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Deterministic Networking Architecture
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Abstract

Deterministic Networking (DetNet) provides a capability to carry specified unicast or multicast data flows for real-time applications with extremely low data loss rates and bounded latency. Techniques used include: 1) reserving data plane resources for individual (or aggregated) DetNet flows in some or all of the relay nodes (bridges or routers) along the path of the flow; 2) providing fixed paths for DetNet flows that do not rapidly change with the network topology; and 3) sequentializing, replicating, tracing and eliminating duplicate packets at various points to ensure the availability of at least one path. The capabilities can be managed by configuration, or by manual or automatic network management.

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Table of Contents

1.	Introduction	3
2.	Terminology	4
2.1.	Terms used in this document	4
2.2.	IEEE 802 TSN to DetNet dictionary	5
3.	Providing the DetNet Quality of Service	5
3.1.	Zero Congestion Loss	7
3.2.	Pinned paths	8
3.3.	Jitter Reduction	8
3.4.	Packet Replication and Elimination	9
4.	DetNet Architecture	10
4.1.	Traffic Engineering for DetNet	10
4.1.1.	The Application Plane	11
4.1.2.	The Controller Plane	11
4.1.3.	The Network Plane	12
4.2.	DetNet flows	13
4.2.1.	Source guarantees	13
4.2.2.	Incomplete Networks	15
4.3.	Queuing, Shaping, Scheduling, and Preemption	15
4.4.	Coexistence with normal traffic	16
4.5.	Fault Mitigation	16
4.6.	Protocol Stack Model	17
4.7.	Exporting flow identification	20
4.8.	Advertising resources, capabilities and adjacencies	21
4.9.	Provisioning model	22
4.9.1.	Centralized Path Computation and Installation	22
4.9.2.	Distributed Path Setup	22
4.10.	Scaling to larger networks	23
4.11.	Connected islands vs. networks	23
5.	Compatibility with Layer-2	23
6.	Open Questions	24
6.1.	Data plane shapers and schedulers	24
6.2.	DetNet flow identification and sequencing	24
6.3.	Flat vs. hierarchical control	25
6.4.	Peer-to-peer reservation protocol	25
6.5.	Wireless media interactions	25
7.	Security Considerations	26

8.	Privacy Considerations	26
9.	IANA Considerations	27
10.	Acknowledgements	27
11.	Access to IEEE 802.1 documents	27
12.	Informative References	27
	Authors' Addresses	31

[1.](#) Introduction

Deterministic Networking (DetNet) is a service that can be offered by a network to data flows (DetNet flows) that are limited, at their source, to a maximum data rate specified by that source. DetNet provides these flows extremely low packet loss rates and assured maximum end-to-end delivery latency. This is accomplished by dedicating network resources such as link bandwidth and buffer space to DetNet flows and/or classes of DetNet flows. Unused reserved resources are available to non-DetNet packets.

The Deterministic Networking Problem Statement

[\[I-D.finn-detnet-problem-statement\]](#) introduces Deterministic Networking, and Deterministic Networking Use Cases

[\[I-D.ietf-detnet-use-cases\]](#) summarizes the need for it.

A goal of DetNet is a converged network in all respects. That is, the presence of DetNet flows does not preclude non-DetNet flows, and the benefits offered DetNet flows should not, except in extreme cases, prevent existing QoS mechanisms from operating in a normal fashion, subject to the bandwidth required for the DetNet flows. A single source-destination pair can trade both DetNet and non-DetNet flows. End systems and applications need not instantiate special interfaces for DetNet flows. Networks are not restricted to certain topologies; connectivity is not restricted. Any application that generates a data flow that can be usefully characterized as having a maximum bandwidth should be able to take advantage of DetNet, as long as the necessary resources can be reserved. Reservations can be made by the application itself, via network management, by an applications controller, or by other means.

Many applications of interest to Deterministic Networking require the ability to synchronize the clocks in end systems to a sub-microsecond accuracy. Some of the queue control techniques defined in [Section 4.3](#) also require time synchronization among relay nodes. The means used to achieve time synchronization are not addressed in this document. DetNet should accommodate various synchronization techniques and profiles that are defined elsewhere to solve exchange time in different market segments.

The present document is an individual contribution, but it is intended by the authors for adoption by the DetNet working group.

2. Terminology

2.1. Terms used in this document

The following special terms are used in this document in order to avoid the assumption that a given element in the architecture does or does not have Internet Protocol stack, functions as a router, bridge, firewall, or otherwise plays a particular role at Layer-2 or higher.

destination

An end system capable of sinking a DetNet flow.

DetNet domain

The portion of a network that is DetNet aware. It includes end systems and other DetNet nodes.

DetNet flow

A DetNet flow is a sequence of packets from a single source, through some number of relay nodes to one or more destinations, that is limited by the source in its maximum packet size and transmission rate, and can thus be ensured the DetNet Quality of Service (QoS) from the network.

DetNet compound flow and DetNet member flow

A DetNet compound flow is a DetNet flow that has been separated into multiple duplicate DetNet member flows, which are eventually merged back into a single DetNet compound flow. "Compound" and "member" are strictly relative to each other, not absolutes; a DetNet compound flow comprising multiple DetNet member flows can, in turn, be a member of a higher-order compound.

DetNet node

A DetNet aware end system or relay node. "DetNet" may be omitted in some text.

DetNet edge node

An instance of a DetNet node that includes a proxy function for one or more source end systems, analogous to a Label Edge Router (LER).

end system

Commonly called a "host" or "node" in IETF documents, and an "end station" in IEEE 802 documents. End systems of interest

to this document are either sources or destinations of L2 and/or L3 DetNet streams.

link

A connection between two DetNet nodes. It may be composed of a physical link or a sub-network technology that can provide appropriate traffic delivery for DetNet flows.

relay node

A router, transit node, bridge, Label Switch Router (LSR), firewall, or any other system that forwards packets from one interface to another.

reservation

A trail of configuration between source to destination(s) through relay nodes associated with a DetNet flow, required to deliver the benefits of DetNet.

source

An end system capable of sourcing a DetNet flow.

2.2. IEEE 802 TSN to DetNet dictionary

This section also serves as a dictionary for translating from the terms used by the IEEE 802 Time-Sensitive Networking (TSN) Task Group to those of the DetNet WG.

Listener

The IEEE 802 term for a destination of a DetNet flow.

relay system

The IEEE 802 term for a DetNet node.

Stream

The IEEE 802 term for a DetNet flow.

Talker

The IEEE 802 term for the source of a DetNet flow.

3. Providing the DetNet Quality of Service

The DetNet Quality of Service can be expressed in terms of:

- o Minimum and maximum end-to-end latency from source to destination; timely delivery and jitter avoidance derive from these constraints
- o Probability of loss of a packet, under various assumptions as to the operational states of the relay nodes and links. A derived

property is whether it is acceptable to deliver a duplicate packet, which is an inherent risk in highly reliable and/or broadcast transmissions

It is a distinction of DetNet that it is concerned solely with worst-case values for the end-to-end latency. Average, mean, or typical values are of no interest, because they do not affect the ability of a real-time system to perform its tasks. In general, a trivial priority-based queuing scheme will give better average latency to a data flow than DetNet, but of course, the worst-case latency can be essentially unbounded.

Three techniques are used by DetNet to provide these qualities of service:

- o Bandwidth reservation and enforcement ([Section 3.1](#)).
- o Pinned paths ([Section 3.2](#)).
- o Packet replication and elimination ([Section 3.4](#)).

The DetNet techniques are meant to address both of the DetNet QoS requirements (latency and packet loss). Given that relay nodes have a finite amount of buffer space, zero congestion loss necessarily results in a maximum end-to-end latency. It also addresses the largest contribution to packet loss, which is buffer congestion. Packet replication and elimination mitigates the second most important contributions to packet loss, namely random media errors and equipment failure.

These three techniques can be applied independently, giving eight possible combinations, including none (no DetNet), although some combinations are of wider utility than others. This separation keeps the protocol stack coherent and maximizes interoperability with existing and developing standards in this (IETF) and other Standards Development Organizations. Some examples of typical expected combinations:

- o Pinned paths (a) plus packet replication (b) are exactly the techniques employed by [[HSR-PRP](#)]. Pinned paths are achieved by limiting the physical topology of the network, and the sequentialization, replication, and duplicate elimination are facilitated by packet tags added at the front or the end of Ethernet frames.
- o Zero congestion loss (a) alone is offered by IEEE 802.1 Audio Video bridging [[IEEE802.1BA-2011](#)]. As long as the network suffers no failures, zero congestion loss can be achieved through the use

of a reservation protocol (MSRP), shapers in every relay node (bridge), and a bit of network calculus.

- o Using all three together gives maximum protection.

There are, of course, simpler methods available (and employed, today) to achieve levels of latency and packet loss that are satisfactory for many applications. Prioritization and over-provisioning is one such technique. However, these methods generally work best in the absence of any significant amount of non-critical traffic in the network (if, indeed, such traffic is supported at all), or work only if the critical traffic constitutes only a small portion of the network's theoretical capacity, or work only if all systems are functioning properly, or in the absence of actions by end systems that disrupt the network's operations.

There are any number of methods in use, defined, or in progress for accomplishing each of the above techniques. It is expected that this DetNet Architecture will assist various vendors, users, and/or "vertical" Standards Development Organizations (dedicated to a single industry) to make selections among the available means of implementing DetNet networks.

3.1. Zero Congestion Loss

The primary means by which DetNet achieves its QoS assurances is to completely eliminate congestion at an output port as a cause of packet loss. Given that a DetNet flow cannot be throttled, this can be achieved only by the provision of sufficient buffer storage at each hop through the network to ensure that no packets are dropped due to a lack of buffer storage.

Ensuring adequate buffering requires, in turn, that the source, and every relay system along the path to the destination (or nearly every relay node -- see [Section 4.2.2](#)) be careful to regulate its output to not exceed the data rate for any DetNet flow, except for brief periods when making up for interfering traffic. Any packet sent ahead of its time potentially adds to the number of buffers required by the next hop, and may thus exceed the resources allocated for a particular DetNet flow.

The low-level mechanisms described in [Section 4.3](#) provide the necessary regulation of transmissions by an edge system or relay node to ensure zero congestion loss. The reservation of the bandwidth and buffers for a DetNet flow requires the provisioning described in [Section 4.9](#). A DetNet node may have other resources requiring allocation and/or scheduling, that might otherwise be over-subscribed and trigger the rejection of a reservation.

3.2. Pinned paths

In networks controlled by typical peer-to-peer protocols such as IEEE 802.1 ISIS bridged networks or IETF OSPF routed networks, a network topology event in one part of the network can impact, at least briefly, the delivery of data in parts of the network remote from the failure or recovery event. Thus, even redundant paths through a network, if controlled by the typical peer-to-peer protocols, do not eliminate the chances of brief losses of contact.

Many real-time networks rely on physical rings or chains of two-port devices, with a relatively simple ring control protocol. This supports redundant paths with a minimum of wiring. As an additional benefit, ring topologies can often utilize different topology management protocols than those used for a mesh network, with a consequent reduction in the response time to topology changes. Of course, this comes at some cost in terms of increased hop count, and thus latency, for the typical path.

In order to get the advantages of low hop count and still ensure against even very brief losses of connectivity, DetNet employs pinned paths, where the path taken by a given DetNet flow does not change, at least immediately, and likely not at all, in response to network topology events. When combined with packet replication and elimination ([Section 3.4](#)), this results in a high likelihood of continuous connectivity. Pinned paths are commonly used in MPLS TE LSPs.

3.3. Jitter Reduction

A core objective of DetNet is to enable the convergence of Non-IP networks onto a common network infrastructure. This requires the accurate emulation of currently deployed mission-specific networks, which typically rely on point-to-point analog (e.g. 4-20mA modulation) and serial-digital cables (or buses) for highly reliable, synchronized and jitter-free communications. While the latency of analog transmissions is basically the speed of light, legacy serial links are usually slow (in the order of Kbps) compared to, say, GigE, and some latency is usually acceptable. What is not acceptable is the introduction of excessive jitter, which may, for instance, affect the stability of control systems.

Applications that are designed to operate on serial links usually do not provide services to recover the jitter, because jitter simply does not exist there. Streams of information are expected to be delivered in-order and the precise time of reception influences the processes. In order to converge such existing applications, there is a desire to emulate all properties of the serial cable, such as clock

transportation, perfect flow isolation and fixed latency. While minimal jitter (in the form of specifying minimum, as well as maximum, end-to-end latency) is supported by DetNet, there are practical limitations on packet-based networks in this regard. In general, users are encouraged to use, instead of, "do this when you get the packet," a combination of:

- o Sub-microsecond time synchronization among all source and destination end systems, and
- o Time-of-execution fields in the application packets.

3.4. Packet Replication and Elimination

After congestion loss has been eliminated, the most important causes of packet loss are random media and/or memory faults, and equipment failures. Both causes of packet loss can be greatly reduced by sending the same packets over multiple paths.

Packet replication and elimination, also known as seamless redundancy [[HSR-PRP](#)], or 1+1 hitless protection, involves three capabilities:

- o Replicating these packets into multiple DetNet member flows and, typically, sending them along at least two different paths to the destination(s), e.g. over the pinned paths of [Section 3.2](#).
- o Providing sequencing information, once, at or near the source, to the packets of a DetNet compound flow. This may be done by adding a sequence number or time stamp as part of DetNet, or may be inherent in the packet, e.g. in a transport protocol, or associated to other physical properties such as the precise time (and radio channel) of reception of the packet.
- o Eliminating duplicated packets. This may be done at any step along the path to save network resources further down, in particular if multiple Replication points exist. But the most common case is to perform this operation at the very edge of the DetNet network, preferably in or near the receiver.

This function is a "hitless" version of, e.g., the 1+1 linear protection in [[RFC6372](#)]. That is, instead of switching from one flow to the other when a failure of a flow is detected, DetNet combines both flows, and performs a packet-by-packet selection of which to discard, based on sequence number.

In the simplest case, this amounts to replicating each packet in a source that has two interfaces, and conveying them through the network, along separate paths, to the similarly dual-homed

destinations, that discard the extras. This ensures that one path (with zero congestion loss) remains, even if some relay node fails. The sequence numbers can also be used for loss detection and for re-ordering.

Alternatively, relay nodes in the network can provide replication and elimination facilities at various points in the network, so that multiple failures can be accommodated.

This is shown in the following figure, where the two relay nodes each replicate (R) the DetNet flow on input, sending the DetNet member flows to both the other relay node and to the end system, and eliminate duplicates (E) on the output interface to the right-hand end system. Any one link in the network can fail, and the Detnet compound flow can still get through. Furthermore, two links can fail, as long as they are in different segments of the network.

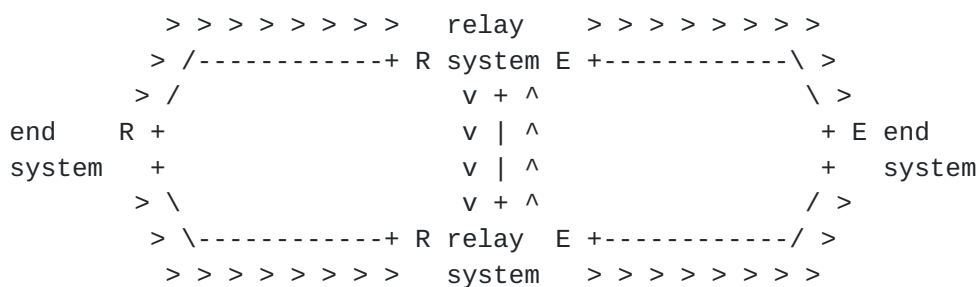


Figure 1

Note that packet replication and elimination does not react to and correct failures; it is entirely passive. Thus, intermittent failures, mistakenly created packet filters, or misrouted data is handled just the same as the equipment failures that are detected handled by typical routing and bridging protocols.

When combining member flows that take different-length paths through the network, and which are also guaranteed a worst-case latency by packet shaping, a merge point may require extra buffering to equalize the delays over the different paths. This equalization ensures that the resultant compound flow will not exceed its contracted bandwidth even after one or the other of the paths is restored after a failure.

4. DetNet Architecture

4.1. Traffic Engineering for DetNet

Traffic Engineering Architecture and Signaling (TEAS) [[TEAS](#)] defines traffic-engineering architectures for generic applicability across packet and non-packet networks. From TEAS perspective, Traffic

Engineering (TE) refers to techniques that enable operators to control how specific traffic flows are treated within their networks.

Because of its very nature of establishing pinned optimized paths, Deterministic Networking can be seen as a new, specialized branch of Traffic Engineering, and inherits its architecture with a separation into planes.

The Deterministic Networking architecture is thus composed of three planes, a (User) Application Plane, a Controller Plane, and a Network Plane, which echoes that of Figure 1 of Software-Defined Networking (SDN): Layers and Architecture Terminology [[RFC7426](#)].:

4.1.1. The Application Plane

Per [[RFC7426](#)], the Application Plane includes both applications and services. In particular, the Application Plane incorporates the User Agent, a specialized application that interacts with the end user / operator and performs requests for Deterministic Networking services via an abstract Flow Management Entity, (FME) which may or may not be collocated with (one of) the end systems.

At the Application Plane, a management interface enables the negotiation of flows between end systems. An abstraction of the flow called a Traffic Specification (TSpec) provides the representation. This abstraction is used to place a reservation over the (Northbound) Service Interface and within the Application plane. It is associated with an abstraction of location, such as IP addresses and DNS names, to identify the end systems and eventually specify intermediate relay nodes.

4.1.2. The Controller Plane

The Controller Plane corresponds to the aggregation of the Control and Management Planes in [[RFC7426](#)], though Common Control and Measurement Plane (CCAMP) [[CCAMP](#)] makes an additional distinction between management and measurement. When the logical separation of the Control, Measurement and other Management entities is not relevant, the term Controller Plane is used for simplicity to represent them all, and the term controller refers to any device operating in that plane, whether is it a Path Computation entity or a Network Management entity (NME). The Path Computation Element (PCE) [[PCE](#)] is a core element of a controller, in charge of computing Deterministic paths to be applied in the Network Plane.

A (Northbound) Service Interface enables applications in the Application Plane to communicate with the entities in the Controller Plane.

One or more PCE(s) collaborate to implement the requests from the FME as Per-Flow Per-Hop Behaviors installed in the relay nodes for each individual flow. The PCEs place each flow along a deterministic sequence of relay nodes so as to respect per-flow constraints such as security and latency, and optimize the overall result for metrics such as an abstract aggregated cost. The deterministic sequence can typically be more complex than a direct sequence and include redundancy path, with one or more packet replication and elimination points.

4.1.3. The Network Plane

The Network Plane represents the network devices and protocols as a whole, regardless of the Layer at which the network devices operate. It includes Forwarding Plane (data plane), Application, and Operational Plane (control plane) aspects.

The network Plane comprises the Network Interface Cards (NIC) in the end systems, which are typically IP hosts, and relay nodes, which are typically IP routers and switches. Network-to-Network Interfaces such as used for Traffic Engineering path reservation in [[RFC5921](#)], as well as User-to-Network Interfaces (UNI) such as provided by the Local Management Interface (LMI) between network and end systems, are both part of the Network Plane, both in the control plane and the data plane.

A Southbound (Network) Interface enables the entities in the Controller Plane to communicate with devices in the Network Plane. This interface leverages and extends TEAS to describe the physical topology and resources in the Network Plane.

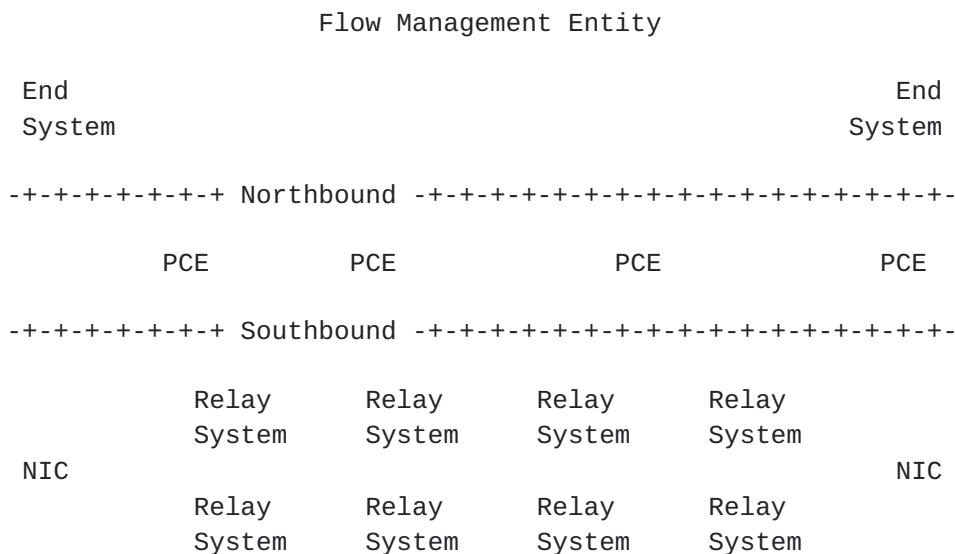


Figure 2

The relay nodes (and eventually the end systems NIC) expose their capabilities and physical resources to the controller (the PCE), and update the PCE with their dynamic perception of the topology, across the Southbound Interface. In return, the PCE(s) set the per-flow paths up, providing a Flow Characterization that is more tightly coupled to the relay node Operation than a TSpec.

At the Network plane, relay nodes may exchange information regarding the state of the paths, between adjacent systems and eventually with the end systems, and forward packets within constraints associated to each flow, or, when unable to do so, perform a last resort operation such as drop or declassify.

This specification focuses on the Southbound interface and the operation of the Network Plane.

4.2. DetNet flows

4.2.1. Source guarantees

DetNet flows can be synchronous or asynchronous. In synchronous DetNet flows, at least the relay nodes (and possibly the end systems) are closely time synchronized, typically to better than 1 microsecond. By transmitting packets from different DetNet flows or classes of DetNet flows at different times, using repeating schedules synchronized among the relay nodes, resources such as buffers and link bandwidth can be shared over the time domain among different DetNet flows. There is a tradeoff among techniques for synchronous

DetNet flows between the burden of fine-grained scheduling and the benefit of reducing the required resources, especially buffer space.

In contrast, asynchronous DetNet flows are not coordinated with a fine-grained schedule, so relay and end systems must assume worst-case interference among DetNet flows contending for buffer resources. Asynchronous DetNet flows are characterized by:

- o A maximum packet size;
- o An observation interval; and
- o A maximum number of transmissions during that observation interval.

These parameters, together with knowledge of the protocol stack used (and thus the size of the various headers added to a packet), limit the number of bit times per observation interval that the DetNet flow can occupy the physical medium.

The source promises that these limits will not be exceeded. If the source transmits less data than this limit allows, the unused resources such as link bandwidth can be made available by the system to non-DetNet packets. However, making those resources available to DetNet packets in other DetNet flows would serve no purpose. Those other DetNet flows have their own dedicated resources, on the assumption that all DetNet flows can use all of their resources over a long period of time.

Note that there is no provision in DetNet for throttling DetNet flows (reducing the transmission rate via feedback); the assumption is that a DetNet flow, to be useful, must be delivered in its entirety. That is, while any useful application is written to expect a certain number of lost packets, the real-time applications of interest to DetNet demand that the loss of data due to the network is extraordinarily infrequent.

Although DetNet strives to minimize the changes required of an application to allow it to shift from a special-purpose digital network to an Internet Protocol network, one fundamental shift in the behavior of network applications is impossible to avoid: the reservation of resources before the application starts. 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 unthrottled (though bandwidth limited) DetNet flows means that bridges and routers have to dedicate buffer resources to specific DetNet flows or to classes of DetNet flows. The requirements of each reservation have to be translated

into the parameters that control each system's queuing, shaping, and scheduling functions and delivered to the hosts, bridges, and routers.

4.2.2. Incomplete Networks

The presence in the network of relay nodes that are not fully capable of offering DetNet services complicates the ability of the relay nodes and/or controller to allocate resources, as extra buffering, and thus extra latency, must be allocated at points downstream from the non-DetNet relay node for a DetNet flow.

4.3. Queuing, Shaping, Scheduling, and Preemption

As described above, DetNet achieves its aims by reserving bandwidth and buffer resources at every hop along the path of the DetNet flow. The reservation itself is not sufficient, however. Implementors and users of a number of proprietary and standard real-time networks have found that standards for specific data plane techniques are required to enable these assurances to be made in a multi-vendor network. The fundamental reason is that latency variation in one system results in the need for extra buffer space in the next-hop system(s), which in turn, increases the worst-case per-hop latency.

Standard queuing and transmission selection algorithms allow a central controller to compute the latency contribution of each relay node to the end-to-end latency, to compute the amount of buffer space required in each relay node for each incremental DetNet flow, and most importantly, to translate from a flow specification to a set of values for the managed objects that control each relay or end system. The IEEE 802 has specified (and is specifying) a set of queuing, shaping, and scheduling algorithms that enable each relay node (bridge or router), and/or a central controller, to compute these values. These algorithms include:

- o A credit-based shaper [[IEEE802.1Q-2014](#)] Clause 34.
- o Time-gated queues governed by a rotating time schedule, synchronized among all relay nodes [[IEEE802.1Qbv](#)].
- o Synchronized double (or triple) buffers driven by synchronized time ticks. [[IEEE802.1Qch](#)].
- o Pre-emption of an Ethernet packet in transmission by a packet with a more stringent latency requirement, followed by the resumption of the preempted packet [[IEEE802.1Qbu](#)], [[IEEE802.3br](#)].

While these techniques are currently embedded in Ethernet and bridging standards, we can note that they are all, except perhaps for packet preemption, equally applicable to other media than Ethernet, and to routers as well as bridges.

4.4. Coexistence with normal traffic

A DetNet network supports the dedication of a high proportion (e.g. 75%) of the network bandwidth to DetNet flows. But, no matter how much is dedicated for DetNet flows, it is a goal of DetNet to coexist with existing Class of Service schemes (e.g., DiffServ). It is also important that non-DetNet traffic not disrupt the DetNet flow, of course (see [Section 4.5](#) and [Section 7](#)). For these reasons:

- o Bandwidth (transmission opportunities) not utilized by a DetNet flow are available to non-DetNet packets (though not to other DetNet flows).
- o DetNet flows can be shaped or scheduled, in order to ensure that the highest-priority non-DetNet packet also is ensured a worst-case latency (at any given hop).
- o When transmission opportunities for DetNet flows are scheduled in detail, then the algorithm constructing the schedule should leave sufficient opportunities for non-DetNet packets to satisfy the needs of the users of the network. Detailed scheduling can also permit the time-shared use of buffer resources by different DetNet flows.

Ideally, the net effect of the presence of DetNet flows in a network on the non-DetNet packets is primarily a reduction in the available bandwidth.

4.5. Fault Mitigation

One key to building robust real-time systems is to reduce the infinite variety of possible failures to a number that can be analyzed with reasonable confidence. DetNet aids in the process by providing filters and policers to detect DetNet packets received on the wrong interface, or at the wrong time, or in too great a volume, and to then take actions such as discarding the offending packet, shutting down the offending DetNet flow, or shutting down the offending interface.

It is also essential that filters and service remarking be employed at the network edge to prevent non-DetNet packets from being mistaken for DetNet packets, and thus impinging on the resources allocated to DetNet packets.

There exist techniques, at present and/or in various stages of standardization, that can perform these fault mitigation tasks that deliver a high probability that misbehaving systems will have zero impact on well-behaved DetNet flows, except of course, for the receiving interface(s) immediately downstream of the misbehaving device. Examples of such techniques include traffic policing functions (e.g. [RFC2475]) and separating flows into per-flow rate-limited queues.

4.6. Protocol Stack Model

Figure 3 illustrates the DetNet data plane layering model. One may compare it to that in [IEEE802.1CB], Annex C, a work in progress.

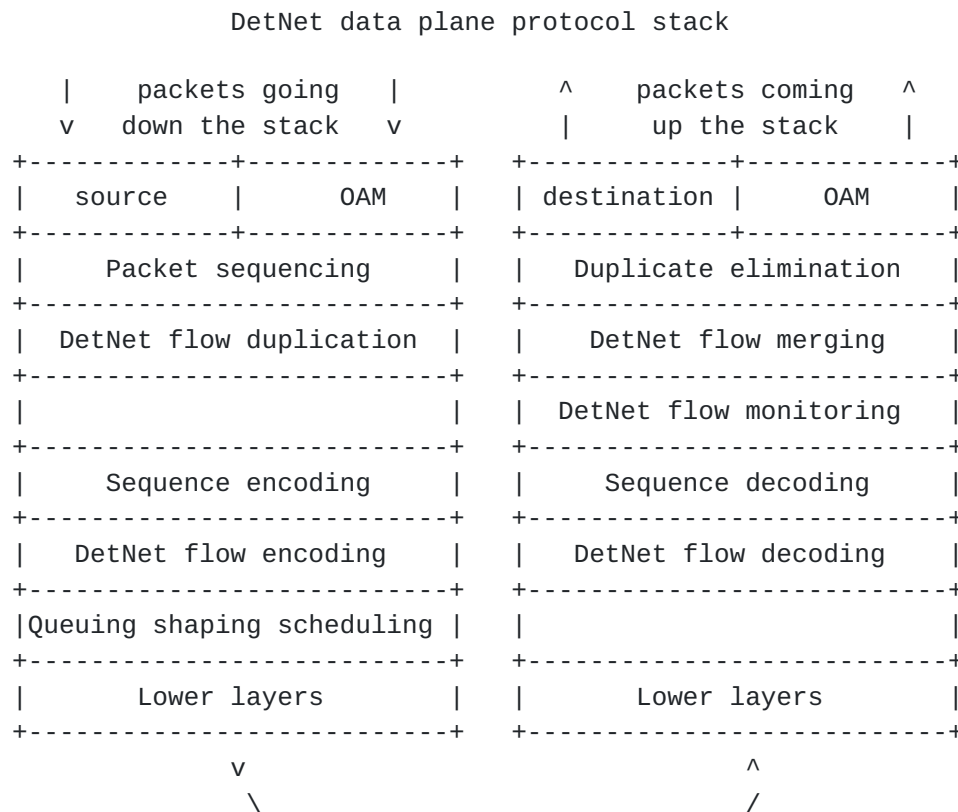


Figure 3

Not all layers are required for any given application, or even for any given network. The layers are, from top to bottom:

Application

Shown as "source" and "destination" in the diagram.

OAM

Operations, Administration, and Maintenance leverages in-band and out-of-band signaling that validates whether the service is effectively obtained within QoS constraints. It is shown in parallel with the user's application, OAM makes use of the same DetNet services. OAM can involve specific tagging added in the packets for tracing implementation or network configuration errors; traceability enables to find whether a packet is a replica, which node performed the replication, and which segment was intended for the replica.

Packet sequencing

Supplies the sequence number for packet replication and elimination ([Section 3.4](#)) for packets going down the stack. Peers with packet elimination. This layer is not needed if a higher-layer transport protocol is expected to perform any packet elimination required by the DetNet flow duplication.

Duplicate elimination

Based on the sequenced number supplied by its peer, packet sequencing, packet elimination discards any duplicate packets generated by DetNet flow duplication. The duplication may also be inferred from other information such as the precise time of reception in a scheduled network. The duplicate elimination layer may also perform resequencing of packets to restore packet order in a flow that was disrupted by the loss of packets on one or another of the multiple paths taken.

DetNet flow monitoring

Many DetNet applications, and particularly those in which multiple applications (e.g. different machine tools) are sharing the same network infrastructure, or even the same physical links, it is critical that a misbehaving DetNet flow does not interfere with the timely delivery of packets belonging to other DetNet flows. The DetNet flow monitoring layer monitors DetNet flows entering a DetNet node and enforces bandwidth and/or sequencing restrictions, taking appropriate action if a misbehaving flow is detected. See [Section 4.5](#). This function is shown in the stack at the point where it can operate on individual DetNet member flows before they are merged into a DetNet compound flow, but in fact, it may be present in different forms in multiple places in the stack to ensure against interference errors.

DetNet flow duplication

Replicates packets going down the stack, that belong to a DetNet compound flow, into two or more DetNet member flows. Note that this function is separate from packet sequencing. Flow duplication can be an explicit duplication and remarking

of packets, or can be performed by, for example, techniques similar to ordinary multicast replication. Peers with DetNet flow merging.

DetNet flow merging

Merges DetNet member flows together for packets coming up the stack belonging to a specific DetNet compound flow. Peers with DetNet flow duplication. DetNet flow merging, together with packet sequencing, duplicate elimination, DetNet flow duplication, and DetNet flow merging, performs packet replication and elimination ([Section 3.4](#)).

Sequence encoding

Encodes the sequence number into packets going down the stack. This function may or may not be a null transformation of the packet, and for some protocols, is not explicitly present, being included in the DetNet flow encoding layer, below. Peers with sequence decoding.

Sequence decoding

Extracts the sequence number from packets coming up the stack for use by the duplicate elimination layer. This function may or may not be a null transformation of the packet, and for some protocols, is not explicitly present, being included in the DetNet flow decoding layer, below. Peers with sequence encoding.

DetNet flow encoding

Encapsulates packets going down the stack, based on the packet's locally-significant DetNet flow identifier, in order to identify to which DetNet flow the packet belongs. This may be a null transformation or might be an explicit encapsulation (e.g., altering the VLAN and destination MAC address). DetNet flow identification is the basis for packet replication and elimination, for assigning per-flow resources (if any) to packets and for defense against misbehaving systems ([Section 4.5](#)). When DetNet flows are assigned to pinned paths, this layer can be indistinguishable from the data forwarding layer(s). Peers with DetNet flow decoding. See [Section 4.7](#) for an explanation of why DetNet flow encoding is not necessarily a part of normal packet transport.

DetNet flow decoding

Extracts a locally-significant DetNet flow identifier from packets coming up the stack, in order to identify to which DetNet flow the packet belongs. This may be a null transformation or might be an explicit decapsulation (e.g.,

altering the VLAN and destination MAC address). Peers with DetNet flow encoding. See also [Section 4.7](#).

Queuing shaping scheduling

This layer provides the latency and congestion loss parts of the DetNet QoS. See [Section 4.3](#). Note that additional shaping elements may be provided for DetNet edge nodes in order to precondition potentially malformed DetNet flows from a source end system.

The reader is likely to notice that Figure 3 does not specify the relationship between the DetNet layers, the IP layers, and the link layers. This is intentional, because they can usefully be placed different places in the stack, and even in multiple places, depending on where their peers are placed.

[4.7](#). Exporting flow identification

An interesting feature of DetNet, and one that invites implementations that can be accused of "layering violations", is the need for lower layers to be aware of specific flows at higher layers, in order to provide specific queuing and shaping services for specific flows. For example:

- o A non-IP, strictly L2 source end system X may be sending multiple flows to the same L2 destination end system Y. Those flows may include DetNet flows with different QoS requirements, and may include non-DetNet flows.
- o A router may be sending any number of flows to another router. Again, those flows may include DetNet flows with different QoS requirements, and may include non-DetNet flows.
- o Two routers may be separated by bridges. For these bridges to perform any required per-flow queuing and shaping, they must be able to identify the individual flows.
- o A Label Edge Router (LERs) may have a Label Switched Path (LSP) set up for handling traffic destined for a particular IP address carrying only non-DetNet flows. If a DetNet flow to that same address is requested, a separate LSP may be needed, in order that all of the Label Switch Routers (LSRs) along the path to the destination give that flow special queuing and shaping.

The need for a lower-level DetNet node to be aware of individual higher-layer flows is not unique to DetNet. But, given the endless complexity of layering and relayering over tunnels that is available to network designers, DetNet needs to provide a model for flow

identification that is at least somewhat better than deep packet inspection. That is not to say that deep inspection will not be used, or the capability standardized; but, there are alternatives.

The main alternative is the sequence encode/decode and, particularly, the DetNet flow encoding/decoding layers shown in Figure 3. In this model, at the time a DetNet flow is established and the resources for it reserved, an alternate encapsulation of the DetNet flow at the lower layer is requested and established. For example:

- o A single unicast DetNet flow passing from router A through a bridged network to router B may be assigned a {VLAN, multicast destination MAC address} pair that is unique within that bridged network. The bridges can then identify the flow without accessing higher-layer headers. Of course, the receiving router must recognize and accept that multicast MAC address.
- o A DetNet flow passing from LSR A to LSR B may be assigned a different label than that used for other flows to the same IP destination.

The DetNet flow encoding/decoding layers shown in Figure 3 perform the required alternate encapsulations. For example, one could place a DetNet flow encoding shim between the Address Resolution Protocol (ARP) layer and the MAC layer, which alters the {VLAN, MAC address} pair to identify particular streams going up and down the stack, so that the layers above the shim need no alteration to service DetNet flows.

In any of the above cases, it is possible that an existing DetNet flow can be used as a carrier for multiple DetNet sub-flows. (Not to be confused with DetNet compound vs. member flows.) Of course, this requires that the aggregate DetNet flow be provisioned properly to carry the sub-flows.

Thus, rather than deep packet inspection, there is the option to export higher-layer information to the lower layer. The requirement to support one or the other method for flow identification (or both) is the essential complexity that DetNet brings to existing control plane models.

4.8. Advertising resources, capabilities and adjacencies

There are three classes of information that a central controller or decentralized control plane needs to know that can only be obtained from the end systems and/or relay nodes in the network. When using a peer-to-peer control plane, some of this information may be required by a system's neighbors in the network.

- o Details of the system's capabilities that are required in order to accurately allocate that system's resources, as well as other systems' resources. This includes, for example, which specific queuing and shaping algorithms are implemented ([Section 4.3](#)), the number of buffers dedicated for DetNet allocation, and the worst-case forwarding delay.
- o The dynamic state of an end or relay node's DetNet resources.
- o The identity of the system's neighbors, and the characteristics of the link(s) between the systems, including the length (in nanoseconds) of the link(s).

[4.9.](#) Provisioning model

[4.9.1.](#) Centralized Path Computation and Installation

A centralized routing model, such as provided with a PCE ([RFC 4655](#) [[RFC4655](#)]), enables global and per-flow optimizations. (See [Section 4.1.](#)) 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.

[4.9.2.](#) Distributed Path Setup

Whether a distributed alternative without a PCE can be valuable should be studied as well. Such an alternative could for instance inherit from the Resource ReSerVation Protocol [[RFC3209](#)] (RSVP-TE) flows.

In a Layer-2 only environment, or as part of a layered approach to a mixed environment, IEEE 802.1 also has work, either completed or in progress. [[IEEE802.1Q-2014](#)] Clause 35 describes SRP, a peer-to-peer protocol for Layer-2 roughly analogous to RSVP [[RFC2205](#)]. Almost complete is [[IEEE802.1Qca](#)], which defines how ISIS can provide multiple disjoint paths or distribution trees. Also in progress is [[IEEE802.1Qcc](#)], which expands the capabilities of SRP.

The integration/interaction of the DetNet control layer with an underlying IEEE 802.1 sub-network control layer will need to be defined.

4.10. Scaling to larger networks

Reservations for individual DetNet flows require considerable state information in each relay node, especially when adequate fault mitigation ([Section 4.5](#)) is required. The DetNet data plane, in order to support larger numbers of DetNet flows, must support the aggregation of DetNet flows into tunnels, which themselves can be viewed by the relay nodes' data planes largely as individual DetNet flows. Without such aggregation, the per-relay system may limit the scale of DetNet networks.

4.11. Connected islands vs. networks

Given that users have deployed examples of the IEEE 802.1 TSN TG standards, which provide capabilities similar to DetNet, it is obvious to ask whether the IETF DetNet effort can be limited to providing Layer-2 connections (VPNs) between islands of bridged TSN networks. While this capability is certainly useful to some applications, and must not be precluded by DetNet, tunneling alone is not a sufficient goal for the DetNet WG. As shown in the Deterministic Networking Use Cases draft [[I-D.ietf-detnet-use-cases](#)], there are already deployments of Layer-2 TSN networks that are encountering the well-known problems of over-large broadcast domains. Routed solutions, and combinations routed/bridged solutions, are both required.

5. Compatibility with Layer-2

Standards providing similar capabilities for bridged networks (only) have been and are being generated in the IEEE 802 LAN/MAN Standards Committee. The present architecture describes an abstract model that can be applicable both at Layer-2 and Layer-3, and over links not defined by IEEE 802. It is the intention of the authors (and hopefully, as this draft progresses, of the DetNet Working Group) that IETF and IEEE 802 will coordinate their work, via the participation of common individuals, liaisons, and other means, to maximize the compatibility of their outputs.

DetNet enabled systems and nodes can be interconnected by sub-networks, i.e., Layer-2 technologies. These sub-networks will provide DetNet compatible service for support of DetNet traffic. Examples of sub-networks include 802.1TSN and a point-to-point OTN link. Of course, multi-layer DetNet systems may be possible too, where one DetNet appears as a sub-network, and provides service to, a higher layer DetNet system.

6. Open Questions

There are a number of architectural questions that will have to be resolved before this document can be submitted for publication. Aside from the obvious fact that this present draft is subject to change, there are specific questions to which the authors wish to direct the readers' attention.

6.1. Data plane shapers and schedulers

A number of techniques have been defined and are being defined by IEEE 802 for queuing, shaping, and scheduling transmissions on Ethernet media, most of which are directly applicable to any other medium. Specific selections of supported techniques are required, because minimizing, and even eliminating, congestion losses depends strongly on the details of the per-hop behavior of sources and relay nodes.

The present authors expect that, at least, the IEEE 802 mechanisms will be supported.

6.2. DetNet flow identification and sequencing

The techniques to be used for DetNet flow identification must be settled. The following paragraphs provide a snapshot of the authors' opinions at the time of writing. These authors anticipate the submission of drafts on this subject. See also [Section 4.7](#)

IEEE 802.1 TSN streams are identified by giving each stream (DetNet flow) a {VLAN identifier, destination MAC address} pair that is unique in the bridged network, and that the MAC address must be a multicast address. If a source is generating, for example, two unicast UDP flows to the same destination, one DetNet and one not, the DetNet flow's packets must be transformed at some point to have a multicast destination MAC address, and perhaps, a different VLAN than the non-DetNet flow's packets.

A similar provision would apply to DetNet packets that are identified by MPLS labels; any bridges between the LSRs need a {VLAN identifier, destination MAC address} pair uniquely identifying the DetNet flow in the bridged network.

Provision is made in current draft of [[IEEE802.1CB](#)] to make these transformations either in a Layer-2 shim in the source end system, on the output side of a router or LSR, or in a proxy function in the first-hop bridge. It remains to be seen whether this provision is adequate and/or acceptable to the IETF DetNet WG.

There are also questions regarding the sequentialization of packets for use with packet replication and elimination ([Section 3.4](#)). [\[IEEE802.1CB\]](#) defines an Ethernet tag carrying a sequence number. If MPLS Pseudowires are used with a control word containing a sequence number, the relationship and interworking between these two formats must be defined.

6.3. Flat vs. hierarchical control

Boxes that are solely routers or solely bridges are rare in today's market. In a multi-tenant data center, multiple users' virtual Layer-2/Layer-3 topologies exist simultaneously, implemented on a network whose physical topology bears only accidental resemblance to the virtual topologies.

While the forwarding topology (the bridges and routers) are an important consideration for a DetNet Flow Management Entity ([Section 4.1.1](#)), so is the purely physical topology. Ultimately, the model used by the management entities is based on boxes, queues, and links. The authors hope that the work of the TEAS WG will help to clarify exactly what model parameters need to be traded between the relay nodes and the controller(s).

6.4. Peer-to-peer reservation protocol

As described in [Section 4.9.2](#), the DetNet WG needs to decide whether to support a peer-to-peer protocol for a source and a destination to reserve resources for a DetNet stream. Assuming that enabling the involvement of the source and/or destination is desirable (see Deterministic Networking Use Cases [\[I-D.ietf-detnet-use-cases\]](#)), it remains to decide whether the DetNet WG will make it possible to deploy at least some DetNet capabilities in a network using only a peer-to-peer protocol, without a central controller.

(Note that a UNI (see [Section 4.1.3](#)) between an end system and an edge relay node, for sources and/or listeners to request DetNet services, can be either the first hop of a per-to-peer reservation protocol, or can be deflected by the edge relay node to a central controller for resolution. Similarly, a decision by a central controller can be effected by the controller instructing the end system or edge relay node to initiate a per-to-peer protocol activity.)

6.5. Wireless media interactions

Deterministic Networking Use Cases [\[I-D.ietf-detnet-use-cases\]](#) illustrates cases where wireless media are needed in a DetNet network. Some wireless media in general use, such as IEEE 802.11

[[IEEE802.1Q-2014](#)], have significantly higher packet loss rates than typical wired media, such as Ethernet [[IEEE802.3-2012](#)]. IEEE 802.11 includes support for such features as MAC-layer acknowledgements and retransmissions.

The techniques described in [Section 3](#) are likely to improve the ability of a mixed wired/wireless network to offer the DetNet QoS features. The interaction of these techniques with the features of specific wireless media, although they may be significant, cannot be addressed in this document. It remains to be decided to what extent the DetNet WG will address them, and to what extent other WGs, e.g. 6TiSCH, will do so.

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.

Furthermore, in a control system where millions of dollars of equipment, or even human lives, can be lost if the DetNet QoS is not delivered, one must consider not only simple equipment failures, where the box or wire instantly becomes perfectly silent, but bizarre errors such as can be caused by software failures. Because there is essential no limit to the kinds of failures that can occur, protecting against realistic equipment failures is indistinguishable, in most cases, from protecting against malicious behavior, whether accidental or intentional. See also [Section 4.5](#).

Security must cover:

- o the protection of the signaling protocol
- o the authentication and authorization of the controlling systems
- o the identification and shaping of the DetNet flows

8. Privacy Considerations

DetNet is provides a Quality of Service (QoS), and as such, does not directly raise any new privacy considerations.

However, the requirement for every (or almost every) node along the path of a DetNet flow to identify DetNet flows may present an

additional attack surface for privacy, should the DetNet paradigm be found useful in broader environments.

9. IANA Considerations

This document does not require an action from IANA.

10. Acknowledgements

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11. Access to IEEE 802.1 documents

To access password protected IEEE 802.1 drafts, see the IETF IEEE 802.1 information page at <https://www.ietf.org/proceedings/52/slides/bridge-0/tsld003.htm>.

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