

DETNET WG  
Internet-Draft  
Intended status: Informational  
Expires: May 4, 2017

CJ. Bernardos  
A. de la Oliva  
UC3M  
L. Cominardi  
InterDigital  
LM. Contreras  
TID  
October 31, 2016

DETNET crosshauling requirements  
draft-bernardos-detnet-crosshaul-requirements-00

Abstract

Future 5G networks will not make a clear distinction between fronthaul and backhaul transport networks, because varying portions of radio access network functionality might be moved toward the network as required for cost reduction and performance increase. This will pose additional challenges on the transport network, driving for a new design of integrated fronthaul and backhaul, usually referred to as crosshaul.

This document present the crosshaul architecture framework being developed by the EU 5G-Crosshaul project, as well as identifies several key requirements for the transport network, with the goal of fostering discussion at the DETNET WG.

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## 1. Introduction

According to recent predictions, mobile data traffic will increase 11-fold between 2013 and 2018. Fifth generation (5G) radio access network (RAN) technologies serving this mobile data tsunami will require fronthaul and backhaul solutions between the RAN and packet core to deal with this increased traffic load. Furthermore, there will be a sizeable growth in the capillarity of the network since traffic load increase in the 5G RAN is expected to stem from an increased number of base stations with reduced coverage (i.e., mobile network densification). To support the increased density of the mobile network (e.g., in terms of interference coordination) and achieve the required 5G capacity, extensive support for novel air interface technologies such as cooperative multipoint (CoMP), carrier aggregation (CA), and massive multiple-input multiple-output (MIMO) will be needed. Such technologies require processing of information from multiple base stations simultaneously at a common centralized

entity and also tight synchronization of different radio sites. Hence, backhaul and fronthaul will have to meet more stringent requirements not only in terms of data rate but also in terms of latency, jitter, and bit error rate.

In this upcoming 5G network environment, the distinction between fronthaul and backhaul transport networks will blur as varying portions of functionality of 5G points of attachment might be moved toward the network as required for cost efficiency reasons. The traditional capacity over provisioning approach on the transport infrastructure will no longer be possible with 5G. Hence, a new generation of integrated fronthaul and backhaul technologies will be needed to bring capital expenditure (CAPEX) and operational expenditure (OPEX) to a reasonable return on investment (ROI) range. Current transport networks cannot cope with the amount of bandwidth required for 5G. Next generation radio interfaces, using 100 MHz channels and squeezing the bit-per-megahertz ratio through massive MIMO or even full duplex radios, requires a 10-fold increase in capacity on the integrated fronthaul and backhaul (crosshaul) segment, which cannot be achieved just through the evolution of current technologies [crosshaul\_magazine].

Current trend is moving towards defining an integrated fronthaul and backhaul into a common packet-based network, as supported by the works working towards the definition of a Next Generation Fronthaul Interface (NGFI, IEEE 1914), the packetization and encapsulation on Ethernet frames of this newly interface (IEEE 1914.1) or the extensions to bridging for Time Sensitive Networking (IEEE 802.1TSN) and their profiling for frontal traffic (IEEE 802.1CM). The design of the crosshaul poses new challenges that need to be tackled. Different project and initiatives are looking at the design of the crosshaul, among which we present here the one by the 5G-Crosshaul EU project (summarized in Section 3). [I-D.ietf-detnet-use-cases] introduces and describes several use cases for DETNET. While there are some documents analyzing DETNET requirements for backhaul and fronthaul, such as [I-D.huang-detnet-xhaul], in this document (Section 4) we derive identify some requirements relevant for the DETNET WG posed by the 5G-Crosshaul design.

## 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].

While [RFC2119] describes interpretations of these key words in terms of protocol specifications and implementations, they are used in this

document to describe requirements for DETNET mechanisms regarding support for integrated backhaul and crosshaul.

The following terms are used in this document:

**Backhaul:** the network or links between radio base station sites (or digital units) and network controller/gateway sites.

**Common Public Radio Interface (CPRI):** industry cooperation aimed at defining a publicly available specification for the key internal interface of radio base stations between the Radio Equipment Control (REC) and the Radio Equipment (RE), which are the two basic building blocks into which a radio base station can be decomposed in order to provide flexible radio base station system architectures for mobile networks.

**Fronthaul:** the connection from a radio base station site (or digital unit) to a remote radio unit. The fronthaul is therefore the transport connection between the functional building blocks of a cellular radio base station. The fronthaul has traditionally been implemented with point-to-point connections based on the Common Public Radio Interface (CPRI) standard.

**In-Phase and Quadrature (IQ):** User plane data between the REC and RE is transported in the form of one or many In-Phase and Quadrature (IQ) data flows. Each IQ data flow reflects the radio signal, sampled and digitised of one carrier at one independent antenna element, the so-called Antenna Carrier (AxC).

### 3. 5G-Crosshaul architecture

The 5G-Crosshaul project is developing an architecture for the next generation of 5G integrated backhaul and fronthaul networks enabling a flexible and software-defined reconfiguration of all networking elements in a multi-tenant and service-oriented unified management environment. The envisioned crosshaul transport network will consist of high-capacity switches and heterogeneous transmission links (e.g., fiber or wireless optics, high-capacity copper, or millimeter-wave) interconnecting remote radio heads, 5G wireless points of attachment (e.g., macro and small cells), pooled-processing units (mini data centers), and points of presence (PoPs) of the core networks of one or multiple service providers.

The 5G-Crosshaul architecture is based on a novel unified data plane protocol able to transport both backhaul and fronthaul traffic, regardless of the functional RAN split. Major challenges for such a protocol are the big amount of data to handle, the synchronization of user data, and reflection of the channel structure of RAN protocols.

A unified data plane is adopted, supporting future RAN evolutions (as they may happen on shorter timescales than transport network upgrades). This new data plane allows CPRI data to be transported in a packetized form over the unified crosshaul data plane.

5G-Crosshaul is also developing a unified control and management plane (network model and interface primitives) to simplify network operations across heterogeneous technologies. Co-existence with legacy infrastructure and support for smooth migration are considered as key requirements for operators.

Three main novel building blocks are considered in 5G-Crosshaul

- o A control infrastructure using a unified, abstract network model for control plane integration (Crosshaul Control Infrastructure, XCI). The XCI is based on existing software defined network (SDN) controllers, to provide the services for novel northbound and southbound interfaces (NBI and SBI), and enable multi-tenancy support in trusted environments. A key aspect of the XCI is the development of new mechanisms to abstract the mobile transport network and aggregate measured contextual information.
- o A unified data plane encompassing innovative high-capacity transmission technologies and novel latency-deterministic switch architectures (Crosshaul Forwarding Element, XFE). This element is the central part of the Xhaul infrastructure, integrating the different physical technologies used for fronthaul and backhaul through a common data frame and forwarding behavior. Developing a flexible frame format is a key aspect of fronthaul/backhaul integration, allowing the transport of fronthaul/backhaul traffic on the same physical link, replacing different technologies by a uniform transport technology for both network segments.
- o A set of computing capabilities distributed across the network (Crosshaul Processing Units, XPU).

5G-Crosshaul follows a unique approach towards the integration of the different network segments (fronthaul and backhaul) into a common transport stratum. In order to integrate the different nature of the fronthaul and backhaul traffic (with their very disparate requirements) and the different technologies that can be used to transport them, a new common transport framing format is defined (the XCF, Crosshaul Common Frame) which is used to perform the forwarding within the Crosshaul. This XCF is based on MAC-in-MAC Ethernet, and all traffic going into a Crosshaul area is adapted to this frame format. In this way, 5G-Crosshaul can leverage all the work performed in IEEE 802.1 (IEEE 802.1TSN and IEEE802.1CM) to transport flows with stringent delay requirements in Ethernet-based networks.

### 3.1. Data plane architecture

Essentially, the XFE is modeled as a modular multi-layer switch, that can support single or multiple link technologies (mmWave, microwave, Ethernet, copper, fiber, etc.). The XFE is mainly made up of a packet switch (5GCrosshaul Packet Forwarding Element, XPFE) and a circuit switch (5G-Crosshaul Circuit Switching Element, XCSE). The packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit switching path is there to complement the packet switching path for those particular traffic profiles that are not suited for packet-based transporting (e.g., legacy CPRI or traffic with extremely low delay tolerance) or just for capacity offloading. The packet switch is controlled by a unified Common Frame (XCF). The circuit switch can have an optical cross-connection component (based on wavelength selective switches) and a TDM part, based on OTN, a new cost effective approach for deterministic delay switching. Note that in this draft we focus on the packet switch only.

MAC-in-MAC has been chosen as the frame format for transporting backhaul and fronthaul traffic within 5G-Crosshaul. Provider Backbone Bridges belongs to IEEE Std 802.1Q and is a set of architecture and protocols for switching over a provider's network, allowing interconnection of multiple Provider Bridge Networks without losing each customer's individually defined VLANs.

## 4. Crosshaul requirements

In this section we enumerate the main requirements for the XCF packet technology (i.e., transport data plane architecture). Additional details will be provided in subsequent revisions of this document.

We start listing below the main functional (qualitative) requirements:

- o Support multiple functional splits simultaneously,
  - \* Including Backhaul and CPRI-like Fronthaul.
- o Multi-tenancy.
  - \* Isolate traffic (guaranteed QoS).
  - \* Separate traffic (tenant privacy).
  - \* Differentiation of forwarding behavior.
  - \* Multiplexing gain.

- \* Tenant ID (identification of tenants' traffic).
- o Coexistence, Compatibility.
  - \* Ethernet (same switching equipment, for example different ports, etc.).
  - \* Security support.
  - \* Synchronization: IEEE1588, IEEE802.1AS.
- o Transport efficiency.
  - \* Short overhead.
  - \* Multi-path support.
  - \* Flow differentiation.
  - \* Class of Service Differentiation.
- o Management.
  - \* In band control traffic (OAM info, ...).
- o Energy efficiency.
  - \* Energy usage proportional to handled traffic (e.g., sleep mode, reduced rate).
- o Support of multiple data link technologies.
  - \* IEEE 802.3, 802.11 (including mmWave), etc.
- o No vendor lock-in.

In addition to the qualitative requirements, there are performance/quantitative requirements:

- o Latency: the maximum end-to-end latency for IQ data between REC and RE MUST be 100 us, including the propagation delay of the links between the devices, internal delays of the devices such as Bridges. For Control and Management (C&M) there is no latency requirement.
- o Frame loss ratio (FLR): can be caused by bit error, network congestion, failures, etc. Late delivery can also imply frame

loss for CPRI data. It MUST be less than  $10E-7$ . For C&M the FLR MUST be less than  $10E-6$ .

- o Synchronization. Depending on the type of radio access technology the requirements are different:
  - \* The maximum absolute time error SHOULD be less than 10ns for intra-band contiguous carrier aggregation radio access technologies.
  - \* The maximum absolute time error MUST be less than 45ns for Multiple-Input and Multiple-Output (MIMO) and transmit diversity radio access technologies.
  - \* The maximum absolute time error MUST be less than 110ns for intra-band non-contiguous and inter-band carrier aggregation radio access technologies.
  - \* The maximum absolute time error MUST be less than 110ns for time division duplex radio access technologies.

## 5. Summary

This document presents a specific solution for the integration of fronthaul and backhaul (being carried out within the framework of the 5G-Crosshaul project), to then derive some key requirements for the discussion and consideration of the DETNET WG.

## 6. IANA Considerations

N/A.

## 7. Security Considerations

TBD.

## 8. Acknowledgments

The authors would like to thank Akbar Rahman for his review of the document.

This work is partially supported by the EU H2020 5G-Crosshaul Project (grant no. 671598).



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### Authors' Addresses

Carlos J. Bernardos  
Universidad Carlos III de Madrid  
Av. Universidad, 30  
Leganes, Madrid 28911  
Spain

Phone: +34 91624 6236  
Email: [cjbc@it.uc3m.es](mailto:cjbc@it.uc3m.es)  
URI: <http://www.it.uc3m.es/cjbc/>

Antonio de la Oliva  
Universidad Carlos III de Madrid  
Av. Universidad, 30  
Leganes, Madrid 28911  
Spain

Phone: +34 91624 8803  
Email: aoliva@it.uc3m.es  
URI: <http://www.it.uc3m.es/aoliva/>

Luca Cominardi  
InterDigital Europe

Email: [Luca.Cominardi@InterDigital.com](mailto:Luca.Cominardi@InterDigital.com)  
URI: <http://www.InterDigital.com/>

Luis M. Contreras  
Telefonica I+D  
Ronda de la Comunicacion, S/N  
Madrid 28050  
Spain

Email: [luismiguel.contrerasmurillo@telefonica.com](mailto:luismiguel.contrerasmurillo@telefonica.com)

DetNet  
Internet-Draft  
Intended status: Informational  
Expires: March 24, 2017

J. Korhonen, Ed.  
Broadcom  
J. Farkas  
G. Mirsky  
Ericsson  
P. Thubert  
Cisco  
Y. Zhuang  
Huawei  
L. Berger  
LabN  
September 20, 2016

DetNet Data Plane Protocol and Solution Alternatives  
draft-ietf-detnet-dp-alt-00

Abstract

This document identifies existing IP and MPLS, and other encapsulations that run over IP and/or MPLS data plane technologies that can be considered as the base line solution for deterministic networking data plane definition.

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## 1. Introduction

Deterministic Networking (DetNet) [I-D.ietf-detnet-problem-statement] provides a capability to carry unicast or multicast data flows for real-time applications with extremely low data loss rates, timely delivery and bounded packet delay variation [I-D.finn-detnet-architecture]. The deterministic networking Quality of Service (QoS) is expressed as 1) the minimum and the maximum end-to-end latency from source (talker) to destination (listener), and 2) probability of loss of a packet. Only the worst-case values for the mentioned parameters are concerned.

There are three techniques to achieve the QoS required by deterministic networks:

- o Congestion protection,
- o explicit routes,
- o service protection.

This document identifies existing IP and Multiprotocol Label Switching (MPLS) [RFC3031], layer-2 or layer-3 encapsulations and transport protocols that could be considered as foundations for a deterministic networking data plane. The full scope of the deterministic networking data plane solution is considered including, as appropriate: quality of service (QoS); Operations, Administration and Maintenance (OAM); and time synchronization among other criteria described in Section 4.

This document does not select a deterministic networking data plane protocol. It does, however, elaborate what it would require to adapt and use a specific protocol as the deterministic networking data plane solution. This document is only concerned with data plane considerations and, specifically, with topics that potentially impact potential deterministic networking aware data plane hardware. Control plane considerations are out of scope of this document.

## 2. Terminology

This document uses the terminology established in the DetNet architecture [I-D.finn-detnet-architecture].

## 3. DetNet Data Plane Overview

A "Deterministic Network" will be composed of DetNet enabled nodes i.e., End Systems, Edge Nodes, Relay Nodes and collectively deliver DetNet services. DetNet enabled nodes are interconnected via Transit Nodes (i.e., routers) which support DetNet, but are not DetNet service aware. Transit nodes see DetNet nodes as end points. All

DetNet enabled nodes are connect to sub-networks, where a point-to-point link is also considered as a simple sub-network. These sub-networks will provide DetNet compatible service for support of DetNet traffic. Examples of sub-networks include IEEE 802.1TSN and OTN. Of course, multi-layer DetNet systems may also be possible, where one DetNet appears as a sub-network, and provides service to, a higher layer DetNet system. A simple DetNet concept network is shown in Figure 1.

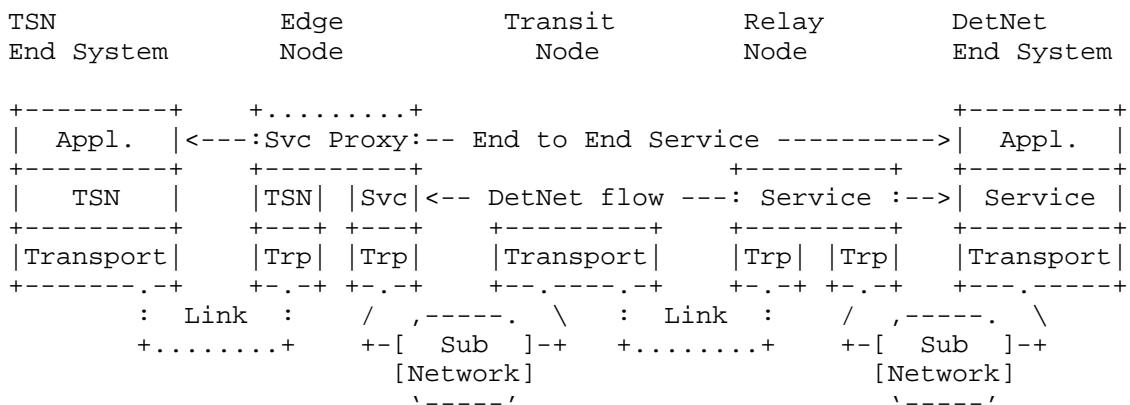


Figure 1: A Simple DetNet Enabled Network

The DetNet data plane is logically divided into two layers (also see Figure 2):

DetNet Service Layer

The DetNet service layer provides adaptation of DetNet services. It is composed of a shim layer to carry deterministic flow specific attributes, which are needed during forwarding and for service protection. DetNet enabled end systems originate and terminate the DetNet Service layer and are peers at the DetNet Service layer. DetNet relay and edge nodes also implement DetNet Service layer functions. The DetNet service layer is used to deliver traffic end to end across a DetNet domain.

DetNet Transport Layer

The DetNet transport layer is required on all DetNet nodes. All DetNet nodes are end points at the transport layer. Non-DetNet service aware transit nodes deliver traffic between DetNet nodes. The DetNet transport layer operates below and supports the DetNet

Service layer and optionally provides congestion protection for DetNet flows.

Distinguishing the function of these two DetNet data plane layers helps to explore and evaluate various combinations of the data plane solutions available. This separation of DetNet layers, while helpful, should not be considered as formal requirement. For example, some technologies may violate these strict layers and still be able to deliver a DetNet service.

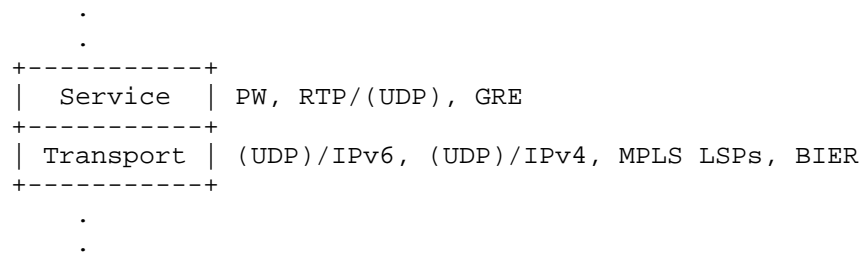


Figure 2: DetNet adaptation to data plane

The two logical layers defined here aim to help to identify which data plane technology can be used for what purposes in the DetNet context. This layering is similar to the data plane concept of MPLS, where some part of the label stack is "Service" specific (e.g., PW labels, VPN labels) and an other part is "Transport" specific (e.g, LSP label, TE label(s)).

In some networking scenarios, the end system initially provides a DetNet flow encapsulation, which contains all information needed by DetNet nodes (e.g., Real-time Transport Protocol (RTP) [RFC3550] based DetNet flow transported over a native UDP/IP network or PseudoWire). In other scenarios, the encapsulation formats might differ significantly. As an example, a CPRI "application's" I/Q data mapped directly to Ethernet frames may have to be transported over an MPLS-based packet switched network (PSN).

There are many valid options to create a data plane solution for DetNet traffic by selecting a technology approach for the DetNet Service layer and also selecting a technology approach for the DetNet Transport layer. There are a high number of valid combinations. Therefore, not the combinations but the different technologies are evaluated along the criteria collected in Section 4. Different criteria apply for the DetNet Service layer and the DetNet Transport layer, however, some of the criteria are valid for both layers.

One of the most fundamental differences between different potential data plane options is the basic addressing and headers used by DetNet end systems. For example, is the basic service a Layer 2 (e.g., Ethernet) or Layer 3 (i.e., IP) service. This decision impacts how DetNet end systems are addressed, and the basic forwarding logic for the DetNet Service layer.

### 3.1. Example DetNet Service Scenarios

In an attempt to illustrate a DetNet data plane, this document uses the Multi-Segment Pseudowire Emulation Edge-to-Edge (PWE3) [RFC5254] reference model shown in Figure 3 as the foundation for different DetNet data plane deployment options and how layering could work. Other reference models are possible but not covered in this document. Note that other technologies can be also used to implement DetNet, Multi-Segment PW is only used here to illustrate functions, features and layering from the perspective of the architecture.

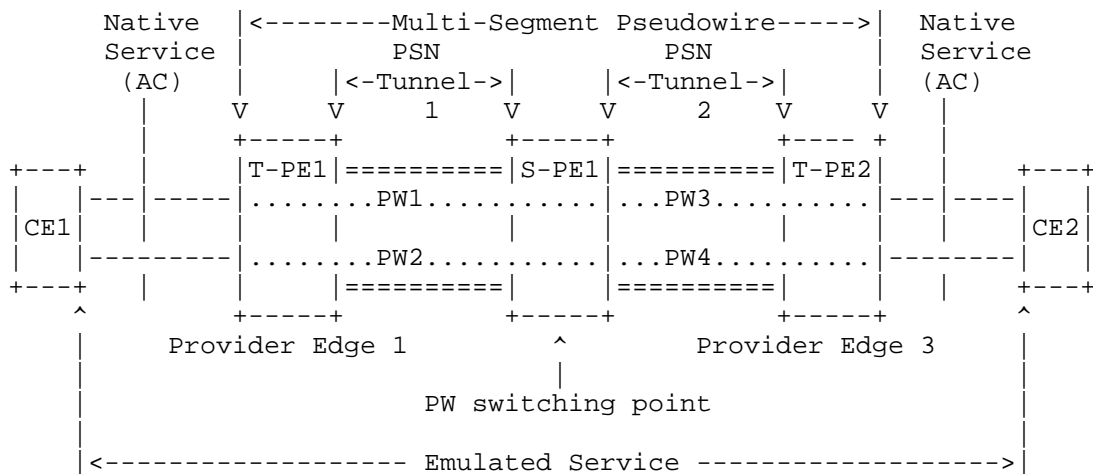


Figure 3: Pseudo Wire switching reference model

Figure 4 illustrates how DetNet can provide services for IEEE 802.1TSN end systems over a DetNet enabled network. The edge nodes insert and remove required DetNet data plane encapsulation. The 'X' in the edge and relay nodes represents a potential DetNet flow packet replication and elimination point. This conceptually parallels L2VPN services, and could leverage existing related solutions as discussed below.



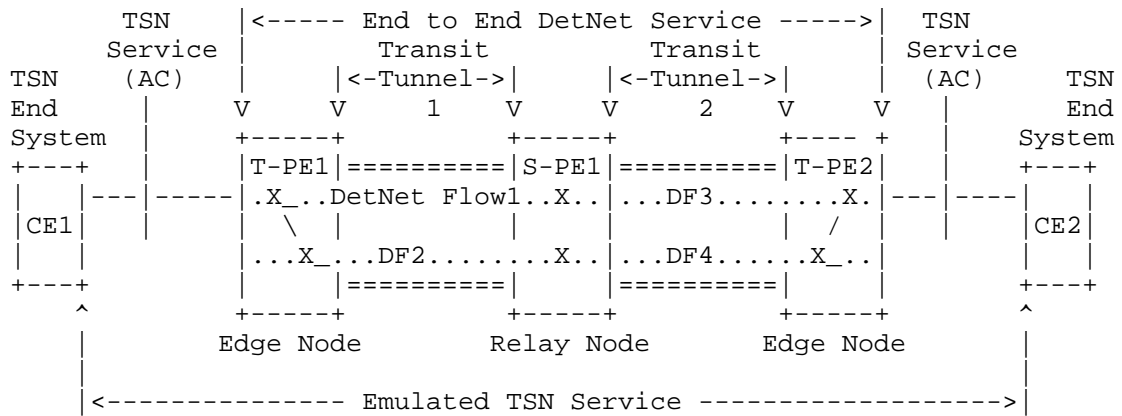


Figure 4: IEEE 802.1TSN over DetNet

Figure 5 illustrates how end to end native DetNet service can be provided. In this case, the end systems are able to send and receive native DetNet flows. For example, as PseudoWire (PW) encapsulated IP. Like earlier the 'X' in the end systems, edge and relay nodes represents potential DetNet flow packet replication and elimination points. Here the relay nodes may change the underlying transport, for example replacing IP with MPLS or tunneling IP over MPLS (e.g., via L3VPNs), or simply interconnect network domains.

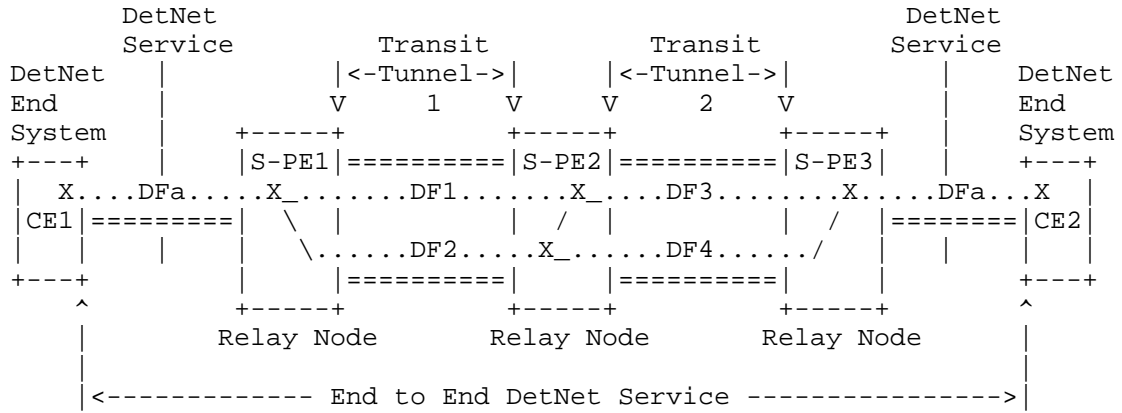


Figure 5: Native DetNet

Figure 6 illustrates how a IEEE 802.1TSN end system could communicate with a native DetNet end system through an edge node which provides a TSN to DetNet inter-working capability. The edge node would add and remove required DetNet data plane encapsulation as well as provide any needed address mapping. As in previous figures, the 'X' in the

end systems, edge and relay nodes represents potential DetNet flow packet duplication and elimination points.

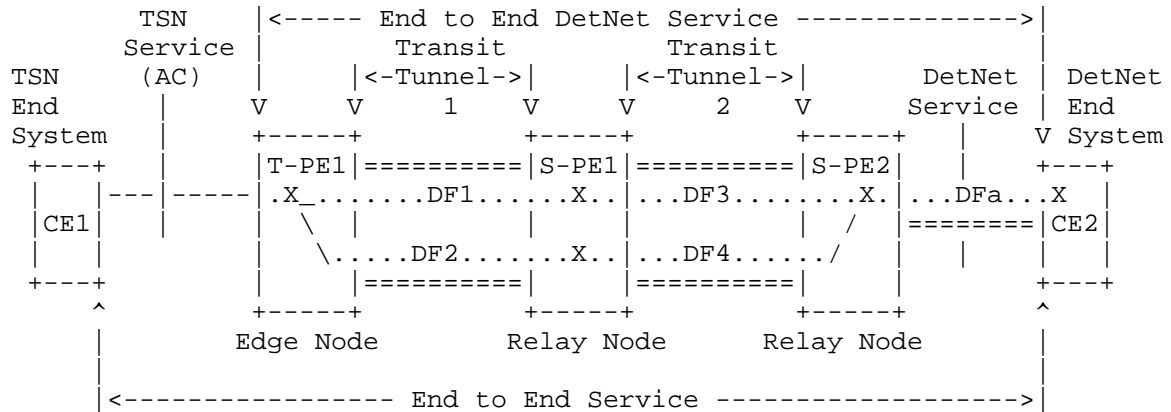


Figure 6: IEEE 802.1TSN to native DetNet

#### 4. Criteria for data plane solution alternatives

This section provides criteria to help to evaluate potential options. Each deterministic networking data plane solution alternative is described and evaluated using the criteria described in this section. The used criteria enumerated in this section are selected so that they highlight the existence or lack of features that are expected or seen important to a solution alternative for the data plane solution.

The criteria for the DetNet Service layer:

- #1 Encapsulation and overhead
- #2 Flow identification (Service ID part of the DetNet flows)
- #3 Packet sequencing and duplicate elimination
- #5 Flow duplication and merging
- #6 Operations, Administration and Maintenance (capabilities)
- #8 Class and quality of service capabilities (DetNet Service specific)
- #10 Technical maturity

The criteria for the DetNet Transport layer:

- #1 Encapsulation and overhead
- #2 Flow identification
- #4 Explicit routes (network path)
- #5 Flow duplication and merging (sometimes, flow duplication and merging is also doable at the transport layer, not just at the service layer)

- #6 Operations, Administration and Maintenance (capabilities, performance management, packet traceability)
- #8 Class and quality of service capabilities (DetNet Transport specific)
- #9 Packet traceability (can be part of OAM)
- #10 Technical maturity

[Editor's Note: numbering is off because #7 is removed.]

[Editor's Note: #9 should(?) be integrated into #6.]

Most of the criteria is relevant for both the DetNet Service and DetNet Transport layers. However, different aspects of the same criteria may be relevant for different layers, for example, as it is the case with criteria #5 Packet replication and elimination.

#### 4.1. #1 Encapsulation and overhead

Encapsulation and overhead is related to how the DetNet data plane carries DetNet flow. In several cases a DetNet flow has to be encapsulated inside other protocols, for example, when transporting a layer-2 Ethernet frame over an IP transport network. In some cases a tunneling like encapsulation can be avoided by underlying transport protocol translation, for example, translating layer-2 Ethernet frame including addressing and flow identification into native IP traffic. Last it is possible that sources and destinations handle deterministic flows natively in layer-3. This criteria concerns what is the encapsulation method the solution alternative support: tunneling like encapsulation, protocol translation or native layer-3 transport. In addition to the encapsulation mechanism this criteria is also concerned with the processing and specifically the encapsulation header overhead.

#### 4.2. #2 Flow identification

The solution alternative has to provide means to identify specific deterministic flows. The flow identification can, for example, be an explicit field in the data plane encapsulation header or implicitly encoded into the addressing scheme of the used data plane protocol or their combination. This criteria concerns the availability and details of deterministic flow identification the data plane protocol alternative has.

#### 4.3. #3 Packet sequencing and duplicate elimination

The solution alternative has to provide means for end systems to number packets sequentially and transport that sequencing information along with the sent packets. In addition to possible reordering of

packets other important uses for sequencing are detecting duplicates and lost packets.

In a case of intentional packet duplication a combination of flow identification and packet sequencing allows for detecting and eliminating duplicates at the destination (see Section 4.5 for more details).

#### 4.4. #4 Explicit routes

The solution alternative has to provide a mechanism(s) for establishing explicit routes that all packets belonging to a deterministic flow will follow. The explicit route can be seen as a form of source routing or a pre-reserved path e.g., using some network management procedure. It should be noted that the explicit route does not need to be detailed to a level where every possible intermediate node along the path is part of the named explicit route. RSVP-TE [RFC3209] supports explicit routes, and typically provides pinned data paths for established LSPs. At Layer-2, the IEEE 802.1Qca [IEEE802.1Qca] specification defines how to do explicit path control in a bridged network and its IETF counter part is defined in [RFC7813]. This criteria concerns the available mechanisms for explicit routes for the data plane protocol alternative.

#### 4.5. #5 Flow duplication and merging

Flow duplication and flow merging are methods being considered to provide DetNet service protection. The objective for supporting flow duplication and flow merging is to enable hitless (or lossless) 1+1 protection. Other methods, if so identified, are also permissible.

The solution alternative has to provide means for end systems, relay and edge nodes to be able to duplicate packets into duplicate flows, and later merge the flows into one for duplicate elimination. The duplication and merging may take place at multiple points in the network in order to ensure that one (or more) equipment failure event(s) still leave at least one path intact for a deterministic networking flow. The goal is again to enable hitless 1+1 protection in a way that no packet gets lost or there is no ramp up time when either one of the paths fails for one reason or another.

Another concern regarding packet duplication is how to enforce duplicated packets to take different route or path while the final destination still remains the same. With strict source routing, all the intermediate hops are listed and paths can be guaranteed to be non-overlapping. Loose source routing only signals some of the intermediate hops and it takes additional knowledge to ensure that there is no single point of failure.

The IEEE 802.1CB (seamless redundancy) [IEEE8021CB] is an example of Ethernet-based solution that defines packet sequence numbering, flow duplication, flow merging, duplicate packet identification and elimination. The deterministic networking data plane solution alternative at layer-3 has to provide equivalent functionality. This criteria concerns the available mechanisms for packet replication and duplicate deletion the data plane protocol alternative has.

#### 4.6. #6 Operations, Administration and Maintenance

The solution alternative should demonstrate availability of appropriate standardized OAM tools that can be extended for deterministic networking purposes with a reasonable effort, when required. The OAM tools do not necessarily need to be specific to the data plane protocol as it could be the case, for example, with MPLS-based data planes. But any OAM-related implications or requirements on data plane hardware must be considered.

The OAM includes but is not limited to tools listed in the requirements for overlay networks [I-D.ooamdt-rtgwg-ooam-requirement]. Specifically, the performance management requirements are of interest at both service and transport layers.

#### 4.7. #8 Class and quality of service capabilities

Class and quality of service, i.e., CoS and QoS, are terms that are often used interchangeably and confused. In the context of DetNet, CoS is used to refer to mechanisms that provide traffic forwarding treatment based on aggregate group basis and QoS is used to refer to mechanisms that provide traffic forwarding treatment based on a specific DetNet flow basis. Examples of CoS mechanisms include DiffServ which is enabled by IP header differentiated services code point (DSCP) field [RFC2474] and MPLS label traffic class field [RFC5462], and at Layer-2, by IEEE 802.1p priority code point (PCP).

Quality of Service (QoS) mechanisms for flow specific traffic treatment typically includes a guarantee/agreement for the service, and allocation of resources to support the service. Example QoS mechanisms include discrete resource allocation, admission control, flow identification and isolation, and sometimes path control, traffic protection, shaping, policing and remarking. Example protocols that support QoS control include Resource ReSerVation Protocol (RSVP) [RFC2205] (RSVP) and RSVP-TE [RFC3209] and [RFC3473].

A critical DetNet service enabled by QoS (and perhaps CoS) is delivering zero congestion loss. There are different mechanisms that maybe used separately or in combination to deliver a zero congestion

loss service. The key aspect of this objective is that DetNet packets are not discarded due to congestion at any point in a DetNet aware network.

In the context of the data plane solution there should be means for flow identification, which then can be used to map a flow against specific resources and treatment in a node enforcing the QoS. For DetNet, certain aspects of CoS and QoS may be provided by the underlying sub-net technology, e.g., actual queuing or IEEE 802.3x priority flow control (PFC).

#### 4.8. #9 Packet traceability

For the network management and specifically for tracing implementation or network configuration errors any means to find out whether a packet is a replica, which node performed replication, and which path was intended for the replica, can be very useful. This criteria concerns the availability of solutions for tracing packets in the context of data plane protocol alternative. Packet traceability can also be part of OAM.

#### 4.9. #10 Technical maturity

The technical maturity of the data plane solution alternative is crucial, since it basically defines the effort, time line and risks involved for the use of the solution in deployments. For example, the maturity level can be categorized as available immediately, available with small extensions, available with re-purposing/ redefining portions of the protocol or its header fields. Yet another important measure for maturity is the deployment experience. This criteria concerns the maturity of the data plane protocol alternative as the solution alternative. This criteria is particularly important given, as previously noted, that the DetNet data plane solution is expected to impact, i.e., be supported in, hardware.

### 5. Data plane solution alternatives

The following sections describe and rate deterministic data plane solution alternatives. In "Analysis and Discussion" section each alternative is evaluated against the criteria given in Section 4 and rated using the following: (M)eets the criteria, (W)ork needed, and (N)ot suitable or too much work envisioned.

## 5.1. DetNet Transport layer technologies

### 5.1.1. Native IPv6 transport

#### 5.1.1.1. Solution description

This section investigates the application of native IPv6 [RFC2460] as the data plane for deterministic networking along the criteria collected in Section 4.

The application of higher OSI layer headers, i.e., headers deeper in the packet, can be considered. Two aspects have to be taken into account for such solutions. (i) Those header fields can be encrypted. (ii) Those header fields are deeper in the packet, therefore, routers have to apply deep packet inspection. See further details in Section 5.2.5.

#### 5.1.1.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

IPv6 can encapsulate DetNet Service layer headers (and associated DetNet flow payload) like any other upper-layer header indicated by the Next Header. The fixed header of an IPv6 packet is 40 bytes [RFC2460]. This overhead is bigger if any Extension Header is used, and a generic behaviour for host and forwarding nodes is specified in [RFC7045]. However, the exact overhead (Section 4.1) depends on what solution is actually used to provide DetNet features, e.g., explicit routing or DetNet service protection if any of these is applied.

IPv6 has two types of Extension Headers that are processed by intermediate routers between the source and the final destination and may be of interest for the data plane signaling, the Routing Header that is used to direct the traffic via intermediate routers in a strict or loose source routing way, and the Hop-by-Hop Options Header that carries optional information that must be examined by every node along a packet's delivery path. The Hop-by-Hop Options Header, when present, must immediately follow the IPv6 Header and it is not possible to limit its processing to the end points of Source Routed segments.

IPv6 also provides a Destination Options Header that is used to carry optional information to be examined only by a packet's destination node(s). The encoding of the options used in the Hop-by-Hop and in the Destination Options Header indicates the expected behavior when a processing IPv6 node does not recognize the Option Type, e.g. skip or drop; it should be noted that due to

performance restrictions nodes may ignore the Hop-by-Hop Option Header, drop packets containing a Hop-by-Hop Option Header, or assign packets containing a Hop-by-Hop Option Header to a slow processing path [I-D.ietf-6man-rfc2460bis] (e.g. punt packets from hardware to software forwarding which is highly detrimental to the performance).

The creation of new Extension Headers that would need to be processed by intermediate nodes is strongly discouraged. In particular, new Extension Header(s) having hop-by-hop behavior must not be created or specified. New options for the existing Hop-by-Hop Header should not be created or specified unless no alternative solution is feasible [RFC6564].

## #2 Flow identification (W)

The 20-bit flow label field of the fixed IPv6 header is suitable to distinguish different deterministic flows. But guidance on the use of the flow label provided by [RFC6437] places restrictions on how the flow label can be used. In particular, labels should be chosen from an approximation to a discrete uniform distribution. Additionally, existing implementations generally do not open APIs to control the flow label from the upper layers.

Alternatively, the Flow identification could be transported in a new option in the Hop-by-Hop Options Header.

## #4 Explicit routes (W)

One possibility is for a Software-Defined Networking (SDN) [RFC7426] based approach to be applied to compute, establish and manage the explicit routes, leveraging Traffic Engineering (TE) extensions to routing protocols [RFC5305] [RFC7752] and evolving to the Path Computation Element (PCE) Architecture [RFC5440], though a number of issues remain to be solved [RFC7399].

Segment Routing (SR) [I-D.ietf-spring-segment-routing] is a new initiative to equip IPv6 with explicit routing capabilities. The idea for the DetNet data plane would be to apply SR to IPv6 with the addition of a new type of routing extension header [I-D.ietf-6man-segment-routing-header] to explicitly signal the path in the data plane between the source and the destination, and/or between replication points and elimination points if this functionality is used.

## #5 Flow duplication and merging (W)



The functionality of replicating a packet exists in IPv6 but is limited to multicast flows. In order to enforce replicated packets to take different routes and eventually again merge flow (bring them to a specific merging point), IP-in-IP encapsulation and Segment Routing could be leveraged to signal a segment in a packet. A replication point would insert a different routing header in each copy it makes, the routing header providing explicitly the hops to the merging point for that particular replica of the packet, in a strict or in a loose source routing fashion. A flow merging point would pop the routing headers from the various copies it gets and do the rest of the required processing for merging the two flows into one flow.

#### #6 Operations, Administration and Maintenance (M/W)

IPv6 enjoys the existing toolbox for generic IP network management. However, IPv6 specific management features are still not at the level comparable to that of IPv4. Particular areas of concerns are those that are IPv6 specific, for example, related to neighbor discovery protocol (ND), stateless address autoconfiguration (SLAAC), subscriber identification, and security. While the standards are already mostly in place the implementations in deployed equipment can be lacking or inadequate for commercial deployments. This is larger issue with older existing equipment.

#### #8 Class and quality of service capabilities (W)

IPv6 provides support for CoS and QoS. CoS is provided by DiffServ which is enabled by IP header differentiated services code point (DSCP) and QoS is defined as part of RSVP [RFC2205]. DiffServ support is widely available, while RSVP for IP packets is generally not supported.

#### #9 Packet traceability (W)

The traceability of replicated packets involves the capability to resolve which replication point issued a particular copy of a packet, which segment was intended for that replica, and which particular packet of which particular flow this is. Sequence also depends on the sequencing mechanism. As an example, the replication point may be indicated as the source of the packet if IP-in-IP encapsulation is used to forward along segments. Another alternate to IP-in-IP tunneling along segments would be to protect the original source address in a destination option similar to the Home Address option [RFC6275] and then use the address of the replication point as source in the IP header.

The traceability also involves the capability to determine if a particular segment is operational. While IPv6 as such has no support for reversing a path, it appears source route extensions such as the one defined for segment routing could be used for tracing purposes. Though it is not a usual practice, IPv6 [RFC2460] expects that a Source Route path may be reversed, and the standard insists that a node must not include the reverse of a Routing Header in the response unless the received Routing Header was authenticated.

#### #10 Technical maturity (M/W)

IPv6 has been around about 20 years. However, large scale global and commercial IPv6 deployments are rather new dating only few years back to around 2012. While IPv6 has proven itself for best effort traffic, DiffServ usage is less common and QoS capabilities are not currently present. Additionally, there are number of small issues to work on as they show up once operations experience grows.

The Cisco 6Lab site [1] provides information on IPv6 deployment per country, indicating figures for prefixes, transit AS, content and users. Per this site, many countries, including Canada, Brazil, the USA, Germany, France, Japan, Portugal, Sweden, Finland, Norway, Greece, and Ecuador, achieve a deployment ratio above 30 percent, and the overall adoption reported by Google Statistics [2] is now above 10 percent.

#### 5.1.1.3. Summary

IPv6 supports a significant portion of the identified DetNet data plane criteria today. There are aspects of the DetNet data plane that are not fully supported, notably QoS, but these can be incrementally added or supplemented by the underlying sub-network layer. IPv6 may be a choice as the DetNet Transport layer in networks where other technologies such as MPLS are not deployed.

#### 5.1.2. Native IPv4 transport

##### 5.1.2.1. Solution description

IPv4 [RFC0791] is in principle the same as IPv6, except that it has a smaller address space. However, IPv6 was designed around the fact that extension headers are an integral part of the protocol and operation from the beginning, although the practice may some times prove differently [RFC7872]. IPv4 does support header options, but these have historically not been supported in hardware-based

forwarding so are generally blocked or handled at a much slower rate. In either case, the use of IP header options is generally avoided. In the context of deterministic networking data plane solutions the major difference between IPv4 and IPv6 seems to be the practical support for header extensibility. Anything below and above the IP header independent of the version is practically the same.

#### 5.1.2.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

The fixed header of an IPv4 packet is 20 bytes [RFC0791]. IP options add overhead, but are not generally used and are not considered as part of this document.

##### #2 Flow identification (W)

The IPv4 header has a 16-bit identification field that was originally intended for assisting fragmentation and reassembly of IPv4 packets as described in [RFC0791]. The identification field has also been proposed to be used for actually identifying flows between two IP addresses and a given protocol for detecting and removing duplicate packets [RFC1122]. However, recent update [RFC6864] to both [RFC0791] and [RFC1122] restricts the use of IPv4 identification field only to fragmentation purposes.

The IPv4 also has a stream identifier option [RFC0791], which contains a 16-bit SATNET stream identifier. However, the option has been deprecated [RFC6814]. The conclusion is that stream identification does not work nicely with IPv4 header alone and a traditional 5-tuple identification might not also be enough in a case of a flow duplication or encrypted flows. For a working solution, upper layer protocol headers such as RTP or PWs may be required for unambiguous flow identification. There is also emerging work within the IETF that may provide new flow identification alternatives.

##### #4 Explicit routes (W)

IPv4 has two source routing option specified: the loose source and record route option (LSRR), and the strict source and record route option (SSRR) [RFC0791]. The support of these options in the Internet is questionable but within a closed network the support may be assumed. But as both these options use IP header options, which are generally not supported in hardware, use of these options are questionable. Of course, the same options of SDN and SR approaches discussed above for IPv6 may be equally applicable to IPv4.

## #5 Flow duplication and merging (W/N)

The functionality of replicating a packet exists in IPv4 but is limited to multicast flows. In general the issue regarding the IPv6 packet replication also applies to IPv4. Duplicate packet detection for IPv4 is studied in [RFC6621] to a great detail in the context of simplified multicast forwarding. In general there is no good way to detect duplicated packets for IPv4 without additional upper layer protocol support.

## #6 Operations, Administration and Maintenance (M)

IPv4 enjoys the extensive and "complete" existing toolbox for generic IP network management.

## #8 Class and quality of service capabilities (M/W)

IPv4 provides support for CoS and QoS. CoS is provided by DiffServ which is enabled by IP header differentiated services code point (DSCP) and QoS is defined as part of RSVP [RFC2205]. DiffServ support is widely available, while RSVP for IP packets is generally not supported.

## #9 Packet traceability (W)

The IPv4 has similar needs and requirements for traceability as IPv6 (see Section 5.1.1.2). The IPv4 has a traceroute option [RFC6814] that could be used to record the route the packet took. However, the option has been deprecated [RFC6814].

## #10 Technical maturity (M/W)

IPv4 can be considered mature technology with over 30 years of implementation, deployment and operations experience. As with IPv6, today's commercial implementations and deployments of IPv4 generally lack any support for QoS.

## 5.1.2.3. Summary

The IPv4 has specifications to support most of the identified DetNet data plane criteria today. However, several of those have already been deprecated or their wide support is not guaranteed. The DetNet data plane criteria that are not fully supported could be incrementally added or supplemented by the underlying sub-network layer. Unfortunately, the IPv4 has had limited success getting its extensions deployed at large. However, introducing new extensions might have a better success in closed networks (like DetNet) than in

Internet. Due to the popularity of the IPv4, it should be considered as a potential choice for the DetNet Transport layer.

5.1.3. Multiprotocol Label Switching (MPLS)

Multiprotocol Label Switching Architecture (MPLS) [RFC3031] and its variants, MPLS with Traffic Engineering (MPLS-TE) [RFC3209] and [RFC3473], and MPLS Transport Profile (MPLS-TP) [RFC5921] is a widely deployed technology that switches traffic based on MPLS label stacks [RFC3032] and [RFC5960]. MPLS is the foundation for Pseudowire-based services Section 5.2.3 and emerging technologies such as Bit-Indexed Explicit Replication (BIER) Section 5.1.4 and Source Packet Routing [3].

MPLS supports the equivalent of both the DetNet Service and DetNet Transport layers, and provides a very rich set of mechanisms that can be reused directly, and perhaps augmented in certain cases, to deliver DetNet services. At the DetNet Transport layer, MPLS provides forwarding, protection and OAM services. At the DetNet Service Layer it provides client service adaption, directly, via Pseudowires Section 5.2.3 and via other label-like mechanisms such as EPVN Section 5.2.4. A representation of these options are shown in Figure 7.

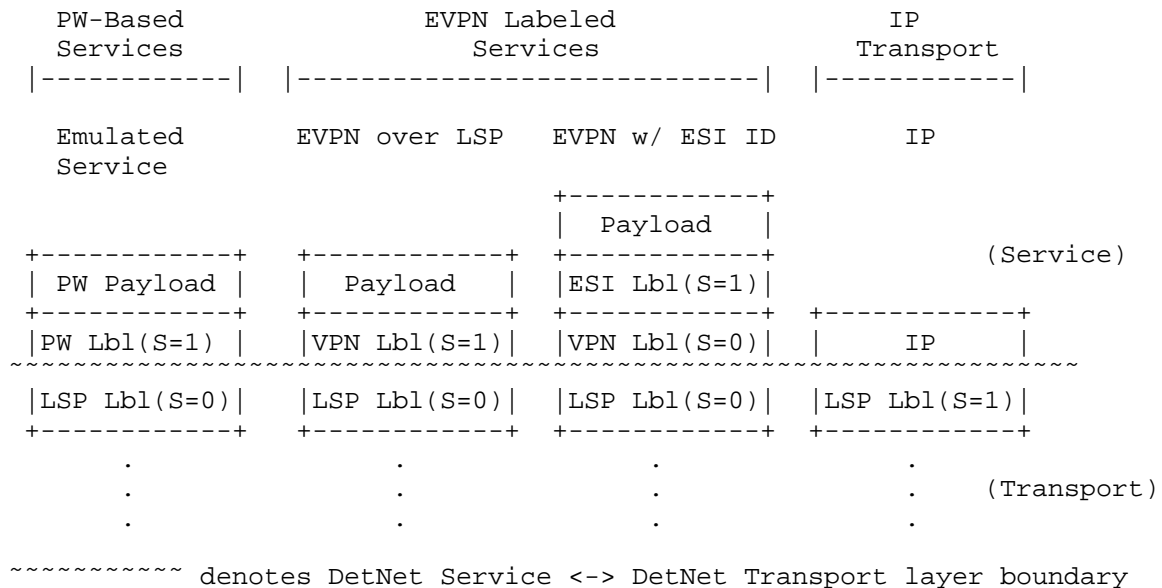


Figure 7: MPLS-based Services

MPLS can be controlled in a number of ways including via a control plane, via the management plane, or via centralized controller (SDN) based approaches. MPLS also provides standard control plane reference points. Additional information on MPLS architecture and control can be found in [RFC5921]. A summary of MPLS control plane related functions can be found in [RFC6373]. The remainder of this section will focus on the MPLS transport data plane, additional information on the MPLS service data plane can be found below in Section 5.2.2.

#### 5.1.3.1. Solution description

The following draws heavily from [RFC5960].

Encapsulation and forwarding of packets traversing MPLS LSPs follows standard MPLS packet encapsulation and forwarding as defined in [RFC3031], [RFC3032], [RFC5331], and [RFC5332].

Data plane Quality of Service capabilities are included in the MPLS in the form of Traffic Engineered (TE) LSPs [RFC3209] and the MPLS Differentiated Services (DiffServ) architecture [RFC3270]. Both E-LSP and L-LSP MPLS DiffServ modes are defined. The Traffic Class field (formerly the EXP field) of an MPLS label follows the definition of [RFC5462] and [RFC3270].

Except for transient packet reordering that may occur, for example, during fault conditions, packets are delivered in order on L-LSPs, and on E-LSPs within a specific ordered aggregate.

The Uniform, Pipe, and Short Pipe DiffServ tunneling and TTL processing models are described in [RFC3270] and [RFC3443] and may be used for MPLS LSPs.

Equal-Cost Multi-Path (ECMP) load-balancing is possible with MPLS LSPs and can be avoided using a number of techniques. The same holds for Penultimate Hop Popping (PHP).

MPLS includes the following LSP types:

- o Point-to-point unidirectional
- o Point-to-point associated bidirectional
- o Point-to-point co-routed bidirectional
- o Point-to-multipoint unidirectional

Point-to-point unidirectional LSPs are supported by the basic MPLS architecture [RFC3031].

A point-to-point associated bidirectional LSP between LSRs A and B consists of two unidirectional point-to-point LSPs, one from A to B and the other from B to A, which are regarded as a pair providing a single logical bidirectional transport path.

A point-to-point co-routed bidirectional LSP is a point-to-point associated bidirectional LSP with the additional constraint that its two unidirectional component LSPs in each direction follow the same path (in terms of both nodes and links). An important property of co-routed bidirectional LSPs is that their unidirectional component LSPs share fate.

A point-to-multipoint unidirectional LSP functions in the same manner in the data plane, with respect to basic label processing and packet-switching operations, as a point-to-point unidirectional LSP, with one difference: an LSR may have more than one (egress interface, outgoing label) pair associated with the LSP, and any packet it transmits on the LSP is transmitted out all associated egress interfaces. Point-to-multipoint LSPs are described in [RFC4875] and [RFC5332]. TTL processing and exception handling for point-to-multipoint LSPs is the same as for point-to-point LSPs.

Additional data plane capabilities include Linear Protection, [RFC6378] and [RFC7271]. And the in progress work on MPLS support for time synchronization [I-D.ietf-mpls-residence-time].

#### 5.1.3.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

There are two perspectives to consider when looking at encapsulation. The first is encapsulation to support services. These considerations are part of the DetNet service layer and are covered below, see Sections 5.2.3 and 5.2.4.

The second perspective relates to encapsulation, if any, which is needed to transport packets across network. In this case, the MPLS label stack, [RFC3032] is used to identify flows across a network. MPLS labels are compact and highly flexible. They can be stacked to support client adaptation, protection, network layering, source routing, etc.

The number of DetNet Transport layer specific labels is flexible and support a wide range of applicable functions and MPLS domain characteristics (e.g., TE-tunnels, Hierarchical-LSPs, etc.).

##### #2 Flow identification (M)

MPLS label stacks provide highly flexible ways to identify flows. Basically, they enable the complete separation of traffic classification from traffic treatment and thereby enable arbitrary combinations of both.

For the DetNet flow identification the MPLS label stack can be used to support n-layers of DetNet flow identification. For example, using dedicated LSP per DetNet flow would simplify flow identification for intermediate transport nodes, and additional hierarchical LSPs could be used to facilitate scaling.

#### #4 Explicit routes (M)

MPLS supports explicit routes based on how LSPs are established, e.g., via TE explicit routes [RFC3209]. Additional, but not required, capabilities are being defined as part of Segment Routing (SR) [I-D.ietf-spring-segment-routing].

#### #5 Flow duplication and merging (M/W)

MPLS as DetNet Transport layer supports the replication via point-to-multipoint LSPs. At the MPLS LSP level, there are mechanisms defined to provide 1+1 protection, which could help in realizing the flow merging function. The current definitions [RFC6378] and [RFC7271] use OAM mechanisms to support and coordinate protection switching and packet loss is possible during a switch. While such this level of protection may be sufficient for many DetNet applications, when truly hitless (i.e., zero loss) switching is required, additional mechanisms will be needed. It is expected that these additional mechanisms will be defined at a DetNet layer.

#### #6 Operations, Administration and Maintenance (M)

MPLS already includes a rich set of OAM functions at both the Service and Transport Layers. This includes LSP ping [ref] and those enabled via the MPLS Generic Associated Channel [RFC5586] and registered by IANA [4].

#### #8 Class and quality of service capabilities (M/W)

As previously mentioned, Data plane Quality of Service capabilities are included in the MPLS in the form of Traffic Engineered (TE) LSPs [RFC3209] and the MPLS Differentiated



Services (DiffServ) architecture [RFC3270]. Both E-LSP and L-LSP MPLS DiffServ modes are defined. The Traffic Class field (formerly the EXP field) of an MPLS label follows the definition of [RFC5462] and [RFC3270]. One potential open area of work is synchronized, time based scheduling. Another is shaping, which is generally not supported in shipping MPLS hardware.

#### #9 Packet traceability (M)

MPLS supports multiple tracing mechanisms. A control based one is defined in [RFC3209]. An OAM based mechanism is defined in MPLS On-Demand Connectivity Verification and Route Tracing [RFC6426].

#### #10 Technical maturity (M)

MPLS as a mature technology that has been widely deployed in many networks for many years. Numerous vendor products and multiple generations of MPLS hardware have been built and deployed.

##### 5.1.3.3. Summary

MPLS is a mature technology that has been widely deployed. Numerous vendor products and multiple generations of MPLS hardware have been built and deployed. MPLS LSPs support a significant portion of the identified DetNet data plane criteria today. Aspects of the DetNet data plane that are not fully supported can be incrementally added. It's worth noting that a number of limitations are in shipping hardware, versus at the protocol specification level, e.g., shaping.

##### 5.1.4. Bit Indexed Explicit Replication (BIER)

Bit Indexed Explicit Replication [I-D.ietf-bier-architecture] (BIER) is a network plane replication technique that was initially intended as a new method for multicast distribution. In a nutshell, a BIER header includes a bitmap that explicitly signals the destinations that are intended for a particular packet, which means that 1) the source is aware of the individual destinations and 2) the BIER control plane is a simple extension of the unicast routing as opposed to a dedicated multicast data plane, which represents a considerable reduction in OPEX. For this reason, the technology is getting a lot of traction from Service Providers. In the context of DetNet, BIER may be applicable for implementing packet replication, as described in Section 5.1.4.

The encapsulation of a BIER packet in an MPLS network is shown in Figure 8

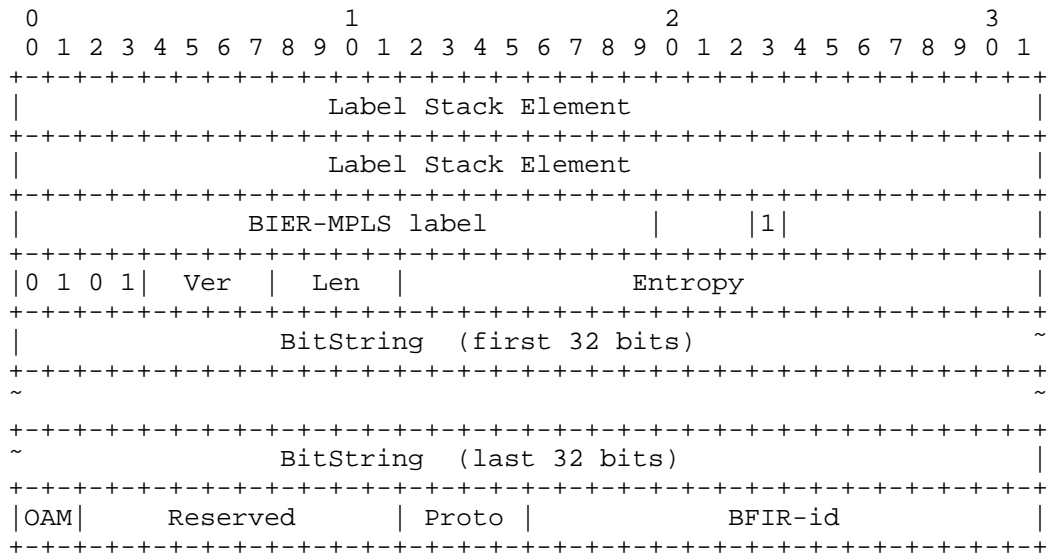


Figure 8: BIER packet in MPLS encapsulation

5.1.4.1. Solution description

A distinctive BIER payload type (with its own Proto(col) ID) would be created for DetNet, providing a header that would identify:

- o Version;
- o Sequence Number;
- o Timestamp;
- o Payload type, e.g. data vs. OAM.

A DetNet node, collocated with a BFIR (Bit-Forwarding Ingress Router) may use multiple BIER sub-domains to create replicated flows. Downstream DetNet nodes, collocated with BFER (Bit-Forwarding Ingress Router) would terminate redundant flows based on Sequence Number and/or Timestamp information. Thus a DetNet node may be collocated with a BFER in one BIER sub- domain and with a BFIR in another, and a DetNet flow could traverse several BIER sub-domains.

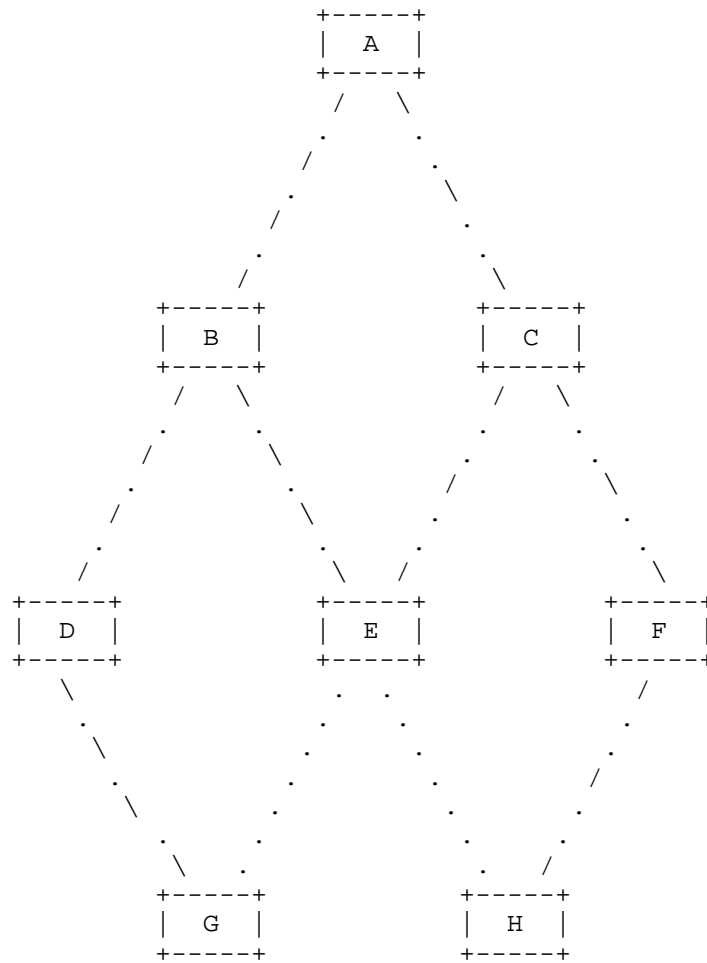


Figure 9: DetNet in BIER domain

Consider a DetNet flow that must traverse BIER enabled domain from A to G and H. DetNet may use three BIER subdomains:

- o A-B-D-E-G (dash-dot): A is BFIR, E and G are BFERs,
- o A-C-E-F-H (dash-double-dot): A is BFIR, E and H are BFERs,
- o E-G-H (dotted): E is BFIR, G and H are BFERs.

DetNet node A sends DetNet into red and purple BIER sub-domains. DetNet node E receives DetNet packet and sends into green sub-domain while terminating duplicates and those that are deemed "too-late".

DetNet nodes G and H receive DetNet flows, terminate duplicates and those that are too-late.

#### 5.1.4.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

BIER over MPLS network encapsulation ("BIER over MPLS"), Figure 8, is being defined [I-D.ietf-bier-mpls-encapsulation] within the BIER working group.

##### #2 Flow identification (M)

Flow identification and separation can be achieved through use of BIER domains and/or Entropy value in the BIER over MPLS, Figure 8.

##### #4 Explicit routes (M)

Explicit routes may be used as underlay for BIER domain. BIER underlay may be calculated using PCE and instantiated using any southbound mechanism.

##### #5 Flow duplication and merging (M/W)

Packet replication, as indicated by its name, is a core function of the Bit-Indexed Explicit Replication. Elimination of the duplicates and/or too-late packets cannot be done within BIER sub-domain but may be done at DetNet overlay at the edge of the BIER sub-domain.

[Editor's note: how about the flow merging?]

##### #6 Operations, Administration and Maintenance (M/W)

BIER over MPLS guarantees that OAM is fate-sharing, i.e. in-band with a data flow being monitored or measured. Additionally, BIER over MPLS enables passive performance measurement, e.g. with the marking method [I-D.mirsky-bier-pmmm-oam]. Existing OAM protocols can be applied and used in BIER over MPLS as demonstrated in [I-D.ooamdt-rtgwg-oam-gap-analysis], while new protocols are being worked on, e.g. ping/traceroute [I-D.kumarzheng-bier-ping] or Path MTU Discovery [I-D.mirsky-bier-path-mtu-discovery].

##### #8 Class and quality of service capabilities (M/W)

Class of Service can be inherited from the underlay of the particular BIER sub-domain. Quality of Service, i.e. scheduling

and bandwidth reservations can be used among other constraints in calculating explicit paths for the BIER sub-domain's underlay.

#### #9 Packet traceability (W)

Ability to do passive performance measurement by using OAM field of the BIER over MPLS, Figure 8, is unmatched and significantly simplifies truly passive tracing of selected flows and packets within them.

#### #10 Technical maturity (W)

The BIER over MPLS is nearing finalization within the BIER WG and several experimental implementations are expected soon.

#### 5.1.4.3. Summary

BIER over MPLS supports a significant portion of the identified DetNet data plane requirements, including controlled packet replication, traffic engineering, while some requirements, e.g. duplicate and too-late packet elimination may be realized as function of the DetNet overlay. BIER over MPLS is a viable candidate as the DetNet Transport layer in MPLS networks.

### 5.2. DetNet Service layer technologies

#### 5.2.1. Generic Routing Encapsulation (GRE)

##### 5.2.1.1. Solution description

Generic Routing Encapsulation (GRE) [RFC2784] provides an encapsulation of an arbitrary network layer protocol over another arbitrary network layer protocol. The encapsulation of a GRE packet can be found in Figure 10.

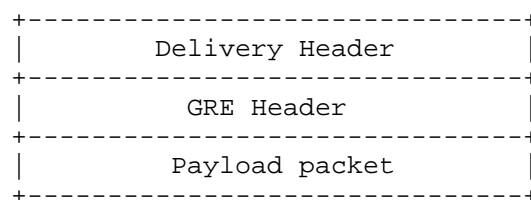


Figure 10: Encapsulation of a GRE packet

Based on RFC2784, [RFC2890] further includes sequencing number and Key in optional fields of the GRE header, which may help to transport

DetNet traffic flows over IP networks. The format of a GRE header is presented in Figure 11.

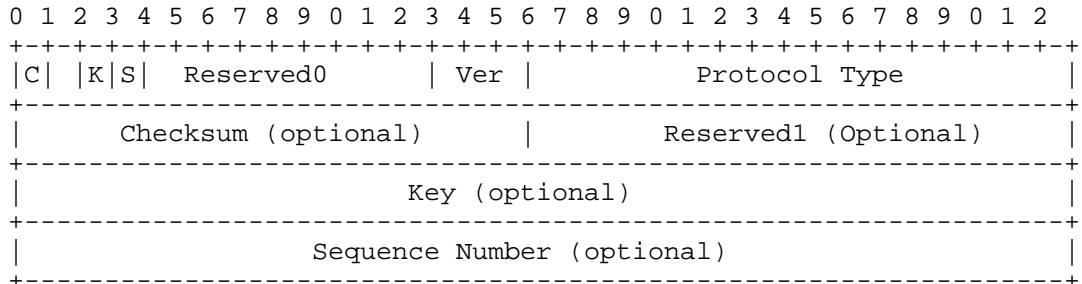


Figure 11: Format of a GRE header

5.2.1.2. Analysis and Discussion

#1 Encapsulation and overhead (M)

GRE can provide encapsulation at the service layer over the transport layer. A new protocol type for DetNet traffic should be allocated as an "Ether Type" in [RFC3232] and in IANA Ethernet Numbers [5]. The fixed header of a GRE packet is 4 octets while the maximum header is 16 octets with optional fields in Figure 11.

#2 Flow identification (W)

There is no flow identification field in GRE header. However, it can rely on the flow identification mechanism applied in the delivery protocols, such as flow identification stated in IP Sections 5.1.1 and 5.1.2 when the delivery protocols are IPv6 and IPv4 respectively. Alternatively, the Key field can also be extended to carry the flow identification. The size of Key field is 4 octets.

#3 Packet sequencing and duplicate elimination (M/W)

As stated in Section 5.2.1, GRE provides an optional sequencing number in its header to provide sequencing services for packets. The size of the sequencing number is 32 bits. The GRE header could be extended to indicate the duplicated packets by defining a flag in reserved fields or using the sequencing number of a flow.

#5 Flow duplication and merging (W/N)

GRE has no flow/packet replication and merging support in its header. It can use the transport IPv4/IPv6 protocols at the

transport layer to replicate the packets and take the different routes as discussed in Section 5.1.1 and Section 5.1.2.

#### #6 Operations, Administration and Maintenance (M)

GRE uses the network management provided by the IP protocols as transport layer.

#### #8 Class and quality of service capabilities (W)

For the class of service capability, an optional code point field to indicate CoS of the traffic could be added into the GRE header. Otherwise, GRE can reuse the class and quality of service of delivery protocols at transport layer such as IPv6 and IPv4 stated in Section 5.1.1 and Section 5.1.2.

#### #10 Technical maturity (M)

GRE has been developed over 20 years. The delivery protocol mostly used is IPv4, while the IPv6 support for GRE is to be standardized now in IETF as [RFC7676]. Due to its good extensibility, GRE has also been extended to support network virtualization in Data Center, which is NVGRE [RFC7637].

#### 5.2.1.3. Summary

As a tunneling protocol, GRE can encapsulate a wide variety of network layer protocols over another network layer, which can naturally serve as the service layer protocol for DetNet. Currently, it supports a portion of the Detnet service layer criteria, and still some are not fully supported but can be incrementally added or supported by delivery protocols at as the transport layer. In general, GRE can be a choice as the DetNet service layer and can work with IPv6 and IPv4 as the DetNet Transport layer.

#### 5.2.2. MPLS-based Services for DetNet

MPLS based technologies support both the DetNet Service and DetNet Transport layers. This, as well as a general overview of MPLS, is covered above in Section 5.1.3. Following sections focus on the DetNet Service Layer which provides client service adaption, via Pseudowires Section 5.2.3 and via native and other label-like mechanisms such as EPVN in Section 5.2.4. A representation of these options was previously discussed and is shown in Figure 7.

The following text is adapted from [RFC5921]:

The MPLS native service adaptation functions interface the client layer network service to MPLS. For Pseudowires, these adaptation functions are the payload encapsulation described in Section 4.4 of [RFC3985] and Section 6 of [RFC5659]. For network layer client services, the adaptation function uses the MPLS encapsulation format as defined in [RFC3032].

The purpose of this encapsulation is to abstract the data plane of the client layer network from the MPLS data plane, thus contributing to the independent operation of the MPLS network.

MPLS may itself be a client of an underlying server layer. MPLS can thus also be bounded by a set of adaptation functions to this server layer network, which may itself be MPLS. These adaptation functions provide encapsulation of the MPLS frames and for the transparent transport of those frames over the server layer network.

While MPLS service can be provided on a true end-system to end-system basis, it's more likely that DetNet service will be provided over Pseudowires as described in Section 5.2.3 or via an EPVN-based service described in Section 5.2.4 .

MPLS labels in the label stack may be used to identify transport paths, see Section 5.1.3, or as service identifiers. Typically a single label is used for service identification.

Packet sequencing mechanisms are added in client-related adaptation processing, see Sections 5.2.3 and 5.2.4.

The MPLS client inherits its Quality of Service (QoS) from the MPLS transport layer, which in turn inherits its QoS from the server (sub-network) layer. The server layer therefore needs to provide the necessary QoS to ensure that the MPLS client QoS commitments can be satisfied.

### 5.2.3. Pseudo Wire Emulation Edge-to-Edge (PWE3)

#### 5.2.3.1. Solution description

Pseudo Wire Emulation Edge-to-Edge (PWE3) [RFC3985] or simply PseudoWires (PW) provide means of emulating the essential attributes and behaviour of a telecommunications service over a packet switched network (PSN) using IP or MPLS transport. In addition to traditional telecommunications services such as T1 line or Frame Relay, PWs also provide transport for Ethernet service [RFC4448] and for generic packet service [RFC6658]. Figure 12 illustrates the reference PWE3 stack model.





MPLS label stack. The protocol type field in the GRE header is set to MPLS Unicast (0x8847) or Multicast (0x8848). MPLS over L2TPv3 over IP encapsulation is specified by [RFC4817]. The MPLS-in-UDP encapsulation is specified by [RFC7510], where the UDP Destination Port indicates tunneled MPLS packet and the UDP Source Port is an entropy value that is generated by the encapsulator to uniquely identify a flow. MPLS-in-UDP encapsulation can be applied to enable UDP-based ECMP (Equal-Cost Multipath) or Link Aggregation. All these solutions can be secured with IPsec [RFC4303].

#### 5.2.3.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

PWs offer encapsulation services practically for practically any type of payload over any PSN. New PW types need a code point allocation [RFC4446] and in some cases an emulated service specific document.

Specifically in the case of the MPLS PSN the PW encapsulation overhead is minimal. Typically minimum two labels and a CW is needed, which totals to 12 octets. PW type specific handling might, however, allow optimizations on the emulated service in the provider edge (PE) device's native service processing (NSP) / forwarder function. These optimizations could be used, for example, to reduce header overhead. Ethernet PWs already have rather low overhead [RFC4448]. Without a CW and VLAN tags the Ethernet header gets reduced to 14 octets (minimum Ethernet header overhead is 26).

The overhead is somewhat bigger in case of IP PSN if an MPLS over IP solution is applied to provide PWs. IP adds at least 20 (IPv4) or 40 (IPv6) bytes overhead to the PW over MPLS overhead; furthermore, the GRE, L2TPv3, or UDP header has to be taken into account if any of these further encapsulations is used.

##### #2 Flow identification (M)

PWs provide multiple layers of flow identification, especially in the case of the MPLS PSN. The PWs are typically prepended with an endpoint specific PW label that can be used to identify a specific PW per endpoint. Furthermore, the MPLS PSN also uses one or more labels to transport packets over specific label switched paths (that then would carry PWs). So, a DetNet flow can be identified in this example by the service and transport layer labels. IP (and other) PSNs may need other mechanisms, such as, UDP port numbers, upper layer protocol header (like RTP) or some IP extension header to provide required flow identification.

## #3 Packet sequencing and duplicate elimination (M)

As mentioned earlier PWs may contain an optional CW that is able to provide sequencing services. The size of the sequence number in the generic CW is 16 bits, which might be, depending on the used link and DetNet flow speed be too little. The PW duplicate detection mechanism is already conceptually specified [RFC3985] but no emulated service makes use of it currently.

## #5 Flow duplication and merging (W)

PWs could use a (extended) version of existing transport layer provided protection mechanisms (e.g., hitless 1+1 protection) for both flow duplication and flow merging. The service layer has to provide the functionality to map DetNet flows into appropriate transport layer connection.

## #6 Operations, Administration and Maintenance (M/W)

PWs have rich control plane for OAM and in a case of the MPLS PSN enjoy the full control plane toolbox developed for MPLS network OAM likewise IP PSN has the full toolbox of IP network OAM tools. There could be, however, need for deterministic networking specific extensions for the mentioned control planes.

## #8 Class and quality of service capabilities (M/W)

In a case of IP PSN the 6-bit differentiated services code point (DSCP) field can be used for indicating the class of service [RFC2474] and 2-bit field reserved for the explicit congestion notification (ECN) [RFC3168]. Similarly, in a case of MPLS PSN, there are 3-bit traffic class field (TC) [RFC5462] in the label reserved for for both Explicitly TC-encoded-PSC LSPs (E-LSP) [RFC3270] and ECN [RFC5129]. Due to the limited number of bits in the TC field, their use for QoS and ECN functions is restricted and intended to be flexible. Although the QoS/CoS mechanism is already in place some clarifications may be required in the context of deterministic networking flows, for example, if some specific mapping between bit fields have to be done.

When PWs are used over MPLS, MPLS LSPs can be used to provide both CoS (E-LSPs and L-LSPs) and QoS (dedicated TE LSPS).

## #10 Technical maturity (M)

PWs, IP and MPLS are proven technologies with wide variety of deployments and years of operational experience. Furthermore, the estimated work for missing functionality (packet replication and

elimination) does not appear to be extensive, since the existing protection mechanism already gets close to what is needed from the deterministic networking data plane solution.

#### 5.2.3.3. Summary

PseudoWires appear to be a strong candidate as the deterministic networking data plane solution alternative for the DetNet Service layer. The strong points are the technical maturity and the extensive control plane for OAM. This holds specifically for MPLS-based PSN.

Extensions are required to realize the packet replication and duplicate detection features of the deterministic networking data plane.

#### 5.2.4. MPLS-Based Ethernet VPN (EVPN)

##### 5.2.4.1. Solution description

MPLS-Based Ethernet VPN (EVPN), in the form documented in [RFC7432] and [RFC7209], is an increasingly popular approach to delivering MPLS-based Ethernet services and is designed to be the successor to Virtual Private LAN Service (VPLS), [RFC4664].

EVPN provides client adaptation and reuses the MPLS data plane discussed above in Section 5.2.2. While not required, the PW Control Word is also used. EVPN control is via BGP, [RFC7432], and may use TE-LSPs, e.g., controlled via [RFC3209] for MPLS transport. Additional EVPN related RFCs and in progress drafts are being developed by the BGP Enabled Services Working Group [6].

##### 5.2.4.2. Analysis and Discussion

###### #1 Encapsulation and overhead (M)

EVPN generally uses a single MPLS label stack entry to support its client adaptation service. The optional addition of a second label is also supported. In certain cases PW Control Word may also be used.

###### #2 Flow identification (W)

EVPN currently uses labels to identify flows per {Ethernet Segment Identifier, VLAN} or per MAC level. Additional definition will be

needed to standardize identification of finer granularity DetNet flows as well as mapping of TSN services to DetNet Services.

### #3 Packet sequencing and duplicate elimination (M)

Like MPLS, EVPN generally orders packets similar to Ethernet. Reordering is possible primarily during path changes and protection switching. In order to avoid misordering due to ECMP, EVPN uses the "Preferred PW MPLS Control Word" [RFC4385] (in which case EVPN inherits this function from PWs) or the entropy labels [RFC6790].

If additional ordering mechanisms are required, such mechanisms will need to be defined.

### #5 Flow duplication and merging (M/W)

EVPN relies on the MPLS layer for all protection functions. See Section 5.1.3 and Section 5.2.2. Some extensions, either at the EVPN or MPLS levels, will be need to support those DetNet applications which require true hitless (i.e., zero loss) 1+1 protection switching. (Network coding may be an interesting alternative to investigate to delivering such hitless loss protection capability.)

### #6 Operations, Administration and Maintenance (M/W)

Nodes supporting EVPN may participate in either or both Ethernet level and MPLS level OAM. It is likely that it may make sense to map or adapt the OAM functions at the different levels, but such has yet to be defined. [RFC6371] provides some useful background on this topic.

### #8 Class and quality of service capabilities (M/W)

EVPN is largely silent on the topics of CoS and QoS, but the 802.1 TSN Ethernet and existing MPLS TE mechanisms can be directly used. The inter-working of such is new work and within the scope of DetNet. The existing MPLS mechanisms include both CoS (E-LSPs and L-LSPs) and QoS (dedicated TE LSPs).

### #10 Technical maturity (M)

EVPN is a second (or third) generation MPLS-based L2VPN service standard. From a data plane standpoint it makes use of existing MPLS data plane mechanisms. The mechanisms have been widely implemented and deployed.

#### 5.2.4.3. Summary

EVPN is the emerging successor to VPLS. EVPN is standardized, implemented and deployed. It makes use of the mature MPLS data plane. While offering a mature and very comprehensive set of features, certain DetNet required features are not fully/directly supported and additional standardization in these areas are needed. Examples include: mapping CoS and QoS; use of labels per DetNet flow, and hitless 1+1 protection.

#### 5.2.5. Higher layer header fields

Fields of headers belonging to higher OSI layers can be used to implement functionality that is not provided e.g., by the IPv6 or IPv4 header fields. However, this approach cannot be always applied, e.g., due to encryption. Furthermore, even if this approach is applicable, it requires deep packet inspection from the routers and switches. There are implementation dependent limits how far into the packet the lookup can be done efficiently in the fast path. When encryption is not used, a safe bet is generally between 128 and 256 octets for the maximum lookup depth. Various higher layer protocols can be applied. Some examples are provided here for the sequence numbering feature (Section 4.3).

##### 5.2.5.1. TCP

The TCP header includes a sequence number parameter, which can be applied to detect and eliminate duplicate packets if DetNet service protection is used. As the TCP header is right after the IP header, it does not require very deep packet inspection; the 4-byte sequence number is conveyed by bits 32 through 63 of the TCP header. In addition to sequencing, the TCP header also contains source and destination port information that can be used for assisting the flow identification.

##### 5.2.5.2. RTP

###### 5.2.5.2.1. Solution Description

Real-time Transport Protocol (RTP) [RFC3550] is often used to deliver time critical traffic in IP networks. RTP is typically carried on top of UDP/IP. However, as noted earlier in Section 5.2.3 PseudoWires also have a well-defined way of embedding and

transposing RTP headers as part of its payload encapsulation headers/sub-layer. RTP is also augmented by its own control protocol RTCP, which monitors the data delivery and provides minimal control and identification functionality. RTCP packets do not carry "media payload". Although both RTP and RTCP are typically used with UDP/IP transport they are designed to be independent of the underlying transport and network layers.

The RTP header includes a 2-byte sequence number, which can be used to detect and eliminate duplicate packets if DetNet service protection is used. The sequence number is conveyed by bits 16 through 31 of the RTP header. In addition to the sequence number the RTP header has also timestamp field (bits 32 through 63) that can be useful for time synchronization purposes. Furthermore, the RTP header has also one or more synchronization sources (bits starting from 64) that can potentially be useful for flow identification purposes.

#### 5.2.5.2.2. Analysis and Discussion

##### #1 Encapsulation and overhead (M)

RTP adds minimum 12 octets of header overhead. Typically 8 octets overhead of UDP header has to be also added, at least in a case when RTP is transported over IP. Although RTCP packets do not contribute to the media payload transport they still consume overall network capacity, since all participants to an RTP session including sources and multicast session destinations are expected to send RTCP reports.

##### #2 Flow identification (M)

The RTP header contains a synchronization source (SSRC) identifier. The intent is that no two synchronization sources within the same RTP session have the same SSRC identifier.

##### #3 Packet sequencing and duplicate elimination (M)

The RTP header contains a 16 bit sequence number. The sequence number can be also used to detect duplicate packets.

##### #5 Flow duplication and merging (M/W)

RTP has precedence of being used for hitless protection switching [ST20227], which essentially is equivalent to DetNet service protection. Furthermore, recent work in IETF for RTP stream duplication [RFC7198] as a mechanism to protect media flows from packet loss is again equivalent to Detnet service protection.

## #6 Operations, Administration and Maintenance (M)

RTP has its own control protocol RTCP for (minimal) management and stream monitoring purposes. Existing IP OAM tools can directly leveraged when RTP is deployed over IP transport.

## #8 Class and quality of service capabilities (M/W)

TBD. [Editor's note: relies on lower layers to provide CoS/QoS]

## #10 Technical maturity (M)

RTP has been deployed and used in large commercial systems for over ten years and can be considered a mature technology.

## 5.2.5.2.3. Summary

RTP appears to be a good candidate as the deterministic networking data plane solution alternative for the DetNet Service layer. The strong points are the technical maturity and the fact it was designed for transporting time-sensitive payload from the beginning. RTP is specifically well suited to be used with (UDP)/IP transport.

Extensions may be required to realize the packet replication and duplicate detection features of the deterministic networking data plane. However, there is already precedence of similar solutions that could potentially be leveraged [ST20227][RFC7198].

## 6. Summary of data plane alternatives

The following table summarizes the criteria (Section 4) used for the evaluation of data plane options.



## Applicability per Alternative

Item #	Meaning
#1	Encapsulation and overhead
#2	Flow identification
#3	Packet sequencing and duplicate elimination
#4	Explicit routes
#5	Flow duplication and merging
#6	Operations, Administration and Maintenance
#8	Class and quality of service capabilities
#9	Packet traceability
#10	Technical maturity

Table 1: Evaluation criteria

There is no single technology that could meet all the criteria on its own. Distinguishing the DetNet Service and the DetNet Transport, as explained in (Section 3), allows a number of combinations, which can meet most of the criteria. There is no room here to evaluate all possible combinations. Therefore, only some combinations are highlighted here, which are selected based on the number of criteria that are met and the maturity of the technology (#10).

The following table summarizes the evaluation of the data plane options that can be used for the DetNet Transport Layer against the evaluation criteria. Each value in the table is from the corresponding section.

## Applicability per Transport Alternative

Solution	#1	#2	#4	#5	#6	#8	#9	#10
IPv6	M	W	W	W	M	W	W	M/W
IPv4	M	W	W	W/N	M	M/W	W	M/W
MPLS	M	M	M	M/W	M	M/W	M	M
BIER	M	M	M	M/W	M/W	M/W	M	W

## Summarizing Transport capabilities

Table 2: DetNet Transport Layer

The following table summarizes the evaluation of the data plane options that can be used for the DetNet Service Layer against the

criteria evaluation criteria. Each value in the table is from the corresponding section.

Applicability per Service Alternative

Solution	#1	#2	#3	#5	#6	#8	#10
GRE	M	W	M/W	W/N	M	W	M
PWE3	M	M	M	W	M/W	M/W	M
EVPN	M	W	M	M/W	M/W	M/W	M
RTP	M	M	M	M/W	M	M/W	M

### Summarizing Service capabilities

Table 3: DetNet Service Layer

PseudoWire (Section 5.2.3) is a technology that is mature and meets most of the criteria for the DetNet Service layer as shown in the table above. From upper layer protocols PWs or RTP can be a candidate for non-MPLS PSNs. The identified work for PWs is to figure out how to implement duplicate detection for these protocols (e.g., based on [RFC3985]). In a case of RTP there is precedence of implementing packet duplication and duplicate elimination [ST20227][RFC7198].

PWs can be carried over MPLS or IP. MPLS is the most common technology that is used as PSN for PseudoWires; furthermore, MPLS is a mature technology and meets most DetNet Transport layer criteria. IPv[46] can be also used as PSN and both are mature technologies, although both generally only support CoS (DiffServ) in deployed networks. RTP is independent of the underlying transport technology and network. However, it is well suited for UDP/IP transport or embedded as a part of the PseudoWire timing sub-layer.

#### 7. Security considerations

This document does not add any new security considerations beyond what the referenced technologies already have.

#### 8. IANA Considerations

This document has no IANA considerations.

## 9. Acknowledgements

The author(s) ACK and NACK.

The following people were part of the DetNet Data Plane Design Team:

Jouni Korhonen  
Janos Farkas  
Norman Finn  
Olivier Marce  
Gregory Mirsky  
Pascal Thubert  
Zhuangyan Zhuang

Substantial contributions were received from:

Balazs Varga (service model)

The DetNet chairs serving during the DetNet Data Plane Design Team:

Lou Berger  
Pat Thaler

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## 10.2. URIs

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- [2] <https://www.google.com/intl/en/ipv6/statistics.html>
- [3] <https://datatracker.ietf.org/wg/spring/charter/>
- [4] <http://www.iana.org/assignments/g-ach-parameters/g-ach-parameters.xhtml>
- [5] <http://ftp.isi.edu/in-notes/iana/assignments/ethernet-numbers>
- [6] <https://tools.ietf.org/wg/bess/>

Appendix A. Examples of combined DetNet Service and Transport layers

Authors' Addresses

Jouni Korhonen (editor)  
Broadcom  
3151 Zanker Road  
San Jose, CA 95134  
USA

Email: [jouni.nospam@gmail.com](mailto:jouni.nospam@gmail.com)

Janos Farkas  
Ericsson  
Konyves Kalman krt. 11/B  
Budapest 1097  
Hungary

Email: [janos.farkas@ericsson.com](mailto:janos.farkas@ericsson.com)

Gregory Mirsky  
Ericsson

Email: [gregory.mirsky@ericsson.com](mailto:gregory.mirsky@ericsson.com)

Pascal Thubert  
Cisco

Email: [pthubert@cisco.com](mailto:pthubert@cisco.com)

Yan Zhuang  
Huawei

Email: [zhuangyan.zhuang@huawei.com](mailto:zhuangyan.zhuang@huawei.com)

Lou Berger  
LabN Consulting, L.L.C.

Email: [lberger@labn.net](mailto:lberger@labn.net)

Internet Engineering Task Force  
Internet-Draft  
Intended status: Informational  
Expires: April 6, 2017

E. Grossman, Ed.  
DOLBY  
C. Gunther  
HARMAN  
P. Thubert  
P. Wetterwald  
CISCO  
J. Raymond  
HYDRO-QUEBEC  
J. Korhonen  
BROADCOM  
Y. Kaneko  
Toshiba  
S. Das  
Applied Communication Sciences  
Y. Zha  
HUAWEI  
B. Varga  
J. Farkas  
Ericsson  
F. Goetz  
J. Schmitt  
Siemens  
X. Vilajosana  
Worldsensing  
T. Mahmoodi  
King's College London  
S. Spirou  
Intracom Telecom  
P. Vizarreta  
Technical University of Munich, TUM  
October 3, 2016

Deterministic Networking Use Cases  
draft-ietf-detnet-use-cases-11

Abstract

This draft documents requirements in several diverse industries to establish multi-hop paths for characterized flows with deterministic properties. In this context deterministic implies that streams can be established which provide guaranteed bandwidth and latency which can be established from either a Layer 2 or Layer 3 (IP) interface, and which can co-exist on an IP network with best-effort traffic.

Additional requirements include optional redundant paths, very high reliability paths, time synchronization, and clock distribution.

Industries considered include wireless for industrial applications, professional audio, electrical utilities, building automation systems, radio/mobile access networks, automotive, and gaming.

For each case, this document will identify the application, identify representative solutions used today, and what new uses an IETF DetNet solution may enable.

#### Status of This Memo

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1. Introduction

This draft presents use cases from diverse industries which have in common a need for deterministic streams, but which also differ notably in their network topologies and specific desired behavior. Together, they provide broad industry context for DetNet and a yardstick against which proposed DetNet designs can be measured (to what extent does a proposed design satisfy these various use cases?)

For DetNet, use cases explicitly do not define requirements; The DetNet WG will consider the use cases, decide which elements are in scope for DetNet, and the results will be incorporated into future drafts. Similarly, the DetNet use case draft explicitly does not suggest any specific design, architecture or protocols, which will be topics of future drafts.

We present for each use case the answers to the following questions:

- o What is the use case?
- o How is it addressed today?
- o How would you like it to be addressed in the future?
- o What do you want the IETF to deliver?

The level of detail in each use case should be sufficient to express the relevant elements of the use case, but not more.

At the end we consider the use cases collectively, and examine the most significant goals they have in common.

## 2. Pro Audio and Video

### 2.1. Use Case Description

The professional audio and video industry ("ProAV") includes:

- o Music and film content creation
- o Broadcast
- o Cinema
- o Live sound
- o Public address, media and emergency systems at large venues (airports, stadiums, churches, theme parks).

These industries have already transitioned audio and video signals from analog to digital. However, the digital interconnect systems remain primarily point-to-point with a single (or small number of) signals per link, interconnected with purpose-built hardware.

These industries are now transitioning to packet-based infrastructure to reduce cost, increase routing flexibility, and integrate with existing IT infrastructure.

Today ProAV applications have no way to establish deterministic streams from a standards-based Layer 3 (IP) interface, which is a fundamental limitation to the use cases described here. Today deterministic streams can be created within standards-based layer 2 LANs (e.g. using IEEE 802.1 AVB) however these are not routable via IP and thus are not effective for distribution over wider areas (for example broadcast events that span wide geographical areas).

It would be highly desirable if such streams could be routed over the open Internet, however solutions with more limited scope (e.g. enterprise networks) would still provide a substantial improvement.

The following sections describe specific ProAV use cases.

#### 2.1.1. Uninterrupted Stream Playback

Transmitting audio and video streams for live playback is unlike common file transfer because uninterrupted stream playback in the presence of network errors cannot be achieved by re-trying the transmission; by the time the missing or corrupt packet has been identified it is too late to execute a re-try operation. Buffering can be used to provide enough delay to allow time for one or more

retries, however this is not an effective solution in applications where large delays (latencies) are not acceptable (as discussed below).

Streams with guaranteed bandwidth can eliminate congestion on the network as a cause of transmission errors that would lead to playback interruption. Use of redundant paths can further mitigate transmission errors to provide greater stream reliability.

### 2.1.2. Synchronized Stream Playback

Latency in this context is the time between when a signal is initially sent over a stream and when it is received. A common example in ProAV is time-synchronizing audio and video when they take separate paths through the playback system. In this case the latency of both the audio and video streams must be bounded and consistent if the sound is to remain matched to the movement in the video. A common tolerance for audio/video sync is one NTSC video frame (about 33ms) and to maintain the audience perception of correct lip sync the latency needs to be consistent within some reasonable tolerance, for example 10%.

A common architecture for synchronizing multiple streams that have different paths through the network (and thus potentially different latencies) is to enable measurement of the latency of each path, and have the data sinks (for example speakers) delay (buffer) all packets on all but the slowest path. Each packet of each stream is assigned a presentation time which is based on the longest required delay. This implies that all sinks must maintain a common time reference of sufficient accuracy, which can be achieved by any of various techniques.

This type of architecture is commonly implemented using a central controller that determines path delays and arbitrates buffering delays.

### 2.1.3. Sound Reinforcement

Consider the latency (delay) from when a person speaks into a microphone to when their voice emerges from the speaker. If this delay is longer than about 10-15 milliseconds it is noticeable and can make a sound reinforcement system unusable (see slide 6 of [SRP\_LATENCY]). (If you have ever tried to speak in the presence of a delayed echo of your voice you may know this experience).

Note that the 15ms latency bound includes all parts of the signal path, not just the network, so the network latency must be significantly less than 15ms.

In some cases local performers must perform in synchrony with a remote broadcast. In such cases the latencies of the broadcast stream and the local performer must be adjusted to match each other, with a worst case of one video frame (33ms for NTSC video).

In cases where audio phase is a consideration, for example beam-forming using multiple speakers, latency requirements can be in the 10 microsecond range (1 audio sample at 96kHz).

#### 2.1.4. Deterministic Time to Establish Streaming

Note: It is still under WG discussion whether this topic (stream startup time) is within scope of DetNet.

Some audio systems installed in public environments (airports, hospitals) have unique requirements with regards to health, safety and fire concerns. One such requirement is a maximum of 3 seconds for a system to respond to an emergency detection and begin sending appropriate warning signals and alarms without human intervention. For this requirement to be met, the system must support a bounded and acceptable time from a notification signal to specific stream establishment. For further details see [ISO7240-16].

Similar requirements apply when the system is restarted after a power cycle, cable re-connection, or system reconfiguration.

In many cases such re-establishment of streaming state must be achieved by the peer devices themselves, i.e. without a central controller (since such a controller may only be present during initial network configuration).

Video systems introduce related requirements, for example when transitioning from one camera feed (video stream) to another (see [STUDIO\_IP] and [ESPN\_DC2]).

#### 2.1.5. Secure Transmission

##### 2.1.5.1. Safety

Professional audio systems can include amplifiers that are capable of generating hundreds or thousands of watts of audio power which if used incorrectly can cause hearing damage to those in the vicinity. Apart from the usual care required by the systems operators to prevent such incidents, the network traffic that controls these devices must be secured (as with any sensitive application traffic).

## 2.2. Pro Audio Today

Some proprietary systems have been created which enable deterministic streams at Layer 3 however they are "engineered networks" which require careful configuration to operate, often require that the system be over-provisioned, and it is implied that all devices on the network voluntarily play by the rules of that network. To enable these industries to successfully transition to an interoperable multi-vendor packet-based infrastructure requires effective open standards, and we believe that establishing relevant IETF standards is a crucial factor.

## 2.3. Pro Audio Future

### 2.3.1. Layer 3 Interconnecting Layer 2 Islands

It would be valuable to enable IP to connect multiple Layer 2 LANs.

As an example, ESPN recently constructed a state-of-the-art 194,000 sq ft, \$125 million broadcast studio called DC2. The DC2 network is capable of handling 46 Tbps of throughput with 60,000 simultaneous signals. Inside the facility are 1,100 miles of fiber feeding four audio control rooms (see [ESPN\_DC2] ).

In designing DC2 they replaced as much point-to-point technology as they could with packet-based technology. They constructed seven individual studios using layer 2 LANS (using IEEE 802.1 AVB) that were entirely effective at routing audio within the LANs. However to interconnect these layer 2 LAN islands together they ended up using dedicated paths in a custom SDN (Software Defined Networking) router because there is no standards-based routing solution available.

### 2.3.2. High Reliability Stream Paths

On-air and other live media streams are often backed up with redundant links that seamlessly act to deliver the content when the primary link fails for any reason. In point-to-point systems this is provided by an additional point-to-point link; the analogous requirement in a packet-based system is to provide an alternate path through the network such that no individual link can bring down the system.

### 2.3.3. Integration of Reserved Streams into IT Networks

A commonly cited goal of moving to a packet based media infrastructure is that costs can be reduced by using off the shelf, commodity network hardware. In addition, economy of scale can be realized by combining media infrastructure with IT infrastructure.

In keeping with these goals, stream reservation technology should be compatible with existing protocols, and not compromise use of the network for best effort (non-time-sensitive) traffic.

#### 2.3.4. Use of Unused Reservations by Best-Effort Traffic

In cases where stream bandwidth is reserved but not currently used (or is under-utilized) that bandwidth must be available to best-effort (i.e. non-time-sensitive) traffic. For example a single stream may be nailed up (reserved) for specific media content that needs to be presented at different times of the day, ensuring timely delivery of that content, yet in between those times the full bandwidth of the network can be utilized for best-effort tasks such as file transfers.

This also addresses a concern of IT network administrators that are considering adding reserved bandwidth traffic to their networks that ("users will reserve large quantities of bandwidth and then never un-reserve it even though they are not using it, and soon the network will have no bandwidth left").

#### 2.3.5. Traffic Segregation

Note: It is still under WG discussion whether this topic will be addressed by DetNet.

Sink devices may be low cost devices with limited processing power. In order to not overwhelm the CPUs in these devices it is important to limit the amount of traffic that these devices must process.

As an example, consider the use of individual seat speakers in a cinema. These speakers are typically required to be cost reduced since the quantities in a single theater can reach hundreds of seats. Discovery protocols alone in a one thousand seat theater can generate enough broadcast traffic to overwhelm a low powered CPU. Thus an installation like this will benefit greatly from some type of traffic segregation that can define groups of seats to reduce traffic within each group. All seats in the theater must still be able to communicate with a central controller.

There are many techniques that can be used to support this requirement including (but not limited to) the following examples.

##### 2.3.5.1. Packet Forwarding Rules, VLANs and Subnets

Packet forwarding rules can be used to eliminate some extraneous streaming traffic from reaching potentially low powered sink devices,

however there may be other types of broadcast traffic that should be eliminated using other means for example VLANs or IP subnets.

#### 2.3.5.2. Multicast Addressing (IPv4 and IPv6)

Multicast addressing is commonly used to keep bandwidth utilization of shared links to a minimum.

Because of the MAC Address forwarding nature of Layer 2 bridges it is important that a multicast MAC address is only associated with one stream. This will prevent reservations from forwarding packets from one stream down a path that has no interested sinks simply because there is another stream on that same path that shares the same multicast MAC address.

Since each multicast MAC Address can represent 32 different IPv4 multicast addresses there must be a process put in place to make sure this does not occur. Requiring use of IPv6 address can achieve this, however due to their continued prevalence, solutions that are effective for IPv4 installations are also required.

#### 2.3.6. Latency Optimization by a Central Controller

A central network controller might also perform optimizations based on the individual path delays, for example sinks that are closer to the source can inform the controller that they can accept greater latency since they will be buffering packets to match presentation times of farther away sinks. The controller might then move a stream reservation on a short path to a longer path in order to free up bandwidth for other critical streams on that short path. See slides 3-5 of [SRP\_LATENCY].

Additional optimization can be achieved in cases where sinks have differing latency requirements, for example in a live outdoor concert the speaker sinks have stricter latency requirements than the recording hardware sinks. See slide 7 of [SRP\_LATENCY].

#### 2.3.7. Reduced Device Cost Due To Reduced Buffer Memory

Device cost can be reduced in a system with guaranteed reservations with a small bounded latency due to the reduced requirements for buffering (i.e. memory) on sink devices. For example, a theme park might broadcast a live event across the globe via a layer 3 protocol; in such cases the size of the buffers required is proportional to the latency bounds and jitter caused by delivery, which depends on the worst case segment of the end-to-end network path. For example on today's open internet the latency is typically unacceptable for audio and video streaming without many seconds of buffering. In such



scenarios a single gateway device at the local network that receives the feed from the remote site would provide the expensive buffering required to mask the latency and jitter issues associated with long distance delivery. Sink devices in the local location would have no additional buffering requirements, and thus no additional costs, beyond those required for delivery of local content. The sink device would be receiving the identical packets as those sent by the source and would be unaware that there were any latency or jitter issues along the path.

#### 2.4. Pro Audio Asks

- o Layer 3 routing on top of AVB (and/or other high QoS networks)
- o Content delivery with bounded, lowest possible latency
- o IntServ and DiffServ integration with AVB (where practical)
- o Single network for A/V and IT traffic
- o Standards-based, interoperable, multi-vendor
- o IT department friendly
- o Enterprise-wide networks (e.g. size of San Francisco but not the whole Internet (yet...))

### 3. Electrical Utilities

#### 3.1. Use Case Description

Many systems that an electrical utility deploys today rely on high availability and deterministic behavior of the underlying networks. Here we present use cases in Transmission, Generation and Distribution, including key timing and reliability metrics. We also discuss security issues and industry trends which affect the architecture of next generation utility networks

##### 3.1.1. Transmission Use Cases

###### 3.1.1.1. Protection

Protection means not only the protection of human operators but also the protection of the electrical equipment and the preservation of the stability and frequency of the grid. If a fault occurs in the transmission or distribution of electricity then severe damage can occur to human operators, electrical equipment and the grid itself, leading to blackouts.

Communication links in conjunction with protection relays are used to selectively isolate faults on high voltage lines, transformers, reactors and other important electrical equipment. The role of the teleprotection system is to selectively disconnect a faulty part by transferring command signals within the shortest possible time.

#### 3.1.1.1.1. Key Criteria

The key criteria for measuring teleprotection performance are command transmission time, dependability and security. These criteria are defined by the IEC standard 60834 as follows:

- o Transmission time (Speed): The time between the moment where state changes at the transmitter input and the moment of the corresponding change at the receiver output, including propagation delay. Overall operating time for a teleprotection system includes the time for initiating the command at the transmitting end, the propagation delay over the network (including equipments) and the selection and decision time at the receiving end, including any additional delay due to a noisy environment.
- o Dependability: The ability to issue and receive valid commands in the presence of interference and/or noise, by minimizing the probability of missing command (PMC). Dependability targets are typically set for a specific bit error rate (BER) level.
- o Security: The ability to prevent false tripping due to a noisy environment, by minimizing the probability of unwanted commands (PUC). Security targets are also set for a specific bit error rate (BER) level.

Additional elements of the the teleprotection system that impact its performance include:

- o Network bandwidth
- o Failure recovery capacity (aka resiliency)

#### 3.1.1.1.2. Fault Detection and Clearance Timing

Most power line equipment can tolerate short circuits or faults for up to approximately five power cycles before sustaining irreversible damage or affecting other segments in the network. This translates to total fault clearance time of 100ms. As a safety precaution, however, actual operation time of protection systems is limited to 70- 80 percent of this period, including fault recognition time, command transmission time and line breaker switching time.

Some system components, such as large electromechanical switches, require particularly long time to operate and take up the majority of the total clearance time, leaving only a 10ms window for the telecommunications part of the protection scheme, independent of the distance to travel. Given the sensitivity of the issue, new networks impose requirements that are even more stringent: IEC standard 61850 limits the transfer time for protection messages to 1/4 - 1/2 cycle or 4 - 8ms (for 60Hz lines) for the most critical messages.

#### 3.1.1.1.3. Symmetric Channel Delay

Note: It is currently under WG discussion whether symmetric path delays are to be guaranteed by DetNet.

Teleprotection channels which are differential must be synchronous, which means that any delays on the transmit and receive paths must match each other. Teleprotection systems ideally support zero asymmetric delay; typical legacy relays can tolerate delay discrepancies of up to 750us.

Some tools available for lowering delay variation below this threshold are:

- o For legacy systems using Time Division Multiplexing (TDM), jitter buffers at the multiplexers on each end of the line can be used to offset delay variation by queuing sent and received packets. The length of the queues must balance the need to regulate the rate of transmission with the need to limit overall delay, as larger buffers result in increased latency.
- o For jitter-prone IP packet networks, traffic management tools can ensure that the teleprotection signals receive the highest transmission priority to minimize jitter.
- o Standard packet-based synchronization technologies, such as 1588-2008 Precision Time Protocol (PTP) and Synchronous Ethernet (Sync-E), can help keep networks stable by maintaining a highly accurate clock source on the various network devices.

#### 3.1.1.1.4. Teleprotection Network Requirements (IEC 61850)

The following table captures the main network metrics as based on the IEC 61850 standard.

Teleprotection Requirement	Attribute
One way maximum delay	4-10 ms
Asymmetric delay required	Yes
Maximum jitter	less than 250 us (750 us for legacy IED)
Topology	Point to point, point to Multi-point
Availability	99.9999
precise timing required	Yes
Recovery time on node failure	less than 50ms - hitless
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	0.1% to 1%

Table 1: Teleprotection network requirements

3.1.1.1.5. Inter-Trip Protection scheme

"Inter-tripping" is the signal-controlled tripping of a circuit breaker to complete the isolation of a circuit or piece of apparatus in concert with the tripping of other circuit breakers.

Inter-Trip protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric delay required	No
Maximum jitter	Not critical
Topology	Point to point, point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on node failure	less than 50ms - hitless
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	0.1%

Table 2: Inter-Trip protection network requirements

3.1.1.1.6. Current Differential Protection Scheme

Current differential protection is commonly used for line protection, and is typical for protecting parallel circuits. At both end of the lines the current is measured by the differential relays, and both relays will trip the circuit breaker if the current going into the line does not equal the current going out of the line. This type of protection scheme assumes some form of communications being present between the relays at both end of the line, to allow both relays to compare measured current values. Line differential protection schemes assume a very low telecommunications delay between both relays, often as low as 5ms. Moreover, as those systems are often not time-synchronized, they also assume symmetric telecommunications paths with constant delay, which allows comparing current measurement values taken at the exact same time.

Current Differential protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric delay Required	Yes
Maximum jitter	less than 250 us (750us for legacy IED)
Topology	Point to point, point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on node failure	less than 50ms - hitless
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	0.1%

Table 3: Current Differential Protection metrics

3.1.1.1.7. Distance Protection Scheme

Distance (Impedance Relay) protection scheme is based on voltage and current measurements. The network metrics are similar (but not identical to) Current Differential protection.

Distance protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric delay Required	No
Maximum jitter	Not critical
Topology	Point to point, point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on node failure performance management	less than 50ms - hitless
Redundancy	Yes, Mandatory
Packet loss	Yes 0.1%

Table 4: Distance Protection requirements

## 3.1.1.1.8. Inter-Substation Protection Signaling

This use case describes the exchange of Sampled Value and/or GOOSE (Generic Object Oriented Substation Events) message between Intelligent Electronic Devices (IED) in two substations for protection and tripping coordination. The two IEDs are in a master-slave mode.

The Current Transformer or Voltage Transformer (CT/VT) in one substation sends the sampled analog voltage or current value to the Merging Unit (MU) over hard wire. The MU sends the time-synchronized 61850-9-2 sampled values to the slave IED. The slave IED forwards the information to the Master IED in the other substation. The master IED makes the determination (for example based on sampled value differentials) to send a trip command to the originating IED. Once the slave IED/Relay receives the GOOSE trip for breaker tripping, it opens the breaker. It then sends a confirmation message back to the master. All data exchanges between IEDs are either through Sampled Value and/or GOOSE messages.

Inter-Substation protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric delay Required	No
Maximum jitter	Not critical
Topology	Point to point, point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on node failure	less than 50ms - hitless
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	1%

Table 5: Inter-Substation Protection requirements

3.1.1.2. Intra-Substation Process Bus Communications

This use case describes the data flow from the CT/VT to the IEDs in the substation via the MU. The CT/VT in the substation send the sampled value (analog voltage or current) to the MU over hard wire. The MU sends the time-synchronized 61850-9-2 sampled values to the IEDs in the substation in GOOSE message format. The GPS Master Clock can send 1PPS or IRIG-B format to the MU through a serial port or IEEE 1588 protocol via a network. Process bus communication using 61850 simplifies connectivity within the substation and removes the requirement for multiple serial connections and removes the slow serial bus architectures that are typically used. This also ensures increased flexibility and increased speed with the use of multicast messaging between multiple devices.

Intra-Substation protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric delay Required	No
Maximum jitter	Not critical
Topology	Point to point, point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on Node failure	less than 50ms - hitless
performance management	Yes, Mandatory
Redundancy	Yes - No
Packet loss	0.1%

Table 6: Intra-Substation Protection requirements

3.1.1.3. Wide Area Monitoring and Control Systems

The application of synchrophasor measurement data from Phasor Measurement Units (PMU) to Wide Area Monitoring and Control Systems promises to provide important new capabilities for improving system stability. Access to PMU data enables more timely situational awareness over larger portions of the grid than what has been possible historically with normal SCADA (Supervisory Control and Data Acquisition) data. Handling the volume and real-time nature of synchrophasor data presents unique challenges for existing application architectures. Wide Area management System (WAMS) makes it possible for the condition of the bulk power system to be observed and understood in real-time so that protective, preventative, or corrective action can be taken. Because of the very high sampling rate of measurements and the strict requirement for time synchronization of the samples, WAMS has stringent telecommunications requirements in an IP network that are captured in the following table:



WAMS Requirement	Attribute
One way maximum delay	50 ms
Asymetric delay Required	No
Maximum jitter Topology	Not critical Point to point, point to Multi-point, Multi-point to Multi-point
Bandwidth	100 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on Node failure performance management	less than 50ms - hitless Yes, Mandatory
Redundancy	Yes
Packet loss	1%
Consecutive Packet Loss	At least 1 packet per application cycle must be received.

Table 7: WAMS Special Communication Requirements

3.1.1.4. IEC 61850 WAN engineering guidelines requirement classification

The IEC (International Electrotechnical Commission) has recently published a Technical Report which offers guidelines on how to define and deploy Wide Area Networks for the interconnections of electric substations, generation plants and SCADA operation centers. The IEC 61850-90-12 is providing a classification of WAN communication requirements into 4 classes. Table 8 summarizes these requirements:

WAN Requirement	Class WA	Class WB	Class WC	Class WD
Application field	EHV (Extra High Voltage)	HV (High Voltage)	MV (Medium Voltage)	General purpose
Latency	5 ms	10 ms	100 ms	> 100 ms
Jitter	10 us	100 us	1 ms	10 ms
Latency Asymetry	100 us	1 ms	10 ms	100 ms
Time Accuracy	1 us	10 us	100 us	10 to 100 ms
Bit Error rate	10 <sup>-7</sup> to 10 <sup>-6</sup>	10 <sup>-5</sup> to 10 <sup>-4</sup>	10 <sup>-3</sup>	
Unavailability	10 <sup>-7</sup> to 10 <sup>-6</sup>	10 <sup>-5</sup> to 10 <sup>-4</sup>	10 <sup>-3</sup>	
Recovery delay	Zero	50 ms	5 s	50 s
Cyber security	extremely high	High	Medium	Medium

Table 8: 61850-90-12 Communication Requirements; Courtesy of IEC

### 3.1.2. Generation Use Case

Energy generation systems are complex infrastructures that require control of both the generated power and the generation infrastructure.

#### 3.1.2.1. Control of the Generated Power

The electrical power generation frequency must be maintained within a very narrow band. Deviations from the acceptable frequency range are detected and the required signals are sent to the power plants for frequency regulation.

Automatic Generation Control (AGC) is a system for adjusting the power output of generators at different power plants, in response to changes in the load.

FCAG (Frequency Control Automatic Generation) Requirement	Attribute
One way maximum delay	500 ms
Asymmetric delay Required	No
Maximum jitter	Not critical
Topology	Point to point
Bandwidth	20 Kbps
Availability	99.999
precise timing required	Yes
Recovery time on Node failure	N/A
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	1%

Table 9: FCAG Communication Requirements

## 3.1.2.2. Control of the Generation Infrastructure

The control of the generation infrastructure combines requirements from industrial automation systems and energy generation systems. In this section we present the use case of the control of the generation infrastructure of a wind turbine.

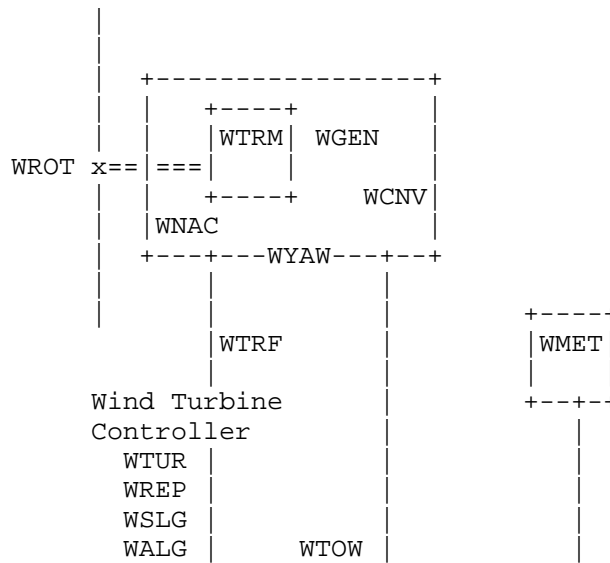


Figure 1: Wind Turbine Control Network

Figure 1 presents the subsystems that operate a wind turbine. These subsystems include

- o WROT (Rotor Control)
- o WNAC (Nacelle Control) (nacelle: housing containing the generator)
- o WTRM (Transmission Control)
- o WGEN (Generator)
- o WYAW (Yaw Controller) (of the tower head)
- o WCNV (In-Turbine Power Converter)
- o WMET (External Meteorological Station providing real time information to the controllers of the tower)

Traffic characteristics relevant for the network planning and dimensioning process in a wind turbine scenario are listed below. The values in this section are based mainly on the relevant references [Ahm14] and [Spe09]. Each logical node (Figure 1) is a part of the metering network and produces analog measurements and status information which must comply with their respective data rate constraints.

Subsystem	Sensor Count	Analog Sample Count	Data Rate (bytes/sec)	Status Sample Count	Data rate (bytes/sec)
WROT	14	9	642	5	10
WTRM	18	10	2828	8	16
WGEN	14	12	73764	2	4
WCNV	14	12	74060	2	4
WTRF	12	5	73740	2	4
WNAC	12	9	112	3	6
WYAW	7	8	220	4	8
WTOW	4	1	8	3	6
WMET	7	7	228	-	-

Table 10: Wind Turbine Data Rate Constraints

Quality of Service (QoS) constraints for different services are presented in Table 11. These constraints are defined by IEEE 1646 standard [IEEE1646] and IEC 61400 standard [IEC61400].

Service	Latency	Reliability	Packet Loss Rate
Analogue measure	16 ms	99.99%	< 10 <sup>-6</sup>
Status information	16 ms	99.99%	< 10 <sup>-6</sup>
Protection traffic	4 ms	100.00%	< 10 <sup>-9</sup>
Reporting and logging	1 s	99.99%	< 10 <sup>-6</sup>
Video surveillance	1 s	99.00%	No specific requirement
Internet connection	60 min	99.00%	No specific requirement
Control traffic	16 ms	100.00%	< 10 <sup>-9</sup>
Data polling	16 ms	99.99%	< 10 <sup>-6</sup>

Table 11: Wind Turbine Reliability and Latency Constraints

### 3.1.2.2.1. Intra-Domain Network Considerations

A wind turbine is composed of a large set of subsystems including sensors and actuators which require time-critical operation. The reliability and latency constraints of these different subsystems is shown in Table 11. These subsystems are connected to an intra-domain network which is used to monitor and control the operation of the turbine and connect it to the SCADA subsystems. The different

components are interconnected using fiber optics, industrial buses, industrial Ethernet, EtherCat, or a combination of them. Industrial signaling and control protocols such as Modbus, Profibus, Profinet and EtherCat are used directly on top of the Layer 2 transport or encapsulated over TCP/IP.

The Data collected from the sensors and condition monitoring systems is multiplexed onto fiber cables for transmission to the base of the tower, and to remote control centers. The turbine controller continuously monitors the condition of the wind turbine and collects statistics on its operation. This controller also manages a large number of switches, hydraulic pumps, valves, and motors within the wind turbine.

There is usually a controller both at the bottom of the tower and in the nacelle. The communication between these two controllers usually takes place using fiber optics instead of copper links. Sometimes, a third controller is installed in the hub of the rotor and manages the pitch of the blades. That unit usually communicates with the nacelle unit using serial communications.

#### 3.1.2.2.2. Inter-Domain network considerations

A remote control center belonging to a grid operator regulates the power output, enables remote actuation, and monitors the health of one or more wind parks in tandem. It connects to the local control center in a wind park over the Internet (Figure 2) via firewalls at both ends. The AS path between the local control center and the Wind Park typically involves several ISPs at different tiers. For example, a remote control center in Denmark can regulate a wind park in Greece over the normal public AS path between the two locations.

The remote control center is part of the SCADA system, setting the desired power output to the wind park and reading back the result once the new power output level has been set. Traffic between the remote control center and the wind park typically consists of protocols like IEC 60870-5-104 [IEC-60870-5-104], OPC XML-DA [OPCXML], Modbus [MODBUS], and SNMP [RFC3411]. Currently, traffic flows between the wind farm and the remote control center are best effort. QoS requirements are not strict, so no SLAs or service provisioning mechanisms (e.g., VPN) are employed. In case of events like equipment failure, tolerance for alarm delay is on the order of minutes, due to redundant systems already in place.

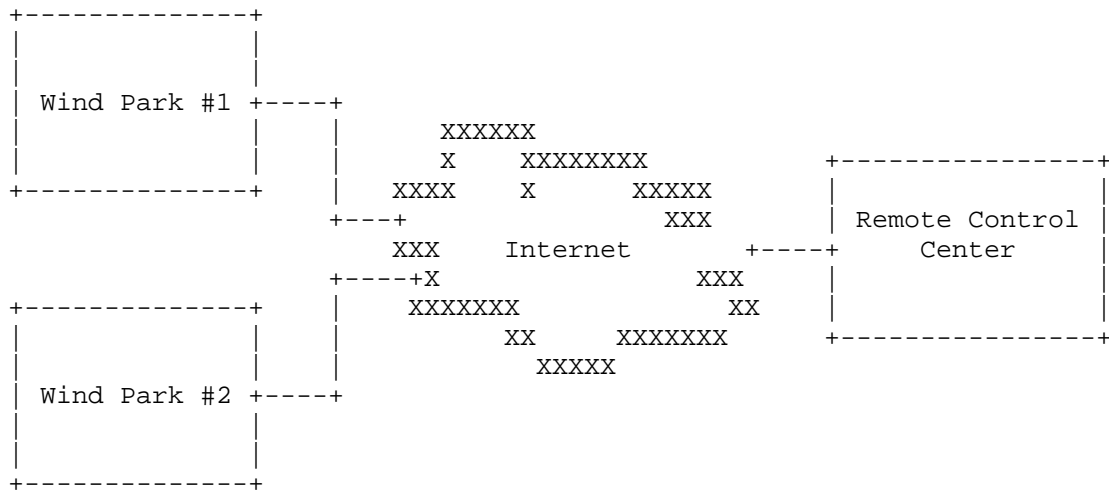


Figure 2: Wind Turbine Control via Internet

We expect future use cases which require bounded latency, bounded jitter and extraordinary low packet loss for inter-domain traffic flows due to the softwarization and virtualization of core wind farm equipment (e.g. switches, firewalls and SCADA server components). These factors will create opportunities for service providers to install new services and dynamically manage them from remote locations. For example, to enable fail-over of a local SCADA server, a SCADA server in another wind farm site (under the administrative control of the same operator) could be utilized temporarily (Figure 3). In that case local traffic would be forwarded to the remote SCADA server and existing intra-domain QoS and timing parameters would have to be met for inter-domain traffic flows.

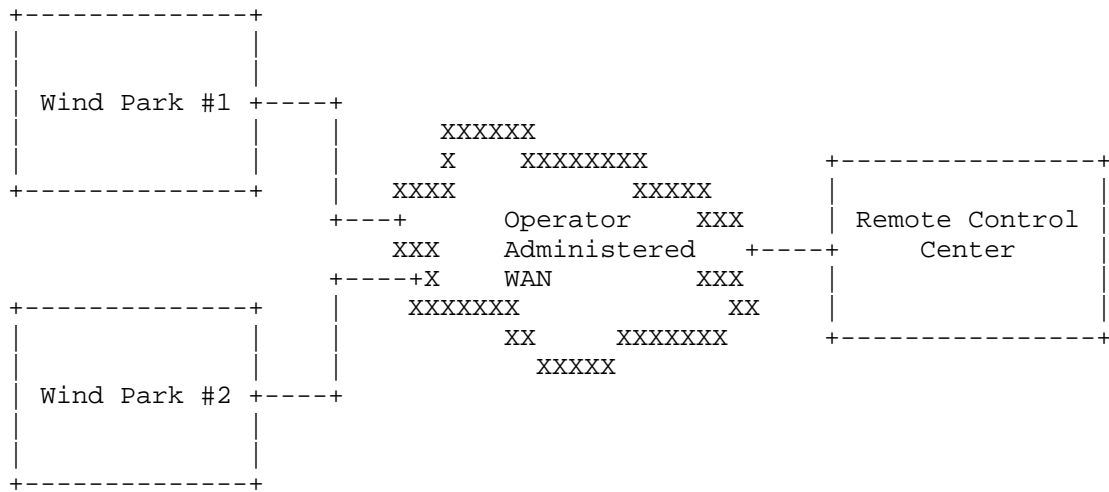


Figure 3: Wind Turbine Control via Operator Administered WAN

3.1.3. Distribution use case

3.1.3.1. Fault Location Isolation and Service Restoration (FLISR)

Fault Location, Isolation, and Service Restoration (FLISR) refers to the ability to automatically locate the fault, isolate the fault, and restore service in the distribution network. This will likely be the first widespread application of distributed intelligence in the grid.

Static power switch status (open/closed) in the network dictates the power flow to secondary substations. Reconfiguring the network in the event of a fault is typically done manually on site to energize/de-energize alternate paths. Automating the operation of substation switchgear allows the flow of power to be altered automatically under fault conditions.

FLISR can be managed centrally from a Distribution Management System (DMS) or executed locally through distributed control via intelligent switches and fault sensors.



FLISR Requirement	Attribute
One way maximum delay	80 ms
Asymmetric delay Required	No
Maximum jitter	40 ms
Topology	Point to point, point to Multi-point, Multi-point to Multi-point
Bandwidth	64 Kbps
Availability	99.9999
precise timing required	Yes
Recovery time on Node failure performance management	Depends on customer impact
Redundancy	Yes, Mandatory
Packet loss	Yes 0.1%

Table 12: FLISR Communication Requirements

### 3.2. Electrical Utilities Today

Many utilities still rely on complex environments formed of multiple application-specific proprietary networks, including TDM networks.

In this kind of environment there is no mixing of OT and IT applications on the same network, and information is siloed between operational areas.

Specific calibration of the full chain is required, which is costly.

This kind of environment prevents utility operations from realizing the operational efficiency benefits, visibility, and functional integration of operational information across grid applications and data networks.

In addition, there are many security-related issues as discussed in the following section.

#### 3.2.1. Security Current Practices and Limitations

Grid monitoring and control devices are already targets for cyber attacks, and legacy telecommunications protocols have many intrinsic network-related vulnerabilities. For example, DNP3, Modbus,

PROFIBUS/PROFINET, and other protocols are designed around a common paradigm of request and respond. Each protocol is designed for a master device such as an HMI (Human Machine Interface) system to send commands to subordinate slave devices to retrieve data (reading inputs) or control (writing to outputs). Because many of these protocols lack authentication, encryption, or other basic security measures, they are prone to network-based attacks, allowing a malicious actor or attacker to utilize the request-and-respond system as a mechanism for command-and-control like functionality. Specific security concerns common to most industrial control, including utility telecommunication protocols include the following:

- o Network or transport errors (e.g. malformed packets or excessive latency) can cause protocol failure.
- o Protocol commands may be available that are capable of forcing slave devices into inoperable states, including powering-off devices, forcing them into a listen-only state, disabling alarming.
- o Protocol commands may be available that are capable of restarting communications and otherwise interrupting processes.
- o Protocol commands may be available that are capable of clearing, erasing, or resetting diagnostic information such as counters and diagnostic registers.
- o Protocol commands may be available that are capable of requesting sensitive information about the controllers, their configurations, or other need-to-know information.
- o Most protocols are application layer protocols transported over TCP; therefore it is easy to transport commands over non-standard ports or inject commands into authorized traffic flows.
- o Protocol commands may be available that are capable of broadcasting messages to many devices at once (i.e. a potential DoS).
- o Protocol commands may be available to query the device network to obtain defined points and their values (i.e. a configuration scan).
- o Protocol commands may be available that will list all available function codes (i.e. a function scan).

These inherent vulnerabilities, along with increasing connectivity between IT and OT networks, make network-based attacks very feasible.

Simple injection of malicious protocol commands provides control over the target process. Altering legitimate protocol traffic can also alter information about a process and disrupt the legitimate controls that are in place over that process. A man-in-the-middle attack could provide both control over a process and misrepresentation of data back to operator consoles.

### 3.3. Electrical Utilities Future

The business and technology trends that are sweeping the utility industry will drastically transform the utility business from the way it has been for many decades. At the core of many of these changes is a drive to modernize the electrical grid with an integrated telecommunications infrastructure. However, interoperability concerns, legacy networks, disparate tools, and stringent security requirements all add complexity to the grid transformation. Given the range and diversity of the requirements that should be addressed by the next generation telecommunications infrastructure, utilities need to adopt a holistic architectural approach to integrate the electrical grid with digital telecommunications across the entire power delivery chain.

The key to modernizing grid telecommunications is to provide a common, adaptable, multi-service network infrastructure for the entire utility organization. Such a network serves as the platform for current capabilities while enabling future expansion of the network to accommodate new applications and services.

To meet this diverse set of requirements, both today and in the future, the next generation utility telecommunications network will be based on open-standards-based IP architecture. An end-to-end IP architecture takes advantage of nearly three decades of IP technology development, facilitating interoperability and device management across disparate networks and devices, as it has been already demonstrated in many mission-critical and highly secure networks.

IPv6 is seen as a future telecommunications technology for the Smart Grid; the IEC (International Electrotechnical Commission) and different National Committees have mandated a specific adhoc group (AHG8) to define the migration strategy to IPv6 for all the IEC TC57 power automation standards.

We expect cloud-based SCADA systems to control and monitor the critical and non-critical subsystems of generation systems, for example wind farms.

### 3.3.1. Migration to Packet-Switched Network

Throughout the world, utilities are increasingly planning for a future based on smart grid applications requiring advanced telecommunications systems. Many of these applications utilize packet connectivity for communicating information and control signals across the utility's Wide Area Network (WAN), made possible by technologies such as multiprotocol label switching (MPLS). The data that traverses the utility WAN includes:

- o Grid monitoring, control, and protection data
- o Non-control grid data (e.g. asset data for condition-based monitoring)
- o Physical safety and security data (e.g. voice and video)
- o Remote worker access to corporate applications (voice, maps, schematics, etc.)
- o Field area network backhaul for smart metering, and distribution grid management
- o Enterprise traffic (email, collaboration tools, business applications)

WANs support this wide variety of traffic to and from substations, the transmission and distribution grid, generation sites, between control centers, and between work locations and data centers. To maintain this rapidly expanding set of applications, many utilities are taking steps to evolve present time-division multiplexing (TDM) based and frame relay infrastructures to packet systems. Packet-based networks are designed to provide greater functionalities and higher levels of service for applications, while continuing to deliver reliability and deterministic (real-time) traffic support.

### 3.3.2. Telecommunications Trends

These general telecommunications topics are in addition to the use cases that have been addressed so far. These include both current and future telecommunications related topics that should be factored into the network architecture and design.

#### 3.3.2.1. General Telecommunications Requirements

- o IP Connectivity everywhere
- o Monitoring services everywhere and from different remote centers

- o Move services to a virtual data center
- o Unify access to applications / information from the corporate network
- o Unify services
- o Unified Communications Solutions
- o Mix of fiber and microwave technologies - obsolescence of SONET/SDH or TDM
- o Standardize grid telecommunications protocol to opened standard to ensure interoperability
- o Reliable Telecommunications for Transmission and Distribution Substations
- o IEEE 1588 time synchronization Client / Server Capabilities
- o Integration of Multicast Design
- o QoS Requirements Mapping
- o Enable Future Network Expansion
- o Substation Network Resilience
- o Fast Convergence Design
- o Scalable Headend Design
- o Define Service Level Agreements (SLA) and Enable SLA Monitoring
- o Integration of 3G/4G Technologies and future technologies
- o Ethernet Connectivity for Station Bus Architecture
- o Ethernet Connectivity for Process Bus Architecture
- o Protection, teleprotection and PMU (Phaser Measurement Unit) on IP

#### 3.3.2.2. Specific Network topologies of Smart Grid Applications

Utilities often have very large private telecommunications networks. It covers an entire territory / country. The main purpose of the network, until now, has been to support transmission network monitoring, control, and automation, remote control of generation

sites, and providing FCAPS (Fault, Configuration, Accounting, Performance, Security) services from centralized network operation centers.

Going forward, one network will support operation and maintenance of electrical networks (generation, transmission, and distribution), voice and data services for ten of thousands of employees and for exchange with neighboring interconnections, and administrative services. To meet those requirements, utility may deploy several physical networks leveraging different technologies across the country: an optical network and a microwave network for instance. Each protection and automatism system between two points has two telecommunications circuits, one on each network. Path diversity between two substations is key. Regardless of the event type (hurricane, ice storm, etc.), one path shall stay available so the system can still operate.

In the optical network, signals are transmitted over more than tens of thousands of circuits using fiber optic links, microwave and telephone cables. This network is the nervous system of the utility's power transmission operations. The optical network represents ten of thousands of km of cable deployed along the power lines, with individual runs as long as 280 km.

#### 3.3.2.3. Precision Time Protocol

Some utilities do not use GPS clocks in generation substations. One of the main reasons is that some of the generation plants are 30 to 50 meters deep under ground and the GPS signal can be weak and unreliable. Instead, atomic clocks are used. Clocks are synchronized amongst each other. Rubidium clocks provide clock and lms timestamps for IRIG-B.

Some companies plan to transition to the Precision Time Protocol (PTP, [IEEE1588]), distributing the synchronization signal over the IP/MPLS network. PTP provides a mechanism for synchronizing the clocks of participating nodes to a high degree of accuracy and precision.

PTP operates based on the following assumptions:

It is assumed that the network eliminates cyclic forwarding of PTP messages within each communication path (e.g. by using a spanning tree protocol).

PTP is tolerant of an occasional missed message, duplicated message, or message that arrived out of order. However, PTP assumes that such impairments are relatively rare.

PTP was designed assuming a multicast communication model, however PTP also supports a unicast communication model as long as the behavior of the protocol is preserved.

Like all message-based time transfer protocols, PTP time accuracy is degraded by delay asymmetry in the paths taken by event messages. Asymmetry is not detectable by PTP, however, if such delays are known a priori, PTP can correct for asymmetry.

IEC 61850 will recommend the use of the IEEE PTP 1588 Utility Profile (as defined in [IEC62439-3:2012] Annex B) which offers the support of redundant attachment of clocks to Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) networks.

### 3.3.3. Security Trends in Utility Networks

Although advanced telecommunications networks can assist in transforming the energy industry by playing a critical role in maintaining high levels of reliability, performance, and manageability, they also introduce the need for an integrated security infrastructure. Many of the technologies being deployed to support smart grid projects such as smart meters and sensors can increase the vulnerability of the grid to attack. Top security concerns for utilities migrating to an intelligent smart grid telecommunications platform center on the following trends:

- o Integration of distributed energy resources
- o Proliferation of digital devices to enable management, automation, protection, and control
- o Regulatory mandates to comply with standards for critical infrastructure protection
- o Migration to new systems for outage management, distribution automation, condition-based maintenance, load forecasting, and smart metering
- o Demand for new levels of customer service and energy management

This development of a diverse set of networks to support the integration of microgrids, open-access energy competition, and the use of network-controlled devices is driving the need for a converged security infrastructure for all participants in the smart grid, including utilities, energy service providers, large commercial and industrial, as well as residential customers. Securing the assets of electric power delivery systems (from the control center to the substation, to the feeders and down to customer meters) requires an

end-to-end security infrastructure that protects the myriad of telecommunications assets used to operate, monitor, and control power flow and measurement.

"Cyber security" refers to all the security issues in automation and telecommunications that affect any functions related to the operation of the electric power systems. Specifically, it involves the concepts of:

- o Integrity : data cannot be altered undetectably
- o Authenticity : the telecommunications parties involved must be validated as genuine
- o Authorization : only requests and commands from the authorized users can be accepted by the system
- o Confidentiality : data must not be accessible to any unauthenticated users

When designing and deploying new smart grid devices and telecommunications systems, it is imperative to understand the various impacts of these new components under a variety of attack situations on the power grid. Consequences of a cyber attack on the grid telecommunications network can be catastrophic. This is why security for smart grid is not just an ad hoc feature or product, it's a complete framework integrating both physical and Cyber security requirements and covering the entire smart grid networks from generation to distribution. Security has therefore become one of the main foundations of the utility telecom network architecture and must be considered at every layer with a defense-in-depth approach. Migrating to IP based protocols is key to address these challenges for two reasons:

- o IP enables a rich set of features and capabilities to enhance the security posture
- o IP is based on open standards, which allows interoperability between different vendors and products, driving down the costs associated with implementing security solutions in OT networks.

Securing OT (Operation technology) telecommunications over packet-switched IP networks follow the same principles that are foundational for securing the IT infrastructure, i.e., consideration must be given to enforcing electronic access control for both person-to-machine and machine-to-machine communications, and providing the appropriate levels of data privacy, device and platform integrity, and threat detection and mitigation.



### 3.4. Electrical Utilities Asks

- o Mixed L2 and L3 topologies
- o Deterministic behavior
- o Bounded latency and jitter
- o Tight feedback intervals
- o High availability, low recovery time
- o Redundancy, low packet loss
- o Precise timing
- o Centralized computing of deterministic paths
- o Distributed configuration may also be useful

## 4. Building Automation Systems

### 4.1. Use Case Description

A Building Automation System (BAS) manages equipment and sensors in a building for improving residents' comfort, reducing energy consumption, and responding to failures and emergencies. For example, the BAS measures the temperature of a room using sensors and then controls the HVAC (heating, ventilating, and air conditioning) to maintain a set temperature and minimize energy consumption.

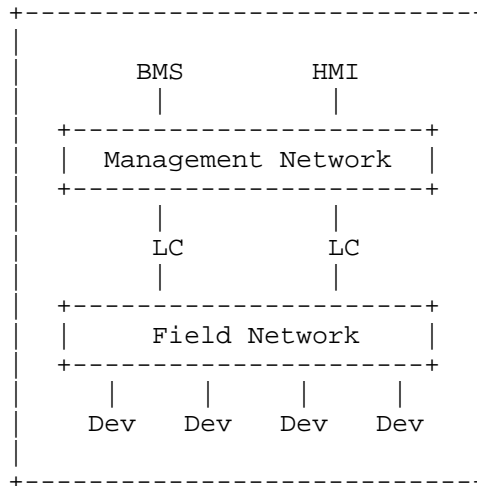
A BAS primarily performs the following functions:

- o Periodically measures states of devices, for example humidity and illuminance of rooms, open/close state of doors, FAN speed, etc.
- o Stores the measured data.
- o Provides the measured data to BAS systems and operators.
- o Generates alarms for abnormal state of devices.
- o Controls devices (e.g. turn off room lights at 10:00 PM).

## 4.2. Building Automation Systems Today

### 4.2.1. BAS Architecture

A typical BAS architecture of today is shown in Figure 4.



BMS := Building Management Server  
 HMI := Human Machine Interface  
 LC := Local Controller

Figure 4: BAS architecture

There are typically two layers of network in a BAS. The upper one is called the Management Network and the lower one is called the Field Network. In management networks an IP-based communication protocol is used, while in field networks non-IP based communication protocols ("field protocols") are mainly used. Field networks have specific timing requirements, whereas management networks can be best-effort.

A Human Machine Interface (HMI) is typically a desktop PC used by operators to monitor and display device states, send device control commands to Local Controllers (LCs), and configure building schedules (for example "turn off all room lights in the building at 10:00 PM").

A Building Management Server (BMS) performs the following operations.

- o Collect and store device states from LCs at regular intervals.
- o Send control values to LCs according to a building schedule.

- o Send an alarm signal to operators if it detects abnormal devices states.

The BMS and HMI communicate with LCs via IP-based "management protocols" (see standards [bacnetip], [knx]).

A LC is typically a Programmable Logic Controller (PLC) which is connected to several tens or hundreds of devices using "field protocols". An LC performs the following kinds of operations:

- o Measure device states and provide the information to BMS or HMI.
- o Send control values to devices, unilaterally or as part of a feedback control loop.

There are many field protocols used today; some are standards-based and others are proprietary (see standards [lontalk], [modbus], [profibus] and [flnet]). The result is that BASs have multiple MAC/PHY modules and interfaces. This makes BASs more expensive, slower to develop, and can result in "vendor lock-in" with multiple types of management applications.

#### 4.2.2. BAS Deployment Model

An example BAS for medium or large buildings is shown in Figure 5. The physical layout spans multiple floors, and there is a monitoring room where the BAS management entities are located. Each floor will have one or more LCs depending upon the number of devices connected to the field network.

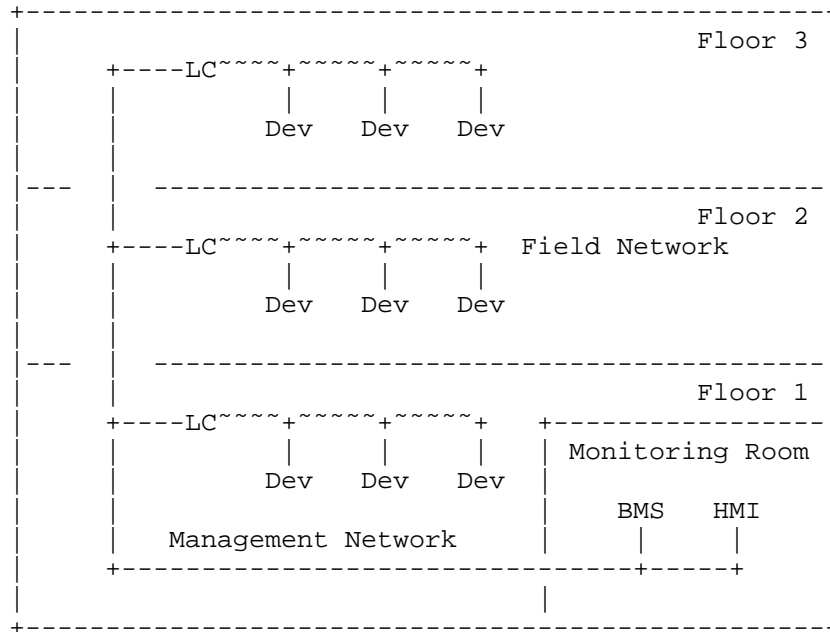


Figure 5: BAS Deployment model for Medium/Large Buildings

Each LC is connected to the monitoring room via the Management network, and the management functions are performed within the building. In most cases, fast Ethernet (e.g. 100BASE-T) is used for the management network. Since the management network is non-realtime, use of Ethernet without quality of service is sufficient for today's deployment.

In the field network a variety of physical interfaces such as RS232C and RS485 are used, which have specific timing requirements. Thus if a field network is to be replaced with an Ethernet or wireless network, such networks must support time-critical deterministic flows.

In Figure 6, another deployment model is presented in which the management system is hosted remotely. This is becoming popular for small office and residential buildings in which a standalone monitoring system is not cost-effective.

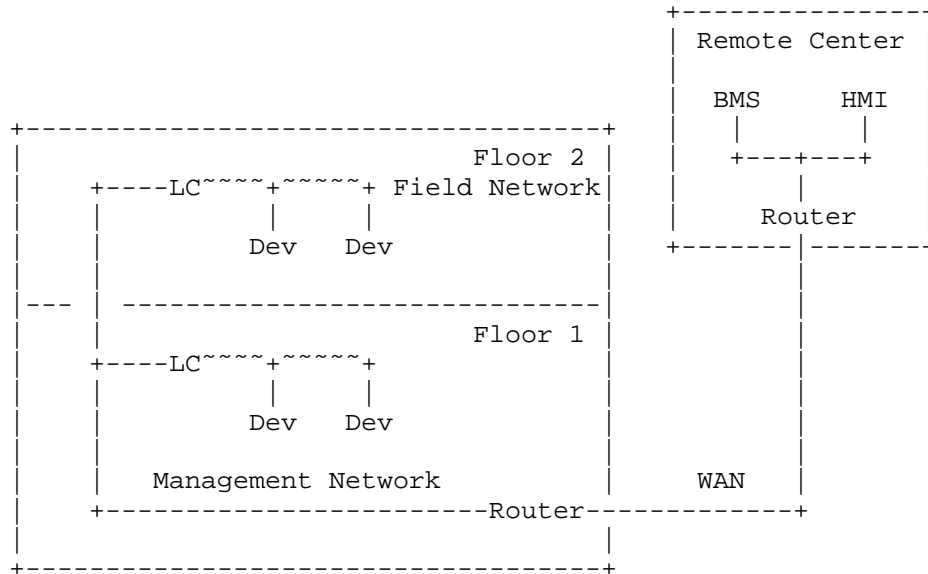


Figure 6: Deployment model for Small Buildings

Some interoperability is possible today in the Management Network, but not in today’s field networks due to their non-IP-based design.

4.2.3. Use Cases for Field Networks

Below are use cases for Environmental Monitoring, Fire Detection, and Feedback Control, and their implications for field network performance.

4.2.3.1. Environmental Monitoring

The BMS polls each LC at a maximum measurement interval of 100ms (for example to draw a historical chart of 1 second granularity with a 10x sampling interval) and then performs the operations as specified by the operator. Each LC needs to measure each of its several hundred sensors once per measurement interval. Latency is not critical in this scenario as long as all sensor values are completed in the measurement interval. Availability is expected to be 99.999 %.

4.2.3.2. Fire Detection

On detection of a fire, the BMS must stop the HVAC, close the fire shutters, turn on the fire sprinklers, send an alarm, etc. There are typically ~10s of sensors per LC that BMS needs to manage. In this

scenario the measurement interval is 10-50ms, the communication delay is 10ms, and the availability must be 99.9999 %.

#### 4.2.3.3. Feedback Control

BAS systems utilize feedback control in various ways; the most time-critical is control of DC motors, which require a short feedback interval (1-5ms) with low communication delay (10ms) and jitter (1ms). The feedback interval depends on the characteristics of the device and a target quality of control value. There are typically ~10s of such devices per LC.

Communication delay is expected to be less than 10 ms, jitter less than 1 sec while the availability must be 99.9999% .

#### 4.2.4. Security Considerations

When BAS field networks were developed it was assumed that the field networks would always be physically isolated from external networks and therefore security was not a concern. In today's world many BASs are managed remotely and are thus connected to shared IP networks and so security is definitely a concern, yet security features are not available in the majority of BAS field network deployments .

The management network, being an IP-based network, has the protocols available to enable network security, but in practice many BAS systems do not implement even the available security features such as device authentication or encryption for data in transit.

#### 4.3. BAS Future

In the future we expect more fine-grained environmental monitoring and lower energy consumption, which will require more sensors and devices, thus requiring larger and more complex building networks.

We expect building networks to be connected to or converged with other networks (Enterprise network, Home network, and Internet).

Therefore better facilities for network management, control, reliability and security are critical in order to improve resident and operator convenience and comfort. For example the ability to monitor and control building devices via the internet would enable (for example) control of room lights or HVAC from a resident's desktop PC or phone application.

#### 4.4. BAS Asks

The community would like to see an interoperable protocol specification that can satisfy the timing, security, availability and QoS constraints described above, such that the resulting converged network can replace the disparate field networks. Ideally this connectivity could extend to the open Internet.

This would imply an architecture that can guarantee

- o Low communication delays (from <10ms to 100ms in a network of several hundred devices)
- o Low jitter (< 1 ms)
- o Tight feedback intervals (1ms - 10ms)
- o High network availability (up to 99.9999% )
- o Availability of network data in disaster scenario
- o Authentication between management and field devices (both local and remote)
- o Integrity and data origin authentication of communication data between field and management devices
- o Confidentiality of data when communicated to a remote device

### 5. Wireless for Industrial

#### 5.1. Use Case Description

Wireless networks are useful for industrial applications, for example when portable, fast-moving or rotating objects are involved, and for the resource-constrained devices found in the Internet of Things (IoT).

Such network-connected sensors, actuators, control loops (etc.) typically require that the underlying network support real-time quality of service (QoS), as well as specific classes of other network properties such as reliability, redundancy, and security.

These networks may also contain very large numbers of devices, for example for factories, "big data" acquisition, and the IoT. Given the large numbers of devices installed, and the potential pervasiveness of the IoT, this is a huge and very cost-sensitive

market. For example, a 1% cost reduction in some areas could save \$100B

#### 5.1.1.1. Network Convergence using 6TiSCH

Some wireless network technologies support real-time QoS, and are thus useful for these kinds of networks, but others do not. For example WiFi is pervasive but does not provide guaranteed timing or delivery of packets, and thus is not useful in this context.

In this use case we focus on one specific wireless network technology which does provide the required deterministic QoS, which is "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH, where TSCH stands for "Time-Slotted Channel Hopping", see [I-D.ietf-6tisch-architecture], [IEEE802154], [IEEE802154e], and [RFC7554]).

There are other deterministic wireless busses and networks available today, however they are incompatible with each other, and incompatible with IP traffic (for example [ISA100], [WirelessHART]).

Thus the primary goal of this use case is to apply 6TiSCH as a converged IP- and standards-based wireless network for industrial applications, i.e. to replace multiple proprietary and/or incompatible wireless networking and wireless network management standards.

#### 5.1.1.2. Common Protocol Development for 6TiSCH

Today there are a number of protocols required by 6TiSCH which are still in development, and a second intent of this use case is to highlight the ways in which these "missing" protocols share goals in common with DetNet. Thus it is possible that some of the protocol technology developed for DetNet will also be applicable to 6TiSCH.

These protocol goals are identified here, along with their relationship to DetNet. It is likely that ultimately the resulting protocols will not be identical, but will share design principles which contribute to the efficiency of enabling both DetNet and 6TiSCH.

One such commonality is that although at a different time scale, in both TSN [IEEE802.1TSNTG] and TSCH a packet crosses the network from node to node follows a precise schedule, as a train that leaves intermediate stations at precise times along its path. This kind of operation reduces collisions, saves energy, and enables engineering the network for deterministic properties.

Another commonality is remote monitoring and scheduling management of a TSCH network by a Path Computation Element (PCE) and Network



Management Entity (NME). The PCE/NME manage timeslots and device resources in a manner that minimizes the interaction with and the load placed on resource-constrained devices. For example, a tiny IoT device may have just enough buffers to store one or a few IPv6 packets, and will have limited bandwidth between peers such that it can maintain only a small amount of peer information, and will not be able to store many packets waiting to be forwarded. It is advantageous then for it to only be required to carry out the specific behavior assigned to it by the PCE/NME (as opposed to maintaining its own IP stack, for example).

Note: Current WG discussion indicates that some peer-to-peer communication must be assumed, i.e. the PCE may communicate only indirectly with any given device, enabling hierarchical configuration of the system.

6TiSCH depends on [PCE] and [I-D.finn-detnet-architecture].

6TiSCH also depends on the fact that DetNet will maintain consistency with [IEEE802.1TSNTG].

## 5.2. Wireless Industrial Today

Today industrial wireless is accomplished using multiple deterministic wireless networks which are incompatible with each other and with IP traffic.

6TiSCH is not yet fully specified, so it cannot be used in today's applications.

## 5.3. Wireless Industrial Future

### 5.3.1. Unified Wireless Network and Management

We expect DetNet and 6TiSCH together to enable converged transport of deterministic and best-effort traffic flows between real-time industrial devices and wide area networks via IP routing. A high level view of a basic such network is shown in Figure 7.

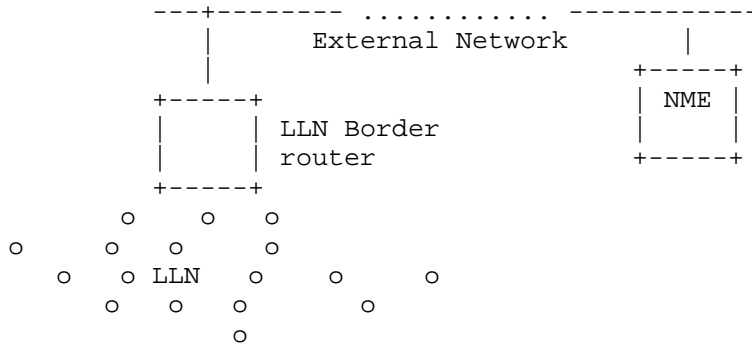


Figure 7: Basic 6TiSCH Network

Figure 8 shows a backbone router federating multiple synchronized 6TiSCH subnets into a single subnet connected to the external network.

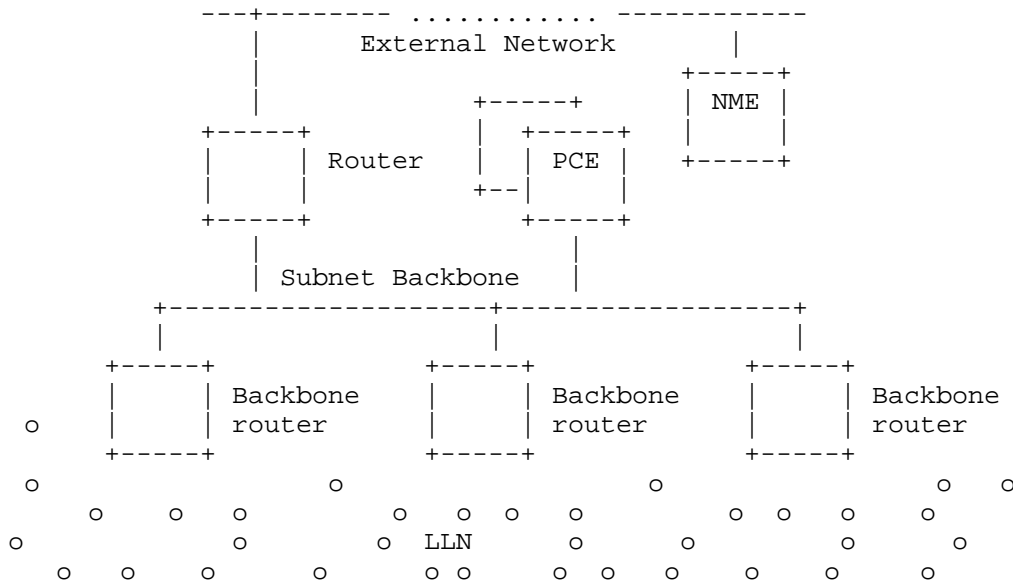


Figure 8: Extended 6TiSCH Network

The backbone router must ensure end-to-end deterministic behavior between the LLN and the backbone. We would like to see this accomplished in conformance with the work done in [I-D.finn-detnet-architecture] with respect to Layer-3 aspects of deterministic networks that span multiple Layer-2 domains.

The PCE must compute a deterministic path end-to-end across the TSCH network and IEEE802.1 TSN Ethernet backbone, and DetNet protocols are expected to enable end-to-end deterministic forwarding.

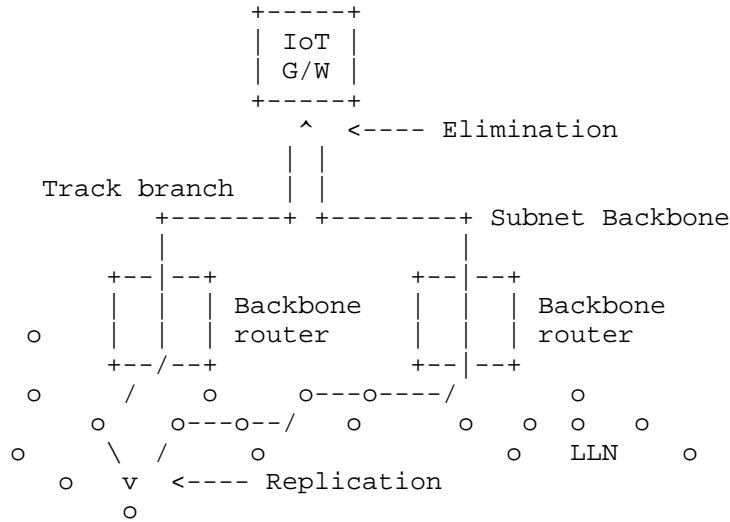


Figure 9: 6TiSCH Network with PRE

5.3.1.1. PCE and 6TiSCH ARQ Retries

Note: The possible use of ARQ techniques in DetNet is currently considered a possible design alternative.

6TiSCH uses the IEEE802.15.4 Automatic Repeat-reQuest (ARQ) mechanism to provide higher reliability of packet delivery. ARQ is related to packet replication and elimination because there are two independent paths for packets to arrive at the destination, and if an expected packet does not arrive on one path then it checks for the packet on the second path.

Although to date this mechanism is only used by wireless networks, this may be a technique that would be appropriate for DetNet and so aspects of the enabling protocol could be co-developed.

For example, in Figure 9, a Track is laid out from a field device in a 6TiSCH network to an IoT gateway that is located on a IEEE802.1 TSN backbone.

In ARQ the Replication function in the field device sends a copy of each packet over two different branches, and the PCE schedules each hop of both branches so that the two copies arrive in due time at the gateway. In case of a loss on one branch, hopefully the other copy of the packet still arrives within the allocated time. If two copies make it to the IoT gateway, the Elimination function in the gateway ignores the extra packet and presents only one copy to upper layers.

At each 6TiSCH hop along the Track, the PCE may schedule more than one timeSlot for a packet, so as to support Layer-2 retries (ARQ).

In current deployments, a TSCH Track does not necessarily support PRE but is systematically multi-path. This means that a Track is scheduled so as to ensure that each hop has at least two forwarding solutions, and the forwarding decision is to try the preferred one and use the other in case of Layer-2 transmission failure as detected by ARQ.

### 5.3.2. Schedule Management by a PCE

A common feature of 6TiSCH and DetNet is the action of a PCE to configure paths through the network. Specifically, what is needed is a protocol and data model that the PCE will use to get/set the relevant configuration from/to the devices, as well as perform operations on the devices. We expect that this protocol will be developed by DetNet with consideration for its reuse by 6TiSCH. The remainder of this section provides a bit more context from the 6TiSCH side.

#### 5.3.2.1. PCE Commands and 6TiSCH CoAP Requests

The 6TiSCH device does not expect to place the request for bandwidth between itself and another device in the network. Rather, an operation control system invoked through a human interface specifies the required traffic specification and the end nodes (in terms of latency and reliability). Based on this information, the PCE must compute a path between the end nodes and provision the network with per-flow state that describes the per-hop operation for a given packet, the corresponding timeslots, and the flow identification that enables recognizing that a certain packet belongs to a certain path, etc.

For a static configuration that serves a certain purpose for a long period of time, it is expected that a node will be provisioned in one shot with a full schedule, which incorporates the aggregation of its behavior for multiple paths. 6TiSCH expects that the programming of the schedule will be done over COAP as discussed in [I-D.ietf-6tisch-coap].

6TiSCH expects that the PCE commands will be mapped back and forth into CoAP by a gateway function at the edge of the 6TiSCH network. For instance, it is possible that a mapping entity on the backbone transforms a non-CoAP protocol such as PCEP into the RESTful interfaces that the 6TiSCH devices support. This architecture will be refined to comply with DetNet [I-D.finn-detnet-architecture] when the work is formalized. Related information about 6TiSCH can be found at [I-D.ietf-6tisch-6top-interface] and RPL [RFC6550].

A protocol may be used to update the state in the devices during runtime, for example if it appears that a path through the network has ceased to perform as expected, but in 6TiSCH that flow was not designed and no protocol was selected. We would like to see DetNet define the appropriate end-to-end protocols to be used in that case. The implication is that these state updates take place once the system is configured and running, i.e. they are not limited to the initial communication of the configuration of the system.

A "slotFrame" is the base object that a PCE would manipulate to program a schedule into an LLN node ([I-D.ietf-6tisch-architecture]).

We would like to see the PCE read energy data from devices, and compute paths that will implement policies on how energy in devices is consumed, for instance to ensure that the spent energy does not exceed the available energy over a period of time. Note: this statement implies that an extensible protocol for communicating device info to the PCE and enabling the PCE to act on it will be part of the DetNet architecture, however for subnets with specific protocols (e.g. CoAP) a gateway may be required.

6TiSCH devices can discover their neighbors over the radio using a mechanism such as beacons, but even though the neighbor information is available in the 6TiSCH interface data model, 6TiSCH does not describe a protocol to proactively push the neighborhood information to a PCE. We would like to see DetNet define such a protocol; one possible design alternative is that it could operate over CoAP, alternatively it could be converted to/from CoAP by a gateway. We would like to see such a protocol carry multiple metrics, for example similar to those used for RPL operations [RFC6551]

#### 5.3.2.2. 6TiSCH IP Interface

"6top" ([I-D.wang-6tisch-6top-sublayer]) is a logical link control sitting between the IP layer and the TSCH MAC layer which provides the link abstraction that is required for IP operations. The 6top data model and management interfaces are further discussed in [I-D.ietf-6tisch-6top-interface] and [I-D.ietf-6tisch-coap].

An IP packet that is sent along a 6TiSCH path uses the Differentiated Services Per-Hop-Behavior Group called Deterministic Forwarding, as described in [I-D.svshah-tsvwg-deterministic-forwarding].

#### 5.3.3. 6TiSCH Security Considerations

On top of the classical requirements for protection of control signaling, it must be noted that 6TiSCH networks operate on limited resources that can be depleted rapidly in a DoS attack on the system, for instance by placing a rogue device in the network, or by obtaining management control and setting up unexpected additional paths.

#### 5.4. Wireless Industrial Asks

6TiSCH depends on DetNet to define:

- o Configuration (state) and operations for deterministic paths
- o End-to-end protocols for deterministic forwarding (tagging, IP)
- o Protocol for packet replication and elimination

### 6. Cellular Radio

#### 6.1. Use Case Description

This use case describes the application of deterministic networking in the context of cellular telecom transport networks. Important elements include time synchronization, clock distribution, and ways of establishing time-sensitive streams for both Layer-2 and Layer-3 user plane traffic.

##### 6.1.1. Network Architecture

Figure 10 illustrates a typical 3GPP-defined cellular network architecture, which includes "Fronthaul" and "Midhaul" network segments. The "Fronthaul" is the network connecting base stations (baseband processing units) to the remote radio heads (antennas). The "Midhaul" is the network inter-connecting base stations (or small cell sites).

In Figure 10 "eNB" ("E-UTRAN Node B") is the hardware that is connected to the mobile phone network which communicates directly with mobile handsets ([TS36300]).

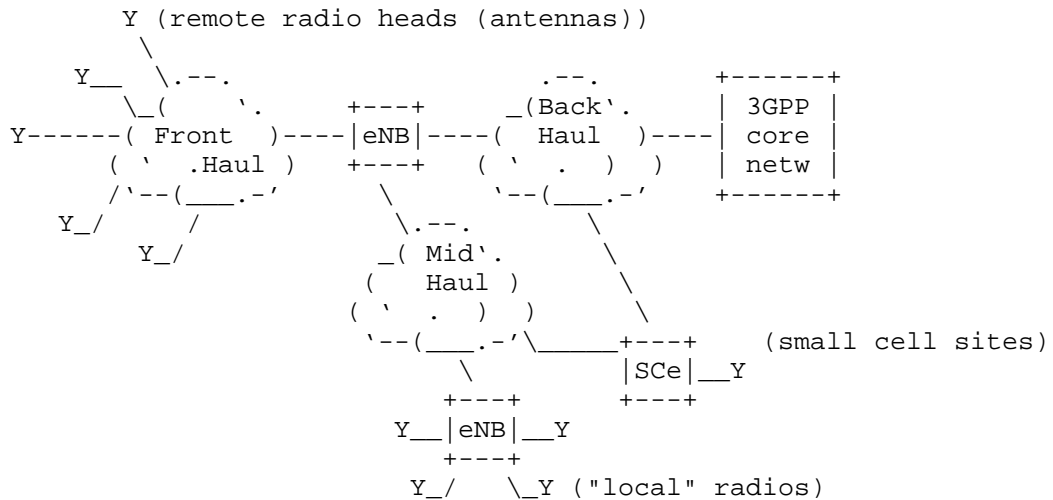


Figure 10: Generic 3GPP-based Cellular Network Architecture

6.1.2. Delay Constraints

The available processing time for Fronthaul networking overhead is limited to the available time after the baseband processing of the radio frame has completed. For example in Long Term Evolution (LTE) radio, processing of a radio frame is allocated 3ms but typically the processing uses most of it, allowing only a small fraction to be used by the Fronthaul network (e.g. up to 250us one-way delay, though the existing spec ([NGMN-fronth]) supports delay only up to 100us). This ultimately determines the distance the remote radio heads can be located from the base stations (e.g., 100us equals roughly 20 km of optical fiber-based transport). Allocation options of the available time budget between processing and transport are under heavy discussions in the mobile industry.

For packet-based transport the allocated transport time (e.g. CPRI would allow for 100us delay [CPRI]) is consumed by all nodes and buffering between the remote radio head and the baseband processing unit, plus the distance-incurred delay.

The baseband processing time and the available "delay budget" for the fronthaul is likely to change in the forthcoming "5G" due to reduced radio round trip times and other architectural and service requirements [NGMN].

[METIS] documents the fundamental challenges as well as overall technical goals of the future 5G mobile and wireless system as the starting point. These future systems should support much higher data

volumes and rates and significantly lower end-to-end latency for 100x more connected devices (at similar cost and energy consumption levels as today's system).

For Midhaul connections, delay constraints are driven by Inter-Site radio functions like Coordinated Multipoint Processing (CoMP, see [CoMP]). CoMP reception and transmission is a framework in which multiple geographically distributed antenna nodes cooperate to improve the performance of the users served in the common cooperation area. The design principal of CoMP is to extend the current single-cell to multi-UE (User Equipment) transmission to a multi-cell-to-multi-UEs transmission by base station cooperation.

CoMP has delay-sensitive performance parameters, which are "midhaul latency" and "CSI (Channel State Information) reporting and accuracy". The essential feature of CoMP is signaling between eNBs, so Midhaul latency is the dominating limitation of CoMP performance. Generally, CoMP can benefit from coordinated scheduling (either distributed or centralized) of different cells if the signaling delay between eNBs is within 1-10ms. This delay requirement is both rigid and absolute because any uncertainty in delay will degrade the performance significantly.

Inter-site CoMP is one of the key requirements for 5G and is also a near-term goal for the current 4.5G network architecture.

#### 6.1.3. Time Synchronization Constraints

Fronthaul time synchronization requirements are given by [TS25104], [TS36104], [TS36211], and [TS36133]. These can be summarized for the current 3GPP LTE-based networks as:

##### Delay Accuracy:

+/-8ns (i.e. +/-1/32 Tc, where Tc is the UMTS Chip time of 1/3.84 MHz) resulting in a round trip accuracy of +/-16ns. The value is this low to meet the 3GPP Timing Alignment Error (TAE) measurement requirements. Note: performance guarantees of low nanosecond values such as these are considered to be below the DetNet layer - it is assumed that the underlying implementation, e.g. the hardware, will provide sufficient support (e.g. buffering) to enable this level of accuracy. These values are maintained in the use case to give an indication of the overall application.

##### Timing Alignment Error:

Timing Alignment Error (TAE) is problematic to Fronthaul networks and must be minimized. If the transport network cannot guarantee low enough TAE then additional buffering has to be introduced at the edges of the network to buffer out the jitter. Buffering is



not desirable as it reduces the total available delay budget. Packet Delay Variation (PDV) requirements can be derived from TAE for packet based Fronthaul networks.

- \* For multiple input multiple output (MIMO) or TX diversity transmissions, at each carrier frequency, TAE shall not exceed 65 ns (i.e.  $1/4 T_c$ ).
- \* For intra-band contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 130 ns (i.e.  $1/2 T_c$ ).
- \* For intra-band non-contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 260 ns (i.e. one  $T_c$ ).
- \* For inter-band carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 260 ns.

Transport link contribution to radio frequency error:

+/-2 PPB. This value is considered to be "available" for the Fronthaul link out of the total 50 PPB budget reserved for the radio interface. Note: the reason that the transport link contributes to radio frequency error is as follows. The current way of doing Fronthaul is from the radio unit to remote radio head directly. The remote radio head is essentially a passive device (without buffering etc.) The transport drives the antenna directly by feeding it with samples and everything the transport adds will be introduced to radio as-is. So if the transport causes additional frequency error that shows immediately on the radio as well. Note: performance guarantees of low nanosecond values such as these are considered to be below the DetNet layer - it is assumed that the underlying implementation, e.g. the hardware, will provide sufficient support to enable this level of performance. These values are maintained in the use case to give an indication of the overall application.

The above listed time synchronization requirements are difficult to meet with point-to-point connected networks, and more difficult when the network includes multiple hops. It is expected that networks must include buffering at the ends of the connections as imposed by the jitter requirements, since trying to meet the jitter requirements in every intermediate node is likely to be too costly. However, every measure to reduce jitter and delay on the path makes it easier to meet the end-to-end requirements.

In order to meet the timing requirements both senders and receivers must remain time synchronized, demanding very accurate clock distribution, for example support for IEEE 1588 transparent clocks in every intermediate node.

In cellular networks from the LTE radio era onward, phase synchronization is needed in addition to frequency synchronization ([TS36300], [TS23401]).

#### 6.1.4. Transport Loss Constraints

Fronthaul and Midhaul networks assume almost error-free transport. Errors can result in a reset of the radio interfaces, which can cause reduced throughput or broken radio connectivity for mobile customers.

For packetized Fronthaul and Midhaul connections packet loss may be caused by BER, congestion, or network failure scenarios. Current tools for eliminating packet loss for Fronthaul and Midhaul networks have serious challenges, for example retransmitting lost packets and/or using forward error correction (FEC) to circumvent bit errors is practically impossible due to the additional delay incurred. Using redundant streams for better guarantees for delivery is also practically impossible in many cases due to high bandwidth requirements of Fronthaul and Midhaul networks. Protection switching is also a candidate but current technologies for the path switch are too slow to avoid reset of mobile interfaces.

Fronthaul links are assumed to be symmetric, and all Fronthaul streams (i.e. those carrying radio data) have equal priority and cannot delay or pre-empt each other. This implies that the network must guarantee that each time-sensitive flow meets their schedule.

#### 6.1.5. Security Considerations

Establishing time-sensitive streams in the network entails reserving networking resources for long periods of time. It is important that these reservation requests be authenticated to prevent malicious reservation attempts from hostile nodes (or accidental misconfiguration). This is particularly important in the case where the reservation requests span administrative domains. Furthermore, the reservation information itself should be digitally signed to reduce the risk of a legitimate node pushing a stale or hostile configuration into another networking node.

Note: This is considered important for the security policy of the network, but does not affect the core DetNet architecture and design.

## 6.2. Cellular Radio Networks Today

### 6.2.1. Fronthaul

Today's Fronthaul networks typically consist of:

- o Dedicated point-to-point fiber connection is common
- o Proprietary protocols and framings
- o Custom equipment and no real networking

Current solutions for Fronthaul are direct optical cables or Wavelength-Division Multiplexing (WDM) connections.

### 6.2.2. Midhaul and Backhaul

Today's Midhaul and Backhaul networks typically consist of:

- o Mostly normal IP networks, MPLS-TP, etc.
- o Clock distribution and sync using 1588 and SyncE

Telecommunication networks in the Mid- and Backhaul are already heading towards transport networks where precise time synchronization support is one of the basic building blocks. While the transport networks themselves have practically transitioned to all-IP packet-based networks to meet the bandwidth and cost requirements, highly accurate clock distribution has become a challenge.

In the past, Mid- and Backhaul connections were typically based on Time Division Multiplexing (TDM-based) and provided frequency synchronization capabilities as a part of the transport media. Alternatively other technologies such as Global Positioning System (GPS) or Synchronous Ethernet (SyncE) are used [SyncE].

Both Ethernet and IP/MPLS [RFC3031] (and PseudoWires (PWE) [RFC3985] for legacy transport support) have become popular tools to build and manage new all-IP Radio Access Networks (RANs) [I-D.kh-spring-ip-ran-use-case]. Although various timing and synchronization optimizations have already been proposed and implemented including 1588 PTP enhancements [I-D.ietf-tictoc-1588overmpls] and [I-D.ietf-mpls-residence-time], these solution are not necessarily sufficient for the forthcoming RAN architectures nor do they guarantee the more stringent time-synchronization requirements such as [CPRI].

There are also existing solutions for TDM over IP such as [RFC5087] and [RFC4553], as well as TDM over Ethernet transports such as [RFC5086].

### 6.3. Cellular Radio Networks Future

Future Cellular Radio Networks will be based on a mix of different xHaul networks (xHaul = front-, mid- and backhaul), and future transport networks should be able to support all of them simultaneously. It is already envisioned today that:

- o Not all "cellular radio network" traffic will be IP, for example some will remain at Layer 2 (e.g. Ethernet based). DetNet solutions must address all traffic types (Layer 2, Layer 3) with the same tools and allow their transport simultaneously.
- o All form of xHaul networks will need some form of DetNet solutions. For example with the advent of 5G some Backhaul traffic will also have DetNet requirements (e.g. traffic belonging to time-critical 5G applications).

We would like to see the following in future Cellular Radio networks:

- o Unified standards-based transport protocols and standard networking equipment that can make use of underlying deterministic link-layer services
- o Unified and standards-based network management systems and protocols in all parts of the network (including Fronthaul)

New radio access network deployment models and architectures may require time- sensitive networking services with strict requirements on other parts of the network that previously were not considered to be packetized at all. Time and synchronization support are already topical for Backhaul and Midhaul packet networks [MEF] and are becoming a real issue for Fronthaul networks also. Specifically in Fronthaul networks the timing and synchronization requirements can be extreme for packet based technologies, for example, on the order of sub +/-20 ns packet delay variation (PDV) and frequency accuracy of +0.002 PPM [Fronthaul].

The actual transport protocols and/or solutions to establish required transport "circuits" (pinned-down paths) for Fronthaul traffic are still undefined. Those are likely to include (but are not limited to) solutions directly over Ethernet, over IP, and using MPLS/PseudoWire transport.

Even the current time-sensitive networking features may not be sufficient for Fronthaul traffic. Therefore, having specific profiles that take the requirements of Fronthaul into account is desirable [IEEE8021CM].

Interesting and important work for time-sensitive networking has been done for Ethernet [TSNTG], which specifies the use of IEEE 1588 time precision protocol (PTP) [IEEE1588] in the context of IEEE 802.1D and IEEE 802.1Q. [IEEE8021AS] specifies a Layer 2 time synchronizing service, and other specifications such as IEEE 1722 [IEEE1722] specify Ethernet-based Layer-2 transport for time-sensitive streams.

New promising work seeks to enable the transport of time-sensitive fronthaul streams in Ethernet bridged networks [IEEE8021CM]. Analogous to IEEE 1722 there is an ongoing standardization effort to define the Layer-2 transport encapsulation format for transporting radio over Ethernet (RoE) in the IEEE 1904.3 Task Force [IEEE19043].

All-IP RANs and xHhaul networks would benefit from time synchronization and time-sensitive transport services. Although Ethernet appears to be the unifying technology for the transport, there is still a disconnect providing Layer 3 services. The protocol stack typically has a number of layers below the Ethernet Layer 2 that shows up to the Layer 3 IP transport. It is not uncommon that on top of the lowest layer (optical) transport there is the first layer of Ethernet followed one or more layers of MPLS, PseudoWires and/or other tunneling protocols finally carrying the Ethernet layer visible to the user plane IP traffic.

While there are existing technologies to establish circuits through the routed and switched networks (especially in MPLS/PWE space), there is still no way to signal the time synchronization and time-sensitive stream requirements/reservations for Layer-3 flows in a way that addresses the entire transport stack, including the Ethernet layers that need to be configured.

Furthermore, not all "user plane" traffic will be IP. Therefore, the same solution also must address the use cases where the user plane traffic is a different layer, for example Ethernet frames.

There is existing work describing the problem statement [I-D.finn-detnet-problem-statement] and the architecture [I-D.finn-detnet-architecture] for deterministic networking (DetNet) that targets solutions for time-sensitive (IP/transport) streams with deterministic properties over Ethernet-based switched networks.

#### 6.4. Cellular Radio Networks Asks

A standard for data plane transport specification which is:

- o Unified among all xHauls (meaning that different flows with diverse DetNet requirements can coexist in the same network and traverse the same nodes without interfering with each other)
- o Deployed in a highly deterministic network environment

A standard for data flow information models that are:

- o Aware of the time sensitivity and constraints of the target networking environment
- o Aware of underlying deterministic networking services (e.g., on the Ethernet layer)

### 7. Industrial M2M

#### 7.1. Use Case Description

Industrial Automation in general refers to automation of manufacturing, quality control and material processing. In this "machine to machine" (M2M) use case we consider machine units in a plant floor which periodically exchange data with upstream or downstream machine modules and/or a supervisory controller within a local area network.

The actors of M2M communication are Programmable Logic Controllers (PLCs). Communication between PLCs and between PLCs and the supervisory PLC (S-PLC) is achieved via critical control/data streams Figure 11.

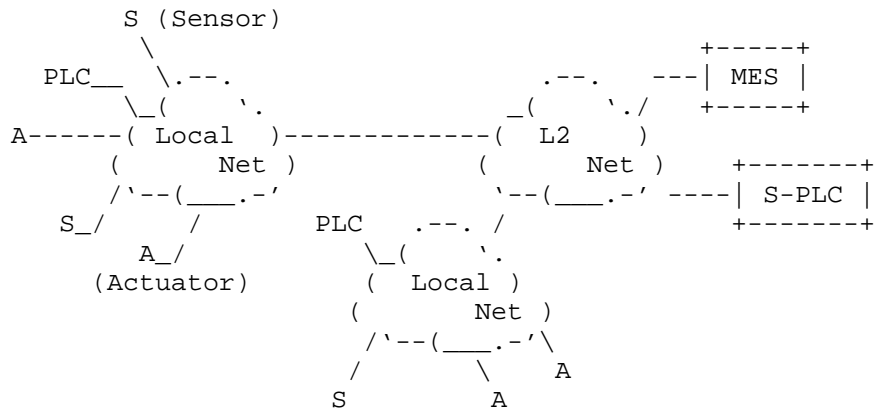


Figure 11: Current Generic Industrial M2M Network Architecture

This use case focuses on PLC-related communications; communication to Manufacturing-Execution-Systems (MESs) are not addressed.

This use case covers only critical control/data streams; non-critical traffic between industrial automation applications (such as communication of state, configuration, set-up, and database communication) are adequately served by currently available prioritizing techniques. Such traffic can use up to 80% of the total bandwidth required. There is also a subset of non-time-critical traffic that must be reliable even though it is not time sensitive.

In this use case the primary need for deterministic networking is to provide end-to-end delivery of M2M messages within specific timing constraints, for example in closed loop automation control. Today this level of determinism is provided by proprietary networking technologies. In addition, standard networking technologies are used to connect the local network to remote industrial automation sites, e.g. over an enterprise or metro network which also carries other types of traffic. Therefore, flows that should be forwarded with deterministic guarantees need to be sustained regardless of the amount of other flows in those networks.

7.2. Industrial M2M Communication Today

Today, proprietary networks fulfill the needed timing and availability for M2M networks.

The network topologies used today by industrial automation are similar to those used by telecom networks: Daisy Chain, Ring, Hub and Spoke, and Comb (a subset of Daisy Chain).

PLC-related control/data streams are transmitted periodically and carry either a pre-configured payload or a payload configured during runtime.

Some industrial applications require time synchronization at the end nodes. For such time-coordinated PLCs, accuracy of 1 microsecond is required. Even in the case of "non-time-coordinated" PLCs time sync may be needed e.g. for timestamping of sensor data.

Industrial network scenarios require advanced security solutions. Many of the current industrial production networks are physically separated. Preventing critical flows from be leaked outside a domain is handled today by filtering policies that are typically enforced in firewalls.

#### 7.2.1. Transport Parameters

The Cycle Time defines the frequency of message(s) between industrial actors. The Cycle Time is application dependent, in the range of 1ms - 100ms for critical control/data streams.

Because industrial applications assume deterministic transport for critical Control-Data-Stream parameters (instead of defining latency and delay variation parameters) it is sufficient to fulfill the upper bound of latency (maximum latency). The underlying networking infrastructure must ensure a maximum end-to-end delivery time of messages in the range of 100 microseconds to 50 milliseconds depending on the control loop application.

The bandwidth requirements of control/data streams are usually calculated directly from the bytes-per-cycle parameter of the control loop. For PLC-to-PLC communication one can expect 2 - 32 streams with packet size in the range of 100 - 700 bytes. For S-PLC to PLCs the number of streams is higher - up to 256 streams. Usually no more than 20% of available bandwidth is used for critical control/data streams. In today's networks 1Gbps links are commonly used.

Most PLC control loops are rather tolerant of packet loss, however critical control/data streams accept no more than 1 packet loss per consecutive communication cycle (i.e. if a packet gets lost in cycle "n", then the next cycle ("n+1") must be lossless). After two or more consecutive packet losses the network may be considered to be "down" by the Application.

As network downtime may impact the whole production system the required network availability is rather high (99,999%).



Based on the above parameters we expect that some form of redundancy will be required for M2M communications, however any individual solution depends on several parameters including cycle time, delivery time, etc.

#### 7.2.2. Stream Creation and Destruction

In an industrial environment, critical control/data streams are created rather infrequently, on the order of ~10 times per day / week / month. Most of these critical control/data streams get created at machine startup, however flexibility is also needed during runtime, for example when adding or removing a machine. Going forward as production systems become more flexible, we expect a significant increase in the rate at which streams are created, changed and destroyed.

#### 7.3. Industrial M2M Future

We would like to see a converged IP-standards-based network with deterministic properties that can satisfy the timing, security and reliability constraints described above. Today's proprietary networks could then be interfaced to such a network via gateways or, in the case of new installations, devices could be connected directly to the converged network.

For this use case we expect time synchronization accuracy on the order of  $\mu$ s.

#### 7.4. Industrial M2M Asks

- o Converged IP-based network
- o Deterministic behavior (bounded latency and jitter )
- o High availability (presumably through redundancy) (99.999 %)
- o Low message delivery time (100 $\mu$ s - 50ms)
- o Low packet loss (burstless, 0.1-1 %)
- o Security (e.g. prevent critical flows from being leaked between physically separated networks)

#### 8. Use Case Common Elements

Looking at the use cases collectively, the following common desires for the DetNet-based networks of the future emerge:

- o Open standards-based network (replace various proprietary networks, reduce cost, create multi-vendor market)
- o Centrally administered (though such administration may be distributed for scale and resiliency)
- o Integrates L2 (bridged) and L3 (routed) environments (independent of the Link layer, e.g. can be used with Ethernet, 6TiSCH, etc.)
- o Carries both deterministic and best-effort traffic (guaranteed end-to-end delivery of deterministic flows, deterministic flows isolated from each other and from best-effort traffic congestion, unused deterministic BW available to best-effort traffic)
- o Ability to add or remove systems from the network with minimal, bounded service interruption (applications include replacement of failed devices as well as plug and play)
- o Uses standardized data flow information models capable of expressing deterministic properties (models express device capabilities, flow properties. Protocols for pushing models from controller to devices, devices to controller)
- o Scalable size (long distances (many km) and short distances (within a single machine), many hops (radio repeaters, microwave links, fiber links...) and short hops (single machine))
- o Scalable timing parameters and accuracy (bounded latency, guaranteed worst case maximum, minimum. Low latency, e.g. control loops may be less than 1ms, but larger for wide area networks)
- o High availability (99.9999 percent up time requested, but may be up to twelve 9s)
- o Reliability, redundancy (lives at stake)
- o Security (from failures, attackers, misbehaving devices - sensitive to both packet content and arrival time)

#### 9. Use Cases Explicitly Out of Scope for DetNet

This section contains use case text that has been determined to be outside of the scope of the present DetNet work.

### 9.1. DetNet Scope Limitations

The scope of DetNet is deliberately limited to specific use cases that are consistent with the WG charter, subject to the interpretation of the WG. At the time the DetNet Use Cases were solicited and provided by the authors the scope of DetNet was not clearly defined, and as that clarity has emerged, certain of the use cases have been determined to be outside the scope of the present DetNet work. Such text has been moved into this section to clarify that these use cases will not be supported by the DetNet work.

The text in this section was moved here based on the following "exclusion" principles. Or, as an alternative to moving all such text to this section, some draft text has been modified in situ to reflect these same principles.

The following principles have been established to clarify the scope of the present DetNet work.

- o The scope of network addressed by DetNet is limited to networks that can be centrally controlled, i.e. an "enterprise" aka "corporate" network. This explicitly excludes "the open Internet".
- o Maintaining synchronized time across a DetNet network is crucial to its operation, however DetNet assumes that time is to be maintained using other means, for example (but not limited to) Precision Time Protocol ([IEEE1588]). A use case may state the accuracy and reliability that it expects from the DetNet network as part of a whole system, however it is understood that such timing properties are not guaranteed by DetNet itself. It is currently an open question as to whether DetNet protocols will include a way for an application to communicate such timing expectations to the network, and if so whether they would be expected to materially affect the performance they would receive from the network as a result.

### 9.2. Internet-based Applications

#### 9.2.1. Use Case Description

There are many applications that communicate across the open Internet that could benefit from guaranteed delivery and bounded latency. The following are some representative examples.

#### 9.2.1.1. Media Content Delivery

Media content delivery continues to be an important use of the Internet, yet users often experience poor quality audio and video due to the delay and jitter inherent in today's Internet.

#### 9.2.1.2. Online Gaming

Online gaming is a significant part of the gaming market, however latency can degrade the end user experience. For example "First Person Shooter" (FPS) games are highly delay-sensitive.

#### 9.2.1.3. Virtual Reality

Virtual reality (VR) has many commercial applications including real estate presentations, remote medical procedures, and so on. Low latency is critical to interacting with the virtual world because perceptual delays can cause motion sickness.

#### 9.2.2. Internet-Based Applications Today

Internet service today is by definition "best effort", with no guarantees on delivery or bandwidth.

#### 9.2.3. Internet-Based Applications Future

We imagine an Internet from which we will be able to play a video without glitches and play games without lag.

For online gaming, the maximum round-trip delay can be 100ms and stricter for FPS gaming which can be 10-50ms. Transport delay is the dominate part with a 5-20ms budget.

For VR, 1-10ms maximum delay is needed and total network budget is 1-5ms if doing remote VR.

Flow identification can be used for gaming and VR, i.e. it can recognize a critical flow and provide appropriate latency bounds.

#### 9.2.4. Internet-Based Applications Asks

- o Unified control and management protocols to handle time-critical data flow
- o Application-aware flow filtering mechanism to recognize the timing critical flow without doing 5-tuple matching

- o Unified control plane to provide low latency service on Layer-3 without changing the data plane
- o OAM system and protocols which can help to provide E2E-delay sensitive service provisioning

### 9.3. Pro Audio and Video - Digital Rights Management (DRM)

This section was moved here because this is considered a Link layer topic, not direct responsibility of DetNet.

Digital Rights Management (DRM) is very important to the audio and video industries. Any time protected content is introduced into a network there are DRM concerns that must be maintained (see [CONTENT\_PROTECTION]). Many aspects of DRM are outside the scope of network technology, however there are cases when a secure link supporting authentication and encryption is required by content owners to carry their audio or video content when it is outside their own secure environment (for example see [DCI]).

As an example, two techniques are Digital Transmission Content Protection (DTCP) and High-Bandwidth Digital Content Protection (HDCP). HDCP content is not approved for retransmission within any other type of DRM, while DTCP may be retransmitted under HDCP. Therefore if the source of a stream is outside of the network and it uses HDCP protection it is only allowed to be placed on the network with that same HDCP protection.

### 9.4. Pro Audio and Video - Link Aggregation

Note: The term "Link Aggregation" is used here as defined by the text in the following paragraph, i.e. not following a more common Network Industry definition. Current WG consensus is that this item won't be directly supported by the DetNet architecture, for example because it implies guarantee of in-order delivery of packets which conflicts with the core goal of achieving the lowest possible latency.

For transmitting streams that require more bandwidth than a single link in the target network can support, link aggregation is a technique for combining (aggregating) the bandwidth available on multiple physical links to create a single logical link of the required bandwidth. However, if aggregation is to be used, the network controller (or equivalent) must be able to determine the maximum latency of any path through the aggregate link.

## 10. Acknowledgments

### 10.1. Pro Audio

This section was derived from draft-gunther-detnet-proaudio-req-01.

The editors would like to acknowledge the help of the following individuals and the companies they represent:

Jeff Koftinoff, Meyer Sound

Jouni Korhonen, Associate Technical Director, Broadcom

Pascal Thubert, CTAO, Cisco

Kieran Tyrrell, Sienda New Media Technologies GmbH

### 10.2. Utility Telecom

This section was derived from draft-wetterwald-detnet-utilities-reqs-02.

Faramarz Maghsoodlou, Ph. D. IoT Connected Industries and Energy Practice Cisco

Pascal Thubert, CTAO Cisco

### 10.3. Building Automation Systems

This section was derived from draft-bas-usecase-detnet-00.

### 10.4. Wireless for Industrial

This section was derived from draft-thubert-6tisch-4detnet-01.

This specification derives from the 6TiSCH architecture, which is the result of multiple interactions, in particular during the 6TiSCH (bi)Weekly Interim call, relayed through the 6TiSCH mailing list at the IETF.

The authors wish to thank: Kris Pister, Thomas Watteyne, Xavier Vilajosana, Qin Wang, Tom Phinney, Robert Assimiti, Michael Richardson, Zhuo Chen, Malisa Vucinic, Alfredo Grieco, Martin Turon, Dominique Barthel, Elvis Vogli, Guillaume Gaillard, Herman Storey, Maria Rita Palattella, Nicola Accettura, Patrick Wetterwald, Pouria Zand, Raghuram Sudhaakar, and Shitanshu Shah for their participation and various contributions.

### 10.5. Cellular Radio

This section was derived from draft-korhonen-detnet-telreq-00.

### 10.6. Industrial M2M

The authors would like to thank Feng Chen and Marcel Kiessling for their comments and suggestions.

### 10.7. Internet Applications and CoMP

This section was derived from draft-zha-detnet-use-case-00.

This document has benefited from reviews, suggestions, comments and proposed text provided by the following members, listed in alphabetical order: Jing Huang, Junru Lin, Lehong Niu and Oilver Huang.

### 10.8. Electrical Utilities

The wind power generation use case has been extracted from the study of Wind Farms conducted within the 5GPPP Virtuwind Project. The project is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 671648 (VirtuWind).

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#### Authors' Addresses

Ethan Grossman (editor)  
Dolby Laboratories, Inc.  
1275 Market Street  
San Francisco, CA 94103  
USA

Phone: +1 415 645 4726  
Email: [ethan.grossman@dolby.com](mailto:ethan.grossman@dolby.com)  
URI: <http://www.dolby.com>

Craig Gunther  
Harman International  
10653 South River Front Parkway  
South Jordan, UT 84095  
USA

Phone: +1 801 568-7675  
Email: [craig.gunther@harman.com](mailto:craig.gunther@harman.com)  
URI: <http://www.harman.com>

Pascal Thubert  
Cisco Systems, Inc  
Building D  
45 Allee des Ormes - BP1200  
MOUGINS - Sophia Antipolis 06254  
FRANCE

Phone: +33 497 23 26 34  
Email: pthubert@cisco.com

Patrick Wetterwald  
Cisco Systems  
45 Allee des Ormes  
Mougins 06250  
FRANCE

Phone: +33 4 97 23 26 36  
Email: pwetterw@cisco.com

Jean Raymond  
Hydro-Quebec  
1500 University  
Montreal H3A3S7  
Canada

Phone: +1 514 840 3000  
Email: raymond.jean@hydro.qc.ca

Jouni Korhonen  
Broadcom Corporation  
3151 Zanker Road  
San Jose, CA 95134  
USA

Email: jouni.nospam@gmail.com

Yu Kaneko  
Toshiba  
1 Komukai-Toshiba-cho, Saiwai-ku, Kasasaki-shi  
Kanagawa, Japan

Email: yu1.kaneko@toshiba.co.jp

Subir Das  
Applied Communication Sciences  
150 Mount Airy Road, Basking Ridge  
New Jersey, 07920, USA

Email: [sdas@appcomsci.com](mailto:sdas@appcomsci.com)

Yiyong Zha  
Huawei Technologies

Email: [zhayiyong@huawei.com](mailto:zhayiyong@huawei.com)

Balazs Varga  
Ericsson  
Konyves Kalman krt. 11/B  
Budapest 1097  
Hungary

Email: [balazs.a.varga@ericsson.com](mailto:balazs.a.varga@ericsson.com)

Janos Farkas  
Ericsson  
Konyves Kalman krt. 11/B  
Budapest 1097  
Hungary

Email: [janos.farkas@ericsson.com](mailto:janos.farkas@ericsson.com)

Franz-Josef Goetz  
Siemens  
Gleiwitzerstr. 555  
Nurnberg 90475  
Germany

Email: [franz-josef.goetz@siemens.com](mailto:franz-josef.goetz@siemens.com)

Juergen Schmitt  
Siemens  
Gleiwitzerstr. 555  
Nurnberg 90475  
Germany

Email: [juergen.jues.schmitt@siemens.com](mailto:juergen.jues.schmitt@siemens.com)

Xavier Vilajosana  
Worldsensing  
483 Arago  
Barcelona, Catalonia 08013  
Spain

Email: [xvilajosana@worldsensing.com](mailto:xvilajosana@worldsensing.com)

Toktam Mahmoodi  
King's College London  
Strand, London WC2R 2LS  
London, London WC2R 2LS  
United Kingdom

Email: [toktam.mahmoodi@kcl.ac.uk](mailto:toktam.mahmoodi@kcl.ac.uk)

Spiros Spirou  
Intracom Telecom  
19.7 km Markopoulou Ave.  
Peania, Attiki 19002  
Greece

Email: [spis@intracom-telecom.com](mailto:spis@intracom-telecom.com)

Petra Vizarreta  
Technical University of Munich, TUM  
Maxvorstadt, ArcisstraBe 21  
Munich, Germany 80333  
Germany

Email: [petra.vizarreta@lkn.ei.tum.de](mailto:petra.vizarreta@lkn.ei.tum.de)

DetNet  
Internet-Draft  
Intended status: Standards Track  
Expires: May 4, 2017

B. Varga, Ed.  
J. Farkas  
Ericsson  
October 31, 2016

DetNet Service Model  
draft-varga-detnet-service-model-01

Abstract

This document describes service model for scenarios requiring deterministic networking.

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## 1. Introduction

A Deterministic Networking (DetNet) service provides a capability to carry a unicast or a multicast data flow for an application with constrained requirements on network performance, e.g., low packet loss rate and/or latency. During the discussion of DetNet use cases, DetNet architecture, and various related networking scenarios, several confusions have been raised due to different service model interpretations. This document defines service reference points, service components and proposes naming for service scenarios to achieve common understanding of the DetNet service model.

## 2. Conventions Used in This Document

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].

The lowercase forms with an initial capital "Must", "Must Not", "Shall", "Shall Not", "Should", "Should Not", "May", and "Optional" in this document are to be interpreted in the sense defined in [RFC2119], but are used where the normative behavior is defined in documents published by SDOs other than the IETF.

## 3. Terminology and Definitions

Additional terms to [I-D.ietf-detnet-architecture] used in this draft.

**DetLink:** Direct link between two entities (node/end system) used for deterministic transport.

**DetNet flow:** A DetNet flow is a sequence of packets to which the DetNet service is to be provided, see [I-D.ietf-detnet-architecture]. This document distinguishes the following three formats of DetNet flows:

**App-flow:** An App-flow is a data flow between the applications requiring deterministic service. An App-flow does not contain any DetNet related attributes.

**DetNet-s-flow:** A DetNet-s-flow is an App-flow extended with some DetNet service layer attributes.

**DetNet-st-flow:** A DetNet-st-flow is an App-flow extended with both DetNet service layer and DetNet transport layer attributes, i.e., encapsulated according to the forwarding paradigm of the DetNet domain.

**DetNet-NNI:** NNI between DetNet domains.

**DetNet-UNI:** UNI of a DetNet edge node to provide DetNet service for a connected node or end system.

**DetNetwork:** Transport network between DetNet-st-flow endpoints.

#### 4. End systems connected to DetNet

Deterministic connectivity service is required by time/loss sensitive application(s) running on an end system during communication with its peer(s). Such a data exchange has various requirements on delay and/or loss parameters.

A DetNet flow [I-D.ietf-detnet-architecture] can have different formats during while it is transported between the peer end systems. Therefore, the following possible formats of a DetNet flow are distinguished in this document:

- o App-flow: native format of a DetNet flow. It does not contain any DetNet related attributes.
- o DetNet-s-flow: specific format of a DetNet flow. It is an App-flow extended with some DetNet service related attributes (i.e., Flow-ID and/or Seq-num).
- o DetNet-st-flow: specific format of a DetNet flow. It is an App-flow extended with both DetNet service layer and DetNet transport layer attributes, i.e., encapsulated according to the forwarding paradigm of the DetNet domain.

App-flow and DetNet-s-flow are generated by end systems. DetNet-st-flow can be generated by a DetNet edge node or an end system that is an integral part of a DetNet domain. Further details are described below. This document uses the exact DetNet flow type where it is important to distinguish the flow type; otherwise, the generic term, i.e., DetNet flow is used.

The native data flow between the source/destination end systems is referred to as application-flow (App-flow) as shown in Figure 1. The traffic characteristics of an App-flow can be CBR (constant bit rate) or VBR (variable bit rate) and can have L1 or L2 or L3 encapsulation (e.g., TDM (time-division multiplexing), Ethernet, IP).

[Note: Interworking function for L1 application-flows is out-of-scope in this document, therefore, not depicted in figures.]





network. Its connection to a DetNet network requires a DetNet edge node, that creates a DetNet-st-flow (with proper Flow-ID and Seq-num attributes) by encapsulating the native data flow according to the forwarding paradigm of the connected DetNet domain.

- o A "DetNet aware end system" may contain some DetNet specific service functionalities and it extends the App-flow with related DetNet specific flow attributes (i.e., Flow-ID and/or Seq-num). The resulting flow is referred to as DetNet-s-flow as it contains service layer specific fields, but the format of the DetNet-s-flow encapsulation is not identical with the forwarding paradigm (i.e., the transport layer) of the DetNet domain. Therefore, it has to be connected to a DetNet edge node. DetNet aware end systems can be, e.g., an IP end system with some DetNet service functions connected to an MPLS-based DetNet domain.
- o A "DetNet end node" has DetNet functionalities and the same forwarding paradigm as the connected DetNet domain. It can be treated as an integral part of the DetNet domain, therefore, it is connected to a DetNet relay node (or to a DetNet transit node). It originates a DetNet-st-flow (i.e., the App-flow is extended within the end system with all the DetNet specific flow attributes used inside the DetNet domain).

These end systems are shown in Figure 3. A DetNet-UNI ("U" on Figure 3) is assumed in this document to be a packet-based reference point and provides connectivity over the DetNet domain. A DetNet-UNI may add forwarding technology specific encapsulation to the App-flow / DetNet-s-flow and transport it as a DetNet-st-flow over the network.

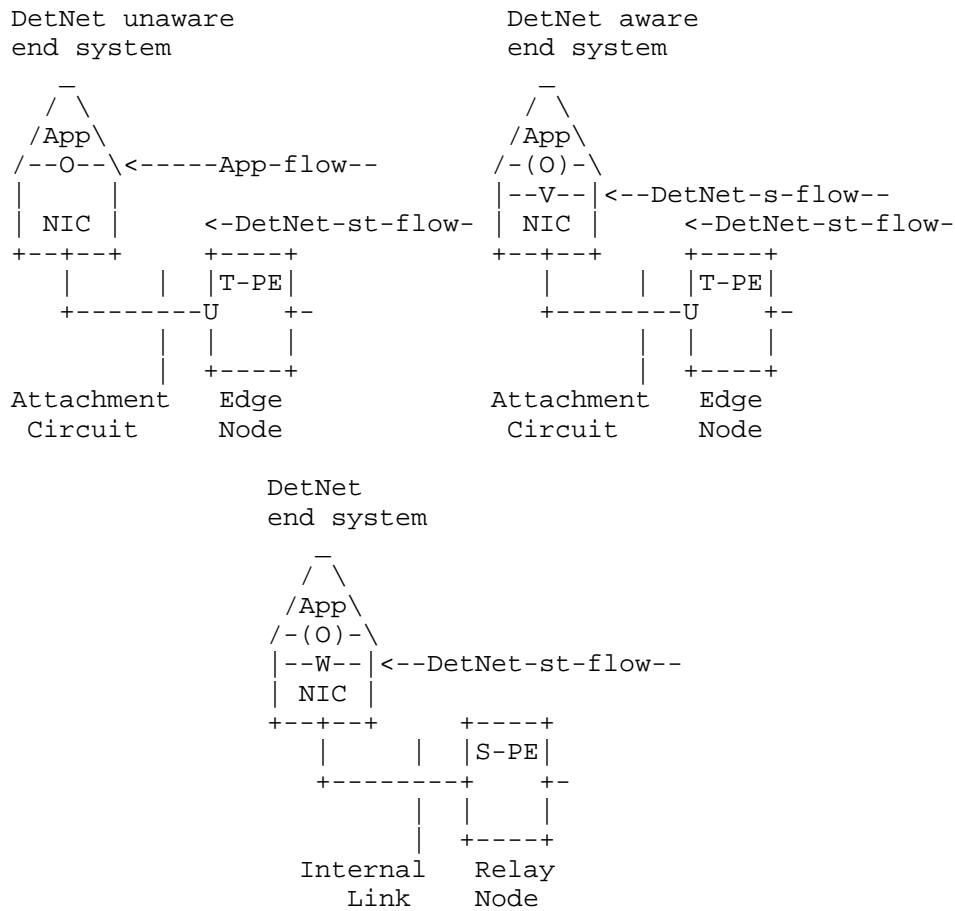


Figure 3: Types of end systems

[Note: DetNet aware end systems can be also treated as a special mix of a DetNet unaware system and a DetNet end system. It is similar to a DetNet end system as its data flow contains DetNet attributes, however, those attributes cannot be used directly inside the DetNet domain, e.g., due to the different transport layer. Therefore, it is also similar to DetNet unaware end systems as it must be connected to a DetNet edge node to adapt, e.g., the encapsulation of the DetNet flow to the forwarding paradigm of the DetNet domain. A typical example showing a DetNet aware end system can be the following scenario: an end system encapsulates its App-flow in IP-RTP packets. It assumes a single connection to its peer, therefore, the Seq-num field is not used by the end-system. It is connected to an MPLS-

based DetNet domain that has redundant paths and applies service protection via the duplication and elimination functionality. As per [I-D.ietf-detnet-architecture], the addition or removal of packet sequencing information is the job of a DetNet edge node. As forwarding is MPLS-based, the Seq-num required for service protection is created and added to the DetNet-s-flow by the DetNet edge node (in the PW control-word field).]

## 5. DetNet service model

### 5.1. Service parameters

The DetNet service can be defined as a service that provides a capability to carry a unicast or a multicast data flow for an application with constrained requirements on network performance, e.g., low packet loss rate and/or latency.

Delay and loss parameters are somewhat correlated because the effect of late delivery can be equivalent to loss. However, not all applications require hard limits on both parameters (delay and loss). For example, some real-time applications allow graceful degradation if loss happens (e.g., sample-based processing, media distribution). Some others may require high-bandwidth connections that make the usage of techniques like flow duplication economically challenging or even impossible. Some applications may not tolerate loss, but are not delay sensitive (e.g., bufferless sensors).

Primary transport service attributes for DetNet transport are:

- o Bandwidth parameter(s),
- o Delay parameter(s),
- o Loss parameter(s),
- o Connectivity type.

Time/loss sensitive applications may have somewhat special requirements especially for loss (e.g., no loss in two consecutive communication cycles; very low outage time, etc.).

Two connectivity types are distinguished: point-to-point (p2p) and point-to-multipoint (p2mp). Connectivity type p2mp is created by a transport layer function (e.g., p2mp LSP). (Note: mp2mp connectivity is a superposition of p2mp connections.)

5.2. Service overview

The figures below show the DetNet service related reference points and components for various end system scenarios (Figure 4 and Figure 5).

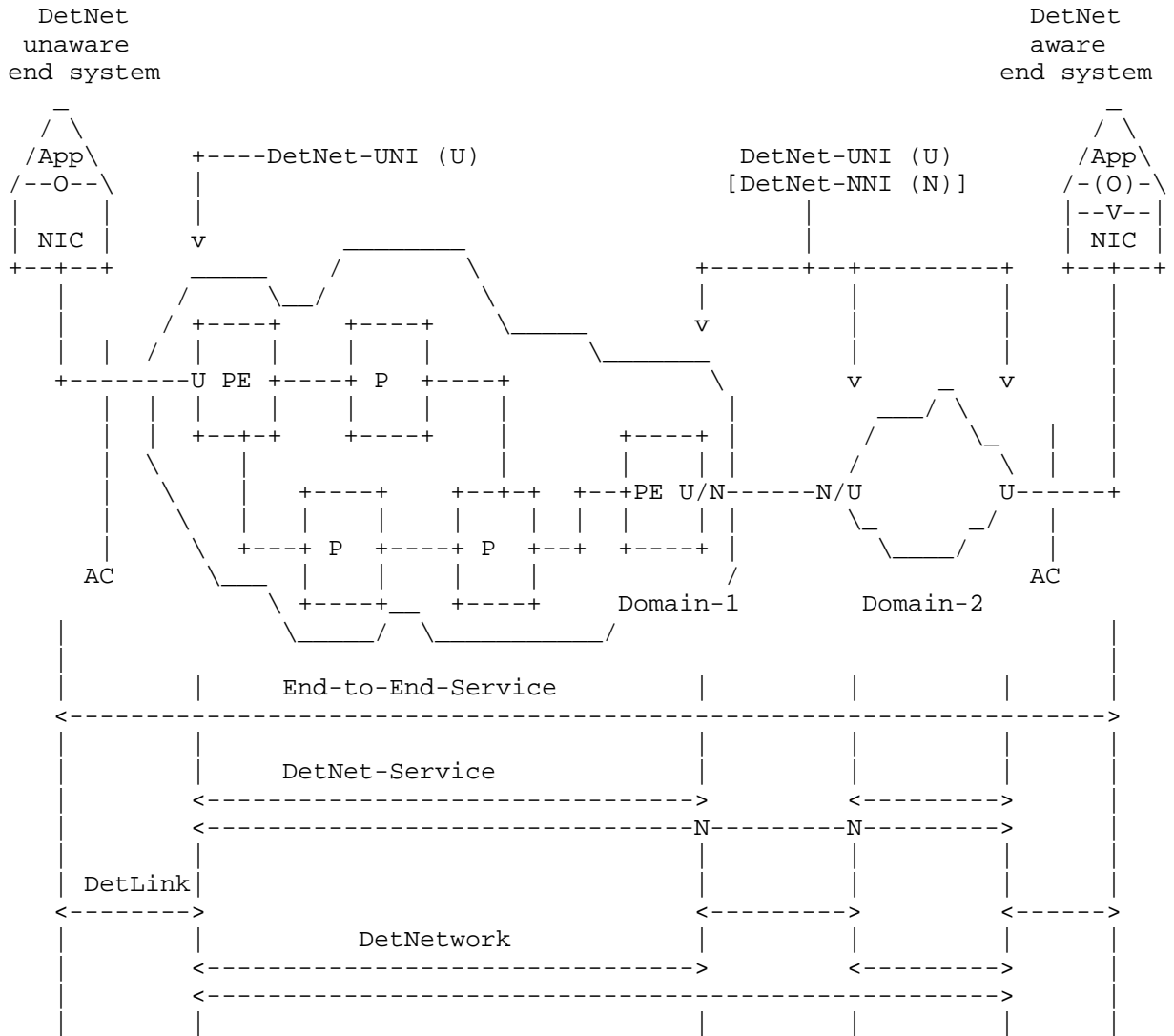


Figure 4: DetNet Service Reference Model (multi-domain)

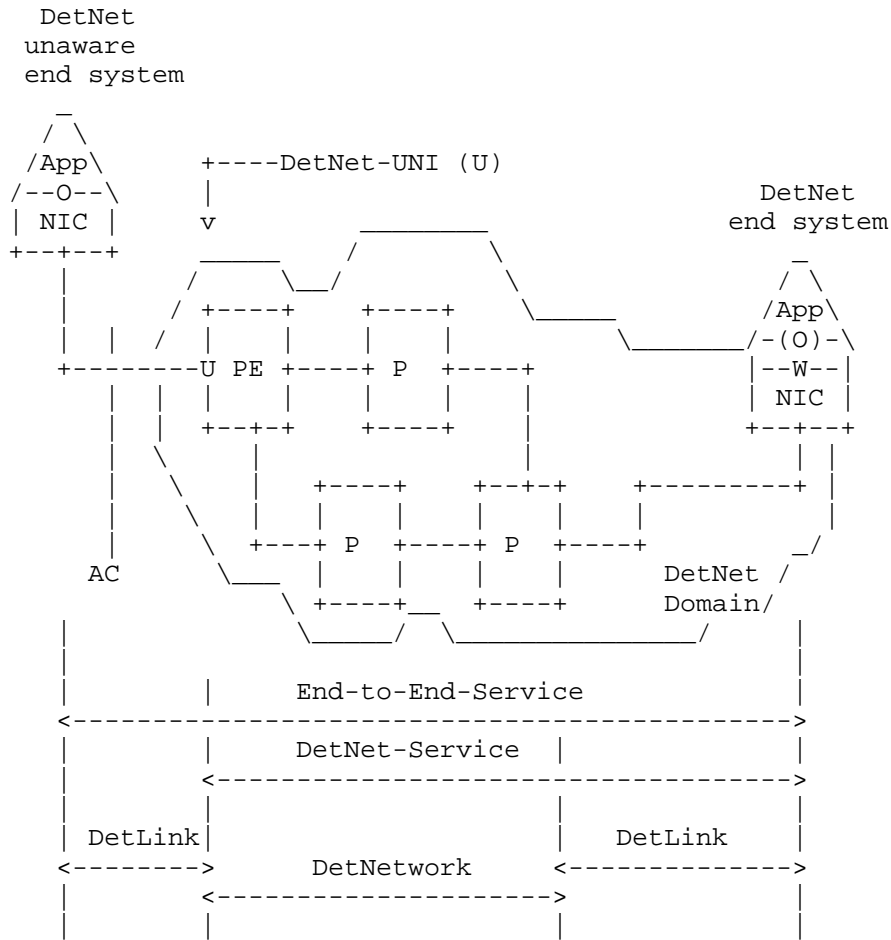


Figure 5: DetNet Service Reference Model (single domain)

### 5.3. Reference Points

From service model design perspective a fundamental question is the location of the service endpoints, i.e., where the service starts and ends. The following reference points can be distinguished for the DetNet use cases:

- o App-flow endpoint: End system's internal reference point ("O") for the native data flow.
- o DetNet-s-flow endpoint: DetNet aware end system's internal reference point ("V").

- o DetNet-st-flow endpoint: DetNet edge node UNI ("U") or DetNet end system's internal reference point ("W").
- o DetNet-UNI: UNI interface ("U") on a DetNet edge node.
- o DetNet-NNI: NNI interface ("N") between DetNet domains.

Data flow endpoints ("O", "V" and "W" in Figure 4 and Figure 5) are more challenging from control perspective as they are internal reference points of end systems. They are providing access to deterministic transport for the native data flow (App-flow).

DetNet-UNI and DetNet-NNI ("U" and "N" in Figure 4) are assumed in this document to be packet-based reference points and provide connectivity over the packet network and between domains. A DetNet-UNI adds networking technology specific encapsulation to the App-flow / DetNet-s-flow in order to transport it as a DetNet-st-flow over the network. There are many similarities regarding the functions of a DetNet-st-flow endpoint ("W") and a DetNet-UNI ("U") but there may be some differences. For example, in-order delivery is expected in end system internal reference points, whereas it is considered optional over the DetNet-UNI.

#### 5.4. Service scenarios

Using the above defined reference points, two major service scenarios can be identified:

- o End-to-End-Service: the service reaches out to final source or destination nodes, so it is an e2e service between application hosting devices (end systems).
- o DetNet-Service: the service connects networking islands, so it is a service between the borders of network domain(s).

End-to-End-Service is defined between App-flow endpoints, whereas DetNet-Service is between DetNet-st-flow endpoints. This allows the peering of same layers/functions.

#### 5.5. Data flows

Three possible DetNet flow formats are distinguished for unambiguous references:

- o App-flow: data flow requiring deterministic transport between two App-flow endpoints; data format is application specific (e.g., bit stream directly mapped to Ethernet frames, etc.). It does not contain any DetNet attributes.

- o DetNet-s-flow: similar to the App-flow, but extended with some DetNet attributes as DetNet aware end systems have some DetNet service layer functionalities. However, the encapsulation format differs from the forwarding paradigm of the connected DetNet domain, so those attributes cannot be used directly.
- o DetNet-st-flow: data flow between DetNet-UNIs ("U") and/or DetNet end systems ("W"). This flow is extended with both DetNet service layer and DetNet transport layer attributes. This format allows simple flow recognition/transport/etc. during forwarding in the DetNet domain.

#### 5.6. Service components/segments

The following building blocks are used as reference to service components/segments:

- o DetLink: direct link between two entities (node/end system) used for deterministic transport.
- o DetNetwork: network between DetNet nodes.

Any DetNet service scenario can be described using DetLink and DetNetwork components/segments. For example, the service between the App-flow endpoints in Figure 4 can be composed as a DetLink-1 (between the end system on the left and the edge node of Domain-1) + DetNetwork-1 (of Domain-1) + DetLink-2 (between Domain-1 and Domain-2) + DetNetwork-2 (of Domain-2) + DetLink-3 (between edge node of Domain-2 and the end system on the right).

### 6. DetNet service instances

#### 6.1. Attributes used by DetNet functions

The three DetNet functions (congestion protection, explicit routes, service protection) require two data flow related attributes to work properly:

- o Flow-ID and
- o Sequence number (Seq-Num).

These attributes are extracted from the ingress packets of the node [I-D.ietf-detnet-architecture]. Flow-ID is used by all the three DetNet functions, but sequence number is used only by the duplicate elimination functionality.



Flow-ID must be unique per network domain. Its encoding format is specific to the forwarding paradigm of the domain and to the capabilities of intermediate nodes to identify data flows. For example, in case of "PW over MPLS", one option is to construct the Flow-ID by the PW label and the LSP label (denoted as [PW-label;LSP-label]). In such a case, intermediate P nodes have to check all labels to identify a DetNet flow, what may not be a valid option in some deployment scenarios. Another possible option is to use a dedicated LSP per data flow, so the LSP label itself can be used as a Flow-ID (denoted as [LSP-label]). In such a case, the intermediate P nodes do not have to check the whole label stack to recognize a data flow (DetNet flow), however, it results in larger L-FIB tables on the MPLS nodes.

[Note: Seq-num requires a control-word in the label stack in MPLS domains, which should be recognized by intermediate S-PE (relay) nodes.]

## 6.2. Service instance for DetNet flows

The DetNet network reference model is shown in Figure 6 for a DetNet-Service scenario (i.e. between two DetNet-UNIs). In this figure, the end systems ("A" and "B") are connected directly to the edge nodes of the PSN ("PE1" and "PE2"). End-systems participating DetNet communication may require connectivity before setting up an App-flow that requires the DetNet service. Such a service instance and the one dedicated for DetNet service share the same attachment circuit. Packets belonging to a DetNet flow are selected by a filter configured on the attachment circuit ("F1" and "F2"). As a result, data flow specific attachment circuits ("AC-A + F1" and "AC-B + F2") are terminated in the flow specific service instance ("SI-1" and "SI-2"). A PSN tunnel is used to provide connectivity between the service instances. The encapsulation used over the PSN tunnel are described in [I-D.ietf-detnet-dp-alt].

The PSN tunnel is used to transport exclusively the packets of the DetNet flow between "SI-1" and "SI-2". The service instances are configured to implement a flow specific routing or bridging function depending on what connectivity the participating end systems require (L3 or L2). The service instance and the PSN tunnel may or may not be shared by multiple DetNet flows. Sharing the service instance by multiple DetNet flows requires properly populated forwarding tables of the service instance.

Serving regular traffic and DetNet flows by the same service instance is out-of-scope in this draft, but some related thoughts are described in Annex 1. Such a combination can provide the required connectivity before setting up a DetNet service.

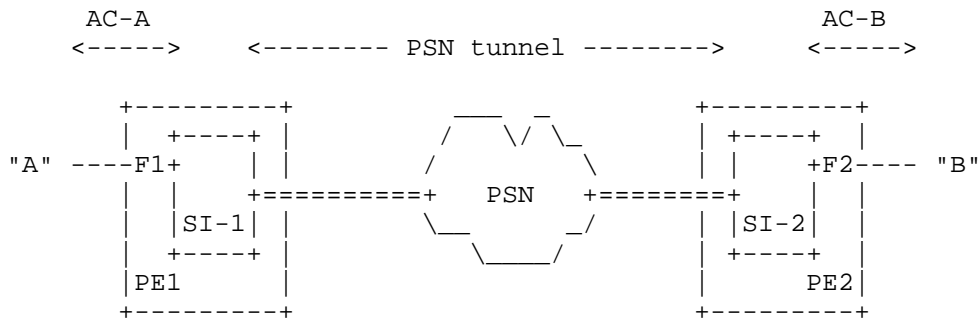


Figure 6: DetNet network reference model

[Note: There are differences in the usage of a "packet PW" for DetNet traffic compared to the network model described in [RFC6658]. In the DetNet scenario, the packet PW is used exclusively by the DetNet flow, whereas [RFC6658] states: "The packet PW appears as a single point-to-point link to the client layer. Network-layer adjacency formation and maintenance between the client equipments will follow the normal practice needed to support the required relationship in the client layer ... This packet pseudowire is used to transport all of the required layer 2 and layer 3 protocols between LSR1 and LSR2".]

## 7. DetNet flows over multiple technology domains

### 7.1. Flow attribute mapping between layers

Transport of DetNet flows over multiple technology domains may require that lower layers are aware of specific flows of higher layers. Such an "exporting of flow identification" (see section 4.7 in [I-D.ietf-detnet-architecture]) is needed each time when the forwarding paradigm is changed on the transport path (e.g., two LSRs are interconnected by a L2 bridged domain, etc.). The three main forwarding methods considered for deterministic networking are:

- o IP routing
- o MPLS label switching
- o Ethernet bridging

The simplest solution for generalized flow identification could be to define a unique Flow-ID triplet per DetNet flow (e.g., [IP: "IPv6-flow-label"+"IPv6-address"; MPLS: "PW-label"+"LSP-label"; Ethernet: "VLAN-ID"+"MAC-address"]). This triplet can be used by the DetNet

encoding function of technology border nodes (where forwarding paradigm changes) to adapt to capabilities of the next hop node. They push a further (forwarding paradigm specific) Flow-ID to packet header ensuring that flows can be easily recognized by domain internal nodes. This additional Flow-ID might be removed when the packet leaves a given technology domain.

[Note: Seq-num attribute may require a similar functionality at technology border nodes.]

The additional (domain specific) Flow-ID can be

- o created by a domain specific function or
- o derived from the Flow-ID added to the App-flow,

so that it must be unique inside the given domain. Note, that the Flow-ID added to the App-flow is still present in the packet, but transport nodes may lack the function to recognize it; that's why the additional Flow-ID is added (pushed).

## 7.2. Flow-ID mapping examples

IP nodes and MPLS nodes are assumed to be configured to push such an additional (domain specific) Flow-ID when sending traffic to an Ethernet switch (as shown in the examples below).

Figure 7 shows a scenario where an IP end system ("IP-A") is connected via two Ethernet switches ("ETH-n") to an IP router ("IP-1").





10. Security Considerations

N/A.

11. Acknowledgements

The authors wish to thank Lou Berger, Norman Finn, Jouni Korhonen and the members of the data plane design team for their various contributions, comments and suggestions regarding this work.

12. Annex 1 - Service Instance shared by DetNet and regular traffic

This Annex contains some thoughts about scenarios where the service instance is shared by DetNet and regular traffic.

12.1. L2 service instance shared by regular and DetNet traffic

In case of a L2 VPN transport, the service instance implements bridging. In MPLS-based PSN, there is a full mesh of PWs between service instances of PE nodes. Adding DetNet flows to the network results in a somewhat modified PW structure, as a DetNet flow requires its unique Flow-ID to be encoded in the labeled packet.

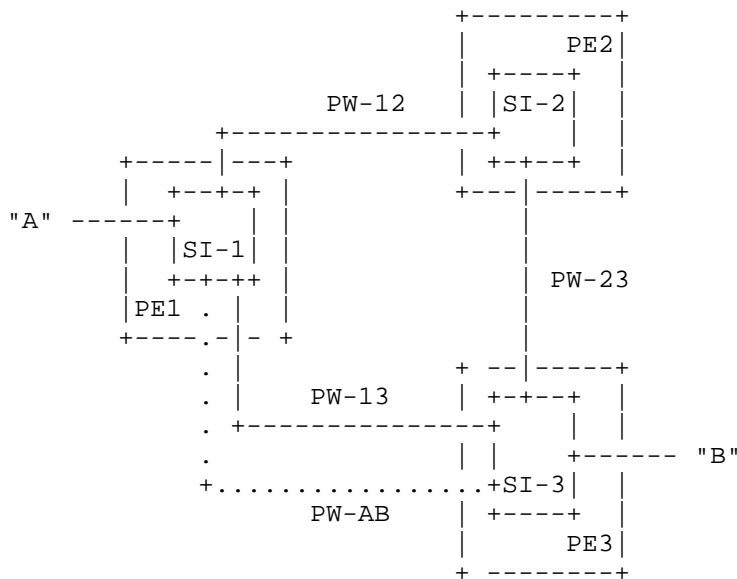


Figure 9: DetNet L2 VPN Service

Figure 9 shows a scenario where there is a DetNet flow between the end systems ("A" and "B"). "SI-n" denotes the L2 VPN service instance of "PEn". Regular traffic of the L2 VPN instance use "PW-12", "PW-13" and "PW-23". However, for transport of DetNet traffic between "A" and "B" a separate PW ("PW-AB") has to be used. "PW-AB" is a somewhat special PW (called here "virtual PW") and it is treated differently than PWs used by regular traffic (i.e., PW-13, PW-12, and PW-23). Namely, "PW-AB" is used exclusively by the DetNet flow between "A" and "B". "PW-AB" does not participate in flooding and no MAC addresses are associated with it (not considered for the MAC learning process). "PW-AB" may use the same LSP as "PW-13" or a dedicated one.

Regular traffic between "A" and "B" has an encapsulation [PW-13\_label ; LSP\_label], whereas DetNet flow has [PW-AB\_label ; LSP\_label].

#### 12.2. L3 service instance shared by regular and DetNet traffic

In case of a L3 DetNet service, the service instance implements routing. In MPLS-based PSN, such a "routing service" can be provided by IP VPNs ([RFC4364]). However, the IP VPN service adds only a single label (VPN label) during forwarding, therefore, the label stack does not contain a "control word" (i.e., there is no field to encode a sequence number). Therefore, transport of DetNet flows requires the combination of IP VPN and PW technologies.

Adding DetNet flows to the network results in a somewhat modified label stack structure, as a DetNet flow requires its packet PW encapsulation ([RFC6658]).

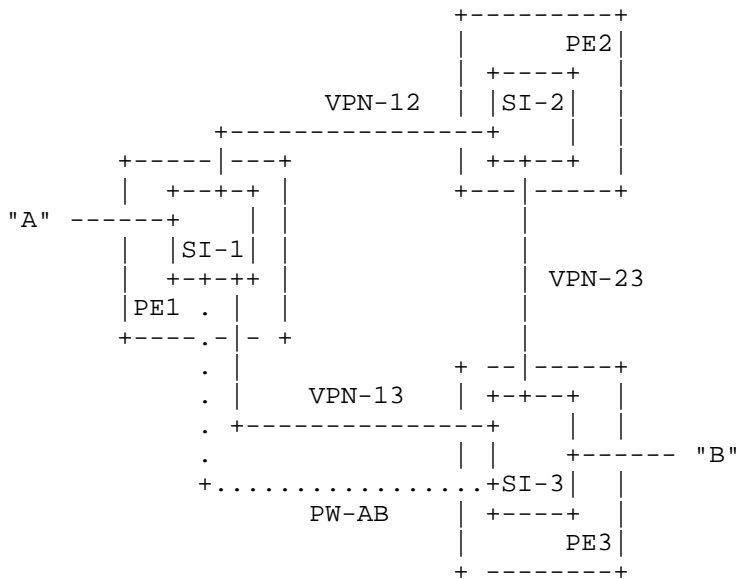


Figure 10: DetNet L3 VPN Service

Figure 10 shows a scenario where there is a DetNet flow between the end systems ("A" and "B"). "SI-n" denotes the L3 VPN service instance of "PEn". Regular traffic of the L3 VPN instance use as service label "VPN-12", "VPN-13" and "VPN-23". However, for transport of DetNet traffic between "A" and "B" a PW ("PW-AB") has to be used, what ensures that DetNet flow can be recognized by intermediate P nodes and a control world can be also present. "PW-AB" is used exclusively by the DetNet flow between "A" and "B". "PW-AB" may use the same LSP as regular traffic (labeled by "VPN-13") or a dedicated one.

Regular traffic between "A" and "B" has an encapsulation [VPN-13\_label ; LSP\_label], whereas DetNet flow has [PW-AB\_label ; LSP\_label].

13. Annex 2 - Integrating Layer 3 and Layer 2 QoS

Sophisticated QoS mechanisms are available in Layer 3 (L3), see, e.g., [RFC7806] for an overview. Although, Layer 2 (L2) QoS and queuing used to be simpler; it has been evolving, it is now equipped with Time-Sensitive Networking (TSN) features [IEEE8021TSN]. The TSN features may be beneficial or even essential for DetNet flows if Layer 2 links or sub-networks are included in their path. Therefore, it is worth investigating the problems arising when both Layer 3 and



Layer 2 QoS features are supported by a node; even without diving deep into solution/implementation details.

In IEEE Std 802.1Q-2005, eight traffic classes are supported, allowing separate queues for each priority as illustrated in Figure 11. Any traffic class-based transmission selection algorithm can be implemented in addition to the strict priority algorithm mandated by IEEE Std 802.1Q-2005. The priority information is encoded in the 3-bit field carried in a tag in the frame header. Note that the IEEE 802.1Q architecture specifies queuing at the output port; however, implementations may differ. Consequently, the following figures only show the queuing at the output port that is selected by the forwarding decision for the transmission of a frame.

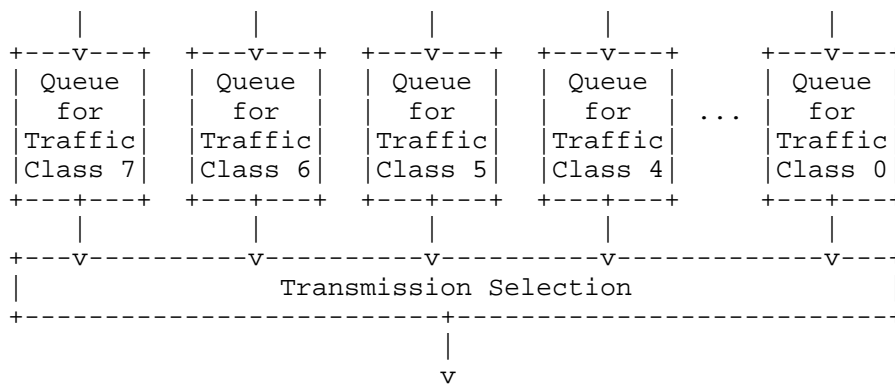


Figure 11: Queuing in IEEE 802.1Q-2005

The Layer 2 QoS architecture has been evolving, see, e.g., IEEE Std 802.1Q-2014 [IEEE8021Q], which specifies the Credit-Based Shaper (originally specified by IEEE Std 802.1Qav). There are recent IEEE 802.3 and 802.1 standards and ongoing projects to enhance the QoS supported by Ethernet and Layer 2 networks. For instance, frame preemption is specified by IEEE Std 802.3br ([IEEE8023br], to be amended to [IEEE8023]) and IEEE Std 802.1Qbu ([IEEE8021Qbu], to be amended to [IEEE8021Q]) where time-critical (express) frames can suspend the transmission of non-time-critical (preemptable) frames while one or more time-critical frames are transmitted. Another recently published specification is IEEE Std 802.1Qbv [IEEE8021Qbv], which specifies time-aware queue-draining controlled by transmission gates in order to schedule the transmission of frames relative to a known timescale, which can be provided by time synchronization. The architecture extended with time-aware queuing and frame preemption is illustrated in Figure 12. These time-sensitive networking extensions provide deterministic behavior in Layer 2 networks. The ongoing IEEE 802.1 projects provide further extensions to the QoS architecture,

e.g., ingress filtering and policing (P802.1Qci), cyclic queuing and forwarding (P802.1Qch), and asynchronous traffic shaping (P802.1Qcr), see [IEEE8021TSN].

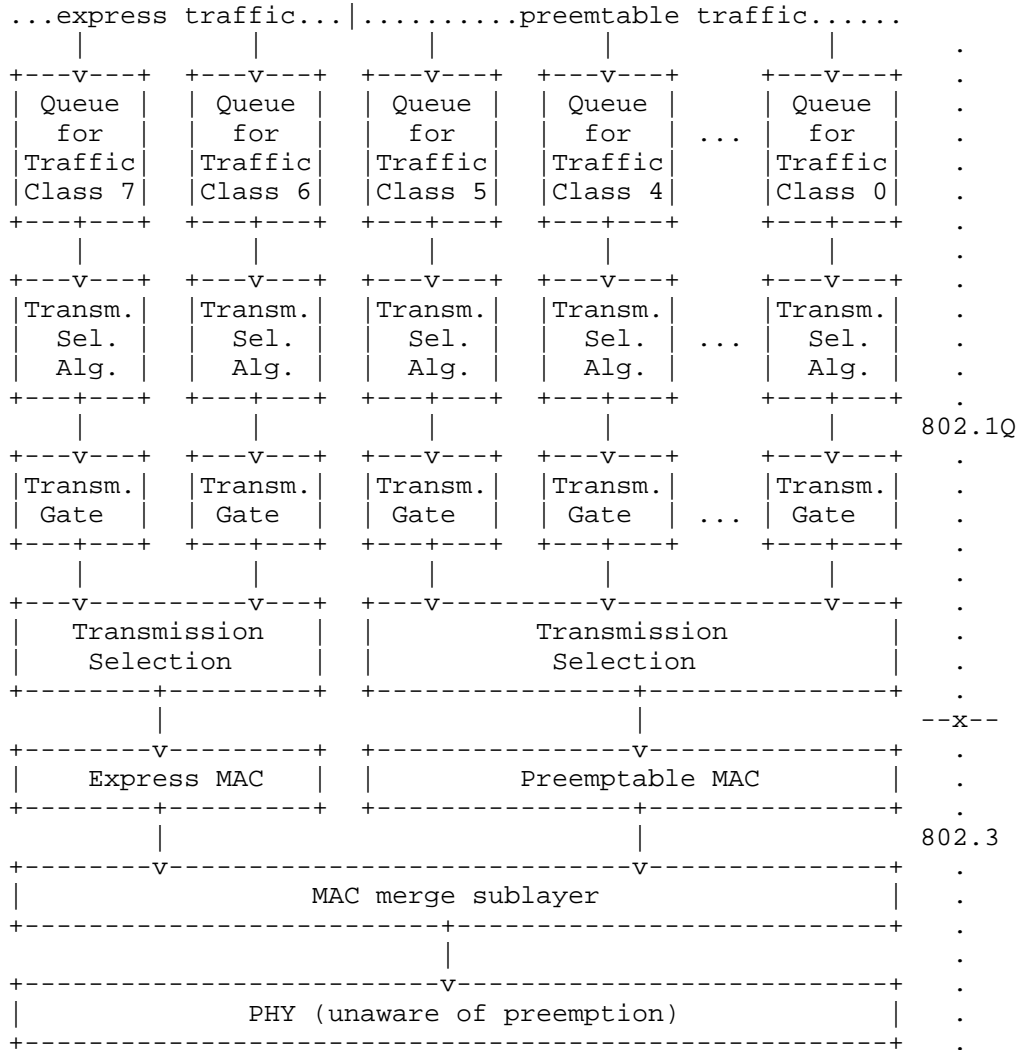


Figure 12: L2 queuing and frame preemption

A QoS architecture integrating both Layer 3 and Layer 2 features is necessary to exploit the benefits provided by the different layers if a DetNet network includes link(s) or sub-network(s) equipped with TSN features. For instance, it can be crucial for a time-critical DetNet

flow to leverage TSN features in a Layer 2 sub-network in order to meet the DetNet flow's requirements, which may be spoiled otherwise.

Figure 13 provides a theoretical illustration for the integration of the Layer 3 and Layer 2 QoS architecture. The figure only shows the queuing after the routing decision. The figure also illustrates potential implementation dependent borders (Brdr). The borders shown in the figure are critical in the sense that the high priority DetNet flows have to be transferred via a different Service Access Points (SAPs) through these borders than the low priority (background) flows. Having a single SAP for these very different traffic types may result in possible QoS degradation for the DetNet flows because packets of other flows could delay the transmission of DetNet packets. For instance, different SAPs are needed for the DetNet flows and other flows when they get to Layer 3 queuing after the routing decision via Brdr-d. Furthermore, a different SAP is needed for DetNet packets than other packets when they get to Layer 2 queuing from Layer 3 queuing via Brdr-c. Similarly, different SAPs are needed for the express and for the preemptable frames when they get to the MAC layer from Layer 2 queuing via Brdr-b, which is provided by the IEEE 802.1Q architecture as shown in Figure 12. It depends on the implementation whether or not Brdr-a exists.



Not all the functions depicted in Figure 13 are necessarily present in an implementation. A function may be combined with another one or may be completely missing. For instance, it may be the case that there is no Layer 3 queuing for DetNet packets, but they get directly to the Layer 2 queues. Alternatively, an implementation may combine the Layer 3 queues and the Layer 2 queues such that there is a single level of queues. There are further alternatives in addition to the ones mentioned here.

Different implementation approaches, i.e., different node designs are illustrated in Figure 14 and Figure 15. Figure 14 illustrates a monolithic node design where there is a single feature rich chip and relatively simple interfaces. The single chip implements all routing (and/or bridging) features as well as almost all QoS features. (Some aspects of frame preemption may be implemented on the interface.) Figure 15 illustrates a linecard-based design where each linecard has its own chip, which implements routing and QoS features.

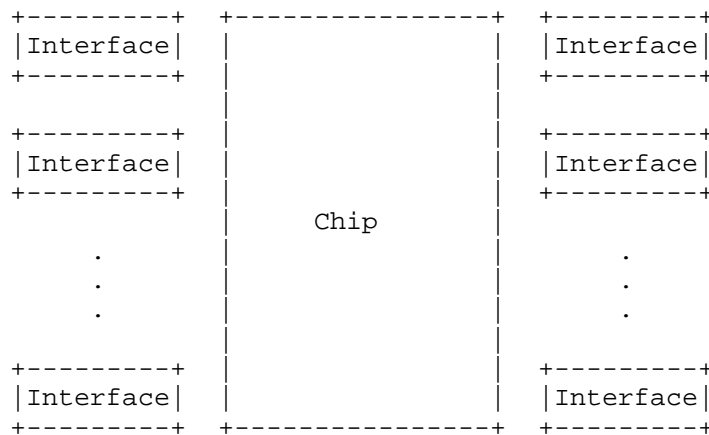


Figure 14: Monolithic node design

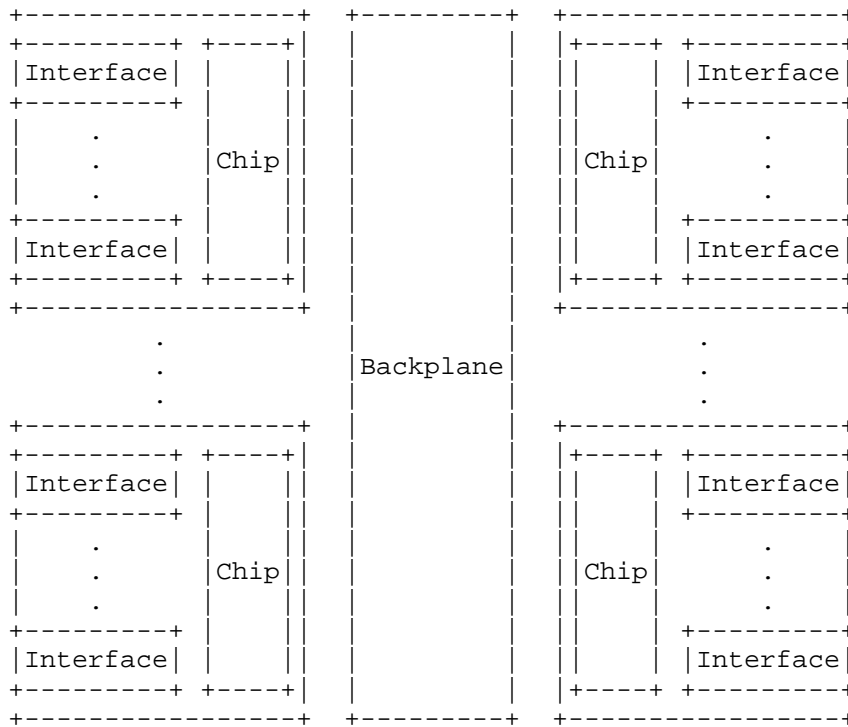


Figure 15: Linecard-based node design

Different implementations have different physical borders, which imply that different borders out of the ones illustrated in Figure 13 exist in a given implementation. For instance, there is no physical border corresponding to Brdr-d (Figure 13) in the monolithic implementation approach (Figure 14). However, Brdr-d is inevitably there in the linecard-based implementation approach (Figure 15) due to the backplane.

Altogether, it is essential to leverage the benefits of both Layer 3 and Layer 2 QoS features if Layer 2 is also involved in the support of a DetNet flow. Exploiting both layers requires attention to the aspects explained related to Figure 12. Nevertheless, the actually important aspects largely depend on the implementation approach chosen, see, e.g., Figure 14 vs. Figure 15.

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## Authors' Addresses

Balazs Varga (editor)  
Ericsson  
Konyves Kalman krt. 11/B  
Budapest 1097  
Hungary

Email: [balazs.a.varga@ericsson.com](mailto:balazs.a.varga@ericsson.com)



Janos Farkas  
Ericsson  
Konyves Kalman krt. 11/B  
Budapest 1097  
Hungary

Email: [janos.farkas@ericsson.com](mailto:janos.farkas@ericsson.com)