5G ACIA

5G-ACIA White Paper

DetNet-Based Deterministic IP Communication Over a 5G Network for Industrial Applications

5G Alliance for Connected Industries and Automation

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1 Executive Summary

Deterministic Networking (DetNet) is an outcome of efforts by the Internet Engineering Task Force (IETF) DetNet Working Group to develop a new layer 3 technology with time-sensitive features. It is relevant to industrial automation use cases for the fifth generation of wireless cellular technology (5G).

This white paper reviews the architecture and features of DetNet and how it relates to IEEE 802.1 Time-Sensitive Networking (TSN). It discusses the technology's applicability to and potential benefits for a variety of 5G industrial use cases and scenarios, including interconnection of TSN segments and cases in which controllers are located in an on-premises edge cloud. Interconnections in which DetNet provides layer-3 connectivity with time-sensitive features may be a powerful solution for some 5G industrial use cases.

Also covered are the current status and limitations of ongoing standardization efforts. The IETF DetNet Working Group has already made substantial progress, but some aspects – including the DetNet controller plane – are still being debated. 3GPP Release 18 already provides standardized 5G support for DetNet under some architectural assumptions.

About 5G-ACIA

The **5G Alliance for Connected Industries and Automation** (5G-ACIA) was established to serve as the main global forum for addressing, discussing, and evaluating relevant technical, regulatory, and business aspects of 5G for the industrial domain. It embraces the entire ecosystem and all relevant stakeholders, which include but are not limited to the operational technology industry (industrial automation companies, engineering companies, production system manufacturers, end users, etc.), the information and communication technology industry (chip manufacturers, network infrastructure vendors, mobile network operators, etc.), universities, government agencies, research facilities, and industry associations. 5G-ACIA's overarching goal is to promote the best possible use of industrial 5G while maximizing the usefulness of 5G technology and 5G networks in the industrial domain. This includes ensuring that ongoing 5G standardization and regulatory activities adequately consider relevant interests and requirements and that new developments in 5G are effectively communicated to and understood by manufacturers.

2 Introduction

DetNet, as defined by the IETF [1], is a layer 3 technology that provides deterministic communication with features that hold promise for 5G industrial automation scenarios. The 3rd Generation Partnership Project (3GPP) has already standardized support for DetNet in Release 18, building on the time-sensitive communication framework defined in Release 17.

This white paper describes the current standardization status of DetNet and possibilities for applying it to 5G industrial automation use cases and deployment scenarios. It looks at DetNet's most useful features, how it relates to TSN, the support that 3GPP provides for it in the form of logical DetNet nodes in 5G, its relevance to 5G industrial use cases, and how it could be used in typical manufacturing network situations. DetNet may prove to be especially useful in cases where there is a need to interconnect subnetworks, for instance by leveraging its IP-based deterministic connectivity, or when services or controllers are contained in on-premises IP-based clouds.

3 Overview of DetNet

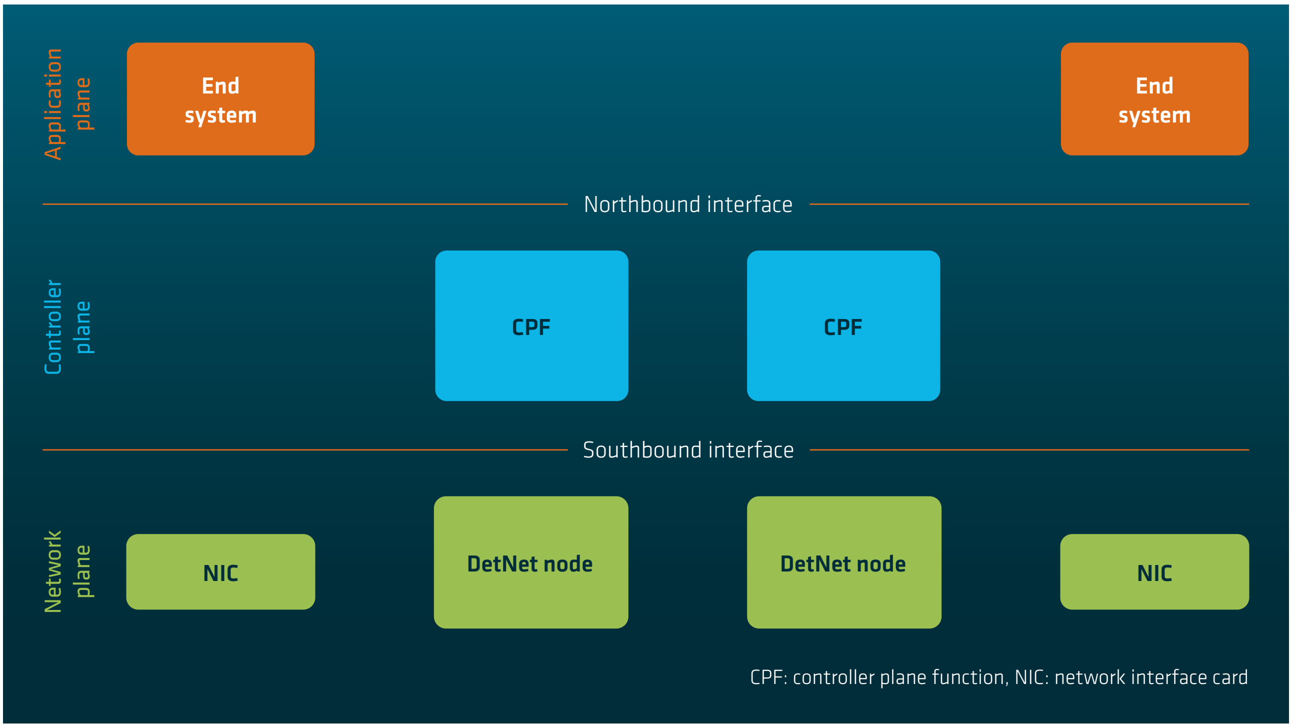
As described by the IETF, DetNet "provides a capability for the delivery of data flows with extremely low packet loss rates and bounded end-to-end delivery latency" [2]. This is accomplished by reserving network resources such as bandwidth and buffer space. DetNet operates in the Internet Protocol (IP) or multiprotocol label switching (MPLS) layers and is intended for use in networks that have either a single administrative control entity or a closed group of such entities [1]. The principal requirements for using DetNet are low latency and high reliability, both of which can be met by appropriately managing resources. If DetNet-supported applications require a notion of time, this can be provided by leveraging synchronization solutions in lower layers. The IETF has formulated specifications for DetNet, which has already achieved a fairly high level of standardization although the controller plane is still being discussed.

3.1 DetNet Architecture

As defined in [2], the architecture of DetNet is divided into planes, three of which have already been specified: the application plane, the network plane, and the controller plane (which performs control and/or management functions). Northbound and southbound interfaces have also been defined to enable communication between planes as shown in figure 1.

Generally speaking, first the end systems inform the controller plane function (CPF) of the requirements of a new DetNet data flow (which IETF calls the "DetNet flow") via the northbound interface. Based on this, as well as on network plane capabilities that are reported via the southbound interface, the CPF performs calculations (for example, to compute paths) and then configures the nodes (DetNet nodes and network interface cards (NICs) at end systems) along the DetNet flow's path via the southbound interface. The northbound interface is not specified in IETF. This interface is part

Figure 1: Planes of the DetNet architecture



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of the software-defined networking (SDN) architecture [3], in other words it is not DetNet-specific. The components and functions on the various planes of the DetNet architecture are described in the following.

3.1.1 Application Plane

The DetNet application plane contains all parts of the end system above the networking layer, including industrial applications. In order to negotiate flows, end systems can communicate with one another via the DetNet application plane. Each end system implements an application (user agent) that interacts with a management interface to request DetNet services via the northbound interface of the DetNet controller plane.

If the northbound interface is not standardized, this interaction could be achieved by applying existing configuration protocols such as NETCONF [4] or RESTCONF [5] (which is used by the southbound interface). Information sent by end systems to CPF could contain parameters similar to those of the IETF DetNet YANG model [6], which is also used for the southbound interface.

3.1.2 Controller Plane

The DetNet controller plane [7] combines control and management planes. In figure 1, the term controller plane function (CPF) refers to any element operating in the DetNet controller plane, regardless of whether it is a path computation element, a network management entity, or a distributed control protocol.

The control plane is responsible for setting and maintaining flows and distributing information that is needed to execute DetNet functions. In order for it to perform these tasks, it should support queue control techniques, be able to advertise available node and link resources, aggregate and disaggregate DetNet flows, identify flows, and adapt to changes in the DetNet domain topology. Resources can be reserved in three ways: by the application itself, centrally by an application's controller, or in a distributed manner using the resource reservation protocol (RSVP).

The DetNet control plane supports the following configuration models [7] (analogously to TSN configuration models):

(i) A SDN-based, fully centralized control plane with a centralized DetNet controller
(ii) A fully distributed control plane that uses distributed control plane signaling protocols
(iii) A hybrid control plane (partly centralized and partly distributed)

Like in TSN, the fully centralized configuration requires a centralized user controller or applications to send flow information, via either the northbound interface or an application programming interface (API), to the centralized DetNet controller, which calculates routes and processes the forwarding information. Then the DetNet controller configures the DetNet nodes using either a NETCONF [4] or RESTCONF [5] protocol and YANG models [6].

In the fully distributed configuration model, multiple control entities together constitute a unified control plane for the network. In this case, configuration information propagates across the network using either signaling protocols such as an interior gateway protocol (IGP) or a resource reservation protocol for traffic engineering (RSVP-TE) [8]. It is also possible to have a multivendor DetNet network (including a second HW source requirement) with standardized distributed control protocols. No DetNet-related extensions have been specified for distributed control protocols yet, however. The fully distributed model, as its name suggests, does not include a central entity; it relies instead on distributed protocols such as IGP or RSVP.

When taking a hybrid approach with a configuration that is both centralized and distributed, some controller plane functions can be performed by a DetNet controller or edge nodes (for example, for establishing explicit paths), while distributed protocols (e. g. for reserving resources) carry out other tasks.

The management plane part configures DetNet network nodes, for example by applying specified YANG models.

To support DetNet network plane mechanisms (described in section 3.1.3 below), the controller plane must be able to:

(i) perform path computation and establish explicit paths,
(ii) support resource allocation (including bandwidth, buffers, and queueing discipline),
(iii) configure devices,
(iv) and compute and establish a set of multiple fixed disjoint paths from one or more packet replication points to one or more packet merging and ordering points in order to support packet replication, elimination, and ordering functions (PREOF). Note that it will probably be impossible to maintain fixed paths while taking a fully distributed approach, since it is usually the case that distributed routing protocols dynamically update paths in response to changes. It is therefore necessary for a central intelligence (such as a path computation element (PCE)) to be in charge of fixed paths.

3.1.3 Network Plane

The network plane comprises network nodes, a data plane for transferring data (described in greater detail in section 3.2), and an operational plane for operations, administration, and maintenance (OAM). DetNet supports two data plane types: MPLS and IP. Each of these has two defined sublayers: service and forwarding.

DetNet service sublayer
The DetNet service sublayer [2] provides service protection in order to minimize or eliminate packet errors, reorder packets for applications that do not tolerate out-of-order packet delivery, and minimize both jitter and the size of buffers at the destination.

Service protection can be provided using packet replication, elimination, and ordering functions (PREOF) along two or more maximally disjoint paths between end systems. These functions are available at network points where replication takes place (usually at the ingress of the DetNet domain) and where duplication, elimination and/or ordering is performed (typically at the DetNet domain's egress). They enable DetNet path redundancy in order to prevent device or link failures from causing packet losses. The placement and order of the PREOF functions, which have not been specified by the IETF, are considered up to but not including implementation.

The end systems in the example shown in figure 2 are DetNet-unaware and therefore do not support the DetNet service sublayer. DetNet nodes at the edge of the DetNet domain execute PREOF via two paths (A and B). This takes place as follows: the DetNet node with a replication function (R) at the ingress of the DetNet domain duplicates received packets and sends them over redundant paths A and B. For example, if packet 1 traveling via path B is lost, packet 2 on path B may reach the DetNet node at the egress of the DetNet domain before the other packet 1 on path A. This DetNet node, which has elimination and ordering (E + O) functions, ensures that the packets are in the correct sequence and removes the extra packet 2 (arriving via path A). As a result, packets 1 and 2 are delivered to the destination end system in sequence and without any replicas.

Another approach used to provide service protection from random media errors is packet encoding. This method involves multiple paths. A network coding method is used to encode the information in a packet of a DetNet flow into multiple transmission units or to combine information from multiple packets in a single transmission unit.

DetNet forwarding sublayer
The DetNet forwarding sublayer ensures a stable forwarding service and shields the DetNet service from being adversely affected by changes in the network topology. The DetNet forwarding sublayer [2] allocates resources and sets explicit routes. Even if the topology changes – because links or nodes elsewhere fail or are disabled – explicit routes will not be affected by changes resulting from the convergence of routing protocols. Two or more explicit, maximally disjoint routes are set and activated to add redundancy. The DetNet forwarding sublayer provides the DetNet service sublayer with the service of explicit routing in order to enable the PREOF mechanism. Congestion in DetNet flows is prevented by allocating bandwidth and buffers and by defining queueing disciplines. A device configuration determines whether or not a given flow is discriminated by reserving output port bandwidth for queue management and the port scheduling algorithm. This

is accomplished with a mapping between a DetNet flow and its resources.

Devices in the DetNet domain are defined on the basis of whether one or both DetNet sublayers are supported.

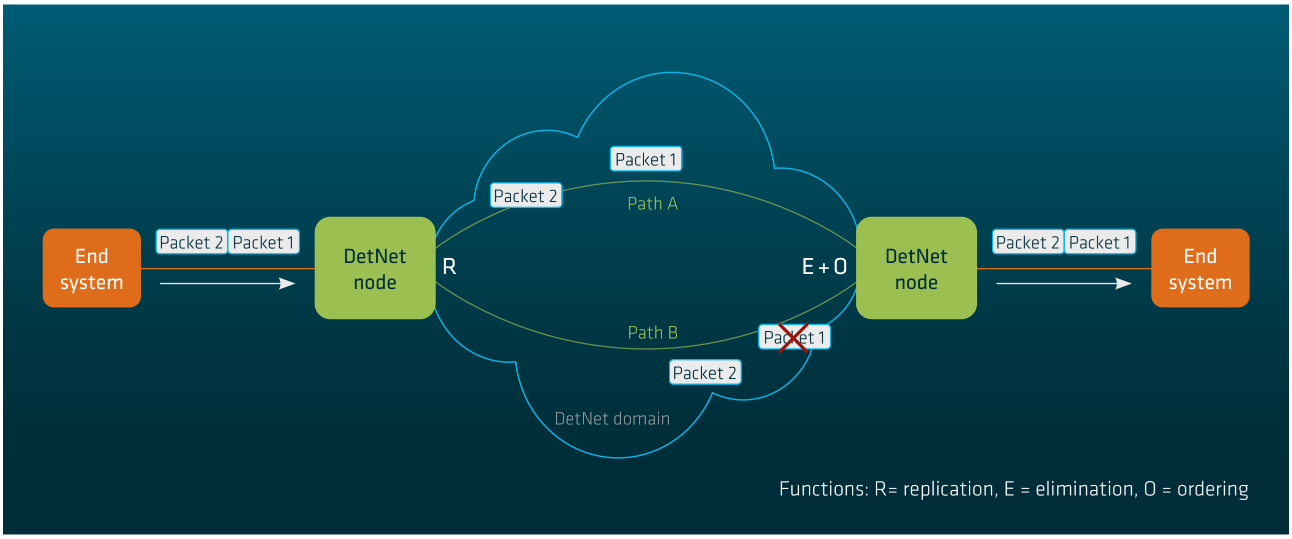
DetNet systems
DetNet systems [2] comprise DetNet nodes and DetNet end systems (the network-plane component of which is the NIC), see figure 1. DetNet nodes are routers that have been extended by adding DetNet features; they can be additionally differentiated by the supported DetNet sublayers.

- DetNet relay nodes implement the DetNet forwarding sublayer and DetNet service sublayer functions.
- DetNet transit nodes only implement the forwarding sublayer and are not necessarily DetNet service-aware.
- DetNet edge nodes are a special case of DetNet relay nodes. Situated at the boundary of the DetNet domain, they act as DetNet service proxies for DetNet-unaware end applications by initiating (at the DetNet domain's ingress) and terminating (at its egress) the DetNet service for application data traffic streams (also called application flows). It contains DetNet service and forwarding sublayers plus a DetNet-unaware entity. In other words, it translates between DetNet-unaware and DetNet traffic.
- DetNet end systems can be regarded as end stations or communication end points (similar to talkers and listeners in the case of TSN). DetNet end systems support the DetNet forwarding sublayer and can include the service sublayer as well. End systems that do not support DetNet (and are therefore DetNet-unaware) require proxies, which are provided by the DetNet edge nodes.

DetNet systems transmit and receive two types of traffic flows, which IETF DetNet defines as application flows and DetNet flows [2].

DetNet flow types
- Application flow (also abbreviated as App-flow) data is carried as regular traffic in a DetNet flow between DetNet-unaware end systems. An App-flow is oblivious to DetNet attributes and DetNet-specific node requirements. The reference points of an App-flow are located at the source and destination. It can be encapsulated in layer 2 Ethernet (for example, a TSN stream) or layer 3 IP.

Figure 2: An example of packet replication, elimination, and ordering functions (PREOF)



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- DetNet flows can contain one or more App-flows, which are aggregated with an N:1 mapping. The endpoints of a DetNet flow must consist of a DetNet ingress node (or source DetNet end system) and a DetNet egress node (or destination DetNet end system). DetNet ingress and egress nodes are usually DetNet edge nodes. If the flow's endpoints are DetNet end systems, the data flow is directly generated as a DetNet flow. In the case of DetNet ingress and egress nodes (or source and destination DetNet end systems, respectively), an encapsulation can be added or removed as appropriate. DetNet ingress and egress nodes can therefore serve as intermediate reference points for an App-flow. A DetNet flow can have a DetNet-specific encapsulation with Flow-ID attributes to identify the App-flow that a packet belongs to, plus a sequence number for detecting duplicate packets and reordering packets. No DetNet-specific encapsulation is defined for IP flows.

3.2 Data Plane Framework

The DetNet data plane oversees data transfers in the DetNet network. The main features of the DetNet data plane are its technology and encapsulation. The IETF has defined two types of DetNet data planes: IP and MPLS. To support DetNet functions, every packet must have two main data flow attributes: a flow identifier and a sequence number. These are encoded in the packet using encapsulation. The following sections discuss the supported data plane technologies while focusing on encapsulation and possible scenarios.

3.2.1 IP Data Plane: Encapsulation

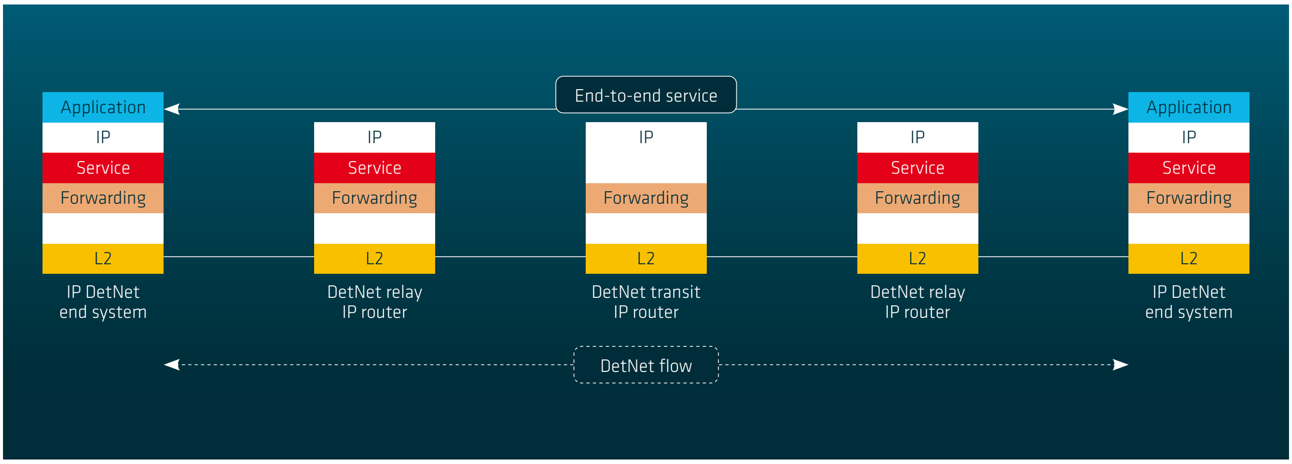
In the IP-based DetNet data plane [9], IP hosts and routers provide the DetNet service to IP-encapsulated data. No DetNet-specific encapsulation has been defined in IETF DetNet for supporting IP flows; instead, existing IP header information is used to identify flows and provide the DetNet service ("6-tuple-based" flow identification with up to six header fields). A 6-tuple contains an IP source address field and an IP destination address field, a field for the next-level protocol or header, specific fields of the next-level protocol (usually two fields) for the transmission control protocol (TCP) or user datagram protocol (UDP) source and destination ports or else a field for Internet protocol security (IPSec) (in other words a security parameter index (SPI) field), plus a field for the IPv4 service type or IPv6 traffic class (a differentiated services code point or DSCP). Note that since a packet sequence number is not part of the IP encapsulation, in this case the DetNet service sublayer is not supported. However, the IETF DetNet Working Group has adopted the proposal made in a request for comments (RFC) [10] to support the service sublayer for integrating PREOF in the IP data plane. This RFC specifies a MPLS-over-UDP tunneling technique for the DetNet IP data plane. A UDP tunnel is used between DetNet IP nodes, and the original IP packet is encapsulated in a MPLS pseudowire (PW) by adding a service label (S-label) and a control word (CW) (see section 3.2.3 for additional details on MPLS encapsulation). The CW holds a sequence number while there are still IP packets on the wire between DetNet nodes.

Alternatively, service protection can be provided for individual subnetworks, for example using technologies such as MPLS or IEEE 802.1 TSN. In this case, service protection is independently provided in each link or subnetwork using domain-specific mechanisms (due to the lack of unified end-to-end sequencing information, which is required for intermediate nodes). Additionally, the IP packet 6-tuple is matched and mapped to a DetNet-capable link or subnetwork for identifying DetNet flows. Operation of IEEE 802.1 TSN end systems over DetNet-enabled IP networks is beyond the scope of IETF DetNet; the same statement also applies to the details of encapsulating Ethernet frames of TSN streams in IP packets at an IP end system or DetNet edge node to produce DetNet IP flows.

3.2.2 IP Data Plane: Scenarios

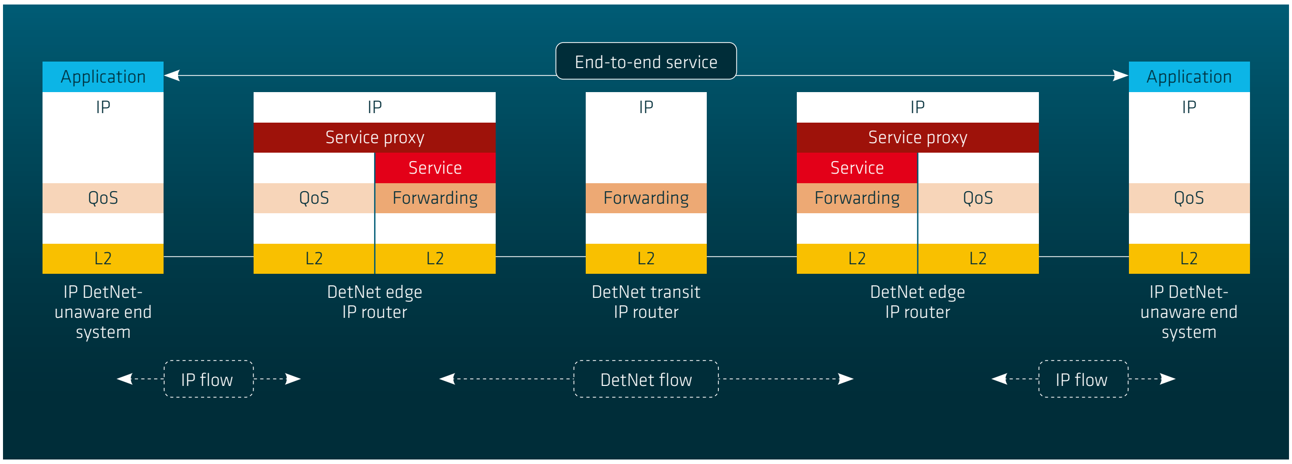
Two scenarios are possible for the DetNet IP data plane, depending on whether or not the end systems are DetNet-aware as shown in figure 3 and figure 4. The red-colored service component indicates that a node is DetNet-service-aware but does not perform any DetNet service sublayer functions such as PREOF (unless the MPLS-over-UDP tunneling technique is used [10]). However, the DetNet service sublayer provides a reference point for the DetNet service, i.e., which makes the node supporting it aware of DetNet flows. Note that in figure 4, the DetNet-unaware entities use legacy forwarding tools similar to those of the DetNet's forwarding sublayer.

Figure 3: DetNet IP data plane with DetNet-aware end systems



Source: 5G-ACIA / ZVEI e. V.

Figure 4: DetNet IP data plane with DetNet service-unaware end systems



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3.2.3 MPLS Data Plane: Encapsulation

The MPLS data plane involves transporting DetNet flows over an MPLS-packet-switched network as a service for IP and Ethernet hosts. In this case, a specific DetNet encapsulation [11] known as DetNet pseudowire (PW) is used. It is based on existing MPLS PW encapsulations and mechanisms. The MPLS-based DetNet data plane encapsulation has the parts shown in figure 5:

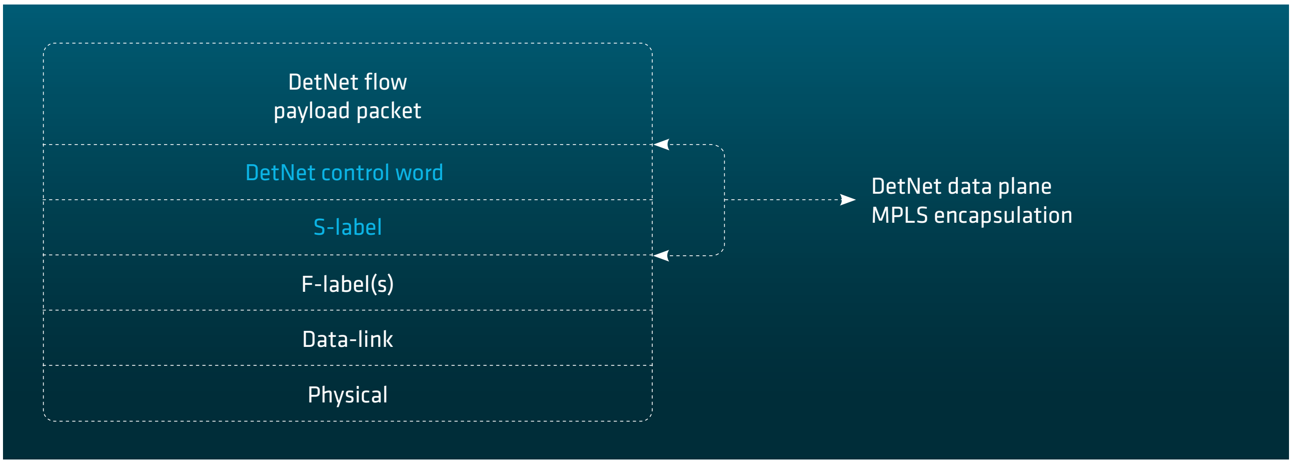
- The DetNet control word (d-CW) contains sequencing information for replicating packets and eliminating duplicates, plus an OAM indicator. The d-CW must always be present in a packet (even if it is not used). The d-CW corresponds to the generic PW MPLS control word defined in RFC 4385 [12].
- The DetNet service label (S-label) identifies a DetNet flow to the peer node that processes it. The S-label must be at the bottom of the label stack and precede the d-CW. The value of the S-label indicates the packet type to the egress edge node.
- There may also be MPLS forwarding label switched path (LSP) labels or F-labels used to direct the packet along the LSP to the next peer node.
- The required data-link encapsulation takes place prior to transmission over physical media.

Depending on the type of end system (layer 3-IP or layer 2-Ethernet), different aspects of encapsulation need to be considered. For layer 2 (Ethernet) end systems, when a DetNet layer 2 service is provided it is mandatory to either retain the layer 2 headers or provide a way to reconstruct them when exiting the DetNet domain. For layer 3 (IP) end systems in which an IP over MPLS routing service is used, the IP headers are modified to match standard router behavior, for example with time-to-live (TTL) handling.

3.2.4 MPLS Data Plane: Scenarios

Two different scenarios need to be considered in connection with the DetNet MPLS-based data plane. The first is a TSN-over-DetNet MPLS-enabled network, which is discussed in section 3.3.2. The second scenario is an IP-over-DetNet MPLS-enabled network as shown in figure 6. Note that the service component in red indicates that no MPLS DetNet service sublayer function is supported. In addition, there can be a subnetwork instead of a single DetNet transit node. Whenever a DetNet-unaware end system is connected to a DetNet node, this DetNet node is replaced with a DetNet edge node.

Figure 5: MPLS-based DetNet data plane encapsulation



Source: 5G-ACIA / ZVEI e. V.

An IP flow is mapped to one or more PWs and MPLS LSPs. The relay nodes map each DetNet flow to MPLS PWs, which are functionally similar to PW switching provider edges (S-PEs), or to terminating provider edges (T-PEs) at the edge of an MPLS network (see figure 6). The transit node (label switching router or LSR) is MPLS LSP-aware and performs switching based on MPLS labels. Transit nodes do not necessarily have any specific knowledge of the DetNet service.

3.3 Relationship Between DetNet and TSN

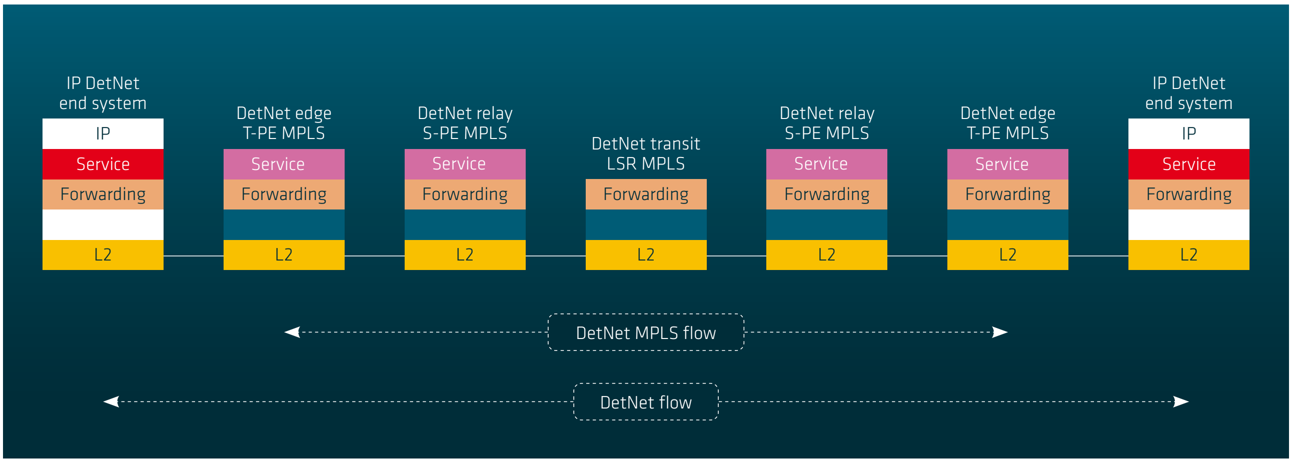
This section presents the functional similarities and differences between DetNet and TSN and describes possible interoperation scenarios involving TSN that have been defined by the IETF. In many of them, DetNet and TSN complement one other.

3.3.1 DetNet and TSN Features for Industrial Automation

DetNet has been defined according to the same time-sensitive communication principles as for TSN. The IETF and the IEEE 802.1 WGs are collaborating closely to align features and enable interworking.

Table 1 lists features for both technologies based on characteristics that are considered necessary for industrial automation traffic (for detailed information on the features required by IEEE 802.1 TSN, see the 5G-ACIA white paper "Integration of 5G with Time-Sensitive Networking for Industrial Communications" [13]), table 1). As shown in table 1 below, most TSN features have counterparts in DetNet. Traffic shapers such as IEEE 802.1Qbv can be used in DetNet by implementing RFC 9320-compliant queueing techniques [14] in a router's NICs. Work is ongoing to implement the same end-to-end data plane features in layer 2 (TSN) and layer 3 (DetNet). TSN frame preemption is not defined for layer 3, but layer 2 capabilities could be used for this purpose. Due to its intrinsic layer 3 data plane interconnection characteristics, DetNet is suitable for managing larger networks than TSN, which – being a layer 2 technology – is more appropriate for local networks.

Figure 6: IP-over-DetNet MPLS-enabled network



Source: 5G-ACIA / ZVEI e. V.

Table 1: TSN and DetNet features for industrial automation

IEEE 802.1 TSN	IETF DetNet
Bounded latency	Bounded latency
Extremely low frame losses	Extremely low packet losses
Frame replication and elimination for reliability (FRER)	Packet replication, elimination, and ordering functions (PREOF)
Ingress policy/time-based (per-stream filtering and policing (PSFP)/ IEEE 802.1Qci and IEEE 802.1Qdj)	Ingress policing provided by IETF tools if supported by the router (see [14] and notes 1 and 2 below)
Ingress policy/rate-based (PSFP/IEEE 802.1Qci and IEEE 802.1Qdj)	Rate-limiting/policing functions supported (e. g., various formats of the access control list (ACL) implemented by all major router vendors)
Scheduled traffic (IEEE 802.1Qbv)	Provided by IETF tools if supported by the router (see [14] and notes 1 and 2)
Time synchronization (IEEE 802.1AS)	Lower-layer-specific time synchronization applies.
Strict priority	Strict priority (see note 3)
Configuration (IEEE 802.1Qcc)	Network configuration with existing protocols and using YANG models
Frame preemption (IEEE 802.1Qbu)	Not defined for layer 3. If required, layer 2 capabilities can be used.

Note 1: The IEEE TSN TG and IETF DetNet WG are closely collaborating with the goal of achieving identical end-to-end data plane characteristics in layers 2 and 3.

Note 2: The ongoing IEEE P802.1DC project [15] is extracting QoS features (incl. TSN features) from IEEE 802.1Q to make it easier to leverage them in non-bridged devices, e. g., end stations, routers, or firewall appliances.

Note 3: The recently updated charter of the DetNet WG is open to contributions specifying queueing techniques for DetNet.

Source: 5G-ACIA / ZVEI e. V.

3.3.2 DetNet and TSN Interoperation Scenarios

Interoperation with TSN is achievable in a few scenarios. In one of these – a TSN over a DetNet MPLS-enabled network [16] – TSN end systems originate Ethernet-encapsulated traffic while DetNet edge nodes provide the DetNet service to ultimately deliver the traffic to another TSN end system, as shown in figure 7.

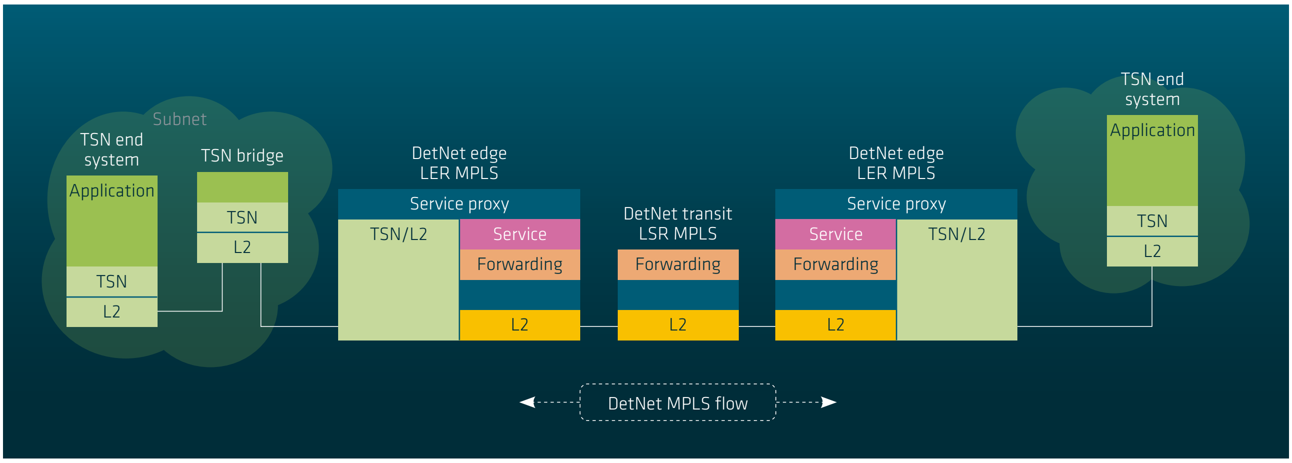
DetNet edge nodes (implemented in label edge routers (LERs)) are responsible for mapping DetNet-unaware traffic to DetNet services to support imposition and disposition of the required DetNet encapsulation. DetNet transit nodes are regular MPLS LSRs and generally unaware of the special requirements of DetNet flows. Figure 7 contains a single transit node, but a subnetwork with multiple transit nodes is also possible.

IETF DetNet does not define encapsulation for the case of TSN over IP because it is assumed that an already-defined tunneling method (e. g., the layer 2 tunneling protocol (L2TP)) is used to encapsulate a layer 2 TSN frame in IP. The L2TP tunnel is created by encapsulating an L2TP frame inside an UDP packet, which in turn is encapsulated inside an IP packet. The source and destination addresses of this IP packet define the endpoints of the connection. An example is shown in figure 8.

There is a second group of scenarios in which TSN is a subnetwork of the DetNet network; here two different cases may be possible: (i) IP over TSN [17] (see figure 9) or alternatively (ii) MPLS over TSN [18].

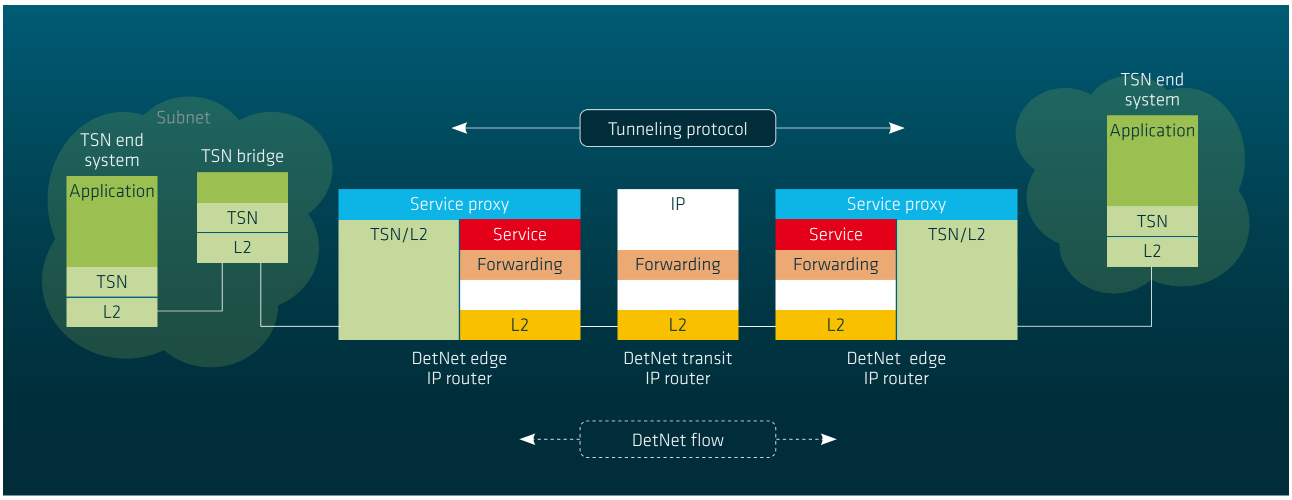
TSN is a subnetwork of DetNet, so DetNet nodes connected via it do not have to be of the edge type. DetNet nodes treat the subnetwork as a layer 2 connection to the next-hop DetNet node. No TSN-DetNet translation takes place within individual DetNet nodes; this should be done by the (TSN) subnetwork. Edge (TSN) nodes will be needed in the TSN subnetwork [16] in order to translate from DetNet to TSN for the connection. Exactly how these capabilities will be implemented in TSN nodes has not yet been specified.

Figure 7: TSN over a DetNet MPLS-enabled network



Source: 5G-ACIA / ZVEI e. V.

Figure 8: TSN over DetNet IP-enabled network



Source: 5G-ACIA / ZVEI e. V.

Note that, in a centralized TSN-DetNet interoperation scenario, the CNC and the DetNet controller should communicate and coordinate the mapping of TSN streams and DetNet flows. How this will be accomplished also still remains to be specified.

3.4 Reliable and Available Wireless (RAW)

The IETF Reliable and Available Wireless (RAW) project is extending the DetNet architecture to support wireless use cases better. RAW was initiated as a separate WG before being integrated in the DetNet WG in 2023. DetNet solutions apply to both wired and wireless networks, but wireless networks pose especially great challenges. RAW is focusing on mastering them while ensuring deterministic communication.

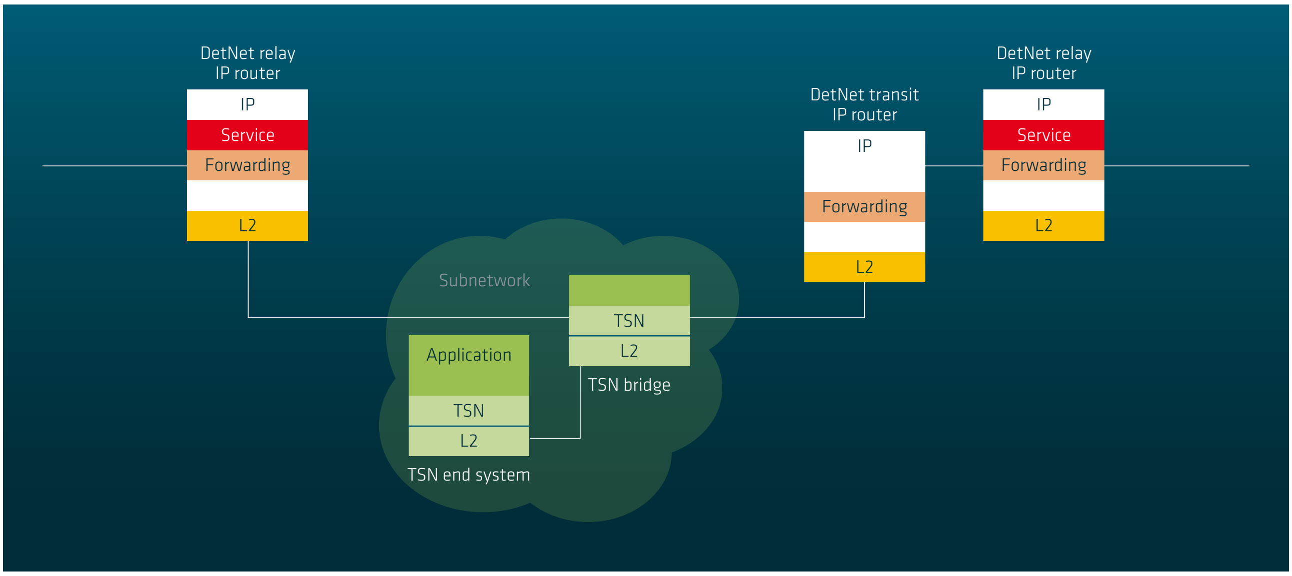
The document "Reliable and Available Wireless (RAW) Use Cases" (RFC 9450) [19], published in 2023 and updated in early 2024, describes and discusses RAW use cases. Other RAW-related IETF draft documents are also currently being prepared and discussed. They address the following:

- RAW technologies: a series of technologies (including 5G) that are capable of scheduled transmissions and therefore suited for carrying time-sensitive flows with high reliability and availability.
- RAW architecture: this extends and adapts the DetNet architecture and other standard IETF concepts and mechanisms to meet the specific challenges of wireless media, especially intermittently lossy connectivity.

3.5 Summary

DetNet includes a feature set that is able to deliver the promised benefits: very low delay, extremely low packet loss, and in-order packet delivery. To minimize delays, resources (such as bandwidth and buffer space) are allocated to devices within the DetNet domain. The use of explicit routes protects services and controls congestion while providing immunity

Figure 9: IP over TSN



Source: 5G-ACIA / ZVEI e. V.

against IP protocol convergence caused by changes in topology. Redundant paths with packet replication and elimination functions minimize packet losses. Finally, use of a packet ordering function can also ensure in-order packet delivery with redundant paths.

DetNet is useful for interconnecting subnetworks (such as layer 2 TSN segments) while meeting deterministic communication requirements such as low and bounded delays and extremely low packet losses. This makes it easy to scale up the network, something that is challenging to configure in layer 2 networks. In addition, IP-based communication with an IP-based edge or local cloud may be more straightforward to achieve with deterministic communication over layer 3 using DetNet.

4 5G Support for DetNet

Similarly to how the 5G system (5GS) has been modeled as a 5GS logical TSN bridge for TSN, it can also be modeled as a logical DetNet node to support DetNet. Here the node granularity is also on a per-user plane function (UPF) basis, and UE interfaces can be defined by adopting the time-sensitive communication (TSC) framework of 3GPP Release 17.

From the IP data plane perspective, it is essential to support DetNet flow identification. A DetNet flow can be associated with a 5G QoS flow in 5GS that is identified according to policy rules defined in the UPF. QoS configurations of the TSC framework can be reused in Release 17 without affecting standardization of the radio access network (RAN).

From the 5G control plane perspective, there is a need to interact with a DetNet controller using a standard configuration protocol such as NETCONF [4] or RESTCONF [5]. This interface could be used to supply information to the DetNet controller and receive configuration instructions for the 5GS. The DetNet YANG model [6] information is mapped to meaningful 5GS parameters. Many of these functions are executed by the time-sensitive communication and time synchronization function (TSCTSF), which was defined for the 5G control plane in 3GPP Release 17 and extended further in Release 18.

3GPP standardized 5GS support for DetNet in Release 18 [20]. The main principles agreed on in 3GPP are summarized below.

4.1 Architectural Assumptions

The following architectural assumptions apply to DetNet support in 5G:

- Integration of 5GS with DetNet uses the IP data plane; the MPLS data plane is not supported.
- The specifications only support the DetNet forwarding sublayer's functions. This means that the 5GS DetNet node behaves like a DetNet transit node.
- IP-based DetNet traffic is carried in IP-type PDU sessions.
- The mapping functions for DetNet are implemented in the TSCTSF.
- Where applicable, DetNet support in 5G reuses the functions of the TSC framework defined in Release 17.
- The existing 3GPP routing mechanisms are reused for DetNet.
- The existing multicast capabilities can be reused for DetNet communications.
- No impact on UE standardization
- No impact on RAN standardization

When the 5GS acts as a logical DetNet node (with per-UPF granularity), each node is identified by a node ID and each interface by an interface ID. Interfaces and ports correspond to PDU sessions on the UE side and network-side interfaces (or UPF-side interfaces) in the network-side TSN translator (NW-TT). Figure 10 shows the standardized architecture.

Note that the 5GS logical DetNet node can connect to a DetNet network on the network side and to a single DetNet system on the UE side. The UE can connect with any type of DetNet-aware system (a DetNet end system or DetNet transit, relay, or edge node/router).

TSCTSF terminates the interface with the DetNet controller. YANG models are exchanged via this control plane interface using an existing configuration protocol (NETCONF or RESTCONF).

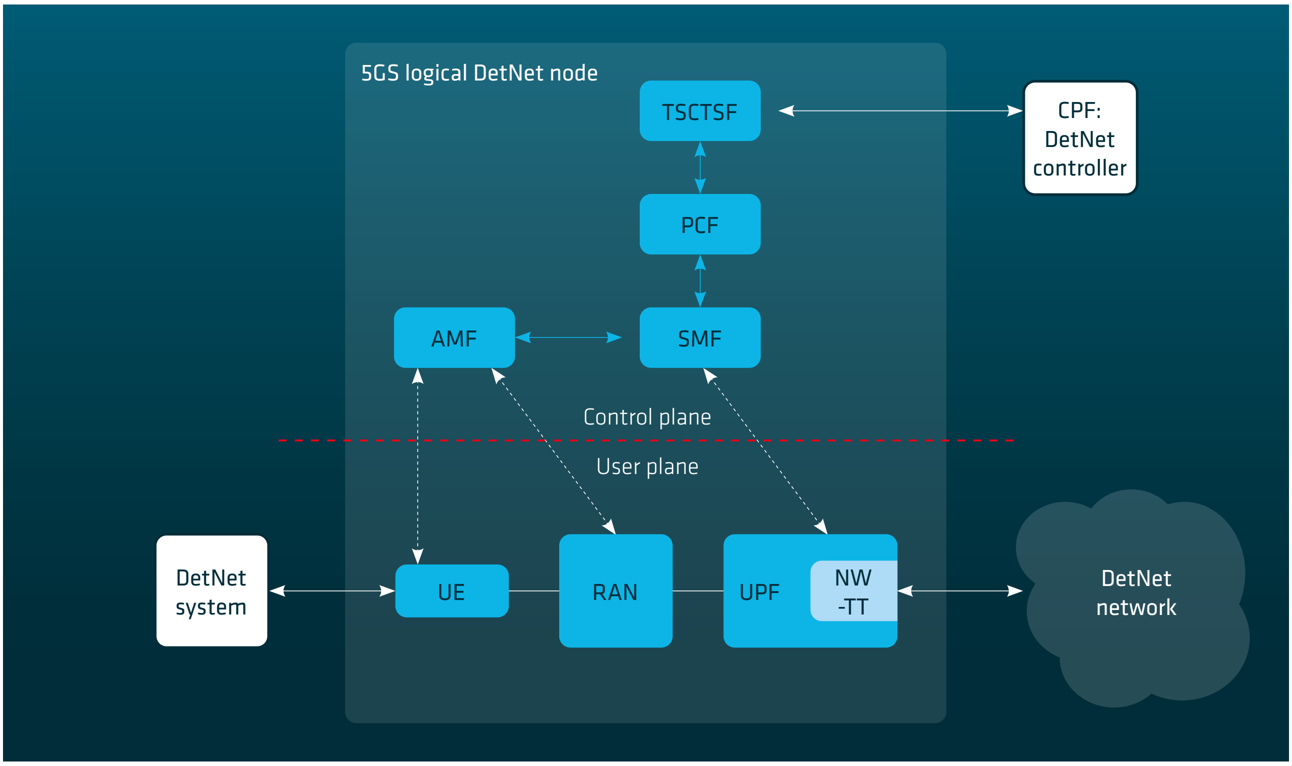
No device-side TSN translator (DS-TT) is required at the UE, but one could be included if the service requires time synchronization (when both DS-TT and NW-TT are needed).

4.2 Exposure

The 5GS exposes or reports information to the DetNet controller via the TSCTSF, which receives it from the session management function (SMF), the UPF, and its NW-TT while following the TSC procedures defined in Release 17. TSCTSF reports the following information to the DetNet controller for each interface:

- Interface type
- IP address
- Subnetwork (prefix length)
- Neighbor address (for network-side interfaces)
- MAC addresses (for network-side interfaces)
- MTU size

Figure 10: Architecture for 5GS interworking with DetNet



Source: 5G-ACIA / ZVEI e. V.

4.3 DetNet-to-5G Parameter Mapping and Configuration

The DetNet controller can configure a 5GS logical DetNet node via the YANG model [6]. A selected number of DetNet parameters can be mapped to known 5G parameters as shown in table 2.

In the YANG models there are also end-to-end parameters that do not directly apply to the segment represented by the 5GS logical DetNet node in the network. The TSCTSF may use end-to-end traffic requirements in the YANG configuration to derive 5GS requirements based on a preconfigured mapping. An optional 5GS YANG extension for a 5GS-specific delay requirement (5G max-delay and 5G max-loss) was defined in 3GPP as a YANG model that imports the YANG model draft-ietf-detnet-yang [6] and adds the 3GPP-specific parameters. Otherwise, TSCTSF maps the DetNet parameters based on a preconfiguration.

The DetNet controller can provide configurations for incoming/outgoing interfaces for use by the TSCTSF to identify the affected PDU session and flow direction (uplink or downlink). The TSCTSF can determine when the communication is UE-to-UE and divide the requirements in the corresponding PDU sessions (one PDU session per UE).

For any static routing request by the DetNet controller, it can be verified at the TSCTSF whether the provided routing information corresponds to how the 5GS has mapped IP addresses to PDU sessions. The TSCTSF indicates to the DetNet controller whether the configuration request has been successful. Alternatively, if the YANG models are extended to include status, the TSCTSF can use this field.

Note that even if the DetNet controller explicitly defines routing at the N6 interface (the 5G network-side interface), the 3GPP specifications do not cover control of the N6 routing, which has been deemed to be beyond the scope of 3GPP. A possible deployment option that would not require any additional 3GPP specifications involves implementing a collocated external router at the UPF and connecting the two via a single interface. This way the DetNet controller can manage routing on the network side (at the N6 interface) using regu-

Table 2: Mapping of DetNet parameters to 5G parameters

DetNet parameters	5G parameters
Max-latency	Required delay
Min-bandwidth	Guaranteed flow bit rate (GFBR)
Max-loss	Required packet error rate (PER)
Max-consecutive-loss-tolerance	Survival time; this mapping is only possible when there is a single packet per interval.
Interval	Periodicity
max-pkts-per-interval * (max-payload-size + protocol header size)	Max burst size
max-pkts-per-interval * (max-payload-size + protocol header size)/ Interval	Maximum flow bit rate (MFBR)
DetNet flow specification (6-tuple)	3GPP flow description (including the DSCP value and optionally the IPv6 flow label and IPSec SPI)

Source: 5G-ACIA / ZVEI e. V.

lar management capabilities supported by the external router. When the UE is connected to a DetNet router, routing can be configured in the downlink using standardized techniques such as 3GPP framed routes, IPv6 prefix delegation, and NAT.

More work will be required to extend 3GPP standards to support the service sublayer with its PREOF feature. It will also be necessary to generalize the support for DetNet so that the DetNet controller can manage explicit route configurations. At the time of writing, 3GPP does not yet support control signaling for the IP routing protocols. Note that there is only limited support for multicast mechanisms in 3GPP. Extensions to enable multicast enhancement may be part of future general standardization work on 3GPP and are not necessarily DetNet-specific.

5 Potential 5G Industrial Automation Use Cases Involving DetNet

Layer 2 and layer 3 deterministic communication can be provided. The question is whether there is actually a need for this in layer 3. Answering it requires analyzing several important factors, including whether a service area of a use case spans a larger area, whether there is a need to link multiple subnetworks, whether a use case requires edge computing support, and whether devices are IP-capable. We define these factors as DetNet markers. DetNet markers are required features that specifically indicate that DetNet is a suitable option for providing the deterministic service instead of or in addition to TSN. As discussed in chapter 3, relevant requirements – such as high reliability, bounded latency, and very low packet losses – can be met with DetNet.

It is worth mentioning that some industrial protocols do not use the IP layer. Take, for example, the case of PROFINET real time (RT) / isochronous real time (IRT) [21]: to minimize the processing time, almost no use is made of intermediate layers (such as IP and transport layers). Specifically, this means that when a frame arrives it is routed from layer 2 straight to the PROFINET application (in layer 7). In such a case, DetNet can be used to create a connection (via DetNet/IP tunnelling) to other PROFINET segments as required. This underscores the scalability and flexibility of DetNet.

However, other industrial protocols – such as the Open DeviceNet Vendors Association (ODVA) EtherNet/IP suite of protocols, which include the Common Industrial Protocol (CIP) – use standard TCP, UDP, and IP protocols. As described in [22], "CIP encompasses a comprehensive suite of messages and services for a variety of manufacturing and process automation applications including control, safety, security, energy, synchronization, motion, configuration and information." EtherNet/IP uses UDP/IP for real-time producer-consumer messaging in applications such as standard and safety I/O, while TCP/IP is used for client-server type messaging for applications such as configuration and provision of information. EtherNet/IP utilizes standard IP in order to natively support standard layer 3 infrastructure, thus making it possible to use the IP data plane of DetNet.

5.1 5G in Industrial Automation Use Cases

According to 3GPP TS 22.104 [23], there are at least nine use cases for "factories of the future" across the following application areas: factory automation, process automation, human-machine interfaces (HMIs) and production IT, and remote monitoring and maintenance.

The next few sections analyze the relevance of DetNet for providing deterministic communication considering each industrial use case in turn. Here three assumptions are made: (1) 5G is capable of supporting any end-to-end latency (starting as low as 1 ms) and meeting stringent packet error rate (PER), communication service availability (CSA), and communication service reliability (CSR) requirements [23] if an appropriate deployment option is chosen, (2) OT applications run in DetNet systems (that is, in UEs or behind the user plane function (UPF)), and (3) appropriate waveforms, numerologies, and spectra (for example FR1, FR2, …) are chosen for the air interface.

New use case examples are also provided and analyzed. These examples reveal new scenarios in which DetNet markers are strongly present.

5.2 Factory Automation

5.2.1 Motion Control

Motion control systems are used when there is a need to precisely control moving and/or rotating parts of machines in a specific manner. A motion controller periodically sends setpoints to one or more actuators, which then execute the required action in one or more processes. To provide the motion controller with feedback on the processes, sensors capture information on their states in real time and periodically send it back.

A controller and actuator typically operate in close proximity to each other within an area measuring 50 m x 10 m x 10 m [23]. Deterministic capabilities can be provided via either Ethernet or IP.

For high-end motion control applications with cycle times as short as 31.25 μs, 5G is probably not a viable option. However, it may be feasible for slower applications involving more complex networks and a cycle time of several milliseconds.

5.2.2 Control-to-Control Communication

Multiple controllers can be used on the shop floor, each of which controls a specific set of machine functions that need to communicate with one another. These usually need to be synchronized for exchanging real-time data and therefore tend to use the same master clock and synchronization protocol within a workspace that typically measures 100 m x 30 m x 10 m.

When multiple motion control units are deployed, there can be a need for control-to-control communication. In the future, it will be possible to use the Open Platform Communications Unified Architecture (OPC UA) to connect controllers that need to interact with the corresponding actuators and sensors via different layer 2-based subnetworks. This may justify the use of IP-based DetNet for deterministic, cross-platform controller-to-controller (C2C) communication.

5G-based DetNet can be useful for providing cross-platform-enabled C2C communication among heterogeneous networks while hiding their subnetworks, which may use different layer 2 technologies.

5.2.3 Mobile Robots and Cooperative Carrying

Going forward, the expectation is that mobile robots and automated guided vehicles (AGVs) will be controlled from the edge cloud. This calls for reliable 5G communication between the controlling entity and the mobile robots. The AGVs will be monitored and controlled by a guidance control system that receives process information in real time, prevents vehicles from colliding with one another, assigns driving jobs to them, and generally manages their traffic. Such a use case can benefit from DetNet, especially when taking advantage of edge/cloud-based computing, which derives benefits from IP-based networking.

Due to the fact that some mobile robot sub-use cases in factory automation require edge-based or centralized fleet control or guidance control, 5G-based DetNet may become the preferred choice for IP-based deterministic communication.

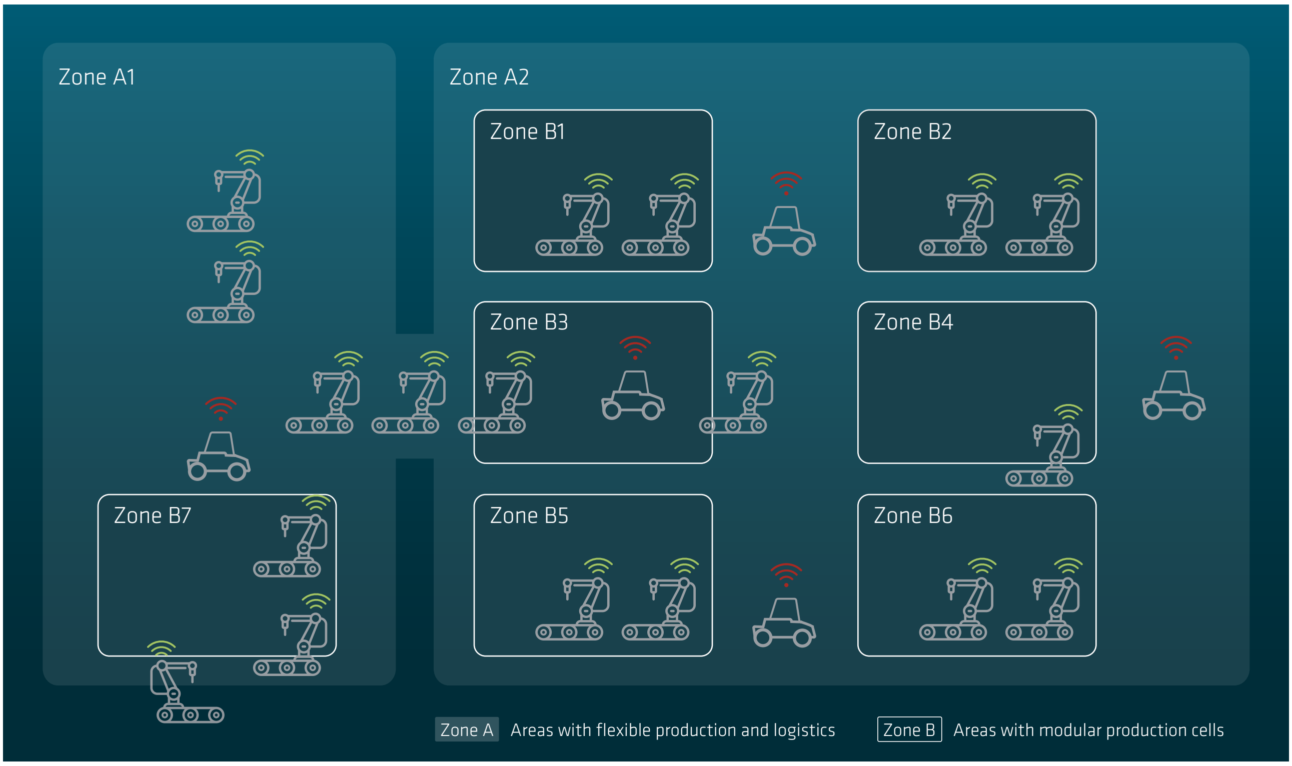
Direct control of devices is time-critical since it involves safety-relevant functions, for example for making emergency stops and avoiding obstacles. It can require an end-to-end latency in the range of 1 to 10 ms. Each mobile robot needs to interact with its surroundings (like intelligent storage racks, stationary robots, and moving machines). This is also time-critical, calling for an end-to-end latency of only 1 ms.

In the case of cooperative carrying by mobile robots as described in clause A.2.2.5 of TS 22.104 [23], communication among collaborating mobile robots or AGVs requires high communication service availability and ultra-low latency in the realm of 1 to 2.5 ms. The case described there involves sidelink communication, so it needs to be determined whether or not DetNet is supported over sidelink.

5.2.4 Example: Flexible Modular Production

Clause 5.15 of 3GPP TR 22.832 [24] describes another suitable use case for deterministic communication over 5G in the context of factory automation: flexible modular production. This is part of the trend toward replacing static sequential production lines with modular production systems as shown in figure 11. Modular systems are characterized by high flexibility and versatility, which factories require in order to accommodate smaller and more differentiated product lots and batches.

Figure 11: Flexible modular production with high flexibility and mobility (source: Siemens)



Source: 5G-ACIA / ZVEI e. V.

This flexibility is achieved by applying strategies for:

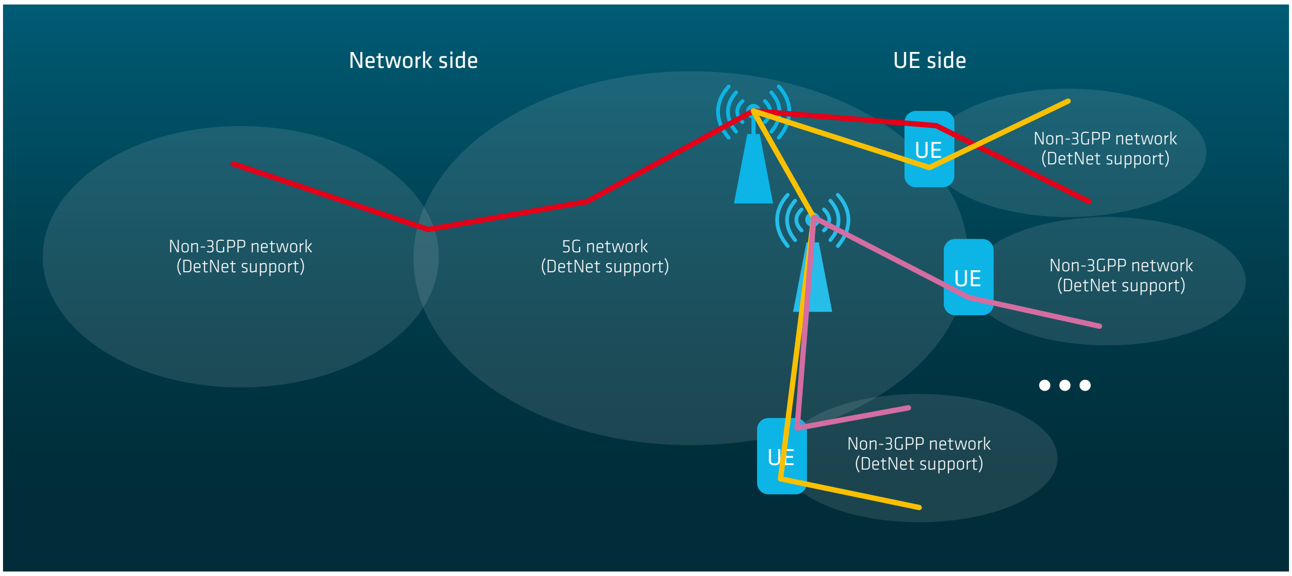
- Appropriately scheduling subsequent production steps
- Self-optimizing algorithms for speeding up the production flow, for example for:
  - Routing of semifinished products
  - Scheduling of machines
  - Continuous monitoring of machines' states to identify ways to improve them
  - Diagnostics and predictive maintenance, which can lead to new machines or AGVs leaving or joining the production process
- Nonstop localization of mobile machines/AGVs to continuously adjust and optimize the production process
- Dynamic setup of deterministic communication streams (by the industrial application)

Those strategies support the deployment of many mobile assets to achieve truly modular production. This use case therefore combines several of the requirements and particularities of the scenarios that have already been discussed in sections 5.2.1, 5.2.2, and 5.2.3. The assets have to communicate with one other in a way that ensures dynamic, safe operation. The ultimate aim is self-organizing production processes.

The dynamic evolution of logistical and production processes is driving constant changes in how mobile actuators, stationary machines, and controllers communicate with one another. For instance, distributed industrial control (a commonly used approach for achieving self-organization of mobile components) relies on a robust communication infrastructure that lets controllers hand control functions over to others with very short response times and high reliability. Reliable deterministic communication is an absolute must for flexible modular production. The network configuration models listed in section 3.1.2 may be able to meet the communication requirements for establishing TSN streams in a novel manufacturing system while either taking a centralized approach or using distributed protocols. The choice of network configuration model depends on the individual deployment case. Figure 12 shows an example of a potential implementation of deterministic communication in this context; in it, a DetNet-aware 5G network is used to wirelessly bridge several DetNet-aware wired networks and enable end-to-end deterministic flows.

When a new production task is assigned to multiple mobile assets, these request that the required DetNet flows are set up among them within the DetNet network (which includes an industrial 5G network for wireless connectivity). The in-

Figure 12: Examples of potential deterministic communication relationships in flexible modular production



Source: 5G-ACIA / ZVEI e. V.

dustrial applications initiate dynamic reservation of DetNet flows for deterministic real-time communication services, which then take place via a user-network interface (UNI) between the end systems and the network. The DetNet controller plane establishes the required explicit paths and reserves flows for the deterministic real-time communication. Depending on the chosen deployment, this can be performed by a centralized DetNet controller, using distributed control plane signaling protocols, or taking a hybrid approach. The deterministic real-time communication services are dynamically reconfigured during the production process to the extent that is required to ensure the mobility of the assets/mobile robots/AGVs. When the production task is finished, the participating machines release the corresponding DetNet flows and "move on" to their next tasks.

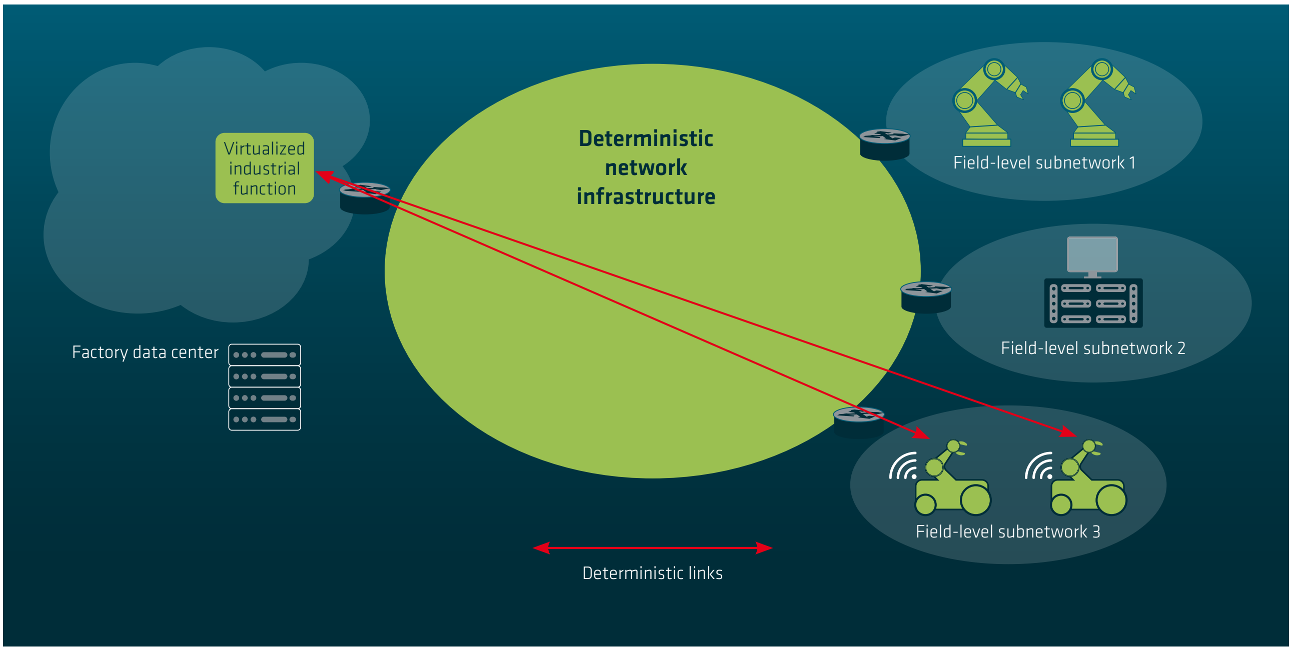
Flexible modular production scenarios benefit from dynamically configured, deterministic communication flows over 5G. DetNet allows deterministic communication in layer 3 and straightforward connection of multiple subnetworks for production assets to safely and fluidly self-organize.

5.2.5 Example: Support for Virtualized Industrial Functions

Interest in virtualized/containerized industrial applications has grown in recent years; examples include virtual programmable logic controllers (PLCs) and virtual distributed control systems (DCSs). The prerequisites for appropriately using virtualized functions include dependable network infrastructures and technologies that ensure deterministic (i. e., predictable) and reliable communication between them and industrial devices. As factory floors grow in size and more flexible production approaches are introduced, legacy solutions based on local area networks (LANs) are approaching their limits. DetNet over 5G can provide a solution for cases in which virtualized industrial functions and applications are hosted in edge clouds and communicate with devices in the field, sometimes via wireless connections.

Figure 13 shows an example of the scenario under discussion. Here a virtualized industrial function hosted in a factory datacenter (or on-premises edge cloud) interacts with AGVs that

Figure 13: Example of a virtualized factory function



Source: 5G-ACIA / ZVEI e. V.

communicate over 5G. The traffic has to traverse different topologies (for the purposes of this example, abstracted as a "deterministic network infrastructure") that rely on network layer mechanisms for routing, reserving resources, and OAM.

This case poses several requirements, all of which can be met by integrating DetNet and 5G technologies:

- Deterministic communication between devices connected by different access media (wired or wireless)
- Determinism for critical industrial traffic (such as control traffic) that
  - needs to have bounded latency and low jitter,
  - can be periodic or aperiodic, and
  - typically requires low bandwidth.
- Multi-domain redundancy: it must be possible to establish duplicated and disjoint communication links between two devices within the integrated network.
- Intelligent allocation of both priority and best-effort traffic
- A high level of security

5.2.6 DetNet Markers for Factory Automation

Table 3 lists DetNet markers for use cases in the field of factory automation. Most use cases have at least one of them, which illustrates the potential of DetNet. DetNet is able to leverage queueing techniques implemented in a router's

Table 3: DetNet markers for factory automation uses cases

Use case	Span area	IP-capable devices	Interconnection of subnetworks	Edge cloud	DetNet applicability
Motion control (cycle 500 us)	50 m x 10 m	Possible	No	No (close proximity of controller and sensor/actuators)	Possible (depending on the DetNet router's capabilities)
Slower motion control (cycle 0.5 – 2ms)	50 m x 10 m	Possible	No	No (close proximity of controller and sensor/actuators)	Possible (depending on the DetNet router's capabilities)
Control-to-control communication	100 m x 30 m	Possible	IP required to interconnect layer 2-based subnets	Possible	Yes
Mobile robots	1 km x 1 km	Possible	Unspecified	Yes (edge cloud processing)	Yes
Mobile robots: cooperative carrying	10 m x 10 m or 50 m x 5 m	Possible	Unspecified	Possible	Possible (it needs to be determined if sidelink can be supported with 5G DetNet)
Example: flexible modular production	1 km x 1 km	Yes	Yes, wireless 5G DetNet interconnects wired subnets	Possible	Yes
Example: support for virtualized industrial functions	100 m x 100 m	Yes	Yes	Yes	Yes

Source: 5G-ACIA / ZVEI e. V.

NICs, including TSN queuing techniques like that specified in IEEE 802.1Qbv (see [14]). As described in section 5.2.3, cooperative carrying requires sidelink; however, it is not yet clear whether DetNet over 5G is able to support this kind of feature.

5.3 Process Automation

5.3.1 Closed-Loop Control

In this use case, controllers in a plant make decisions and issue commands to actuators based on continuous measurements by several installed sensors. The latency and availability requirements are therefore very strict. According to clause A.2.3.1 of TS 22.104 [23], typically the service space spans 100 m x 100 m x 50 m and an end-to-end latency of about 10 ms is required.

A large-scale, closed-loop process automation control use case spanning large service areas can benefit from 5G-based DetNet.

5.3.2 Process and Asset Monitoring

In this use case, wireless sensors are used to monitor conditions in the plant, proper functioning of assets, and stocks of materials. This requires deploying 5G networks over a service space spanning at least 10 km x 10 km x 50 m. The required end-to-end latency is about 100 ms.

In large service areas like these, 5G-based DetNet may be appropriate for supporting process and asset monitoring use cases.

5.3.3 Plant Asset Management

According to clause A.2.3.3 of [23], plant asset management requires an end-to-end latency on the order of a few seconds. On a fairly large service area spanning 10 km x 10 km x 50 m, it can be provided by a normal 5GS without necessarily involving DetNet. If there are also stringent latency, packet error rate, and CSA requirements, however, this would be an appropriate use for 5G-based DetNet.

5.3.4 Example: 5G Sensor Systems for Closed-Loop Control and Process Monitoring

The use of 5G-capable sensor systems holds great potential for production technology. In addition to completely wirelessly transmitting data across large distances, this approach enormously reduces the installation effort. The sensors can be flexibly placed on the shop floor and directly connected to data processing systems via 5G.

IP-based communication with wireless communication technologies has the major advantage of making it easy to integrate common IT systems for data processing. Emerging technologies such as factory clouds or edge devices can also be integrated in the process with less effort. With this networking option, not only sensors but also actuators such as robots and machines can be wirelessly integrated and controlled. Virtualization and offloading of applications to cloud and edge systems increase flexibility while reducing the amount of hardware on the shop floor.

For the use cases described in 5.3.1 and 5.3.2, deterministic communication is needed to maintain the quality of production. A production shop floor usually has distinct subnetworks for machines, sensors, and IT systems. The prerequisites are not always met for installing a LAN along with data sources, a data processing entity, and data consumers. This largely rules out layer 2 technologies for routing data, including the exclusive use of TSN for deterministically transmitting data. It would, however, be possible to use layer 3 for routing across multiple subnetworks. DetNet could then be deployed for deterministic data transmission, thus enabling time-critical connections to the factory cloud or edge devices.

Different connection categories can be distinguished for using 5G sensor systems in closed-loop control (5.3.1) or monitoring (5.3.2) use cases; they are visualized in figure 14. These categories, and the corresponding endpoints of a closed-loop and monitoring chain, are usually deployed in different subnetworks. Examples include:

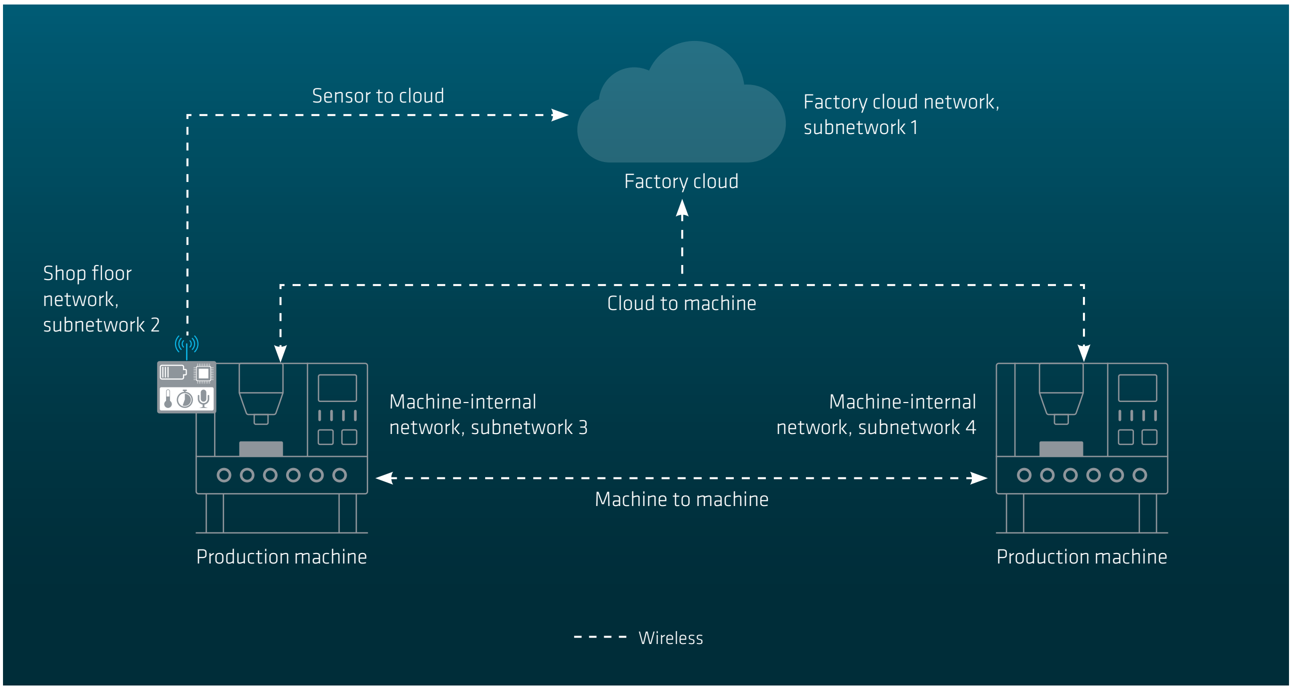
1. Cloud-to-machine: here there is usually a separate network for the factory cloud (equivalent to an edge cloud) or the virtual machines containing the applications (subnetwork 1), similarly to (centralized) cloud data center networks.
2. Sensor-to-cloud: for security reasons, the shop floor is not connected to the enterprise or IT network, instead being contained within its own subnetwork. The sensors of a 5G network for a shop floor would also belong to this subnetwork (subnetwork 2).
3. Machine-to-machine: finally, the main purpose of a machine-internal network is to enable relevant sensors and actuators to control the machine. Subnetworks of this kind are usually optimized for the machine-internal communication technology used (subnetworks 3 and 4).

These networks cannot exchange data using layer 2 switching. The only way for them to do so in real time is DetNet, which allows deterministic routing in layer 3.

5.3.5 DetNet Markers for Process Automation

Table 4 summarizes the DetNet markers for process automation uses cases. For most of them, there is at least one marker indicating potential for using DetNet. The case of plant asset management does not have stringent communication requirements, so connectivity via the 5G system is sufficient.

Figure 14: Connectivity for closed-loop control and monitoring applications with 5G sensor systems



Source: 5G-ACIA / ZVEI e. V.

Table 4: DetNet markers for process automation use cases

Use case	Span area	IP-capable devices	Interconnection of subnetworks	Edge cloud	DetNet applicability
Closed-loop control	100 m x 100 m	Possible	Unspecified	Unspecified	Yes, especially for large-scale closed-control loop
Process and asset monitoring	10 km x 10 km	Yes	Unspecified	Yes	Yes
Plant asset management	10 km x 10 km	Yes	Unspecified	Yes	No need, requirements are relaxed. 5G alone is enough.
Example: 5G sensor systems for closed-loop control and asset monitoring	1 km x 1 km	Yes	Yes	Yes (compute offload, edge devices)	Yes

Source: 5G-ACIA / ZVEI e. V.

5.4 HMIs and Production IT

5.4.1 Mobile Control/Operation Panels

Mobile control/operation panels are used to monitor, configure, maintain, control, and troubleshoot assets such as production lines, machines, or robots. They can also be used to trigger emergency stops or change the positions of robots and other machines. Due to the criticality of these safety functions, the control panels used require ultra-reliable low-latency communications; in the cases of assembly robots and milling machines, for instance, the end-to-end latency can be as low as 1 to 4 ms. Other sub-use cases – like controlling mobile cranes, mobile pumps, and fixed portal cranes – call for an end-to-end latency of roughly 12 to 30 ms. Non-wired mobile control/operating panels requiring stringent latency can therefore also benefit from 5G-based DetNet.

5.4.2 Augmented Reality

To achieve smaller, more power-efficient augmented reality (AR) headsets, processing needs to be offloaded to an edge server. This in turn requires good connectivity. Bidirectional transmission of messages between an augmented reality device and an image processing server calls for an end-to-end latency on the order of 10 ms.

Since AR requires IP-based interactions with (edge) application servers, 5G-based DetNet can be appropriate for supporting this use case.

5.4.3 Example: Deterministic Communication in the Cloud-Edge-IoT Continuum

Migrating software to containers is a widely used technique for maximizing the availability of applications or horizontally scaling them. Today it is mainly applied in the cloud domain using well-established orchestration technologies such as Kubernetes and other, complementary tools. However, several vertical application areas reveal a need to extend container migration to the edge domain and even to the IoT domain. This idea, also referred to as the "cloud-edge-IoT continuum", involves developing containerized applications that are able to intelligently migrate among different types of devices, which can be located in any of these domains. In addition to scaling up applications and increasing their availability, this migration is also needed to support low-latency requirements, optimize processing and storage, and even improve data governance, among other things.

Building a computing continuum across the cloud, edge, and IoT domains requires integrating diverse networking technologies and access media as well as mechanisms to provide deterministic assurances for traffic entering and leaving containerized applications. Among various technology integration options that could be used for these scenarios, DetNet over 5G has potential for meeting the requirements of this use case (in addition to those already discussed):

- Deterministic, cost-effective establishment of new streams. This can be achieved with mechanisms such as dynamic online reconfiguration.
- Sufficient northbound interfaces for network controllers for integrated networks and interfaces with continuum intelligence (orchestrator).

5.4.4 DetNet Markers for HMIs and Production IT

Table 5 lists DetNet markers for use cases in the areas of HMIs and production IT, which clearly reveal the potential of DetNet.

5.5 Remote Monitoring and Maintenance

Remote monitoring and maintenance involve monitoring certain processes and/or assets in order to continuously check conditions and enable sensor-data-based predictive maintenance. Captured data can be used for big data analytics for optimizing future parameter sets of a process. The data acquisition process is not typically latency-critical for these use cases.

Since this use case does not require deterministic communication, there is no need for DetNet in it.

5.6 5G in Industrial Automation Use Cases Benefiting from DetNet

Whether or not DetNet is appropriate for a given use case depends, as a minimum, on the following criteria (including DetNet markers):

- Whether the protocol stack of an underlying industrial protocol (such as PROFINET RT/IRT or Ethernet/IP) uses IP, or in general whether IP communication is required
- The ability to support a use case’s required KPIs

Table 5: DetNet markers for HMIs and production IT use cases

Use case	Span area	IP-capable devices	Interconnection of subnetworks	Edge cloud	DetNet applicability
Mobile control/operation panels	50 m x 50 m or 100 m x 100 m	Yes	Unspecified	Possible	Yes
Augmented reality	50 m x 10 m	Yes	Unspecified	Yes (compute offload)	Yes
Deterministic communication for the cloud-edge-IoT continuum	100 m x 100 m	Yes (edge cloud devices are connected via IP)	Yes	Yes	Yes

Source: 5G-ACIA / ZVEI e. V.

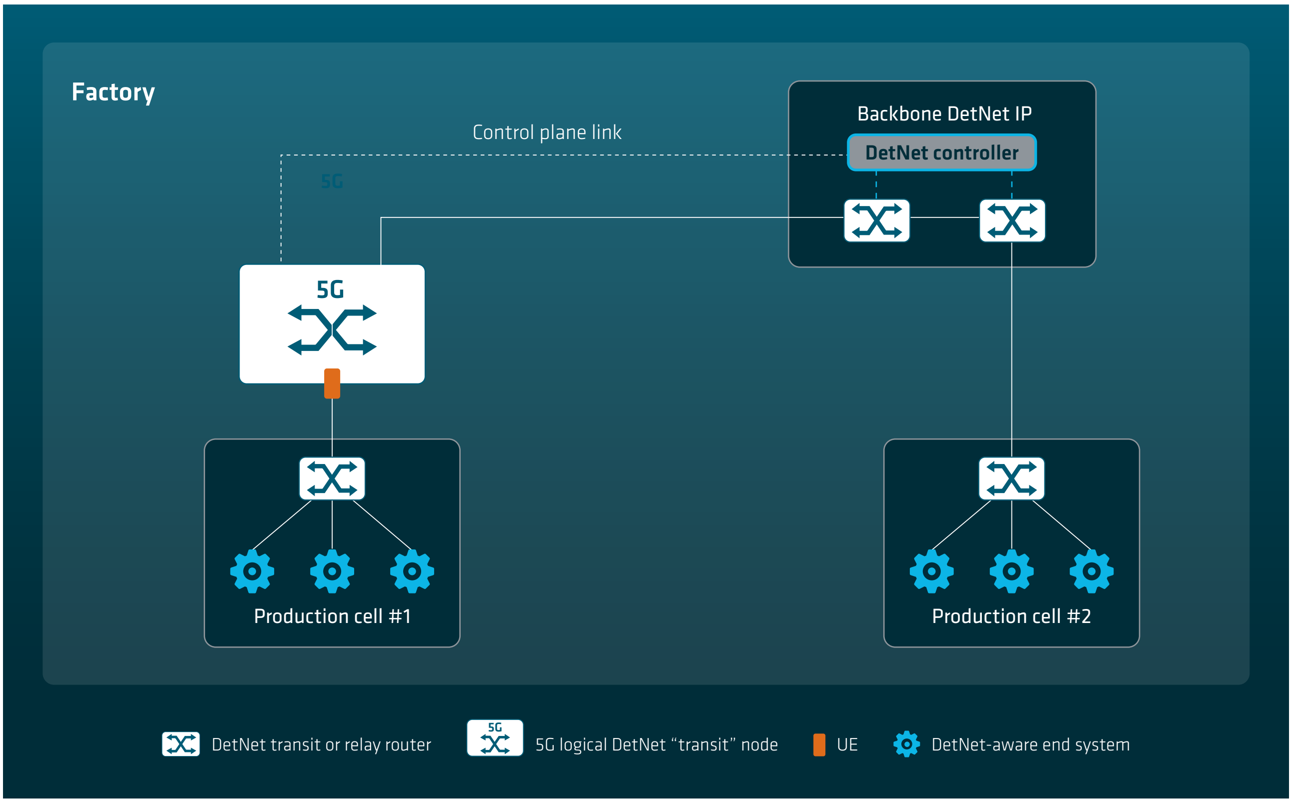
- Whether edge/cloud-based processing is required for leveraging IP-based technologies
- Whether a given use case relies on the use of sidelink and whether DetNet can be supported over sidelink
- The size of the service area for which multiple subnetworks need to be connected

Based on the analysis in sections 5.2 to 5.5, it is clear that many industrial use cases would benefit from the use of 5G-based DetNet.

6 DetNet in 5G Industrial Deployment Scenarios

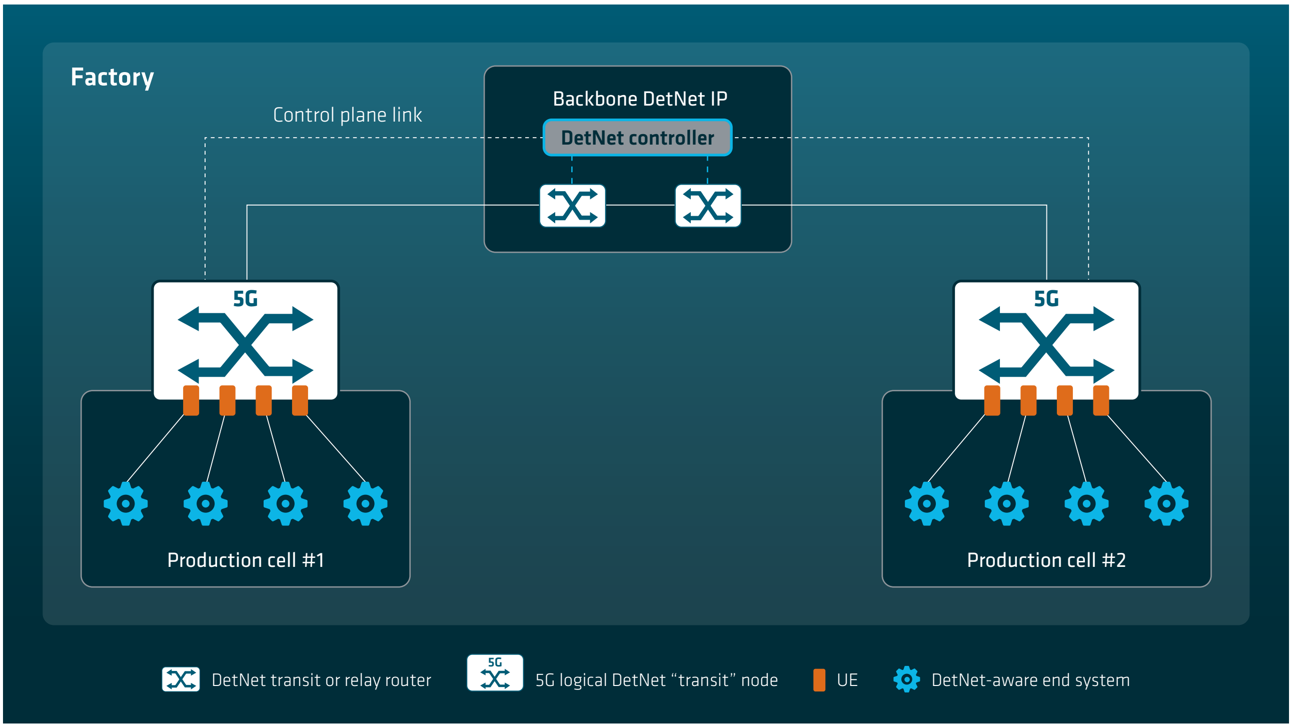
This chapter analyzes two cases in particular: (1) when DetNet is the only technology used (greenfield), i.e. "pure" DetNet deployment scenarios, and (2) when DetNet is deployed in combination with TSN. It is important to note that when 5G is used, the same system can be configured to represent one or more 5G logical DetNet nodes. Note also that only the centralized approach is considered (see 3.1.2) and applied to every scenario.

Figure 15: Local control scenario based on DetNet (centralized approach), with 5G DetNet node in the backbone



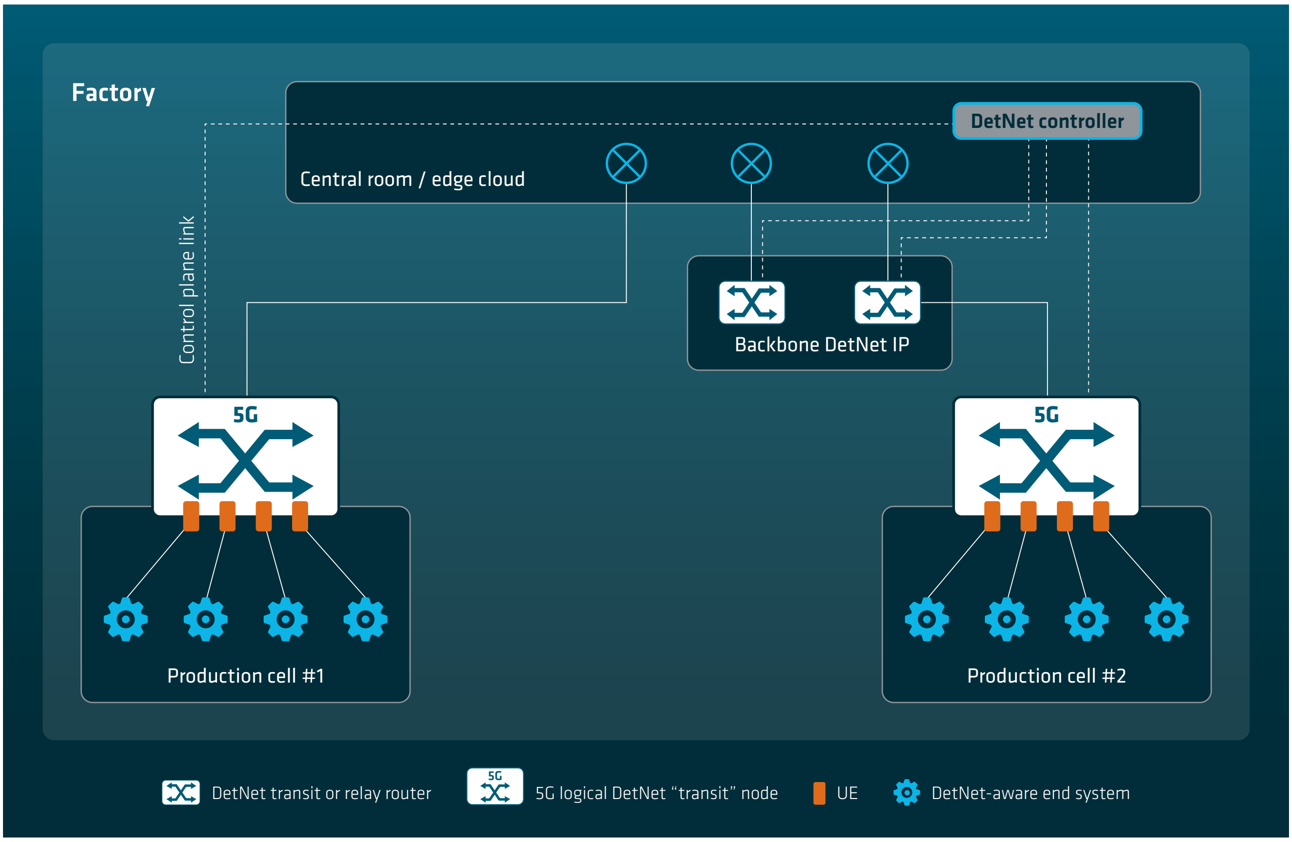
Source: 5G-ACIA / ZVEI e. V.

Figure 16: A local DetNet-based control scenario (centralized approach) with 5G DetNet nodes at the production cells or stations



Source: 5G-ACIA / ZVEI e. V.

Figure 17 : Control in a central room or edge cloud with a DetNet-based backbone (centralized approach) with 5G DetNet nodes at the production cells/stations



Source: 5G-ACIA / ZVEI e. V.

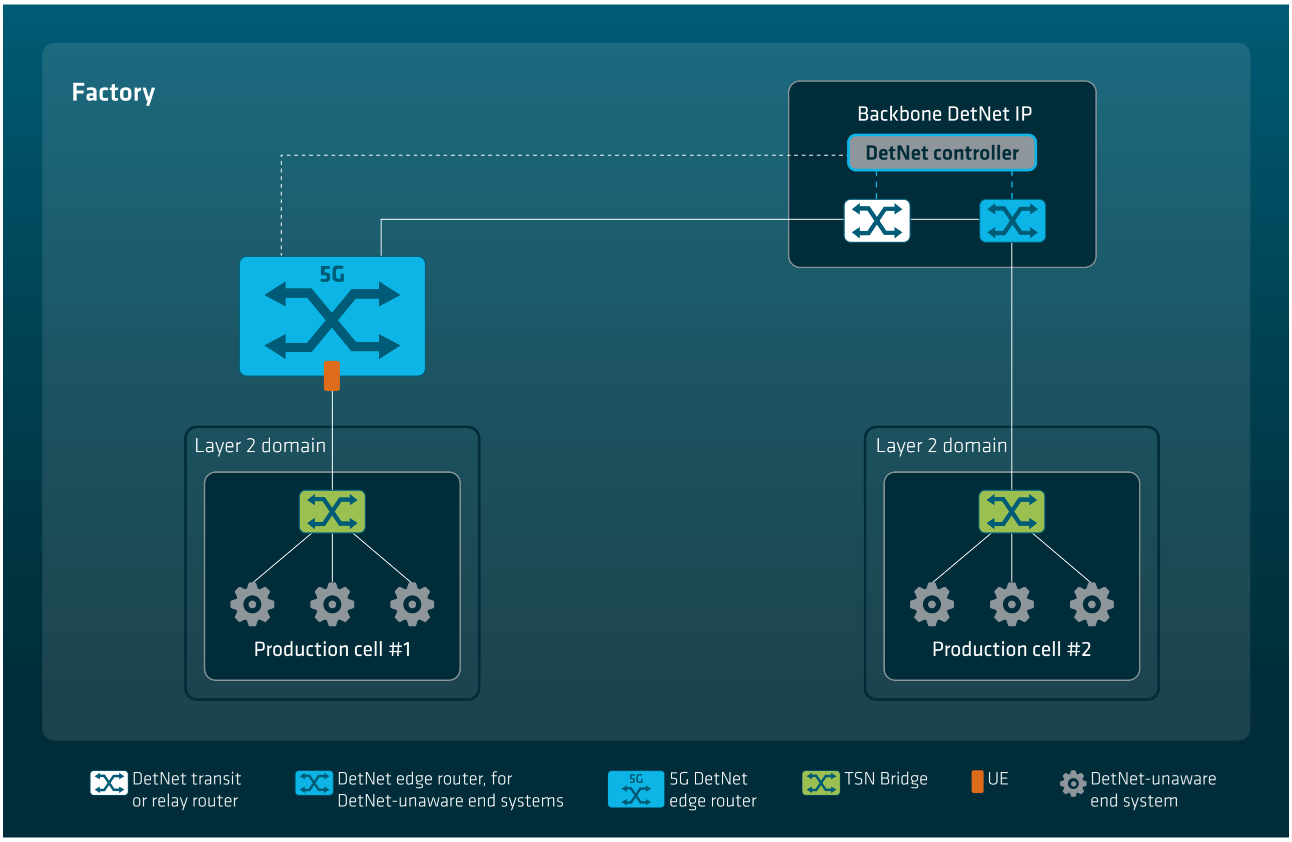
6.1 Pure DetNet Deployment Scenarios

This section focuses on the use of DetNet in industrial automation scenarios. This can be considered as a "greenfield" deployment case for DetNet. When the 5G system is used as a DetNet node in an industrial backbone network with local control as shown in figure 15, the 5G DetNet node provides wireless connections between DetNet nodes in the backbone and at production cells/machines. Note that, if the DetNet nodes interact with end systems that are DetNet-unaware, the DetNet node should be of the edge type (see section 3.1.3).

In figure 16, 5G nodes act as DetNet nodes for wirelessly linking the DetNet backbone with the devices in the production cells/stations. In this case, the 5G DetNet node supports communication at the production cells by connecting to DetNet-aware end systems.

Control may instead be performed in a central room or in the edge cloud (see figure 17). Depending on the factory's characteristics, this connectivity can span larger distances. This may be challenging to provide with layer 2 and TSN. The 5G system – acting as a DetNet transit node – directly links machines/production cells to the control room/edge cloud, a DetNet-based backbone, and other machines/production cells.

Figure 18: Local control (when taking a centralized approach) with DetNet backbone, TSN at the production cell/station, and a 5G system with a 5G DetNet node in the backbone (this scenario is not currently supported by 3GPP since 5G is only modeled as a transit node)



Source: 5G-ACIA / ZVEI e. V.

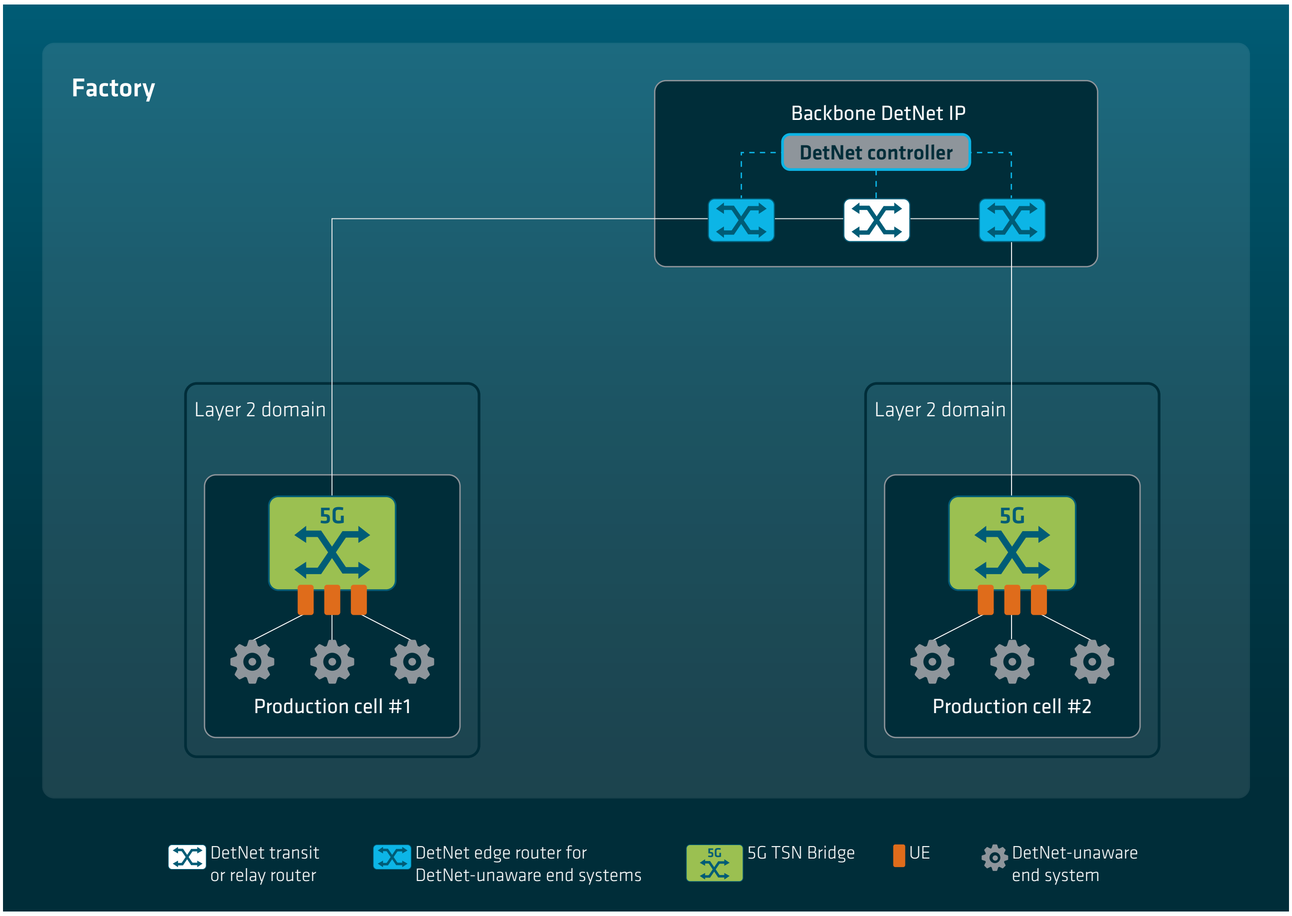
6.2 DetNet and TSN Combinations in Deployment Scenarios

This section addresses combined TSN and DetNet scenarios for industrial automation. TSN over DetNet is a deployment in which TSN segments are interconnected via a DetNet-based backbone. A DetNet edge router is required for connecting the TSN segments.

Figure 18 shows a case in which control is local and a 5G node acting as a DetNet edge node connects the TSN segment at the production cell/station to the backbone or another segment. Note, however, that 3GPP Release 18 has only specified 5GS as a logical DetNet transit node and this scenario is therefore not currently supported.

Figure 19 illustrates the possibility of combining TSN and DetNet with 5G serving as the TSN bridge to the production cells. The DetNet edge nodes (blue) have both TSN and DetNet entities, bridge TSN streams and DetNet flows, and perform required service translations. No additional standardization is needed for a 5G system acting as a TSN bridge, since it is already covered by 3GPP Release 16. This example merely illustrates the general use of DetNet (wired nodes) in a factory environment.

Figure 19: Local control (centralized approach) with DetNet backbone and 5G TSN bridge at the production cells/stations



Source: 5G-ACIA / ZVEI e. V.

7 Conclusions

DetNet is a promising new IP-based technology for deterministic communication as specified by IETF that is potentially applicable to 5G industrial automation use cases. This white paper presents the basic principles and relevant features of the DetNet architecture. Most notably, it provides packet replication elimination and ordering functions (PREOF) and explicit routing. Although DetNet supports MPLS and IP data planes, the focus is on the IP-based DetNet data plane since 5G does not specifically support MPLS. The relationship between DetNet and TSN is also described in terms of their interconnectivity, and their features are compared. DetNet is able to support TSN functions such as scheduled traffic (IEEE 802.1Qbv) and per-stream filtering and policing (IEEE 802.1Qci) [14]. The IETF DetNet WG is collaborating closely with the IEEE 802.1 WG with the aim of supporting a common architecture and similar functionalities. The DetNet controller plane is still being discussed at IETF. With regard to 5G support for DetNet, this white paper surveys the extensions in 3GPP that enable communication with a centralized DetNet controller and how DetNet flows are configured in the 5G system.

Based on analysis of a variety of use cases involving DetNet over 5G, it appears to be a promising option for meeting the requirements of the vast majority of 5G industrial use cases. To illustrate this, 5G deployment scenarios involving DetNet have been presented for two main industrial automation cases, namely pure DetNet deployment and a combination of DetNet and TSN. DetNet offers the additional benefit of interconnecting deterministic traffic flows (DetNet flows) between subnetworks and facilitating connectivity with controllers located in the edge cloud, which is usually IP-based.

8 Definitions of Acronyms and Key Terms

3GPP
The 3rd Generation Partnership Project (3GPP) is an umbrella term for a consortium embracing a number of standards organizations worldwide that are collaborating to develop globally accepted specifications for mobile telecommunications. As its name implies, it was originally created to establish specifications for the third generation (3G) of mobile communication systems. It has continued working on subsequent generations, including the fifth generation (5G), which is considered in this white paper.

5G-ACIA
The 5G Alliance for Connected Industries and Automation is the globally leading organization for shaping and promoting industrial 5G.

AF
Application function.

AGV
Automated guided vehicle.

AMF
Access management function.

Application flow
Data transported (regular traffic) over a DetNet flow between DetNet-unaware end systems.

AR
Augmented reality.

C2C
Controller-to-controller.

CIP
Common industrial protocol.

CNC
Centralized network configuration.

CPF
Controller plane function.

d-CW
DetNet control word.

DetNet
Deterministic networking.

DetNet controller
A centralized DetNet-specific controller that gets requirements for traffic flows to be served by the DetNet network, obtains the required capabilities, and configures DetNet nodes and end systems via a standard management interface.

DetNet controller plane
This comprises a control plane and a management plane. The control plane part is responsible for setting and maintaining flows and distributing information that is required to support DetNet functions. The management plane part configures DetNet network nodes, for example using specified YANG models, and performs OAM operations.

DetNet data plane
This oversees transfers of data within the DetNet network; it can be IP- or MPLS-based.

DetNet end system
A DetNet-aware end system that is able to directly generate DetNet flows.

DetNet edge node
A node at the edge of the DetNet network that acts as a proxy between DetNet-aware and DetNet-unaware network nodes or end systems. It supports both DetNet forwarding and service sublayers.

DetNet flow
A data traffic stream with the DetNet-specific identification and encapsulation required to provide DetNet services to the network. It may aggregate one or more application flows.

DetNet forwarding sublayer
This involves allocating resources for DetNet flows over paths provided by the underlying network. It is responsible for providing explicit routes.

DetNet relay node
A DetNet node that supports both DetNet forwarding and service sublayers.

DetNet service sublayer
This provides protection to minimize or eliminate packet errors, reorders packets for applications that cannot tolerate out-of-order delivery, and minimizes jitter and the size of required buffers at the destination.

DetNet transit node
A DetNet node that only supports the DetNet forwarding sublayer.

DSCP
Differentiated services code point.

Explicit routes
Routes that are dynamically set for one or more DetNet flows; they are unaffected by changes induced by convergence of routing protocols.

HMI
Human-machine interface.

IETF
Internet Engineering Task Force.

IP
Internet Protocol.

IPSec
IP security.

L2TP
Layer 2 tunneling protocol.

LER
Label-edge router.

LSP
Label-switched path.

LSR
Label-switching router.

MPLS
Multiprotocol Label Switching.

N6
Also known as the UPF-side interface, it is located between the UPF and an external network on the 5G system's network side.

NEF
Network Exposure Function.

NETCONF
Network Configuration Protocol.

NIC
Network interface card.

OAM
Operations, administration, and management.

ODVA
Open DeviceNet Vendors Association.

OPC UA
Open Platform Communications Unified Architecture.

PCE
Path computation element.

PCF
Policy Control Function.

PDU session
Packet data unit session for achieving connectivity between the UE and UPF.

PREOF
Packet replication, elimination, and ordering functions.

PSFP
Per-stream filtering and policing.

PW
Pseudowire.

RAN
Radio access network.

RESTCONF
Representational State Transfer Configuration Protocol.

RFC
Request for Comments.

RSVP-TE
Resource Reservation Protocol - Traffic Engineering.

SDN
Software-defined networking.

SMF
Session management function.

SPI
Security parameter index.

TCP
Transmission control protocol.

TSC
Time-sensitive communication.

TSCTSF
Time-sensitive communication and time synchronization function.

TSN
Time-sensitive networking.

UDP
User Datagram Protocol.

UE
User equipment.

UNI
User-network interface.

UPF
User plane function.

UPF/NW-TT
The user plane function and its network-side TSC translator.

YANG model
Yet Another Next Generation Model.

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Contact
5G-ACIA
Lyoner Strasse 9
60528 Frankfurt am Main
Germany
Phone: +49 69 6302-209
Email: info@5g-acia.org
www.5g-acia.org

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