Deterministic Networking Reading Notes

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The reading materials are available at

`https://github.com/jamesrenxiangyu/Deterministic-Netowrk-Reading-Notes`

Contents

The reading summary mainly follows the structures below. For survey paper and RFC documents:

- What is the paper about.
- What are the key points discussed/introduced in the paper.
- What are the current research issues/directions and why.
- Ideas on existing works.

For research paper:

- What are the key points of the paper.
- What are the advantages.
- What are the disadvantages and why.
- Whether there are improvements.

1 Overview of Deterministic Networks

In this section, the note first summaries several recent works on Deterministic Networks (DetNet), introducing the definition of DetNet, the background knowledge, current research status, and use cases. The overview of DetNet helps to understand DetNet in the big picture. In the mean time, the note will remark on some of the papers regarding the conclusions, ideas, and question.

1.1 Deterministic Networking (DetNet) vs Time Sensitive Networking (TSN) [1] – 2019

The paper mainly summarized the features of IEEE TSN and IETF DetNet, respectively. IEEE TSN was originated from the Audio Video Bridging (AVB) industrial standard, established in IEEE 802.1 standard in 2007, and later extended to the current IEEE TSN. TSN is confined in layer 2, mainly focusing on addressing time synchronization, and bounded latency and zero congestion loss issues. The time synchronization is standardized in IEEE 802.1 AS by sharing time reference network-wide. Several standards were established to address the latter ones, e.g., IEEE 802.1 Qbv, IEEE 802.1 Qbu, and IEEE 802.1 Qch. The reliability issue is addressed by frame replication and elimination in TSN, which was standardized in IEEE 802.1 CB.

On the other hand, the DetNet WG extends the ULL service to layer 3. The goal of DetNet is similar to TSN, i.e., achieve time synchronization, zero congestion loss and high reliability, and high security. It is worth mentioning that DetNet considers not only the delay upper bound but also the lower bound, aiming at smaller jitter. Although DetNet is still under developing, several critical Internet drafts have been proposed in the RFC documents. In this paper, the architecture, data-plane framework, and security are briefly discussed.

Last but not the least, the paper listed several use cases for both TSN and DetNet, respectively. For example, TSN with bounded latency and high-reliability are necessary in 5G scenario, such as helping network slicing and realize the fronthaul connection in Ethernet bridged networks. According to the paper, the future works of TSN focus on how to fit for large-scale network, and thereby, enhance interconnectivity and simplify network management. DetNet, although not standardized yet, is promising in machine-to-machine communication (M2M), and professional audio and video industry (ProAV).

Remark: This is a simple summary of two on-going projects TSN and DetNet. It gives us an overview of their history, features, and current research status.

1.2 RFC 8557: Deterministic Networking Problem Statement [2] – 2019

This document briefly introduces the expected outcome of implementing DetNet, the possible solutions and their corresponding difficulties. As it is written in the literature, DetNet aims to establish a multip-hop path over IP or MPLS network for particular flow that satisfies the given QoS requirements (low latency and jitter, zero congestion loss, high delivery ratio, etc.) regardless other flows the in network. Some specific features of DetNet are mentioned.

- Time synchronization.
- Support deterministic packet flows with following features:
  - Can be either unicast or multicast.
  - Absolute guarantees of minimum and maximum end-to-end latency. Maybe tight jitter.
  - A packet loss ratio beyond the classical range for a particular medium, in the range of 10^{-9} to 10^{-12} or better on Ethernet and on the order of 10^{-5} in wireless sensor mesh networks.
  - High resource usage efficiency. Absorb more than half of the network's available bandwidth.
  - Free of network-imposed delay, such as throttling, congestion feedback.
- Multiple methods of controlling critical packet transmission, such as scheduling, shaping, limiting, at each hop.
- Robust defenses against misbehaving hosts, routers, or bridges, in both the data plane and the control plane. Guarantees no impact from other flows.
- One or more methods on resource reservations.

The literature mainly discussed the possible solutions or requirements from the following perspectives.

- Supported topology. In any case, routers and switches in between should not need to be aware of whether the path is end to end or a tunnel.
- Flow Characterization. Before a path is established for a critical flow, the expression of the flow characteristics, and how network can serves them must be specified.

- Centralized path computation and installation. To enable a centralized model, DetNet should produce a description of the high-level interaction and data models based on Path Computation Element (PCE).
- Distributed Path Setup. One possible solution is to build on RSVP-TE.
- Duplicated Data Format. A small number of packet formats and supporting protocols are required to support packet duplication and elimination on non-congruent paths.
- Security. The time of delivery of a packet can be very important due to the virtualization of networks over same infrastructure. Security of DetNet must cover the protection of signaling protocol, the authentication and authorization of the controlling nodes, identification and shaping of the flows, and isolation of flows from leakage.

Remark. *Our recent work DSRBP matches most of the features mentioned in the literature. Some extra considerations for DSRBP may include: (1) guarantee both maximum and minimum latency (current work guarantees maximum delay only). (2) standardize flow/packet characterization. (3) Incorporate packet duplication and elimination to satisfy ultra high reliability.*

1.3 RFC 8655: Deterministic Networking Architecture [3]

This document summaries the overall DetNet architecture which aims to provide URLL service to end users. The paper identifies several key components and possible techniques that may be used in DetNet. Some specific terms are also defined to avoid misunderstanding with other concepts. Three main techniques are introduced to provide/maintain DetNet QoS, namely resource allocation/reservation, service protection, and explicit routes.

- Resource allocation. Resource allocation operates by assigning resources, e.g., buffer space or link bandwidth, to a DetNet flow along its path. A DetNet flow is assumed to be rate limited but assigned with sufficient resources, thus transport layer congestion control is not required (but should not impact negatively).
- Service protection. Service protection is designed to prevent packet loss due to device failure or media errors. Key methods include packet replication and elimination, multiple path, etc. Disorder packet is a consequence of packet duplication and multi-path, thus, packet reordering is also required. Network coding is also a possible method to use.

```
     |  packets going  |         ^  packets coming   ^
     v down the stack  v         |   up the stack    |
  +-----------------------+   +-----------------------+
  |        Source         |   |      Destination      |
  +-----------------------+   +-----------------------+
  |   Service sub-layer:  |   |   Service sub-layer:  |
  |   Packet sequencing   |   | Duplicate elimination |
  |    Flow replication   |   |      Flow merging     |
  |    Packet encoding    |   |    Packet decoding    |
  +-----------------------+   +-----------------------+
  | Forwarding sub-layer: |   | Forwarding sub-layer: |
  |  Resource allocation  |   |  Resource allocation  |
  |    Explicit routes    |   |    Explicit routes    |
  +-----------------------+   +-----------------------+
  |     Lower layers      |   |     Lower layers      |
  +-----------------------+   +-----------------------+
              v                           ^
               \_________________________/
```

Figure 1: DetNet protocol stack

- Explicit routes. DetNet employs explicit routes where the path taken by a given DetNet flow does not change, at least not immediately and likely not at all, in response to network topology events. The use of explicit routes helps to provide in-order delivery because there is no immediate route change with the network topology, but the changes are plannable as they are between the different explicit routes.

There are other issues need to be addressed in DetNet, such as coexistence with normal traffic (bandwidth sharinng, traffic shaping and scheduling to avoid starvation), fault mitigation (detect failures using policers or filters), etc. A conceptual DetNet architecture is proposed to support the aforementioned services and functions as shown in Fig. 1. The service sub-layer is mainly responsible for providing service to upper layer such as service protection, while the forwarding sub-layer supports the service in the underlay network such as resource allocation and routing.

On the other hand, an overview of the DetNet network is also provided as shown in Fig. 2. A DetNet-enabled network is composed of DetNet edge and relay nodes, respectively. The DetNet edge nodes and relay nodes are interconnected by DetNet transit node which only support forwarding function. All DetNet nodes are connected to sub-networks, e.g. MPLS-TE, TSN, etc. Fig. 1. DetNet end systems are also categorized into fours classes in terms of forwarding sub-layer and service sub-layer awareness. It is worth noticing that if more DetNet unaware nodes are deployed as transit nodes, the DetNet QoS can be harmed due to lack of service protection and resource allocation for DetNet flows.

```
TSN               Edge        Transit         Relay        DetNet
End System        Node         Node           Node       End System

+----------+   +.........+                               +----------+
|  Appl.   |<--:Svc Proxy:-- End-to-End Service -------->|  Appl.   |
+----------+   +---------+                  +---------+  +----------+
|   TSN    |   |TSN| |Svc|<- DetNet flow --: Service :-->| Service  |
+----------+   +---+ +---+  +---------+     +---------+  +----------+
|Forwarding|   |Fwd| |Fwd|  |   Fwd   |     |Fwd| |Fwd|  |Forwarding|
+-------.--+   +-.-+ +-.-+  +--.----.-+     +-.-+ +-.-+  +---.------+
        :  Link  :    /  ,-----. \   : Link  :    /  ,-----.  \
        +........+    +-[  Sub- ]-+  +.......+    +-[  Sub- ]-+
                        [network]                   [network]
                         `-----'                     `-----'
```

Figure 2: DetNet-enabled network

Remark. *This RFC document gives a conceptual architecture of DetNet including fundamental techniques such as service protection, resource allocation, and explicit route. From my point of view, traffic classification and flow characterization is the base of realizing DetNet service. Packet duplication and elimination function placement and decision making is an interesting research topic. Since DetNet assumes a centralized controlled protocol, resource allocation is only feasible within small-scaled network with limited number of traffic flows. Network dynamics can be harmful to centralized-based method too.*

1.4 RFC 8678: Deterministic Networking Use Cases [4]

This RFC identifies a range of applications and scenarios that requires deterministic services, i.e., guaranteed bandwidth, latency, etc. The use cases covers a large scope, including, professional audio and video (ProAV), electrical utilities, wireless for industrial applications, cellular radio, industrial machine to machine (M2M), private blockchain, network slicing, etc. Since so many topics are covered, part of them is summarised and analyzed here according to my personal interest.

1.4.1 Professional Audio and Video

ProAV industries such cinema, music and film creation, live shows are transitioning from point to point single link per signal to packet based infrastructures to reduce cost and integrate with current IT infrastructures. Some key use cases in ProAV includes:

- Uninterrupted streaming playback. Retransmission of ProAV for live playbacks is impractical as it is more time critical unlike file transfers. Buffering to provide delay space for retries alone is insufficient in time critical scenarios. FEC can be an option to address this issue.

- Synchronized streaming playback. Synchronization in this context mainly refers to the consistence between audio and video when multiple paths are taken for transmission. Typical tolerance for audio/video synchronization is one National Television System Committee (NTSC) video frame (about 33 ms). Current solution is to has the sink application delay all packets but on the slowest path.

- Sound reinforcement. Sound reinforcement requires a maximum delay of 15 ms in total (from microphone to speaker). In some cases, such as beamforming using multiple speakers, the latency should be within tens of microseconds.

- Secure transmission. Secure in this context refers to securely transmit sensitive traffics (such as amplifier control signals) to prevent harm to audience.

The future ProAV is anticipated to have the following features.

- Interconnect L2 islands.

- High reliability streaming paths.

- Integration of reserved streams into IT networks.

- Sharing bandwidth with best-effort traffics to improve bandwidth efficiency.

- Traffic Segregation. Prevent unnecessary process at devices with low cpu power.

- Multicast addressing to keep bandwidth utilization of shared links to a minimum. To ensure the multicast address is only associated to one stream.

- Reduced device costs due to reduced buffer memory.

Remark. *RFC DetNet Architecture is capable of addressing several issues in ProAV. For example, packet duplication and elimination to provide high reliability streaming paths, explicit path and resource allocation to provide Diffserv services. Multicast addressing may require other function blocks to support.*

1.4.2 Building automation system (BAS)

The BAS is an essential component in IoT scenario which manages equipment and sensors in a building to improve living comfort. Key functions in BAS include monitor devices, store measured data, data analysis (e.g., fault detection), and control devices. Current BAS architecture contains two layers of network, namely management network, and field network. Management network is normally IP-based best-effort network, whereas field network is non-IP-based time-critical network.

Future BAS anticipates lower energy consumption but finer-grained environment monitoring with more sensors. Building networks will be connected to other networks, such as, enterprise network, the Internet, etc.

1.4.3 Wireless for industrial application

Wireless networks are essential to industrial application in many aspect. Normally large amount of devices are involved in the network, where a small cost reduction may bring huge benefits. Some existing wireless networks support deterministic QoS such as 6TiSCH, but are not compatible with each other or IP traffic. Some common features include, precise scheduling, remote monitoring and scheduling management by path computation entity (PCE) and network management entity (NME).

In the future, wireless networks are expected to enable converged transport of deterministic and best-effort traffic flows between real-time industrial devices and WANs via IP routing. 6TiSCH in particular can be co-developed with DetNet in terms of retries, schedule management, path management, IP interface, and security, etc.

1.4.4 Cellular Radio

The cellular network architecture includes “Fronthaul", “ Midhaul", and “Backhaul" network segments. The fronthaul is the network connecting base stations to the Remote Radio Heads (RRHs) or antennas. The midhaul is the network that interconnects base stations (or small-cell sites). The "Backhaul" is the network or links connecting the radio base station sites to the network controller/gateway sites (i.e., the core of the 3GPP cellular network). Here how DetNet can help fronthaul to reduce delay is mainly discussed.

Current fronthaul networks typically consist of (1) Dedicated point-to-point fiber connection. (2) Proprietary protocols and framing. The midhaul and backhaul adopts IP-network or MPLS-TP, Clock distribution and synchronization using IEEE 1588 and syncE.

The transport time budget covers scheduling/queueing delay, transmission delay, and link propagation delay. DetNet helps improve fronthaul network by controlling and reducing the delay budget consumption through precise resource allocation. For example, control the bandwidth assignment of the fronthaul link and the scheduling of fronthaul packets over this link, provide adequate buffer provisioning for each flow to reduce the packet loss rate. Apart from reducing delay, DetNet can provide flow isolation, e.g., flows from different network slices.

Transport is also assumed to be error-free. The transport errors in fronthaul and midhaul refer to packet loss due BER, congestion, or network failure. Existing methods to eliminate traffic loss face serious challenges. For example, Retransmission and applying FEC introduce too much delay, redundant streams occupies high bandwidth. In addition, the fronthaul links are assumed to be symmetric, i.e., with equal priority and cannot preempt or delay one another.

The future cellular radio networks are envisioned to be based on a mix of Xhauls. Some requests to achieve new cellular radio networks include: (1) Unified among all Xhauls. (2) Deployed in a highly deterministic network environment. (3) Capable of supporting multiple functional splits simultaneously. (4) Capable of supporting network slicing and multi-tenancy. (5) Capable of transporting both in-band and out-of-band control traffic. (6) Deployable over multiple data-link technologies.

1.4.5 Network slicing

Network slicing divides the underlying network infrastructure into several independent logical networks which share the same resources. Network slicing provides flexibility of resource allocation and service quality customization.

DetNet can help improve network slicing from two perspectives.

- Across slices. DetNet should provide hard isolation among slices, i.e., different user's deterministic performance.
- Within a slice. Deterministic performance can be provided to both DetNet-aware slices and non-DetNet-aware slices.

A typical use case of DetNet in 5G is the hard service isolation bearer network. With DetNet, services of different slices would not compete for resources (e.g., bandwidth, reliability requirements) which lead to failure in QoS-guarantee.

There are some limitations of DetNet in network slicing, too. For example, network slicing essentially requires multipoint-to-multipoint guarantees while DetNet provides point-to-point or point-to-multipoint. Scalability is another issue in centralized DetNet. (**Remark**: A distributed DetNet solution is essential in addressing this issue.)

Remark. *In this RFC document, a variety of potential DetNet use cases (9 in total) are introduced. The analysis of each use case follows the sequence: (1) Mechanism overview. (2) Existing solutions/research status. (3) Feasibility of DetNet usage. (4) Request to DetNet.*

The common requests of the use cases can be summarised as follows.

- *Strict latency-guaranteed service. End-to-end delay-guarantee is the essential feature of DetNet. Both delay upper bound and lower bound should be guaranteed. Apart from that, a tight jitter is also desired in some time-critical applications such as ProAV.*
- *Hard service isolation. Service isolation ensures QoS-guarantee among multiple traffics as well as easier management, allows more flexibility.*
- *Coexistence with best-effort traffics. Adoption of DetNet should be practically feasible. DetNet traffics should not affect best-effort traffics while the reserved resources should be available to the best-effort whenever possible.*

2 Appendix A

References

[1] X. Yang, D. Scholz, and M. Helm, "Deterministic networking (detnet) vs time sensitive networking (tsn)," *Network*, vol. 79, 2019.

[2] N. Finn and P. Thubert, "Deterministic networking problem statement," *draft-finn-detnet-problem-statement-05 (work in progress)*, 2016.

[3] N. Finn, P. Thubert, B. Varga, and J. Farkas, "Deterministic networking architecture," *RFC 8655*, 2019.

[4] E. Grossman, C. Gunther, P. Thubert, P. Wetterwald, J. Raymond, J. Korhonen, Y. Kaneko, S. Das, Y. Zha, B. Varga *et al.*, "Deterministic networking use cases," *RFC 8578*, 2019.