

Synchronization in packet-based networks: challenges and solutions

A range of technologies can be used to deliver synchronization solutions in next-generation packet networks. And there may be more than one solution in which a network employs multiple transport technologies – for example, in the mobile backhaul. To ensure that the overall business objectives are met, the solution of choice is dependent on a detailed understanding of the requirements.

Market trends

Access transport networks are evolving from dedicated-service, narrowband and highly bit-optimized PDH/SDH-based networks to multiservice, wideband and over-provisioned packet-based networks. At the same time, the demand for greater bandwidth continues to grow unabated. This demand is being fueled by fixed and mobile broadband as well as offerings such as IPTV, video on demand (VoD) and peer-to-peer services.

For high-capacity low-cost services to be commercially viable, operators must decrease their per-bit production costs. Accordingly, access networks are destined to become

large bit pipes for transporting multiple services. Apart from providing a stipulated quality of service (QoS) and standard traffic separation, they will offer very little functionality. To enable the use of standard, cost-effective transport equipment, the services that use access networks may put only limited requirements on transport.

The passing of reference synchronization sources over transport networks also becomes an issue as operators move from time division multiplexing (TDM) to asynchronous transport technologies.

Synchronization requirements in packet networks

Phase, time and frequency synchronization

Network synchronization is a generic concept that depicts a way of distributing common time and frequency references to all the nodes of a network in order to align their time and frequency scales.

Generally speaking, synchronization is the act of synchronizing the operation of different devices or processes by aligning their time scales. The term is also regularly used to indicate a common frequency, whereas the more appropriate term is syntonization. The term frequency synchronization is also frequently mentioned and will be used throughout this paper.

The term phase synchronization implies that all associated nodes have access to a reference timing signal whose rising edges occur at the same instant. This term might also include the notion of frame timing (that is, the point in time when the time slot of an outgoing frame is to be generated).

Time synchronization is the distribution of an absolute time reference to the real-time clocks of a telecommunications network. All the associated nodes have access to

information about absolute time (in other words, each period of the reference timing signal is marked and dated) and share a common timescale. Note that distributing time synchronization is one way of achieving phase synchronization.

The standard timescale of the International Telecommunication Union (ITU) is Coordinated Universal Time (UTC). UTC can be distributed using time of day (ToD) information through radio and satellite navigation systems, telephone modems, and portable clocks. Effective and convenient distribution of ToD calls for a hierarchical time synchronization network and a protocol that can read a server clock, transmit the data to one or more clients, and adjust each client clock.

In internet protocol (IP) networks, the protocol of choice is the network time protocol (NTP). Developed by David Mills at the University of Delaware, NTP has become an industry standard for synchronizing time in computers and network equipment. The protocol is based on messages transported over IP and user datagram protocol (UDP) packets.

One of the main issues to address when deploying next-generation networks is the distribution of timing over packet networks. A key aspect of these networks is that all service-related functions are independent from the underlying packet-based transport technologies.

Packet switching was originally introduced to handle typically asynchronous data, but the ongoing evolution of packet networks calls for new and challenging synchronization requirements, including the distribution of synchronization over asynchronous media, such as traditional Ethernet networks. Relevant standardization bodies are already extensively involved in specifying requirements and solutions for the correct operation of TDM transport over packet networks and for the distribution of reference timing signals over packet networks.

Two main aspects summarize the need for synchronization (frequency, phase or both) in

packet networks. These are:

- support of the services carried over the packet network (including proper interworking with legacy TDM networks); and
- support of the end-application operations, such as radio base stations.

The equipment deployed at the edges of the packet networks generally drives the synchronization requirements, not the transport network elements. This differs from TDM networks, where the synchronization requirements also relate to the operation of the transport network itself. For example, frequency synchronization must be employed for SDH network elements in order to limit pointer adjustments and to meet the strict jitter and wander limits that apply to network interfaces.

Because packet networks do not inherently carry synchronization new solutions are necessary.

Frequency synchronization

Packet networks rely on frequency synchronization to handle the TDM interfaces at the network boundaries. The task of generating and carrying the correct timing of TDM services over packet networks is termed Circuit Emulation Service Clock Recovery. The requirements are defined in terms of

- proper recovery of the long-term accuracy of the original timing reference; and
- controlling phase noise according to relevant standards (for instance, ITU-T G.8261 wander budget, and ITU-T G.823 traffic interface masks).

A typical application, in terms of supporting end-applications, entails supporting frequency synchronization requirements for the air interface. To minimize disturbance, to facilitate handover between base stations, and to fulfill the regulatory requirements, various mobile technologies,

such as GSM, WCDMA and LTE, stipulate that the radio signal must be generated in strict compliance with frequency accuracy requirements (see Table 1).

Table 1. Frequency accuracy requirements put on the radio signal

Mobile technology	Frequency accuracy requirement
GSM (ETSI TS 145 010)	50ppb or 100ppb (pico base station)
WCDMA (3GPP TS 25.104, TS 25.105)	50ppb (wide area), 100ppb (local area), 250ppb (FDD home base stations)
LTE (3GPP TR 36.104)	50ppb (wide area), (local area and home base stations under definition)

Phase and time synchronization

Phase synchronization is often needed to support additional requirements for the air interface, as in the case of TDD systems (for instance, LTE TDD) or when supporting multimedia broadcast/multicast service (MBMS).

Ordinary WCDMA MBMS does not require accurate phase synchronization, since it has been specified and designed to work properly in networks that satisfy the 50ppb frequency accuracy requirement. This requirement, which is guaranteed by the WCDMA node synchronization function (see 3GPP TS 25.402), limits phase drift to between 10ms and 20ms.

But when MBMS is based on single-frequency network (MBSFN) mode, timing must be accurate to within a few microseconds. This is because identical waveforms are transmitted simultaneously from multiple cells. The signals from these cells are then combined as the multipath components of a single cell. Terminals must thus perceive the signals of an entire group of transmitting cells as though they came from a single cell. Therefore, all transmissions must be very tightly synchronized and deliver exactly the same content to each base station.

When the radio access in the UMTS mobile system is based on UTRA-TDD (for instance, TD-CDMA, TD-SCDMA) the timing between base stations must be accurate to within 3 μ s (see 3GPP TR 25.836). Similar requirements apply to LTE-TDD systems. However by putting some limitations on the deployment (for instance, cell range or isolation) and radio frame configuration, one can define LTE TDD

systems to operate with phase accuracy to within tens of microseconds.

Phase synchronization might also apply to GSM systems in order to synchronize the phase of transmissions from different base stations. By synchronizing phase in the GSM radio access network, one can optimize the use of bandwidth and enhance radio network capacity. In this case, the phase synchronization of base station transmissions must be accurate to less than one microsecond.

Time synchronization is required to support billing and alarm functions. In this context, synchronization must be accurate to within hundreds of milliseconds.

Stringent time synchronization requirements may apply to the generation of signals over the air interface. In the case of CDMA2000, for example, the time error should be less than 3 μ s (see 3GPP2 C.S0010-B and 3GPP2 C.S0002-C). This same requirement applies to LTE FDD unicast, in order to support synchronous CDMA2000 interworking.

One emerging time-synchronization application is the monitoring of delays in IP networks. In this case, the requirement is accuracy to within a few hundreds of microseconds.

Other end-applications, such as voice over IP (VoIP) or IPTV, might also require synchronization (frequency or time) although the associated requirements are usually less stringent. For voice services, for instance, frequency accuracy of 4.6ppm is considered adequate.

Solutions from a system integrator and network operator perspective

The sections that follow present an overview of potential synchronization solutions. The focus is on the analysis of wireless networks and circuit-emulation services, which put

some very challenging requirements on synchronization.

The need for synchronization in TDM networks (SDH or PDH) is well understood.

Providers of TDM circuit services typically maintain a timing distribution network that uses the physical layer to carry a reference timing signal that can be traced to a primary reference clock.

GSM and WCDMA base stations that are connected via TDM networks can be synchronized via TDM timing (PDH or SDH). Following a master-slave architecture, the timing (frequency

synchronization) is distributed over the TDM links from an accurate primary reference clock to slave clocks.

When the timing is carried by PDH links, the slave clocks must be able to tolerate the wander carried by traffic signals. The tolerance figure is driven mainly by the 50ppb requirement put on the air interface (typically up to 16ppb can be accepted in the long term at the input of the base station).

Frequency synchronization

The following options may be considered for distributing a reference timing signal that supports frequency synchronization:

- ❖ Distributed PRC arrangements – for instance, by implementing a GPS receiver at the end-application.
- ❖ Master-slave arrangement over TDM or other physical layers, such as synchronous Ethernet or microwave (with the master signal based on cesium or

GPS technology).

- ❖ Packet-based methods deployed without timing support from the network, using NTP or PTP packets.
- ❖ Packet-based methods deployed with timing support from the network nodes, using NTP or PTP packets.
- ❖ Traffic packets (for instance via RTP packets that carry circuit-emulated E1s).

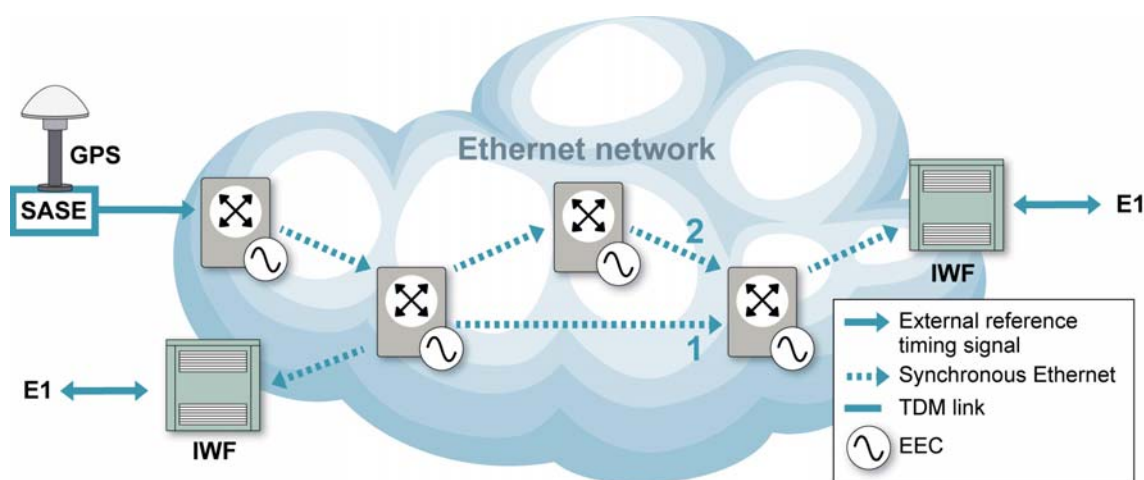


Figure 1: Example of synchronous Ethernet supporting E1 CES

Solutions based on synchronous Ethernet

ITU-T Recommendations G.8261, G.8262, and G.8264 define the distribution of timing over synchronous Ethernet physical interfaces. The system clock (Ethernet equipment clock, EEC) uses the bit rate carried by the Ethernet physical interfaces

and drives the frequency of all outgoing interfaces (see figure 1).

This method can only be used to distribute frequency synchronization. The performance in this case is the same as that of an SDH-based synchronization network. Two advantages of using synchronous Ethernet are that the related performance is

independent of packet delay variations, and the synchronization network can be built as per SDH practice. This solution presents some aspects that need to be considered:

- All network elements in the distribution path between the master and the end-application must support synchronous Ethernet.
- The operating expenses for managing a synchronization network based on the physical layer (such as synchronous Ethernet) are generally higher than for a flat synchronization network (that is, PRC-distributed architecture), or for packet-based solutions deployed without support from the transport network.

- The task of planning network synchronization is complicated, primarily due to the installed base of equipment that does not support synchronous Ethernet.
- The use of other technologies in the access network (for instance, VDSL) requires proper interworking between different synchronization techniques. In some cases, however, the necessary interworking solutions might not yet exist.
- Synchronous Ethernet can only be implemented within one network operator domain; that is, the timing of a mobile operator generally cannot be distributed across the transport network of a different operator (see figure 2).

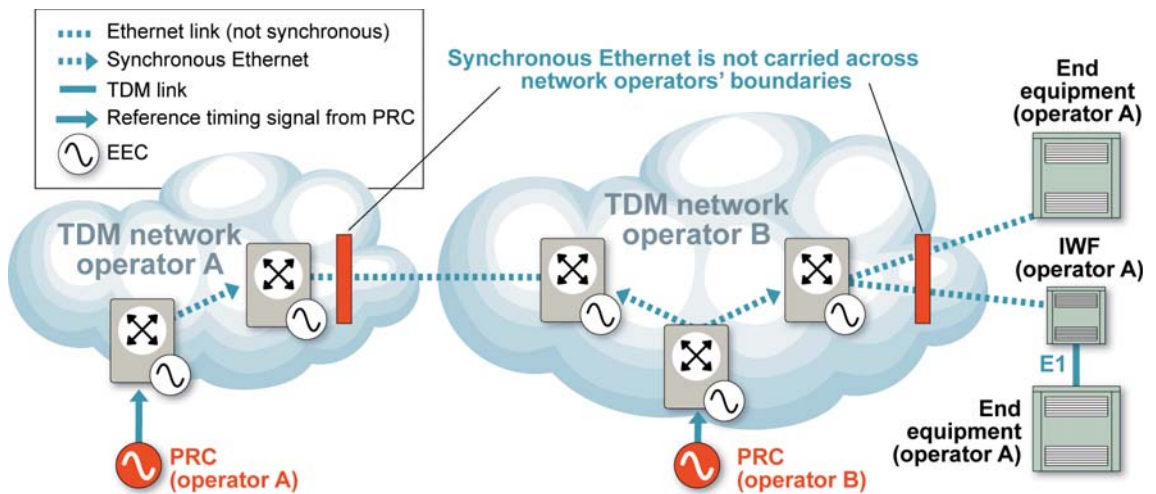


Figure 2: Synchronous Ethernet can only operate within one network operator domain

Note: When interworking occurs between operators at the TDM level and the traffic is carried via circuit emulation, synchronous

Ethernet could be a suitable option for supporting the differential clock-recovery method (see figure 3).

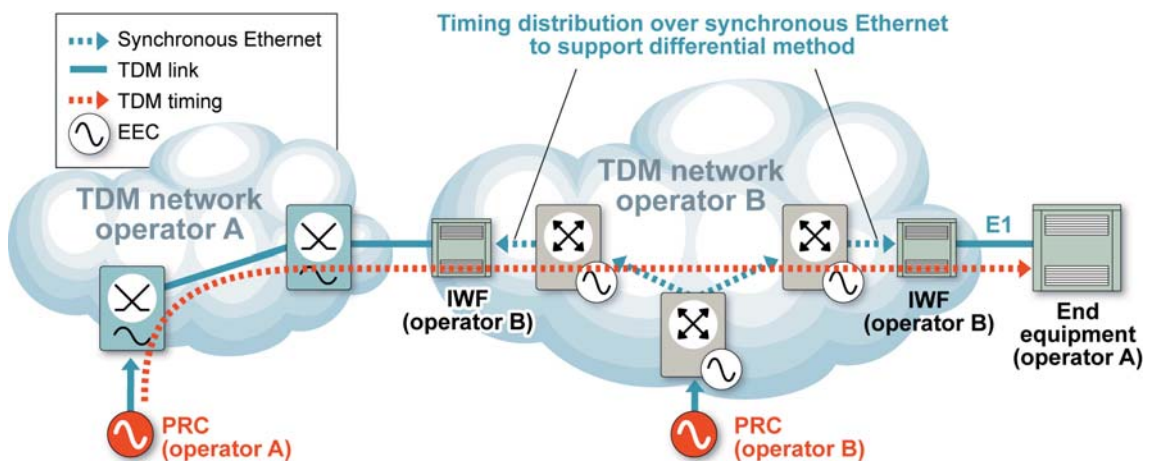


Figure 3: Synchronous Ethernet supporting differential CES method

Packet-based solutions

Packet-based methods distribute timing via packets that carry timestamps generated by a master (server) that has access to an accurate reference, such as GPS (see figure 4).

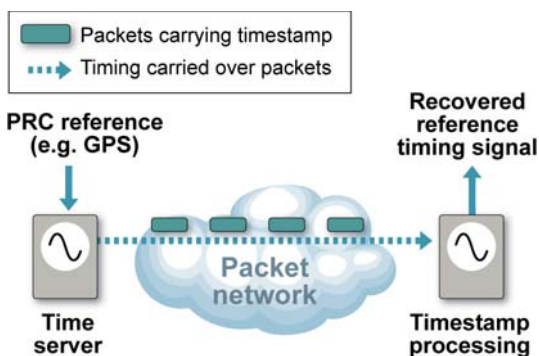


Figure 4: Packet-based methods of distributing synchronization

The receiving equipment typically recovers the timing by comparing the local timing with the arrival times of the packets. Therefore, when deploying packet-based solutions, one must take into account the impact of packet delay variation in the network. Indeed, the ability of the clock recovery algorithm to filter the packet delay variation is a key aspect of defining the performance of packet-based methods, especially when they are used without processing and hardware or software support in the network nodes.

A related aspect is the quality of the oscillator in the receiving equipment. An OCXO, for example, can tolerate much

greater packet delay variation than a TCXO.

Generally, the actual packet format used has very limited impact on the achievable performances.

The main packet protocols currently defined are network time protocol (NTP) and precision time protocol (PTP). NTP (v3 is defined in RFC 1305 and v4 is going to be released soon) is a layer-3 protocol that distributes time of day. The NTP specifications define both a protocol and an algorithm for distributing time. The NTP packets can also be used to distribute a frequency reference. Note, however, that to recover frequency, a separate and specific timing-recovery algorithm must be developed.

PTP, defined in IEEE 1588, was initially introduced to be used in industrial automation and test and measurement environments. IEEE 1588 v2 includes features that make it suitable for use in telecommunications. IEEE 1588 solely defines a protocol – no algorithm has been standardized for recovering timing. Packet delay variation is filtered by using proprietary algorithms in much the same way as when NTP packets are employed.

The PTP packets can be used without any support from the network elements. However, much of the interest in PTP relates to the additional functions that the intermediate nodes implement to reduce the impact of packet delay variation. These aspects are relevant for supporting strict time and phase requirements.

Strict time and phase synchronization

Strict time and phase synchronization applies to applications that require accuracy to less than a microsecond or to within a few microseconds. If this is the case, the following options should be considered:

- ❖ A distributed PRC approach, implementing a global navigation satellite system (GNSS) receiver in the end-application (a GPS receiver, for example).
- ❖ Packet-based methods (typically with support of intermediate nodes).
- ❖ Proprietary methods (for instance, via radio signals).

At present, the only reliable solution is based on GNSS.

Hardware as well as software support is under definition for the intermediate network nodes (for example, Ethernet switches) when packet-based methods are used to distribute accurate time synchronization, phase synchronization, or both. In the case of PTP, these functions are the boundary and transparent clocks (see figure 5).

The transparent clock provides a means of measuring the delay that has been added by the network element and of measuring the

delays on links connected to the network element. The end-equipment can use this information to recover the time reference. The boundary clock, by contrast, terminates and regenerates timestamp packets.

Note: In addition to packet delay variation, asymmetry in the network affects performance when time is distributed via packet-based methods. This aspect also impacts the way a packet-based solution can be engineered from a network perspective – for instance, in terms of network size and

synchronization redundancy.

It should be possible to distribute accurate time and phase synchronization in a network where all the nodes implement boundary and transparent clock functions. Please note, however, that the requirements put on the transport network are severe: Every network element must implement specific hardware and software functions. Moreover, it may be problematic to implement this kind of solution when the RAN and transport infrastructure have different operators.

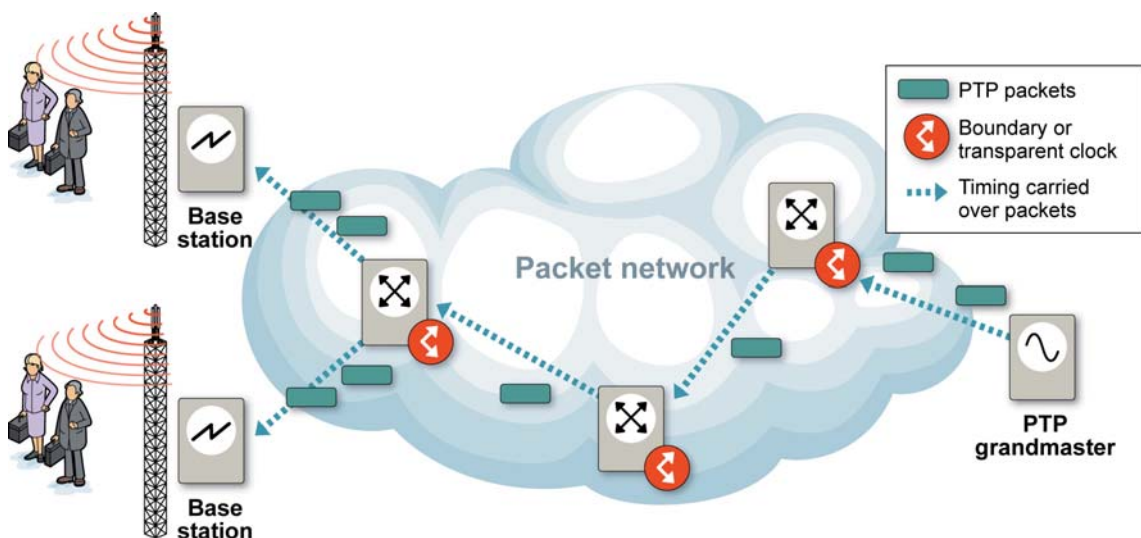


Figure 5: Packet-based method with support from network nodes

Less strict time and phase synchronization

When the time and phase synchronization requirements are less strict, packet-based methods (for example, using NTP) without timing support from the network could be used to support applications with

requirements for accuracy down to a few milliseconds. In a controlled environment, they may be used for applications with requirements down to hundreds or tens of microseconds.

CES timing recovery

The interworking function has three main options for recovering the timing of CES services as follows:

- Network synchronous method – the timing of the service (for example, E1) is synchronous with the timing of the synchronization network.
- Differential method – the timing of the service is recovered using the timing of the

synchronization network as reference; the difference in frequency between the service clock signal and the network clock signal is carried via messages over the packet network.

- Adaptive method – the timing is generally recovered by comparing the expected arrival time as calculated by the local oscillator with the actual arrival time.

Choosing a solution

Given the complex scenarios associated with next-generation networks (NGN), operators must carefully consider the synchronization solution. Below follow some of the considerations they should bear in mind when determining whether or not a synchronization solution is feasible and effective at meeting business objectives:

- What are the relevant synchronization

requirements (support of LTE TDD, FDD, CES, and MBSFN)?

- Will there be a single network operator domain or will interworking be an issue between operators?
- Is there a mixture of technologies (IP, Ethernet, SDH, xDSL, microwave)?
- Is this a greenfield deployment or is there any legacy equipment?

Packet-based methods for delivering frequency synchronization in the RAN

To provide a solution that is always feasible and effective for mobile applications, network operators should control synchronization from within the RAN domain without putting additional requirements on the transport network.

This is fully possible for GSM, WCDMA FDD and LTE FDD base stations. Indeed, given that the base stations have a stable oscillator, one can employ packet-based methods without timing support from the

network (for example, transparent clock type of functions).

A solution that uses NTP packets has already been successfully deployed in mobile networks. The solution uses an NTP time server with access to an accurate reference (such as GPS) to control the frequency of oscillators in the base station. The NTP server may be integrated into telecom platforms (such as the RNC) or deployed as standalone equipment (see figure 6).

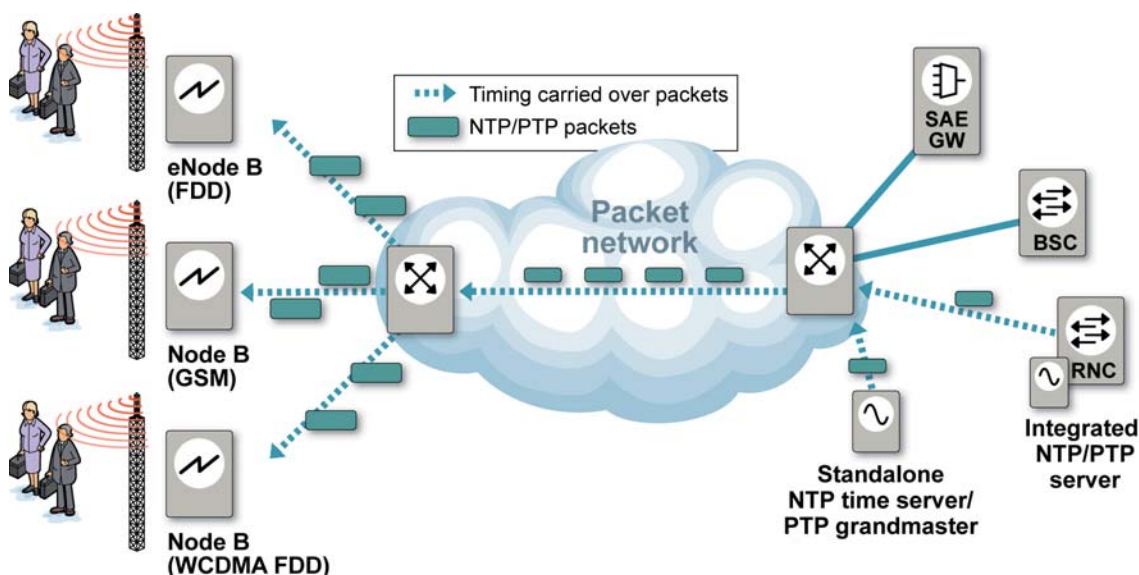


Figure 6: Packet-based method that supports frequency synchronization in the RAN

Figure 7 shows the frequency deviation at the output of a GSM pico base station OCXO, which is synchronized via NTP packets

distributed over ADSL links. The deviation is well within the requirements for the period of operation (one month shown).

Recovered frequency accuracy (BS output) over 1 month

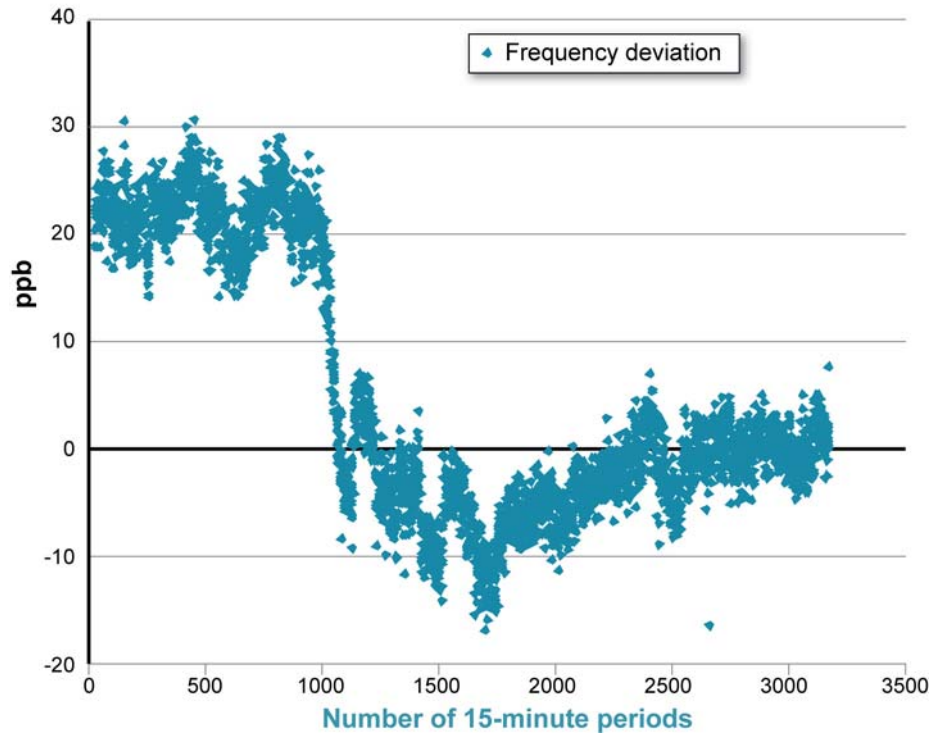


Figure 7: Test results over ADSL connections (period of operation: one month). Despite the challenging environment (the measured packet delay variation in this ADSL connection ranged from hundreds of microseconds up to about 10ms), the frequency deviation on the recovered timing signal for this period was well below the +/- 100ppb requirement for the pico base station application

The use of PTP (IEEE1588 v2) packets (without intermediate node support) is analogous to NTP packets and would provide a similar level of quality. However, the interest

in IEEE1588 v2 is primarily related to the ability to deploy boundary and transparent clocks as a means of supporting very accurate time and phase synchronization.

Synchronous Ethernet applicability

As a layer-1 technology, synchronous Ethernet is similar to supplying synchronization via the E1/T1 bearer, which is currently the most common method of supplying timing to radio base stations. However, unlike E1/T1 timing distribution, synchronous Ethernet can only be used in a single operator domain. This limitation will likely restrict its application in many networks, particularly in the RAN where operators commonly use leased lines. Where multiple domains are not an issue, synchronous Ethernet can deliver a high-

quality timing reference. Synchronous Ethernet is typically used:

- from a site that houses a cesium- or GPS-based primary reference clock to adjacent sites that handle TDM services (for instance, to support CES timing recovery, using the differential method or network synchronous mode); and
- to an access site that distributes the synchronization by means of some other synchronization method (for example, a packet-based method).

Circuit emulation – general recommendations

The following considerations apply to the circuit-emulation timing recovery option:

- ❖ Network synchronous operation is recommended when a traceable PRC signal is available at the interworking function and the service clock is synchronous with the network clock.
- ❖ Differential methods are recommended when a traceable PRC reference is available at the interworking function and the service clock must be preserved.
- ❖ Adaptive methods are recommended when a traceable PRC reference is not available at the interworking function and the service clock must be preserved. In this case, the packet delay variation must be controlled in the network.

Phase and time synchronization via GNSS and packet-based methods

Synchronous Ethernet cannot provide phase and time synchronization. If phase synchronization, time synchronization or both are needed, then operators must consider packet-based methods or GNSS.

When applications require accurate phase and time synchronization (for example, LTE TDD and MBSFN), the strict synchronization requirements can be guaranteed by means of GNSS. This approach puts no additional requirements on the transport network but, due to the requirement to deploy and maintain an external antenna, it is not always

the preferred solution.

Packet-based methods, on the other hand, may be used (without support from the transport network) to support applications with requirements for accuracy down to a few milliseconds; in some cases, they may be used for applications with requirements down to hundreds or tens of microseconds (for example, LTE TDD network deployments with a limited number of hops; see figure 8, where a base station with access to GPS delivers accurate time and phase via packets to adjacent base stations).

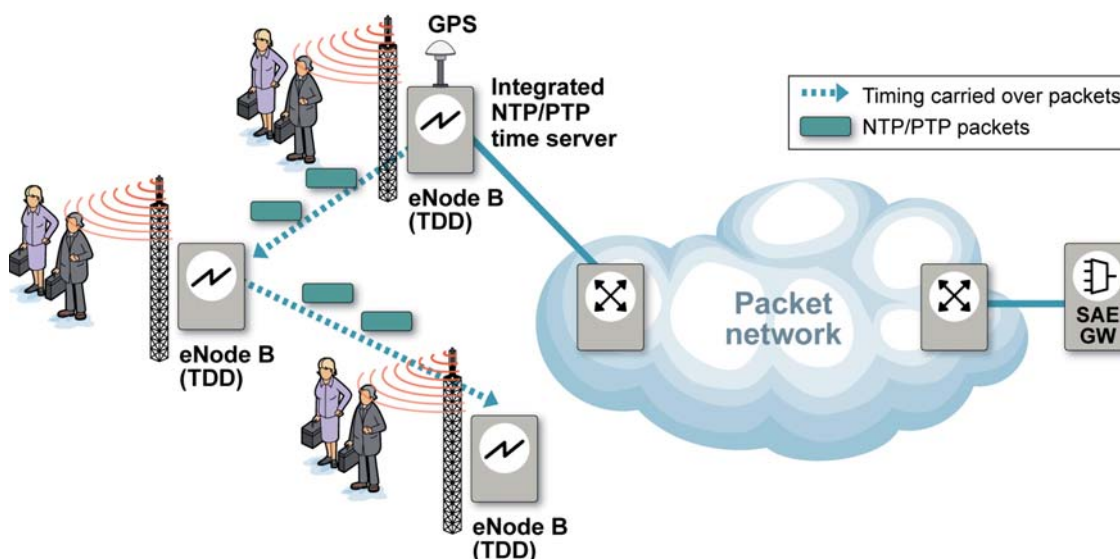


Figure 8: Future scenarios for distributing accurate time and phase

It is anticipated that standardization bodies will actively continue to enhance the packet-based methods (for instance, using IEEE1588 v2). This work will include timing support from the network in order to support accurate time

and phase synchronization as an alternative to GPS.

Table 2 summarizes the options that apply for distributing a reference timing signal over packet networks.

Table 2: Methods of distributing reference timing signals over packet-based networks

Technology	Main standards / recommendations	Type of synchronization	Typical applications
Synchronous Ethernet	ITU-T G.8261 ITU-T G.8262 ITU-T G.8264	Frequency	CES clock recovery (Network synchronous and differential)
		Time-phase: N/A	N/A
Distributed PRC (typically GPS)	Technology referenced in all TDM and packet sync relevant standards	Frequency	CES clock recovery (Network synchronous and differential) ¹
		Time-phase	TDD systems, MBSFN
Packet-based methods without support from the network (PTP/NTP)	NTP V3: RFC 1305 NTP V4 draft PTP V2: IEEE1588-2008 Under study within ITU-T (ITU-T G.826x series)	Frequency	GSM and FDD mobile systems
		Time-phase	Billing, alarming; packet-network monitoring; LTE TDD (special cases)
Packet-based methods with support from the network (PTP/NTP)	NTP V3: RFC 1305 NTP V4 draft PTP V2: IEEE1588-2008 Under study within ITU-T (ITU-T G.826x series)	Frequency	Note 1
		Time-phase	TDD systems; MBSFN

¹ If deployed for time and phase synchronization purposes, this option can also be used to synchronize frequency in the end-system.

Glossary

3GPP	Third Generation Partnership Project	TCXO	temperature controlled crystal oscillator
ADSL	Asymmetric Digital Subscriber Line	TDD	time division duplex
ATM	Asynchronous Transfer Mode	TDM	time division multiplex
BS	base station	ToD	time of day
BSC	base station controller	UMTS	Universal Mobile Telecommunications System
BTS	base transceiver station	UTC	Coordinated Universal Time
CDMA	code division multiple access	UTRA-TDD	UMTS Terrestrial Radio Access – time division duplex
CES	circuit emulation service	VDSL	Very high-speed digital subscriber line
E1	2048 kbit/s PDH E-carrier	VoD	video on demand
EEC	Synchronous Ethernet Equipment Clock	VoIP	Voice over IP. VoIP technology enables users to transmit voice calls via the internet using packet-linked routes. It is also called IP telephony.
FDD	frequency division duplex	WCDMA	wideband code division multiple access
GNSS	Global Navigation Satellite System	xDSL	This refers collectively to all types of digital subscriber lines, e.g. ADSL and VDSL.
GPS	Global Positioning System		
GSM	Global System for Mobile communications		
IP DSLAM	IP DSL access multiplexer		
ISP	In-Service Performance		
IWF	Interworking Function		
LTE	Long Term Evolution		
MBMS	Multimedia Broadcast/Multicast Service		
MBSFN	Multi Media Broadcast over a Single Frequency Network		
NGN	next generation network		
NTP	network time protocol		
OCXO	oven controlled crystal oscillators		
PDH	Plesiochronous Digital Hierarchy		
PDV	Packet Delay Variation		
ppb	part per billion		
PRC	primary reference clock		
PTP	precision time protocol		
QoS	quality of service		
RAN	radio access network		
RNC	radio network controller		
SAE GW	System Architecture Evolution Gateway		
SASE	Stand Alone Synchronization Equipment		
SDH	synchronous digital hierarchy		

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