Deterministic Networking - DetNet

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Abstract—**Deterministic networking is rapidly gaining importance, as several network applications and industries demand deterministic network services. Several of those network applications demand low end-to-end latencies and low packet loss. The IETF Deterministic Networking architecture provides network-layer services and IEEE 802.1 Time-Sensitive Networking provides data link-layer services. Both DetNet and TSN play a critical role in providing real-time low latency and deterministic services for the next-generation networks. In such context, this paper presents a broad overview of DetNet and summarizes its key features.**

Index Terms—**Deterministic Networking (DetNet), Time Sensitive Networking (TSN), Ultra-Low Latency (ULL)**

1. Introduction

Traditional Ethernet does not fulfill the communication requirements of critical real-time systems such as aerospace, industrial automation, automobiles, etc., which require high-bandwidth and low delay for communication networks with the increasing communication data traffic. Therefore, industries and customers turn their attention to Quality of Service (QoS) metrics and Ultra-Low Latency (ULL) paradigms, which provide end-to-end latencies in a matter of a few microseconds and milliseconds, depending on the applied applications [1] [2].

The IEEE 802.1 Time-Sensitive Networking Task Group (TG) and the IETF Deterministic Networking Working Group (WG) are collaborating [2] to establish a common architecture for Layers 2 and 3 of the OSI[1] model. DetNet focuses on Layer 3 routed segments, whereas TSN focuses on Layer 2 bridged networks [2]. Their main goal is to provide support for high reliability in packet delivery, deterministic worst-case bounds on latency [2] and better worst-case QoS metrics for best-effort flows [3]. This survey is intended to provide a comprehensive overview of the IETF DetNet and its features and discuss its current state and future.

The rest of this paper is organized as follows. Section 2 deals with some background studies on Deterministic Networking and how it emerged and gained interest. Section 3 provides an overview of IEEE TSN and TSN-related studies and focuses on the data link layer. Section 4 covers an overview of IETF DetNet, its architecture, flow types and practical use cases and focuses primarily on the network layer. Section 5 illustrates the existing DetNet and TSN standards and studies and provides some similarities and differences between both paradigms, and tries to summarize their key features. Previously published related work and research studies on this article are provided in Section 6. Finally, in Section 7 we discuss and review practical problems in DetNet and conclude this proceeding with future research directions.

1. OSI - Open Systems Interconnection

2. Background

The increasing demand for ultra-low latency networking standards led to the development of a unified data link-layer protocol by the IEEE 802.1 WG called Audio Video Bridging (AVB) in 2005 [4]. AVB ensured real-time requirements such as the transmission of audio and video streams but lacked fault-tolerance to enhance its reliability [5] and was subject to some system failures and malicious cyber attacks [4].

Consequently, in 2012, the IEEE 802.1 WG expanded the current AVB and renamed it to **Time-Sensitive Networking (TSN)**. The TSN enhances time synchronization, supports the scheduling of real-time time-sensitive data streams, and improves the streams' reservation ability [4]. Together with this expansion, the networks were getting larger, requiring deterministic networks. For example, public infrastructures such as electricity automation require deterministic paradigms over a wide area, whereas the TSN provides support for Layer 2 control systems and cannot support structures beyond LAN boundaries. Therefore, Layer 3 networks were required without losing Layer 2 capabilities [6].

Motivated by these shortcomings, the IETF, in cooperation with Standards Development Organizations (SDOs) and IEEE 802 developed the **Deterministic Networking (DetNet) WG** in 2015 [7]. A key feature of DetNet is the ability to establish a multi-hop path over the IP network with a particular flow and ultra-low jitter and low latency [6].

In general, latency refers to a time delay in an end-to-end packet delivery between a sender and a receiver. Thus, the term ultra-low latency usually refers to latencies that have speeds under 1 millisecond. The term bounded latency is often used in ULL systems and describes time delay that must not exceed some predetermined value, e.g., to ensure the appropriate functionality in automation systems.

Jitter refers to variations of packet latencies, which are often caused by congestion. Therefore, two key QoS metrics of ULL networking are jitter and latency.

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3. Overview of Time-Sensitive Networking

The IEEE 802.1 TSN TG standards and services extend the Ethernet data-link layer and guarantee data transmission with ultra-low latency and jitter [2]. The TSN is based on a best-effort packet network consisting of bridges and network appliances.

3.1. TSN Features

Time synchronization: Time synchronization is accomplished using IEEE 1588 Precision Time Protocol (PTP) configuration, which is, e.g., a stand-alone standard IEEE 802.1AS [8]. All of the devices in a network can synchronize their internal clocks with an accuracy of up to 10ns.

Contracts between transmitters: Each TSN flow functions with a contract between the transmitter of the flow and the network. Therefore, such features are provided:

- **Zero congestion loss and bounded latency:** Congestion and packet loss are caused by the overflowing streams in the network node. These shortcomings are eliminated thanks to buffer allocation and queuing algorithms [2]. Buffer allocation is accomplished through computing worst-case buffer requirements. There are a couple of queuing algorithms defined in IEEE Std 802.1Q, which are: Credit Based Shaper (CBS), Time-Scheduled Queues, Transmission Preemption and Asynchronous Traffic Shaping (ATS).
- **Ultra reliability:** Equipment failure is also one of the main reasons for packet loss. The main method of improving the reliability of TSN networks is Frame Replication and Elimination for Reliability (FRER) [9].

A sample FRER is illustrated in Figure 1. Packets can be both replicated and eliminated at each node of the TSN Timing Model [7].

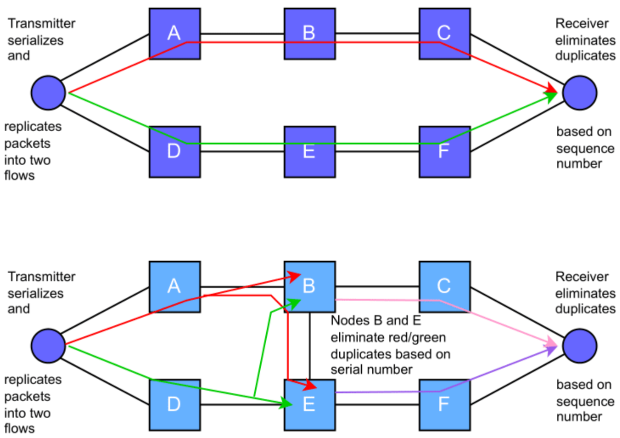

Figure 1: Packet replication and elimination [7]

3.2. TSN Use Cases

TSN use cases are similar to DetNet use cases and are thoroughly explained in [7]. Some of them are:

- Professional audio and video studios.
- Electrical power generation and distribution.
- Cellular radio.
- Automotive and other vehicle applications.

4. Overview of Deterministic Networking

In this section, a detailed overview of the IETF Deterministic Networking (DetNet) WG will be described. According to [2], the IETF DetNet WG collaborates with IEEE 802.1 TSN TG to define a common architecture for Layers 2 and 3. DetNet is considered to be a representative wide-area networking technology. To overcome the limitations of the LAN-based narrow-area networking technologies, such as TSN, IP/MPLS[2]-based wide-area networking technology is being standardized [10]. Like TSN, DetNet's main goal is to support deterministic worst-case bounds on latency, jitter, zero/low packet loss and reliability.

4.1. DetNet Architecture

DetNet data plane and functionality are composed of two sub-layers: DetNet service sub-layer and DetNet forwarding sub-layer. Each one of these layers is classified according to the DetNet flow. The service sub-layer provides service protection functions and classifies time-determined flows. The service protection function duplicates and delivers packets through several packets, and deletes the duplicated packets according to their sequence number [10]. The forwarding sub-layer provides explicit routes and resource reservations for time-determined flows, which are the basis of wide-area networks. Note that these sub-layers are helpful, but not mandatory to implement and should not be considered a formal requirement. Some technologies are still capable of providing DetNet services, even if they do not adhere to this strict sub-layer division. The illustration of the DetNet data-plane layering model is presented in Table 1. Not all sub-layers are required for a particular network or a particular application.

TABLE 1: DetNet Data-Plane Protocol Stack [11]

Sub-layers	Source	Destination
Service sub-layer	Packet sequencing Flow replication Packet encoding	Duplicate elimination Flow merging Packet decoding
Forwarding sub-layer	Resource allocation Explicit routes	Resource allocation Explicit routes
	Lower layers	Lower layers

Application: Source and Destination are considered to be any application that is going through the stack.

Packet sequencing: This sub-layer supplies the sequence number for packet elimination and replication. It is not needed if a higher-layer protocol performs the sequencing.

Duplicate elimination: This sub-layer discards all duplicate packets generated by DetNet flow replication based on the specified sequence number. It can also resequence the packets to restore the order of the packets, which may be disrupted by the loss of packets on multiple paths [11].

2. IP/MPLS - Internet Protocol/Multiprotocol Label Switching: routing system that enables fast data switching

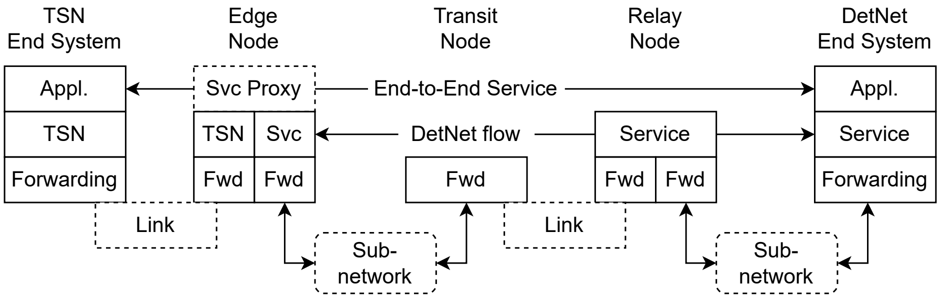

Figure 2: A simple DetNet-enabled network [11]

Flow replication: This sub-layer is part of DetNet service protection. Packets belonging to DetNet compound flow are replicated, apart from packet sequencing, into several DetNet member flows. This replication may also be performed using techniques such as multicast replication but with resource allocation implications [11].

Flow merging: The functions for flow merging combine DetNet member flows together for packets coming up the stack. This sub-layer performs packet replication and elimination, together with packet sequencing, duplicate elimination and flow replication [11].

Packet encoding and decoding: These sub-layers take packets from different DetNet member flows. Packet encoding combines the information and transmits them to different DetNet member flows. Packet decoding computes the original packets and transmits them to different DetNet member flows.

Resource allocation: Providing paths for DetNet flows, queuing, and shaping mechanisms are usually provided by this sub-layer.

Explicit routes: These are arrangements of fixed paths, based on the DetNet forwarding sub-layer that is specified in advance to avoid the effects of network convergence on DetNet flows [11].

A simple concept of a DetNet network is illustrated in Figure 2. In this figure, "Fwd" and "Forwarding" refer to the forwarding sub-layer, "Svc" and "Service" refer to the service sub-layer [11].

4.2. DetNet Flow Types

Depending on the type of end systems, DetNet flow may have different formats. According to the end system types, the following four types of a DetNet flow are distinguished:

App-flow: The native data (payload) flows between the DetNet source and destination end systems.

DetNet-s-flow: This flow contains the DetNet-related specific attributes that provide services for elimination and replication functions. This flow is a specific data flow format that requires the service protection feature and is bound to the service sub-layer.

DetNet-f-flow: This is also a specific format of a DetNet flow. This flow is bound to the forwarding sub-layer and contains specific attributes that provide services for congestion protection.

DetNet-sf-flow: This is a specific data flow format, which signals the forwarding function during forwarding. This flow is bound to the both service and forwarding sub-layers of the DetNet stack model.

4.3. DetNet Use cases

DetNet is not considered to be "a new kind of network", but is supported by Ethernet extensions, including elements of TSN and related standards. There are several use cases in [12], which explains the type of these use cases, their future, and what IETF should deliver to enable them. DetNet shares same use cases [12] as TSN, including some additional cases:

- Building automation systems (BASs)
- Industrial machine to machine (M2M)
- Private blockchain
- Mining industry
- Network slicing

However, there are various use cases, which were considered by DetNet WG and the Design Team to be out of the scope of DetNet. The scope of DetNet networks is limited to services that can be centrally controlled, e.g., corporate networks. From this point of view, "the open Internet" is excluded from DetNet networks. Maintaining a high-quality user experience and low latency is critical for the use cases listed below. Due to jitter and time delay, these use cases, when run over the open Internet, are considered to be outside the scope of DetNet [12]. These use cases are:

- Media content delivery
- Online Gaming
- Virtual Reality

Nevertheless, we provide a detailed overview of the two applications that fall under the scope of DetNet from the use cases listed above.

Building Automation Systems (BASs): Building Automation Systems manage devices and sensors in a facility to improve the comfort of occupants, reduce energy consumption and respond to emergencies and failures [12]. For instance, the BAS controls the heating, ventilation, and air conditioning to maintain and reduce energy consumption. The basic architecture of BAS is shown in Figure 3. The BAS network has two layers: the upper layer – management network and the lower layer – field network. IP-based communication protocols are used in the upper layer, while in the lower layer, non-IP-based

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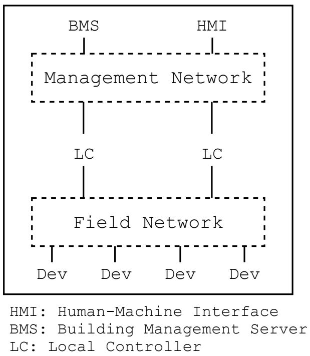

Figure 3: BAS Architecture [12]

communication protocols are used. Management networks can be best effort, whereas field networks have particular timing requirements.

Private Blockchain: Blockchain has spread far beyond its original host into several other industries. These industries are logistics, security, smart manufacturing, legal rights, and others. Designated and carefully managed networks of these industries, in which blockchain runs, may require deterministic networking. These kinds of implementations are called "private blockchains". Blockchain operation could be much more efficient if DetNet services were available to reduce packet loss and latency [12].

Currently, private blockchain runs in Layer 2 or Layer 3 VPNs without guaranteed determinism. Industries have realized that implementing and improving determinism in their blockchain networks would also improve the performance of their service, because low latency would speed up the consensus process. Some of the private blockchain requests [12] to the IETF are listed below:

- Layer 2 and 3 multicasts of blockchain traffic
- Item and block delivery with low latency and low packet loss
- Coexistence of IT traffic and blockchain in a single network

5. Comparison of DetNet and TSN

There are several differences and similarities between these two standards. The main difference between DetNet and TSN is the layering in the OSI model. DetNet operates on the Layer 3 protocols whereas TSN is confined to Layer 2.

The data plane of these standards is also different. DetNet nodes can connect to other subnetworks, such as Optical Transport Network (OTN) and MPLS Traffic Engineering. TSN cannot achieve multi-layer systems, while DetNet can. However, TSN and DetNet share the same features such as time synchronization, frame replication and elimination.

DetNet has to deal with more security challenges than TSN because it operates on Layer 3 networks and in open environments, which results in more security threats. As a result, DetNet focuses on and offers more security solutions than TSN. An example of such an attack is a man-in-the-middle attack, which can impose and adjust delays in a node and undermine a real-time application [13].

6. Related Work

There are a couple of surveys on Deterministic Networking in [6] [12] [11]. An IEFT draft of the problem statement on deterministic networking has been presented in [6]. A broad survey about the use cases of deterministic networking and its overall architecture has been provided in [12] and [11] respectively. A sample *DetNet Simulator* based on OMNET++ and NeSTiNG, which overcomes some limitations such as allowing simulations of the full DetNet/TSN protocol stack, has been presented in [3]. A broad survey of the Audio and Video Bridging (AVB) standard, the predecessor of TSN, has been introduced in [4] and in [5]. An introduction to Time-Sensitive Networking and its essential features has been provided in [7]. Furthermore, an up-to-date comprehensive survey of the studies that specifically target the support of ULL in 5G networks, DetNet and TSN has been presented in [2] and in [10].

Many applications are likely to use techniques to increase the probability that a particular packet will be delivered. And when topology-fixed paths are used, which are protected against congestion loss a Frame Replication and Elimination for Reliability standard can guarantee a substantial reduction in the probability of packet loss than any other standards. Therefore, a survey on Frame Replication and Elimination for Reliability has been provided in [9].

7. Discussion and Conclusion

One of the future challenges of Deterministic Networking is packet replication and elimination (PRE). DetNet can ensure reliability, the increase in the probability of packets reaching their destination and the overall reduction of end-to-end latency [14] through packet replication and elimination. However, the increase in effective bandwidth required for a DetNet flow is a major disadvantage of PRE. This can be overcome by reducing the replication level, but it can affect the reliability and thus impact the balance between packet replication and bandwidth [2]. Nevertheless, the balance must be ensured for the operation of the DetNet.

This paper provided a broad overview of deterministic network management and control systems, which can operate on DetNet components and provide ULL services and features such as low jitter, low congestion loss, reliability and time synchronization. This survey also discusses the differences and similarities between DetNet and TSN standards and provides their features and use cases. Despite their shortcomings and numerous limitations, there is a need for an extensive evaluation of both DetNet and TSN standards. A combination of these standards has a high chance of impacting the traditional Ethernet networks and providing effective low latency services to users.

References

[1] J. Prados-Garzon, T. Taleb, and M. Bagaa, “LEARNET: Reinforcement Learning Based Flow Scheduling for Asynchronous Deterministic Networks,” pp. 1–6, 2020.

[2] A. Nasrallah, A. S. Thyagaturu, Z. Alharbi, C. Wang, X. Shao, M. Reisslein, and H. ElBakoury, "Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 88–145, Firstquarter 2019.

[3] V. Addanki and L. Iannone, "Moving a step forward in the quest for Deterministic Networks (DetNet)," pp. 1–9, 2020.

[4] L. Deng, G. Xie, H. Liu, Y. Han, R. Li, and K. Li, "A Survey of Real-Time Ethernet Modeling and Design Methodologies: From AVB to TSN," *ACM Computing Surveys*, vol. 55, no. 2, pp. 1–36, 2022.

[5] O. Kleineberg, P. Fröhlich, and D. Heffernan, "Fault-tolerant Audio and Video Bridging (AVB) Ethernet: A novel method for redundant stream registration configuration," *Proceedings of 2012 IEEE 17th International Conference on Emerging Technologies & Factory Automation*, pp. 1–8, 2012.

[6] N. Finn and P. Thubert, "Deterministic Networking Problem Statement," pp. 1–11, 2019.

[7] N. Finn, "Introduction to Time-Sensitive Networking," *IEEE Communications Standards Magazine*, vol. 2, no. 2, pp. 22–28, 2018.

[8] K. B. Stanton, "Distributing deterministic, accurate time for tightly coordinated network and software applications: IEEE 802.1AS, the TSN profile of PTP," *IEEE Communications Standards Magazine*, vol. 2, no. 2, pp. 34–40, 2018.

[9] I. L. S. Committee, "IEEE Standard for Local and metropolitan area networks-Frame Replication and Elimination for Reliability," *IEEE Communications Standards Magazine*, pp. 1–102, 2017.

[10] E. Kim, Y. Ryoo, B. Yoon, and T. Cheung, "Active control and management system for providing the ultra-low latency service on deterministic networks," *2021 Twelfth International Conference on Ubiquitous and Future Networks*, pp. 70–74, 2021.

[11] N. Finn, P. Thubert, B. Varga, and J. Farkas, "Deterministic Networking Architecture," pp. 1–38, 2019.

[12] E. Grossman, "Deterministic Networking Use Cases," pp. 1–97, 2019.

[13] T. Mizrahi, "Security Requirements of Time Protocols in Packet Switched Networks," pp. 1–36, 2014.

[14] J. De Armas, P. Tuset, T. Chang, F. Adelantado, T. Watteyne, and X. Vilajosana, "Determinism through path delivery: Why packet replication makes sense," *2016 International Conference on Intelligent Networking and Collaborative Systems (InCoS)*, pp. 150–154, 2016.