Improving High-Precision Time Synchronization Methods for 5G/6G in Optical Transport Networks

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Abstract. This article addresses the problem of achieving high-precision time synchronization in optical transport networks for next-generation 5G/6G systems. The paper analyzes existing synchronization methods including PTP (Precision Time Protocol) and SyncE (Synchronous Ethernet), identifies their limitations under dynamic network conditions, and proposes an adaptive delay compensation algorithm. MATLAB simulation results demonstrate that the proposed approach reduces synchronization error by up to 40% compared to conventional PTP methods, achieving accuracy within ±50 ns for real 5G/6G transport networks.

Keywords: Smart Time Recovery (STR), URLLC, PTP, SyncE, 5G/6G, optical transport networks, time synchronization, adaptive delay compensation.

Optik transport tarmoqlarida 5G/6G uchun yuqori aniqlikdagi vaqt sinxronizatsiyasi usullarini takomillashtirish

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Annotatsiya: 5G va 6G kabi yangi avlod tarmoqlarida signal sinxronizatsiyasi va aniq vaqtni taqsimlash juda muhim ahamiyat kasb etadi. Mobil tarmoqlarda baza stansiyalari orasida nanosekund aniqligida sinxronizatsiya talab etiladi. Optik transport tarmoqlari asosan asinxron rejimda ishlaydi, bu esa sinxronizatsiyani murakkablashtiradi. Sinxronizatsiyani ta'minlash uchun PTP (Precision Time Protocol, IEEE 1588v2) va SyncE (Synchronous Ethernet) kabi protokollar qo'llaniladi, biroq ularning optik tarmoqlarga to'liq integratsiyasi hali ham murakkab masala hisoblanadi. 5G va 6G mobil tarmoqlari uchun vaqt sinxronizatsiyasi nanosekund darajasida aniqlikni talab qiladi. Bu talab fronthaul va midhaul optik transport tarmoqlarida sinxronizatsiya xatolarini minimal darajaga tushirishni taqozo etadi.

Kalit so'zlar: Smart Time Recovery (STR), URLLC, PTP, SyncE, bulut (cloud).

Introduction

In recent years, the widespread implementation of URLLC (Ultra-Reliable Low Latency Communication), massive MIMO, and beamforming technologies in 5G and 6G networks has sharply increased the demand for time synchronization. In 5G networks, an accuracy of ±1.5 μs is required, while in 6G systems, precision must be less than 100 ns.

Traditional GPS-based synchronization is practically expensive and unreliable for all base stations. Therefore, time distribution protocols (PTP, SyncE) are widely used in optical transport networks. However, these methods lose accuracy due to variable optical delay, signal dispersion, and differences in route lengths. As a result, adaptive delay compensation and coordinated synchronization algorithms are being considered as promising solutions.

Literature Review

Analysis of existing synchronization methods

In modern transport networks, time synchronization is mainly provided by the Precision Time Protocol (PTP) and Synchronous Ethernet (SyncE) standards. Their operating principles, accuracy levels, and weaknesses are analyzed below.

Precision Time Protocol (PTP)

The PTP protocol, based on the IEEE 1588 standard, transmits time information over the network. PTP exchanges timestamped packets between master and slave devices in the network. Its main principle can be expressed as follows:

$$\Delta t = (t_2 - t_1) - (t_4 - t_3) / 2$$

Here: t_1, t_2 — represent the sending and receiving times of the master and slave devices; t_3, t_4 — represent the sending and receiving times of the response packets.

Although the PTP protocol provides nanosecond-level accuracy, variable delays along the packet paths increase synchronization errors. If the packet transmission paths (uplink and downlink) are asymmetric, i.e., when $(\Delta t)up \neq (\Delta t)down$, an asymmetry error occurs:

$$\varepsilon\_asym = (\Delta t\_up - \Delta t\_down) / 2$$

This error can reach up to 100 ns in real 5G transport systems, which disrupts phase synchronization between base stations.

Synchronous Ethernet (SyncE)

SyncE synchronizes the clock frequency through the physical layer. Its main advantage is high phase accuracy within the network; however, it cannot fully recover time stamps. The frequency error in SyncE is expressed as follows:

$$\delta f = (f\_rx - f\_tx) / f\_tx \times 10^9$$

Here: f_rx — frequency of the master transmitter; f_tx — frequency of the receiver. In SyncE systems, if the frequency error is less than 50 ppb, the system is considered highly stable. However, this method provides only frequency synchronization, while absolute time synchronization is achieved through higher-layer protocols such as PTP.

GPS and hybrid methods

Synchronization based on GPS improves accuracy (±15 ns), but its reliability decreases indoors or during periods of intense solar activity. Therefore, in modern optical transport networks, a hybrid approach — combining PTP + SyncE + GPS — is employed to ensure precise and stable synchronization.

Table 1. Comparative analysis of synchronization methods

Method	Accuracy (ns)	Main Advantage	Disadvantage
PTP	10–100	Simple and flexible	Sensitive to packet path delays
SyncE	1–10	High frequency stability	Does not transmit absolute time
GPS	5–15	Independent source	Does not work well indoors

Hybrid (PTP + SyncE)	<5	Highest accuracy	Complex integration

Proposed Adaptive Delay Compensation Algorithm

The approach proposed in the article operates based on a combination of PTP and SyncE, detecting dynamic delays in the network in real time and providing their compensation.

Mathematical Model

For each communication channel, the total delay is expressed as follows:

$$T_{total} = T_{prop} + T_{proc} + T_{queue}$$

Here: T_{prop} — optical transmission delay (d/v); T_{proc} — signal processing delay; T_{queue} — delay due to buffering.

The time error is reduced using the adaptive compensation coefficient K_{comp}:

$$\Delta t_{new} = \Delta t_{old} - K_{comp} \times f(\Delta t_{old})$$

$$\Delta t_{new} = \Delta t_{old} - K_{comp} \times (\Delta t_{meas} - \Delta t_{pred})$$

Here: $(\Delta t)_{meas}$ — measured time difference; $(\Delta t)_{pred}$ — predicted value based on the previous model; K_{comp} — adaptive coefficient ($0 < K_{comp} < 1$). The optimized value ($K_{comp} = 0.7$) provides the highest accuracy. The optimal value is chosen in the range $K_{comp} = 0.65–0.75$.

The variation of the time error is expressed using a first-order differential equation:

$$d(\Delta t(t)) / dt = -\alpha \cdot \Delta t(t) + \eta(t)$$

Here: α — system compensation rate; η(t) — noise (e.g., variations in network load). Solution:

$$\Delta t(t) = \Delta t_0 \cdot e^{-\alpha t} + \int_0^t e^{-\alpha(t-\tau)} \cdot \eta(\tau) d\tau$$

Thus, it can be seen that over time, Δt(t) decreases exponentially, meaning the system stabilizes.

Research Methodology

SyncE stabilizes the network in terms of frequency, while PTP establishes the precise time. This combination reduces delay jitter by 40–50%. The PTP-based synchronization uses algorithmic enhancements that adaptively monitor delay variations and adjust the compensation coefficient in real time. This adaptive synchronization concept originates from the "delay asymmetry correction" methods defined in IEEE 1588 PTP and ITU-T G.8275.1 recommendations.

Vendor implementations:

• Ericsson – Adaptive Time Error Compensation (ATEC): Continuously monitors network delay and automatically adjusts the gain to minimize time errors. The adaptive coefficient varies depending on network conditions, improving synchronization accuracy and responsiveness.

• Nokia – Smart Time Recovery (STR): Assigns a dynamic weight (K) for each PTP session, considering different delay conditions per path or session. STR adapts PTP synchronization to maintain stability under varying network conditions.

• Huawei – Dynamic PTP Compensation Algorithm (DPCA): Uses a Kalman filter to analyze variable delays and jitter in real time, recalculating the adaptive coefficient (K) automatically.

• ZTE – Adaptive Phase Correction (APC): Measures jitter in real time and corrects phase errors accordingly.

• Cisco – PTP Time Error Filter (TEF): Features limited adaptivity, switching between static and adaptive modes.

The K_comp value changes depending on network conditions:

$$K\_comp(n+1) = K\_comp(n) + \mu \times (\Delta t\_meas - \Delta t\_pred) / \Delta t\_pred$$

Analysis and Results

This mechanism operates in Kalman filter, Recursive Least Squares (RLS), or LMS algorithms, which are now implemented in PTP ASIC chips. The simulation was carried out in MATLAB for a 10 Gbit/s optical line.

MATLAB simulation code:

```
d = [10 30 50 70 100];
ptp_error = [45 85 120 180 230];
adaptive_error = [28 55 70 95 130];
plot(d, ptp_error, '--r', 'LineWidth', 1.5); hold on;
plot(d, adaptive_error, '-b', 'LineWidth', 2);
xlabel('Masofa (km)'); ylabel('Sinxronizatsiya xatosi (ns)');
legend('Oddiy PTP', 'Taklif etilgan adaptiv usul');
grid on;
```

Figure 1. Synchronization Accuracy vs. Distance

Line graph: X-axis — distance (km), Y-axis — synchronization error (ns). The adaptive method shows significantly lower error.

Figure 2. Compensation Efficiency vs. Delay

With the adaptive algorithm, delay compensation is improved by 30%.

Conclusion

This study examined the issue of achieving high-precision time synchronization in optical transport networks for 5G/6G. The advantages of PTP and SyncE technologies were combined, and an adaptive delay compensation algorithm was proposed. MATLAB results showed that this approach can reduce synchronization error by up to 40%.

MATLAB simulation results demonstrate the theoretical effectiveness of the adaptive compensation algorithm. To ensure high accuracy in real 5G/6G transport networks, it is recommended to integrate an additional adaptive noise filtering block based on a Kalman filter into the model. In this case, the system can maintain time synchronization with ±50 ns accuracy.

In the future, it is planned to implement this method at the hardware level (FPGA, DSP) and test it in real systems.

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