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A Case for Assisted Partial Timing Support Using Precision Timing Protocol Packet Synchronization for LTE-A

Tim Pearson and Kishan Shenoi

Tim Pearson is with Sprint.

Kishan Shenoi is with Qulsar, Inc.

Abstract

North American service providers are in the process of upgrading their radio access networks with next generation LTE equipment. They are finalizing a 4G rollout that involves highly stringent timing requirements, but in many cases they are relying on sole-source synchronization by using Global Navigation Satellite System (GNSS). Natural occurring disturbances, as well as unintentional radio frequency jamming, intentional jamming, and spoofing, make GNSS vulnerable to interference.

This article presents a novel approach for addressing the issue of GNSS vulnerability by introducing a standard means of providing a redundant packet-based synchronization source for LTE base stations. It also describes how this new approach can mitigate noise caused by asymmetry and transit delay variation in packet networks.

Introduction

This article presents a unique approach that will allow North American service providers the ability to support packet synchronization over their owned or leased Ethernet mobile backhaul (MBH) networks as a means of backing up the Global Navigation Satellite System (GNSS), used for synchronization at enhanced Node-B (eNBs). Ethernet MBH providers could accommodate this approach with a minimum of expense and deployments.

Before the solution is discussed, this article explores:

- Long Term Evolution (LTE) timing requirements and challenges.
- Reliance on GNSS for LTE timing requirements.
- ITU-T standards updates for providing synchronization over packet-based networks.
- Breakdown of noise sources in packet networks.

The article then provides a high-level review of the new method of IEEE 1588™ 2008 Precision Timing Protocol (PTP) [1]. This novel method could meet real-world use cases to backup GNSS and provide a unique ability to support real-time monitoring of packet-based synchronization. The article concludes by testing the proposed solution using a simulated model. While security of the PTP remains a concern for service providers, this article does not address PTP security requirements that are under study in various standards groups.

LTE Timing Requirements and Challenges

This section focuses on various LTE eNB requirements and challenges as it relates to synchronization.

With the advent of commercially available smart wireless devices, a forecast of ever-increasing data has forced service providers to meet higher Radio Access Network (RAN) throughput. 3GPP (Beyond 3rd Generation Partnership Project) has standardized LTE for helping meet these higher bandwidths. 3GPP technologies are constantly evolving through generations of cellular and mobile networks. Since the completion of the first LTE and the Evolved Packet Core specifications, 3GPP has become the focal point for mobile systems beyond 3G.

LTE utilizes two means of radio duplexing schemes: Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). FDD has two separate frequencies for transmit and receive at the radio access point; TDD uses the same frequency for both transmit and receive. While this allows for spectrum efficiencies, there is an added challenge of higher phase synchronization requirements at the eNB so the base stations do not interfere with each other.

Requirements for LTE and LTE-Advanced: Frequency, Phase, and Time Synchronization

LTE spectrum operates within the frequency range of 450MHz to 3800MHz and supports FDD and TDD. FDD synchronization includes requirements for frequency accuracy but may also include phase accuracy to support certain features, for example enhanced Circuit Switch Fallback (eCSFB) or enhanced Multimedia Broadcast Service (MBMS). For those cell sites that are within 3km of each other, TDD synchronization requirements have higher phase accuracy of $3\,\mu s$ [2] to support eNB alignment of $1.5\,\mu s$, which is needed for enhanced Inter-cell Interference Coordination (eICIC) or Up-Link/Down-Link-UL/DL Coordinated Scheduling.

Requirements for Macro Cells

For higher synchronization demands of frequency, phase and time, North American service providers have relied on the use of GNSS at the macro cell tower using oscillators with suitable holdover during intervals when satellites signals were lost. The holdover period is the measure of time that an oscillator is able to maintain synchronization (frequency and/or phase) within a defined performance objective after the loss of its reference.

The core of any synchronization system is its oscillator. Almost universally, LTE base station equipment uses Oven Controlled Crystal Oscillators (OCXO). Depending on the OCXO performance characteristics, type of crystal cut, and temperature variation tolerances, the macro LTE base stations may provide from 4 to 18 hours of holdover with an accuracy of $\pm 1.5\,\mu s$.

Requirements for Small Cells

Both in-building and outdoor small cell deployments address some of the higher data demands by offloading capacity from the macro cell towers. The correct placement of small cells can efficiently utilize one of the service providers most costly assets, spectrum. Placing the LTE base station in near proximity to the wireless users will maximize the user experience. This often means placing cells indoors or on the sides of buildings, which may make it challenging to get a reliable line-of-sight GNSS signal for synchronization. Compared to macro cells, small cells are normally equipped with a lower grade crystal oscillator to provide a lower cost point. Therefore, the holdover is significantly limited to just a few minutes with an accuracy of $\pm 1.5\,\mu s$.

When appropriate, synchronization architects may consider localized distribution of PTP over a LAN approach with stronger holdover capability. A high performing OCXO, located in an aggregation node, would sustain small cell oscillator's holdover capacity.

GNSS Reach has its Challenges

In general, in-building small cells lack direct line-of-sight to the GNSS celestial array; therefore, packet distributive timing is a leading candidate for providing frequency, phase, and time synchronization. The challenge for service providers is to ensure that these packet based synchronization alternatives, transported over dynamic packet networks, offer reliable and accurate frequency, phase, and time synchronization at the base station and small cell eNBs.

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LTE Synchronization Reliance on GNSS

Many North American service providers have relied on GNSS for nearly 20 years as their sole source for frequency, phase, and time for CDMA and location based services. However, concerns exist regarding GNSS reliability and vulnerability. The North American service providers general assumption is that the GNSS signal is ideal. However, there may be conditions when the GNSS signal is not ideally suited, such as the sole source of synchronization and specific locations where GNSS is not available.

GNSS Reliability

There are no known reliable statistics for GNSS reliability in the United States. In addition, averaging national footprint GNSS reliability does not tell the entire story. Nevertheless, most North American service providers consider that overall GNSS provides a high degree of reliability. However, each individual base station's GNSS receiver may experience different impairments such as multi-path interference, malfunction of the antenna/receiver, or a limited view of the sky. Depending on the eNBs' oscillator and the service supported, short GNSS outages may not affect wireless services. However, the real concern remains for those scenarios when the GNSS outage extends beyond the oscillator's capability to meet the synchronization demands.

A loss of synchronization at the LTE base stations may cause degraded service such as bad quality or worst yet dropped calls. Without a redundant synchronization source, eNBs must be self-reliant and determine their own synchronization accuracy. Upon the loss of GNSS the eNB calculates a self-assessed time holdover duration based on its oscillator position and on the frequency and time requirements. Therefore, their internal clock could shut themselves down before their oscillator has truly degraded, or even worse continue to operate in a degraded manner thereby becoming disruptive to neighboring eNBs.

Minimizing the effects of GNSS outages is not totally within the service provider's control. Even if the GNSS antenna receivers are positioned correctly, have line of sight, use costly jam-resistant antennas, and the equipment is properly maintained, the sensitivity due to low receive power is an easy target at the GNSS center frequency for spectral interference.

The United States' Department of Homeland Security (DHS) and the United Kingdom's Royal Academy of Engineering (RAoE) have outlined risks associated with a single source Position, Navigation, Timing (PNT) system and the vulnerabilities associated with GNSS [3, 4]. The key point from these recommendations is that a reliable backup to GNSS is required.

The United States was set to provide a means of backing up GNSS by deploying eLORAN (enhanced Long Range Navigation) but defunded it. This has resulted in the decommissioning of the LORAN systems. This leaves North American service providers with few effective options for providing a reliable backup to GNSS.

GNSS Vulnerability

Base stations that use Code-Division Multiple Access (CDMA) have always relied on GNSS as a means of providing consistent frequency, phase, and time. Some North American service

Simply put, a PTP-unaware network element introduces noise that is uncorrected and thus can accumulate PDV along the path. The PTS network is restricted to providing complete PTP support as most limits result from dynamic noise. PTS is currently under study in ITU-T Rec. G.8271.2.

providers used rubidium clocks in every base station as a means of providing holdover in the event of the loss of GNSS signals. The satellites themselves are rarely the cause of GNSS failures, as most failures are due to antenna fatigue or damage from hazardous weather conditions.

GNSS signals are low power signals and require sensitive receivers capable of detecting GNSS signals in the order of –160dB/Hz. As a result, receivers are also vulnerable to interference. Of concern to service providers is the threat of intentional interference caused in part by jamming or spoofing.

- Jamming is the use of a transmitter at one or more GNSS center frequencies to overwhelm the GNSS receiver with noise.
- Spoofing is the use of a transmitter that mimics a GNSS signal with power greater than available from the actual satellites.

Service providers need frequency, phase, and time synchronization at the edge of their RANs for LTE FDD and TDD services, and the reliance on GNSS as a single source is not advisable. Question 13 of ITU-T Study Group 15 ("Q13") has a mandate to address standards related to network synchronization. They are currently working on standards that address many of the issues influencing deployment of packet-based timing mechanisms to support RANs [5–7]. Later we review how Q13 has recently taken up the study of using PTP as a means of providing a backup to GNSS.

Synchronization Standards Work

The ITU-T SG15/Q13 has been working to define aspects related to transferring frequency, phase and time over packet networks as networks continue to evolve away from Time Division Modulation (TDM) to packet. This section reviews ITU-T's ongoing efforts and details various aspects of the work by other standards groups (i.e. IETF and IEEE) that addresses packet-based synchronization.

To date, distributing timing over packet-based networks has used IETF's Network Time Protocol (NTP) and Simple Network Time Protocol (SNTP) [8]. However, NTP and SNTP can only achieve sub-millisecond accuracy over the wide area network; neither can meet the highly stringent accuracy of phase synchronization requirements in the LTE RAN.

ITU-T Ongoing Synchronization Work

The ITU-T Recommendations cover network performance aspects (i.e. network limits), network elements (i.e. clocks), and various architectures to extend frequency distribution, such as expanding Synchronous Optical Network (SONET)-based synchronization frequency distribution. ITU-T has also recognized the need to expand synchronization to cover the new phase requirements of advanced wireless applications. Figure 1 identifies pertinent ITU-T Recommendations and ongoing work.

ITU-T Frequency Physical Layer Synchronization: SyncE

ITU-T Rec. G.8262 (*Timing characteristics of synchronous Ethernet equipment slave clock (EEC)*) [5] defines SyncE as "a means of using Ethernet to transfer timing (frequency) via the Ethernet PHY layer." Therefore, each network node actively participates in the synchronization path, albeit for frequency purposes. Most LTE base stations accept SyncE inputs.

With reference to SyncE, most North American Ethernet MBH providers have avoided this option. With a dependency on GNSS, they do not see a cost/benefit, as each legacy network element needs augmentation or replacement in order to achieve transference of clock signals over the Ethernet core or MBH physical layer networks. As they upgrade their legacy network equipment, it would serve them to require SyncE as a minimum requirement for frequency synchronization support.

ITU-T Full Timing Support

ITU-T Q13 has been working since 2008 toward a full timing support (FTS) model for PTP. ITU-T SG15/Q13 first developed frequency transfer, including Hypothetical Reference Models (HRMs) and packet delay variation (PDV) network limits in the ITU-T G.826x series of Recommendations. Frequency, phase, and time distribution, is addressed in the G.827x series of Recommendations. G.8275.1 relies on physical-layer frequency assist using SyncE and full timing support whereby all network elements are PTP-aware. These PTP-aware elements provide timing support.

Various service providers in both China and Europe support or have implemented the full timing support model. Most North American service providers are not considering upgrading their networks to achieve this full timing support, but they may be interested in providing network-based support for frequency, phase, and time at the RAN. One goal for Ethernet MBH providers, which is clear, is that supporting frequency and time must minimize network upgrades.

ITU-T Partial Timing Support

ITU-T's Partial Timing Support (PTS) model, viewed as beneficial for some service providers, must be able to operate over existing packet networks with limited augmented network elements (clocks). A PTP-unaware network element introduces noise (e.g. packet delay variation) that is uncorrected and thus can accumulate PDV along a path consisting of multiple network elements. PTS networks could use SyncE or PTP for frequency and for time support. The PTS budget allocation is currently under study in ITU-T Rec. G.8271.2. Compared to networks deploying FTS as defined in G.8271.1, the APTS G.8271.2 requires a higher dynamic Time error budget due to the increase PDV.

Precision Timing Protocol IEEE Std. 1588™ 2008 (PTP)

The Precision Time Protocol (PTP) time transfer protocol exchanges messages between a master and slave devices and allows the slave devices

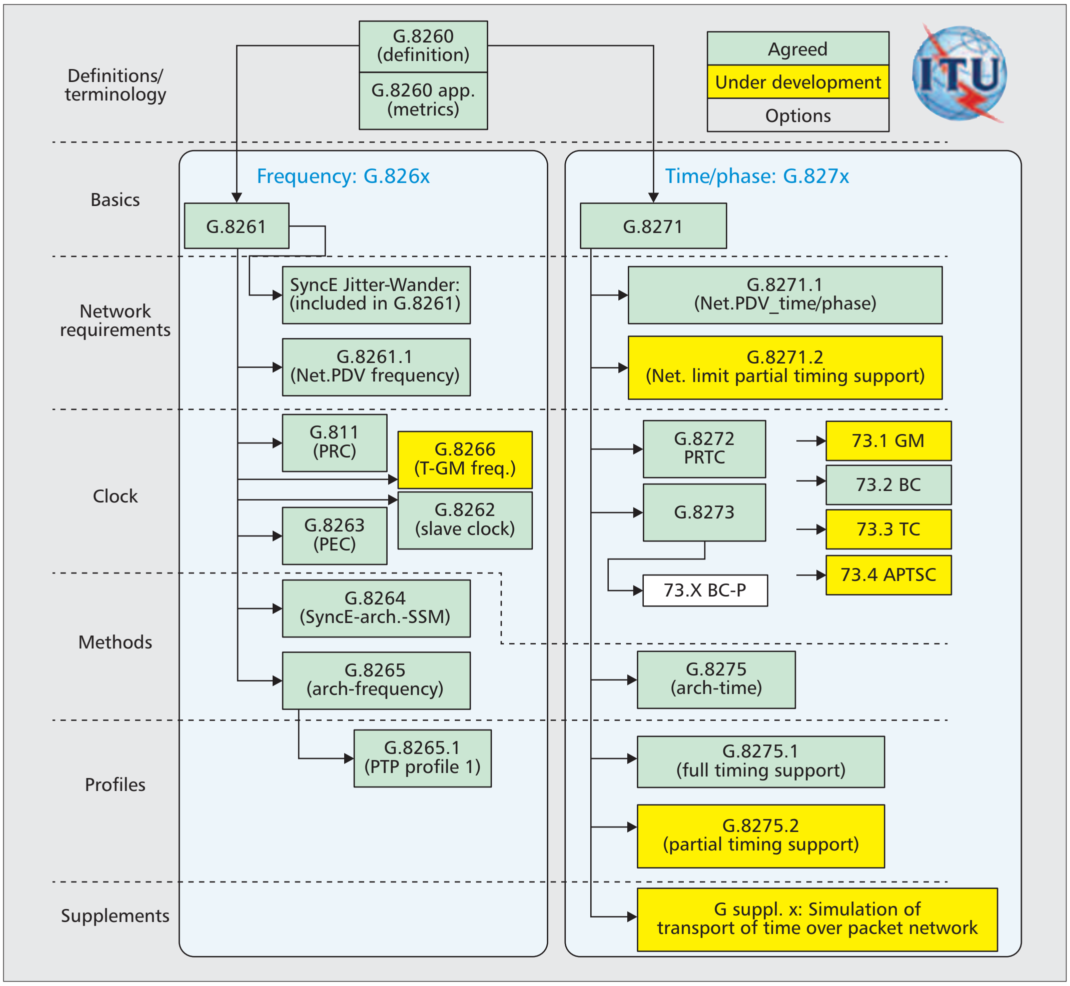

Figure 1. ITU-T SG15/Q13 work related to packet-based synchronization and timing (April, 2014).

to calculate and adjust their local time-base to match that of the master. A key IEEE 1588 2008 (PTP) assumption is that the network path is symmetric. While this is generally the case in LAN environments, in a wide area network environment, asymmetry is a significant issue. Any asymmetry in the connection medium represents a lower bound on the time transfer accuracy that is achievable. A significant source of asymmetry in any packet network results from traffic load differential of the upstream to downstream congestion flows. These dynamic packet flows are the biggest challenge for PTP.

Analyzing the Noise Sources

The effect of PDV reduces the accuracy of PTP. Table 1 provides a description of three types of PDV sources: static, pseudo-static, and dynamic. All contribute to asymmetry, and the dynamic forms contribute to PDV in one direction as well.

Noise sources generally introduce error on the timing signal transported across the packet network. This error source may introduce high frequency variation or low frequency variation. ITU-T Rec. G.810 [6] defines wander as phase variations at a rate less than 10Hz. Metrics such as Maximum Time Interval Error (MTIE) and Time Deviation (TDEV) are useful for quantifying wander and for measuring frequency transfer. Metrics used for time transfer and measurement techniques are currently under study.

Assisted Partial Timing Support

This section outlines a new approach and for some, possibly a new way of thinking about PTP distribution. This approach considers the notion that even though a network deployment involves PTP-unaware elements the time transfer could provide a means of redundancy to the clock, normally delivered by a GNSS receiver.

There were five proposed design criteria when considering the new partial timing support model:

1. Redundancy to GNSS, to mitigate reliability concerns (i.e. jamming, spoofing).
2. The solution must provide holdover as required, depending on cell type.
3. Macro and small cell frequency, phase, and time synchronization are required.
4. The PTS approach must meet synchronization requirements for the service provider's use-cases.
5. Key performance indicators (KPIs) for monitoring and managing Ethernet access networks.

North American service providers have successfully used GNSS with a very high degree

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Noise error type	Description of the noise
Static: physical router/switch/ boundary clock asymmetry.	• Occurs within routers/switches due to differences of the forward (up) and reverse (down) paths.
Static: fiber asymmetry.	• Path distance between the forward (up) and reverse (down) paths. • Measured asymmetry of fibers within the same sheath. • Lambda dispersion. • Temperature fiber distortion.
Pseudo-static: change from one static path/link/route, possibly known asymmetry, to another unknown asymmetry path/route.	• Change in fiber paths due to (Layer1) re-configuration. • Change in link paths due to (Layer2) switch. • Change in routed paths due to (Layer2.5/Layer3) re-route.
Dynamic: router/switch asymmetry.	• High priority PTP packets waiting on larger packets proceeding through congested queues. • Scheduler class of service/quality of service delay. • Jitter buffers.
Dynamic: network element physical asymmetry.	• Time-stamping in the MAC, lower precision internal processor clock speeds (8Khz vs. 125 Khz).
Dynamic: asymmetry modulation schemes.	• Networks that are asymmetric.

Table 1. Noise impacting packet timing.

of reliability. The PTS architecture promoted in this article utilizes PTP as a means of "backup" for GNSS. This backup architecture is known as Assisted Partial Timing Support (APTS).

In Fig. 2 the T-GM (Telecom Profile Grandmaster) together with a Primary Reference Timing Clock (PRTC) provides a steady PTP stream to the Interworking Function (IWF) through the APTS capable backhaul network. In this case the IWF is a generic function, which describes a clocking device with several synchronous inputs and several outputs as required. In the APTS architecture, the eNB uses GNSS as its direct source of synchronization. Therefore, the GNSS sets and locks the phase and time in the clock/IWF. In the event of a GNSS failure, the PTP stream provides synchronization backup. Note, that although figure 2 shows a single T-GM, there could be cases where the Clock/IWF is integrated into the eNB. In addition, there may be cases where multiple grandmasters are used.

Algorithms incorporate the GNSS information into the timing information carried by the PTP stream so that the PTP time and frequency matches the GNSS implied reference when GNSS is unavailable. GNSS, PTP and the local oscillator information is suitable for both jamming and spoofing detection techniques. This work is for further study.

In the simplest case the PTP grandmaster uses GNSS as a PRTC. The APTS clock monitors the PTP stream for quality using the IWF's own timing clock connected to the GNSS and onboard oscillator if necessary. The GNSS information helps to quantify the quality of the PTP flow from the clock/IWF to the eNB. Static and dynamic noise introduced in the APTS networks during a rerouting configuration while the GNSS signal at the IWF is unavailable is an area for further study.

APTS is applicable primarily to locations of eNBs with adequate GNSS signal strength. A later section discusses how applying APTS benefits service providers with new capabilities of accurately monitoring synchronization over Ethernet MBH networks. It also reviews an early monitoring and reporting structure for KPIs with long-duration measurements profiles.

Specifying KPIs and Monitoring Ethernet Mobile Backhaul Networks

The APTS approach allows performance monitoring of the Ethernet MBH networks while GNSS is active and presumes that the network behavior remains, statistically speaking, unchanged when GNSS is lost.

Metrics: Key Performance Indicators

North American service providers rely on standards development for KPIs. APTS standards must provide KPIs for network limits, clock specifications, architecture methods, and telecom profiles. These KPIs will be instrumental for Implementations Agreements (IAs) and Service Level Agreements (SLAs) between service providers and Ethernet MBH providers. In addition, it may be in the service provider's best interest to share their ideal clock reference clock/IWF synchronization source with their

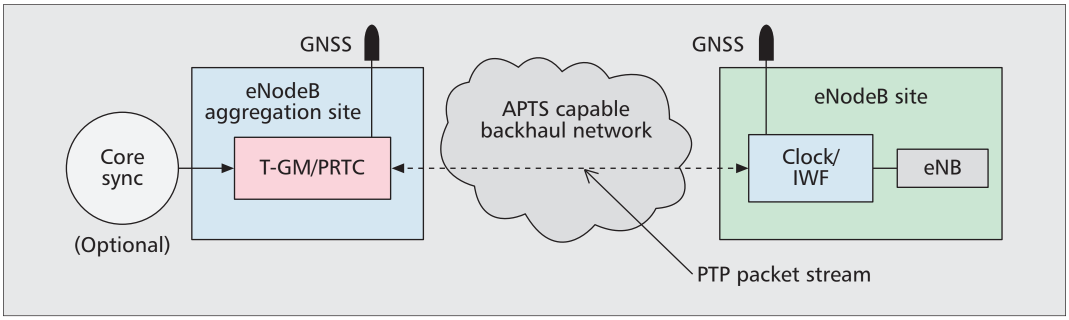

Figure 2. Assisted partial timing support application (isolated synchronization view).

Ethernet MBH providers. Doing so would allow the MBH provider a precise reference to measure their PDV. This is an area for further study.

Service providers would like KPIs that examine and quantify:

- Dynamic frequency/time error estimate.
- PDV metrics.
- Re-route event detection.
- Congestion event detection.
- Change of clock source.
- Traceability change.

Metrics proposed for APTS include MTIE, TDEV, Max |TE|, Constant |TE|, and network usability metrics such as floor-population that characterize amplitude statistics of PDV. ITU-T Rec. G.8260 [7] provides explanations of these and related metrics.

Reporting: Early Warning KPIs and Alarms

Service providers Operations Support Systems can use KPI alarm reporting to adjust the network as needed and evaluate performance metrics. Many KPIs are binary; this form of "pass/fail" classification is useful, but may not be sufficient. As an example, the unique response of time drift (wander) is not instantaneously available. Wander needs to be observed and measured over a prolonged period. Therefore, as seen in Fig. 3 it is advantageous to introduce an upper limit and a lower limit KPI. This will result in an alarm warning KPI state that service providers can use to their advantage.

APTS addresses GNSS outages where the oscillator provides holdover. This synchronization outage is detectable within the system. As previously mentioned, spoofing detection would need to obtain and utilize information present within the IWF's timing clock. Standards related to active performance reliability requirements and testing for PTP are still under study in the ITU-T SG15/Q13.

This section reviewed several advantages of APTS, such as GNSS backup and active monitoring. The next section reviews known PDV constraints, which pose the greatest challenge in an APTS network. In addition, the next section also reviews how PTP may transfer across the APTS network.

Packet Delay Variation Challenges in a APTS Model

In PTP timing-transfer architectures, the notion of FTS is that all intervening network elements between the PTP master and the PTP slave clocks are PTP-aware and perform either a boundary clock and/or transparent clock function. APTS networks may or may not require boundary clocks and/or transparent clocks to support a standard based PDV budget network profile. PTP-unaware network elements can transfer packet-based synchronization provided they satisfy some simple properties related to timing.

APTS utilizes PTP streams to backup GNSS. During a GNSS failure the PTP stream can be used to syntonize (also known as frequency alignment) the IWF clock and thus achieve time holdover. The MTIE of the recovered clock provides an indication of the quality of the holdover.

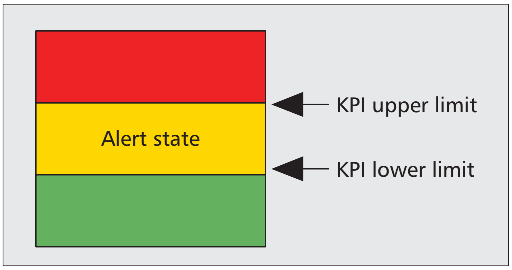

Figure 3. Upper/lower KPIs.

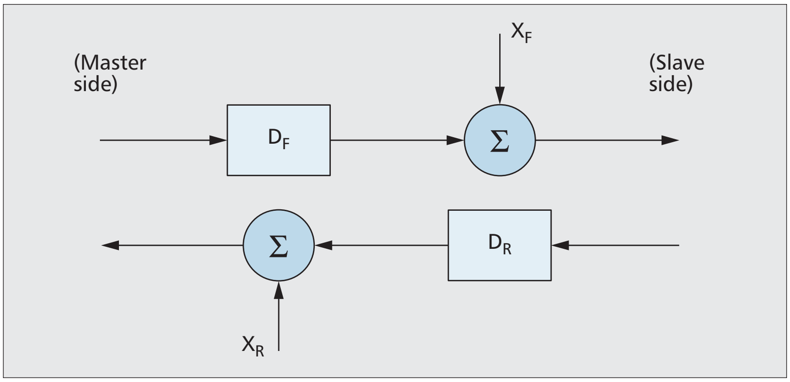

Figure 4. Transit delay model for PTP-unaware network element.

Let us consider that GNSS provides ±100ns accuracy. As an example, upon a loss of GNSS there could be an additional 400ns of transient error. This could result in a worst-case scenario of 500ns of time error. Therefore, the total requirement of ±1.5 μs leaves a budget of ±1 μs for holdover.

A question that is certain to arise for the APTS configuration composed of PTP aware and unaware network element will be, "Should one-way, forward and reverse (frequency synchronization) or two-way (frequency/phase) be used?" Some initial considerations are evaluated in the following section, but standards related to using PTPs Sync_Message and Delay_Request messaging exchange mechanisms to support APTS are under study in the ITU-T SG15/Q13.

Equipment Constraints

As discussed previously, when PTP packets traverse a network element, they will experience a static delay, also referred to as a floor delay, as well as a dynamic delay that is dependent on load. Figure 4 shows a simplified timing model.

The delays are made-up of floor delay (D) and a dynamic delay (X). The subscripts F and R indicate the forward direction from master to slave and in reverse from the slave to the master. The interpretation of floor delay is the minimum transit delay experienced by a timing packet, generally associated with near-zero load conditions. In order to support frequency transfer, D_F and D_R must be nominally constant, time-invariant, and load-invariant. Ideally the two directions are independent, but measurements indicate that there is a small effect of load in one direction on the floor in the opposite direction.

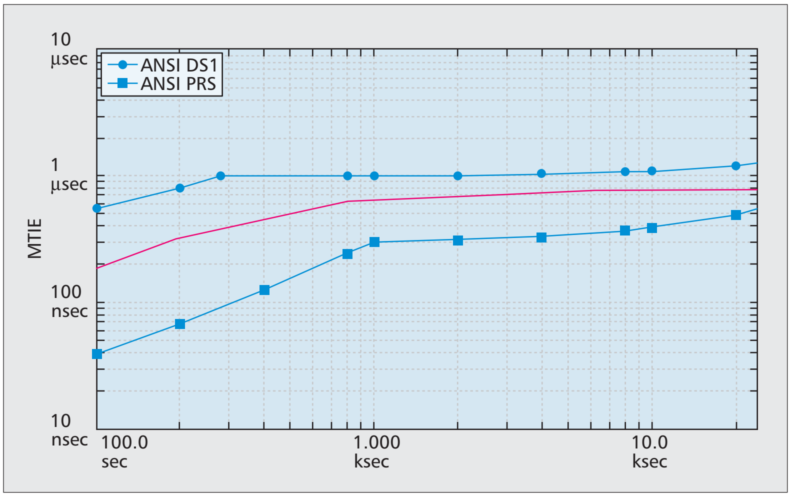

Figure 5. MTIE Computation assuming 1-percentile selection in 100s windows.

X_F/X_R is a non-negative random variable whose probability density function is dependent on the load through the network elements. Quality of timing recovery is proportional to the number of minimal delayed PTP packets. Under low-load conditions, a substantial percentage of PTP packets will experience the minimum floor delay and the quality of recovered timing will be excellent. At higher traffic levels, the number of packets passing through the network with minimum delay will diminish, which may stress clock recovery.

Slave Classification

Review of the floor delay is not complete without a discussion about the slave. Considering PTP packet distribution, the slave performs nearly all work to obtain an accurate representation of the IWF's timing clock. However, the ITU-T has not yet standardized on a PTP clock G.8273.4 applicable in the APTS configuration.

All network elements in the path of PTP packets can introduce packet delay variation. PDV is load dependent. Consequently, APTS can be used provided the number of intervening PTP-unaware network elements are limited and the traffic load is not excessive. In addition to these parameters, different slaves could provide different levels of tolerance to PDV, depending on the oscillator type and other factors such as algorithms utilized and the specific use cases. The next section provides a model that incorporates dynamic and static delay aspects, just reviewed, over the APTS network.

Modeling PDV Noise

There is limited real-world network data that is publicly available that can conclusively validate the capability of PTP to serve as a means of GNSS backup. Consequently, the normal approach is to use simulation models to generate PDV files played back through network emulators. The network emulator is located between the master and slave clocks. To validate the holdover of the slave, the performance of slave clocks timing output is measured.

Metrics that quantify the spectral characteristics of the PDV noise sequence provide guidance on relative performance levels at the slave clocks, given some information regarding slave clock class and the achievable filtering bandwidth.

Simulation studies assume the following attributes for the network element and network behavior. These assumptions are as follows:

- The behavior of the traffic load is varying dynamically.
- Service providers shape packet streams at their egress to smooth traffic into the expected Ethernet MBH network's policed ingress port policy. The load was adapted every 250ms, though in practice it could be less.
- In the simulation results described later, this variable load is to have a mean of 60 percent and standard deviation equal to 20 percent.
- The manner in which instantaneous load varies is a flicker sequence. Several studies (e.g. [9]) have indicated that load variations in packet networks exhibit self-similar behavior and therefore can be modeled as a flicker sequence.
- The instantaneous load is proportional to the probability that the link's queue is congested. The occupied queue leads to impairment of timely PTP packet transmission.
- The wait time can be as much as the length of the packet expressed in time units (packet size divided by link bit rate). The simulation performed assumed that 90 percent of the interfering packets were of maximum size (approximately 1.5kbyte).

Simulation Example

The simulation modeled a five-element network assuming all links were Gigabit Ethernet. The mean load assumed was 60 percent with a possible variation of 20 percent in standard deviation of instantaneous load that followed a flicker sequence that changed every 250ms. The packet rate was set at 32 packets per second.

A separate flicker noise sequence with a mean of 60 percent and standard deviation of 20 percent was created for simulating the load of each switching element. The simulation followed a Monte Carlo method. Each flicker sequence value provided the effective load on the element for 250ms duration. The 250ms duration establishes a set-limit for separate allowable bursts through each of the five elements in the packet-switched network. In order to simulate a real-world network and provide realistic PTP PDV, three separate random generators, which generate fractional values between 0 and 1, were used to produce the following effects:

- Queuing delay effects: delay experienced by a packet in an element.
- Sequential blocking delay effects: the size of the interfering packet in an element.
- Head-of-line blocking delay effects: fractional value of the interfering packet size provides additional delay to simulate the phenomenon of packet delay beyond the egress queues.

A "typical" slave performance in a frequency transfer mode assumed that packet selection occurs over 100s windows. For each 100s window, the representative transit delay was computed as the average of the transit delay of the 1 percent "fastest" packets. A simple choice of filter time constant is roughly 10 times the window interval and consequently the clock recovery filter bandwidth is set at 1 millihertz. Figure 5 shows the predicted MTIE of the recovered clock, and the American National Standards Institute (ANSI) Digital Signal 1 (DS1)/Primary Reference Source (PRS) masks were plotted to provide a context of reference.

Figure 5 shows how the MTIE meets the noise margin (holdover) objective of 1 μ s, indicating that the one-way PTP stream as modeled is adequate to provide a frequency reference to support time holdover. Additional testing based on real network behavior is required to provide definitive conclusions. Some slave clock implementations may use sophisticated algorithms, combining information from both directions of transmission, thereby providing even better performance. Under these assumed simulated network conditions, the PTP slave can provide holdover of the order of 800ns, while allowing for other noise sources such as transients that occur when the IWF loses and regains GNSS timing. This simulation shows that one-way PTP frequency or SyncE has merit and could be used to hold phase during the loss of GNSS. Duration of the holdover interval is for further study.

Summary

This article echoed the message of the ever-increasing demands on the RAN and various challenges for providing synchronization to macro and small cells. In general, North American service providers have a strong reliance on GNSS, but at the same time they are aware and concerned about all potential vulnerabilities. As of April 2014, ITU-T, Study Group 15 Question 13 has standardized the FTS model G.8275.1 to minimize the use of GNSS by using packet-based synchronization networks. The biggest challenge in any packet based synchronization mechanism involves accommodating the effects of PDV and asymmetry.

This article reviewed APTS for backing-up GNSS. While available, GNSS provides a reference clock to measure the PTP packets at the eNB and thereby allow unprecedented real-time network monitoring of packet-based synchronization systems. APTS also enables an early warning system to detect and report on small changes over long periods.

Classifications of slaves in the standards would be beneficial to account for various use cases. The simulation showed that a simple slave clock could provide a holdover of the order of 1 μ s over a dynamic five-node network.

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Biographies

Tim Pearson received his bachelor degree in Electronic Engineering Technology from the University of Nebraska Lincoln/Omaha in 1987. He introduced the Assisted Partial Timing Support contribution into ITU-T Group 15/Question 13 in September 2013 and participates in ATIS and MEF standards bodies. He has over 20 synchronization patent applications. He is currently a Technology Strategist reporting to Sprint's CTO group.

Kishan Shenoi received his bachelors, masters, and doctorate degrees from IIT-Delhi, Columbia University, and Stanford University, respectively, in 1972, 1973, and 1977. He is active in standards bodies and co-chair of the technical committee of NIST-WSTS. He is named on 45 patents and has several publications, including two books, *Digital Signal Processing in Telecommunications* (1995) and *Synchronization and Timing in Telecommunications* (2009). He is currently CTO of Qulsar, Inc.

While available, GNSS provides a reference clock to measure the PTP packets at the eNB and thereby allow unprecedented real-time network monitoring of packet-based synchronization system. APTS also enables an early warning system to detect and report on small changes over long periods.