Deterministic Networking (DetNet) vs Time Sensitive Networking (TSN)

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***Abstract*—With increasing demands of highly reliable networks with bounded latency and low jitter, a lot of Ultra-Low Latency Network studies are in progress. This paper focuses on IEEE Time Sensitive Networking (TSN) and IETF Deterministic Networking (DetNet). We analyze the similarities and differences between these two networking standards and give a survey of the published standards and possible future work of the DetNet and TSN Task Groups.**

***Index Terms*—Time Sensitive Networking, Deterministic Networking, Ultra-Low Latency, Network Standards**

1. Introduction

Ethernet is a series of connectivity services, first standardized by IEEE 802.3 Ethernet Working Group (WG) in 1983. Ethernet has been widely adopted for regular Internet/Data center since the 1980s and for telecommunication and industry networks recently due to its cost-effectiveness and flexibility [1]. However, with the increasing demand on real-time capabilities in industrial applications, tranditional Ethernet lacks Quality of Service (QoS) metrics of end-to-end latencies. Therefore, markets and customers turn their attention to Ultra-Low Latency (ULL) networking standards, which can signaficantly reduce the latencies to milliseconds. [2]

Among these ULL networks, the IEEE Time-Sensitive Network (TSN) Task Group (TG) and the IETF Deterministic Network (DetNet) TG are of interest. These two TGs devote to providing deterministic networking standards with low bounded latency and high reliability. While TSN standards focus only on OSI model Layer 2 (LANs), the DetNet standards extend the technologies to Layer 3 (IP) [3]. This paper aims to give an overview over these two standards and discuss their current state and future.

The content of this paper will be organized as follows. In Section 2 we will discuss the previously published related work on this topic. The background studies i.e. the history of TSN TG and DetNet TG will be reviewed in Section 3. In Section 4 and Section 5, a basic overview of TSN and DetNet will be introduced. To get further insights into the research value, Section 6 demonstrates a range of practical use cases. As a next step, we will discuss the current state and the future work of TSN and DetNet in Section 7. Finally, the conclusion of this TSN and DetNet survey will be given in Section 8.

2. Related work

The documents on the official website of the TSN TG [4], [5] only cover the published standards or in progress projects of IEEE 802. The files of DetNet TG are currently just Internet drafts [6], [7], [8]. Here [6] is the IETF draft of DetNet problem statement. By contrast, a general Introduction to TSN has been published in the IEEE Communications Standards Magazine in [3]. Additionally, a survey on Ultra-Low Latency networking including TSN, DetNet and related 5G ULL Research has been presented in [9]. In order to differ from all these previous literatures, this paper provides a comparison of TSN and DetNet and tries to summarize their corresponding features and up-to-date progress.

Different from optimized Ehternet fieldbus, such as EtherCAT (Ethernet for Control Automation Technology), TSN or DetNet are add-ons to the best effort switched environment. Besides IEEE TSN and IETF DetNet, there are also some other related standards and researches in the field of ULL Network, e.g. Wireless High Performance (WirelessHp) and Multefire. [10] To meet the ULL requirements in industrial sites, specifications like WirelessHP are applied. The goal of Wireless HP is to realize multi-Gbps data rate aggregation and lower the packet transmission time within microseconds through physical layer solution. Moreover, Multefire, a Long-Term Evolution (LTE) based technology can also be used to boost data rate and reduce transmission time and latency. [10]

In contrast to these related studies, TSN and DetNet mainly focus on deterministic latency and specify a series of standards to achieve ULL and reliable networking over best-effort Ethernet networks.

3. Background Studies

The predecessor of TSN standards was Audio Video Bridging (AVB) industrial standards. Audio Video Bridging TG was established in 2007 by the IEEE 802.1 standards committee. This TG is chartered to specify time-synchronized low latency streaming services over IEEE 802 networks. AVB standards specify the implementation of a plug-and-play home or audio or video production studio but only operate in OSI model Layer 2. [3]

Motivated by the great success of AVB standards, the IEEE committee plans to expand AVB applications into industrial fields. Therefore, in 2012 the AVB TG was renamed as TSN TG [3]. The TSN TG aims to establish deterministic network services and to reduce the latency to microseconds or milliseconds to meet precise industrial control or automation demands [9]. TSN also only works in bridged Layer 2 networks.

With the increasing progress in TSN standards, people want such ULL Networking not just confined to Layer 2.

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In 2015 the IETF created its DetNet TG. The goal of the DetNet TG is to extend bounded latency, low latency jitter and highly-reliable services to both Layer 2 and Layer 3. [3]

As mentioned in Section 2, the TSN TG has already published a series of networking standards, while the documents of the DetNet TG are currently just Internet drafts and still in progress.

4. Overview of Time Sensitive Networking

This section provides a survey of the features and standards of TSN.

4.1. TSN Features

TSN TG is based on AVB TG and chartered to implement bounded latency, low latency jitter over traditional Ethernet. The significant characteristics of TSN Networks are as follows:

Time synchronization: In order to meet the requirements of real-time control or automation, time sensitive network is designed as a time-aware network. The clock of all devices in a Time-Sensitive network must be synchronized. This technique can be realized through various variants of existing timing specific protocols like IEEE 1588. One IEEE official offered synchronization standard is IEEE 802.1AS. Through network-wide shared time reference, TSN is capable to fix the transition delays and send packets at the time arranged. [9]

Bounded latency and zero congestion loss: Congestion happens when there are overflowing streams in a node that beyond the capability of the network. Network congestion is the main reason of packet loss and latency. [3] Thanks to buffer allocation, queuing algorithm and frame preemption, TSN achieves bounded low latency and zero congestion loss.

The principle of realizing zero congestion loss is computation of buffers in the worst-case. Figure 1 defines packet latency into five components: Output delay, Link delay, Preemption delay, Processing delay and Queuing delay. [3]

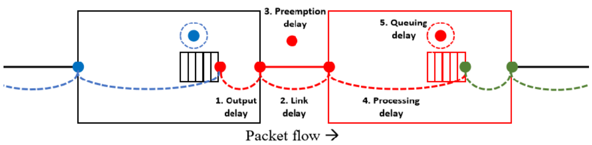

Figure 1: TSN Timing Model [3]

The uncertainties in networks during transmission like abrupt interruptions of packets and states of forwarding nodes lead to variability of these delay times. Buffers in the queue are allocated to compensate the variations of delay.

Additionally, the queuing delay is assumed to be calculable according to the queuing algorithm applied to TSN. Since the packet selection schedule of queuing algorithm applied to TSN are mathematically analyzable, the buffer requirement in the worst-case can be predicted. [3]

The queuing mechanism is mainly standardized in IEEE 802.1Qav, which aims to constrain the number of buffers required in a network. Credit-based shaper (CBS) is the key concept of the queuing algorithm. When there exists no frame in the queue, the credit is set to zero. The credits increase when a frame is added into the queue and decrease when a frame is sent. This mechanism allows a queue to transmit only if the credits are nonnegative and the channel is not occupied [9]. CBS also defines constraint parameters such as maximum frame size, maximum reference size and maximum port transition rate. Thus, the latency per bridge can be limited [3]. The flow chart in Figure 2 clearly illustrates the CBS operation for a given queue.

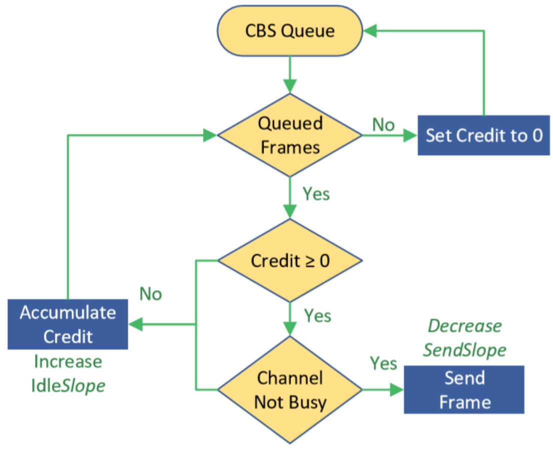

Figure 2: Flowchart of CBS operation for a given queue [9]

Another mentionable technique here is frame preemption, specified in IEEE Std 802.1 Qbu and IEEE 802.3 br. In IEEE 802.1Qbv a guard band is added in front of scheduled time-critical traffic to prevent low priority traffic from transmission when that transmission cannot be finished before the scheduled traffic window. The preemption mechanism enables midway stop of frame transmission before the start of a guard band and execute the transmission of another frame with higher priority. After accomplishment, the original transmission can continue. [9]

Ultra reliability: The core technique improving the reliability of TSN is frame replication and elimination. This technique reduces the packet loss caused by equipment failure in network. The procedures of frame replication and elimination are documented in IEEE 802.1CB: 1) number the sequence of packets and replicate them in the network, 2) identify the redundant and eliminate packages at or near the destination. [11]

Moreover, as shown in the second case of Figure 3, packets can also be re-replicated or eliminated at various nodes, like node B and node E. Thus, a failure of node A and E or node B and C will not affect the packet end-to-end delivery in TSN. Through this mechanism, TSN is capable to handle multiple errors and increase the transmission reliability.

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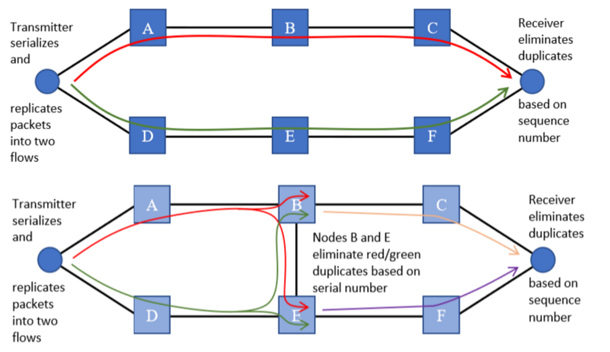

Figure 3: Mechanisms of packet replication and elimination [3]

4.2. TSN standards

Above survey only covers some key features of TSN. The TSN TG also standardizes many other meaningful techniques and mechanisms, these standards will be summarized in this subsection.

Most of these standards are amendments for IEEE 802.1Q-2018: Bridges and Bridged Networks. Project ID with capital letters indicates stand-alone documents, such as IEEE 802.1CM. Lower case letters in project ID means the standards are amendments, e.g. IEEE Std 802.1Qbu. [3] Based on introduced features in Section 4.1, this paper splits published standards into three groups as shown in Table 1:

TABLE 1: TSN published Standards Summary

Group	Standard Name	Features
Time Synchronization	IEEE 802.1AS	Timing models and clock synchronization for TSN
Zero Congestion Loss	IEEE 802.1Qbu	Frame Preemption
	IEEE 802.1Qbv	Enhancements for scheduled traffic
	IEEE 802.1Qch	Cyclic Queuing and Forwarding, amendment for IEEE Std 802.1Q
	IEEE 802.1Qcp	YANG Data Model
	IEEE 802.1CM	Time-Sensitive Networking for Fronthaul
	IEEE 802.1Qcc	Stream Reservation Protocol (SRP), amendment for IEEE Std 802.1Q
Reliability	IEEE 802.1CB	Frame Replication and Elimination for Reliability
	IEEE 802.1Qci	PerStream Filtering and Policing
	IEEE 802.1Qca	Path Control and Reservation

IEEE 802.1AS is based on IEEE 1588v2 and specifies the precise timing model and clock synchronization in TSN. Analog to Precision Time Protocol (PTP) defined by IEEE 1588, IEEE 802.1AS defines generalized PTP (gPTP), which enables synchronous transportation over all media. The prerequisite of IEEE 802.1AS is that all bridges and end stations in network should be time aware. Then, IEEE 802.1AS selects one system as grandmaster and assign the ports in the network as master, slave or passive roles. This helps to form a synchronization hierarchy in TSN. The grandmaster is expected to transmit synchronization information on slave ports and loops can be broken through passive role ports. This mechanism ensures the network wide clock synchronization. [12]

IEEE 802.1Qbv is standardized as enhancements to traffic scheduling Time-Aware Shaper (TAS). This standard helps to construct the well-defined QoS for TSN through specified TAS. The mechanism of this standard is as follows: 1) time-aware traffic windows are used to schedule the critical traffic streams, 2) a guard band is added before scheduled traffic windows to prevent transmission interrupted by lower priority frames. [9]

IEEE 802.1Qch Cyclic Queuing and Forwarding (CQF) aims to synchronize enqueue and dequeue operations in TSN. Through CQF synchronization, frames can be transmitted in a cyclic manner. And the network transit latency can be characterized by the cycle time. [9]

IEEE 802.1Qcp standardizes the YANG data model and utilizes Unified Modeling Language (UML) representation. YANG is a formalized data modeling language widely adopted in industries. Motivated by this, TSN TG decided to establish standards supporting YANG data modeling. IEEE 802.1Qcp is also applied to support other specifications. [9]

IEEE 802.1CM refers to TSN profiles for fronthaul, its application will be explained in Section 6.1.

IEEE 802.1CB specifies frame replication and elimination. The mechanism applied in this standard has been covered in Section 4.1.

5. Overview of Deterministic Networking

This section intends to offer an overview of the features and currently established internet drafts and RFCs of DetNet.

5.1. DetNet Features

The IETF DetNet TG has similar charters to the TSN TG. Therefore, DetNet also has features such as time synchronization, zero congestion loss and reliability like TSN. Additionally, DetNet devotes to extend the ULL and highly reliable services to layer 3 networks. DetNet TG also works on coexistence of DetNet with normal traffic and DetNet misbehavior mitigation. [7]

Time synchronization: Like in TSN, devices in DetNet should share common timing reference. DetNet time synchronization is realized through existing IEEE 1588 and IEEE 802.1AS.

Zero congestion loss and Reliability: Similar to TSN techniques stated in Section 4, ULL characteristics and zero congestion loss in DetNet are achieved through queuing algorithms, buffer reservation and packet preemption. Since queuing algorithms also fit well to routers, the number of buffers in the worst-case is analogously mathematically analyzable in DetNet. [9]

One difference in DetNet is that in order to get lower jitter, end-to-end latency DetNet has not only upper bounds but also lower bounds. The concrete methods of jitter minimization include: 1) network-wide time synchronization to sub-microsecond accuracy 2) count time-of-execution fields into the application packet. To ensure the reliability of DetNet, filters and policers are applied to detect failures and error of packets. When fault is detected, filters and policers will disrupt and adjust the transmission. Moreover, packet replication and elimination techniques are also applied in DetNet. [7]

To fix the coexistence issue with normal traffic, DetNet assigns critical flows with higher priority than best-effort flows. This will not threaten the network operation, since both critical flows and best-effort traffic have bounded latency and bandwidth in DetNet.

Security: Security considerations are another essential feature in DetNet. To achieve request security and control security of DetNet resources, authentication and authorization should be used for devices connected to a DetNet domain to ensure that the administrative configuration of parameters is constrained to authorized devices. [7]

Control of DetNet can be classified as centralized or distributed. For centralized control of DetNet, Abstraction and Control of Traffic Engineered Networks (ACTN) is used for security considerations. For distributed control of DetNet, security considerations are expected to be achieved through the security properties of the deployed DetNet protocols. [7]

5.2. DetNet Internet-drafts

Since Deterministic networking TG has no published standards, Table 2 lists up-to-date DetNet Internet drafts and RFCs. (June,2019) Some critical Internet drafts among them are selected to be explained further in this section.

***-architecture** introduces the overall DetNet architecture and the mechanisms used to achieve DetNet QoS. The DetNet QoS includes resource allocation, service protection and explicit routes. Similar to TSN, provision of sufficient buffer at each node and packet replication and elimination are also used in DetNet to ensure ULL services. [7]

***-data-plane-framework** introduces the framework for DetNet controller plane and its requirements. DetNet services are currently specified on IP networks or MPLS (Multiprotocal Label Switching) networks. Encapsulation in DetNet enables the flows to be transmitted to other data plane technology beyond its original stream type.

***-security** discusses security problems in DetNet and collects related considerations from other DetNet drafts. Security is highly important in DetNet, since DetNet which operates in higher OSI model layer owns more potential of cyber-attack. Various threats such as delay attack, path manipulation and their corresponding mitigations through path redundancy, encryption, performance analytics or DetNet node authentication are all analyzed in this documentation. [13]

DetNet TG has updated two RFCs in May 2019. RFC8557 (was draft-ietf-detnet-problem-statement) illustrates the necessity of establishing DetNet for industrial applications and RFC8578 (was draft-ietf-detnet-use-cases) describes a series of DetNet use cases in various fields.

TABLE 2: DetNet official Internet drafts Summary

draft-ietf-detnet	Features
-architecture	Introduce DetNet architecture and the used techniques to carry real-time unicast/multicast data streams
-data-plane-framework	Specify the framework for DetNet controller plane and its requirements
-dp-sol-ip	DetNet IP Data Plane Encapsulation
-dp-sol-mpls	DetNet MPLS (Multiprotocal Label Swichting) Data Plane Encapsulation
-flow-information-model	an overview of DetNet model for integration over Layer 2 and Layer 3
-ip	Describe how can DetNet operate over IP packet switched network
-ip-over-mpls	Describe how can DetNet operate in an IP over MPLS packet switched network
-ip-over-tsn	Describe how can DetNet operate in an IP over TSN
-mpls	DetNet Data Plane: MPLS
-mpls-over-tsn	DetNet Data Plane: MPLS over IEEE 802.1 Time Sensitive Networking
-mpls-over-udp-ip	DetNet Data Plane: MPLS over IP
-tsn-vpn-over-mpls	DetNet Data Plane: IEEE 802.1 Time Sensitive Networking over MPLS
-security	Deterministic Networking (DetNet) Security Considerations
-topology-yang	Deterministic Networking (DetNet) Topology YANG Model
-yang	Deterministic Networking (DetNet) Configuration YANG Model

6. Use Cases

Various applications in industries require deterministic flows, which is exactly the core of TSN and DetNet [8]. Besides, DetNet enables interconnection between Layer 2 and Layer 3. Therefore, TSN and DetNet use cases cover a wide range of industries including professional audio and video, control and automation systems, industrial machine-to-machine, vehicle applications etc. [8] We only introduce selected examples in this section, more details can be obtained from [3] and [8].

6.1. Use Case of TSN

One use case is the TSN applicability in 5G (5th generation mobile/wireless networks). TSN with bounded latency and high-reliability are necessary in 5G scenario.

TSN helps network slicing and realize the fronthaul connection in Ethernet bridged networks [9]. Network slicing implies that there is no interference between applications or users. Moreover, TSN techniques like resource reservation and traffic scheduling are helpful to aggregate

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dataflow in 5G Bearer Networks. As shown in Figure 4 IEEE Std 802.1CM specifies TSN profiles for 5G fronthaul. [14] The detailed demonstration of 5G mechanism exceeds the scope of this survey.

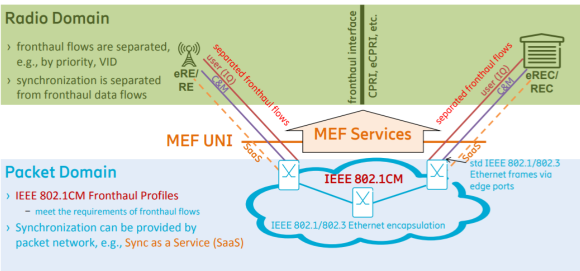

Figure 4: Fronthaul details with IEEE Std 802.1CM [14]

6.2. Use Case of DetNet

As DetNet standardization is still in progress, it has appealing potentials in industrial applications but no concrete examples currently. Therefore, this subsection only selects two typical applications from [8] to provide readers a general overview of DetNet use cases.

One promising DetNet use case is industrial Machine to Machine (M2M). Industrial M2M communication is mainly executed through Programmable Logic Controllers. DetNet in this use case is deployed to ensure the critical control/data flow is successfully delivered end to end within demanded time constraints. Industrial M2M with requirements like time synchronization, low packet loss, ultra-low delivery time and reliability are exactly corresponding to the characteristics of DetNet. [8]

Another typical use case is the professional audio and video industry (ProAV), including broadcast and music or film production. These industries are now faced with the transition to packet-based infrastructure and integration with IT infrastructure. With the support of DetNet services, ProAV applications will be able to interconnect Layer 2 and Layer 3 and then achieve broadcast over wider areas. [8]

7. Future work of TSN and DetNet researches

In contrast to DetNet researches, the TSN studies are currently isolated from external networks and only restricted to small-scale domains like in-vehicle networks. However, the industrial use cases of TSN such as Machine-to-Machine Communication or Industrial Control and Automation systems often are equipped with highly complex infrastructure. Further TSN studies may need to find a solution to enhance the interconnectivity and simplify the network management mechanisms. [9] Additionally, the standards considering security and privacy may also be interesting future research topics for TSN.

Since the IETF DetNet is a rising study field in recent years, DetNet architecture and standards still need a long way to be implemented and improved. For example, DetNet interconnection between Layer 2 and Layer 3 is realized with support of TSN LAN services, hence DetNet requires stable resource sharing techniques over Layer 2. Another important future study will be the concrete use cases of the integration of DetNet with traditional external networks.

8. Comparison of Time-Sensitive Networking and Deterministic Networking

IEEE TSN and IETF DetNet can be compared in the following aspects:

OSI Layer: The most important difference between TSN and DetNet is the OSI layer they operate on. While TSN is confined to Layer 2, DetNet extends the corresponding properties to Layer 3 or even higher layers.

Bounded Latency: Another difference is that in TSN only upper bound is predefined to reduce latency. However, in DetNet exist both upper and lower bounds to realize jitter minimization.

Data plane: DetNet nodes can connect to other subnetworks including MPLS Traffic Engineering (TE), IEEE TSN and Optical Transport Network (OTN). Also multilayer DetNet systems can be constructed in the future, which cannot be achieved with TSN. [14]

Security: DetNet TG also pays more attention on security considerations than TSN TG, since DetNet, which expands its scope to higher OSI model layer, is faced with higher cyber-attack probabilities.

Current status: The IEEE TSN TG has already specified and published a series of standards which have been adopted to concrete use cases. By contrast, the IETF DetNet TG is still immature and remains in its starting stage.

9. Conclusion

Both TSN and DetNet TG aim to create highly reliable ULL networks with features like time synchronization, zero congestion loss, reliability and security for real-time industrial applications. DetNet TG is chartered to expand TSN mechanisms beyond Layer 2 LANs to higher layer, for example, time synchronization techniques and frame replication and elimination mechanisms are deployed both in TSN and DetNet. This survey also discusses the possible future studies of these two networks include the enhancement of interconnectivity and further security considerations. With increasing researches in TSN and DetNet, more and more concrete use cases in the field of industrial M2M communication and ProAV etc. will be implemented in the future. Despite some limitations of current standards or internet drafts, TSN and DetNet combined with optimized Ethernet fieldbus such as EtherCAT will impact the traditional IEEE 802 networks significantly.

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