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Do CDMA based mobile networks need to be synchronized?

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Mobile communication networks based on the cdmaOne and cdma2000 standards require that the base-stations of their radio access networks be synchronized. All the base-stations of the network need a 1PPS phase reference with an accuracy of 3 µs. The Global Positioning System (GPS) is currently the only practical way of implementing this type of synchronization. This paper proposes a two-fold protection concept for the base-station's phase clock. In case of a GPS-reception problem, the phase reference signal is maintained using the auxiliary frequency reference signal taken from the SONET (Synchronous Optical Network) transport network. When the latter fails (double failure), the clock eventually enters holdover mode. The paper analyses the performance of the two protection modes, and compares it to the requirements of CDMA-based mobile networks.

Precision, Stability, Innovation, Support

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1 Introduction

Third Generation (3G) mobile communication networks are currently being deployed in several countries. These new networks will eventually replace today's D-AMPS and GSM mobile telephony networks. 3G networks will bring new services such as Internet access and multimedia applications. These new services are made possible by the higher data rates provided by 3G technologies. The term 3G actually includes a family of different mobile communication technologies. cdma2000 is one of these 3G technologies. cdma2000 is an evolution of the already existing cdmaOne. Networks based on the cdmaOne and cdma2000 standards require that the base-stations of their radio access networks be synchronized. All the base-stations need a 1PPS (1 Pulse Per Second) phase reference with an accuracy of 3 µs. This phase-synchronization is required in order to support handover of a connection when the user moves from one radio access network cell to another. During this move, the connection must be handed over from the base-station of the first cell to the base-station of the second cell.

The Global Positioning System (GPS) is currently the only practical way of implementing this type of synchronization. This means that all base-stations of a cdma network must be equipped with a GPS-receiver capable of delivering a 1PPS signal with 3 µs accuracy. This is easily achieved with GPS — most GPS-receivers optimised for timing provide accuracies in the range of 20 to 100 ns. Mobile communication networks also require a high degree of availability, since safety critical user applications rely more and more on public mobile networks. Although the GPS has an excellent system availability track record, there is a real possibility of radio interference at some base-station sites. In order to protect a base-station against failures caused by radio interference problems, the base-station’s clock must be able to provide the 1PPS phase reference for some time under failure conditions affecting the satellite to receiver chain. The usual way of achieving this is by using the base-station clock’s holdover mode. An alternative is to use a clock that can be slaved not only to the GPS as a primary reference, but also to an auxiliary external signal. This additional signal is extracted from the transport network. SONET (Synchronous Optical Network) transport networks work with frequency-synchronous optical carrier signals. The idea is to derive a frequency reference signal from that optical carrier, and to use this reference to drive the base-station clock in case of failing GPS-reception. The base-stations clock has three operation modes:

1. Phase-locked Mode (PM): the clock is phase-locked to the GPS-receiver
2. Frequency-locked Mode (FM): the clock is locked to an external frequency reference signal
3. Holdover Mode (HM): the clock runs on its internal oscillator

These operation modes provide a double protection for the base-station’s phase reference signal, i.e. for the 1PPS signal. In case of a GPS-reception problem, the phase reference signal is maintained using the auxiliary frequency reference signal (Frequency-locked Mode). When the latter fails (double failure), the clock eventually enters Holdover Mode. An interesting question is: “For how long can the required 1PPS accuracy be maintained under failure conditions?” This depends mainly on the stability of the frequency reference signal derived from the transport network, and the holdover performance of the internal oscillator.

2 Clock Structure

Figure 1 shows the logical bloc diagram of a GPS-clock providing the three operation modes mentioned earlier. The blocs shown in the diagram have the following functions:

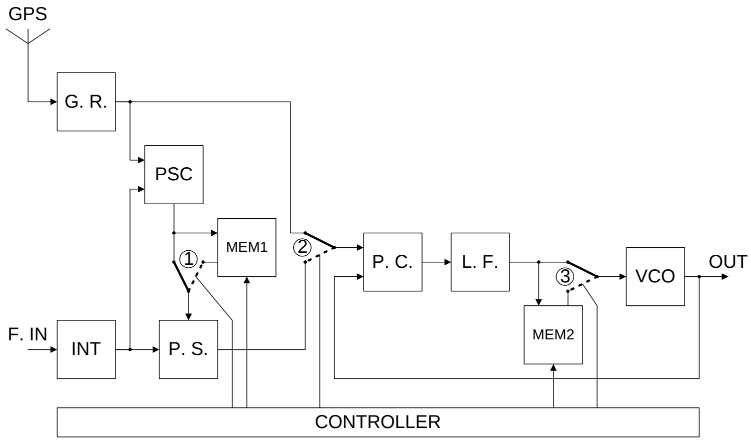

Figure 1: GPS-receiver with Phase-locked, Frequency-locked and Holdover Modes.

G. R.: GPS-receiver, which delivers a 1 PPS signal.

INT: Interface for the frequency reference signal coming from the transport network; derives a 1PPS signal from the input signal, which typically comes with a rate of 1544 kbit/s.

P. S.: Phase Shifter; the phase shifter adds a delay to the 1PPS signal derived from the frequency reference signal ; this delay is adjusted by the Phase Shift Controller PSC, so that the delayed 1PPS signal is always in phase with the PPS signal coming from the GPS-receiver.

PSC : Phase Shift Controller; see above.

MEM1: This digital memory continuously stores the control information used to steer the Phase Shifter; this control information is used in case of failure of the 1PPS coming from the GPS-receiver.

MEM2: The second digital memory stores the control signal that normally steers the VCO; in case the system enters Holdover Mode, the last stored control signal value is applied to the VCO.

L. F.: This is the PLL's loop filter.

P. C.: Phase comparator ; it measures the phase difference of the 1PPS signal coming from the front end, and the 1PPS signal fed back from the clock's output; the phase comparator is part of a conventional Phase Locked Loop (PLL).

Switch 1: This switch is normally in the left position (Phase-locked Mode); in case of failure of the 1PPS coming from the GPS-receiver, the switch selects the output of the memory as the new control signal for the Phase Shifter; this switchover puts the system into Frequency-locked Mode.

Switch 2: This switch is in the upper position in Phase-locked Mode, and in lower position in Frequency-locked Mode.

Switch 3: This switch is in upper position when the system is in Phase-locked or Frequency-locked Mode; moving the switch to the lower position causes the system to enter Holdover Mode.

VCO: This is the internal oscillator; normally, i.e. in all operation modes except in Holdover Mode, the VCO is part of the loop forming the PLL.

The important point in the block diagram (Figure 1) is the presence of the two digital memories. There is one used for holding information about the last measured phase (MEM1), and another one for holding information about the last measured frequency (MEM2). The value stored in MEM1 is used when the system switches from Phase-locked Mode to Frequency-locked Mode. The stored value is applied to the phase shifter, in order to make sure that the 1PPS signal at its output is in phase with the GPS. The value stored in MEM2 is used when the system enters Holdover Mode. The stored value is applied to the VCO, in order to make sure it generates the same frequency as it was locked to just before the switchover event.

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 $2x10^{-11}$, 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 $7.2x10^{-9}$ and only for less than 1.1% of time.

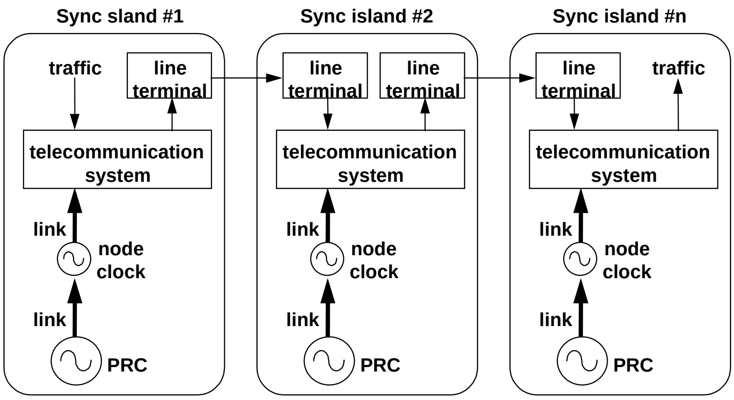

Figure 1: Pseudo-synchronous network model

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

Equation 4:

$0.989 \approx (PRC_{avail})^x \times (nodeclock_{avail})^y \times (link_{avail})^z$

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 $7.2x10^{-9}$ and $3.6x10^{-9}$ (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 $5x10^{-10}$ 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 $2x10^{-8}$ 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.

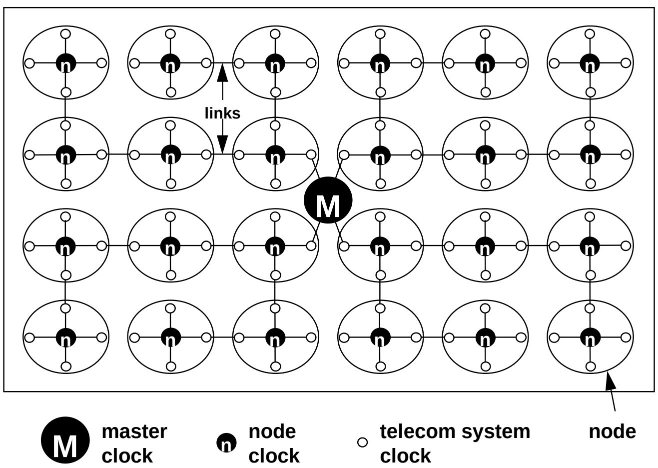

Figure 2: Centralized master clock network synchronization

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.

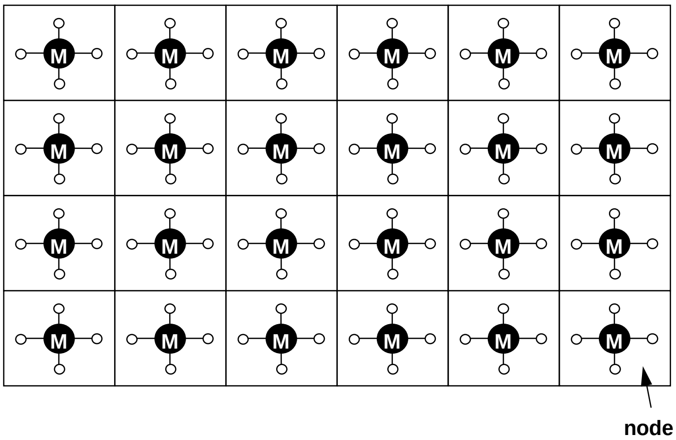

Figure 3: Fully distributed master clocks network synchronization

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.

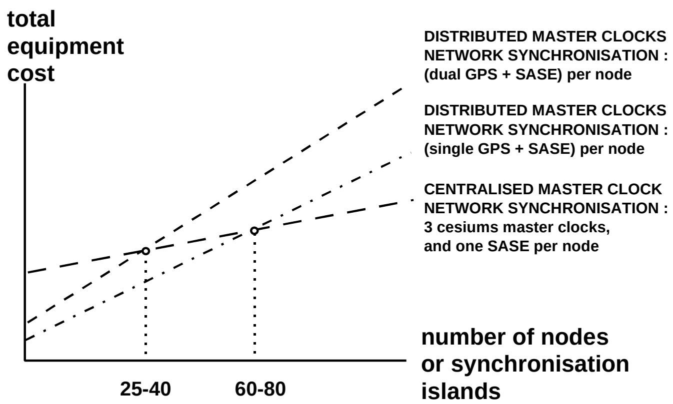

Figure 4: Cost break points of centralised master clock versus distributed master clocks network synchronization

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.

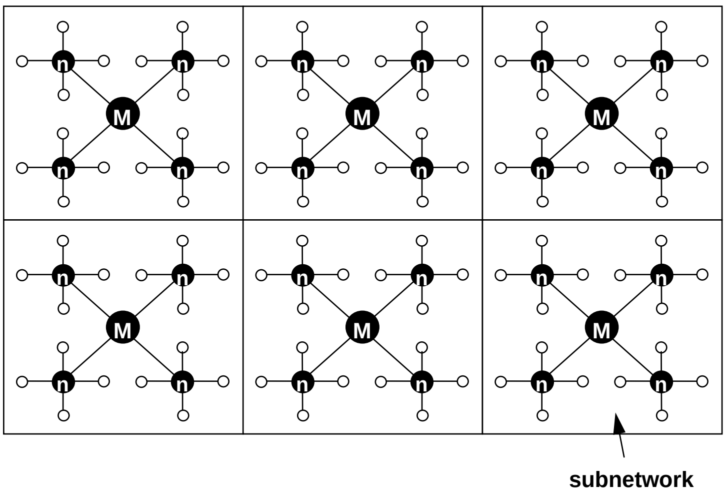

Figure 5: Partially distributed master clocks network synchronization

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.

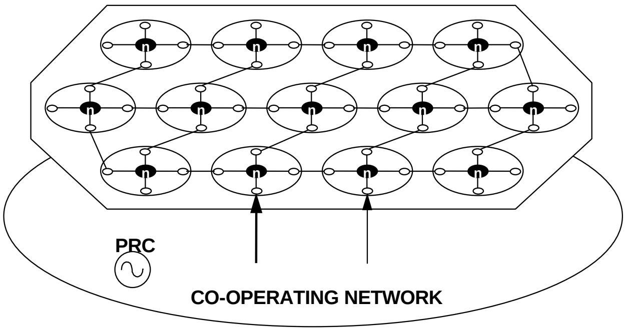

Figure 6: Clocks signals from a co-operating network to two gateway nodes

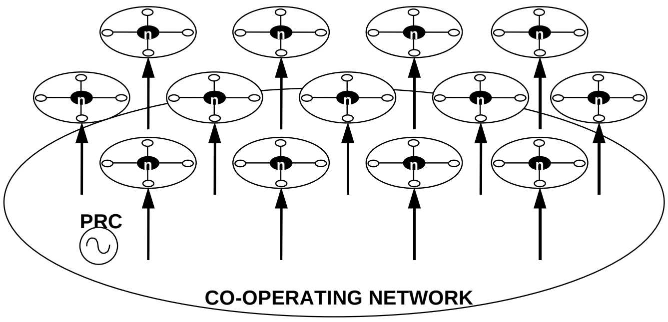

Figure 7: Clocks signals from a co-operating network to every node

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.

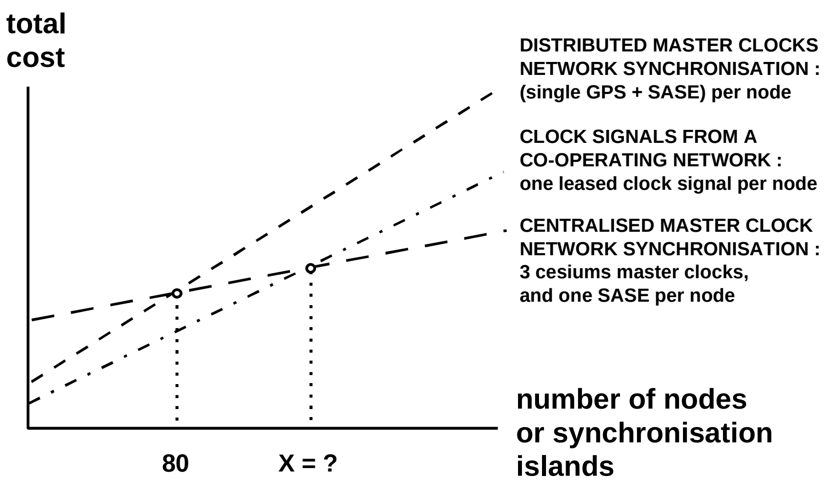

Figure 8: Cost break points of using clock signals from a co-operating network versus centralized and distributed master clocks network synchronization

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.

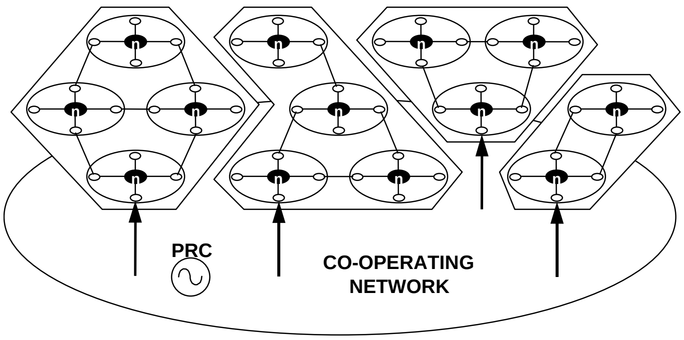

Figure 9: Clocks signals from a co-operating network to four subnetworks

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.

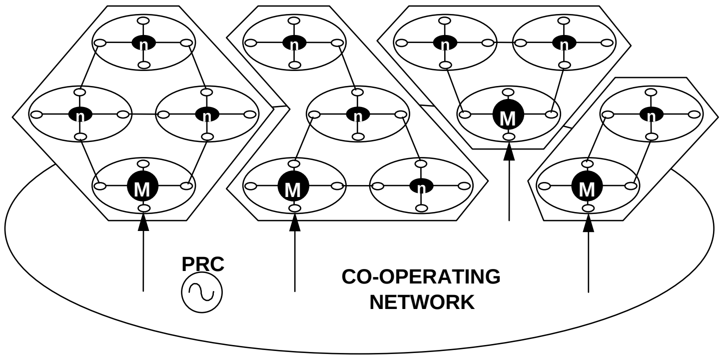

Figure 10: Hybrid network synchronization

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.

8 References

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