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CENI DIP Networking Test Report

Purple Mountain Laboratories for Network Communication and Security
Huawei Network Technology Laboratory
Beijing University of Posts and Telecommunications
Jiangsu Future Networks Innovation Institute

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Academician's Message

Over the past 50 years, the TCP/IP system and related technologies have achieved great success and are one of the most important driving forces behind the progress of human civilization. Over the past 20 years, the rapid development of informatization has provided an inexhaustible driving force for China's economic development and shortened the distance between people and between people and society. In the next 10 years or even longer, future network technologies will deeply serve various industries and gradually become the basic support for social production activities. We hope to work with more people to develop network technologies and contribute to the knowledge progress of countries, peoples, and the world.

Liu Yunjie

Academician of Chinese Academy of Engineering

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1 Overview

As China's first major national scientific and technological infrastructure in the communications and information field, the China Environment for Network Innovations (CENI) provides an open and large-scale test environment for the deployment, testing, and verification of future network architecture and key technologies. Purple Mountain Laboratories for Network Communication and Security, Huawei Network Technology Laboratory, Beijing University of Posts and Telecommunications, and Jiangsu Future Networks Innovation Institute have carried out joint research and deployment tests on CENI and deterministic IP (DIP)[1]. The tests focus on the deterministic quality of the data plane's forwarding. The high-precision aggregation cycle scheduling and cycle mapping technologies are used to implement long-distance and scalable deterministic forwarding at Layer 3. This solves the forwarding jitter caused by traffic aggregation and microbursts and eliminates the long tail effect of E2E delay, meeting the requirements of high-precision services and devices.

2 DIP Deployment and Testing

2.1 Deployment and Testing of the CENI Backbone Network and Yangtze River Delta Comprehensive Test Network

DIP is deployed and tested based on the CENI backbone network and Yangtze River Delta comprehensive test network. The purpose is to deploy prototypes and verify the design principles and performance of DIP. We tested the effectiveness of DIP on medium-, short-, and long-distance transmission links and verified that E2E jitter stability is irrelevant to the number of hops. We also identified the possibility of supporting future high-precision network applications represented by industrial production networks. Table 2-1 describes test information.

Table 2-1 Test methods

No.	Test Name	Test Objective
1.1	DIP testing on the Beijing-Nanjing thousand-kilometer loopback network	Verify the WAN networking capability. Specifically, perform DIP device networking tests based on CENI's Beijing-Nanjing thousand-kilometer transmission backbone network to verify that DIP supports WAN networking without geographical restrictions in long-distance and multi-hop scenarios.
1.2	DIP testing on the Yangtze River Delta comprehensive test network	Verify functions. Specifically, perform DIP device networking tests based on the Yangtze River Delta comprehensive test network. Use a tester to send traffic to construct microbursts, and compare the results of traditional IP's best-effort forwarding with those of DIP's deterministic forwarding to verify the DIP design principles.

2.1.1 Beijing-Nanjing Thousand-Kilometer Loopback Network

Among the national nodes on the CENI backbone network, Beijing, Shijiazhuang, Zhengzhou, Wuhan, Hefei, and Nanjing nodes were selected for DIP deployment, as shown in Figure 2-1.

[1] DIP is equivalent to Large-scale Deterministic Network (LDN) in ETSI GR NGP 016 V1.1.1

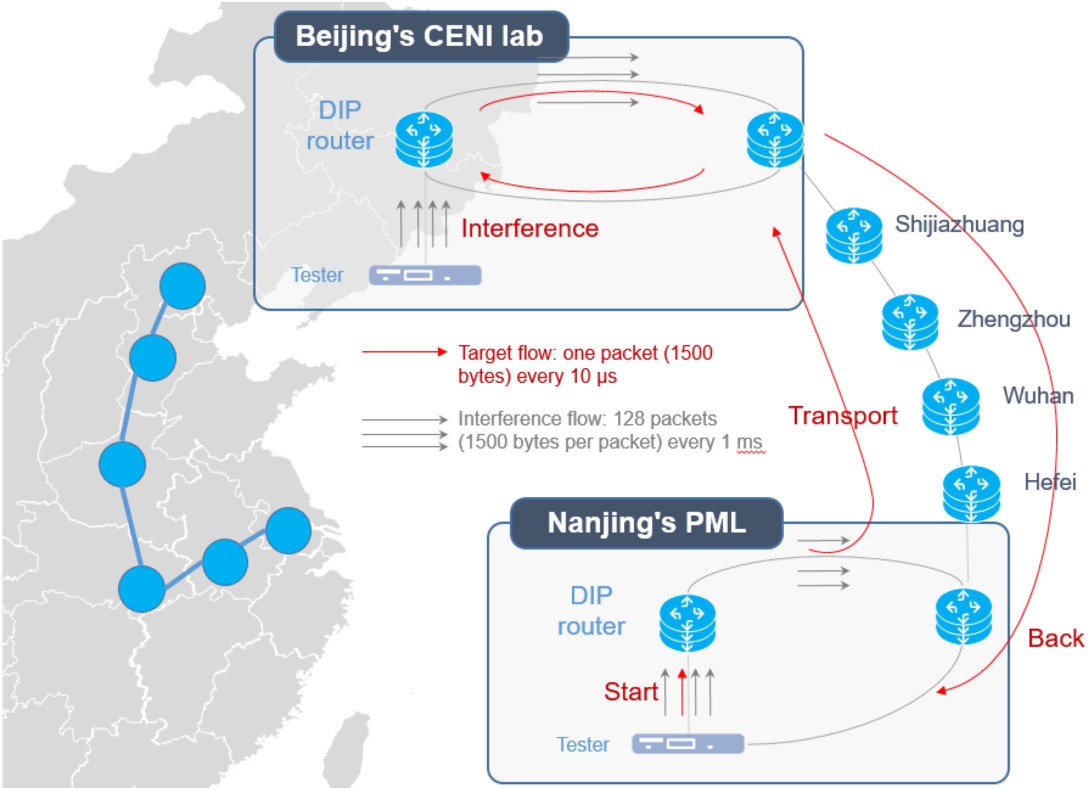
Test flows started from the Purple Mountain Laboratories in Nanjing, passed through the Hefei, Wuhan, Zhengzhou, Shijiazhuang, and Beijing nodes, and then returned to the tester of the Nanjing node along the original path. The test flows passed through 11 DIP devices in total. In addition, testers were used in the equipment rooms in Beijing and Nanjing to introduce interference flows to simulate network congestion and traffic bursts. Table 2-2 lists the target flow and interference flow parameters.

Table 2-2 Test flow parameters

Target flow parameters:	Packet sending rate: 1.2 Gbps; packet length: 1500 bytes; packet sending time cycle: 10 μs; port rate: 10 Gbps
Interference flow parameters:	Packet sending rate: 1.2 Gbps; packet length: 1500 bytes; burst size*: 128; port rate: 10 Gbps
*Number of packets sent within 1 ms	

Figure 2-1 shows that the target flows passed through 11 routing devices. When the interference flows burst, traditional IP's best-effort forwarding encounters sawtooth jitter, but DIP's forwarding undergoes stable jitter. Figure 2-3 shows the process where the jitter of traditional IP increased as the interference flows increased. The curve variation in the figure is a good confirmation of the analysis based on the network calculus theory (see section 2.3 Deterministic Capability Analysis Based on the Network Calculus Theory). Table 2-3 lists the test results of CENI. **In the scenario where the round-trip test path exceeded 2000 km and passed through multiple devices, using DIP devices for WAN networking at the thousand-kilometer level could still ensure stable E2E jitter. DIP is the only multi-hop deterministic forwarding technology currently that can support a Layer 3 large-scale long-distance network where core network devices do not need to maintain per-flow state.**

Figure 2-1 Beijing-Nanjing thousand-kilometer loopback network deployment*



*The cut-through mode was configured on the ingress devices — which were not counted into the 11 hops — in Beijing and Nanjing.

Figure 2-2 Test results of the CENI Beijing-Nanjing thousand-kilometer loopback network

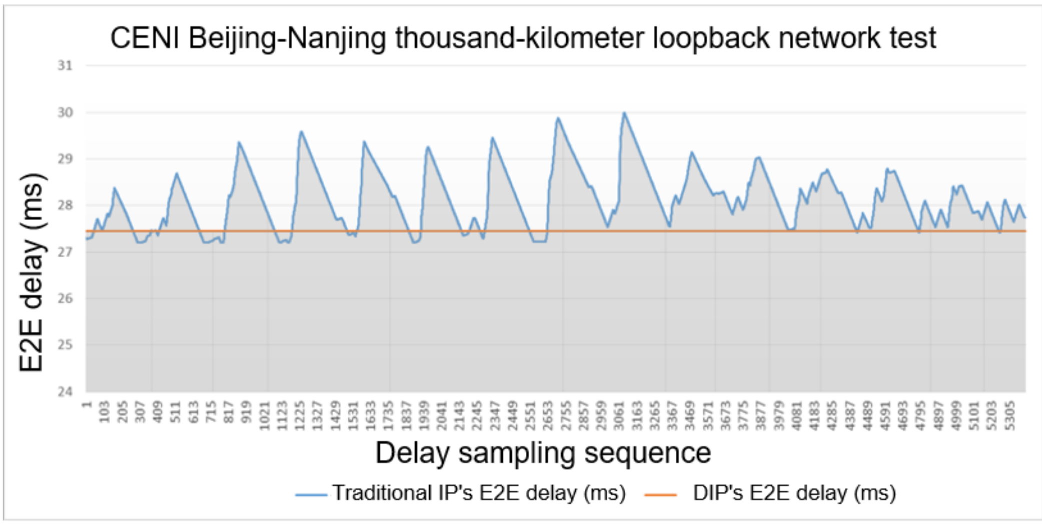


Figure 2-3 Jitter changes in DIP testing on the Beijing-Nanjing thousand-kilometer loopback network

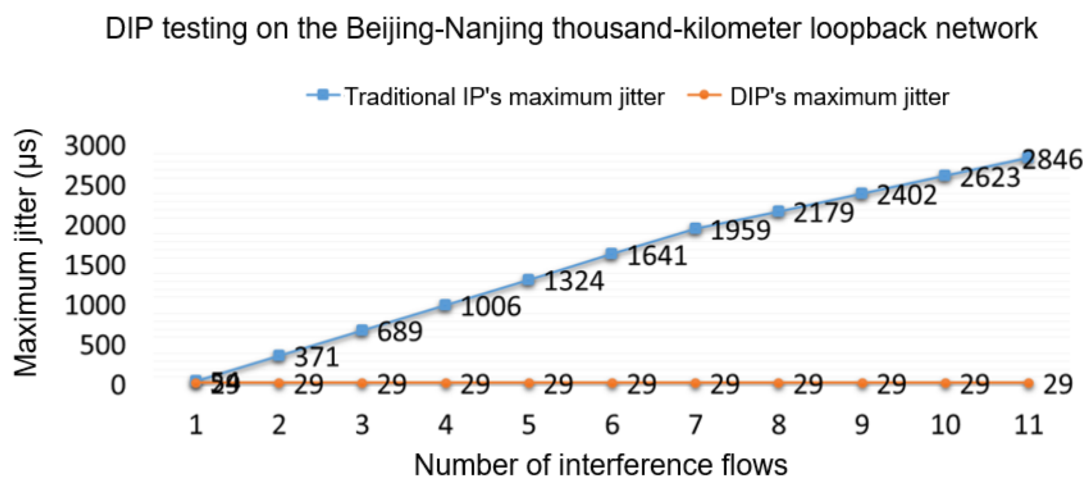


Table 2-3 DIP test results of the Beijing-Nanjing thousand-kilometer loopback network

Number of Interference Flows	E2E Delay of Traditional IP Forwarding (**μs**)				E2E Delay of DIP Forwarding (**μs**)			
	Minimum	Average	Maximum	**Maximum Jitter**	Minimum	Average	Maximum	**Maximum Jitter**
1	27142	27146	27196	**54**	27176	27195	27205	**29**
2	27142	27152	27513	**371**	27176	27195	27205	**29**
3	27142	27162	27831	**689**	27176	27195	27205	**29**
4	27142	27211	28148	**1006**	27176	27195	27205	**29**
5	27142	27269	28466	**1324**	27176	27195	27205	**29**
6	27142	27338	28784	**1641**	27176	27195	27205	**29**
7	27143	27388	29102	**1959**	27176	27195	27205	**29**
8	27143	27444	29322	**2179**	27176	27195	27205	**29**
9	27143	27601	29545	**2402**	27176	27195	27205	**29**
10	27143	27713	29766	**2623**	27176	27195	27205	**29**
11	27143	27827	29989	**2846**	27176	27195	27205	**29**

2.1.2 Yangtze River Delta Comprehensive Test Network

In the Yangtze River Delta comprehensive test network, DIP devices were deployed in eight cities: Nanjing, Suzhou, Yangzhou, Taizhou, Zhenjiang, Wuxi, Changzhou, and Shanghai. In this networking test, the ring topology between the Nanjing, Yangzhou, Taizhou, and Shanghai nodes was selected. As shown in Figure 2-4, topology test flows started from the Purple Mountain Laboratories in Nanjing, passed through Yangzhou, Taizhou, and Shanghai, and then returned to the tester in Nanjing. The test flows passed through five DIP devices along the path. In addition, a tester was used in the Nanjing equipment room to introduce interference flows and construct microbursts[2] by injecting traffic into multiple interfaces and sending it out of one interface to simulate network congestion and traffic bursts. Table 2-2 lists the target flow and interference flow parameters.

Figure 2-4 Ring test topology of the Yangtze River Delta comprehensive test network

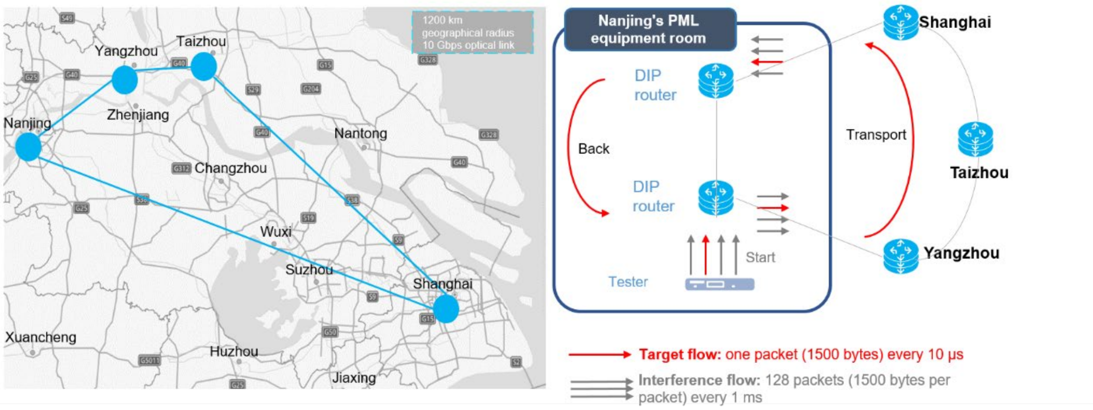


Figure 2-5 shows that — in traditional IP's best-effort forwarding mode — the E2E transmission of the test network was obviously affected by microbursts, and the delay displayed sawtooth jitter. In DIP forwarding mode, DIP packets were always processed by specific timeslots and resources during Layer 3 network forwarding. No matter how many interference flows existed, DIP forwarding could always maintain stable jitter at an ultra-low level at the network layer.

Figure 2-6 shows the process where the jitter of traditional IP increased as the interference flows increased. Table 2-4 lists the test results of the Yangtze River Delta comprehensive test network. According to the test results, when traditional IP forwarding was used, the jitter tested on the Yangtze River Delta comprehensive test network was more than 35% of the overall E2E delay, and even more serious in traffic burst scenarios. DIP was not affected by interference flows, and the E2E delay jitter was always limited to 30 μs. Since DIP has requirements on the packet enqueuing rule and time cycle, the minimum delay of DIP forwarding is slightly higher than that of traditional IP forwarding. However, the results show that the extra delay can be completely ignored. The delay and jitter test results of multiple DIP test flows are the same as those of a single flow because DIP is resource-exclusive.

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[2] https://support.huawei.com/enterprise/en/doc/EDOC1000060766/426cffd9?idPath=24030814|21782165|21782236|252837173

Figure 2-5 Test results of the Yangtze River Delta comprehensive test network

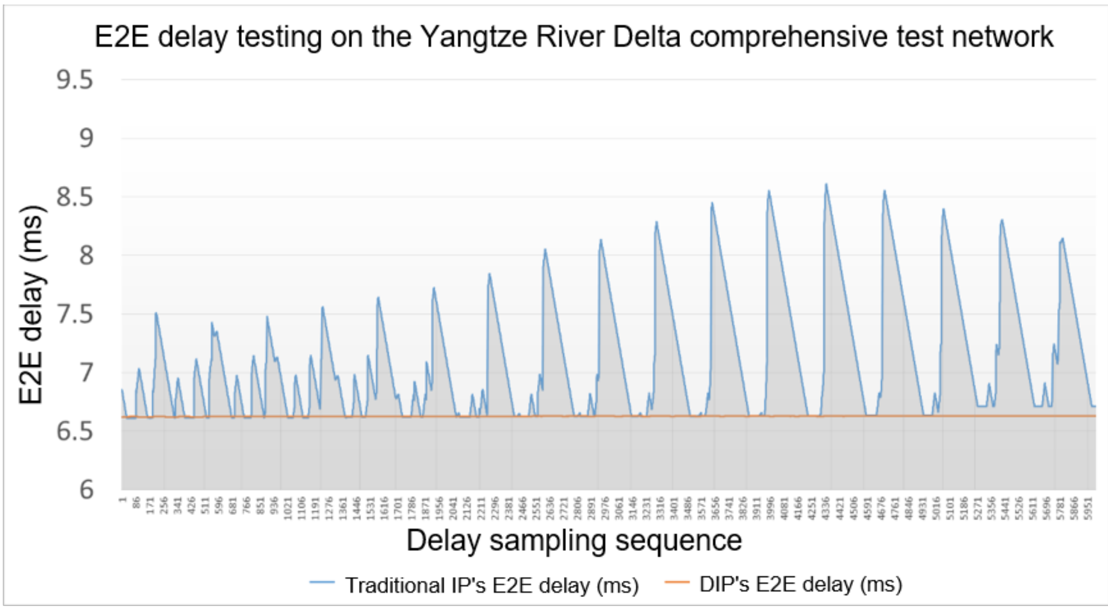


Figure 2-6 Jitter changes in DIP testing on the Yangtze River Delta comprehensive test network

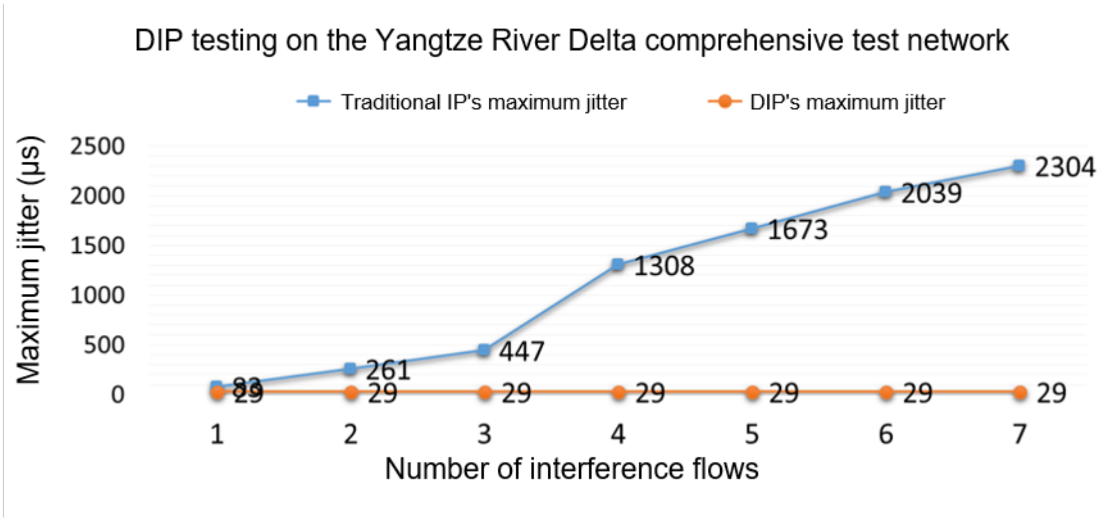


Table 2-4 DIP test results of the Yangtze River Delta comprehensive test network

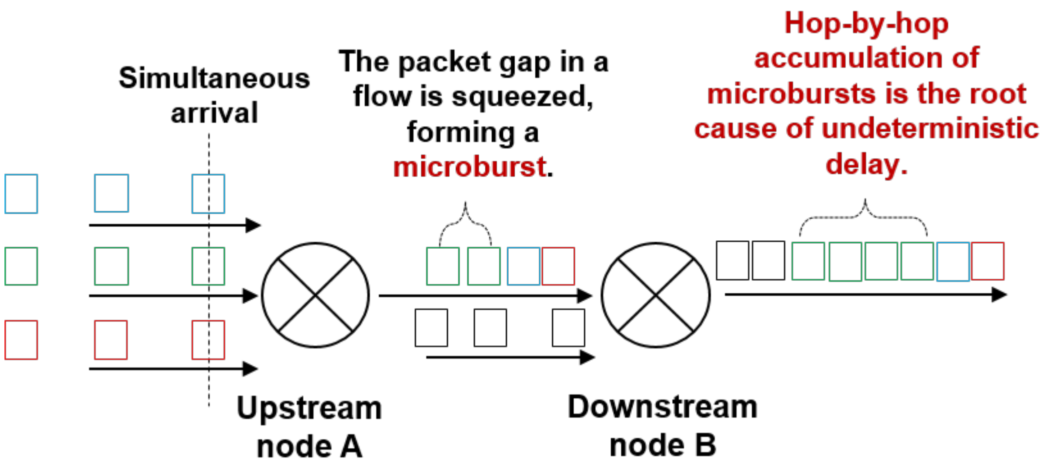
Number of Interference Flows	E2E Delay of Traditional IP Forwarding (μs)				E2E Delay of DIP Forwarding (μs)			
	Minimum	Average	Maximum	**Maximum Jitter**	Minimum	Average	Maximum	**Maximum Jitter**
1	6304	6306	6386	**83**	6360	6374	6389	**29**
2	6304	6311	6564	**261**	6360	6374	6389	**29**

3	6304	6321	6751	**447**	6360	6374	6389	**29**
4	6304	6370	7612	**1308**	6360	6374	6389	**29**
5	6304	6463	7977	**1673**	6360	6374	6389	**29**
6	6304	6577	8343	**2039**	6360	6374	6389	**29**
7	6304	6695	8608	**2304**	6360	6374	6389	**29**

2.2 Layer 3 Deterministic Forwarding and Application Requirements

As more applications and services are carried on the network, deterministic service quality becomes an important service requirement. TSN is a typical Layer 2 deterministic communication technology. Based on strict clock synchronization, data packets must be forwarded within a specified time cycle. As a result, the effective physical distance is limited. In a wide area, data packets must be routed through multiple hops to reach the destination. IP technology is based on statistical multiplexing. In a most extreme case, as shown in Figure 2-7, data packets of multiple flows may arrive at one network device (e.g., upstream node A) at the same time because of no control on the arrival time of each data packet, and are queued on the outbound interface for scheduling. Queuing squeezes the gap of packets in the original flow, forming microbursts. Assuming that downstream node B has several upstream nodes like A, microbursts are accumulated to form microburst iterations. After multiple hops, the deterministic delay cannot be guaranteed.

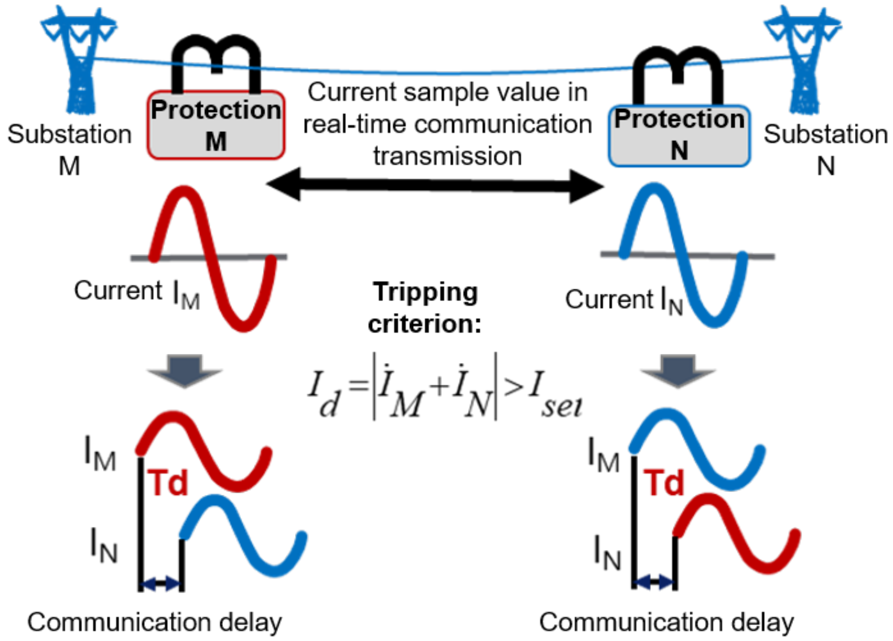
Figure 2-7 Causes of microbursts and Layer 3 undeterministic forwarding



A large number of services have high deterministic forwarding requirements on signal transmission. If only high bandwidth is used at the network layer to solve problems, many applications cannot be remotely deployed on the network in the future. Tele-surgery requires millisecond-level transmission delay and microsecond-level jitter to ensure that each action on the subject side can be perfectly reproduced on the receptor side. The purpose of relay protection is to automatically detect whether the cables between substations are faulty, which is of great significance to energy security. To avoid incorrect judgment caused by delay deviation, IEC

61850[3] defines that the difference (jitter) between two unidirectional delays cannot be greater than 200 μs, and the jitter of each unidirectional delay cannot exceed 50 μs. Industrial production and manufacturing require a large number of equipment clusters and precise E2E signal transmission. The jitter of control signaling will increase security risks and the defect rate, seriously affecting the production efficiency. Visible industrial production and manufacturing require signal transmission jitter in hundreds of microseconds to ensure the effect of quasi-bus technology.

Figure 2-8 Delay and jitter requirements in relay protection scenarios



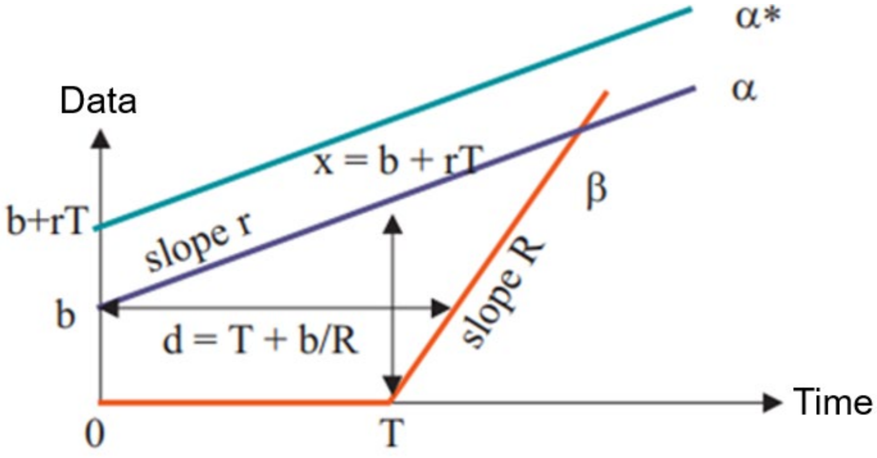
In the future, more application scenarios pose high requirements on the deterministic communication quality of the network. In addition to guaranteeing bandwidth and E2E delay, jitter must be ensured to meet requirements in more industrial scenarios.

2.3 Deterministic Capability Analysis Based on the Network Calculus Theory

The network calculus theory provides a method for calculating the upper bound for the E2E delay of a network. When the network topology, each node's service curve (comprehensive abstract description of the node processing delay characteristics, interface capacity, and shaping and scheduling algorithms), and the traffic arrival curve and E2E path of all flows are given, the worst E2E queuing delay can be calculated. The upper bound for the E2E delay can then be obtained by adding the propagation delay.

[3] https://webstore.iec.ch/searchform&q=61850

Figure 2-9 Basic model of network calculus



Based on the network calculus theory, academia has proved[4, 5] that — in common scenarios (the topology and traffic may be arbitrary) — the traditional IP statistical multiplexing forwarding mode can provide an extremely poor upper bound or even no upper bound for the E2E delay. Specifically, when the network diameter (the maximum number of hops through which traffic passes) is h, the upper bound for the delay can be obtained only when the maximum link bandwidth usage meets the condition $\mathrm{v} < 1/(\mathrm{h}-1)$, and the upper bound for the delay increases rapidly with the number of hops. When the condition $\mathrm{v} \geq 1/(\mathrm{h}-1)$ is met, there is no upper bound for the delay.

The upper bound for the E2E delay in traditional IP DiffServ scenarios is as follows:

$$\text{if } \mathrm{v} < \frac{1}{h-1}, \qquad \mathrm{d} \leq \frac{(e+\tau)h}{1-(h-1)v}$$

$$\text{else}, \qquad \mathrm{d} \to \infty$$

v is the maximum link bandwidth usage, e is the maximum node processing delay, τ is the maximum initial burst serialization delay (total number of initial bursts divided by the link bandwidth), and h is the number of E2E hops.

In addition to best-effort forwarding, this conclusion applies to DiffServ forwarding.

Based on statistical multiplexing, DIP uses the cycle shaping and scheduling mechanism to form isolation between time cycles, preventing microbursts and hop-by-hop accumulation and breaking the vicious circle of "sudden increase of the traffic arrival curve results in initial service delay increase, and then further leads to sudden increase of the traffic leaving curve" in the network calculus. This makes the E2E delay linearly and slowly increase with the number of hops, and

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[4] Zhang Z L, Duan Z, Hou Y T. Fundamental trade-offs in aggregate packet scheduling[C]//Proceedings Ninth International Conference on Network Protocols. ICNP 2001. IEEE, 2001: 129-137.

[5] Charny A, Le Boudec J Y. Delay bounds in a network with aggregate scheduling[C]//International Workshop on Quality of Future Internet Services. Springer, Berlin, Heidelberg, 2000: 1-13.

ensures that the upper bound for the E2E jitter is constant. The upper bound for the E2E delay in DIP scenarios is as follows:

$$\mathrm{d} = \sum_{i \le h} (\zeta + \ell_i) \pm \zeta$$

ζ is the length of the DIP time cycle, ℓ_i is the clock phase offset of the ith hop, and h is the number of E2E hops. DIP implements precise shaping and scheduling periodically to avoid microbursts. The delay of each hop is determined, and the E2E delay linearly increases with the number of hops, implementing the E2E microsecond-level deterministic quality.

Figure 2-10 Comparison of upper bounds for E2E delays (queuing delays)

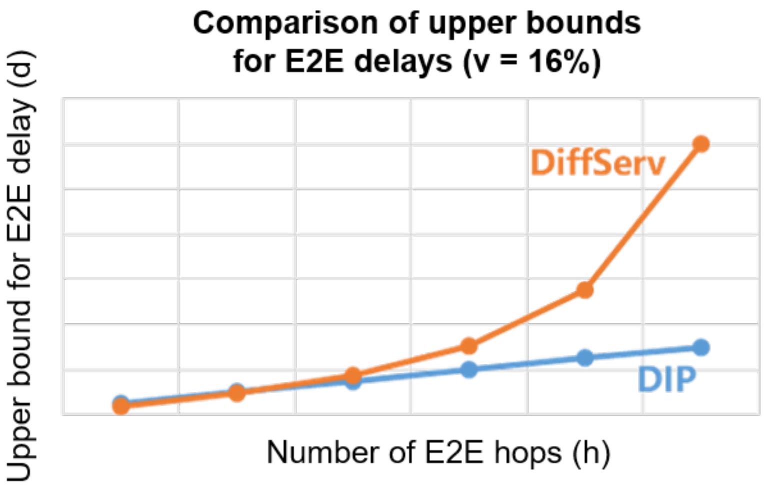


Figure 2-10 compares the E2E delay trends of DIP and DiffServ when the maximum link bandwidth usage v is 16% (very light load). Even in the case of extremely light load, the E2E delay of DiffServ starts to increase sharply after three hops. As a result, there is no upper bound for the E2E delay after data packets passing through seven hops. The E2E delay of DIP increases linearly, even when the network usage is much greater than 16% or even in the case of full load (as shown by the blue curve in the figure).

3 Test Conclusion and Future DIP Networking and Test Planning

The CENI DIP networking test has achieved good results. By building large-scale deployment and test environments covering 13 cities in China, including Beijing, Wuhan, Nanjing, and Shanghai, Purple Mountain Laboratories for Network Communication and Security, Huawei Network Technology Laboratory, Beijing University of Posts and Telecommunications, and Jiangsu Future Networks Innovation Institute jointly carried out the world's first deterministic WAN innovation test. Based on the statistical multiplexing feature of traditional IP, Huawei DIP devices can incrementally provide deterministic forwarding capabilities with strict and stable jitter guarantee. These capabilities have been verified in the CENI backbone network and Yangtze River Delta comprehensive test network. The deterministic communication is the core capability for future networks to deeply support industrial production-level applications and services. It plays a significant role in promoting smart manufacturing and digital society. The success of this test is an important milestone for deploying, testing, and verifying the future network architecture and key technologies in CENI.

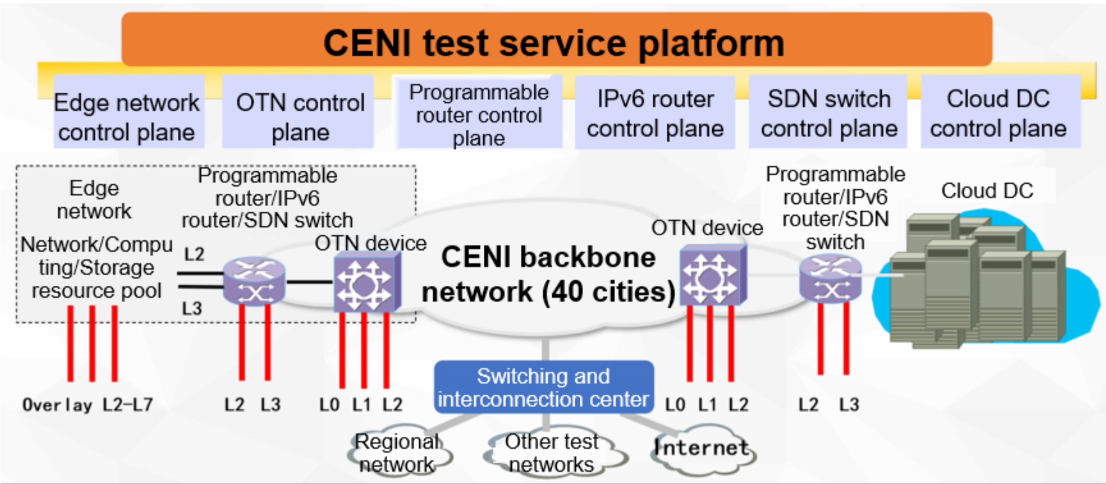
Appendix 1: CENI Network Overview

As the network scale continuously expands and the number of users increases, the traditional Internet architecture faces many challenges in terms of route scalability, security, mobility support, energy consumption, and more. In addition, new technologies and services — such as cloud computing, industrial Internet, artificial intelligence, blockchain, 4K/8K, AR/VR, holographic communication, 5G/B5G, and satellite Internet — are becoming increasingly mature, posing various personalized requirements on future networks. However, the traditional Internet is limited by its best-effort feature and cannot provide flexible and customizable network service capabilities.

To adapt to the new trend of global network transformation in the future, break through core technologies for the Internet, and ensure the mid- and long-term development of the Internet industry in China, CENI is listed in the *Medium and Long-Term Plan for Key National Technology Infrastructure Construction (2012-2030)* of the State Council Doc. No. 8 [2013]. As China's first key national technology infrastructure in the communications and information field, CENI serves the national cyber power strategy and aims to achieve leapfrog development of core network technologies from following to leading. CENI will cover 40 major cities in China, including 88 backbone network nodes, 133 edge network test nodes, and 4 cloud data centers. The goal is to build an advanced, open, flexible, and sustainable large-scale universal test infrastructure, which meets China's test and verification requirements for major scientific and technological projects such as the next-generation Internet, cyberspace security, and air-ground integrated networks during the 13th Five-Year and 14th Five-Year Plan periods, and achieves innovative achievements 5 to 10 years ahead of the industry.

The overall CENI design complies with basic principles, such as demand-driven development, unified top-level design, both stability and advancement, and full resource sharing. CENI provides an advanced, open, flexible, high-speed, and reliable test environment for multi-scenario network innovation technologies and applications at L0 to L7.

Figure A-1 System architecture of the future network test infrastructure



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