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Deterministic Networking Problem Statement
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Abstract

This paper documents the needs in various industries to establish multi-hop paths for characterized flows with deterministic properties .

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1. Introduction

Operational Technology (OT) refers to industrial networks that are specifically deployed in order to monitor production systems and support control loops and movement detection operations for process control (i.e., continuous manufacturing) and factory automation (i.e., discrete manufacturing), as well as protection systems used in power distribution automation (the SmartGrid). Due to its different goals, OT has evolved in parallel but in a manner that is radically different from Information Technology/Information and Communications Technology (IT/ICT), focusing on highly secure, reliable and deterministic networks, with limited scalability over a bounded and closed area.

In OT environments, deterministic networks are characterized as providing a guaranteed bandwidth with extremely low packet loss rates, bounded latency, and low jitter.

The convergence of IT and OT technologies, also called the Industrial Internet, represents a major evolution for both sides. For IT, it means a new level of Quality of Service whereby the transfer of packets is completely controlled and repeatable, different flows are perfectly isolated from one another, and packet loss and system

downtimes are reduced drastically; for OT, it means sharing IT resources between deterministic and stochastic flows in order to retrieve vasts amounts of so-far unmeasured data and enable additional optimizations.

The work has already started; in particular, the industrial automation space has been developing a number of Ethernet-based replacements for existing digital control systems (DCS), often not packet-based (fieldbus technologies). These replacements are meant to provide similar behavior as the incumbent protocols, and their common focus is to transport a fully characterized flow over a well-controlled environment (i.e., a factory floor), with a bounded latency, extraordinarily low frame loss, and a very narrow jitter. Examples of such protocols include PROFINET [Profinet], ODVA Ethernet/IP [EIP], and EtherCAT.

As an example, Industrial Automation segregates the network along the broad lines of the Purdue Enterprise Reference Architecture (PERA) [ISA95], using different technologies at each level, and public infrastructures such as the power distribution grid require deterministic properties over the Wide Area. To fully serve an industrial application between a wireless sensor and a virtualized control system operating from the carpeted floor, a deterministic path may span, for instance, across a (limited) number of 802.1 bridges and then a (limited) number of IP routers. In that example, the IEEE802.1 bridges may be operating at Layer-2 over Ethernet whereas the IP routers may be 6TiSCH [TiSCH] nodes operating at Layer-2 and/or Layer-3 over the IEEE802.15.4 MAC.

In parallel, the need for determinism in professional and home audio/video markets drove the formation of the Audio/Video Bridging (AVB) standards efforts in IEEE 802.1. With the demand for connectivity and multimedia in transportation, AVB is being evaluated for application in vehicle head units, rear seat entertainment modules, amplifiers, camera modules, and engine control systems. Automotive AVB networks share the OT requirements for deterministic networks

characteristics.

Other instances of in-vehicle deterministic networks have arisen as well for control networks in cars, trains and buses, as well as avionics, with, for instance, the mission-critical "Avionics Full-Duplex Switched Ethernet" (AFDX) that was designed as part of the ARINC 664 standards. Existing automotive control networks such as the LIN, CAN and FlexRay standards were not designed to cover the increasing demands in terms of bandwidth and scalability that we see with various kinds of Driver Assistance Systems (DAS); it results that new multiplexing technologies based on Ethernet are now getting traction.

Other industries where strong needs for deterministic networks are now emerging include: radio access networks [I-D.korhonen-detnet-telreq], the SmartGrid [I-D.wetterwald-detnet-utilities-reqs], and ProAudio networks [I-D.gunther-detnet-proaudio-req].

This wider application scope for deterministic networks has led to the IEEE802.1 AVB Task Group becoming the Time-Sensitive Networking (TSN) Task Group (TG) [IEEE802.1TSNTG], additionally covering industrial and vehicular applications.

The networks in consideration are now extending beyond the LAN boundaries and require secure deterministic forwarding and connectivity over a mixed Layer-2/Layer-3 network. The properties of deterministic networks will have specific requirements for the use of routed networks to support these applications and a new model must be proposed to integrate determinism in IT technology.

The proposed model should enable a fully scheduled operation orchestrated by a central controller, and may support a more distributed operation with probably lesser capabilities. In any fashion, the model should not compromise the ability of a network to keep carrying the sorts of traffic that is already carried today in conjunction with new, more deterministic flows.

Once the abstract model is agreed upon, the IETF will need to specify the signaling elements to be used to establish a path and the tagging elements to be used identify the flows that are to be forwarded along that path. The IETF will also need to specify the necessary

protocols, or protocol additions, based on relevant IETF technologies such as PCE [PCE], TEAS [TEAS], CCAMP [CCAMP] and MPLS [MPLS], to implement the selected model.

As a result of this work, it will be possible to establish a multi-hop path over the IP network, for a particular flow with given timing and precise throughput requirements, and carry this particular flow along the multi-hop path with such characteristics as low latency and ultra-low jitter, duplication and elimination of packets over non-congruent paths for a higher delivery ratio, and/or zero congestion loss, regardless of the amount of other flows in the network. Depending on the network capabilities and on the current state, requests to establish a path by an end-node or a network management entity may be granted or rejected, an existing path may be moved or removed, and flows exceeding their contract may face packet declassification and drop.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. On Deterministic Networking

The Internet is not the only digital network that has grown dramatically over the last 30-40 years. Video and audio entertainment, and control systems for machinery, manufacturing processes, and vehicles are also ubiquitous, and are now based almost entirely on digital technologies. Over the past 10 years, engineers in these fields have come to realize that significant advantages in both cost and in the ability to accelerate growth can be obtained by basing all of these disparate digital technologies on packet networks.

The goals of Deterministic Networking are to enable the migration of applications that use special-purpose fieldbus technologies (HDMI, CANbus, ProfiBus, etc... even RS-232!) to packet technologies in general, and the Internet Protocol in particular, and to support both

these new applications, and existing packet network applications, over the same physical network.

Considerable experience ([ODVA],[AVnu], [Profinet],[IEC62439], etc...) has shown that these applications need a some or all of a suite of features that includes:

1. Time synchronization of all host and network nodes (routers and/or bridges), accurate to something between 10 nanoseconds and 10 microseconds, depending on the application.

2. Support for critical packet flows that:

    * Can be unicast or multicast;

    * Need absolute guarantees of minimum and maximum latency end-to-end across the network; sometimes a tight jitter is required as well;

    * Need a packet loss ratio beyond the classical range for a particular medium, in the range of 1.0e-9 to 1.0e-12, or better, on Ethernet, and in the order of 1.0e-5 in Wireless Sensor mesh Networks;

    * Can, in total, absorb more than half of the network's available bandwidth (that is, massive over-provisioning is ruled out as a solution);

    * Cannot suffer throttling, congestion feedback, or any other network-imposed transmission delay, although the flows can be meaningfully characterized either by a fixed, repeating transmission schedule, or by a maximum bandwidth and packet size;

3. Multiple methods to schedule, shape, limit, and otherwise control the transmission of critical packets at each hop through the network data plane;

4. Robust defenses against misbehaving hosts, routers, or bridges,

both in the data and control planes, with guarantees that a critical flow within its guaranteed resources cannot be affected by other flows whatever the pressures on the network;

5. One or more methods to reserve resources in bridges and routers to carry these flows.

Time synchronization techniques need not be addressed by an IETF Working Group; there are a number of standards available for this purpose, including IEEE 1588, IEEE 802.1AS, and more.

The multicast, latency, loss ratio, and non-throttling needs are made necessary by the algorithms employed by the applications. They are not simply the transliteration of fieldbus needs to a packet-based fieldbus simulation, but reflect fundamental mathematics of the control of a physical system.

With classical forwarding latency- and loss-sensitive packets across a network, interactions among different critical flows introduce fundamental uncertainties in delivery schedules. The details of the queuing, shaping, and scheduling algorithms employed by each bridge or router to control the output sequence on a given port affect the detailed makeup of the output stream, e.g. how finely a given flow's packets are mixed among those of other flows.

This, in turn, has a strong effect on the buffer requirements, and hence the latency guarantees deliverable, by the next bridge or router along the path. For this reason, the IEEE 802.1 Time-Sensitive Networking Task Group has defined a new set of queuing, shaping, and scheduling algorithms (see Section 5.2) that enable each bridge or router to compute the exact number of buffers to be allocated for each flow or class of flows. The present authors

assume that these techniques will be used by the DetNet Working Group.

Robustness is a common need for networking protocols, but plays a more important part in real-time control networks, where expensive equipment, and even lives, can be lost due to misbehaving equipment.

Reserving resources before packet transmission is the one fundamental

shift in the behavior of network applications that is impossible to avoid. In the first place, a network cannot deliver finite latency and practically zero packet loss to an arbitrarily high offered load. Secondly, achieving practically zero packet loss for un-throttled (though bandwidth limited) flows means that bridges and routers have to dedicate buffer resources to specific flows or to classes of flows. The requirements of each reservation have to be translated into the parameters that control each host's, bridge's, and router's queuing, shaping, and scheduling functions and delivered to the hosts, bridges, and routers.

4. Related IETF work

4.1. Deterministic PHB

[I-D.svshah-tsvwg-deterministic-forwarding] defines a Differentiated Services Per-Hop-Behavior (PHB) Group called Deterministic Forwarding (DF). The document describes the purpose and semantics of this PHB. It also describes creation and forwarding treatment of the service class, and how the code-point can be mapped into one of the aggregated Diffserv service classes [RFC5127].

4.2. 6TiSCH

Industrial process control already leverages deterministic wireless Low power and Lossy Networks (LLNs) to interconnect critical resource-constrained devices and form wireless mesh networks, with standards such as [ISA100.11a] and [WirelessHART].

These standards rely on variations of the [IEEE802154] timeSlotted Channel Hopping (TSCH) [RFC7554] Medium Access Control (MAC), and a form of centralized Path Computation Element (PCE), to deliver deterministic capabilities.

The TSCH MAC benefits include high reliability against interference, low power consumption on characterized flows, and Traffic Engineering capabilities. Typical applications are open and closed control loops, as well as supervisory control flows and management.

The 6TiSCH Working Group focuses only on the TSCH mode of the

IEEE802.15.4e standard. The WG currently defines a framework for managing the TSCH schedule. Future work will standardize deterministic operations over so-called tracks as described in [I-D.ietf-6tisch-architecture]. Tracks are an instance of a deterministic path, and the DetNet work is a prerequisite to specify track operations and serve process control applications. The dependencies that 6TiSCH has on PCE and DetNet work are further discussed in [I-D.thubert-6tisch-4detnet].

[RFC5673] and [I-D.ietf-roll-rpl-industrial-applicability] section 2.1.3 and next discuss application-layer paradigms, such as Source-sink (SS) that is a Multipeer to Multipeer (MP2MP) model that is primarily used for alarms and alerts, Publish-subscribe (PS, or pub/sub) that is typically used for sensor data, as well as Peer-to-peer (P2P) and Peer-to-multipeer (P2MP) communications. Additional considerations on Duocast and its N-cast generalization are also provided for improved reliability.

5. Related work in other standards organizations

5.1. Bridged solutions

Completed and ongoing work in other standards bodies have, to date, produced viable solutions, suitable for carrying IP traffic for a subset of the applications of interest to DetNet, but only over bridged networks, not through routers. Among these are:

- o IEEE 802 Audio-Video Bridging [IEEE802.1BA-2011].
- o IEEE 802 Time-Sensitive Networking (TSN) Task Group (TG) [IEEE802.1TSNTG]
- o ISO/IEC HSR and PRP [IEC62439].

5.2. Queuing and shaping

A number of standards are completed or in progress in the IEEE 802.1 (bridging) and IEEE 802.3 (Ethernet) Working Groups related to the queuing and transmission of Ethernet frames. Most of these standards could be applied to non-Ethernet or non-802 media with equal facility, and so will likely be of use to DetNet. See the DetNet architecture draft [I-D.finn-detnet-architecture] for a detailed list.

6. Problem Statement

6.1. DetNet architecture

An architecture that defines the space in which the various parts of the DetNet solution operate is required. A start has been made with [I-D.finn-detnet-architecture]. The main consideration is to build on art that is deployed in existing OT networks.

These networks are systematically designed around a central controller that has a God's view on the devices, their capabilities, and their links to neighbors. The controller gets requests to establish flows with certain Traffic Specifications, and programs the necessary resources in the network to support those flows.

This design, referred to as Software Defined Networking (SDN), simplifies the computation and the setup of paths, and ensures a better view and an easier control of the network by an operator. To inherit from this art, it has been determined early in DetNet discussions that the work would initially focus on an SDN model as well.

DetNet should thus produce the complete SDN architecture with describes at a high level the interaction and data models to:

- report the topology and device capabilities to the central controller;
- request a path setup for a new flow with particular characteristics over the service interface and control it through its life cycle;
- signal the new path to the devices, modify it to cope with various events such as loss of a link, update it and tear it down;
- expose the status of the path to the end devices (UNI interface)
- provide additional reliability through redundancy, in particular with packet replication and elimination;
- indicate the flows and packet sequences in-band with the flows;

The related concepts are already laid out at the IETF with [RFC7426], which introduces the following elements:

```
           SDN Layers and Architecture Terminology per RFC 7426

                     o--------------------------------o
                     |                                |
                     | +-------------+   +----------+ |
                     | | Application |   |  Service | |
                     | +-------------+   +----------+ |
                     |       Application Plane        |
                     o---------------Y----------------o
                                     |
       *-----------------------------Y---------------------------------*
       |           Network Services Abstraction Layer (NSAL)           |
       *------Y------------------------------------------------Y-------*
              |                                                |
              |               Service Interface                |
              |                                                |
       o------Y------------------o       o---------------------Y------o
       |      |    Control Plane |       | Management Plane    |      |
       | +----Y----+   +-----+   |       |  +-----+       +----Y----+ |
       | | Service |   | App |   |       |  | App |       | Service | |
       | +----Y----+   +--Y--+   |       |  +--Y--+       +----Y----+ |
       |      |           |      |       |     |               |      |
       | *----Y-----------Y----* |       | *---Y---------------Y----* |
       | | Control Abstraction | |       | | Management Abstraction | |
       | |     Layer (CAL)     | |       | |      Layer (MAL)       | |
       | *----------Y----------* |       | *----------Y-------------* |
       |            |            |       |            |               |
       o------------|------------o       o------------|---------------o
                    |                                 |
                    | CP                              | MP
                    | Southbound                      | Southbound
                    | Interface                       | Interface
                    |                                 |
       *------------Y---------------------------------Y----------------*
       |         Device and resource Abstraction Layer (DAL)           |
       *------------Y---------------------------------Y----------------*
       |            |                                 |                |
       |    o-------Y----------o   +-----+   o--------Y----------o     |
       |    | Forwarding Plane |   | App |   | Operational Plane |     |
```

```
|    o-----------------o    +-----+    o-------------------o     |
|                       Network Device                            |
+----------------------------------------------------------------+
```

Figure 1

6.2. Flow Characterization

Deterministic forwarding can only apply on flows with well-defined characteristics such as periodicity and burstiness. Before a path can be established to serve them, the expression of those characteristics, and how the network can serve them, for instance in shaping and forwarding operations, must be specified.

6.3. Centralized Path Computation and Installation

A centralized routing model, such as provided with a PCE, enables global and per-flow optimizations. The model is attractive but a number of issues are left to be solved. In particular:

o whether and how the path computation can be installed by 1) an end device or 2) a Network Management entity,

o and how the path is set up, either by installing state at each hop with a direct interaction between the forwarding device and the PCE, or along a path by injecting a source-routed request at one end of the path following classical Traffic Engineering (TE) models.

6.4. Distributed Path Setup

Whether a distributed alternative without a PCE can be valuable could be studied as well. Such an alternative could for instance inherit from the Resource ReSerVation Protocol [RFC5127] (RSVP) flows. But the focus of the work should be to deliver the centralized approach first.

6.5. Duplicated data format

In some cases the duplication and elimination of packets over non-congruent paths is required to achieve a sufficiently high delivery ratio to meet application needs. In these cases, a small number of packet formats and supporting protocols are required (preferably, just one) to serialize the packets of a DetNet stream at one point in the network, replicate them at one or more points in the network, and discard duplicates at one or more other points in the network, including perhaps the destination host. Using an existing solution would be preferable to inventing a new one.

7. Security Considerations

Security in the context of Deterministic Networking has an added dimension; the time of delivery of a packet can be just as important as the contents of the packet, itself. A man-in-the-middle attack,

for example, can impose, and then systematically adjust, additional delays into a link, and thus disrupt or subvert a real-time application without having to crack any encryption methods employed. See [RFC7384] for an exploration of this issue in a related context.

Typical control networks today rely on complete physical isolation to prevent rogue access to network resources. DetNet enables the virtualization of those networks over a converged IT/OT infrastructure. Doing so, DetNet introduces an additional risk that flows interact and interfere with one another as they share physical resources such as Ethernet trunks and radio spectrum. The requirement is that there is no possible data leak from and into a deterministic flow, and in a more general fashion there is no possible influence whatsoever from the outside on a deterministic flow. The expectation is that physical resources are effectively associated with a given flow at a given point of time. In that model, Time Sharing of physical resources becomes transparent to the individual flows which have no clue whether the resources are used by other flows at other times.

Security must cover:

- o the protection of the signaling protocol

- o the authentication and authorization of the controlling nodes

o the identification and shaping of the flows

o the isolation of flows from leakage and other influences from any activity sharing physical resources.

8. IANA Considerations

This document does not require an action from IANA.

9. Acknowledgments

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