

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

Introduction

Once a routine network function, timing and synchronization requirements are changing rapidly as mobile network and backhaul technologies evolve. Carriers successfully solved the problem of distributing frequency synchronization through asynchronous Ethernet backhaul networks using the IEEE 1588 Precision Time Protocol (PTP) and/or Synchronous Ethernet (SyncE). Looking forward, LTE-Time Division Duplex and LTE-Advanced impose new, very stringent time and phase synchronization requirements. With the advent of small cells, several additional backhaul technologies are in the mix. Together, stringent timing for phase and new backhaul technologies for small cells have pushed cell site synchronization issues to the forefront.

This paper reviews the requirements and challenges of timing and synchronization for LTE-TDD, LTE-A and backhaul networks, considers the problems that must be solved, and presents solutions that are being proposed and developed. While each section could easily be the subject of a separate paper with deeper coverage, it is the purpose of this paper to provide a general overview of the subject.

Synchronization and UTC Traceability

Timing and synchronization are fundamental to digital network operations. Historically, relatively easy frequency synchronization was all that was required. LTE-TDD and LTE-A technologies add requirements for phase and time. Figure 1 helps to understand the differences.

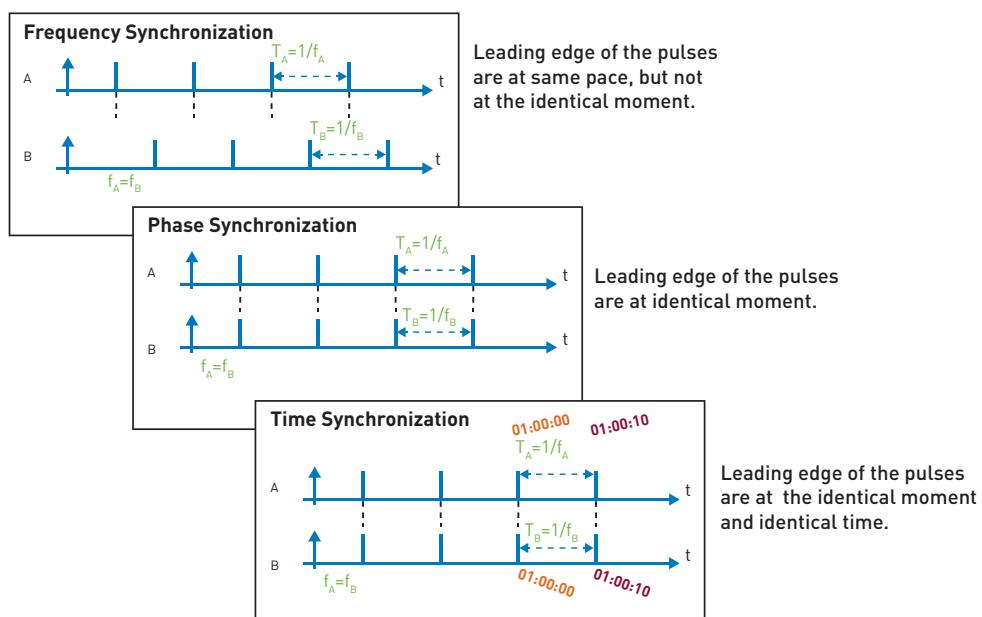


Figure 1: Frequency, Phase and Time Synchronization

Discussions of timing and synchronization often make reference to accuracy and precision. In many cases, the difference does not matter within the context, however, for a more complete understanding; figure 2 draws an analogy to hitting the center of a target.

Carrier networks achieve the necessary precision and accuracy by basing performance on a very precise and accurate primary reference. The reference, in nearly all cases, is from signals transmitted by GNSS satellite systems (GPS, GLONASS or Beidou). A high quality GNSS receiver derives frequency and

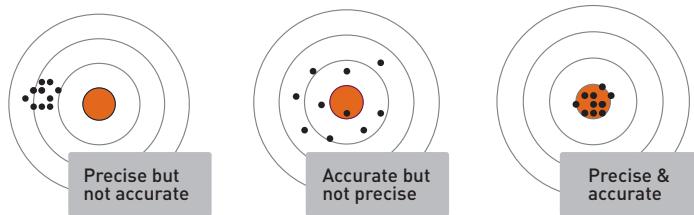


Figure 2: Accuracy and Precision

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

calculates time from the satellite signals, and the synchronization equipment then uses it as a reference for network timing. The best timing and sync equipment will also use additional frequency inputs such as Synchronous Ethernet or E1/T1 signals which enable the solution to converge more quickly on the precise and accurate time, and improve holdover when the GNSS signals are impaired or only available intermittently.

It is essential that the time and phase reference in LTE-TDD and LTE-A networks is traceable to Coordinated Universal Time (UTC). ITU-T G.8272 defines requirements for a Primary Reference Time Clock (PRTC); a time and phase advancement compared to the long established standards for the Primary Reference Clocks (PRC) and Primary Reference Sources (PRS) used for frequency synchronization. Without the common UTC time reference cell sites cannot operate as intended. It must be emphasized that SyncE is only a frequency reference, and cannot be used by a PTP clock (such as a Boundary Clock) as a primary time reference.

Timing and Sync Requirements for LTE

2G, 3G and LTE-Frequency Division Duplex mobile technologies require only frequency synchronization with accuracy within 50 parts per billion at the radio interface. To meet this requirement, 16 ppb is specified at the base station interface to the backhaul network. LTE-Time Division Duplex and LTE-Advanced services have the same frequency requirement as the earlier generations, but also specify requirements for phase and time. Figure 3 provides a summary of the synchronization requirements.

LTE-Advanced requirements are a work-in-progress in the standards bodies. Though not consented at this time [mid-2013] it is probable that the requirements will be $\pm 1.5 \mu\text{s}$ or $\pm 5 \mu\text{s}$ depending on the application; though some of the discussion indicates that 500 nanoseconds ($\pm .5 \mu\text{s}$) may be required for some service situations. LTE-A covers multiple techniques rather than a single technology. Not all features will be deployed

Application	Frequency Network /Air	Phase	Note
GSM, UMTS, WCDMA, LTE – FDD	16 ppb / 50 ppb	--	--
CDMA2000	16 ppb / 50 ppb	$\pm 3 \mu\text{s}$ to $\pm 10 \mu\text{s}$	--
LTE – TDD	16 ppb / 50 ppb	$\pm 1.5 \mu\text{s}$ $\pm 5 \mu\text{s}$	$\leq 3 \text{ km}$ cell radius $> 3 \text{ km}$ cell radius
LTE MBMS (LTE-FDD & LTE-TDD)	16 ppb / 50 ppb	$\pm 10 \mu\text{s}$	inter-cell time difference
LTE- Advanced	16 ppb / 50 ppb	$\pm 1.5 \mu\text{s}$ to $\pm 5 \mu\text{s}$	In discussion by members of the 3GPP

Figure 3: Frequency and Phase Synchronization Requirements

LTE-Advanced	Type of Coordination	Phase
eICIC	enhanced Inter-cell Interference Coordination	± 1.5 to $\pm 5 \mu\text{s}$
CoMP Moderate to tight	UL coordinated scheduling	$\pm 5 \mu\text{s}$
	DL coordinated scheduling	$\pm 5 \mu\text{s}$
CoMP Very tight	DL coordinated beamforming	$\pm 1.5 \mu\text{s}$
	DL non-coherent joint transmission	$\pm 5 \mu\text{s}$
	UL joint processing	$\pm 1.5 \mu\text{s}$
	UL selection combining	$\pm 1.5 \mu\text{s}$
	UL joint reception	$\pm 1.5 \mu\text{s}$

Figure 4: LTE-Advanced Synchronization Requirements

everywhere, leading to differences in real world requirements. Figure 4 presents what they may be when the standards are complete.

Residential and enterprise small cells, also known as femtocells, are different in that they use broadband Internet access service as their backhaul. As such, they are not covered in the solutions described in this paper which address distributing synchronization over mobile backhaul networks. These cells

typically use the less precise Network Time Protocol (NTP), and require frequency accuracy of 100-250 ppb for their air interface.

Impact of Failure

Investment in small cells and LTE networks is made to increase capacity and coverage. When synchronization fails, both objectives are lost. Figure 5 presents a “cumulative” look of what can go wrong.

Application	Need for compliance	Impact of non-compliance
LTE -FDD	Call initiation	Call interference and dropped calls
LTE -FDD	Time slot alignment	Packet loss/collisions and spectral inefficiency
LTE-A MBSFN	Proper time alignment of video signal decoding from multiple BTSs	Video broadcast interruption
LTE-A MIMO/ COMP	Coordination of signals to/from multiple base stations	Poor signal quality at edge of cells, LBS accuracy
LTE-A eICIC	Interference coordination	Spectral inefficiency and service degradation

Needs and Impacts are cumulative, that is: “plus all of the above”.

Figure 5: Why Synchronization is Important.

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

Enhanced Intercell Interference Coordination (eICIC)

Coordination (eICIC) wholly depends on the accuracy of distributed time. Out-of-spec timing in networks that require only frequency synchronization impacts only the footprint of the failed NodeB. In LTE-TDD and LTE-A networks, eICIC enables small cells to operate in cooperation with each other and with overlapping macro cells. Should a cell transmit at the wrong time, it will interfere with the signals at the other base stations in the coverage area—leading to overall spectral inefficiency and broader service degradation.

Solutions for Stringent Time and Phase Synchronization

There are three primary techniques to meet the stringent phase and time synchronization requirements of LTE-TDD and LTE-A networks: “GNSS everywhere”, PTP with “full on-path support”, and PTP with “partial on-path support and/or Edge Grandmaster”. Each solution has advantages and disadvantages, and we will look at each in turn.

GNSS Everywhere

A seemingly simple approach is to deploy a GNSS receiver with every mobile base station. The GNSS receiver can be a standalone device or embedded into the base station. A GNSS receiver can also be integrated into a collocated or nearby cell site router (CSR) or network interface device (NID) if they also support sync distribution to the base station, typically using PTP. Though straight forward, this approach is not economically or technically feasible at every location, and it will also leave the eNodeBs vulnerable to GNSS signal interference.

Challenges to economic or technical feasibility are most pronounced in the case of public access small cells. These small cells (also known as metro cells, microcells and picocells) are planned for deployment where either higher capacity or greater coverage is needed. Many (perhaps most) of these

environments do not provide easy access to GNSS signals. Cell sites may be indoors such as in sports arenas, concert venues, shopping malls or office buildings where satellite signals do not reach and where it is not feasible to connect to a remote antenna. Many outdoor locations also present problems. Urban canyons, where small cells must be located near street level, offer limited visibility to the upper atmosphere. Deployed in the shadow of tall buildings, the base stations cannot see or lock onto the multiple satellite signals needed to make precise time calculations. Additional problem deployment areas include tunnels and subways, and even city parks and tree lined streets where dense foliage can attenuate satellite signals below the level of receiver sensitivity.

Though pricing models for small cell base station equipment offerings are still emerging, it is reasonable to assume there will be a cost for an integrated GNSS receiver

and antenna—a cost that will be borne by every small cell deployment that uses it. Though smaller as a percentage of total site costs, GNSS installation and maintenance also figure in to the capital and operational expense of macro sites as well. Figure 6 attempts to convey that, while GNSS receivers and antennas are not expensive individually, the large number of locations and the on-going maintenance may prove this alternative to be a poor economic choice.

The vulnerability of GNSS signals is of growing concern. The signals are very weak at the earth’s surface and easily interfered with. Though usually discussed in the context of positioning systems, such things as GPS jammers and spoofers, atmospheric interference, multi-path from reflected signals, radiation from malfunctioning electronics, or simply bad weather damaging an antenna installation are common causes for failure. These vulnerabilities can be mitigated with a

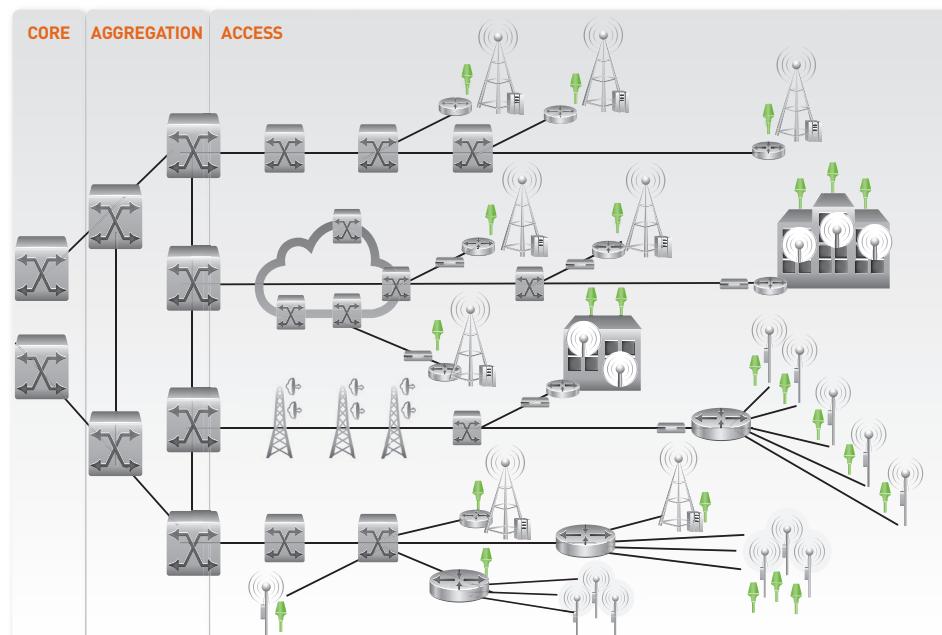


Figure 6: GNSS for Every Base Station, Cell Site Router or NID

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

high quality holdover oscillator such as a rubidium miniature atomic clock in the base station; but, though feasible in macro base stations, this solution is not economically practical for small cells.

Carriers choosing “GNSS everywhere” still need a solution for situations where it is not feasible, and best practice also points to the need for a backup timing source. Consequently, the network distributed time

solutions described below will have an important role for every carrier: either as the primary timing solution, as an alternative source where GNSS cannot be deployed, or as a backup when GNSS is impaired.

PTP, Profiles and Boundary Clocks

The IEEE 1588 Precision Time Protocol (PTP) was developed in response to broad industry and government need to enable accurate distribution of time and frequency over packet-based networks.

IEEE 1588 employs a client/server architecture to maintain precise synchronization across all network components. The server (PTP Grandmaster Clock) is the primary reference source for all of the PTP clients within its network domain. It continuously sends out sync, follow-up and delay response messages to all of its clients. Clients continuously send delay request messages to the server to maintain synchronization through the packet-based network. Using the time stamped packets, clients determine frequency and calculate accurate time that is traceable to the primary reference of the Grandmaster.

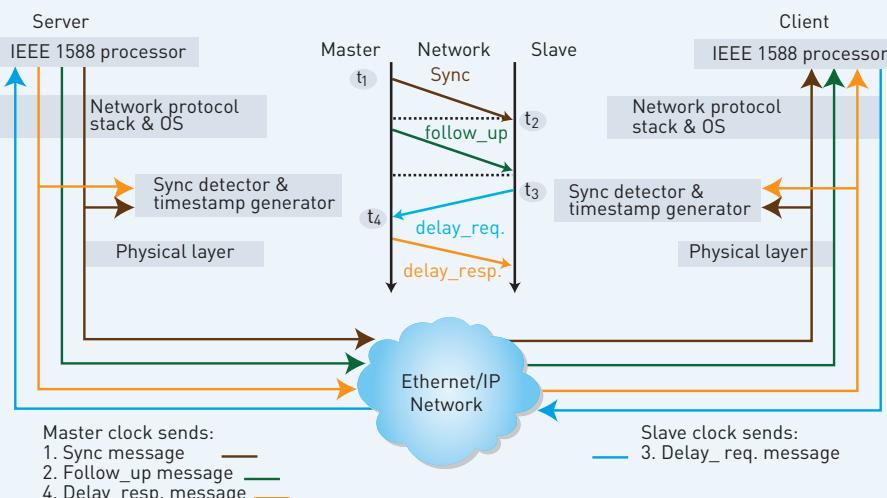
The IEEE standard is designed broadly to serve a great variety of applications. To enable ease of deployment and equipment interoperability while meeting the requirements of specific applications, IEEE 1588-2008 introduced the concept of profiles. Profiles specify particular combinations of PTP options and attribute values

to support a given application. For example a profile may specify layer 2 or layer 3, unicast or multicast, the message exchange rate, and whether on-path support is required. The “Telecom Profile” (recommendation ITU-T G.8265.1) is intended to address the application of PTP to the frequency synchronization of telecommunication systems, primarily cellular base stations. ITU-T G.8275.1 and G.8275.2 are works-in-progress to address time and phase synchronization.

The PTP standard includes provisions to maintain accuracy across a network (refer also to the sidebar Packet Delay Variation and Asymmetry). Boundary Clocks are one option for this on-path

support. Usually embedded in network elements, Boundary Clocks function as a PTP client in the upstream direction and as a grandmaster to other Boundary Clocks and clients in the downstream direction. By compensating for delays in the switch and refreshing the PTP packets, Boundary Clocks help to maintain accuracy and are still traceable to the original Grandmaster clock with a primary UTC reference.

IEEE 1588 also defines Transparent Clocks as a technique to support accuracy across a network. Transparent Clocks are not currently provided for in the PTP profiles for telecom industry, and need not be covered here.



Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

PTP Profile with Full On-path Support (G.8275.1)

IEEE 1588-2008 Precision Time Protocol is a proven technology for distributing synchronization over packet-based backhaul networks to mobile network elements that require frequency synchronization. There are hundreds of networks successfully using this technology today following the G.8265.1 standard PTP profile or a pre-standard implementation. It is typically deployed using a centralized PTP Grandmaster (with GNSS primary reference to meet G.8272 PRTC requirements), which then interoperates with slave or client software in the mobile network elements, enabling the client to determine frequency and calculate the time.

PTP, using the frequency profile as deployed today, will likely not meet the stringent time and phase accuracy requirements of LTE-TDD and LTE-Advanced networks. Consequently the ITU is developing new standards, including new profiles that take advantage of capabilities provided in IEEE 1588-2008.

ITU-T G.8275.1 is a work-in-progress for a new PTP profile that enables the stringent

time and phase requirements at the base station to be met over a network from a centralized PTP Grandmaster many hops away. Maintaining precision and accuracy is achieved through deployment of “full on-path support” of the PTP timing signals. On-path support is provided by a Boundary Clock function embedded in every network element in the path between the grandmaster and the client; including all switches, routers, microwave radios, NIDs, etc. Each Boundary Clock (BC) incorporates a PTP client that interoperates with its immediate upstream element to recover time, and then acts as a PTP Grandmaster to deliver time to connected downstream Boundary Clocks or end device clients.

Synchronous Ethernet [SyncE] is covered in the proposed standard as providing frequency reference support for better performance, but it is not a requirement. Early experience indicates SyncE should be included in the deployments. Figure 7 is a simplified depiction of a network following the G.8275.1 PTP profile.

Full on-path support will best fit scenarios where new backhaul equipment is being deployed at every location

(i.e.: Greenfields), but it has practical disadvantages in other network scenarios. Many mobile service providers do not own or control their backhaul networks. Independent, third party backhaul network providers may not be willing to upgrade their network elements for full on-path support, or may only do so at increased prices to the mobile network operator. Even wireline networks owned by the same company as the mobile operator may resist the cost of a comprehensive upgrade, retrofit or replacement. As precise timing has become an essential, yet more difficult, component for evolving LTE networks, a “sync SLA” should be included in the relationship between wireless and backhaul operations, and monitoring and reporting added to operational practices.

Pre-standard ITU-G.8275.1, in early deployments, use layer 2 multicast. While this may present no problem in Greenfield scenarios, many carriers have implemented network policies for MPLS and IP networking at higher layers that may have to be revised (and networks re-engineered) to implement a multicast network service at layer 2.

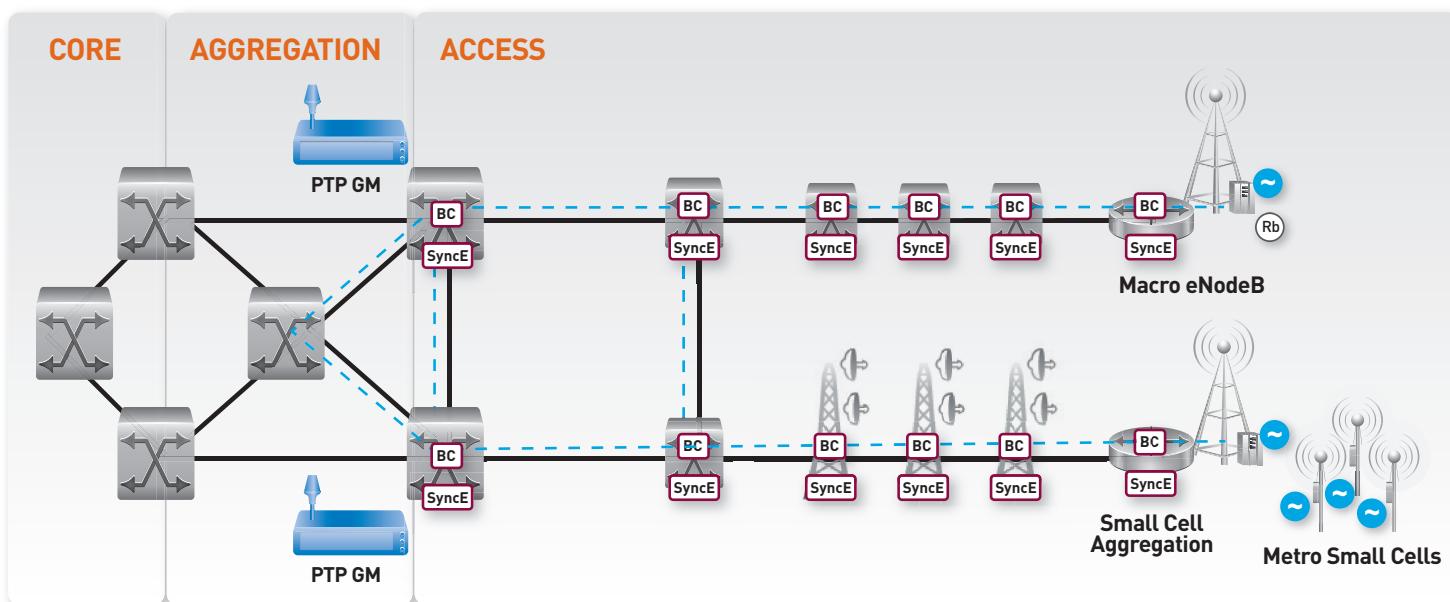


Figure 7: Backhaul network using the ITU-T G.8275.1 profile for phase synchronization

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

Another problem introduced by the need for stringent phase and time synchronization is the impact of packet delay variation (PDV) or asymmetry as the PTP packets travel back and forth across the network. Boundary Clocks adjust the timestamp to account for the time resident

in the network element, including packet processing, buffering and queuing delays that create packet delay variation which would otherwise introduce errors in the time calculation. However, Boundary Clocks alone cannot compensate for path asymmetry—differences in the upstream and downstream paths between the

grandmaster and client. Network path asymmetry can be severe enough to move the time calculations of the client out of spec, requiring the operator to manually measure and enter time offset adjustments to compensate, and then adjust when the paths change.

Packet Delay Variation and Asymmetry

Timing and synchronization, fundamental in all mobile networks, is even more critical as small cells are added and networks evolve to LTE-TDD and LTE-A technologies. Backhaul network performance can dramatically impact PTP timing accuracy, and thereby the mobile network itself—affecting service quality and customer satisfaction.

The problem is Packet Delay Variation (PDV) which represents the change in latency from packet to packet. Packet delay itself has no effect on the accuracy of the clock: constant delay would allow an accurate time offset calculation by the PTP client. Variable delay, however, induces noise in the PTP client's perception of the time at the master which can result in variation in time calculations based on the timestamps in the PTP packets.

Delay can vary as PTP packets are processed, buffered and queued along with the payload traffic through the network switches and routers, and it tends to be correlated to network

load which can be highly asymmetric in nature. As the amount of traffic in the network increases, the delay variation is also likely to increase. Asymmetry is also introduced by the physical topology of the network as packets travel different and changing paths in the upstream and downstream directions.

Sources of Asymmetry

1. Switch delay variation:

- Switch transit: packet processing, buffering and queuing
- Payload variation increases variation in switch delay

2. Network path variation:

- Variation between upstream and downstream paths in the network
- Path asymmetry alone can cause timing performance to be out of spec.
- An out-of-phase cell can impact services on overlapping cells

Time accuracy is affected by both the magnitude of the packet delay variation and how effective the client is at removing this noise. Synchronization elements deployed in the network vary in how effectively they filter this noise. Embedded Boundary Clocks adjust only for the switch delay variation in its host switch; it cannot adjust for variations or asymmetries in other network switches and it cannot compensate at all for network path asymmetry. Network timing elements with a GNSS reference can compensate for all variations, including network path asymmetry.

Comparing a PTP input from a centralized grandmaster and a local GNSS reference; an Edge Grandmaster can determine the typical offset and apply it to provide superior accuracy when the GNSS reference is not available. Superior designs learn multiple offset for different backhaul network paths and continue to provide accurate performance even through backhaul network rearrangements.

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

PTP Profile with Partial On-path Support and/or Edge Grandmaster (G.8275.2)

Responding to the need for a phase timing solution that is more feasible in non-Greenfield, real-world scenarios, another PTP profile (G.8275.2) has been proposed to the ATIS/ITU standards bodies: "a new profile to support time and phase distribution over existing deployed networks...compatible with the PTP profile for frequency distribution defined in G.8265.1". This proposal will require considerable more work before it becomes a standard, but in practice, it can be deployed in networks today.

In simple terms, this approach endorses two solutions that can be employed

separately or in combination to provide the best synchronization architecture for a wide range of network scenarios.

"Partial on-path support" is deployment of advanced boundary clocks at intermittent locations through the network. In a managed Ethernet network it may be possible to locate an advanced boundary clock at selected locations and maintain timing within spec at the base stations. Key to this approach is to limit the number of hops and path asymmetry between the grandmaster and the client. Advanced boundary clocks have superior oscillators and can leverage additional inputs such as SyncE and E1/T1 circuits as a frequency

reference to maintain high accuracy timestamps to the next clients in the path.

Edge Grandmasters ensure accuracy by deploying closer to the clients, and thereby reducing the hops and putting problem parts of the backhaul network behind them. Edge Grandmasters include a GNSS reference to meet G.8272 PRTC requirements and perform much like centralized PTP Grandmaster equipment commonly deployed today, except they are scaled and cost optimized for deployment closer to the network edge.

Figure 8 depicts some of the many network scenarios that can be solved with partial on-path support and/or Edge Grandmaster deployment.

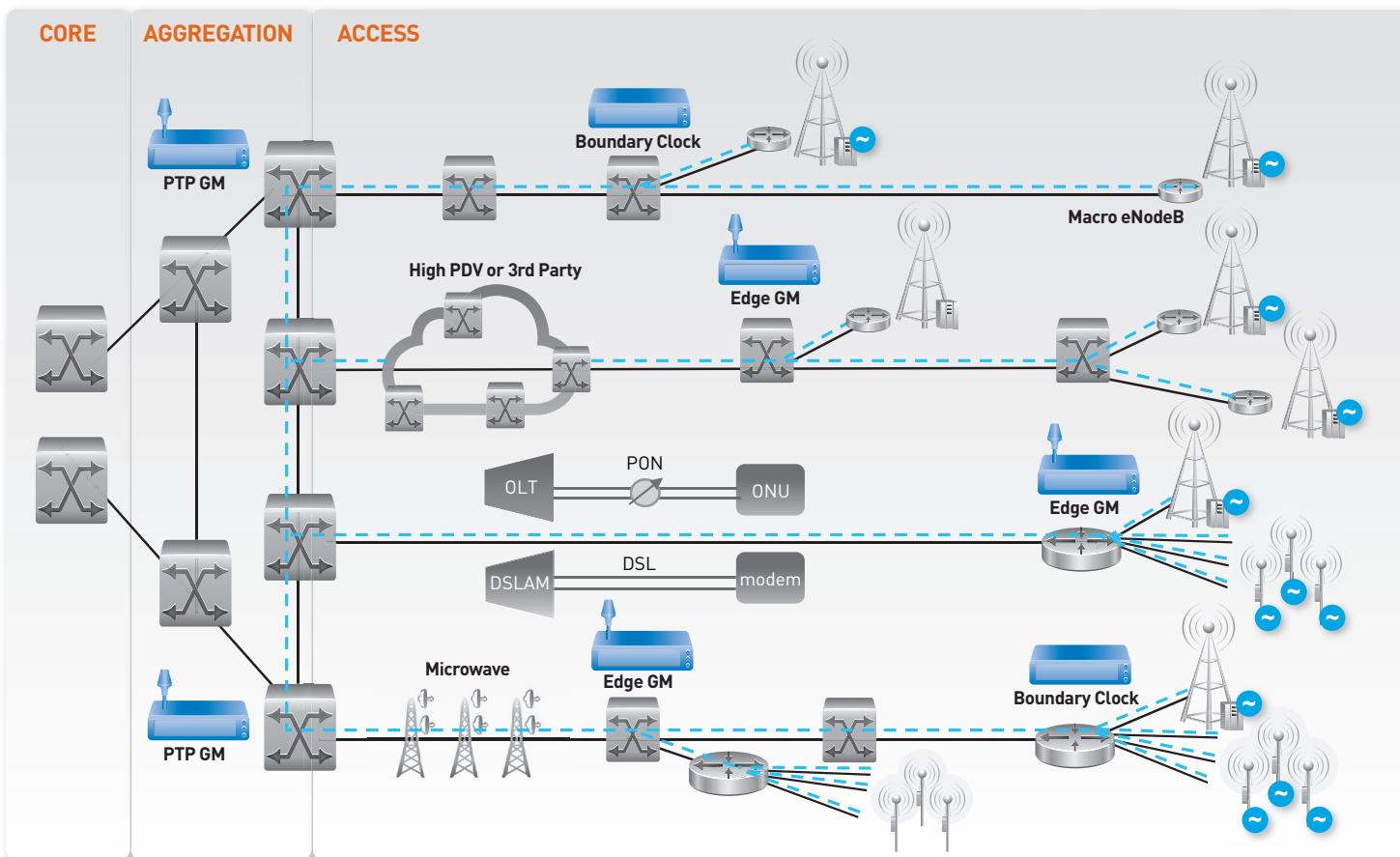


Figure 8: Partial on-path support and/or Edge Grandmaster deployment scenarios

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

Though outside the topic of the paper, it is worth noting that the solution described above and illustrated in figure 8 may also be applied for frequency synchronization in 2G, 3G and LTE-FDD networks where many of the same issues related to backhaul network performance and control exist.

Edge Grandmasters may include a PTP input capability, allowing PTP signal exchanges with a centralized grandmaster to continue as a precise time reference should the GNSS reference be impaired. During periods of normal operation the Edge Grandmaster will track the time offset between the GNSS calculation and the calculation based on PTP with the centralized grandmaster. When GNSS is lost, the Edge Grandmaster can apply that offset to the PTP calculation and continue to provide a level of accurate timestamps that the backhaul network alone could not support.

Additional capabilities in both advanced PTP Boundary Clocks and Edge Grandmasters may include utilizing a frequency input such as SyncE or E1/T1 as an additional reference, and providing extended holdover for all connected clients with a higher quality oscillator such as a rubidium miniature atomic clock as depicted in figure 9.

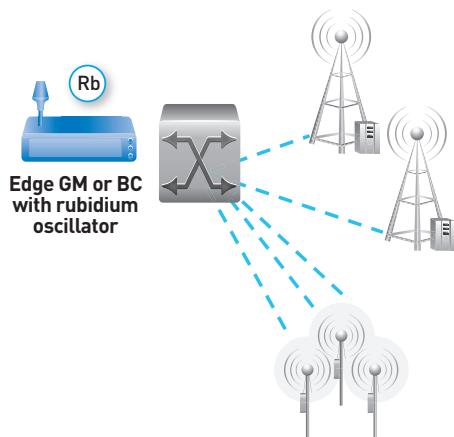


Figure 9: A single rubidium oscillator provides extended holdover to multiple base stations.

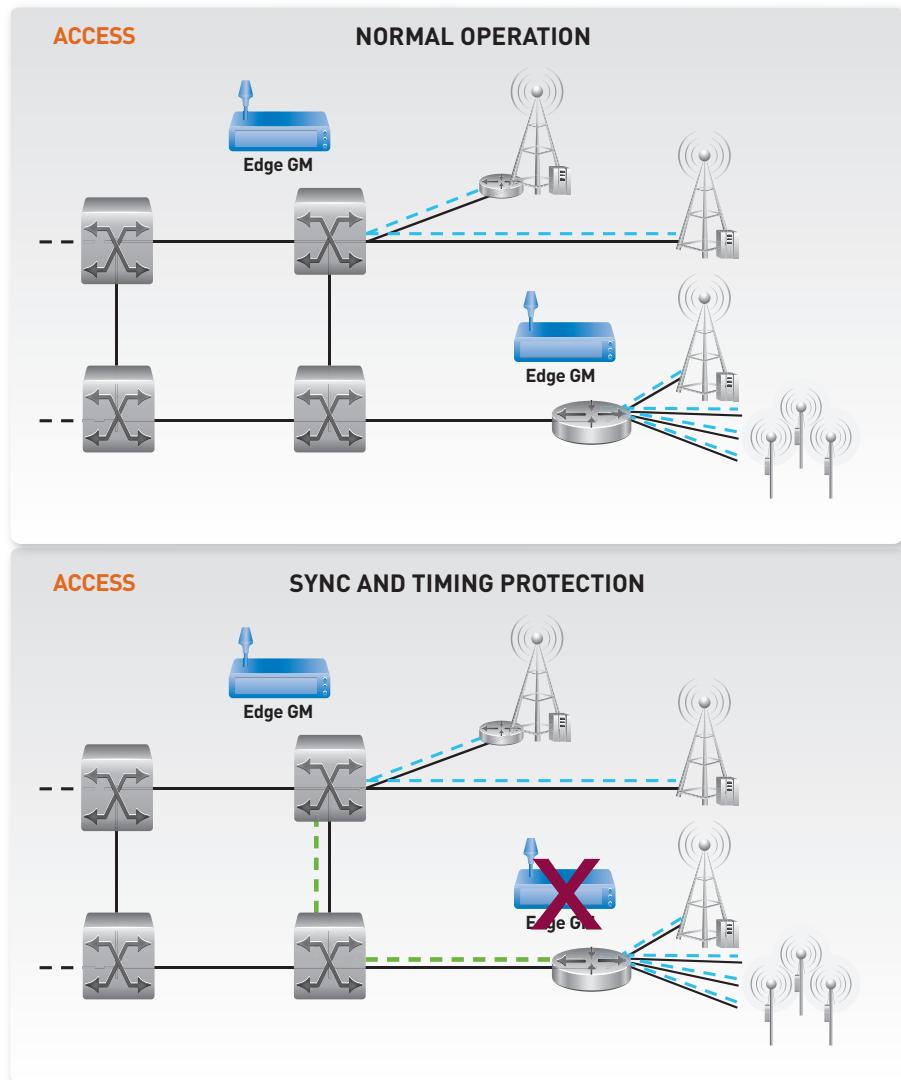


Figure 10: Edge Grandmasters provide backup to each other.

Timing and synchronization are a critical component to LTE-TDD and LTE-Advanced network operations, and therefore protecting this function is more essential than ever. Enhanced holdover is one protection alternative. Another alternative, enabled by

this architecture, is that relatively nearby Edge Grandmasters can backup each other (shown in figure 10), as opposed to requiring PTP clients to re-sync with a centralized grandmaster that may be so many hops away that accurate timing is not possible.

Timing and Synchronization for LTE-TDD and LTE-Advanced Mobile Networks

Edge Grandmaster and/or partial on-path support with advanced Boundary Clocks provide many advantages:

- Tremendous flexibility to work in diverse network scenarios provides network planners with the tools for every situation
- Enables small cell deployments where GNSS/GPS is not economically or technically feasible
- Cost savings by avoiding backhaul network upgrades for embedded Boundary Clocks (and possibly also upgrade for SyncE)
- Avoids issues related to high packet delay variation, asymmetry and/or 3rd party backhaul
- Timing and synchronization protection techniques to maintain high mobile network availability and performance
- Synchronization reliability is not threatened by failure of one of many embedded Boundary Clock (where failure of one BC breaks the timing chain to the downstream clocks)
- Makes extended holdover possible as cost of a superior rubidium oscillator is leveraged across multiple base stations
- Leverages existing investment in centralized PTP grandmaster and SyncE, preserves practices put in place for frequency synchronization
- Preserves MPLS network and engineering practices (operates at layer 3)

Conclusion: Finding the Right Solution for Your Network

The important and difficult question: "How should I synchronize my LTE-TDD and LTE-Advanced networks?" does not have a single easy answer. The stringent requirements for phase and time cannot be met using the typical "frequency synchronization distributed over the backhaul network" techniques in practice today, and so new solutions must be adopted.

The right answer for your network is driven by your service delivery network fundamentals:

- The mobile network technology and services determines the timing and synchronization requirements: LTE-TDD, LTE-A, eICIC requirements, CoMP requirements, etc.
- Mobile network equipment selection and cell site locations (particularly for small cells) define what can and cannot be done.
- Backhaul network technologies, topologies, performance and control drive decisions for synchronization equipment and deployment locations.

Once the technical limits and possibilities are understood, the solution alternatives and their relative costs can be assessed.

Simply deploying GNSS receivers and antennas everywhere is not economically or technically feasible for all situations, and GNSS alone exposes the base stations to the vulnerabilities of the satellite signal based systems. Network distributed time, using the IEEE 1588 Precision Time Protocol, will be part of virtually every mobile network operator's network.

Full on-path support is most feasible in Greenfield situations where every new switch and router can include SyncE and Boundary Clock support. Network path asymmetry and sync protection remain as issues.

Edge Grandmasters deployments or advance Boundary Clock offer the flexibility to fit a wide range of network scenarios and offer solutions for sync protection and can compensate for all switch and path asymmetry.

Symmetricom® is a leader in PTP Grandmaster deployments for mobile networks and stands ready to help analyze and recommend the right solution for your operation. Additional technical information, test results, recommended best practices, cost comparison aid, equipment demonstration, lab test procedures and network sync audit aids can all be made available to help plan the best synchronization distribution architecture for your network. And, of course, Symmetricom supplies and supports best-in-class PTP Grandmaster, Edge Grandmaster, and advanced Boundary Clock equipment, to network operators around the world.