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**An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4
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Abstract

This document describes a network architecture that provides low-latency, low-jitter and high-reliability packet delivery. It combines a high speed powered backbone and subnetworks using IEEE 802.15.4 time-slotted channel hopping (TSCH) to meet the requirements of LowPower wireless deterministic applications.

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[1.](#) Introduction

Wireless Networks enable a wide variety of devices of any size to get interconnected, often at a very low marginal cost per device, at any distance ranging from Near Field to interplanetary, and in circumstances where wiring may be impractical, for instance on fast-moving or rotating devices.

In the other hand, Deterministic Networks enable traffic that is highly sensitive to jitter, quite sensitive to latency, and with a high degree of operational criticality so that loss should be minimized at all times. Applications that need such networks are presented in [[I-D.ietf-detnet-use-cases](#)]. They include Professional Media and Operation Technology (OT) Industrial Automation Control Systems (IACS).

The Medium access Control (MAC) of IEEE Std 802.15.4 [[IEEE802154](#)] has evolved with the IEEE Std 802.15.4e timeslotted Channel Hopping (TSCH) [[RFC7554](#)] mode to provide deterministic properties on wireless networks. TSCH was initially introduced with the IEEE Std 802.15.4e amendment [[IEEE802154e](#)] of the IEEE Std 802.15.4 standard and constituted a part of the standard from that day. For all practical purpose, this document is expected to be insensitive to the revisions of the IEEE Std 802.15.4 standard, which is thus referenced undated.

Proven Deterministic Networking standards for use in Process Control, including ISA100.11a [[ISA100.11a](#)] and WirelessHART [[WirelessHART](#)], have demonstrated the capabilities of the IEEE Std 802.15.4 TSCH MAC for high reliability against interference, low-power consumption on well-known flows, and its applicability for Traffic Engineering (TE) from a central controller.

In order to enable the convergence of IT and OT in LLN environments, 6TiSCH ports the IETF suite of protocols that are defined for such environments over the TSCH MAC. 6TiSCH also provides large scaling capabilities, which, in a number of scenarios, require the addition

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of a high speed and reliable backbone and the use of IP version 6 (IPv6). The 6TiSCH Architecture introduces an IPV6 Multi-Link subnet model that is composed of a federating backbone and a number of IEEE Std 802.15.4 TSCH low-power wireless networks attached and synchronized by Backbone Routers.

The architecture defines mechanisms to establish and maintain routing and scheduling in a centralized, distributed, or mixed fashion, for use in multiple OT environments. It is applicable in particular to industrial control systems, building automation that leverage distributed routing to address multipath over a large number of hops, in-vehicle command and control that can be as demanding as industrial applications, commercial automation and asset Tracking with mobile scenarios, home automation and domotics which become more reliable and thus provide a better user experience, and resource management (energy, water, etc.).

2. Terminology

2.1. BCP 14

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [BCP 14 \[RFC2119\]](#) [RFC8174] when, and only when, they appear in all capitals, as shown here.

2.2. References

The draft uses domain-specific terminology defined or referenced in:

"Terms Used in IPv6 over the TSCH mode of IEEE 802.15.4e"
[[I-D.ietf-6tisch-terminology](#)],

"Neighbor Discovery Optimization for Low-power and Lossy Networks"
[[RFC6775](#)],

"Registration Extensions for 6LoWPAN Neighbor Discovery"
[[I-D.ietf-6lo-rfc6775-update](#)], and

"Terms Used in Routing for Low-Power and Lossy Networks (LLNs)"
[[RFC7102](#)].

Other terms in use in LLNs are found in "Terminology for Constrained-Node Networks" [[RFC7228](#)].

Readers are expected to be familiar with all the terms and concepts that are discussed in

- o "Neighbor Discovery for IP version 6" [[RFC4861](#)],
- o "IPv6 Stateless Address Autoconfiguration" [[RFC4862](#)],
- o "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing" [[RFC6606](#)].

The draft also conforms to the terms and models described in [[RFC3444](#)] and [[RFC5889](#)] and uses the vocabulary and the concepts defined in [[RFC4291](#)] for the IPv6 Architecture and refers [[RFC4080](#)] for reservation

In addition, readers would benefit from reading:

- o "Multi-Link Subnet Issues" [[RFC4903](#)],
- o "Mobility Support in IPv6" [[RFC6275](#)],
- o "RPL applicability in industrial networks" [[I-D.ietf-roll-rpl-industrial-applicability](#)],
- o "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals" [[RFC4919](#)].
- o "Optimistic Duplicate Address Detection" [[RFC4429](#)],
- o "Neighbor Discovery Proxies (ND Proxy)" [[RFC4389](#)],
- o "FCFS SAVI: First-Come, First-Served Source Address Validation Improvement for Locally Assigned IPv6 Addresses" [[RFC6620](#)], and
- o "Optimistic Duplicate Address Detection" [[RFC4429](#)]

prior to this specification for a clear understanding of the art in ND-proxying and binding.

2.3. Subset of a 6LoWPAN Glossary

This document often uses the following acronyms:

6BBR: 6LoWPAN Backbone Router (proxy for the registration)

6LBR: 6LoWPAN Border Router (authoritative on DAD)

6LN: 6LoWPAN Node

6LR: 6LoWPAN Router (relay to the registration process)

6CIO: Capability Indication Option

(E)ARO: (Extended) Address Registration Option

(E)DAR: (Extended) Duplicate Address Request

(E)DAC: (Extended) Duplicate Address Confirmation

DAD: Duplicate Address Detection

DODAG: Destination-Oriented Directed Acyclic Graph

LLN: Low-Power and Lossy Network (a typical IoT network)

NA: Neighbor Advertisement

NCE: Neighbor Cache Entry

ND: Neighbor Discovery

NDP: Neighbor Discovery Protocol

NS: Neighbor Solicitation

ROVR: Registration Ownership Verifier (pronounced rover)

RPL: IPv6 Routing Protocol for LLNs (pronounced ripple)

RA: Router Advertisement

RS: Router Solicitation

TSCH: timeslotted Channel Hopping

TID: Transaction ID (a sequence counter in the EARO)

3. High Level Architecture

3.1. 6TiSCH Stack

The 6TiSCH architecture presents a reference stack that is implemented and interop tested by a conjunction of opensource, IETF and ETSI efforts. One goal is to help other bodies to adopt the stack as a whole, making the effort to move to an IPv6-based IoT stack easier. Now, for a particular environment, some of the choices that are made in this architecture may not be relevant. For instance, RPL is not required for star topologies and mesh-under Layer-2 routed networks, and the 6LoWPAN compression may not be

sufficient for ultra-constrained cases such as some Low Power Wide Area (LPWA) networks. In such cases, it is perfectly doable to adopt a subset of the selection that is presented hereafter and then select alternate components to complete the solution wherever needed.

The IETF proposes multiple techniques for implementing functions related to routing, transport or security. In order to control the complexity of the possible deployments and device interactions, and to limit the size of the resulting object code, the architecture limits the possible variations of the stack and recommends a number of base elements for LLN applications. In particular, UDP [[RFC0768](#)] [[RFC8200](#)] and the Constrained Application Protocol [[RFC7252](#)] (CoAP) are used as the transport / binding of choice for applications and management as opposed to TCP and HTTP.

The resulting protocol stack is represented below:

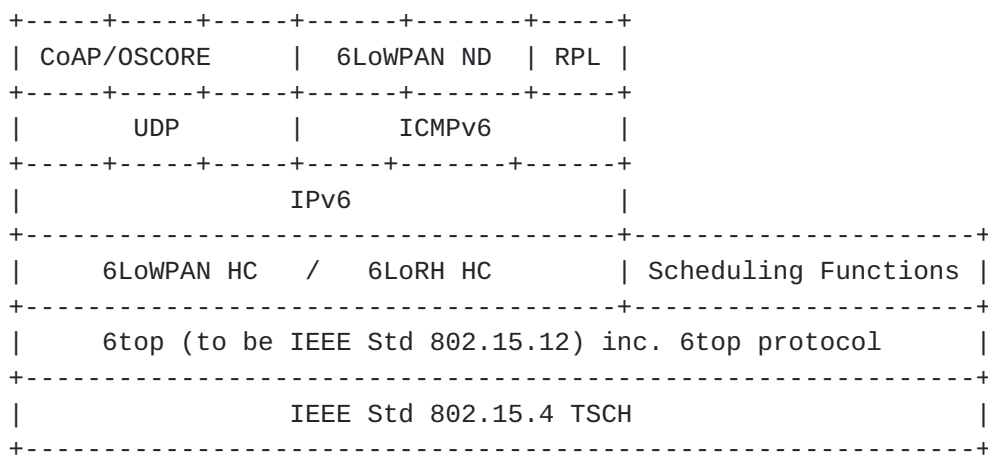


Figure 1: 6TiSCH Protocol Stack

RPL is the routing protocol of choice for LLNs. So far, there was no identified need to define a 6TiSCH specific Objective Function. The Minimal 6TiSCH Configuration [[RFC8180](#)] describes the operation of RPL over a static schedule used in a slotted aloha fashion, whereby all active slots may be used for emission or reception of both unicast and multicast frames.

The 6LoWPAN Header Compression [[RFC6282](#)] is used to compress the IPv6 and UDP headers, whereas the 6LoWPAN Routing Header (6LoRH) [[RFC8138](#)] is used to compress the RPL artifacts in the IPv6 data packets, including the RPL Packet Information (RPI), the IP-in-IP encapsulation to/from the RPL root, and the Source Route Header (SRH) in non-storing mode.

The Datagram Transport Layer Security (DTLS) [[RFC6347](#)] sitting either under CoAP or over CoAP so as to traverse proxies, as well as Object Security for Constrained RESTful Environments (OSCORE) [[I-D.ietf-core-object-security](#)], are examples of protocols that could be used to protect application payload, and OSCORE is used in particular by the "Minimal Security Framework for 6TiSCH" [[I-D.ietf-6tisch-minimal-security](#)] for the the Join Process.

An overview of the the initial steps of a device in a network can be found in [Section 3.7](#); the security aspects of the join process are further detailed in [Section 6](#).

The 6TiSCH Operation sublayer (6top) is a sublayer of a Logical Link Control (LLC) that provides the abstraction of an IP link over a TSCH MAC and schedules packets over TSCH cells, as further discussed in the next sections, providing in particular dynamic cell allocation with the 6top Protocol (6P) [[RFC8480](#)].

3.2. TSCH: A Deterministic MAC Layer

Though at a different time scale (several orders of magnitude), both IEEE Std 802.1TSN and IEEE Std 802.15.4 TSCH standards provide Deterministic capabilities to the point that a packet that pertains to a certain flow may traverse a network from node to node following a very precise schedule, as a train that enters and then leaves intermediate stations at precise times along its path. With TSCH, time is formatted into timeslots, and individual communication cells are allocated to unicast or broadcast communication at the MAC level. The time-slotted operation reduces collisions, saves energy, and enables to more closely engineer the network for deterministic properties. The channel hopping aspect is a simple and efficient technique to combat multipath fading and co-channel interference.

6TiSCH builds on the IEEE Std 802.15.4 TSCH MAC and inherits its advanced capabilities to enable them in multiple environments where they can be leveraged to improve automated operations. The 6TiSCH Architecture also inherits the capability to perform a centralized route computation to achieve deterministic properties, though it relies on the IETF DetNet Architecture [[I-D.ietf-detnet-architecture](#)], and IETF components such as the Path Computation Element (PCE) [[PCE](#)], for the protocol aspects.

On top of this inheritance, 6TiSCH adds capabilities for distributed routing and scheduling operations based on the RPL routing protocol and capabilities to negotiate schedule adjustments between peers. These distributed routing and scheduling operations simplify the deployment of TSCH networks and enable wireless solutions in a larger variety of use cases from operational technology in general.

Examples of such use-cases in industrial environments include plant setup and decommissioning, as well as monitoring of lots of lesser importance measurements such as corrosion and events. RPL also enables mobile use cases such as mobile workers and cranes, as presented in [[I-D.ietf-roll-rpl-industrial-applicability](#)].

3.3. Scheduling TSCH

A scheduling operation attributes cells in a Time-Division-Multiplexing (TDM) / Frequency-Division Multiplexing (FDM) matrix called the Channel distribution/usage (CDU) to either individual transmissions or as multi-access shared resources (see the 6TiSCH Terminology [[I-D.ietf-6tisch-terminology](#)] for more on these terms). Scheduling effectively enables multiple communications at a same time in a same interference domain using different channels; but a node equipped with a single radio can only transmit or receive on one channel at any given point of time.

From the standpoint of a 6TiSCH node (at the MAC layer), its schedule is the collection of the times at which it must wake up for transmission, and the channels to which it should either send or listen at those times. The schedule is expressed as one or more slotframes that repeat over and over. Slotframes may collide and require a device to wake up at a same time, in which case a priority indicates which slotframe is actually activated.

The 6top sublayer hides the complexity of the schedule from the upper layers. The Link that IP may utilize between the 6TiSCH node and a peer may in fact be composed of a pair of cell bundles, one to receive and one to transmit. Some of the cells may be shared, in which case the 6top sublayer must perform some arbitration.

The 6TiSCH architecture identifies four ways a schedule can be managed and CDU cells can be allocated: Static Scheduling, Neighbor-to-Neighbor Scheduling, Remote Monitoring and Schedule Management, and Hop-by-hop Scheduling.

Static Scheduling: This refers to the minimal 6TiSCH operation whereby a static schedule is configured for the whole network for use in a slotted-Aloha fashion. The static schedule is distributed through the native methods in the TSCH MAC layer. This operation leverages RPL to maintain a loopless graph for routing and time distribution. It is specified in the Minimal 6TiSCH Configuration [[RFC8180](#)] specification. and does not preclude other scheduling operations to co-exist on a same 6TiSCH network.

Neighbor-to-Neighbor Scheduling: This refers to the dynamic adaptation of the bandwidth of the Links that are used for IPv6 traffic between adjacent routers. Scheduling Functions such as the "6TiSCH Minimal Scheduling Function (MSF)" [[I-D.ietf-6tisch-msf](#)] influence the operation of the MAC layer to add, update and remove cells in peers schedule, using 6P [[RFC8480](#)] for the negotiation of the MAC resources.

Remote Monitoring and Schedule Management: This refers to the central computation of a schedule and the capability to forward a frame based on the cell of arrival. In that case, the related portion of the device schedule as well as other device resources are managed by an abstract Network Management Entity (NME), which may cooperate with the PCE in order to minimize the interaction with and the load on the constrained device. This model is the TSCH adaption of the "DetNet Architecture" [[I-D.ietf-detnet-architecture](#)], and it enables Traffic Engineering with deterministic properties.

Hop-by-hop Scheduling: This refers to the possibility to reserves cells along a path for a particular flow using a distributed mechanism.

It is not expected that all use cases will require all those mechanisms. Static Scheduling with minimal configuration one is the only one that is expected in all implementations, since it provides a simple and solid basis for convergecast routing and time distribution.

A deeper dive in those mechanisms can be found in [Section 4.4](#).

[3.4. Routing and Forwarding Over TSCH](#)

6TiSCH leverages the RPL routing protocol for interoperable distributed routing operations. RPL is applicable to Static Scheduling and Neighbor-to-Neighbor Scheduling. The architecture also supports a centralized routing model for Remote Monitoring and Schedule Management. It is expected that a routing protocol that is more optimized for point-to-point routing than RPL [[RFC6550](#)], such as the "Asymmetric AODV-P2P-RPL in Low-Power and Lossy Networks" [[I-D.ietf-roll-aodv-rpl](#)] (AODV-RPL), which derives from the Ad Hoc On-demand Distance Vector Routing (AODV) [[I-D.ietf-manet-aodvv2](#)] will be selected for Hop-by-hop Scheduling.

The 6TiSCH architecture supports three different forwarding models, the classical IPv6 Forwarding, where the node selects a feasible successor at Layer-3 on a per packet basis and based on its routing table, G-MPLS Track Forwarding, which switches a frame received at a

particular timeslot into another timeslot at Layer-2, and 6LoWPAN Fragment Forwarding, which allows to forward individual 6LoWPAN fragments along the route set by the first fragment.

IPv6 Forwarding: This is the classical IP forwarding model, with a Routing Information Based (RIB) that is installed by the RPL routing protocol and used to select a feasible successor per packet. The packet is placed on an outgoing Link, that the 6top layer maps into a (Layer-3) bundle of cells, and scheduled for transmission based on QoS parameters. On top of RPL, this model also applies to any routing protocol which may be operated in the 6TiSCH network, and corresponds to all the distributed scheduling models, Static, Neighbor-to-Neighbor and Hop-by-Hop Scheduling.

G-MPLS Track Forwarding: This model corresponds to the Remote Monitoring and Schedule Management. In this model, A central controller (hosting a PCE) computes and installs the schedules in the devices per flow. The incoming (Layer-2) bundle of cells from the previous node along the path determines the outgoing (Layer-2) bundle towards the next hop for that flow as determined by the PCE. The programmed sequence for bundles is called a Track and can assume shapes that are more complex than a simple direct sequence of nodes.

6LoWPAN Fragment Forwarding: This is an hybrid model that derives from IPv6 forwarding for the case where packets must be fragmented at the 6LoWPAN sublayer. The first fragment is forwarded like any IPv6 packet and leaves a state in the intermediate hops to enable forwarding of the next fragments that do not have a IP header without the need to recompose the packet at every hop.

This can be broadly summarized in the following table:

Forwarding Model	Routing	Scheduling
classical IPv6	RPL	Static (Minimal Configuration)
/		Neighbor-to-Neighbor (SF+6P)
6LoWPAN Fragment F.	Reactive P2P	Hop-by-Hop (TBD)
G-MPLS Track Fwrdding	PCE	Remote Monitoring and Schedule Mgt

Figure 2: Routing, Forwarding and Scheduling

3.5. A Non-Broadcast Multi-Access Radio Mesh Network

A 6TiSCH network is an IPv6 [RFC8200] subnet which, in its basic configuration, is a single Low Power Lossy Network (LLN) operating over a synchronized TSCH-based mesh.

Inside a 6TiSCH LLN, nodes rely on 6LoWPAN Header Compression (6LoWPAN HC) [RFC6282] to encode IPv6 packets. From the perspective of the network layer, a single LLN interface (typically an IEEE Std 802.15.4-compliant radio) may be seen as a collection of Links with different capabilities for unicast or multicast services.

6TiSCH nodes are not necessarily reachable from one another at Layer-2 and an LLN may span over multiple links. This effectively forms an homogeneous non-broadcast multi-access (NBMA) subnet, which is beyond the scope of existing IPv6 ND methods. Extensions to IPv6 ND have to be introduced.

Within that subnet, neighbor devices are discovered with 6LoWPAN Neighbor Discovery [RFC6775] (6LoWPAN ND), whereas RPL [RFC6550] enables routing in the so called Route Over fashion, either in storing (stateful) or non-storing (stateless, with routing headers) mode.

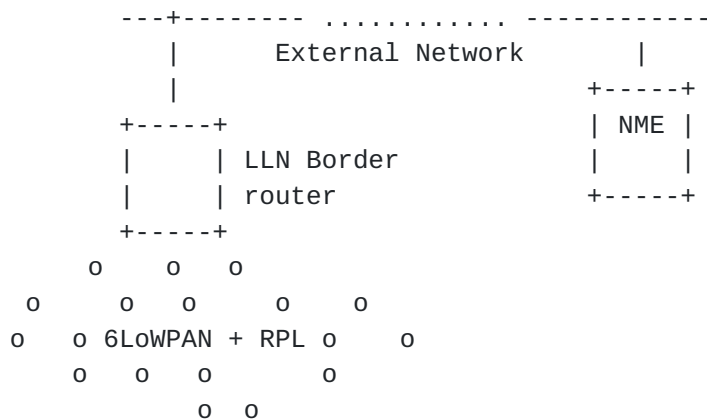


Figure 3: Basic Configuration of a 6TiSCH Network

6TiSCH nodes join the mesh by attaching to nodes that are already members of the mesh. Some nodes act as routers for 6LoWPAN ND and RPL operations, as detailed in [Section 4.1](#). Security aspects of the join process by which a device obtains access to the network are discussed in [Section 6](#).

With TSCH, devices are time-synchronized at the MAC level. The use of a particular RPL Instance for time synchronization is discussed in

[Section 4.2.4](#). With this mechanism, the time synchronization starts at the RPL root and follows the RPL DODAGs with no timing loop.

RPL forms Destination Oriented Directed Acyclic Graphs (DODAGs) within Instances of the protocol, each Instance being associated with an Objective Function (OF) to form a routing topology. A particular 6TiSCH node, the LLN Border Router (LBR), acts as RPL root, 6LoWPAN HC terminator, and Border Router for the LLN to the outside. The LBR is usually powered. More on RPL Instances can be found in [section 3.1](#) of RPL [[RFC6550](#)], in particular "3.1.2. RPL Identifiers" and "3.1.3. Instances, DODAGs, and DODAG Versions". RPL adds artifacts in the data packets that are compressed with a 6LoWPAN addition 6LoRH [[RFC8138](#)].

Additional routing and scheduling protocols may be deployed to establish on-demand Peer-to-Peer routes with particular characteristics inside the 6TiSCH network. This may be achieved in a centralized fashion by a PCE [[PCE](#)] that programs both the routes and the schedules inside the 6TiSCH nodes, or by in a distributed fashion using a reactive routing protocol and a Hop-by-Hop scheduling protocol.

A Backbone Router may be connected to the node that acts as RPL root and / or 6LoWPAN 6LBR and provides connectivity to the larger campus / factory plant network over a high speed backbone or a back-haul link. A Backbone Router may perform proxy IPv6 Neighbor Discovery (ND) [[RFC4861](#)] operations over the backbone on behalf of the 6TiSCH nodes so they can share a same IPv6 subnet and appear to be connected to the same backbone as classical devices. A Backbone Router may alternatively redistribute the registration in a routing protocol such as OSPF [[RFC5340](#)] or BGP [[RFC2545](#)], or inject them in a mobility protocol such as MIPv6 [[RFC6275](#)], NEMO [[RFC3963](#)], or LISP [[RFC6830](#)].

This architecture expects that a 6LoWPAN node can connect as a leaf to a RPL network, where the leaf support is the minimal functionality to connect as a host to a RPL network without the need to participate to the full routing protocol. The architecture also expects that a 6LoWPAN node that is not aware at all of the RPL protocol may also connect as a host but the specifications for this to happen are not available at the time of this writing.

[3.6](#). A Multi-Link Subnet Model

An extended configuration of the subnet comprises multiple LLNs. The LLNs are interconnected and synchronized over a backbone, that can be wired or wireless. The backbone can be a classical IPv6 network, with Neighbor Discovery operating as defined in [[RFC4861](#)] and

[RFC4862]. This architecture requires work to standardize the the registration of 6LoWPAN nodes to the Backbone Routers.

In the extended configuration, a Backbone Router (6BBR) operates as described in [I-D.ietf-6lo-backbone-router]. The 6BBR performs ND proxy operations between the registered devices and the classical ND devices that are located over the backbone. 6TiSCH 6BBRs synchronize with one another over the backbone, so as to ensure that the multiple LLNs that form the IPv6 subnet stay tightly synchronized.

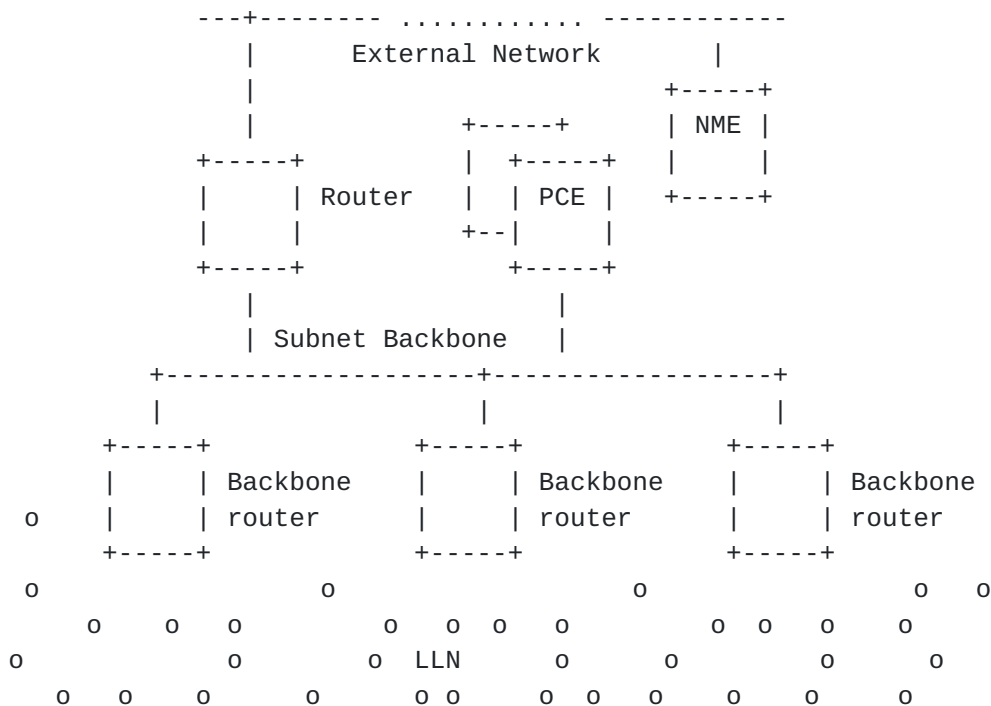


Figure 4: Extended Configuration of a 6TiSCH Network

As detailed in [Section 4.1](#) the 6LoWPAN ND 6LBR and the root of the RPL network need to be collocated and share information about the devices that is learned through either protocol but not both. The combined RPL root and 6LBR may be collocated with the 6BBR, or directly attached to the 6BBR. In the latter case, it leverages the extended registration process defined in [I-D.ietf-6lo-backbone-router] to proxy the 6LoWPAN ND registration to the 6BBR on behalf of the LLN nodes, so that the 6BBR may in turn perform proxy classical ND operations over the backbone.

If the Backbone is Deterministic (such as defined by the Time Sensitive Networking WG at IEEE), then the Backbone Router ensures that the end-to-end deterministic behavior is maintained between the LLN and the backbone. The DetNet Architecture [I-D.ietf-detnet-architecture] studies Layer-3 aspects of

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Deterministic Networks, and covers networks that span multiple Layer-2 domains.

3.7. Join Process and Registration

As detailed in [Section 6](#), a node that wishes to join the 6TiSCH network with a preshared key (PSK) performs the role of the pledge in the 6TiSCH Constrained Join Protocol (CoJP)

[[I-D.ietf-6tisch-minimal-security](#)] In order to join, the pledge is helped by a Join Proxy (JP) that relays the link-scope 6JP Join request over the IP network to the Join Registrar/Coordinator (JRC) that can authenticate the pledge and validate that it is attached to the appropriate network. As a result of this exchange the pledge is in possession of a Link-Layer material including a key and a short address, and all traffic is secured at the Link Layer .

Figure 5 illustrates that very initial step.

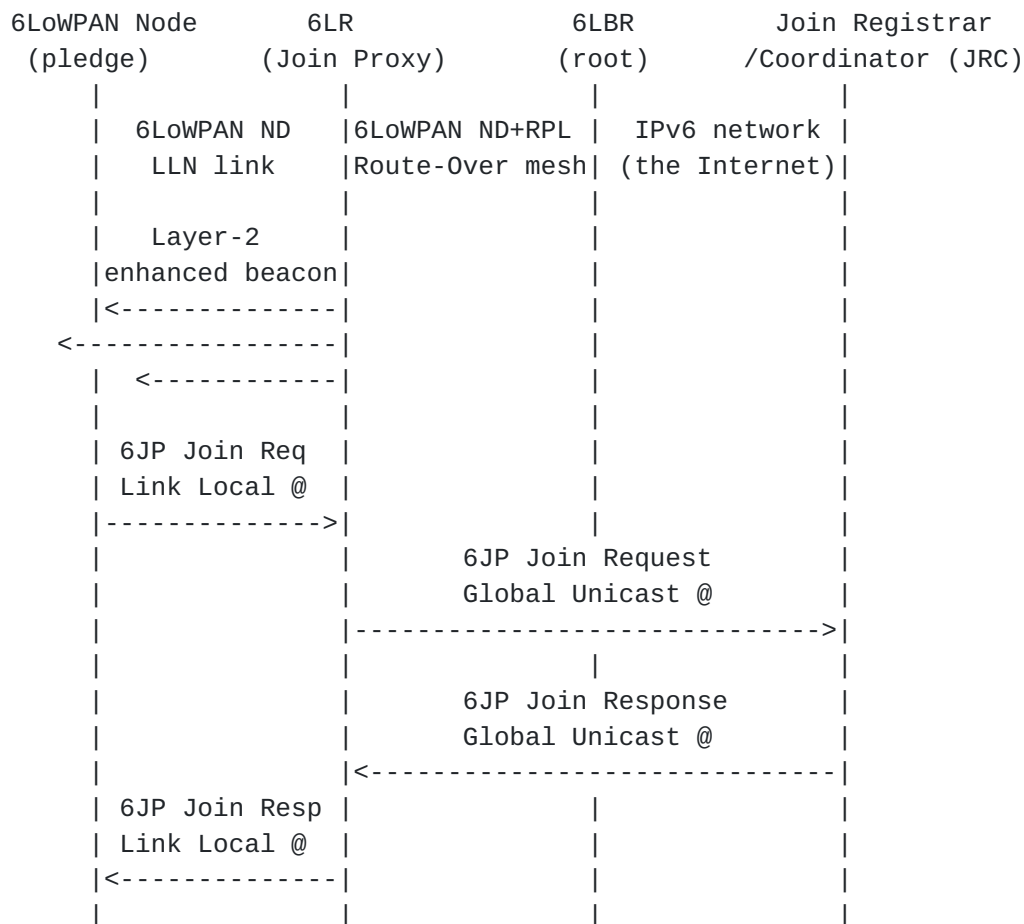


Figure 5: (Re-)Registration Flow over Multi-Link Subnet

As detailed in [Section 4.1](#), the combined 6LoWPAN ND 6LBR and root of the RPL network learn information such as the device Unique ID (from 6LoWPAN ND) and the updated Sequence Number (from RPL), and perform 6LoWPAN ND proxy registration to the 6BBR of behalf of the LLN nodes.

Figure 6 illustrates the initial IPv6 signaling that enables a 6LN to form a global address and register it to a 6LBR using 6LoWPAN ND [\[I-D.ietf-6lo-rfc6775-update\]](#), is then carried over RPL to the RPL root, and then to the 6BBR.

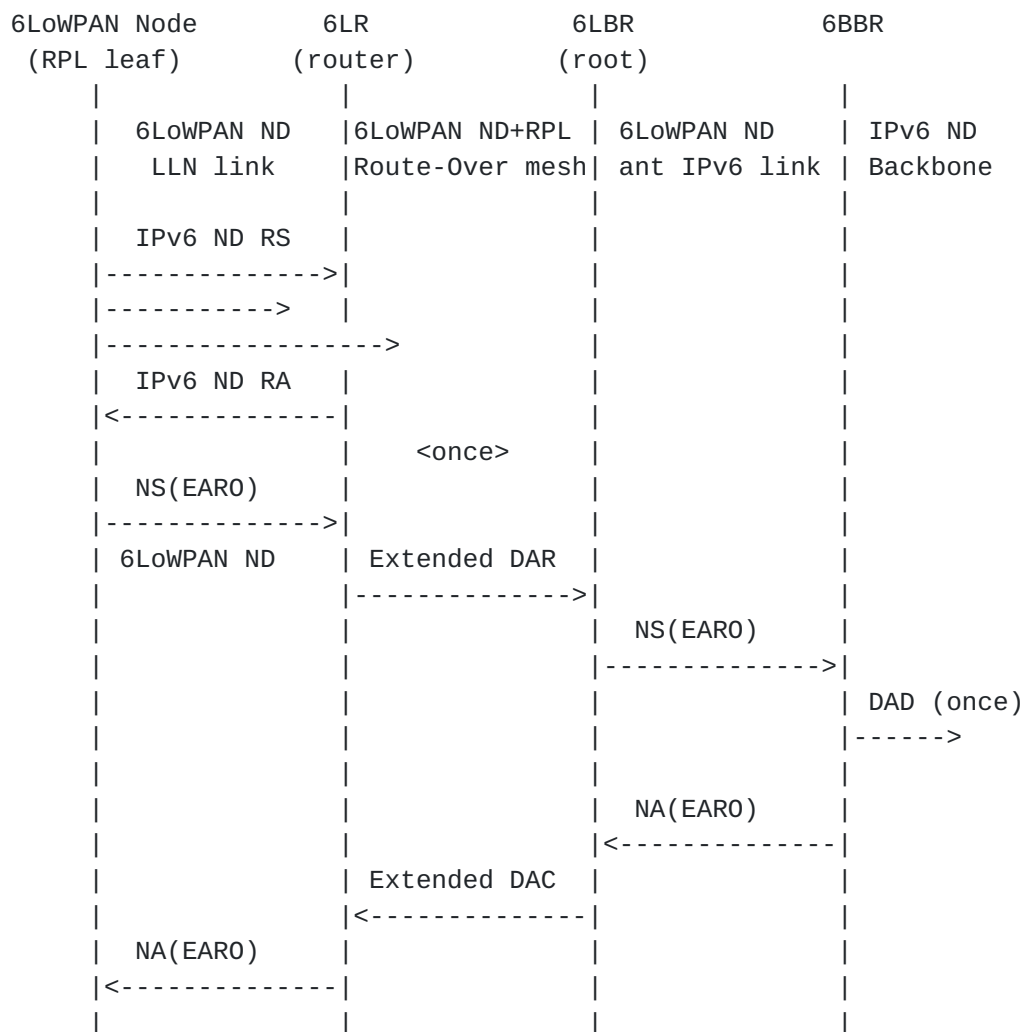


Figure 6: Initial Registration Flow over Multi-Link Subnet

Figure 7 illustrates the repeating IPv6 signaling that enables a 6LN to keep a global address alive and registered to its 6LBR using 6LoWPAN ND [\[I-D.ietf-6lo-rfc6775-update\]](#), using 6LoWPAN ND at the 6LR, RPL to the RPL root, and then 6LoWPAN ND again to the 6BBR.

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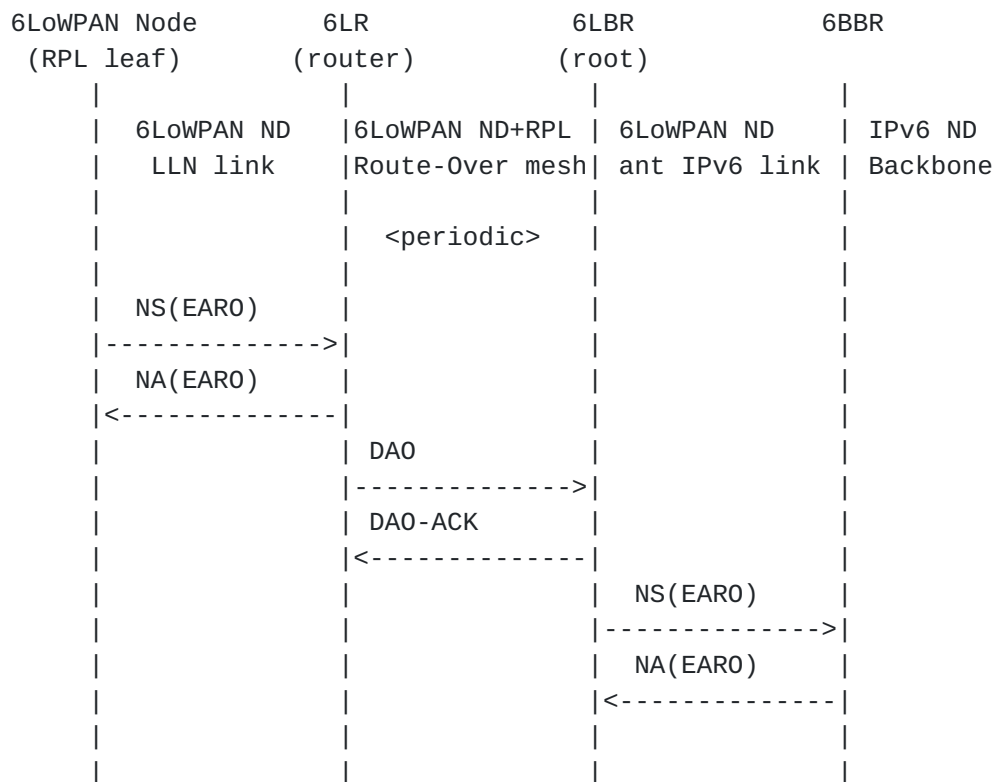


Figure 7: Next Registration Flow over Multi-Link Subnet

As the network builds up, a node should start as a leaf to join the RPL network, and may later turn into both a RPL-capable router and a 6LR, so as to accept leaf nodes to recursively join the network.

4. Architecture Components

4.1. 6LoWPAN (and RPL)

4.1.1. RPL Leaf Support in 6LoWPAN ND

RPL needs a set of information in order to advertise a leaf node through a DAO message and establish reachability.

At the bare minimum the leaf device must provide a sequence number that matches the RPL specification in [section 7](#). Section 5.3 of [\[I-D.ietf-6lo-backbone-router\]](#), on the Extended Address Registration Option (EARO), already incorporates that addition with a new field in the option called the Transaction ID.

If for some reason the node is aware of RPL topologies, then providing the RPL InstanceID for the instances to which the node

wishes to participate would be a welcome addition. In the absence of such information, the RPL router must infer the proper instanceID from external rules and policies.

On the backbone, the InstanceID is expected to be mapped onto a an overlay that matches the instanceID, for instance a VLANID.

This architecture leverages [[I-D.ietf-6lo-backbone-router](#)] that extends 6LoWPAN ND [[RFC6775](#)] to carry the counter as an abstract Transaction ID (TID).

4.1.2. RPL Root And 6LBR

With [[RFC6775](#)], information on the 6LBR is disseminated via an Authoritative Border Router Option (ABRO) in RA messages. The discovery and liveliness of the RPL root are obtained through the RPL protocol [[RFC6550](#)]. The capability to support the update to [RFC6775](#) [[I-D.ietf-6lo-rfc6775-update](#)] is indicated in the 6LoWPAN Capability Indication Option (6CIO).

"Routing for RPL Leaves" [[I-D.thubert-roll-unaware-leaves](#)] details the basic interaction of 6LoWPAN ND and RPL and enables a plain 6LN that supports [[I-D.ietf-6lo-rfc6775-update](#)] to obtain return connectivity via the RPL network as a non-RPL-aware leaf. Though the above specification enables a model where the separation is possible, this architecture recommends to collocate the functions of LBR and RPL root.

When 6LoWPAN ND is coupled with RPL, the 6LBR and RPL root functionalities are co-located in order that the address of the 6LBR be indicated by RPL DIO messages and to associate the unique ID from the DAR/DAC exchange with the state that is maintained by RPL. The DAR/DAC exchange becomes a preamble to the DAO messages that are used from then on to reconfirm the registration, thus eliminating a duplication of functionality between DAO and DAR messages.

Even though the root of the RPL network is integrated with the 6LBR, it is logically separated from the Backbone Router (6BBR) that is used to connect the 6TiSCH LLN to the backbone. This way, the root has all information from 6LoWPAN ND and RPL about the LLN devices attached to it.

This architecture also expects that the root of the RPL network (proxy-)registers the 6TiSCH nodes on their behalf to the 6BBR, for whatever operation the 6BBR performs on the backbone, such as ND proxy, or redistribution in a routing protocol. This relies on an extension of the 6LoWPAN ND registration described in [[I-D.ietf-6lo-backbone-router](#)].

This model supports the movement of a 6TiSCH device across the Multi-Link Subnet, and allows the proxy registration of 6TiSCH nodes deep into the 6TiSCH LLN by the 6LBR / RPL root. This requires an alteration from [\[RFC6775\]](#) whereby the Target Address of the NS message is registered as opposed to the Source, which, in the case of a proxy registration, is that of the 6LBR / RPL root itself.

[4.2.](#) TSCH and 6top

[4.2.1.](#) 6top

6top 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 operations are specified in [\[RFC8480\]](#). In particular, 6top provides a management interface that enables an external management entity to schedule cells and slotFrames, and allows the addition of complementary functionality, for instance to support a dynamic schedule management based on observed resource usage as discussed in [Section 4.4.2](#).

The 6top data model and management interfaces are further discussed in [Section 4.4.3](#).

[4.2.1.1.](#) Hard Cells

The architecture defines "soft" cells and "hard" cells. "Hard" cells are owned and managed by an separate scheduling entity (e.g. a PCE) that specifies the slotOffset/channelOffset of the cells to be added/moved/deleted, in which case 6top can only act as instructed, and may not move hard cells in the TSCH schedule on its own.

[4.2.1.2.](#) Soft Cells

6top contains a monitoring process which monitors the performance of cells, and can move a cell in the TSCH schedule when it performs poorly. This is only applicable to cells which are marked as "soft". To reserve a soft cell, the higher layer does not indicate the exact slotOffset/channelOffset of the cell to add, but rather the resulting bandwidth and QoS requirements. When the monitoring process triggers a cell reallocation, the two neighbor devices communicating over this cell negotiate its new position in the TSCH schedule.

[4.2.2.](#) Scheduling Functions and the 6P protocol

In the case of soft cells, the cell management entity that controls the dynamic attribution of cells to adapt to the dynamics of variable rate flows is called a Scheduling Function (SF). There may be multiple SFs with more or less aggressive reaction to the dynamics of

the network. The "6TiSCH Minimal Scheduling Function (MSF)" [[I-D.ietf-6tisch-msf](#)] provides a simple scheduling function that can be used by default by devices that support dynamic scheduling of soft cells.

The SF may be seen as divided between an upper bandwidth adaptation logic that is not aware of the particular technology that is used to obtain and release bandwidth, and an underlying service that maps those needs in the actual technology, which means mapping the bandwidth onto cells in the case of TSCH.

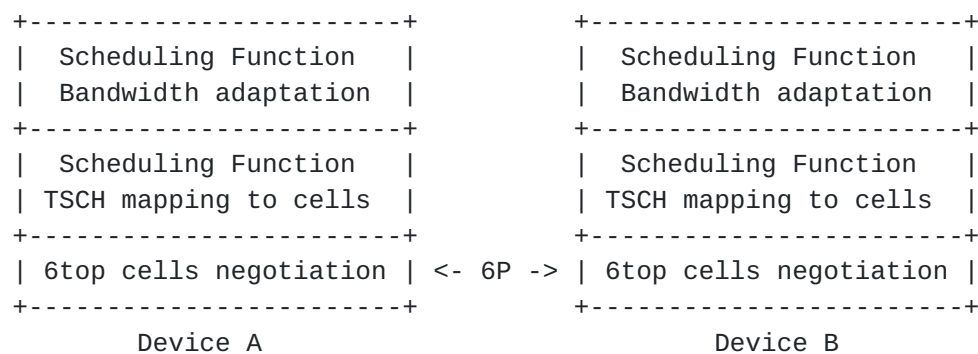


Figure 8: SF/6P stack in 6top

The SF relies on 6top services that implement the 6top Protocol (6P) [[RFC8480](#)] to negotiate the precise cells that will be allocated or freed based on the schedule of the peer. It may be for instance that a peer wants to use a particular time slot that is free in its schedule, but that timeslot is already in use by the other peer for a communication with a third party on a different cell. The 6P protocol enables the peers to find an agreement in a transactional manner that ensures the final consistency of the nodes state.

4.2.3. 6top and RPL Objective Function operations

An implementation of a RPL [[RFC6550](#)] Objective Function (OF), such as the RPL Objective Function Zero (OF0) [[RFC6552](#)] that is used in the Minimal 6TiSCH Configuration [[RFC8180](#)] to support RPL over a static schedule, may leverage, for its internal computation, the information maintained by 6top.

Most OFs require metrics about reachability, such as the ETX. 6top creates and maintains an abstract neighbor table, and this state may be leveraged to feed an OF and/or store OF information as well. A neighbor table entry may contain a set of statistics with respect to that specific neighbor including the time when the last packet has been received from that neighbor, a set of cell quality metrics (e.g.

RSSI or LQI), the number of packets sent to the neighbor or the number of packets received from it. This information can be obtained through 6top management APIs and used for instance to compute a Rank Increment that will determine the selection of the preferred parent.

6top provides statistics about the underlying layer so the OF can be tuned to the nature of the TSCH MAC layer. 6top also enables the RPL OF to influence the MAC behaviour, for instance by configuring the periodicity of IEEE Std 802.15.4 Extended Beacons (EBs). By augmenting the EB periodicity, it is possible to change the network dynamics so as to improve the support of devices that may change their point of attachment in the 6TiSCH network.

Some RPL control messages, such as the DODAG Information Object (DIO) are ICMPv6 messages that are broadcast to all neighbor nodes. With 6TiSCH, the broadcast channel requirement is addressed by 6top by configuring TSCH to provide a broadcast channel, as opposed to, for instance, piggybacking the DIO messages in Enhanced Beacons. Consideration was given towards finding a way to embed the Route Advertisements and the RPL DIO messages (both of which are multicast) into the IEEE Std 802.15.4 Enhanced Beacons. It was determined that this produced undue timer coupling among layers, that the resulting packet size was potentially too large, and required it is not yet clear that there is any need for Enhanced Beacons in a production network.

4.2.4. Network Synchronization

Nodes in a TSCH network must be time synchronized. A node keeps synchronized to its time source neighbor through a combination of frame-based and acknowledgment-based synchronization. In order to maximize battery life and network throughput, it is advisable that RPL ICMP discovery and maintenance traffic (governed by the trickle timer) be somehow coordinated with the transmission of time synchronization packets (especially with enhanced beacons). This could be achieved through an interaction of the 6top sublayer and the RPL objective Function, or could be controlled by a management entity.

Time distribution requires a loop-free structure. Nodes taken in a synchronization loop will rapidly desynchronize from the network and become isolated. It is expected that a RPL DAG with a dedicated global Instance is deployed for the purpose of time synchronization. That Instance is referred to as the Time Synchronization Global Instance (TSGI). The TSGI can be operated in either of the 3 modes that are detailed in [section 3.1.3](#) of RPL [RFC6550], "Instances, DODAGs, and DODAG Versions". Multiple uncoordinated DODAGs with independent roots may be used if all the roots share a common time

source such as the Global Positioning System (GPS). In the absence of a common time source, the TSGI should form a single DODAG with a virtual root. A backbone network is then used to synchronize and coordinate RPL operations between the backbone routers that act as sinks for the LLN. Optionally, RPL's periodic operations may be used to transport the network synchronization. This may mean that 6top would need to trigger (override) the trickle timer if no other traffic has occurred for such a time that nodes may get out of synchronization.

A node that has not joined the TSGI advertises a MAC level Join Priority of 0xFF to notify its neighbors that is not capable of serving as time parent. A node that has joined the TSGI advertises a MAC level Join Priority set to its DAGRank() in that Instance, where DAGRank() is the operation specified in [section 3.5.1 of \[RFC6550\]](#), "Rank Comparison".

A root is configured or obtains by some external means the knowledge of the RPLInstanceID for the TSGI. The root advertises its DagRank in the TSGI, that must be less than 0xFF, as its Join Priority in its IEEE Std 802.15.4 Extended Beacons (EB). We'll note that the Join Priority is now specified between 0 and 0x3F leaving 2 bits in the octet unused in the IEEE Std 802.15.4e specification. After consultation with IEEE authors, it was asserted that 6TiSCH can make a full use of the octet to carry an integer value up to 0xFF.

A node that reads a Join Priority of less than 0xFF should join the neighbor with the lesser Join Priority and use it as time parent. If the node is configured to serve as time parent, then the node should join the TSGI, obtain a Rank in that Instance and start advertising its own DagRank in the TSGI as its Join Priority in its EBs.

4.2.5. SlotFrames and Priorities

6TiSCH enables in essence the capability to use IPv6 over a MAC layer that enables to schedule the transmissions. In order to ensure that the medium is free of contending packets when time arrives for a scheduled transmission, a window of time is defined around the scheduled transmission time where the medium must be free of contending energy.

One simple way to obtain such a window is to format time and frequencies in cells of transmission of equal duration. This is the method that is adopted in IEEE Std 802.15.4 TSCH as well as the Long Term Evolution (LTE) of cellular networks.

In order to describe that formatting of time and frequencies, the 6TiSCH architecture defines a global concept that is called a Channel

Distribution and Usage (CDU) matrix; a CDU matrix is a matrix of cells with an height equal to the number of available channels (indexed by ChannelOffsets) and a width (in timeslots) that is the period of the network scheduling operation (indexed by slotOffsets) for that CDU matrix. The size of a cell is a timeslot duration, and values of 10 to 15 milliseconds are typical in 802.15.4 TSCH to accommodate for the transmission of a frame and an ack, including the security validation on the receive side which may take up to a few milliseconds on some device architecture.

A CDU matrix iterates over and over with a well-known channel rotation called the hopping sequence. In a given network, there might be multiple CDU matrices that operate with different width, so they have different durations and represent different periodic operations. It is recommended that all CDU matrices in a 6TiSCH domain operate with the same cell duration and are aligned, so as to reduce the chances of interferences from slotted-aloha operations. The knowledge of the CDU matrices is shared between all the nodes and used in particular to define slotFrames.

A slotFrame is a MAC-level abstraction that is common to all nodes and contains a series of timeslots of equal length and precedence. It is characterized by a slotFrame_ID, and a slotFrame_size. A slotFrame aligns to a CDU matrix for its parameters, such as number and duration of timeslots.

Multiple slotFrames can coexist in a node schedule, i.e., a node can have multiple activities scheduled in different slotFrames, based on the precedence of the 6TiSCH topologies. The slotFrames may be aligned to different CDU matrices and thus have different width. There is typically one slotFrame for scheduled traffic that has the highest precedence and one or more slotFrame(s) for RPL traffic. The timeslots in the slotFrame are indexed by the SlotOffset; the first cell is at SlotOffset 0.

When a packet is received from a higher layer for transmission, 6top inserts that packet in the outgoing queue which matches the packet best (Differentiated Services [[RFC2474](#)] can therefore be used). At each scheduled transmit slot, 6top looks for the frame in all the outgoing queues that best matches the cells. If a frame is found, it is given to the TSCH MAC for transmission.

4.2.6. Distributing the reservation of cells

6TiSCH expects a high degree of scalability together with a distributed routing functionality based on RPL. To achieve this goal, the spectrum must be allocated in a way that allows for spatial reuse between zones that will not interfere with one another. In a

large and spatially distributed network, a 6TiSCH node is often in a good position to determine usage of spectrum in its vicinity.

Use cases for distributed routing are often associated with a statistical distribution of best-effort traffic with variable needs for bandwidth on each individual link. With 6TiSCH, the abstraction of an IPv6 link is implemented as a pair of bundles of cells, one in each direction; the size of a bundle is optimal when both the energy wasted idle listening and the packet drops due to congestion loss are minimized. This can be maintained if the number of cells in a bundle is adapted dynamically, and with enough reactivity, to match the variations of best-effort traffic. In turn, the agility to fulfill the needs for additional cells improves when the number of interactions with other devices and the protocol latencies are minimized.

6TiSCH limits that interaction to RPL parents that will only negotiate with other RPL parents, and performs that negotiation by groups of cells as opposed to individual cells. The 6TiSCH architecture allows RPL parents to adjust dynamically, and independently from the PCE, the amount of bandwidth that is used to communicate between themselves and their children, in both directions; to that effect, an allocation mechanism enables a RPL parent to obtain the exclusive use of a portion of a CDU matrix within its interference domain. Note that a PCE is expected to have precedence in the allocation, so that a RPL parent would only be able to obtain portions that are not in-use by the PCE.

The 6TiSCH architecture introduces the concept of chunks ([I-D.ietf-6tisch-terminology](#)) to operate such spectrum distribution for a whole group of cells at a time. The CDU matrix is formatted into a set of chunks, each of them identified uniquely by a chunk-ID. The knowledge of this formatting is shared between all the nodes in a 6TiSCH network. 6TiSCH also defines the process of chunk ownership appropriation whereby a RPL parent discovers a chunk that is not used in its interference domain (e.g lack of energy detected in reference cells in that chunk); then claims the chunk, and then defends it in case another RPL parent would attempt to appropriate it while it is in use. The chunk is the basic unit of ownership that is used in that process.

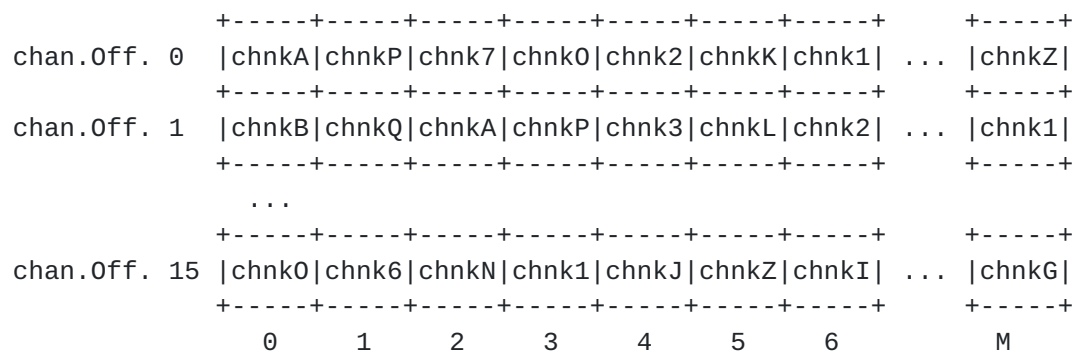


Figure 9: CDU matrix Partitioning in Chunks

As a result of the process of chunk ownership appropriation, the RPL parent has exclusive authority to decide which cell in the appropriated chunk can be used by which node in its interference domain. In other words, it is implicitly delegated the right to manage the portion of the CDU matrix that is represented by the chunk. The RPL parent may thus orchestrate which transmissions occur in any of the cells in the chunk, by allocating cells from the chunk to any form of communication (unicast, multicast) in any direction between itself and its children. Initially, those cells are added to the heap of free cells, then dynamically placed into existing bundles, in new bundles, or allocated opportunistically for one transmission.

The appropriation of a chunk can also be requested explicitly by the PCE to any node. In that case, the node still may need to perform the appropriation process to validate that no other node has claimed that chunk already. After a successful appropriation, the PCE owns the cells in that chunk, and may use them as hard cells to set up Tracks.

4.3. Communication Paradigms and Interaction Models

[I-D.ietf-6tisch-terminology] defines the terms of Communication Paradigms and Interaction Models, which can be placed in parallel to the Information Models and Data Models that are defined in [RFC3444].

A Communication Paradigms would be an abstract view of a protocol exchange, and would come with an Information Model for the information that is being exchanged. In contrast, an Interaction Models would be more refined and could point on standard operation such as a Representational state transfer (REST) "GET" operation and would match a Data Model for the data that is provided over the protocol exchange.

Section 2.1.3 of [[I-D.ietf-roll-rpl-industrial-applicability](#)] and next sections discuss application-layer paradigms, such as Source-sink (SS) that is a Multipeer to Multipeer (MP2MP) model primarily used for alarms and alerts, Publish-subscribe (PS, or pub/sub) that is typically used for sensor data, as well as Peer-to-peer (P2P) and Peer-to-multipeer (P2MP) communications. Additional considerations on Duocast and its N-cast generalization are also provided. Those paradigms are frequently used in industrial automation, which is a major use case for IEEE Std 802.15.4 TSCH wireless networks with [[ISA100.11a](#)] and [[WirelessHART](#)], that provides a wireless access to [[HART](#)] applications and devices.

This specification focuses on Communication Paradigms and Interaction Models for packet forwarding and TSCH resources (cells) management. Management mechanisms for the TSCH schedule at Link-layer (one-hop), Network-layer (multithop along a Track), and Application-layer (remote control) are discussed in [Section 4.4](#). Link-layer frame forwarding interactions are discussed in [Section 4.6](#), and Network-layer Packet routing is addressed in [Section 4.7](#).

[4.4. Schedule Management Mechanisms](#)

6TiSCH uses 4 paradigms to manage the TSCH schedule of the LLN nodes: Static Scheduling, neighbor-to-neighbor Scheduling, remote monitoring and scheduling management, and Hop-by-hop scheduling. Multiple mechanisms are defined that implement the associated Interaction Models, and can be combined and used in the same LLN. Which mechanism(s) to use depends on application requirements.

[4.4.1. Static Scheduling](#)

In the simplest instantiation of a 6TiSCH network, a common fixed schedule may be shared by all nodes in the network. Cells are shared, and nodes contend for slot access in a slotted aloha manner.

A static TSCH schedule can be used to bootstrap a network, as an initial phase during implementation, or as a fall-back mechanism in case of network malfunction. This schedule is pre-established, for instance decided by a network administrator based on operational needs. It can be pre-configured into the nodes, or, more commonly, learned by a node when joining the network using standard IEEE Std 802.15.4 Information Elements (IE). Regardless, the schedule remains unchanged after the node has joined a network. RPL is used on the resulting network. This "minimal" scheduling mechanism that implements this paradigm is detailed in [[RFC8180](#)].

4.4.2. Neighbor-to-neighbor Scheduling

In the simplest instantiation of a 6TiSCH network described in [Section 4.4.1](#), nodes may expect a packet at any cell in the schedule and will waste energy idle listening. In a more complex instantiation of a 6TiSCH network, a matching portion of the schedule is established between peers to reflect the observed amount of transmissions between those nodes. The aggregation of the cells between a node and a peer forms a bundle that the 6top layer uses to implement the abstraction of a link for IP. The bandwidth on that link is proportional to the number of cells in the bundle.

If the size of a bundle is configured to fit an average amount of bandwidth, peak traffic is dropped. If the size is configured to allow for peak emissions, energy is be wasted idle listening.

The 6top Protocol [[RFC8480](#)] specifies the exchanges between neighbor nodes to reserve soft cells to transmit to one another. Because this reservation is done without global knowledge of the schedule of other nodes in the LLN, scheduling collisions are possible. An optional Scheduling Function (SF) such as MSF [[I-D.ietf-6tisch-msf](#)] is used to monitor bandwidth usage and perform requests for dynamic allocation by the 6top sublayer. The SF component is not part of the 6top sublayer. It may be collocated on the same device or may be partially or fully offloaded to an external system.

Monitoring and relocation is done in the 6top layer. For the upper layer, the connection between two neighbor nodes appears as an number of cells. Depending on traffic requirements, the upper layer can request 6top to add or delete a number of cells scheduled to a particular neighbor, without being responsible for choosing the exact slotOffset/channelOffset of those cells.

4.4.3. Remote Monitoring and Schedule Management

The work at the 6TiSCH WG is focused on non-deterministic traffic and does not provide the generic data model that would be necessary to monitor and manage resources of the 6top sublayer. It is recognized that CoAP can be appropriate to interact with the 6top layer of a node that is multiple hops away across a 6TiSCH mesh.

The entity issuing the CoAP requests can be a central scheduling entity (e.g. a PCE), a node multiple hops away with the authority to modify the TSCH schedule (e.g. the head of a local cluster), or a external device monitoring the overall state of the network (e.g. NME). It is also 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.

With respect to Centralized routing and scheduling, it is envisioned that the related component of the 6TiSCH Architecture would be an extension of the Deterministic Networking Architecture [[I-D.ietf-detnet-architecture](#)], which studies Layer-3 aspects of Deterministic Networks, and covers networks that span multiple Layer-2 domains. The DetNet architecture is a form of SDN Architecture and is composed of three planes, a (User) Application Plane, a Controller Plane (where the PCE operates), and a Network Plane which in our case is the 6TiSCH LLN. The generic SDN architecture is discussed in Software-Defined Networking (SDN): Layers and Architecture Terminology [[RFC7426](#)] and is represented below:

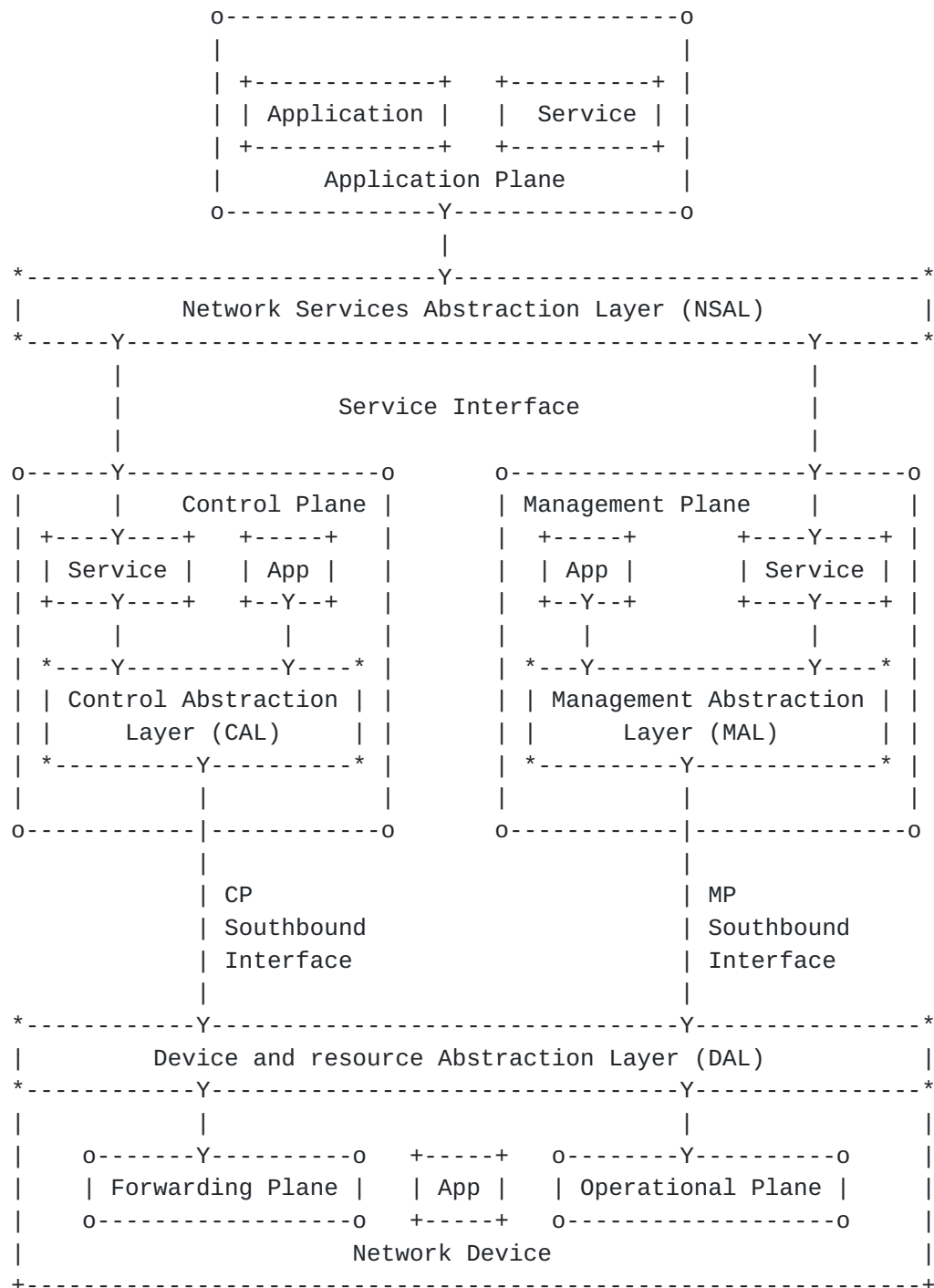
SDN Layers and Architecture Terminology per [RFC 7426](#)

Figure 10

The PCE establishes end-to-end Tracks of hard cells, which are described in more details in [Section 4.6.1](#). The DetNet work is expected to enable end to end Deterministic Path across heterogeneous

network (e.g. a 6TiSCH LLN and an Ethernet Backbone). This model fits the 6TiSCH extended configuration, whereby a 6BBR federates multiple 6TiSCH LLN in a single subnet over a backbone that can be, for instance, Ethernet or Wi-Fi. In that model, 6TiSCH 6BBRs synchronize with one another over the backbone, so as to ensure that the multiple LLNs that form the IPv6 subnet stay tightly synchronized.

If the Backbone is Deterministic, then the Backbone Router ensures that the end-to-end deterministic behavior is maintained between the LLN and the backbone. It is the responsibility of the PCE to compute a deterministic path and to end across the TSCH network and an IEEE Std 802.1 TSN Ethernet backbone, and that of DetNet to enable end-to-end deterministic forwarding.

4.4.4. Hop-by-hop Scheduling

A node can reserve a Track ([Section 4.5](#)) to a destination node multiple hops away by installing soft cells at each intermediate node. This forms a Track of soft cells. It is the responsibility of the 6top sublayer of each node on the Track to monitor these soft cells and trigger relocation when needed.

This hop-by-hop reservation mechanism is expected to be similar in essence to [\[RFC3209\]](#) and/or [\[RFC4080\]](#)/[\[RFC5974\]](#). The protocol for a node to trigger hop-by-hop scheduling is not yet defined.

4.5. On Tracks

4.5.1. General Behavior of Tracks

The architecture introduces the concept of a Track, which is a directed path from a source 6TiSCH node to a destination 6TiSCH node across a 6TiSCH LLN. A Track is the 6TiSCH instantiation of the concept of a Deterministic Path as described in [\[I-D.ietf-detnet-architecture\]](#). Constrained resources such as memory buffers are reserved for that Track in intermediate 6TiSCH nodes to avoid loss related to limited capacity. A 6TiSCH node along a Track not only knows which bundles of cells it should use to receive packets from a previous hop, but also knows which bundle(s) it should use to send packets to its next hop along the Track.

A Track is composed of bundles of cells with related schedules and logical relationships and that ensure that a packet that is injected in a Track will progress in due time all the way to destination. Multiple cells may be scheduled in a Track for the transmission of a single packet, in which case the normal operation of IEEE Std 802.15.4 Automatic Repeat-reQuest (ARQ) can take place; the

acknowledgment may be omitted in some cases, for instance if there is no scheduled cell for a possible retry.

There are several benefits for using a Track to forward a packet from a source node to the destination node.

1. Track forwarding, as further described in [Section 4.6.1](#), is a Layer-2 forwarding scheme, which introduces less process delay and overhead than Layer-3 forwarding scheme. Therefore, LLN Devices can save more energy and resource, which is critical for resource constrained devices.
2. Since channel resources, i.e. bundles of cells, have been reserved for communications between 6TiSCH nodes of each hop on the Track, the throughput and the maximum latency of the traffic along a Track are guaranteed and the jitter is maintained small.
3. By knowing the scheduled time slots of incoming bundle(s) and outgoing bundle(s), 6TiSCH nodes on a Track could save more energy by staying in sleep state during in-active slots.
4. Tracks are protected from interfering with one another if a cell belongs to at most one Track, and congestion loss is avoided if at most one packet can be presented to the MAC to use that cell. Tracks enhance the reliability of transmissions and thus further improve the energy consumption in LLN Devices by reducing the chances of retransmission.

[4.5.2](#). **Serial Track**

A Serial (or simple) Track is the 6TiSCH version of a circuit; a bundle of cells that are programmed to receive (RX-cells) is uniquely paired to a bundle of cells that are set to transmit (TX-cells), representing a Layer-2 forwarding state which can be used regardless of the network layer protocol.

A Serial Track is thus formed end-to-end as a succession of paired bundles, a receive bundle from the previous hop and a transmit bundle to the next hop along the Track. For a given iteration of the device schedule, the effective channel of the cell is obtained by adding a pseudo-random number to the channelOffset of the cell, which results in a rotation of the frequency that used for transmission.

The bundles may be computed so as to accommodate both variable rates and retransmissions, so they might not be fully used at a given iteration of the schedule.

4.5.3. Complex Track with Replication and Elimination

As opposed to a Serial Track that is a sequence of nodes and links, a Complex Track is shaped as a directed acyclic graph towards a destination to support multi-path forwarding and route around failures.

A Complex Track may also branch off and rejoin, for the purpose of the DetNet Packet Replication and Elimination (PRE), over non congruent branches. PRE may be used to complement Layer-2 ARQ to meet industrial expectations in Packet Delivery Ratio (PDR), in particular when the Track extends beyond the 6TiSCH network in a larger DetNet network.

The art of Deterministic Networks already include PRE techniques. Example standards include the Parallel Redundancy Protocol (PRP) and the High-availability Seamless Redundancy (HSR) [[IEC62439](#)].

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). It is also possible that the field device only uses the second branch if sending over the first branch fails.

In the art of TSCH, a path does not necessarily support PRE but it is almost 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.

4.5.4. DetNet End-to-end Path

Ultimately, DetNet should enable to extend a Track beyond the 6TiSCH LLN. Figure 11 illustrates a Track that is laid out from a field device in a 6TiSCH network to an IoT gateway that is located on an 802.1 Time-Sensitive Networking (TSN) backbone.

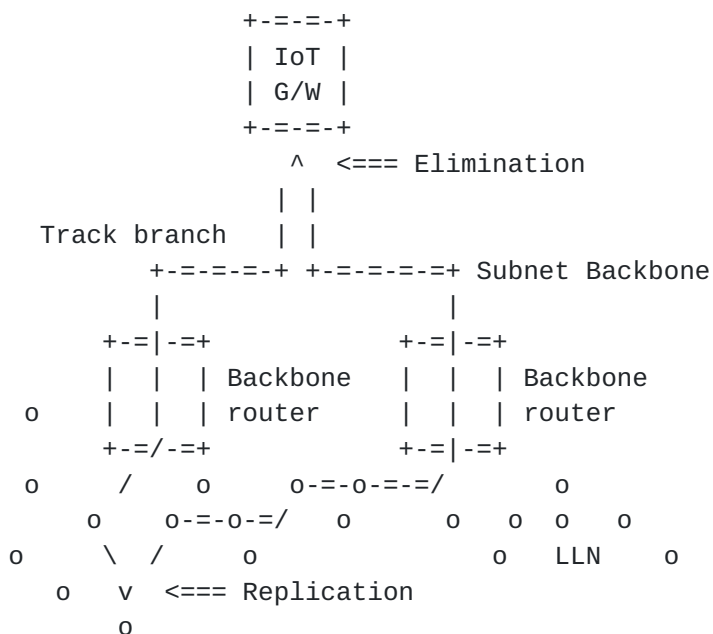


Figure 11: End-to-End deterministic Track

The Replication function in the 6TiSCH Node 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 makes it in due 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.

4.5.5. Cell Reuse

The 6TiSCH architecture provides means to avoid waste of cells as well as overflows in the transmit bundle pof a Track, as follows:

In one hand, a TX-cell that is not needed for the current iteration may be reused opportunistically on a per-hop basis for routed packets. When all of the frame that were received for a given Track are effectively transmitted, any available TX-cell for that Track can be reused for upper layer traffic for which the next-hop router matches the next hop along the Track. In that case, the cell that is being used is effectively a TX-cell from the Track, but the short address for the destination is that of the next-hop router. It results that a frame that is received in a RX-cell of a Track with a destination MAC address set to this node as opposed to broadcast must be extracted from the Track and delivered to the upper layer (a frame with an unrecognized

destination MAC address is dropped at the lower MAC layer and thus is not received at the 6top sublayer).

On the other hand, it might happen that there are not enough TX-cells in the transmit bundle to accommodate the Track traffic, for instance if more retransmissions are needed than provisioned. In that case, the frame can be placed for transmission in the bundle that is used for Layer-3 traffic towards the next hop along the Track as long as it can be routed by the upper layer, that is, typically, if the frame transports an IPv6 packet. The MAC address should be set to the next-hop MAC address to avoid confusion. It results that a frame that is received over a Layer-3 bundle may be in fact associated to a Track. In a classical IP link such as an Ethernet, off-Track traffic is typically in excess over reservation to be routed along the non-reserved path based on its QoS setting. But with 6TiSCH, since the use of the Layer-3 bundle may be due to transmission failures, it makes sense for the receiver to recognize a frame that should be re-Track, and to place it back on the appropriate bundle if possible. A frame should be re-Track if the Per-Hop-Behavior group indicated in the Differentiated Services Field of the IPv6 header is set to Deterministic Forwarding, as discussed in [Section 4.7.1](#). A frame is re-Track by scheduling it for transmission over the transmit bundle associated to the Track, with the destination MAC address set to broadcast.

[4.6.](#) Forwarding Models

By forwarding, this specification means the per-packet operation that allows to deliver a packet to a next hop or an upper layer in this node. Forwarding is based on pre-existing state that was installed as a result of a routing computation [Section 4.7](#). 6TiSCH supports three different forwarding model, G-MPLS Track Forwarding (TF), 6LoWPAN Fragment Forwarding (FF) and IPv6 Forwarding (6F).

[4.6.1.](#) Track Forwarding

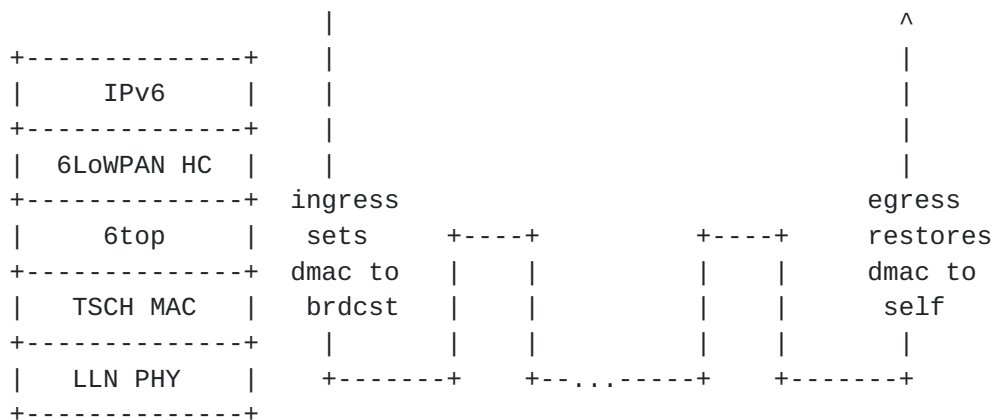
Forwarding along a Track can be seen as a Generalized Multi-protocol Label Switching (G-MPLS) operation in that the information used to switch a frame is not an explicit label, but rather related to other properties of the way the packet was received, a particular cell in the case of 6TiSCH. As a result, as long as the TSCH MAC (and Layer-2 security) accepts a frame, that frame can be switched regardless of the protocol, whether this is an IPv6 packet, a 6LoWPAN fragment, or a frame from an alternate protocol such as WirelessHART or ISA100.11a.

A data frame that is forwarded along a Track normally has a destination MAC address that is set to broadcast - or a multicast address depending on MAC support. This way, the MAC layer in the intermediate nodes accepts the incoming frame and 6top switches it without incurring a change in the MAC header. In the case of IEEE Std 802.15.4, this means effectively broadcast, so that along the Track the short address for the destination of the frame is set to 0xFFFF.

There are 2 modes for a Track, transport mode and tunnel mode.

[4.6.1.1.](#) Transport Mode

In transport mode, the Protocol Data Unit (PDU) is associated with flow-dependant meta-data that refers uniquely to the Track, so the 6top sublayer can place the frame in the appropriate cell without ambiguity. In the case of IPv6 traffic, this flow identification is transported in the Flow Label of the IPv6 header. Associated with the source IPv6 address, the Flow Label forms a globally unique identifier for that particular Track that is validated at egress before restoring the destination MAC address (DMAC) and punting to the upper layer.



Track Forwarding, Transport Mode

[4.6.1.2.](#) Tunnel Mode

In tunnel mode, the frames originate from an arbitrary protocol over a compatible MAC that may or may not be synchronized with the 6TiSCH network. An example of this would be a router with a dual radio that is capable of receiving and sending WirelessHART or ISA100.11a frames with the second radio, by presenting itself as an access Point or a Backbone Router, respectively.

In that mode, some entity (e.g. PCE) can coordinate with a WirelessHART Network Manager or an ISA100.11a System Manager to specify the flows that are to be transported transparently over the Track.

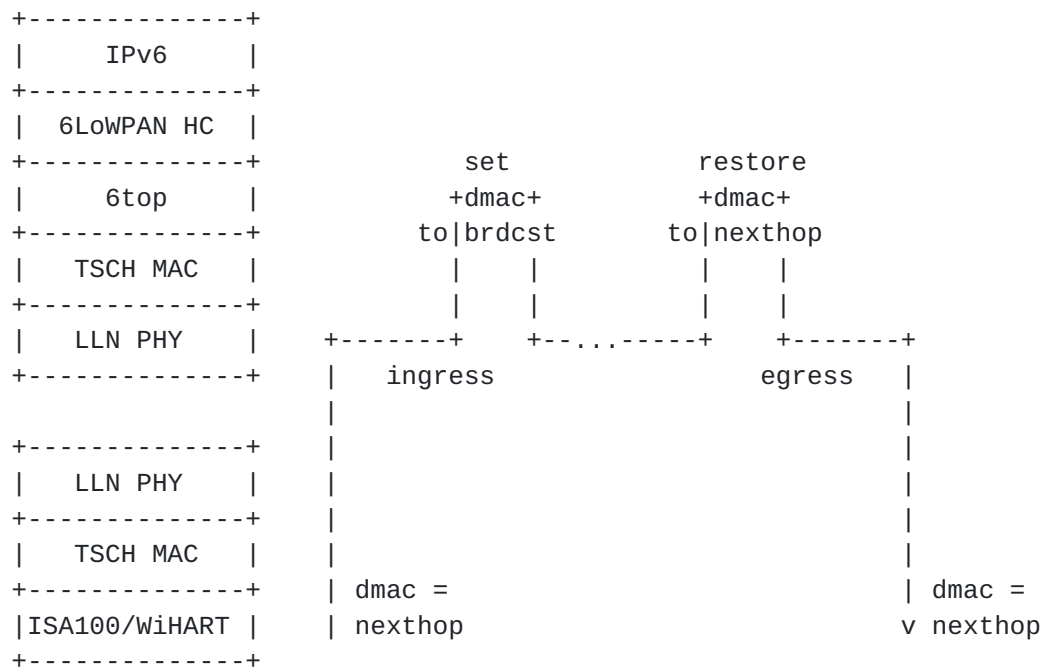


Figure 12: Track Forwarding, Tunnel Mode

In that case, the flow information that identifies the Track at the ingress 6TiSCH router is derived from the RX-cell. The dmac is set to this node but the flow information indicates that the frame must be tunneled over a particular Track so the frame is not passed to the upper layer. Instead, the dmac is forced to broadcast and the frame is passed to the 6top sublayer for switching.

At the egress 6TiSCH router, the reverse operation occurs. Based on metadata associated to the Track, the frame is passed to the appropriate Link Layer with the destination MAC restored.

4.6.1.3. Tunnel Metadata

Metadata coming with the Track configuration is expected to provide the destination MAC address of the egress endpoint as well as the tunnel mode and specific data depending on the mode, for instance a service access point for frame delivery at egress. If the tunnel egress point does not have a MAC address that matches the configuration, the Track installation fails.

In transport mode, if the final Layer-3 destination is the tunnel termination, then it is possible that the IPv6 address of the destination is compressed at the 6LoWPAN sublayer based on the MAC address. It is thus mandatory at the ingress point to validate that the MAC address that was used at the 6LoWPAN sublayer for compression matches that of the tunnel egress point. For that reason, the node that injects a packet on a Track checks that the destination is effectively that of the tunnel egress point before it overwrites it to broadcast. The 6top sublayer at the tunnel egress point reverts that operation to the MAC address obtained from the tunnel metadata.

4.6.2. IPv6 Forwarding

As the packets are routed at Layer-3, traditional QoS and Active Queue Management (AQM) operations are expected to prioritize flows; the application of Differentiated Services is further discussed in [\[I-D.svshah-tsvwg-lln-diffserv-recommendations\]](#).

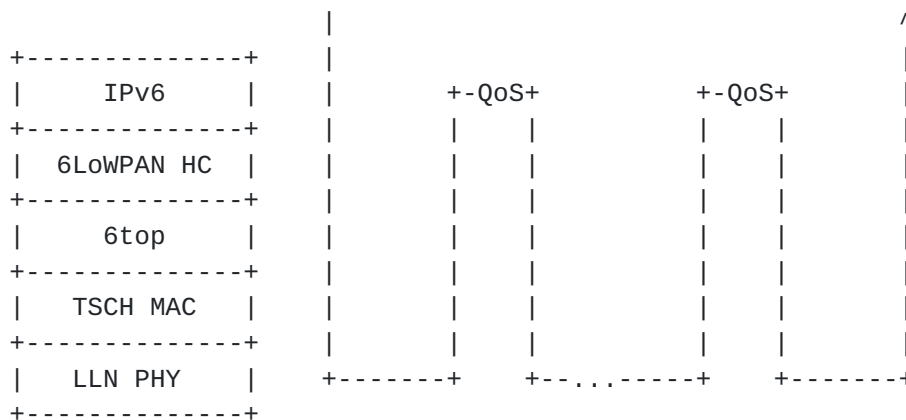


Figure 13: IP Forwarding

4.6.3. Fragment Forwarding

Considering that 6LoWPAN packets can be as large as 1280 bytes (the IPv6 MTU), and that the non-storing mode of RPL implies Source Routing that requires space for routing headers, and that a IEEE Std 802.15.4 frame with security may carry in the order of 80 bytes of effective payload, an IPv6 packet might be fragmented into more than 16 fragments at the 6LoWPAN sublayer.

This level of fragmentation is much higher than that traditionally experienced over the Internet with IPv4 fragments, where fragmentation is already known as harmful.

In the case to a multihop route within a 6TiSCH network, Hop-by-Hop recomposition occurs at each hop in order to reform the packet and

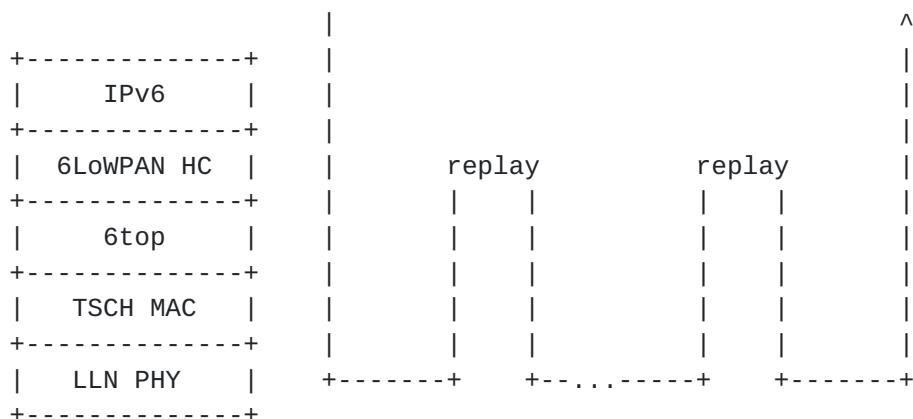


Figure 15: Forwarding Next Fragment

A bitmap and an ECN echo in the end-to-end acknowledgment enable the source to resend the missing fragments selectively. The first fragment may be resent to carve a new path in case of a path failure. The ECN echo set indicates that the number of outstanding fragments should be reduced.

4.7. Distributed vs. Centralized Routing

6TiSCH enables a mixed model of centralized routes and distributed routes. Centralized routes can for example be computed by a entity such as a PCE. Distributed routes are computed by RPL.

Both methods may inject routes in the Routing Tables of the 6TiSCH routers. In either case, each route is associated with a 6TiSCH topology that can be a RPL Instance topology or a Track. The 6TiSCH topology is indexed by a Instance ID, in a format that reuses the RPLInstanceID as defined in RPL [[RFC6550](#)].

Both RPL and PCE rely on shared sources such as policies to define Global and Local RPLInstanceIDs that can be used by either method. It is possible for centralized and distributed routing to share a same topology. Generally they will operate in different slotFrames, and centralized routes will be used for scheduled traffic and will have precedence over distributed routes in case of conflict between the slotFrames.

4.7.1. Packet Marking and Handling

All packets inside a 6TiSCH domain must carry the Instance ID that identifies the 6TiSCH topology that is to be used for routing and forwarding that packet. The location of that information must be the same for all packets forwarded inside the domain.

For packets that are routed by a PCE along a Track, the tuple formed by the IPv6 source address and a local RPLInstanceID in the packet identify uniquely the Track and associated transmit bundle.

For packets that are routed by RPL, that information is the RPLInstanceID which is carried in the RPL Packet Information, as discussed in [section 11.2 of \[RFC6550\]](#), "Loop Avoidance and Detection".

The RPL Packet Information (RPI) is carried in IPv6 packets as a RPL option in the IPv6 Hop-By-Hop Header [\[RFC6553\]](#).

A compression mechanism for the RPL packet artifacts that integrates the compression of IP-in-IP encapsulation and the Routing Header type 3 [\[RFC6554\]](#) with that of the RPI in a 6LoWPAN dispatch/header type is specified in [\[RFC8025\]](#) and [\[RFC8138\]](#).

Either way, the method and format used for encoding the RPLInstanceID is generalized to all 6TiSCH topological Instances, which include both RPL Instances and Tracks.

[4.7.2.](#) Replication, Retries and Elimination

6TiSCH expects elimination and replication of packets along a complex Track, but has no position about how the sequence numbers would be tagged in the packet.

As it goes, 6TiSCH expects that timeslots corresponding to copies of a same packet along a Track are correlated by configuration, and does not need to process the sequence numbers.

The semantics of the configuration will enable correlated timeslots to be grouped for transmit (and respectively receive) with a 'OR' relations, and then a 'AND' relation would be configurable between groups. The semantics is that if the transmit (and respectively receive) operation succeeded in one timeslot in a 'OR' group, then all the other timeslots in the group are ignored. Now, if there are at least two groups, the 'AND' relation between the groups indicates that one operation must succeed in each of the groups.

On the transmit side, timeslots provisioned for retries along a same branch of a Track are placed a same 'OR' group. The 'OR' relation indicates that if a transmission is acknowledged, then further transmissions should not be attempted for timeslots in that group. There are as many 'OR' groups as there are branches of the Track departing from this node. Different 'OR' groups are programmed for the purpose of replication, each group corresponding to one branch of the Track. The 'AND' relation between the groups indicates that

transmission over any of branches must be attempted regardless of whether a transmission succeeded in another branch. It is also possible to place cells to different next-hop routers in a same 'OR' group. This allows to route along multi-path tracks, trying one next-hop and then another only if sending to the first fails.

On the receive side, all timeslots are programmed in a same 'OR' group. Retries of a same copy as well as converging branches for elimination are converged, meaning that the first successful reception is enough and that all the other timeslots can be ignored.

4.7.3. Differentiated Services Per-Hop-Behavior

Additionally, an IP packet that is sent along a Track uses the Differentiated Services Per-Hop-Behavior Group called Deterministic Forwarding, as described in [\[I-D.svshah-tsvwg-deterministic-forwarding\]](#).

5. IANA Considerations

This specification does not require IANA action.

6. Security Considerations

This architecture operates on IEEE Std 802.15.4 and expects Link-Layer security to be enabled at all times between connected devices, except for the very first step of the device join process, where a joining device may need some initial, unsecured exchanges so as to obtain its initial key material.

The Minimal Security Framework for 6TiSCH [\[I-D.ietf-6tisch-minimal-security\]](#) describes the minimal mechanisms required to support secure enrollment of a pledge to a 6TiSCH network based on PSK. The specification enables to establish of Link-Layer keys, typically used in combination with a variation of Counter with CBC-MAC (CCM) [\[RFC3610\]](#), and set up a secure end-to-end session between the joining node (called the pledge) and the join registrar/coordinator (JRC) in charge of authenticating the node via a Join Proxy (JP). It can also be used to obtain a Link Layer short address as a side effect. CoJP uses shared slots which are a constrained resource, so it is optimized to limit the number of messages to the strict minimum. As an example, Neighbor Discovery between the pledge and the JP can be skipped when the IPv6 Link Local addresses that are used derive from the node's EUI-64 address.

The "6tisch Zero-Touch Secure Join protocol" [\[I-D.ietf-6tisch-dtsecurity-zerotouch-join\]](#) wraps the minimal security draft with a flow inspired from ANIMA "Bootstrapping Remote

Secure Key Infrastructures (BRSKI)"
[[I-D.ietf-anima-bootstrapping-keyinfra](#)].

6.1. Join Process Highlights

The BRSKI architecture specifies three logical elements to describe the join process:

Pledge: Node that wishes to become part of the network;

Join Registrar/Coordinator (JRC) : An entity that arbitrates network access and hands out network parameters (such as keying material);

Join Proxy (JP), a one-hop (radio) neighbor of the joining node that acts as proxy network node and may provide connectivity with the JRC.

The join protocol consists of three major activities:

Device Authentication: The Pledge and the JP mutually authenticate each other and establish a shared key, so as to ensure on-going authenticated communications. This may involve a server as a third party.

Authorization: The JP decides on whether/how to authorize a Pledge (if denied, this may result in loss of bandwidth). Conversely, the Pledge decides on whether/how to authorize the network (if denied, it will not join the network). Authorization decisions may involve other nodes in the network.

Configuration/Parameterization: The JP distributes configuration information to the Pledge, such as scheduling information, IP address assignment information, and network policies. This may originate from other network devices, for which the JP may act as proxy. This step may also include distribution of information from the Pledge to the JP and other nodes in the network and, more generally, synchronization of information between these entities.

The device joining process is depicted in Figure 16, where it is assumed that devices have access to certificates and where entities have access to the root CA keys of their communicating parties (initial set-up requirement). Under these assumptions, the authentication step of the device joining process does not require online involvement of a third party. Mutual authentication is performed between the Pledge and the JP using their certificates, which also results in a shared key between these two entities.

The JP assists the Pledge in mutual authentication with a remote server node (primarily via provision of a communication path with the server), which also results in a shared (end-to-end) key between those two entities. The server node may be a JRC that arbitrages the network authorization of the Pledge (where the JP will deny bandwidth if authorization is not successful); it may distribute network-specific configuration parameters (including network-wide keys) to the Pledge. In its turn, the Pledge may distribute and synchronize information (including, e.g., network statistics) to the server node and, if so desired, also to the JP. The actual decision of the Pledge to become part of the network may depend on authorization of the network itself.

The server functionality is a role which may be implemented with one (centralized) or multiple devices (distributed). In either case, mutual authentication is established with each physical server entity with which a role is implemented.

Note that in the above description, the JP does not solely act as a relay node, thereby allowing it to first filter traffic to be relayed based on cryptographic authentication criteria - this provides first-level access control and mitigates certain types of denial-of-service attacks on the network at large.

Depending on more detailed insight in cost/benefit trade-offs, this process might be complemented by a more "relaxed" mechanism, where the JP acts as a relay node only. The final architecture will provide mechanisms to also cover cases where the initial set-up requirements are not met or where some other out-of-sync behavior occurs; it will also suggest some optimizations in case JRC-related information is already available with the JP (via caching of information).

When a device rejoins the network in the same authorization domain, the authorization step could be omitted if the server distributes the authorization state for the device to the JP when the device initially joined the network. However, this generally still requires the exchange of updated configuration information, e.g., related to time schedules and bandwidth allocation.

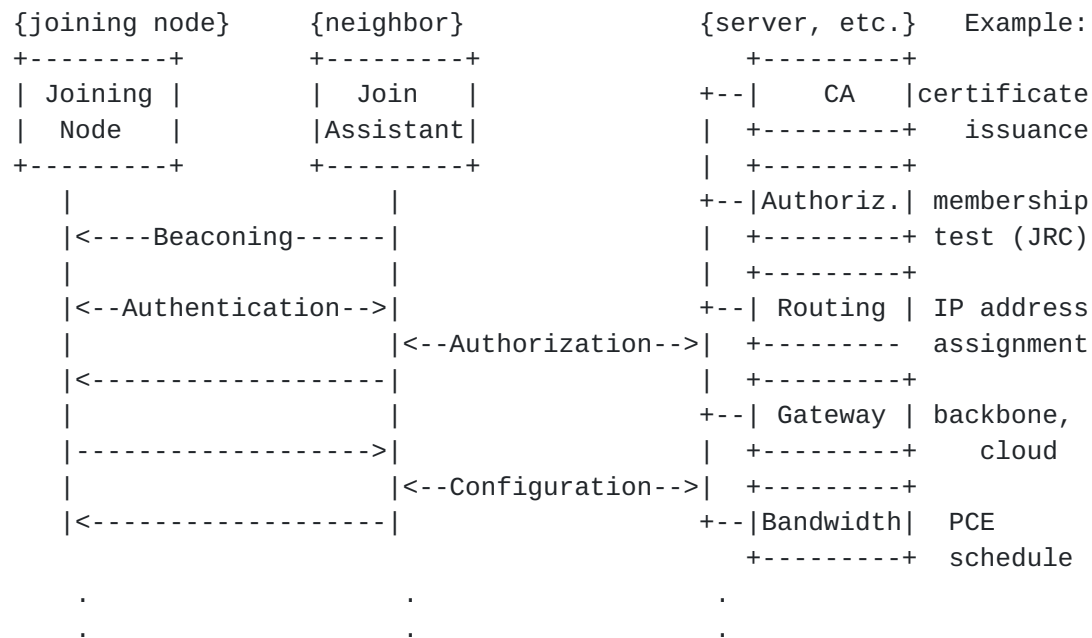


Figure 16: Network joining, with only authorization by third party

7. Acknowledgments

7.1. Contributors

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Appendix A. Dependencies on Work In Progress

In order to control the complexity and the size of the 6TiSCH work, the architecture and the associated IETF work are staged and the WG is expected to recharter multiple times. This document is been incremented as the work progressed following the evolution of the WG charter and the availability of dependent work. The intent was to publish when the WG concludes on the covered items.

At the time of publishing:

- o The need of a reactive routing protocol to establish on-demand constraint-optimized routes and a reservation protocol to establish Layer-3 Tracks is being discussed at 6TiSCH but not chartered for.
- o The operation of the Backbone Router [[I-D.ietf-6lo-backbone-router](#)] is stable but the RFC is not

published yet. The protection of registered addresses against impersonation and take over will be guaranteed by Address Protected Neighbor Discovery for Low-power and Lossy Networks [[I-D.ietf-6lo-ap-nd](#)], which is not yet published either.

- o The work on centralized Track computation is deferred to a subsequent work, not necessarily at 6TiSCH. A Predicable and Available Wireless (PAW) bar-BoF took place; PAW may form as a WG and take over that work. The 6TiSCH Architecture should thus inherit from the DetNet [[I-D.ietf-detnet-architecture](#)] architecture and thus depends on it. The Path Computation Element (PCE) should be a core component of that architecture. Around the PCE, a protocol such as an extension to a TEAS [[TEAS](#)] protocol will be required to expose the 6TiSCH node capabilities and the network peers to the PCE, and a protocol such as a lightweight PCEP or an adaptation of CCAMP [[CCAMP](#)] G-MPLS formats and procedures will be used to publish the Tracks, as computed by the PCE, to the 6TiSCH nodes.
- o BIER-TE-based OAM, Replication and Elimination [[I-D.thubert-bier-replication-elimination](#)] leverages Bit Index Explicit Replication - Traffic Engineering to control in the data plane the DetNet Replication and Elimination activities, and to provide traceability on links where replication and loss happen, in a manner that is abstract to the forwarding information, whereas a 6LoRH for BitStrings [[I-D.thubert-6lo-bier-dispatch](#)] proposes a 6LoWPAN compression for the BIER Bitstring based on 6LoWPAN Routing Header [[RFC8138](#)].
- o The security model and in particular the join process depends on the ANIMA [[ANIMA](#)] Bootstrapping Remote Secure Key Infrastructures (BRSKI) [[I-D.ietf-anima-bootstrapping-keyinfra](#)] in order to enable zero-touch security provisioning; for highly constrained nodes, a minimal model based on pre-shared keys (PSK) is also available.
- o The current charter positions 6TiSCH on IEEE Std 802.15.4 only. Though most of the design should be portable on other link types, 6TiSCH has a strong dependency on IEEE Std 802.15.4 and its evolution. The impact of changes to TSCH on this Architecture should be minimal to non-existent, but deeper work such as 6top and security may be impacted. A 6TiSCH Interest Group at the IEEE maintains the synchronization and helps foster work at the IEEE should 6TiSCH demand it.
- o Work is being proposed at IEEE (802.15.12 PAR) for an LLC that would logically include the 6top sublayer. The interaction with the 6top sublayer and the Scheduling Functions described in this document are yet to be defined.

- o ISA100 [[ISA100](#)] Common Network Management (CNM) is another external work of interest for 6TiSCH. The group, referred to as ISA100.20, defines a Common Network Management framework that should enable the management of resources that are controlled by heterogeneous protocols such as ISA100.11a [[ISA100.11a](#)], WirelessHART [[WirelessHART](#)], and 6TiSCH. Interestingly, the establishment of 6TiSCH Deterministic paths, called Tracks, are also in scope, and ISA100.20 is working on requirements for DetNet.

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