OSCILLOQUARTZ
An ADVA Optical Networking Company

How to Synchronize Telecommunications Networks

White paper

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TELECOM NETWORKS
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1 Introduction

To meet the telecommunication needs of a fast growing global economy, existing networks are being enhanced using new technologies and many new network operators are emerging after deregulation. Network synchronization is very important for switching, transmission and data networks, such as telephony, Plesiochronous Digital Hierarchy (PDH), Synchronous Optical Network (SONET), Synchronous Digital Hierarchy (SDH), and Asynchronous Transfer Mode (ATM) networks. It is essential that the telecommunication systems in these networks are synchronized to meet the Quality of Service (QoS) demanded by network users. A network planner has to understand the object of network synchronization, the related international specifications, the general synchronization network design requirements, plus the merits and limits of different synchronization methods before planning a synchronization network.

1.1 Telecommunication node

There are usually many nodes in a telecommunications network. A node can be one system or many systems connected together, e.g. a radio base station or a telephone switching and data transmission centre. Generally every telecommunication system within a node is synchronized to the node clock (Ref.4).

1.2 Node clock

A node clock is the ‘heart’ of a node. It can be inside a telecommunications system, e.g. a Digital Cross-Connect (DCC) system, or Stand-Alone Synchronization Equipment (SASE). The node clock is also called the Building Integrated Timing Supply (BITS) or Synchronization Supply Unit (SSU).

2 The Object of Network Synchronization

If the node clocks in a telecommunication network operate asynchronously then the transmit and receive rates of telecommunication systems in each node would be different to the other nodes. In this case, the input buffers of the telecommunication systems would frequently overflow or underflow, causing data errors commonly referred to as slips. (Ref.1, Ref.2, Ref.5)

The object of network synchronization is therefore to avoid and to minimise slips. This can only be achieved by synchronizing all the node clocks, and hence all the telecommunication systems, to the same master clock or to a number of pseudo-synchronous (very closely matched, nearly synchronous) master clocks.

In practice, master clocks or Primary Reference Clocks (PRCs) are Cesium beam oscillators, and slave node clocks are usually Ovenised Crystal Quartz Oscillators (OCXOs).

The interruption of different services due to slips is shown in table 1.

Service	Effect of slips
Voice (uncompressed)	Only 5% of slips will lead to audible clicks
Voice (compressed)	A slip will cause a click
Facsimile	A slip can wipe out several lines
Modem	A slip can cause several seconds of drop out
Compressed video	A slip can wipe out several lines. More slips can freeze frames for several seconds
Encrypted data protocol	Slips will reduce transmission throughput

Table 1: Effect of slips on services

The slip rate between systems can be calculated by equation 1 below, and slip rates for 8k frames per second signals under various frequency differences are shown in table 2.

Equation 1:

Slips per day = frequency difference × traffic frames/second × seconds/day (86400)

Frequency difference between systems	Slip rate for 8k frames per second signals
0	0
10^{-11}	1 slip in 4.8 months
10^{-10}	1 slip in 14.5 days
10^{-9}	1 slip in 1.45 days
10^{-8}	6.9 slips per day
10^{-7}	2.9 slips per hour
10^{-6}	28.8 slips per hour
10^{-5}	4.8 slips per minute

Table 2: Frequency differences and slip rates

Apart from frequency difference, wander levels that exceed the input tolerance of telecommunication systems would also cause slips. Wander is slow modulation of the clock or traffic signals from their ideal positions in time (Ref.5) and very low frequency (μHz) wander is impossible to filter out in a synchronization network.

Contraction and expansion of transmission cables under varying temperatures generate very low frequency wander on the traffic/synchronization signals. The levels of wander generated by optical fibre and copper cables are shown in equations 2 and 3, respectively.

Equation 2:

Wander generated by optical fibre cable $\approx 80\text{ps/km/}^{o}\text{C}$

Equation 3:

Wander generated by copper cable $\approx 725\text{ps/km/oC}$

Node clocks and telecommunication system clocks can generate high amplitude (µs) wander, if they are badly designed or if their OCXOs have drifted in frequency over many years in operation (ageing). Also SONET and SDH networks can generate high amplitude wander on their tributary outputs. (Ref.10 and Ref.11)

3 International Telecommunication Union (ITU) Recommendations

3.1 ITU-T G.823 (Ref.9)

The relative wander tolerance of telecommunication systems in 2 Mbit/s digital networks must be at least 18µs. In practice, however, the relative wander tolerance of many telecommunication systems is only just above 18µs. Therefore a relative wander level above 18µs would generally cause slips and interruption to services.

3.2 ITU-T G.811 (Ref.6)

The minimum frequency accuracy, i.e. the maximum frequency offset from Co-ordinated Universal Time (UTC) for a PRC is 10^{-11}. Therefore the maximum frequency difference between any two PRCs is $2\text{x}10^{-11}$, and the maximum slip rate between two PRC synchronized (sub)networks is 1 slip in 2.4 months for 8k frames per second signals, e.g. 64 kbit/s and 2 Mbit/s signals.

3.3 ITU-T G.822 (Ref.8)

For an end-to-end inter-national tandem traffic connection as shown in figure 1, the nominal slip rate is 1 slip in 72/(n-1) days, where n is the number of pseudo-synchronous PRCs along the tandem traffic connection. Note that this equation is also applicable to intra-national tandem traffic connections.

For category (a) traffic performance, the maximum slip rate is 5 slips per day in 24 hours, for greater than 98.9% of time. According to equation 1, the overall maximum frequency difference along a pseudo-synchronous tandem traffic connection is $7.2\text{x}10^{-9}$ and only for less than 1.1% of time.

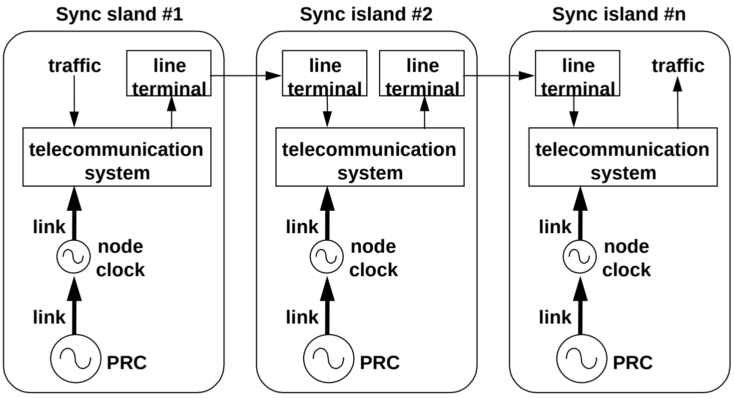

Figure 1: Pseudo-synchronous network model

The relationship between category (a) traffic performance, PRC availability, node clock availability, and link availability can be expressed by equation 4.

Equation 4:

$$0.989 \approx (\mathrm{PRC}_{avail})^{x} \times (\mathrm{nodeclock}_{avail})^{y} \times (\mathrm{link}_{avail})^{z}$$

x = total number of PRCs along the end-to-end tandem traffic connection.

y = total number of node clocks along the end-to-end tandem traffic connection.

z = total number of links between the PRC and node clocks, and the total number of links between the node clocks and the telecommunication systems along the end-to-end tandem traffic connection.

To meet ITU-T G.822 category (a) performance, according to equation 4, the availability of each PRC, node clock and link must be >>0.989 (typical network operator requirement is 0.9995). Non availability of local and transit node clocks to category (a) performance is when they have lost all their PRC synchronization network connections, i.e. when they are in hold-over mode and that their output frequencies has drifted beyond 7.2×10^{-9} and 3.6×10^{-9} (see section 3.4), respectively.

3.4 ITU-T G.812 (Ref.7)

For transit node clocks, the maximum frequency offset when entering holdover mode is 5×10^{-10} and the maximum frequency drift whilst in holdover mode is 10^{-9} per 24 hours. According to equation 1, ITU-T G.822 category (a) traffic performance is violated when a transit node clock remains in the hold-over mode for longer than 3.5 days (halved from equation 1 because slips occur at the transit node in hold-over and at the next PRC synchronized transit or local node). Therefore the repair time of a transit node failure must be less than 3.5 days.

For local node clocks, the maximum frequency offset when entering holdover mode is 10^{-8} and the maximum frequency drift whilst in holdover mode is 2×10^{-8} per 24 hours. According to equation 1, ITU-T G.822 category (a) traffic performance is violated when a local node clock remains in the holdover mode for longer than six hours. Therefore local (and transit) node clocks must be protected against single failures.

4 General Synchronization Network Design Requirements

To protect the synchronization network against single failures, the following redundancies are necessary:

a) The PRC is internally or externally duplicated or triplicated, i.e. 1+1 or 1+2 protected.

b) The node clocks are internally 1+1 protected.

c) The node clocks have two or more diverse connections to a PRC.

d) The telecommunication systems have two or more connections to their node clock.

Additionally, any autonomous protection switching in the synchronization network must not cause further network synchronization problems, especially timing loops (slave clocks synchronising back to themselves). The long term frequency offset caused by a timing loop can be 10^{-7} or higher, which would seriously degrade the quality of many services, e.g. on telephony signalling systems and Global System for Mobile communications (GSM) base stations. When a timing loop is unknowingly created, it can be very difficult to find and break.

This is because the error is often hidden and that the frequency offset is not alarmed by any slave clock or telecommunication system. Also it is impossible to determine the head end of the timing loop since there is no provision of synchronisation trace identifier in transmission signals.

5 Methods to Synchronize Telecommunication Networks

5.1 Centralised master clock network synchronization

The centralised master clock synchronization network has only one active master clock, as shown in figure 2. The master clock is logically located at the centre of the synchronization network, and the node clocks are either directly or indirectly connected to it. Since every node clock and telecommunication system clock operate at the same frequency as the master clock, there is no difference in the transmit and receive traffic rates between nodes.

Therefore the end-to-end on-net traffic slip rate is nominally zero, when there is no failure in the network.

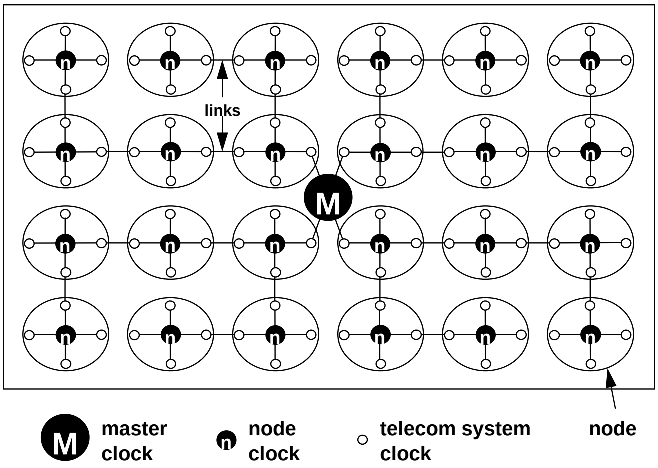

Figure 2: Centralized master clock network synchronization

To construct a centralised master clock synchronization network, it is important to ensure that the synchronisation links would not generate induce high amplitude (µs) wander on the synchronization signals. Therefore very long over-ground cables that are subject to wide temperature changes, and SONET or SDH tributary connections should not be used as synchronization links.

The synchronization signals should only be transported over SONET or SDH connections as aggregate signals, or over pure PDH connections as tributary signals. Therefore only network operators who own all their SONET, SDH or PDH transmission links could implement centralised master clock network synchronisation. (Ref. 10 and Ref.11)

If the level of wander in a centralised master clock synchronization network exceeds 18µs, then it would be necessary to partition it into several centralised master clock synchronization subnetworks.

5.2 Distribution master clocks network synchronization

The distributed master clocks synchronization network has a number of active pseudo-synchronous master clocks. It is actually a collection of small autonomous centralised master clock synchronization subnetworks (islands) grouped together. A group of small synchronisation subnetworks is easier to plan and implement than a large synchronization network. There is less wander in the subnetworks, as the PRC synchronisation subnetwork connections are shorter. Also the chance of a timing loop being accidentally created is significantly reduced, since synchronisation subnetworks are smaller. However, the nominal end-to-end on-net traffic slip rate is 1 slip in 72/(n-1) days where n is the number of pseudo-synchronous PRCs along a tandem traffic connection.

It is technically feasible to deploy a fully distributed master clocks synchronization network, as shown in figure 3, but it would be too expensive to deploy a Cesium clock in every node. An economical method to generate the required master clock signals is to use the timing from navigation receivers; e.g. Global Positioning System (GPS), to discipline the node clocks.

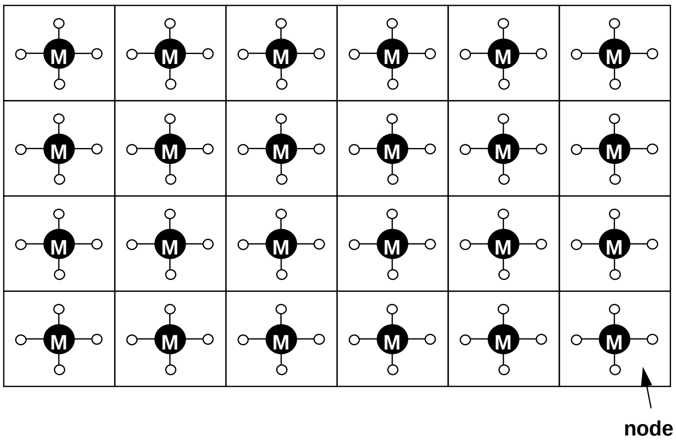

Figure 3: Fully distributed master clocks network synchronization

Although a basic GPS receiver is small and inexpensive, it must be connected to a relatively large and expensive SASE to obtain PRC performance. Ideally two GPS receivers should be deployed in each node to provide the necessary protection and availability. Therefore it is not economical to deploy fully distributed GPS master clocks network synchronization for very large networks, with more than 40 nodes as shown in figure 4.

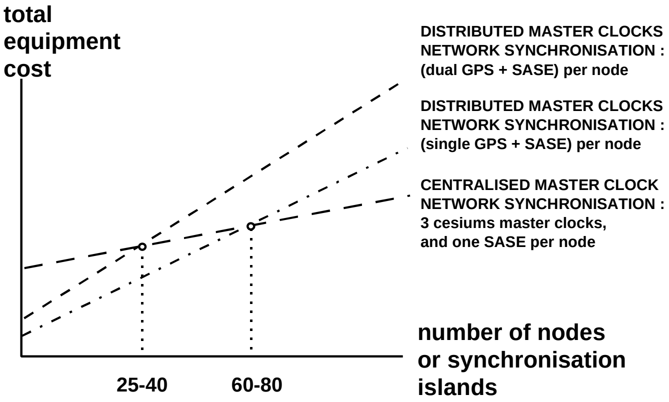

Figure 4: Cost break points of centralised master clock versus distributed master clocks network synchronization

It is more economical to deploy a partially distributed master clocks synchronization network as shown in figure 5, where each master clock is responsible for the synchronization of a regional subnetwork.

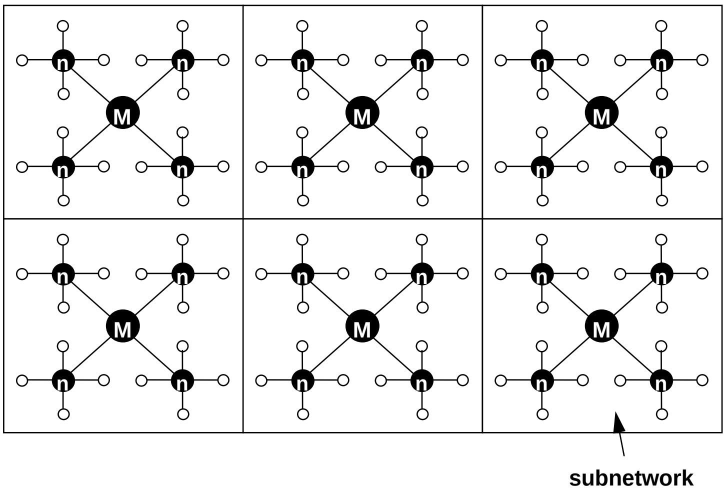

Figure 5: Partially distributed master clocks network synchronization

Note that the off-air signals from the GPS satellites can be intentionally or unintentionally jammed by a local transmitter and they can be blocked by some obstruction. In some areas, local authority planning permission is required to install the unsightly antennas. Furthermore, the active GPS antennas can be damaged by lightning hits, and that the length of the coaxial cable from the antenna is limited (typically 100m without a down-converter). Since the availability of the GPS transmission or reception cannot be guaranteed, it is prudent to use as many GPS receivers as necessary and as few as possible, or only use the GPS timing signals as back-ups.

5.3 Clocks signals from a co-operating network

If a co-operating (or adjacent) network has master clock signals that are easily accessible then a network planner could, in theory, use them to synchronise his network. In this case his synchronisation network is slaved to the co-operating network, and both networks are operating at the same frequency. Therefore the slip rates for on-net and off-net traffic to the co-operating network are nominally zero. However, any disturbance in the master synchronization network would also disturb the slave synchronization network. Hence the quality (e.g. frequency offset, wander amplitude and signal availability) of the clock signals from the co-operating network must be fully specified and guaranteed before they are used.

Clock signals from a co-operating network can be received at a few synchronization gateway nodes only, as shown in figure 6, or at every node as shown in figure 7. Figure 6 is equivalent to centralised master clock network synchronization, and figure 7 is equivalent to fully distributed master clocks network synchronization.

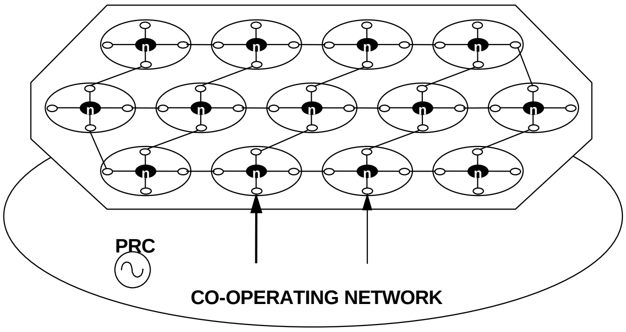

Figure 6: Clocks signals from a co-operating network to two gateway nodes

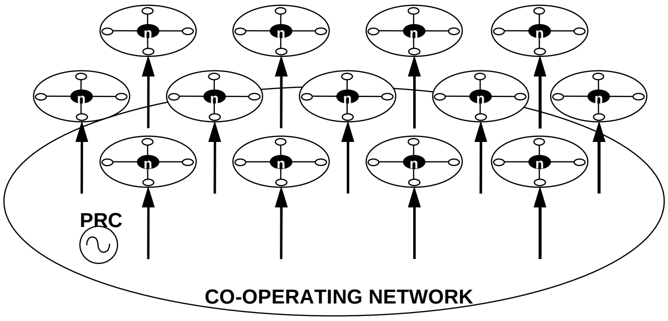

Figure 7: Clocks signals from a co-operating network to every node

If a co-operating network operator guarantees the master clock signals, then there is usually a significant fee involved. The cost to lease many clock signals could be very high, and therefore it would make this method uneconomical for large networks with many nodes as shown in figure 8.

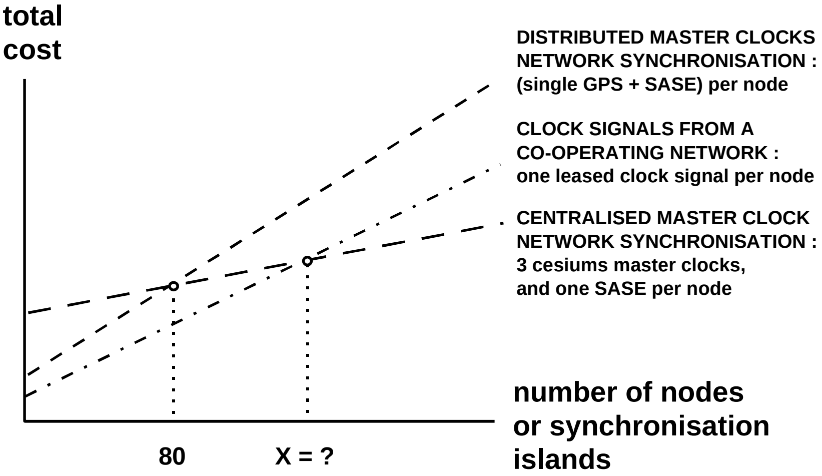

Figure 8: Cost break points of using clock signals from a co-operating network versus centralized and distributed master clocks network synchronization

A low cost solution is to use a few guaranteed leased master clock signals from a co-operating network to synchronize a small number of subnetworks as shown in figure 9.

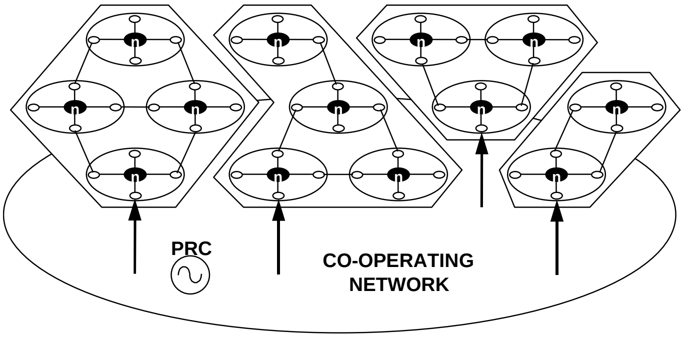

Figure 9: Clocks signals from a co-operating network to four subnetworks

6 Which Network Synchronization Method?

Table 3 summaries the features of different network synchronization methods. For each synchronization method, there is a maximum or minimum network size for optimum cost. A network synchronization solution may be inexpensive when the network is small, but would become very expensive when the network grows beyond a certain size.

Therefore, a network planner should weight the technical and financial merits of each network synchronisation method, for the foreseeable growth of his traffic network, before choosing a final solution.

Since each network synchronization method has different merits and drawbacks, and that the structure of every telecommunications network is different, it is impractical to apply the same network synchronization method to every network. Therefore a network planner should verify the practicality of each network synchronisation method on a realistic paper or computer model before choosing a final solution.

It is possible that an optimum solution would involve all the aforementioned network synchronization methods. Figure 10 shows a synchronization network partitioned into a few synchronization subnetworks that are individually synchronized by a primary PRC and a secondary clock signal from a co-operating network.

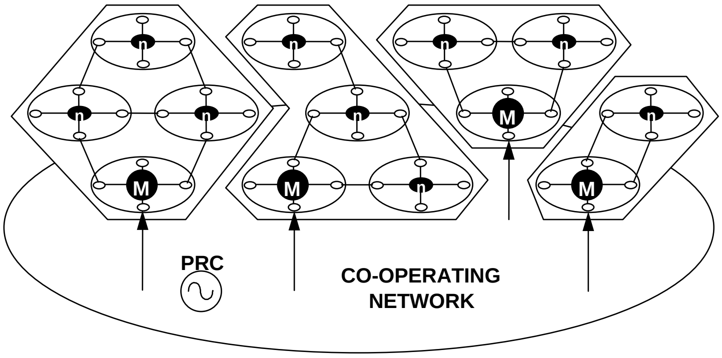

Figure 10: Hybrid network synchronization

Synchronisation method	Network planning	Chance of creating timing loops	Network wander level	Nominal on-net slip rate	Synchronisation links required between nodes	Network size for optimum cost
Centralised master clock	Slightly Difficult	Very low if the sync plan is well designed	High for large networks covering wide areas	Nil, if the network wander levels are within limits	Own SONET or SDH aggregate. Own or leased tributaries over pure PDH connections	>40 nodes
Fully distributed master clocks	Very easy	Impossible	Negligible	1 slip in $\frac{72}{(n-1)}$ days n = number of master clocks	None	<40 nodes
Partially distributed master clocks	Easy	Very low for small sub-networks with well designed sync plans	Low for small sub-networks	1 slip in $\frac{72}{(n-1)}$ days n = number of master clocks	Own SONET or SDH aggregates. Own or leased tributaries over pure PDH connections	<40 sub-networks
Fully distributed clock signals from a co-operating network	Very easy	Impossible	Dependent on the co-operating network	Zero for on-net and off-net traffic to the co-operating network	None	Depends on the cost of leased clock signals
Partially distributed clock signals from a co-operating network	Easy	Very low for small sub-networks with well designed sync plans	Dependent on the co-operating network	Zero for on-net and off-net traffic to the co-operating network	Own SONET or SDH aggregates. Own or leased tributaries over pure PDH connections	Depends on the cost of leased clock signals

Table 3: Summary of features for various network synchronization methods

7 Conclusions and Recommendations

Each network synchronization method has its unique merits or limits, and there is no generic solution for every network. However, the following recommendations are generally applicable:

a) If a traffic network is constructed using own PDH, SONET or SDH transmission links, then any aforementioned synchronization method can be deployed. However, the optimum (cost versus performance) solution for a network with more than 40 nodes is centralized master clock network synchronization.

b) If a traffic network is constructed using SONET or SDH tributaries (e.g. leased lines), then fully distributed master clocks network synchronization or fully distributed clock signals from a co-operating network can be deployed. Note that the latter method is only recommended if the clock signals are fully specified and guaranteed to have very high availability to ITU-T G.811 performance.

c) If a centralized master clock synchronization network is found to have excessive levels of wander, i.e. the Maximum Time Interval Error (MTIE) and Time Deviation (TDEV) measurements are above the international recommendations, then it is necessary to adopt distributed master clocks network synchronization.

Also an initial synchronization solution may evolve to other synchronization solutions at different phases of the network. e.g. a network synchronization strategy could be:

a) Phase 1 - fully distributed clock signals from a co-operating network.

b) Phase 2 - partially distributed GPS master clocks and clock signals from co-operating network as back-up.

c) Phase 3 - centralized Cesium master clock and partially distributed GPS master clocks as back up.

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