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An Architecture for IPv6 over Timeslotted Channel Hopping
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Abstract

This document presents an architecture for an IPv6 multilink subnet that is composed of a high speed powered backbone and a number of IEEE802.15.4e TSCH wireless networks attached and synchronized by Backbone Routers. Route Computation may be achieved in a centralized fashion by a Path Computation Element, in a distributed fashion using the Routing Protocol for Low Power and Lossy Networks, or in a mixed mode. The Backbone Routers perform proxy Neighbor discovery operations over the backbone on behalf of the wireless device, so they can share a same subnet and appear to be connected to the same backbone as classical devices.

Requirements Language

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 RFC 2119 [RFC2119].

material or to cite them other than as "work in progress."

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Table of Contents

1. Introduction

The emergence of radio technology enabled a large variety of new types of devices to be interconnected, at a very low marginal cost compared to wire, at any range from Near Field to interplanetary distances, and in circumstances where wiring could be less than practical, for instance rotating devices.

At the same time, a new breed of Time Sensitive Networks is being developped to enable traffic that is highly sensitive to jitter and quite sensitive to latency. Such traffic is not limited to voice and video, but also includes command and control operations such as found in industrial automation or in-vehicule sensors and actuators.

At IEEE802.1, the "Audio/Video Task Group", was renamed TSN for Time Sensitive Networking to address Deterministic Ethernet. The IEEE802.15.4 Medium Access Control (MAC) has evolved with IEEE802.15.4e that provides in particular the Timeslotted Channel Hopping (TSCH) mode for industrial-type applications.

Though at a different time scale, both standards provide Deterministic capabilities to the point that a packet that pertains to a certain flow will cross the network from node to node following a very precise schedule, like a train leaves intermediate stations at precise times along its path. The time slotted aspect reduces collisions, and saves energy, and enables to more closely engineer the network for deterministic properties. The channel hopping aspect is a simple and efficient technique to get around statistical interference by WiFi emitters.

This document presents an architecture for an IPv6 multilink subnet that is composed of a high speed powered backbone and a number of IEEE802.15.4e TSCH wireless networks attached and synchronized by backbone routers. Route Computation may be achieved in a centralized fashion by a Path Computation Element (PCE), in a distributed fashion using the Routing Protocol for Low Power and Lossy Networks (RPL), or in a mixed mode. The Backbone Routers perform proxy Ipv6 Neighbor Discovery (ND) operations over the backbone on behalf of the wireless devices, so they can share a same IPv6 subnet and appear to be connected to the same backbone as classical devices.

2. Terminology

The draft uses terminology defined in [I-D.palattella-6tsch-terminology], [I-D.chakrabarti-nordmark-6man-efficient-nd], [RFC5191] and [RFC4080].

It conforms to the terms and models described for IPv6 in [RFC5889] and uses the vocabulary and the concepts defined in [RFC4291] for IPv6.

3. Applications and Goals

The architecture derives from existing industrial standards for Process Control by its focus on Deterministic Networking, in particular with the use of the IEEE802.15.4e TSCH MAC and the centralized path computation element. This approach leverages the TSCH MAC benefits for high reliability against interference, low-power consumption on deterministic traffic, and its Traffic Engineering capabilities. Deterministic Networking applies in particular to open and closed control loops, as well as supervisory control flows, and management.

Additional industrial use cases are addressed with the addition of a more autonomic and distributed routing based on RPL. These use cases 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.

A Backbone Router is included in order to scale the factory plant subnet to address large deployments, with proxy ND and time synchronization over a high speed backbone.

The architecture also applies to building automation that leverage RPL's storing mode to address multipath over a large number of hops, in-vehicule 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.).

4. Overview and Scope

The scope of the present work is a subnet that, in its basic configuration, is made of a IEEE802.15.4e Timeslotted Channel Hopping (TSCH) [I-D.watteyne-6tsch-tsch-lln-context] MAC Route-Over Low Power Lossy Network (LLN).

```
            +-----+
            |     | LLN Border
            |     | router
            +-----+
          o    o   o
   o     o   o     o
      o   o LLN   o    o     o
         o   o   o       o
                 o
```

The LLN devices communicate over IPv6 [RFC2460] using the 6LoWPAN Header Compression (6LoWPAN HC) [RFC6282]. From the Layer 3 perspective, a single LLN interface (typically an IEEE802.15.4 radio) may be seen as a collection of Links with different capabilities for unicast or multicast services. An IPv6 subnet will span over multiple links, effectively forming a multilink subnet. Within that subnet, Neighbor Devices are discovered with 6LoWPAN Neighbor Discovery (6LoWPAN ND) [RFC6775]. The Routing Protocol for Low Power and Lossy Networks (RPL) [RFC6550] enables routing within the LLN, typically within the multilink subnet in the so called Routing Over fashion. 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 LLN device, usually powered, acts as RPL root, 6LoWPAN HC terminator, and LLN Border Router (LBR) to the outside.

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]. The backbone can also support Efficiency aware IPv6 Neighbor Discovery Optimizations [I-D.chakrabarti-nordmark-6man-efficient-nd] in mixed mode as described in [I-D.thubert-6lowpan-backbone-router].

Security is often handled at layer 2 and Layer 4. Authentication during the join process is handled with the Protocol for Carrying Authentication for Network Access (PANA) [RFC5191].

The LLN devices are time-synchronized at MAC level. The MAC coordinator that serves as time source is loosely coupled with the RPL parent; this way, the time synchronization starts at the RPL root and follows the RPL DODAGs with no timing loop.

In the extended configuration, the functionality of the LBR is enhanced to that of Backbone Router (BBR). A BBR is an LBR, but also an Energy Aware Default Router (NEAR) as defined in [I-D.chakrabarti-nordmark-6man-efficient-nd]. The BBR performs ND proxy operations between the registered devices and the classical ND devices that are located over the backbone. 6TSCH BBRs 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 (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.

```
            ---+------------------------
               |      External Network
               |
            +-----+                  +-----+
            |     | Router           |     | PCE
            |     |                  |     |
            +-----+                  +-----+
               |                        |
               |     Subnet Backbone    |
         +--------------------+------------------+
         |                    |                  |
      +-----+             +-----+             +-----+
      |     | Backbone    |     | Backbone    |     | Backbone
 o    |     | router      |     | router      |     | router
      +-----+             +-----+             +-----+
 o                  o                   o                 o   o
     o    o   o         o   o  o   o         o  o   o    o
o             o        o  LLN      o      o         o      o
   o   o    o      o      o o     o  o   o    o    o     o
```

The main architectural blocks are arranged as follows:

```
     +-----+-----+-----+-----+-------+-----+
     |PCEP |   CoAP    |PANA |6LoWPAN| RPL |
     | PCC |DTLS |     |     |   ND  |     |
     +-----+-----+-----+-----+-------+-----+-----+
     | TCP |       UDP       |    ICMP     |RSVP |
     +-----+-----+-----+-----+-------+-----+-----+
     |                 IPv6                      |
     +-------------------------------------------+
     |               6LoWPAN HC                  |
     +-------------------------------------------+
     |                   6top                    |
     +-------------------------------------------+
     |             802.15.4e   TSCH              |
     +-------------------------------------------+
```

RPL is the routing protocol of choice for LLNs. (TBD RPL) whether there is a need to define a 6TSCH OF.

(tbd NME) COMAN is working on network Management for LLN. They are considering the Open Mobile Alliance (OMA) Lightweight M2M (LWM2M) Objet system. This standard includes DTLS, CoAP (core plus the Block and Observe patterns), SenML and CoAP Resource Directory.

(tbd PCC) need to work with PCE WG to define flows to PCE, and define how to accomodate PCE routes and reservation. Will probably look a lot like GMPLS

(tbd Backbone Router) need to work with 6MAN to define ND proxy. Also need BBR sync sync between deterministic ethernet and 6TSCH

LLNs.

IEEE802.1TSN: external, maintain consistency.

IEEE802.15.4: external, (tbd need updates?).

ISA100.20 Common Network Management: external, maintain consistency.

IoT6 European Project: external, maintain consistency.

5. Centralized vs. Distributed Routing

6TSCH supports a mix model of centralized routes that are computed by a Path Computation Entity and distributed routes that are computed by RPL over a common physical LLN.

Both RPL and the PCE may inject routes in the Routing Tables of the 6TSCH routers. In either case, each route is associated with a topology that is indexed by an instanceID, as defined in RPL [RFC6550]. RPL and PCE rely on shared sources to define Global and Local InstanceIDs.

It is possible for RPL and PCE to share a same topology, in which case the PCE routes have precedence over RPL routes in case of a conflict.

Inside the 6TSCH domain, the flow label is used to indicate the topology that must be used for routing and the associated Routing Tables as discussed in [I-D.thubert-roll-flow-label].

6. Forwarding Models

6TSCH supports three different forwarding model, G-MPLS Track Forwarding (TF), 6LoWPAN Fragment Forwarding (FF) and IPv6 Forwarding (6F).

6.1. Track Forwarding

Track Forwarding is the simplest and fastest. A set of input cells are uniquely bound to a set of output cells, representing a forwarding state that can be used regardless of the uppoer layer protocol. This model can effectively be seen as a G-MPLS operation in that the information used to switch is not an explicit label but related to other properties of the way the packet was received, a particular cell in the case of 6TSCH. 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 of ISA100.11a.

A Track is defined end-to-end as a succession of Timeslots and a Timeslot belongs to at most one Track. For a given iteration of a Slotframe, the Timeslot is associated uniquely with a cell which indicates the channel at which the Timeslot operates for that iteration.

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

Conversely, a frame that is received along a Track with a destination MAC address set to this node is extracted from the Track stream and delivered to the upper layer. A frame with an unrecognized MAC address is just ignored at the MAC layer and thus is not received at the 6top sublayer.

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

6.1.1. Transport Mode

```
                       |                                    ^
     +--------------+    |                                    |
     |     IPv6     |    |                                    |
     +--------------+    |                                    |
     |  6LoWPAN HC  |    |                                    |
     +--------------+  ingress                              egress
     |     6top     |   sets     +-----+         +-----+     restores
     +--------------+  dmac to   |     |         |     |     dmac to
     |   TSCH MAC   |   brdcst   |     |         |     |      self
     +--------------+    |       |     |         |     |       |
     |   LLN PHY    |    +-------+     +--...-----+     +-------+
     +--------------+
```

In transport mode, the PDU is associated with flow information that refers uniquely to the Track, so the 6top sublayer can place the frame in the appropriate Timeslot without ambiguity. In the case of IPv6 traffic, the identification of that flow information is transported in the Flow Label in 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 dmac and punting to the upper layer.

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 perfectly synchronized with the 6TSCH network. An example of this would be a router with a dual radio that is capable to receive and send WirelessHART or ISA100.11a frames with the second radio, by presenting itself as an Access Point or a Backbone Router, respectively.

In that mode, the PCE may coordinate with a WirelessHART Network Manager or an ISA100.11a System Manager in order to specify the flows that are to be transported transparently over the Track.

```
        +--------------+
        |     IPv6     |
        +--------------+
        |  6LoWPAN HC  |
        +--------------+          set            restore
        |     6top     |         +dmac+          +dmac+
        +--------------+         |    |          |    |
        |   TSCH MAC   |         |    |          |    |
        +--------------+         |    |          |    |
        |   LLN PHY    |    +-------+    +--...-----+    +-------+
        +--------------+    |   ingress                egress   |
                            |                                   |
        +--------------+    |                                   |
        |   LLN PHY    |    |                                   |
        +--------------+    |                                   |
        |   TSCH MAC   |    |                                   |
        +--------------+    |                                   |
        |ISA100/WiHART |    |                                   v
        +--------------+
```

In that case, the flow information that identifies the Track is uniquely derived from the information at the receiving end, for instance the incoming Timeslots, or an ISA100.11a ContractId. At the ingress 6TSCH router, the packet destination is recognized as self but the flow information indicates that the frame must be tunneled over a particular 6top Track so the packet is not punted to upper layer. Instead, it is passed to the 6top sublayer for switching. The 6top sublayer in the ingress router overrides the destination MAC to broadcast and forwards.

At the egress 6top 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.

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 acces 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.

6.2. Fragment Forwarding

Considering that 6LoWPAN packets can be as large as 1280 bytes, which is the IPv6 MTU, and that the non-storing mode of RPL implies Source Routing that requires space for routing headers, and that a 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 6TSCH network, Hop-by-Hop recomposition would occur at each hop in order to reform the packet and route it. This creates additional latency and forces intermediate nodes to store a portion of a packet for an indetermined time, thus impacting critical resources such as memory and battery.

[I-D.thubert-roll-forwarding-frags] describes a mechanism whereby the datagram tag in the 6LoWPAN Fragment is used as a label for switching at the 6LoWPAN sublayer. The draft allows for a degree of flow control base on an Explicit Congestion Notification, as well as end-to-end individual fragment recovery. In that model, the first fragment is routed based on the IPv6 header that is present in that fragment.

```
                           |                                    ^
           +--------------+   |                                    |
           |     IPv6     |   |       +----+          +----+       |
           +--------------+   |       |    |          |    |       |
           |  6LoWPAN HC  |   |       learn           learn        |
           +--------------+   |       |    |          |    |       |
           |     6top     |   |       |    |          |    |       |
           +--------------+   |       |    |          |    |       |
           |   TSCH MAC   |   |       |    |          |    |       |
           +--------------+   |       |    |          |    |       |
           |   LLN PHY    |   +-------+    +--...-----+    +-------+
           +--------------+
```

The 6LoWPAN sublayer learns the next hop selection, generates a new datagram tag for transmission to the next hop, and stores that information indexed by the incoming MAC address and datagram tag. The next fragments are then switched based on that stored state.

```
                           |                                    ^
           +--------------+   |                                    |
           |     IPv6     |   |                                    |
           +--------------+   |                                    |
           |  6LoWPAN HC  |   |       replay          replay       |
           +--------------+   |       |    |          |    |       |
           |     6top     |   |       |    |          |    |       |
           +--------------+   |       |    |          |    |       |
           |   TSCH MAC   |   |       |    |          |    |       |
           +--------------+   |       |    |          |    |       |
           |   LLN PHY    |   +-------+    +--...-----+    +-------+
           +--------------+
```

A bitmap and an ECN echo in the end-to-end acknowledgement 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.

6.3. IPv6 Forwarding

As the packets are routed at layer 3, traditional QoS and RED operations are expected to prioritize flows with differentiated services. A new class of service for Deterministic Forwarding is being defined to that effect in [I-D.svshah-tsvwg-lln-diffserv-recommendations].

```
                               |                                    ^
           +--------------+    |                                    |
           |     IPv6     |    |       +-QoS+          +-QoS+       |
           +--------------+    |       |    |          |    |       |
           |  6LoWPAN HC  |    |       |    |          |    |       |
           +--------------+    |       |    |          |    |       |
           |     6top     |    |       |    |          |    |       |
           +--------------+    |       |    |          |    |       |
           |   TSCH MAC   |    |       |    |          |    |       |
           +--------------+    |       |    |          |    |       |
           |   LLN PHY    |    +-------+    +--...-----+    +-------+
           +--------------+
```

7. Functional Flows

8. Network Synchronization

Nodes in a TSCH are time synchronized. A node keeps synchronized to its time source neighbor(s) 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 synch 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 the Device Management Entity.

9. TSCH and 6top

9.1. 6top

6top is a sublayer which is the next higher layer to TSCH and which offers a set of commands defining data and management interfaces. 6top is defined in [I-D.draft-wang-6tsch-6top]

The management interface of 6top enables an upper layer to schedule cells and Slotframes in the TSCH schedule.

If the scheduling entity explicitly specifies the slotOffset/channelOffset of the cells to be added/deleted, those cells are marked as "hard". 6top cannot move hard cells in the TSCH schedule. Hard cells are typically used by an central PCE.

6top contains a monitoring process which monitors the performance of cells, and can move a cell in the TSCH schedule when it performs bad. This is only applicable to cells which are marked as "soft". To reserve a soft cell, the higher layer does not indicate the 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 motes communicating over this cell negociate its new position in the TSCH schedule.

9.2. Slotframes and Priorities

6top uses priority queues to manage concurrent data flows of different priorities. When a packet is received from an higher layer for transmission, the I-MUX module of 6top inserts that packet in the outgoing queue which matches the packet best (DSCP can therefore be used). At each scheduled transmit slot, the MUX module looks for the frame in all the outgoing queues that best matches the cells. If a frame is found, it is given to TSCH for transmission.

9.3. Centralized Flow Reservation

In a centralized setting, a PCE computes the TSCH schedule, and communicates with the different nodes in the network to configure their TSCH schedule. Since it has full knowledge of the network's topology, the PCE can compute a collision-free schedule, which results in a high degree of communication determinism.

The protocol for the PCE to communicate with the motes is not yet defined. This protocol typically reserves hard cells on the transmitter side of a dedicated cell, and the negociation protocol of 6top takes care of reserving the same cell on the receiver node.

9.4. Distributed Flow Reservation

In a distributed setting, no central PCE in present in the network. Nodes use 6top to reserve soft cells with their neighbors. Since no node has full knowledge of the network's topology and the traffic requirements, scheduling collisions are possible, for example because of a hidden terminal problem.

A schedule collision can be detected if two motes have multiple dedicated cells schedule to one another. The monitoring process of 6top can be configured to continuously compute the packet delivery ratio of those cells, and it can declare a soft cell to perform bad when the statistics for that cell are significantly worse than for the other cells to the same neighbor.

When this happens, the monitoring process of 6top moves the cell to another location in the 6TSCH schedule, through a re-negociation procedure with the neighbor.

The entity that builds and maintains the schedule in a distributed fashion is not yet defined.

9.5. Packet Marking and Handling

```
              ---+----------------
       Sender                                            Receiver
    +-----------+     +-----+     +-----+      +-----+      +-----------+
    |Application|---->| R1  |---->| R2  |----->|BBR  |----->|Application|
    |   +--+    |     |+--+|     |+--+|      |+--+|      |   +--+    |
    |   |NE|====|=====||NE||=====||NE||======||NE||======|===|NE|    |
    |   +--+    |     |+--+|     |+--+|      |+--+|      |   +--+    |
    |    |^     |     | |^ |     | |^ |      | |^ |      |    |^     |
    |    v|     |     | v| |     | v| |      | v| |      |    v|     |
    |   +--+    |     |+--+|     |+--+|      |+--+|      |   +--+    |
    |   |6T|    |     ||6T||     ||6T||      ||6T||      |   |6T|    |
    |   |us|    |     ||us||     ||us||      ||us||      |   |us|    |
    |   +--+    |     |+--+|     |+--+|      |+--+|      |   +--+    |
    +-----------+     +-----+     +-----+      +-----+      +-----------+

       +--+
       |NE| = NSIS      ==== = Signaling    ---> = Data flow messages
       +--+   Entity           Messages           (unidirectional)

       +--+
       |6T|   6top layer
       |us| (and IEEE802.15.4e TSCH MAC below)
       +--+
```

reservation Deterministic flow allocation (hard reservation of Timeslots) eg centralized RSVP? metrics? Hop-by-hop interaction with 6top. Lazy reservation (use shared slots to transport extra burst and then dynamically (de)allocate) Classical QoS (dynamic based on observation)

10. Management

11. IANA Considerations

This specification does not require IANA action.

12. Security Considerations

This specification is not found to introduce new security threat.

13. Acknowledgements

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