

**Summary:** This bulletin examines how network anomalies disrupt Precision Time Protocol synchronization on long terrestrial links used for grid timing. Using a CAST testbed with emulated impairments, we measured delay, offset, and time interval error while monitoring packet rates. Symmetric delays did not perturb synchronization, whereas asymmetric delays produced false offsets; jitters were largely filtered out, but they delayed synchronization recovery; moderate packet loss was tolerated, while severe loss forced holdover and loss of synchronization.

## Precision Time Protocol Synchronization Under Network Impairments

### Introduction

The Center for Alternative Synchronization and Timing (CAST) team investigates ways to deliver time synchronization services over long-distance terrestrial links to align grand master clocks (GMCs) with remote boundary clocks (BCs), which serve as the local timing authorities for downstream power grid time-critical devices such as phasor measurement units [1]. Network-induced timing irregularities can interfere with Precision Time Protocol (PTP) operations and consequently disrupt grid operations, potentially leading to outages or instability. This bulletin examines PTP-pertinent network traffic anomalies and analyzes how such anomalies disrupt PTP operations.

### Network Causes of PTP Synchronization Disruption

Network anomalies interfere with PTP operation by introducing packet delays or packet losses, which are categorized as follows:

- **Traffic Congestion:** Unstable delays cause jitters, affecting packet timing.
- **Network Asymmetry:** Different paths for master-to-slave (m-s) and slave-to-master (s-m) messages result in inaccurate PTP delay calculations that lead to clock offset time errors.
- **Packet Loss:** Dropped PTP packets force slave devices to rely solely on internal clocks, undermining synchronization accuracy.
- **Cyberattacks:** Attacks, such as distributed denial-of-service (DDoS) or man-in-the-middle, disrupt, alter, or mislead timing data.

### PTP Synchronization Process

As shown in Figure 1, PTP calculates time offsets between a master and a slave clock via timestamped message exchanges [2]:

1. Master sends Sync message at time  $t_1$ ; slave receives it at time  $t_2$ .
2. Slave sends Delay\_Req message at time  $t_3$ ; master receives it at time  $t_4$ .
3. Transmission times:  $m-s = t_2 - t_1$ ,  $s-m = t_4 - t_3$ .
4. Mean delay:  $\text{Delay}_{\text{mean}} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$ .
5. Calculated offset:  $\text{Offset} = \frac{(t_2 - t_1) - (t_4 - t_3)}{2}$ .
6. Slave adjusts its clock using the offset to achieve synchronization.

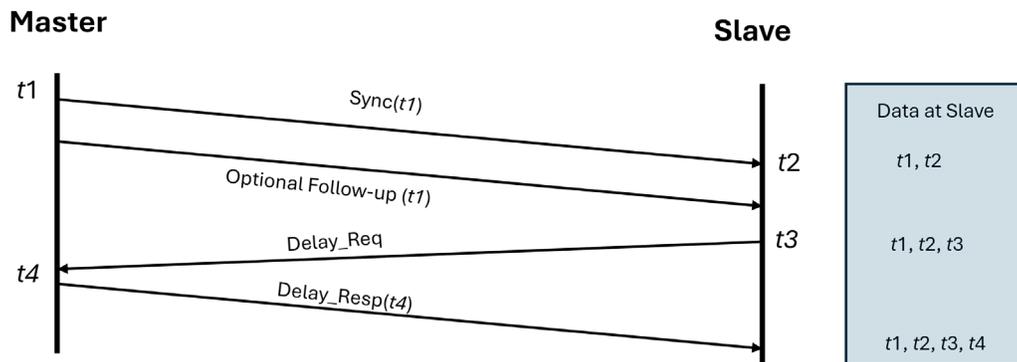


Figure 1: PTP synchronization messaging.

PTP assumes transmission symmetry; therefore, asymmetry or disruptions in packet flow can distort offset calculations, leading to synchronization failure. For instance, unequal delays in  $m-s$  and  $s-m$  messages violate this assumption, causing timing inaccuracies.

### Time Interval Error and Anomaly Monitoring

Time interval error (TIE) quantifies long-term phase variations ("wander") in clock signals. Derived from time error (TE), which measures the phase difference between master and slave clocks, TIE is calculated over  $k$  clock cycles:

$$\text{TE}(n) = t_{\text{slave}}(n) - t_{\text{master}}(n)$$

$$\text{TIE}(n, k) = \text{TE}(n + k) - \text{TE}(n)$$

where  $n$  is the cycle index. TIE behavior, including its maximum (MTIE) and time deviation (TDEV), can be distorted by PTP packet anomalies, such as delays or losses, thus disrupting synchronization. CAST leverages these metrics to monitor how anomalies affect time-critical operations.

### Network Anomaly Experimental Testbed

For controlled experiments, an in-house testbed was established, connecting an internal master clock (MC) and a BC (also called a slave), both ADVA OSA 5422 devices, via a Netropy network emulator (Figure 2). This setup simulates various traffic anomalies, enabling researchers to monitor data such as delays, offsets, and TIE. These observations are analyzed to correlate network disruptions with PTP parameters and evaluate their effects on synchronization performance. Additionally, CAST assessed the

commercial tool “Meinberg PTP Track Hound” [3] to evaluate its PTP monitoring and analysis capabilities, particularly with respect to detecting PTP packet loss.

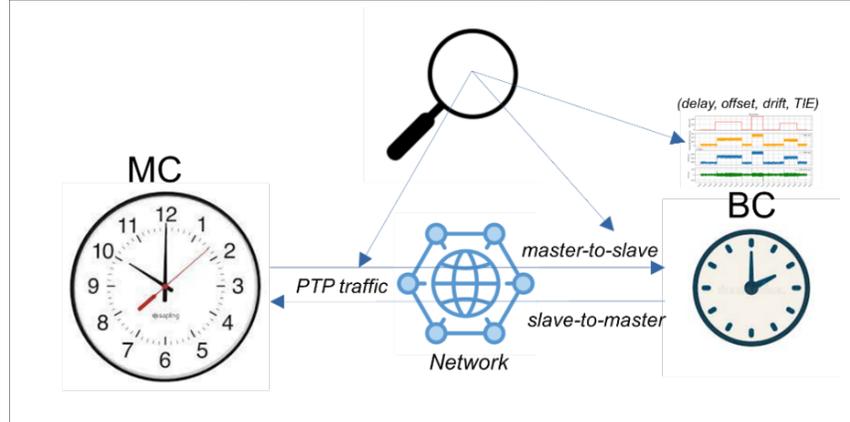


Figure 2: Network anomaly experimental testbed.

## Network Anomalies and Their Effect on PTP Performance

In this section, we examine four PTP network traffic anomalies and analyze how each affects which timing parameters:

### 1. Symmetric static delay

A symmetric delay affects both transmission directions equally. One example is when network congestion or specific device configurations introduce an equal delay on both m–s and s–m paths. Symmetric delays can alter raw delay measurements, but they typically do not cause synchronization errors. This trend was validated by the following experiment and results.

- Start with a stable, synced m–s link on the testbed.
- Apply a symmetric static delay  $D = 600 \mu\text{s}$  to the m–s and s–m paths (using a network emulator). The value of symmetric delay is selected arbitrarily yet is sufficiently large to illustrate its effect on the PTP traffic.
- The TIE plot of the slave clock (Figure 3, top), showing the raw m–s PTP delay, immediately demonstrated a step-down change corresponding to the introduced two-way delays.
- At the same time, the slave’s self-reported time with respect to the Global Navigation Satellite System (GNSS) (Figure 3, bottom) showed no meaningful offset or time change—only fluctuation in tens of nanoseconds, consistent with the normal jitter and not attributable to the  $600 \mu\text{s}$  symmetric delay. This result also matches PTP theory:

- Mean path delay:  $\text{mean} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} = D.$

- Offset:  $(t_2 - t_1) - \text{mean} = D - D = 0.$

- Therefore, symmetric delays cancel out in the offset calculation, and the slave requires no adjustment.

- Conclusion: Symmetric static delays do not affect PTP synchronization. Internally, PTP’s mean delay would increase by  $D$ , but it eventually cancels out in the offset calculation, so the slave clock remains in sync. The observed TIE step down reflects only the added delay measurement but not a loss of synchronization.

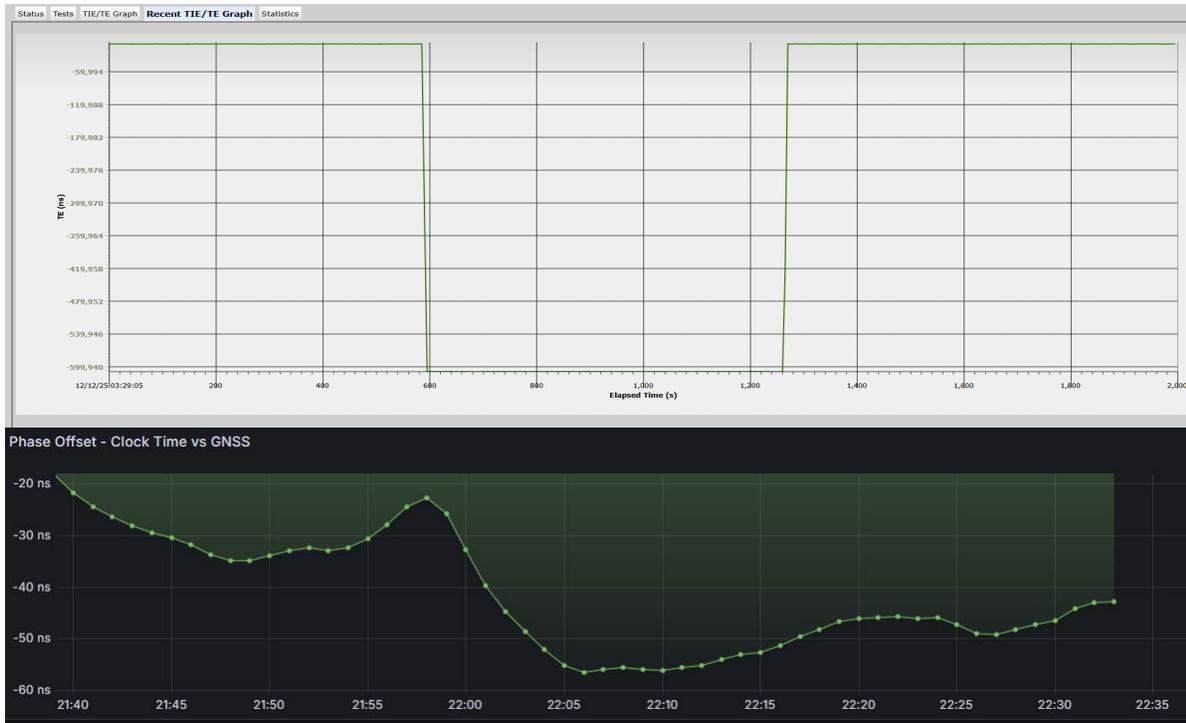


Figure 3. Effect of a symmetric static delay on PTP synchronization. (Top) The slave’s TIE, measured on the downstream PTP flow, shows an immediate step down when a symmetric delay  $D = 600 \mu\text{s}$  was applied to both m–s and s–m paths. (Bottom) The slave’s self-reported time remains stable (only in tens of nanoseconds normal jitter), consistent with the theory: mean =  $\frac{(t_2 - t_1) + (t_4 - t_3)}{2} = D$ ; offset =  $(t_2 - t_1) - \text{mean} = 0$ . The symmetric delay cancels out in calculating the offset, while the slave clock remains in sync.

## 2. Asymmetric static delay

Asymmetric delay occurs when a delay happens only on one of the two signal paths (commonly the m–s). Such a scenario could stem from misconfigured routing, non-PTP-aware network devices, or simply uneven network paths. An asymmetric static delay is problematic for PTP because the protocol assumes symmetric path timings [4].

Figure 4 summarizes our TIE observation and the slave clock reported time relative to GNSS during an asymmetric static delay:

- A static  $600 \mu\text{s}$  delay was introduced on the m–s path only.
- The TIE trace (Figure 4, top) monitoring the raw PTP downstream delay correspondingly stepped down by approximately  $600 \mu\text{s}$  at the onset of delay, consistent with the added one-way delay.
- The slave’s GNSS-referenced time showed an erroneous offset of about  $300 \mu\text{s}$  (with transient lags behind the start/stop time), indicating mis-synchronization due to the asymmetry.

- This follows PTP’s two-way calculation validated the erroneous 300 μs observation, a result from violating PTP symmetry assumption:
  - $\text{mean} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} = \frac{600 + 0}{2} = 300 \mu\text{s}.$
  - $\text{offset} = (t_2 - t_1) - \text{mean} = 600 - 300 = 300 \mu\text{s}.$
- A lag also occurred between the time the one-way delay was applied and the time the erroneous 300 μs offset on the slave clock was observed. This lag is due to the clock's finite bandwidth and the internal filtering/damping mechanisms designed to prevent the clock from reacting too abruptly to short-term jitters or transient delays. Different clock devices have different built-in damping mechanisms.
- Repeated runs with varied delay values yielded similar correlation results between injected asymmetric delays and offset anomalies.
- Conclusion: When the symmetry assumption is violated, PTP underestimates one-way delay and derives a spurious offset. Under such circumstances, the amplitude of injected asymmetry aligns with the observed TIE and GNSS-referenced offset changes, providing strong diagnostic evidence of path delay asymmetry as the dominant source of the measured timing error.



Figure 4. Effect of an asymmetric static delay on PTP. (Top) The TIE trace steps by approximately 600 μs when a one-way delay  $D = 600 \mu\text{s}$  is applied on the m–s path only. (Bottom) The slave’s GNSS-referenced time shows a spurious offset of about 300 μs, consistent with PTP’s symmetry assumption:  $\text{mean} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} = \frac{600 + 0}{2} = 300 \mu\text{s}$  and  $\text{offset} = (t_2 - t_1) - \text{mean} = 600 - 300 = 300 \mu\text{s}$ . Violating symmetry causes PTP to underestimate the one-way delay and derive a false offset.

### 3. Asymmetric jitter (random or varying delays)

Jitters are characterized by unpredictable variations in packet delay due to network congestion, fluctuating load, or sporadic interference. Unlike a steady delay, jitter causes the delay values to fluctuate over time.

Figure 5 demonstrates our experiment results with the TIE trace and the slave clock time with reference to GNSS, when asymmetric jitters are introduced on m-s path:

- We injected time-varying delays on the m-s path, ranging from 200 to 800  $\mu\text{s}$ . We then immediately applied a 2000  $\mu\text{s}$  static delay, following the jitter, on the same path.
- The TIE trace (Figure 5, top) shows one-way delay fluctuations consistent with the injected jitter, and then a clear immediate step down when the static delay was applied.
- The delay fluctuations momentarily perturb mean delay and offset estimates.
- However, the slave's GNSS-referenced time (Figure 5, bottom) showed no offset step down during the jitter period, indicating the clock's internal filtering and transient suppression mechanism.
- After the jitter and subsequent static delay (that came with corresponding offset step down), the recovery took a while once delays ceased. This delay indicates that sustained jitter slows convergence and can increase offset drift.
- Conclusion: Asymmetric jitter produces noticeable TIE variability while the clock built-in short-term filtering function maintains overall synchronization. However, if severe or persistent, jitters can degrade stability, lengthen recovery time, and potentially increase offset drift or stress the clock's outlier rejection.

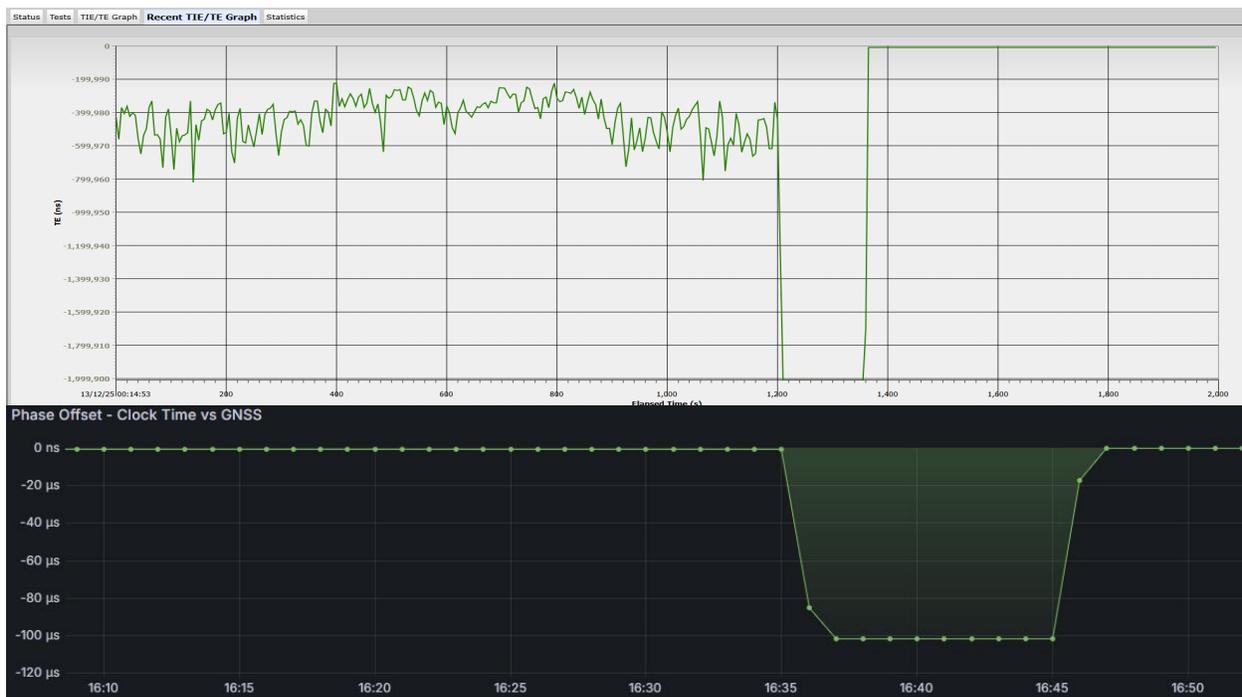


Figure 5. Effect of asymmetric jitter on PTP. (Top) TIE (m-s path) shows fluctuations and a clear step down, with injected jitter of 200–800  $\mu\text{s}$  on the m-s path, followed by a 2000  $\mu\text{s}$  static delay. (Bottom)

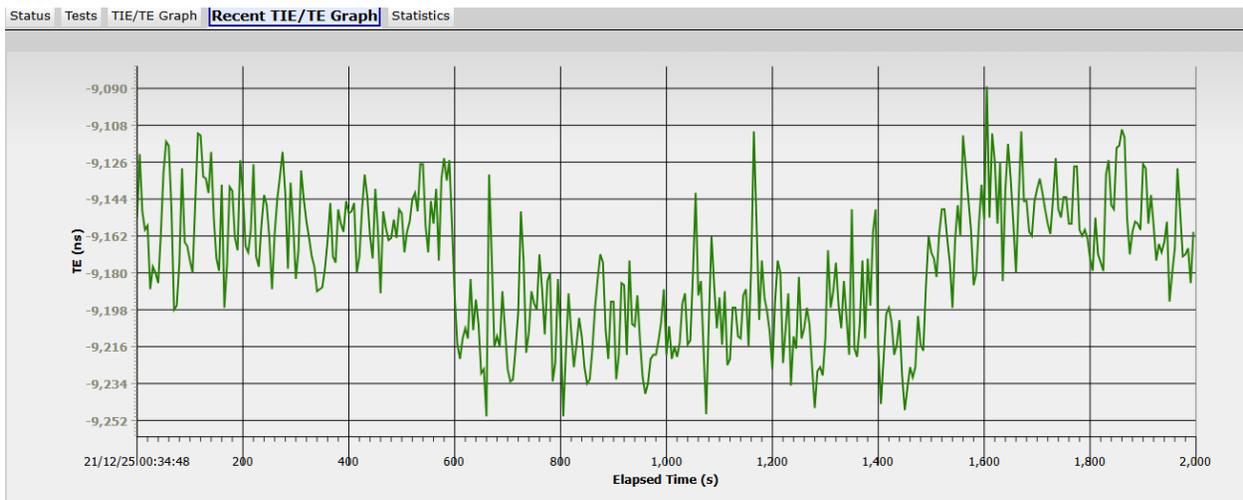
Slave time relative to GNSS shows no offset step during the jitter period, indicating servo filtering and transient suppression. After the static delay and jitter cease, recovery is slower, suggesting that sustained jitter increases settling time and can exacerbate offset drift.

#### 4. Packet loss

Packet loss involves the dropping of PTP messages (such as Sync, Delay\_Req, or Delay\_Resp) due to factors like network congestion, device malfunction, or routing issues.

Figure 6 shows the effect of 30% symmetric packet loss on clock timing when applied to m-s and s-m paths.

- We introduced 30% packet loss on the m-s and s-m paths.
- The PTP packet rate (Figure 6, middle), captured with Meinberg PTP Track Hound, shows an immediate step down in total PTP packet rate at the start of the 30% loss and a step up at the end. The total (Sync + Delay\_Req + Delay\_Resp) drops from ~390 to ~260 packets per second. Assuming the pre-loss mix is roughly one-third each, and because Sync at the tap is unaffected while Delay\_Req/Delay\_Resp traverse the lossy path both ways, their observed rates should scale by  $0.7^2 = 0.49$ . The expected post-loss total is  $1/3 + 0.49 \times 2/3 \approx 0.66$  of baseline (i.e., about two-thirds [about 260 out of 390]), consistent with the setup.
- The TIE trace (Figure 6, top) shows a small deviation of about 50 ns during the packet-loss interval and returns to the baseline after recovery at the end of the packet-loss simulation.
- The slave's GNSS-referenced time (Figure 6, bottom) shows no significant offset change during the 30% loss period. This result indicates that the PTP system tolerated the light packet loss well and maintained synchronization with the master.



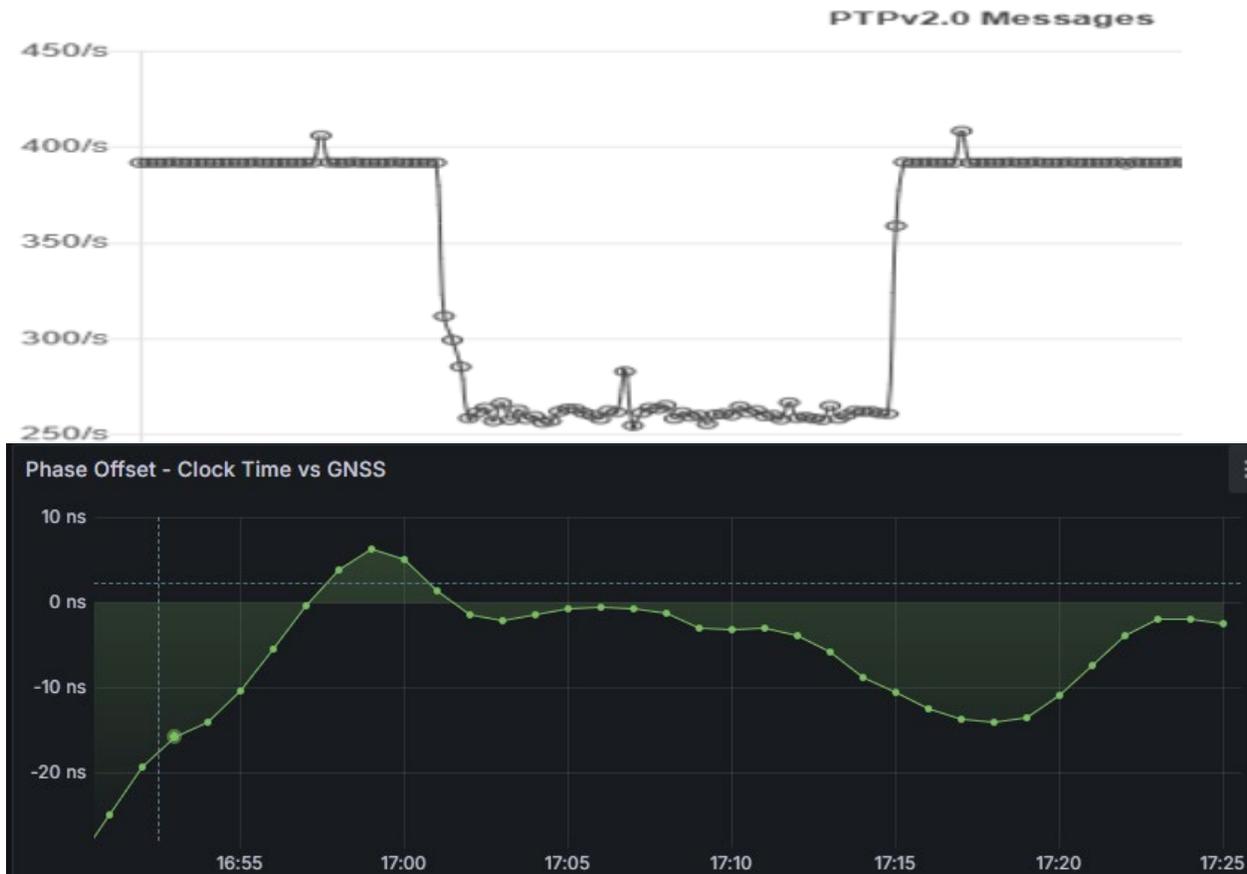


Figure 6. Effect of 30% symmetric packet loss (applied to m–s and s–m paths) on PTP. (Top) TIE shows a small deviation of about 50 ns during the loss interval and returns to baseline after recovery. (Middle) Meinberg PTP Track Hound shows the total PTP packet rate (Sync, Delay\_Req, Delay\_Resp) stepping down from about 390 to about 260 packets/s, consistent with Sync at the tap being unaffected and Delay\_Req/Delay\_Resp scaling down by  $0.7^2 = 0.49$ , yielding an expected total of  $1/3 + 0.49 \times 2/3 \approx 0.66$  of baseline. (Bottom) The slave’s GNSS-referenced time shows no offset change, indicating synchronization was maintained despite the loss.

Figure 7 shows the effect of 95% symmetric packet loss on clock timing when applied to the m–s and s–m paths. Approximately 10 s after the 95% packet-loss interval began, the TIE trace (Figure 7, top) shows a complete loss of synchronization (red indicators). With 95% loss in both directions, the total PTP packet rate (Sync, Delay\_Req, Delay\_Resp) drops from about 390 to about 130 packets/s, with Delay\_Req and Delay\_Resp nearly disappearing. The received messages are too sparse for the slave to calculate offset and delay. As such, it cannot maintain a lock to the master; the slave clock exhibits a large offset step and transitions to holdover (Figure 7, bottom).

PTP systems can maintain timing and synchronization in the presence of light packet loss by leveraging previously established synchronization information. However, under severe packet loss conditions, the reduced message rates severely degrade the system’s ability to compute accurate timing. At very high loss levels, synchronization will fail entirely, forcing the system into a holdover state in which timing error gradually accumulates, increasing the risk of operational disruption.

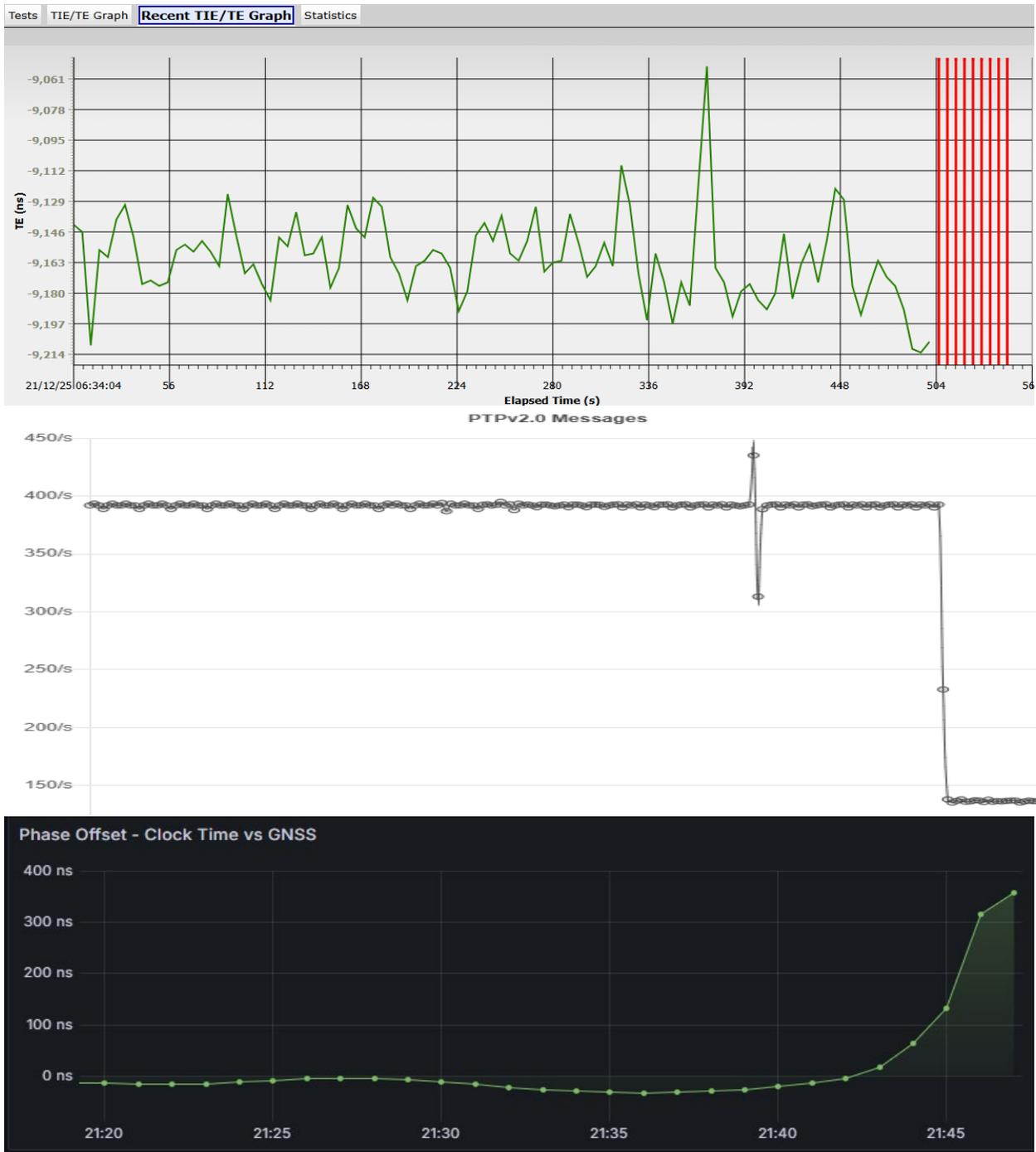


Figure 7. Effect of 95% symmetric packet loss (m-s and s-m). (Top) The red lines in TIE show synchronization shut down. (Middle) The total PTP packet rate drops significantly. (Bottom) The slave's ability to track offset and stay in sync with the master is largely lost at the onset of extremely high packet loss.

## Conclusion

This study provides visibility on how network anomalies propagate into PTP timing estimates and ultimately affect CAST synchronization. Using a network emulator between MC and BC, we injected

controlled impairments in symmetric as well as asymmetric paths, including varying severity levels of packet delays and losses. Increased asymmetric delays, jitter, and bandwidth saturation bias can obscure the two-way measurements used to compute PTP offset and delay, eventually resulting in degraded synchronization accuracy. Under severe conditions, these errors can disable PTP and cause PTP-dependent devices to malfunction, resulting in loss of synchronization and potential disruptions to critical applications such as power and industrial control systems.

To mitigate such risks, robust, PTP-aware network design and proactive monitoring must be employed. Additional effective measures include redundant GMCs, dual-homed or dual-path connectivity, and usage of Parallel Redundancy Protocol for hitless failover; configuring switches and routers as boundary or transparent clocks to minimize queuing and asymmetry; isolating and prioritizing PTP traffic via dedicated networks or virtual LANs with quality of service; and designing paths for maximal symmetry. The anomaly observables and the causal correlations identified here can also provide additional actionable precursors for monitoring or investigation, facilitating early detection and remediation before pending service disruptions.

## References

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