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Requirements for Large-Scale Deterministic Networks
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Abstract

Aiming at the large-scale deterministic network with long hops, large per-hop time variation, great number of flows and/or multiple domains without the same time source, this document describes the technical and operational requirements when the different deterministic levels of applications co-exist and are transported. This document also describes the corresponding Deterministic Networking (DetNet) data plane enhancement requirements.

Status of This Memo

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Table of Contents

1. Introduction	3
2. Conventions Used in This Document	4
3. Technical Requirements in Large-Scale Deterministic Networks	5
3.1. Tolerate Time Asynchrony	5
3.1.1. Support Asynchronous Clocks Across Domains	5
3.1.2. Tolerate Clock Jitter & Wander within a Clock Synchronous Domain	6
3.1.3. Provide Mechanisms not Requiring Full Time Synchronization	6
3.1.4. Support Asynchronization based Methods	6
3.2. Support Large Single-hop Propagation Latency	7
3.3. Accommodate the Higher Link Speed	8
3.4. Be Scalable to The Large Number of Flows	9
3.5. Tolerate Failures of Links or Nodes and Topology Changes	10
3.6. Support Enhancement of Queuing Mechanisms	11
3.6.1. Support Configuration of Multiple Queuing Mechanisms	11
3.6.2. Support Queuing Mechanisms Switchover Crossing Multi-domains	12
4. Data Plane Enhancement Requirements	13
4.1. Support Aggregated Flow Identification	13
4.2. Support Information used by Functions ensuring Deterministic Latency	14
4.3. Support Redundancy Related Fields	14
4.4. Support Explicit Path Selection	14
5. Conclusion	15
6. Security Considerations	15
7. IANA Considerations	15
8. Acknowledgements	15
9. Contributors	15

10. Normative References	15
Appendix A. Examples of Large-Scale Deterministic Network Trials	18
Authors' Addresses	19

1. Introduction

Packet networks are evolving from bandwidth-guaranteed Quality of Service (QoS) to latency-guaranteed QoS that guarantees bounded latency and definite latency. Bounded latency and definite latency can be further understood as in-time delivery, in which a packet arrives without exceeding a predetermined time, and on-time delivery, in which a packet arrives at a predetermined time, respectively. In addition, network survivability, which typically guarantees traffic recovery within 50 ms in the event of a network failure, is evolving to a level that guarantees lossless recovery. In order to realize the evolution of QoS and network survivability of these networks, Time-Sensitive Networking (TSN) technology and Deterministic Networking (DetNet) technology are considered to be essential.

TSN is a set of standards developed by the IEEE 802.1 TSN Task Group (TG) [IEEE802.1TSN] and specifies mechanisms and protocols necessary to realize highly available IEEE 802.1 networks with bounded latency to carry time-sensitive, real-time application traffic.

DetNet, of which architecture is defined in RFC 8655 [RFC8655], provides a capability to carry specified unicast or multicast data flows for real-time applications with extremely low data loss rates and bounded latency under a single administrative control or within a closed group of administrative control. The overall framework for DetNet data plane is provided in [RFC8938], and various documents on different data plane technologies and their interworking technologies to extend the service range of data that TSN intends to deliver to the IP (Internet Protocol) and MPLS (Multi-Protocol Label Switching) networks have been standardized.

Since TSN and DetNet were proposed, application use cases have always been one of the hottest topics. After years of development, TSN has been used in several industries, and has enough public awareness of the industry for its scope. DetNet also has done a lot of work and the standards are mature, and people become concerned about how to meet deterministic service demand in large-scale networks.

In this document we define a large-scale DetNet network as a network that requires DetNet solutions for typically one or more of the following key attributes:

- * There is relaxed clock synchronization or no clock synchronization in different domains.
- * The end to end path is a combination of short and long distance hops.
- * There are various transmission rate supported at the different ports and on different network node.
- * There are a large number of flows which may has different level demands of DetNet service accrossing multi-domains.
- * The topology change and failures of link might be more common.
- * The mechanisms used to ensure bounded latency (e.g. queuing mechanism) may be multiple or have different configuration/parameter in multi-domains.

Such domains are normally within a single administrative control network or multiple cooperating administrative networks within a closed group of administrative control [RFC8655]. However they may belong to different AS domains and be controlled by multiple peering or cascaded controllers, and at the same time they may not have the same time clock source. Maintaining per flow status becomes impractical in the large scale network. Aggregation and disaggregation of flows take place at the boundaries of Detnet domains as well as within a Detnet domain with various rules. The flow identification and packet treatment should take care of one or combined changes introduced by the large-scale network.

Based on the defination and characteristics above, this document describes requirements for large-scale deterministic networks which demands the enhancement based on the existing bounded latency mechanisms and the corresponding data plane to ensure the detnet service for single administrative network or multiple (cooperating) administrative networks that defined in the detnet charter. The deterministic network for open internet is not within current scope.

2. Conventions Used in This Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119][RFC8174] when, and only when, they appear in all capitals, as shown here.

While [RFC2119] and [RFC8174] describe interpretations of these key words in terms of protocol specifications and implementations, they are used in this document to describe technical and operational requirements to realize large-scale deterministic networks.

3. Technical Requirements in Large-Scale Deterministic Networks

Due to the attributes described in Introduction Section, the corresponding technical requirements should be considered.

3.1. Tolerate Time Asynchrony

The large-scale network may span over multiple networks with one or more cooperating administrative domains. There are many types of network nodes in the multiple domains which may introduce disparate local time variation, which require the tolerance of time asynchrony.

3.1.1. Support Asynchronous Clocks Across Domains

A large-scale network may span over multiple networks with one or more administrative domains. One of DetNet's objectives is to stitch TSN islands together. All devices inside a TSN domain are time-synchronized, and most of TSN technologies rely on precise time synchronization [IEEE802.1Qbv][IEEE802.1Qch][IEEE802.1Qav]. However, different TSN islands may have different clocks which are not synchronized as shown in Figure 2, where the time difference of two TSN domains is D . DetNet needs to connect these two TSN domains together and provide end-to-end deterministic latency service. The mechanism adopted by a large-scale deterministic network MUST be prepared to cope with non-synced TSN domains. This can be done, for example, by putting extra buffer space at the ingress of a new domain, increasing the dead time as a guard band, or using some timing compensation mechanism. This document does not intend to list all the potential ways.

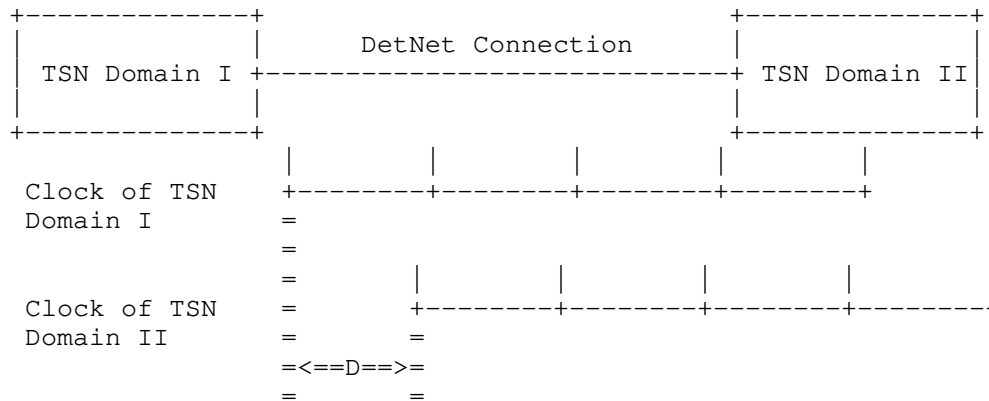


Figure 1: Clock asynchrony between two TSN islands

3.1.2. Tolerate Clock Jitter & Wander within a Clock Synchronous Domain

Within a single time synchronization domain, different clock accuracy is expected, for example the crystal oscillator in Ethernet is specified at 100 ppm [Fast-Ethernet-MII-clock], Synchronous Ethernet (SyncE) can achieve 50 ppb [G.8262], and more precise time synchronization [G.8273] is expected in 5G mobile backhaul. The clocks experience different jitter and wander. It may cause different level of asymmetry of the path. The large-scale networks SHOULD be able to recover or absorb such time variance within a domain and across multiple domains.

3.1.3. Provide Mechanisms not Requiring Full Time Synchronization

Some networks like mobile backhaul use frequency synchronization, such as SyncE, instead of the strict time synchronization. It is usually hard to achieve the full time synchronization in large-scale networks when considering the size of the network topology. It is desired that the same deterministic performance in term of the bounded latency and jitter SHOULD be achieved when full time synchronization is not available, that is to say, when only partial synchronization (SyncE is one of the examples) is in use.

3.1.4. Support Asynchronization based Methods

There are a large number of traffic flows in a large-scale network and some of them are acyclic. Asynchronization based methods can meet the requirements of those traffic flows. Moreover, The mechanisms not requiring the time and/or frequency synchronization eliminate the hardware cost and difficulty at the network nodes. [IEEE802.1Qcr] conceptually uses per-flow based asynchronous shaper

to achieve bounded latency. The effectiveness of the per-flow based asynchronous shaper can be proven through mathematical analysis. It can naturally tolerate the time variance, but it exhibits the concerns of per-flow state buffer management as shown in [I-D.eckert-detnet-bounded-latency-problems]. When it is in use, the requirement in Section 4.3 SHOULD be carefully met.

3.2. Support Large Single-hop Propagation Latency

In a large-scale network, a single hop distance is enough to generate large latency. The speed of optical transmission in fiber is 200 km/ms. Thus, the propagation delay of a single hop can be in the order of a few milliseconds. It is much greater than that of a LAN, and introduces impacts on queuing mechanisms, such as cyclic or time aware scheduling method. So the queuing mechanism for LAN networks needs to be extended, such as considering the propagation latency when setting the period in both time synchronization or frequency synchronization based methods, or setting the extra buffer in the asynchronization based methods, to meet the requirements of deterministic forwarding between the network nodes.

Here, we use an example to describe the influence of Large Single-hop Propagation Latency on cycle based methods, but not to specify any solution. For a cyclic based method, suppose a large-scale network wants to keep using the simple cycle mapping relationship, however the link distance between two nodes is longer. Moreover, a downstream node may have many upstream nodes each with different link propagation delays (e.g., 9 us, 10 us, 11 us, 15 us and 20 us). In order to absorb the longest link propagation delay, the length of cycle must be set to at least 20 us. However, since packet's arrival time varies within the receiving cycle, larger cycle length means larger delay variance.

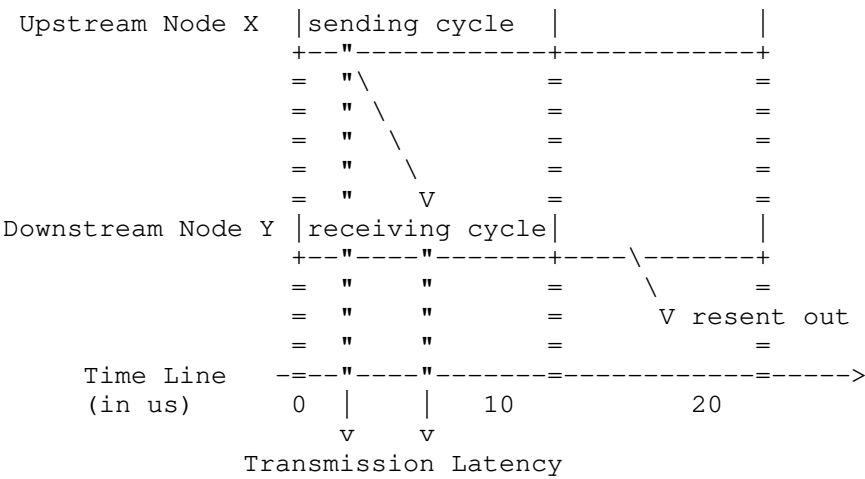


Figure 2: The influence of transmission latency on a cyclic method

3.3. Accommodate the Higher Link Speed

A large-scale network normally uses higher speed links, especially for its backbone. Current deterministic mechanisms used in a local network is usually deployed in link speed of 10 Mbps or 1 Gbps, or possibly 10 Gbps. The data rates of 10G, 100G, 400G and even higher are commonly used in wide area networks. With the increasing of the data rate, the network scheduling cycle can be reduced if the same amount of the data is required to be sent each cycle for each application. Or more data can be sent if the network cycle time remains the same. For the former, it requires the more precise time control (e.g. cycle in the order of a few microseconds or sub-microseconds) for the input stream gate and the timed output buffer. For the latter, more buffer space is required which imposes more complex buffer or queue management and larger memory consumption.

Another aspect to consider is the aggregation of the flows. In the large-scale network, the number of flows can be hundreds or tens of thousands. They can be aggregated into a small number of deterministic path or tunnels. It is practical to have a few flow-based or aggregated-flow based status in the local network. But in higher speed and larger scale networks, it is hardly feasible. If [IEEE802.1Qcr] is in use, it requires more buffers comparing to the other full/partial time synchronized mechanisms. Therefore, it requires optimizations to support higher link speeds.

3.4. Be Scalable to The Large Number of Flows

The large-scale network may have more traffic flows, which has different levels demand of detnet service, and access in/ leave out the detnet more irregular. The deterministic latency forwarding mechanisms MUST scale to networks of significant size with the massive traffic flows.

There are a large number of flows which may has different demands of DetNet service in large-scale deterministic network. [RFC8578] provides various use cases and their requirements in the areas of industry, electricity, buildings, etc. Some of them clearly specify the requirements for latency and jitter, while some others do not for the jitter. Different types of users have different demands, just as a network provider provides different network services for personal business or enterprise business.

One kind has critical SLA requirement, such as remote control or cloud Programmable Logic Controller (PLC) of manufacturing and differential protection of electricity. If these services exceed the boundaries of latency and jitter, it will bring property losses and security risks, so they cannot tolerate with any non-deterministic situation and can pay more on the network service. Another kind has relatively loose levels of SLA requirement, such as cloud gaming, cloud VR and online meeting for "consumer" networks. The users of these applications hope to have a better network experience, but they can tolerate it to a certain extent. For instance, exceeding the upper boundary of latency within a small probability is acceptable. Those different applications expect different kind of solutions, which are related to the cost more or less. For strict deterministic services, strict technologies need to be used, and all network devices may need to be upgraded. For non-strict deterministic services, it may only be necessary to upgrade some network devices (maybe edge nodes) or share corresponding network resources.

Critical latency requirements:

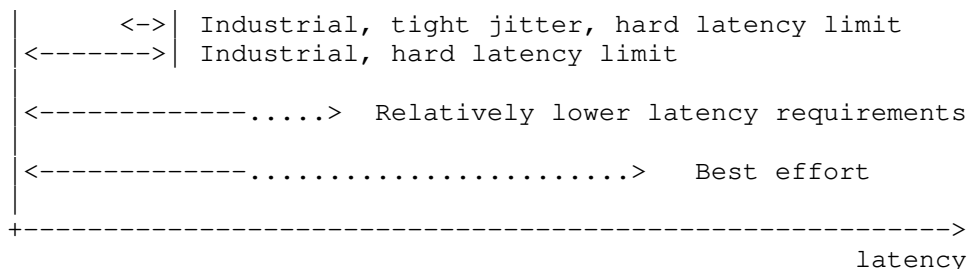


Figure 3: Different levels of application requirements

Besides, It is almost impossible to identify individual IP flows at the DetNet data plane because of the large overhead and resource reservation for a massive number of flows. DetNet allows the leverage of the flow aggregation. With the large scaling of the network, proper provision at the control plane to accommodate such higher aggregation is required. Individual flows may join and exit the aggregated flow rapidly which causes the dynamic in identification of the aggregated DetNet flow. The wildcards and value ranges used in the identification may have to change in order to ensure the aggregated flows have compatible deterministic characteristics.

The micro-burst will happen more often due to the massive traffic flows, so some methods to decrease it are needed.

[I-D.du-detnet-layer3-low-latency] introduces a reference method requiring a scalable buffer to adjust the speed of sending the packets, so as to keep a uniform transmission rate, and it also support the flow aggregation. Moreover, the edge shaping based solution to reduce the micro-burst may also work to some extent.

3.5. Tolerate Failures of Links or Nodes and Topology Changes

The large-scale network may have more network devices, and the increase or decrease of network devices in large-scale networks is more frequent than that in LANs. A simple use case to understand is ultra-low-latency (public) 5G transport networks, which would require DetNet extend to every 5G base station. For some network operators, their networks may need to connect to ~100 K base stations (serving multiple mobile networks operators), and this number will only increase with 5G.

On the one hand, the numerous devices may lead to more network link failures. Path switching or re-convergence of routing will cause high latency of packet loss and retransmission, which is usually in seconds before the network becomes stable again. It is necessary to support certain mechanisms to adapt to failures of links or nodes and topology changes.

One the other hand, the change of the number of devices may affect the implementation and adjustment of deterministic network mechanism, such as the topology discovery, queuing mechanism and packet replication and elimination. For instance, The full disjoint paths when implementing the Packet Replication, Elimination, and Ordering Functions (PREOF) gives a better chance of survival when one of the nodes or links in the path fails. At the same time, it brings the challenges of finding paths with similar distance and/or number of hops so that there is enough buffer space to absorb the latency difference caused by different paths when the scale is large. So, a method is expected to support flexible planning of multiple paths and provide a solid foundation for the implementation of PREOF.

3.6. Support Enhancement of Queuing Mechanisms

3.6.1. Support Configuration of Multiple Queuing Mechanisms

It is required to provide diversified deterministic service for various applications in a large-scale network and to support the corresponding diversified queuing mechanisms (possibly at multiple DetNet QoS levels). Different queuing mechanisms can provide different levels of latency, jitter and other guarantees, and there may be situations where a network device provides multiple queuing mechanisms at the same time. For example, a network aggregation device may use the mechanisms specified in [IEEE802.1Qbv] and [IEEE802.1Qcr], and other mechanisms to forward traffic to different paths at the same time. By providing a variety of queuing mechanisms to meet diversified deterministic service requirements, compared with small scale environment, this demand is particularly prominent in large-scale networks. For instance, there may be more than eight queues or sub-queues to support more complicated queuing mechanisms comparing with the eight traffic classes in TSN enabled networks.

Accordingly, the configuration for multiple queuing mechanisms is complicated in large-scale deterministic networks and MUST support the unified or simplified scheduling and management of multiple queuing mechanisms. For example, in the distributed scenario with no controller, the related information of the queuing mechanisms could be advertised among the domain, including the types and related algorithms, queue forwarding capability with different levels of latency and jitter guarantees, etc. In the centralized scenario, the queuing mechanisms and other information could be reported to the controller to build a deterministic network resource topology pool for path calculation. In addition, for refined management of forward resources and providing resource assurance for deterministic forwarding when establishing/ deleting sessions, it is required to establish unified mechanisms on quantification and measurement of resources associated with interfaces and queues.

3.6.2. Support Queuing Mechanisms Switchover Crossing Multi-domains

In large-scale deterministic networks, it may across multiple network domains and adopt a variety of different queuing mechanisms within each domain. It is required to support the inter-domain deterministic mechanism at the inter-domain boundary nodes such as the priority redefinition and rescheduling of queues to achieve the end-to-end latency, bounded jitter and packet loss ratio.

Moreover, changing from one queuing mechanism to another may generate additional end-to-end latency and/or jitter which should be taken into consideration, because the different scheduling granularities or phase differences between the two domains requires flexible flow aggregation and queue stitching function. For example, when a flow is forwarded across multiple network domains based on different queuing mechanisms, such as a time synchronous Qbv mechanism [IEEE802.1Qbv] and an asynchronous Qcr mechanism [IEEE802.1Qcr], a collaboration mechanism crossing multi-domains MUST be considered, such as increasing the buffer of inter-domain devices to provide enough adjustment space for the flow to cross different queuing mechanisms, the expected method of jitter compression to reduce the coupling between two domains' queuing mechanisms, or the additional traffic shaping solutions to make the traffic smooth, so as to provide end-to-end deterministic services across multiple network domains.

4. Data Plane Enhancement Requirements

According to [RFC8938], the DetNet data plane can provide or carry two metadata in MPLS and IP data planes: Flow-ID and sequence number. The Flow-ID could be used for identification of the DetNet flow or aggregate flow, and the sequence number could be used for PREOF for each DetNet flow. The Flow-ID is used by both the service and forwarding sub-layers, but the sequence number is only used by the service layer. Metadata can also be used for OAM indications and instrumentation of DetNet data plane operation.

Generally speaking, more data plane metadata and related processing SHOULD be supported in the large-scale deterministic networks. By introducing IPv6 Extension Headers [RFC8200] and Segment Routing over IPv6 [RFC8986], native IPv6 data plane should be supported with the IPv6-specific enhancement. This section lists the data plane enhancement requirements based on but not limited to the technical requirements in Section 3, describing how to use IP and/or MPLS, and related OAM, to support a data plane method of flow identification and packet treatment over Layer 3.

4.1. Support Aggregated Flow Identification

Current IPv6 aggregated flow identification is generally based on 5 or 6 tuples, IP prefixes, or wildcards as indicated in [RFC8938]. However, in large-scale deterministic networks the number of individual flows is huge, and they may randomly join and leave the aggregated flow at each hop. Such behaviours lead to the difficulty in identifying aggregated flows by relying on the prefixes or wildcards.

In addition, the deterministic services may demand different deterministic QoS requirements according to different levels of application requirements. The flow identification with service-level aggregation should be supported. Flow identification is also used to quickly push a packet to a suitable queue. In a large-scale network, there are large amount of flows requiring deterministic latency service and normal forwarding service. Explicit flow identification makes it easier to quickly distinguish the DetNet flows without requiring the longest match rule on multiple tuples in IP data plane. Therefore, explicit aggregated flow identification SHOULD be supported.

4.2. Support Information used by Functions ensuring Deterministic Latency

According to Section 3.1, a large-scale network should support synchronized or asynchronized queuing mechanisms. Different queuing mechanisms require different information to be defined as the DetNet-specific metadata to help the functions of ensuring deterministic latency, including regulation, queue management.etc. For instance, the data plane needs to support the identification of cycle for cyclic queuing and forwarding or the latency related information for time based queuing in order to enable the applicability of the respective queuing and/or scheduling mechanisms in the large scale network.

When different queuing mechanisms are deployed at a network node, metadata used for each queuing mechanism should be provided at the same time. When multiple metadata carried in one packet, metadata should be self-described and extensible to tolerate variable number of metadata. Meanwhile, extra data will cause extra processing, referring to fixed or variable length lookups, total number of read/write access to the packet header.etc. So the data plane processing efficiency also needs to be considered when ensuring deterministic latency, but the specific method or solution is out of scope of this document.

This document does not specify what metadata and what format to be carried in data plane. The solution document should be specific enough on why and how the information carried as data plane meta data works in conjunction with the queuing or other functions and how it helps the large scale network deployment.

4.3. Support Redundancy Related Fields

Sequence number is the only metadata currently defined for redundancy feature of Detnet. MPLS data plane uses Detnet-over-MPLS label stack to carry it. At the same time, native IPv6 data plane should be able to carry this information too. If specific IP encapsulation or tunnel is in use, this meta data should be defined explicitly for that data plane.

4.4. Support Explicit Path Selection

Explicit route at the control plane and/or management is required so that the "best" path can be selected to meet the latency requirement for DetNet flows. At the data planes, MPLS label stack can be used for this purpose. IP data plane enhancement is required to support the explicit path selection based on IP source routing or SRv6.

5. Conclusion

This document specifies the technical requirements when ensuring the deterministic features in the large-scale networks, and the corresponding data plane enhancement requirements to support the them. Some of the proposed queuing mechanisms and trials are cited and the authors of the document think those proposals give reasonably sound insights to enhancement the current queuing mechanisms to meet the deterministic requirements of the large-scale networks.

6. Security Considerations

There are no IANA actions required by this document.

7. IANA Considerations

This section will be described later.

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Appendix A. Examples of Large-Scale Deterministic Network Trials

Some trials have been carried out to verify the concept of large-scale deterministic networks.

In order to verify the deterministic technology of large-scale networks, a trial of Deterministic IP on China Environment for Network Innovations (CENI), which is a network built for new network technology trial, was deployed. A network with a distance of 3,000 km over 13 hops was tested, and the jitter was controlled within 100us.

In order to verify the remote control on Deterministic IP, which required that the latency should be controlled within 4 ms and jitter should be controlled within 20 us. A trial cooperated with Baosteel spanned 600 km was deployed. Baosteel is a Chinese steel company and put forward this demand. Both of the first and second trials are based on a frequency synchronization solution. The mechanism details could be found in . [I-D.dang-queuing-with-multiple-cyclic-buffers][I-D.qiang-detnet-large-scale-detnet].

In order to realize multi flows synchronization on an inter-provincial network in an exhibition, Emergen proposed the requirement that two flows of video and virtual reality (VR) were sent from province A, and arrived at province B together, so people can see the synchronization of video collected by camera and the VR model. This requirement was proposed to facilitate the virtual industry product deployment. Due to time and other problems, it was realized by the edge network device for a relatively lower levels of service level agreement (SLA).

Teaming up with a smart factory operator, network operators, equipment companies, and universities, ETRI demonstrated an ultra-low latency, high-reliability 5G wired and wireless network-based remote industrial Internet of Things (IIoT) service by connecting a control center and a smart factory through three different operators' networks at a distance of 280 km. In this trail, it was demonstrated

that real-time remote smart manufacturing service is possible by making round-trip delay below 3 ms within a smart factory and below 10 ms between remote 5G industrial devices. In the future, the team plans to examine feasibility of large-scale deterministic networking by connecting smart factories in Gyeongsan, South Korea and Oulu, Finland.

These trials show that both operators and enterprise users begin to put forward requirements for the certainty of large-scale networks, but the implementation technologies are not exactly the same.

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