

General Technical Guide for Industrial All-Optical Network Evolution: Imperative of Clock Synchronization — Why NTP Fails to Meet Industrial Control Requirements

1. Guide Overview and Scope of Application

1.1 Compilation Basis

This guide is compiled in strict accordance with the **internationally recognized IEEE/IEC standard system**. Core reference standards include: IEEE 1588-2019 (IEC 61588:2021) *Precision Time Protocol (PTP) Specification*, IEC/IEEE 60802 *Industrial Automation Ethernet*, IEC/IEEE 61850-9-3 *Precision Time Protocol Specification for Power Automation*, ITU-T G.698.x series industrial all-optical network standards, and IEEE 802.1AS (gPTP) time-sensitive networking synchronization standard.

1.2 Applicable Scenarios

This guide targets scenarios under the **industrial all-optical network architecture**, including intelligent manufacturing, smart grid, rail transit, automotive Ethernet, process industry, and high-end equipment control. It focuses on core services such as distributed equipment coordination, closed-loop real-time control, sequence of events (SOE) recording, fault wave recording, and high-precision sampling. It clarifies the imperative of clock synchronization, demonstrates the applicability shortcomings of the NTP protocol, and provides a standardized basis for the selection of all-optical network synchronization solutions.

1.3 Core Definitions

- **Industrial All-Optical Network:** An industrial communication network built based on optical fiber media, passive optical network (PON), and optical switching technologies, featuring low loss, large bandwidth, anti-electromagnetic interference, and low latency; it is the core carrier for Industry 4.0 and OT/IT convergence.
- **Clock Synchronization:** Includes time synchronization (phase alignment, absolute time) and frequency synchronization (phase consistency, clock frequency). Industrial control requires simultaneous fulfillment of high precision, low jitter, and high reliability.
- **NTP:** Network Time Protocol, a time synchronization solution for general IT scenarios with millisecond-level synchronization precision.
- **Imperative Threshold:** The minimum synchronization performance threshold for stable operation in industrial control scenarios, verified by both international

standards and field tests.

2. Clock Synchronization for Industrial All-Optical Networks: Core Imperatives and Standard Requirements

2.1 Clock Synchronization as the Foundation of Industrial Control

The essence of industrial control is **distributed real-time coordination**. All intelligent devices (PLCs, servo drives, sensors, IEDs, robots) must execute instructions, collect data, and record events based on a unified time reference. Once synchronization fails, it will directly cause out-of-sync control, data disorder, fault misjudgment, equipment downtime, and even production safety accidents.

Although the industrial all-optical network solves the bandwidth and anti-interference problems of transmission media, **insufficient clock synchronization precision** remains the core bottleneck restricting deterministic control. Moreover, the low-latency characteristics of the all-optical network further amplify the requirements for synchronization precision rather than reducing them.

2.2 Industrial Synchronization Performance Indicators Defined by International Standards

In accordance with the IEEE/IEC series of standards, the rigid indicator requirements for clock synchronization in industrial control scenarios are clear and far higher than those in general IT scenarios, as detailed below:

Industrial Scenario	Synchronization Precision Requirement	Jitter/Wander Upper Limit	Basis Standard
Conventional Discrete Manufacturing/Motion Control	$\leq 1\mu\text{s}$ (Sub-microsecond Level)	$\leq 50\text{ns}$	IEC/IEEE 60802, IEEE 1588
Smart Grid Differential Protection/Fault Wave Recording	$\leq 1\mu\text{s}$ (Compliant across 15 switches)	$\leq 25\text{ns}$	IEC/IEEE 61850-9-3

TSN + All-Optical Network Deterministic Transmission	≤500ns	≤20ns	IEEE 802.1AS
High-End Equipment/Precision Assembly	≤100ns~500ns	≤10ns	IEEE 1588-2019
Sequence of Events (SOE) Recording	≤1ms (Minimum), Preferred ≤100μs	≤100ns	IEC 61850, IEC 61588

2.3 Special Requirements for Synchronization in Industrial All-Optical Networks

- **No Error Accumulation in Multi-Hop Cascading:** Synchronization errors shall be controllable and not amplified step by step under the multi-stage optical switching and splitting architecture of all-optical networks.
- **Deterministic Delay Compensation:** Despite low latency in optical fiber transmission, precise measurement and dynamic correction of link delays are still required.
- **Strong Anti-Electromagnetic Interference:** The stability of the synchronization link is not affected by the complex electromagnetic environment on industrial sites.
- **Seamless Redundant Hot Backup Switching:** No synchronization interruption or large jump occurs when the backup clock switches over upon the failure of the master clock.
- **Software-Hardware Decoupling Adaptation:** Supports hardware timestamp acceleration for optical network devices and terminal equipment.

3. Core Defects of NTP Protocol: Root Causes of Failing to Meet Industrial Control Imperatives

3.1 Basic Characteristics and Precision Ceiling of NTP (Standard Perspective)

NTP (RFC 5905) is a time synchronization protocol designed for the general Internet, positioned as non-real-time and coarse-grained synchronization with **no standard adaptability for industrial control scenarios**. Its performance has an insurmountable ceiling:

- **Upper Limit of Synchronization Precision:** Only **1~10ms** in the optimal LAN scenario, degrading to 10~100ms in WAN/multi-hop scenarios, far lower than the sub-microsecond-level imperative of industrial control.
- **Standard Positioning Difference:** In the IEEE/IEC industrial standard system, NTP is only classified as a general IT protocol and is not included in any mandatory standards for industrial automation.
- **No Frequency Synchronization Capability:** Only achieves absolute time alignment and cannot meet the rigid demand for clock frequency synchronization in industrial control.

3.2 Technical Defects: Fatal Shortcomings in Industrial Scenarios

3.2.1 Timestamp Mechanism: Uncontrollable Errors Introduced by Software Timestamping

NTP adopts **application-layer software timestamping**. Timestamp capture is affected by operating system scheduling, protocol stack processing, process blocking, and interrupt delay, resulting in errors up to milliseconds or even tens of milliseconds with uncontrollable jitter. The low-latency transmission advantage of industrial all-optical networks is completely offset by NTP software timestamping errors.

3.2.2 Delay Processing: No Precise Compensation and Extremely Poor Link Adaptability

- NTP only roughly estimates the round-trip link delay and **does not support one-way delay measurement**, making it unable to adapt to asymmetric all-optical network links.
- No residence delay correction mechanism; forwarding delays in multi-hop optical networks and switches directly accumulate into synchronization errors.
- In case of network congestion and traffic jitter, the delay of NTP synchronization packets changes abruptly, leading to an instantaneous degradation of precision.

3.2.3 Clock Architecture: No Hierarchical Optimization and Extremely Poor Robustness

NTP adopts a peer-to-peer communication mode with **no Best Master Clock Algorithm (BMCA)** and no multi-hop optimization architectures such as Boundary Clock (BC) and Transparent Clock (TC). Synchronization errors are amplified step by step in multi-level all-optical network topologies, making global synchronization impossible. In addition, there is no clock redundancy switching mechanism, and a master clock failure leads to full-network out-of-sync.

3.2.4 Industrial Adaptability: No Hardware Acceleration and Deterministic Guarantee

NTP does not natively support hardware timestamping and cannot adapt to the hardware synchronization functions of industrial all-optical network equipment, optical modules, and switches. Synchronization packets have no priority scheduling and are easily crowded out by large data traffic, failing to ensure deterministic transmission and completely failing to meet the IEC 61508 functional safety requirements.

3.3 Measured Failure Scenarios: Typical Faults of NTP in Industrial Control

- **Out-of-Sync Motion Control:** Millisecond-level deviations cause coordination errors of servo motors, resulting in defective products in precision assembly and production line sorting, and an increase in downtime rate.
- **SOE Event Disorder:** When a fault occurs, the timestamp deviation reported by equipment exceeds milliseconds, making it impossible to determine the sequence of events and leading to fault location failure and protection maloperation.
- **Distorted Data Acquisition:** Asynchronous timestamps of multi-node sensors cause timing disorder of high-frequency sampling data, invalidating digital twins and closed-loop control.
- **All-Optical Network Adaptation Failure:** Under the low-latency characteristics of optical links, the high proportion of NTP software delay leads to further degradation of synchronization precision.

4. Alternative Clock Synchronization Solutions for Industrial All-Optical Networks (IEEE/IEC Standard System)

4.1 Mainstream Standard Solution: IEEE 1588 PTP (IEC 61588)

PTP is an **industrial precision time synchronization standard protocol** jointly issued by IEEE/IEC, specially designed for distributed measurement and control networks. It is perfectly adapted to the industrial all-optical network architecture and remedies all defects of NTP:

- **Compliant Precision:** With hardware timestamping, single-hop precision $\leq 10\text{ns}$, and $\leq 1\mu\text{s}$ across 15 devices in multi-hop TC/BC architecture, meeting the imperatives of all industrial scenarios.
- **Architecture Adaptation:** Supports Boundary Clock (BC) and Transparent Clock (TC), blocking multi-hop error accumulation and adapting to multi-level all-

optical network topologies.

- **Standard Compatibility:** Included in the IEC 61850, IEC 60802, and TSN standard systems, supporting seamless docking of all-optical network equipment and industrial terminals.
- **Redundant Reliability:** BMCA supports hot backup of multiple clock sources with seamless switching and no synchronization interruption.

4.2 Exclusive Solution for TSN + All-Optical Networks: IEEE 802.1AS (gPTP)

A generalized precision time protocol optimized based on IEEE 1588, serving as the synchronization core of Time-Sensitive Networking. It is adapted to deterministic transmission scenarios of all-optical networks, with end-to-end synchronization precision $\leq 500\text{ns}$ and microsecond-level latency control, perfectly matching the low-latency characteristics of industrial all-optical networks.

4.3 Exclusive Solution for Power/Rail Transit: IEC/IEEE 61850-9-3

A customized PTP specification for the power industry, requiring synchronization precision $\leq 1\mu\text{s}$ across 15 transparent clocks. It supports PRP/HSR redundant networking, adapts to high-reliability scenarios of industrial all-optical networks, and meets stringent requirements such as relay protection and fault wave recording.

5. Conclusion and Evolution Recommendations

5.1 Core Conclusion

Limited by its design positioning, standard specifications, and technical architecture, the NTP protocol **cannot meet the imperative threshold of industrial control in terms of synchronization precision, determinism, robustness, and industrial adaptability**. It can only be used for non-real-time, non-critical services in industrial scenarios (e.g., background logging, operation and maintenance management), and must never be used for core services such as closed-loop control, high-precision sampling, SOE recording, and relay protection. Under the industrial all-optical network architecture, IEEE 1588 PTP (IEC 61588) and its derivative standard solutions must be adopted to fulfill the clock synchronization imperatives.

5.2 Evolution Recommendations for Industrial All-Optical Network Synchronization

1. **Solution Selection:** Adopt IEEE 1588-2019 PTP for conventional industrial scenarios, IEEE 802.1AS gPTP for TSN + all-optical network scenarios, and IEC/IEEE 61850-9-3 for power/rail transit scenarios.
2. **Hardware Adaptation:** Industrial all-optical network switches, optical modules, and terminal equipment must support hardware timestamping and TC/BC clock modes.
3. **Topology Optimization:** Adopt Transparent Clock (TC) to reduce multi-hop errors, and combine with Boundary Clock (BC) for hierarchical synchronization in complex topologies.
4. **Redundant Deployment:** Configure multiple master clock sources and implement seamless switching through BMCA to ensure synchronization reliability.
5. **Standard Implementation:** Strictly follow IEEE/IEC standard parameter configurations to avoid performance degradation caused by non-standard modifications.

6. Appendix: Standard Index

- IEEE 1588-2019 (IEC 61588:2021): Precision Time Protocol (PTP) Specification
- IEC/IEEE 60802: Industrial Automation Ethernet
- IEC/IEEE 61850-9-3: Power Utility Precision Time Protocol Profile
- IEEE 802.1AS-2020: Generalized Precision Time Protocol (gPTP)
- ITU-T G.698.x: Industrial All-Optical Network Physical Layer Specifications