over a period of time. This is visually shown in the diagram below where accuracy and stability is shown if the goal is to hit the centre of the target using multiple shots.



In order to quantify the quality of timing and synchronisation, many different timing metrics exist. These are specifically designed for the timing technologies they are measuring and the characteristics of the signal that are of interest. Measurements must be made against another clock of known and dependable quality during relevant network or environmental conditions and over a period of time long enough to fully characterise the measured clock.

Technology	Common Measurement Metrics	Notes
Time	TIE – Time Interval Error cTE – Constant Time Error dTE – Dynamic Time Error	These metrics apply to a wide range of timing protocols
Frequency	TIE – Time Interval Error MTIE – Maximum Time Interval Error TDEV – Time Deviation ADEV – Allan Deviation FFO – Fractional Frequency Offset	These metrics apply to a wide range of timing protocols
Packet Timing (e.g. IEEE-1588/PTPv2)	FPP – Floor Packet Percentage minTDEV – Minimum TDEV MATIE- Maximum Average TIE MAFE – Maximum Average Frequency Error PDV – Packet Delay Variation	Relevant metrics depend highly on the clock algorithms in downstream equipment Technologies are PTPv2

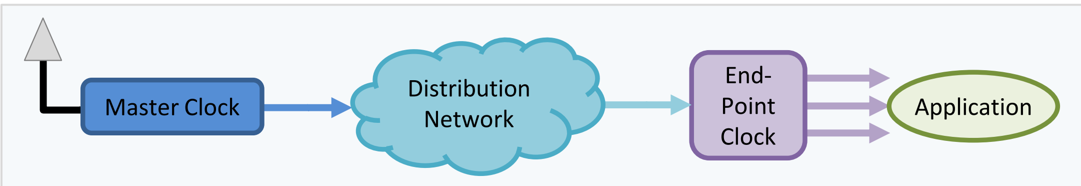
Network Synchronisation

Typically a time dependent application consists of a defined network containing multiple, sometimes many thousands, of clocks that each require synchronisation within set tolerances. These tolerances differ between applications, however in most cases where it is required the quality of timing and synchronisation is of critical importance and poor quality will directly impact the performance of the application or the usefulness of the data generated by it.

Clocks get their time from timing sources; sources include the inherent frequency stability of their internal oscillator or atomic standard, via external off-air source of timing signals such as Global Navigation Satellite Systems (GNSS), or from clocks within the timing network. Timing is transferred between clocks in the network via either physical layer signals such as frequencies or pulses, and/or a data stream containing time codes and usually additional information regarding the originating clock.

In order to achieve a required synchronisation quality, the hardware and software configuration of all clocks, nodes and, where relevant, the timing distribution path must be performed with specific focus to the timing aspects of each element.

Terminology differs between applications however the primary elements have similar functions, in this document, clocks that get their timing from their inherent stability or from an external off-air source such as GNSS are described as Master Clocks, clocks that directly support the application are End Point Clocks, the path between is the Distribution Network which may also contain intermediate clocks.



As the physical or logical distance increases between the Master Clock and an end-point, the quality of the synchronisation that can be achieved degrades due to factors such as network traffic and environmental changes. The quality of the clocking algorithms or hardware at the end point can also significantly impact performance and it is common for different vendors' hardware to perform better or worse than one another even at identical points in the timing network.

As the need for network synchronisation grows and timing requirements are becoming ever more stringent, the task of identifying the causes of error and inaccuracy in all elements of the end-to-end timing chain is increasing in both importance and complexity.

Applications for Timing and Synchronisation

The table below shows some of the common uses for timing and synchronisation within various industry sectors.

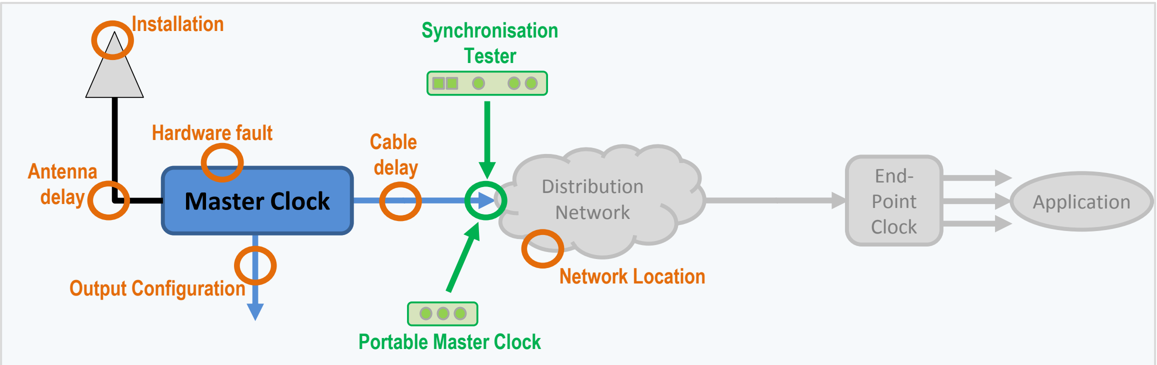
Sector	Primary Timing Applications	Test/Calibration Points
Telecoms (Fixed Line)	Transport/Multiplexing Data read/write integrity	Master Clock Performance SDH/SyncE Node Performance
Telecoms (Mobile)	Base station air-interface synchronisation Radio optimisation techniques such as MIMO, eICIC and CoMP	Master Clock Performance Mobile Base Station Gateway/Access Router
Telecoms (Cable)	Passive Optical Network (PON) Multiplexing DOCSIS cable modem termination	Master Clock Performance Optical Line Termination system or backhaul DOCSIS Time Server
Finance	Time synchronisation between trading platforms Data time-stamping and event correlation Execution of trades at the correct time	Master Clock Performance Server Cards (e.g. PCIe)
Power	Intelligent Electronic Device (IED) synchronisation Data time-stamping (logging, correlation) Synchrophasor (PMU) measurements	Master Clock Performance Input to IED or Synchrophasor Test points on IED or Synchrophasor
Broadcast	Single Frequency Networks (SFN)	Master Clock Performance On-air signal equipment

Sources of Synchronisation Quality Issues

Master Clocks

Timing within a network begins at the Master Clocks for that network or sub-network; it is then distributed across the network to the end-points, sometimes via other clocks in the network. Synchronisation quality is measured by comparing the clock at the measurement point against an **independent** reference signal of **known quality.**

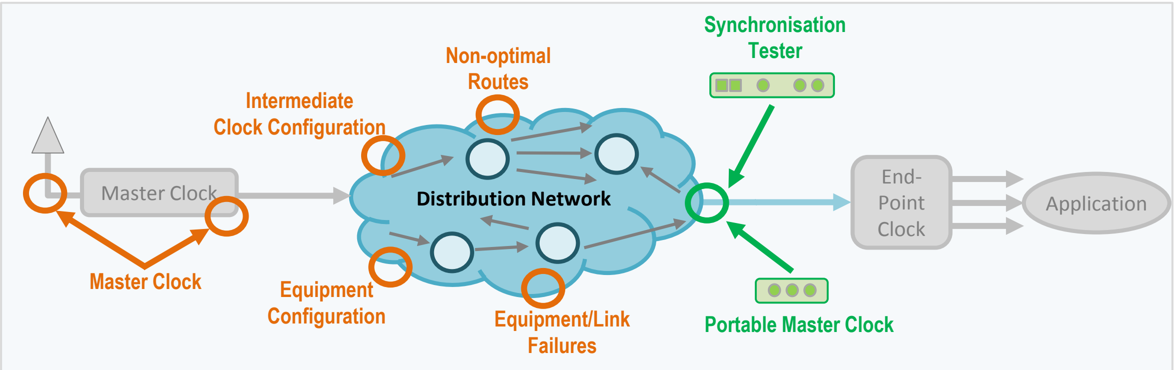
As timing begins at the Master Clock it is critical that this is installed and configured correctly as any errors here will affect **all** end-points or applications that depend on this clock.



MASTER CLOCK TESTING		
Sources of Error	**Issues with Measurement**	**Measurement Solutions**
Poor **installation or sources of interference**, especially with regard to any external antenna Incorrect choice of **location in network topology** Incorrect **cable delay** settings from antenna and output signals **Faulty hardware** **Incorrect configuration** of output (physical or packet flags)	No **reference standard** to measure against. Inability to get a good quality signal or known test equipment Tester does not support **all required signal types**	1) Test equipment with reliable and highly accurate references 2) Portable master clock supporting all protocols for use in empirically finding the optimal network locations before deployment 3) **Test equipment with the ability to test all required signal types and protocols** 4) Training or consultancy for installation design

Distribution Network

There are a number of methods of timing transport and distribution and providing the synchronisation is within the required tolerances at the end-point, the method of distribution is generally not of importance to the application. However, if testing reveals poor synchronisation at the end-point clock, it is likely that investigation into the timing distribution path will be required.

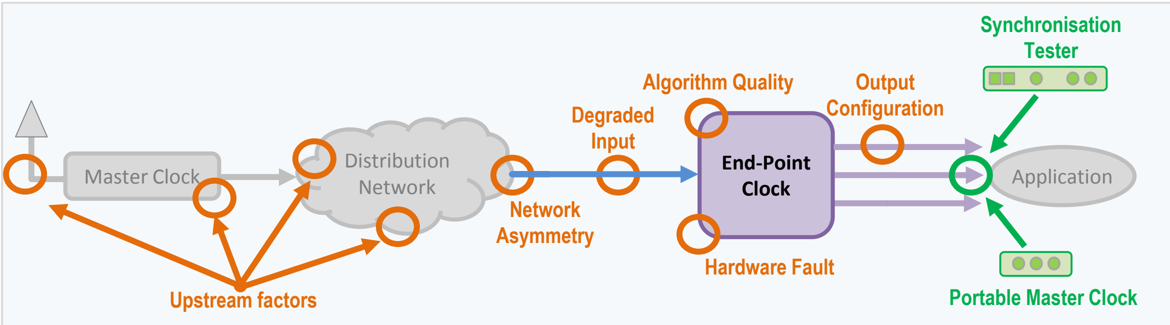


DISTRIBUTION PATH or NETWORK TESTING		
Sources of Error	**Issues with Measurement**	**Measurement Solutions**
Issues with **Master Clock** as described in previous section. Incorrect **configuration** of transmission equipment. Poor quality or incorrectly configured intermediate clocks, e.g. SDH nodes or Transparent/Boundary clocks Poor **network planning**, leading to non-optimal route length or timing path characteristics Equipment and link failures	Inability to **rapidly move** test or Master Clocks around the network topology to determine points of error Measuring the distribution with Ethernet/IP networking (as opposed to **timing) measurement tools** does not show the effects on clock performance	1) Use of **portable test equipment** to quickly traverse the network and identify the point of errors 2) Test equipment that is able to **recover and analyse** the clock at test points in the distribution network 3) **Training or consultancy** regarding network design and planning

End-Point Clocks

End-point clocks are at the point in the network where the synchronisation quality directly impacts the efficiency of the application that relies on them. Performing testing at this point will reveal the total of all errors and degradations accumulated in the end-to-end timing chain.

All other factors being equal, it is the stability of the internal oscillator and the clock recovery algorithm that have the greatest bearing on the quality of timing and synchronisation available to the application.



END POINT CLOCK TESTING		
Sources of Error	**Issues with measurement**	**Measurement Solutions**
Issues with the distribution network as described in previous section **Degradation of timing quality of the input** leading to poor output quality Unknown **network asymmetry** resulting in fixed timing offsets Bad quality **clocking algorithms** at end-point Incorrect **Output configuration**	Typically testing is done at a location where there is no method of sourcing a high quality accurate reference signal – such as indoors where no GNSS is available Asymmetry is **impossible to calculate without having an independent source of calibrated time**	1) **Portable source of accurate time** and frequency as a reference input to test equipment - ideally this should be able to be easily taken outside to lock to a GNSS reference, then ported indoors to the test location 2) Test equipment that is able to **recover and analyse a clock** at the end-point and provide an independent view of what should be achieved 3) Equipment with **nanosecond accuracy to an independent source of external time,** or to a **calibrated portable time source** to show fixed offsets due to asymmetry

Timing and Synchronisation Technologies

The table below shows the common technologies employed to for timing and synchronisation and the type of equipment that is required to measure or calibrate them to ensure optimal performance.

Type	Protocol / Characteristic	Measurement / Calibration
GNSS/GPS/GLONASS eLORAN or other radio source	Source of off-air time, affected by interference, faulty hardware or incorrect installation and/or configuration	Using an **external source of known quality time**, typically long term Typically pulse or time-code against a known reference to show errors **Test: ToD, 1PPS, Frequency**
Atomic Standard (e.g. Cesium)	Standalone source of frequency, degrades when out of calibration, or hardware goes faulty Bad configuration or tuning parameters can also degrade the quality of timing	Using an **external source of known quality time**, typically long term Typically pulse or frequency against a known reference to show errors **Test: ToD, 1PPS, Frequency**
Pulse or Frequency Signal	Physical distribution of frequency or pulses. Typically used for inter-node timing within the same building or site	Using an **external source of known quality frequency** **Test: xMHz, xPPS**
Time of Day	Various formats exist, consists of a data stream holding time code information and typically an accurate pulse for nanosecond alignment	Using an **external source of known quality time**, typically long term Typically pulse or time-code against a known reference to show errors **Test: 1PPS, ToD**
IEEE 1588 (PTPv2)	Packet distribution of frequency and time, affected by network configuration and distance in network topology from Master Clock Use of PTPv2 aware network equipment such as Transparent and Boundary clocks gives quality gains provided they work correctly	Using an **external source of known quality time**, or with known quality **PTPv2 Slave clock** Packet flow is measured for **Packet Delay Variation** metrics to show the quality of the flow Analysis of **Transparent** and **Boundary Clock performance** **Test: PTPv2**
Synchronous Ethernet (SyncE)	Physical distribution of frequency. Degrades with length of sync chain and incorrect configuration of ports and clock flags	Using an **external source of known quality frequency** **Test: SyncE Clock** and **ESMC messages**
SDH/SONET/TDM	Physical distribution of frequency. Degrades with length of sync chain and incorrect configuration of ports Use of inline clocks, such as SSU	Using an **external source of known quality frequency** **Test: E1/T1 Signals or Sync Out**

Synchronisation Design, Calibration and Measurement Solutions

Portable source of trusted UTC time and PRC frequencies

Primary use case for this equipment is to provide highly accurate and stable reference signals of known quality to be used as input to other test equipment, resulting in accurate results that can be used to qualify, troubleshoot and optimise timing performance at the measurement point.

Characteristics of such a reference source should include:

- *Ability to lock to GPS for time and frequency accuracy, with the ability to hold 200 nanosecond accuracy over 8 hours if disconnected from GPS and integrated into the test environment.*
- *Portable (UTC/time) reference*
- *Broad range of output frequencies including 2MHz, 10Mhz, 1PPS and IRIG-B*
- *1PPS Measurement function*
- *Easy to setup and configure*
- *Rechargeable long-life battery for maximum portability*
- *Ability to serve PTP/1588v2, NTP and SyncE protocols*

Test Equipment that is optimised for Timing

Primary use case for this equipment is to test all required aspects of the equipment or network, resulting in accurate results that can be used to qualify, troubleshoot and optimise timing performance at the measurement point.

Characteristics of such test equipment should include:

- *Ability to use external timing sources or equipment as measurement references*
- *Internal GPS or Rubidium reference*
- *Fibre optic and Electrical inputs*
- *Continuous collection and analysis of measurement data*
- *Comparison to standard quality masks*
- *Simple presentation and display*
- *Broad range of input frequencies including 2.048MHz, 10MHz, xMHz and 1PPS*
- *PTP/1588v2 measurement and PDV analysis*
- *Synchronous Ethernet frequency stability testing and ESMC decoding.*
- *Time of Day measurement (TOD+1PPS)*

Sync & Timing Training

Synchronisation and timing can be complicated subjects to understand, however, specific training courses on these subjects can assist. Important characteristics of such a training course are:

- *Internationally recognised vendor neutral with a non-commercial, pure knowledge bias featuring the latest technologies, procedures and current synchronisation knowledge*
- *Covering all aspects of synchronisation and timing systems, technologies and implementation techniques*
- *Ability to be tailored to specific requirements and can be held at vendors, or customer premises*
- *As well as formal delivery, sometimes it is beneficial to attend synchronisation test and network hardware training and workshops to receive practical hands-on experience of using and measuring synchronisation equipment and signals*

Sync & Timing Consultancy

Detailed planning of a new deployment or network change is the first vital step. Testing of new equipment and network infrastructure is crucial both prior to and during deployment, and tactical or long-term monitoring of sync health is a key factor in maintaining on-going confidence of network timing quality.

Synchronisation testing and analysis services should recommend the most efficient way to test network sync health by identifying critical points in a network and employing the most appropriate test equipment to maximise the scope and benefits of the testing. Once the data has been collected it should be presented in a comprehensive report along with detailed analysis of the current sync performance and, if required, recommendations on how to improve areas of concern.

Services should include: Sync network data collection, analysis and reporting and, if appropriate, a long term timing quality monitoring service.

Planning and design services provide should expert advice and documentation for implementation of synchronisation and timing within SDH, PON, Ethernet and IP, using G8.x, DOCSIS, NTP, PTPv2 technologies.

Bespoke synchronisation plans must take into account all network requirements and conform to relevant ITU, IEEE, IEC and other relevant published standards. Using best practices and planning rules, tailored recommendations and should be delivered in a comprehensive report that documents all the key components and technical calculations along with supporting data, network diagrams and rationale.

Sync delivery technologies and products are constantly evolving it is important that a long term strategic view of synchronisation and timing is incorporated into any current requirements.

Acronyms Used

SDH	Synchronous Digital Hierarchy
PON	Passive Optical Network
ESMC	Ethernet Synchronisation Messaging Channel
IP	Internet Protocol
DOCSIS	Data Over Cable Service Interface Specification
DTI	DOCSIS Timing Interface
NTP	Network Time Protocol
PTPv2	Precise Time Protocol (IEEE1588) Version 2
TIE	Time Interval Error, the basic measurement of timing signal errors against a reference
ToD	Time of Day
1PPS	One Pulse Per Second
MIMO	Multiple Input/Multiple Output, increases data throughput of radio devices
Hz	Hertz (cycle per second)
MHz	Mega Hertz (1000x cycles per second)
eICIC	Enhanced Inter-Cell Interference Coordination, improves data throughput of multiple cells
CoMP	Co-operative Multipoint, increases data throughput of multiple cells
PMU	Power Measurement Unit
GPS	Global Positioning System (USA)
GLONASS	Russian Global Satellite System
SyncE	Synchronous Ethernet
E1/T1	Signals originally defined for use in SDH/SONET but still commonly used today