

6TiSCH
-Draft
Standards Track

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Cisco Intended status:

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February 14, 2014 An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4e draft-ietf-6tisch-architecture-01 Abstract This document presents an architecture for an IPv6 Multi-Link 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. The TSCH schedule can be static or dynamic. 6TiSCH defines mechanisms to establish and maintain the routing and scheduling operations in a centralized, distributed, or mixed fashion. Backbone Routers perform proxy Neighbor Discovery operations over the backbone on behalf of the wireless devices, 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]. Status of this Memo This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79. Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <http://datatracker.ietf.org/drafts/current/>. Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress." This Internet-Draft will expire on August 16, 2014. Copyright Notice Thubert, Watteyne & Assimi Expires August 16, 2014 [Page 1]

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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 would be less than practical, for instance rotating devices. At the same time, a new breed of Time Sensitive Networks is being developed 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-vehicle 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 crosses the network from node to node following a very precise schedule, as a train that leaves intermediate stations at precise times along its path. With TSCH, time is formatted into timeslots, and an individual timeslot is 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 external interference (for example by WiFi emitters). This document presents an architecture for an IPv6 Multi-Link 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 Thubert, Watteyne & Assi Expires August 16, 2014

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. Timeslots and other device resources are managed by an abstract Network Management Entity (NME) that may cooperate with the PCE in order to minimize the interaction with and the load on the constrained device.

2. Terminology Readers are expected to be familiar with all the terms and concepts that are discussed in "neighbor Discovery for IP version 6" [RFC4861], "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals" [RFC4919], neighbor Discovery Optimization for Low-power and Lossy Networks [RFC6775] and "Multi-link Subnet Support in IPv6" [I-D.ietf-ipv6-multilink-subnets]. Readers may benefit from reading the "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks" [RFC6550] specification; "Multi-Link Subnet Issues" [RFC4903]; "Mobility Support in IPv6" [RFC6275]; "neighbor Discovery Proxies (ND Proxy)" [RFC4389]; "IPv6 Stateless Address Autoconfiguration" [RFC4862]; "FCFS SAVI: First-Come, First-Served Source Address Validation Improvement for Locally Assigned IPv6 Addresses" [RFC6620]; and "Optimistic Duplicate Address Detection" [RFC4429] prior to this specification for a clear understanding of the art in ND-proxying and binding. The draft uses terminology defined or referenced in [I-D.ietf-6tisch-terminology], [I-D.chakrabarti-nordmark-6man-efficient-nd], [I-D.ietf-roll-rpl-industrial-applicability], [RFC5191] and [RFC4080]. 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.

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 [IEEE802154e] and the centralized PCE. 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.

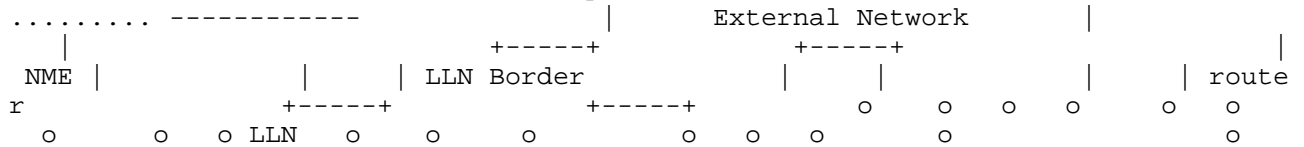
An incremental set of industrial requirements are addressed with the addition of an autonomic and distributed routing operation based on RPL. These use cases include plant setup and decommissioning, as well as monitoring of lots of lesser importance measurements such as

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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-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.).

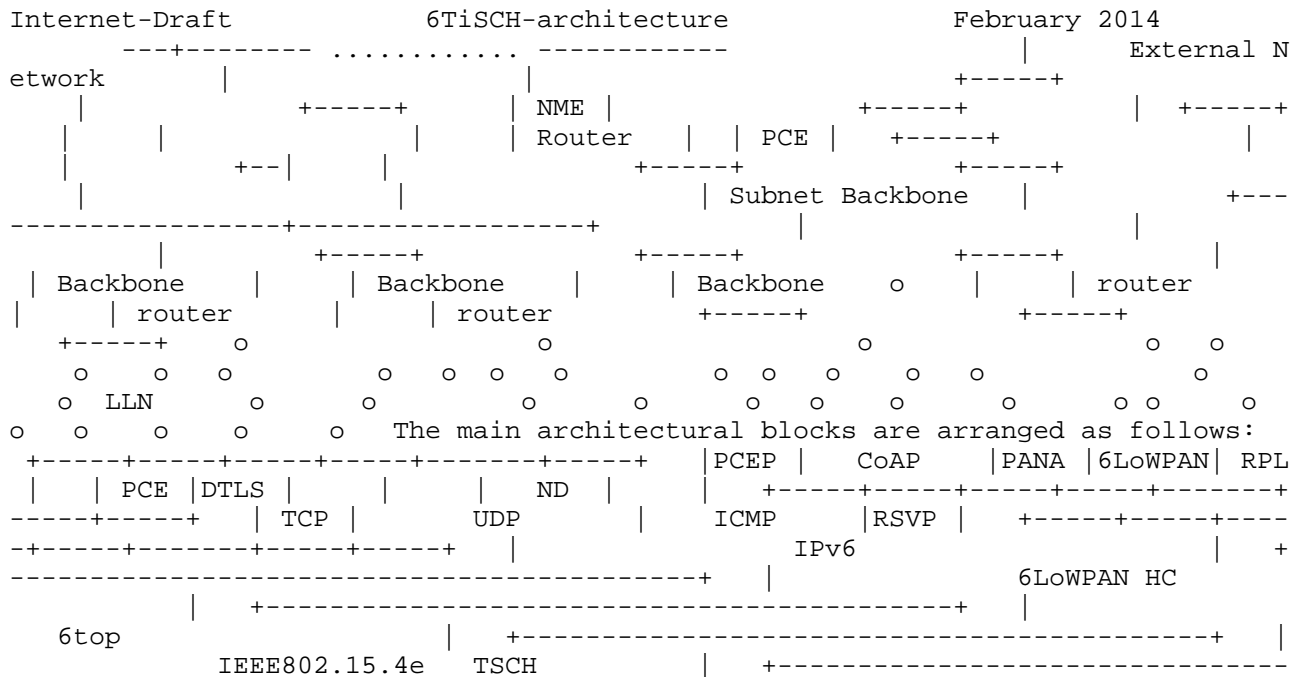
4. Overview and Scope

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.ietf-6tisch-tsch] MAC Low Power Lossy Network (LLN).



The LLN devices communicate over IPv6 [RFC2460] using the 6LoWPAN Header Compression (6LoWPAN HC) [RFC6282]. From the perspective of Layer 3, a single LLN interface (typically an IEEE802.15.4-compliant radio) may be seen as a collection of Links with different capabilities for unicast or multicast services. A single IPv6 subnet spans over multiple links, effectively forming a Multi-Link subnet. Within that subnet, neighbor Devices are discovered with 6LoWPAN neighbor Discovery (6LoWPAN ND) [RFC6775]. RPL [RFC6550] enables routing within the LLN, typically within the Multi-Link subnet in the so called Route 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 Thubert, Watteyne & Assi Expires August 16, 2014

ng topology. A particular LLN device, the LLN Border Router (LBR), acts as RPL root, 6LoWPAN HC terminator, and LLN Border Router (LBR) to the outside. The LBR is usually powered. More on RPL Instances can be found in RPL [RFC6550], sections "3.1.2. RPL Identifiers" and "3.1.3. Instances, DODAGs, and DODAG Versions". 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 can be handled by the Protocol for Carrying Authentication for Network access (PANA) [RFC5191]. The LLN devices are time-synchronized at the MAC level. The LBR that serves as time source is a RPL parent in a particular RPL instance that serves for time synchronization; 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. 6TiSCH 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. Thubert, Watteyne & Assi Expires August 16, 2014



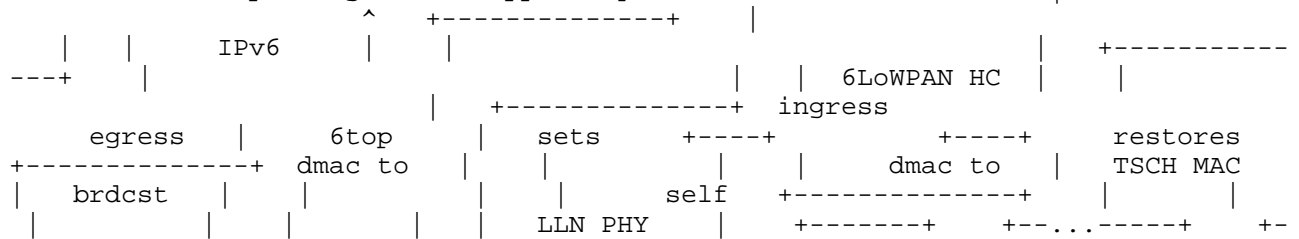
The main architectural blocks are arranged as follows:

RPL is the routing protocol of choice for LLNs. (TBD RPL) whether there is a need to define a 6TiSCH OF. (tbd NME) COMAN is working on network Management for LLN. They are considering the Open Mobile Alliance (OMA) Lightweight M2M (LWM2M) Object system. This standard includes DTLS, CoAP (core plus Block and Observe patterns), SenML and CoAP Resource Directory. (tbd PCE) need to work with PCE WG to define flows to PCE, and define how to accommodate PCE routes and reservation. Will probably look a lot like GMPLS. Thubert, Watteyne & Assi Expires August 16, 2014 [Page 7]

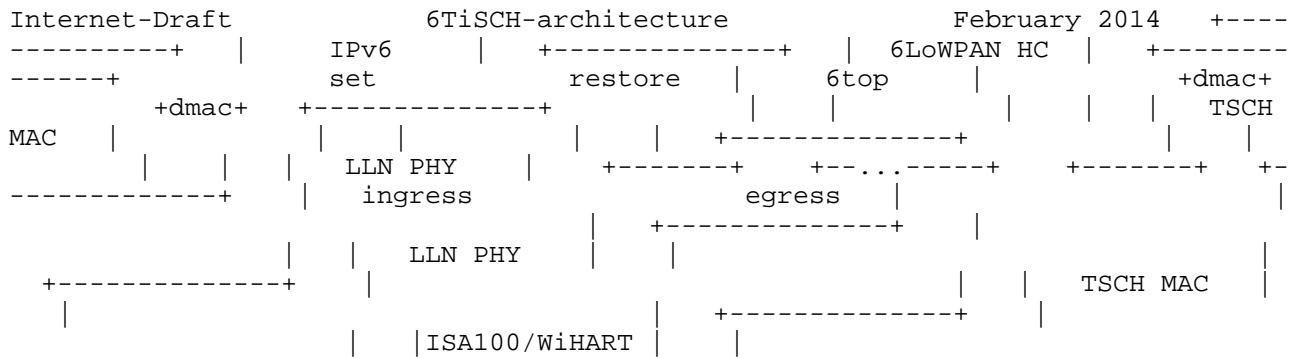
PANA) There is a debate whether PANA (layer 3) or IEEE802.1x (layer 2) should be used in the join process. There is also a debate whether the node should be able to send any unprotected packet on the medium. Regardless, the security model must ensure that, prior to a join process, packets from a untrusted device must be controlled in volume and in reachability. (tbd Backbone Router) need to work with 6MAN to define ND proxy. Also need BBR sync between deterministic Ethernet and 6TiSCH LLNs. IEEE802.1TSN: external, maintain consistency. See also AVnu. IEEE802.15.4: external, (tbd need updates?). ISA100.20 Common Network Management: external, maintain consistency. The 6TiSCH Operation sublayer (6top) [I-D.wang-6tisch-6top-sublayer] is an Logical Link Control (LLC) or a portion thereof that provides the abstraction of an IP link over a TSCH MAC.5. 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. [I-D.roll-rpl-industrial-applicability] section 2.1.3. and next discusses application-layer paradigms, such as Source-sink (SS) that is a Multipeer to Multipeer (MP2MP) model that is 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 IEEE802.15.4e TSCH wireless networks with [ISA100.11a] and [HART].Thubert, Watteyne & Assi Expires August 16, 2014 [Page 8]

This specification focuses on Communication Paradigms and Interaction Models for packet forwarding and TSCH resources (cells) management. Link-layer and Network-layer Packet forwarding interactions are discussed in Section 6, whereas Link-layer (one-hop), Network-layer (multithop along a track), and Application-layer (remote control) management mechanisms for the TSCH schedule are discussed in Section 8.6. Forwarding Models 6TiSCH 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 upper 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 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 Track is defined end-to-end as a succession of timeslots. 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 data frame that is forwarded along a Track has a destination MAC address 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 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 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 ModeThubert, Watteyne & AssiExpires August 16, 2014

In transport mode, the PDU is associated 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, 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.

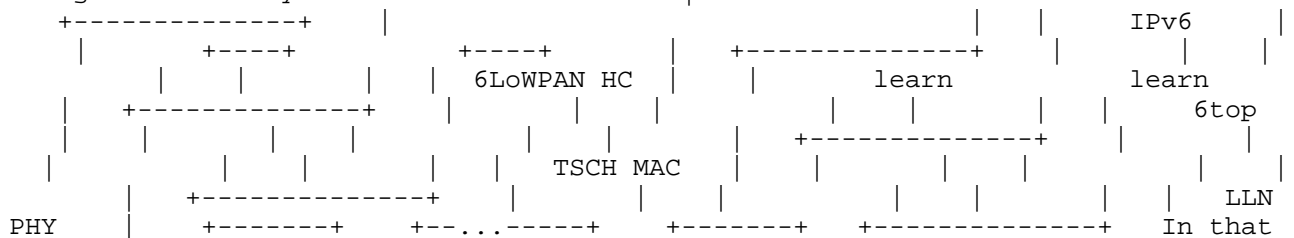


6.1.2. Tunnel Mode In tunnel mode, the frames originate from an arbitrary protocol over a compatible MAC that may or may not be synchronized with the 6TiSCH network. An example of this would be a router with a dual radio that is capable of receiving and sending WirelessHART or ISA100.11a frames with 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.



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 6TiSCH 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 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 revertsThubert, Watteyne & AssiExpires August 16, 2014 [Page 11]

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 (the IPv6 MTU), and that the non-storing mode of RPL implies Source Routing that requires space for routing headers, and that a IEEE802.15.4 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 recombination occurs 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 undetermined 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 based 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. 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. Thubert, Watteyne & Assi Expires August 16, 2014 [Page 12]

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 [I-D.wang-6tisch-6top-sublayer]. 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 Section 8.2. The 6top data model and management interfaces are further discussed in Section 8.3. 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 for example used by a 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 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 nodes communicating over this cell negotiate its new position in the TSCH schedule.7.2.

6top and RPL Objective Function operations An implementation of a RPL [RFC 6550] Objective Function (OF), such as the RPL Objective Function Zero (OF0) [RFC 6552] that is used in the Minimal 6TiSCH Configuration [I-D.ietf-6tisch-minimal] to support RPL over a static schedule, may leverage, for its internal computation, the information maintained by 6top. In particular, 6top creates and maintains an abstract neighbor table. A neighbor table entry contains a set of statistics with respect to that specific neighbor including the ASN when the last packet has been received from that neighbor, a set of cell quality metrics (RSSI, 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 as detailed in the 6top sublayer specification [I-D.wang-6tisch-6top-sublayer] and used 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 EBs. By augmenting the EB periodicity, it is possible to change the network dynamics so as to improve the support of mobile devices.

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Some RPL control messages, such as the DODAG Information Object (DIO) are broadcast to all neighbor nodes. The broadcast channel requirement is addressed by 6top by configuring TSCH to provide such a channel, as opposed to, for instance, carrying DIO messages in Enhance Beacons. In the TSCH schedule, each cell has the LinkType attribute. Setting the LinkType to ADVERTISING indicates that the cell MAY be used to send an Enhanced Beacon. When a node forms its Enhanced Beacon, the cell, with LinkType=ADVERTISING, SHOULD be included in the FrameAndLinkIE, and its LinkOption field SHOULD be set to the combination of "Receive" and "Timekeeping". The receiver of the Enhanced Beacon MAY be listening at the cell to get the Enhanced Beacon ([IEEE802154e]). 6top takes this way to establish broadcast channel, which not only allows TSCH to broadcast Enhanced Beacons, but also allows an upper layer like RPL. To support DIO and DAO broadcasts, 6top uses the payload of a Data Packet to carry the DIO or DAO. The message is inserted into the queue associated with the cells which LinkType is set to ADVERTISING. Then, taking advantage of the broadcast cell feature established with FrameAndLinkIE (as described above), the data packet with DIO or DAO in the payload can be received by neighbors, which enforces the maintenance of DODAG. A LinkOption combining "Receive" and "Timekeeping" bits indicates to the receivers of the Enhanced Beacon that the cell MUST be used as a broadcast cell. The frequency of sending Enhanced Beacons or other broadcast messages by the upper layer is determined by the timers associated with the messages. For example, the transmission of Enhance Beacons is triggered by a timer in 6top; transmission of a DIO message is triggered by the trickle timer of RPL.7.3. 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 acknowledgement-based synchronization. In order to maximize battery life and network throughput, it is advisable that RPL ICM P 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.

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distribution requires a loop-less 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 RPL [RFC6550] section "3.1.3. 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. A node that has not joined the TSGI advertises a MAC level Join Priority of 0xFF to notify its neighbors that it 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 [RFC6550], section "3.5.1. Rank Comparison". A root is configured or obtains by some external means the knowledge of the RPL InstanceID for the TSGI. The root advertises its DagRank in the TSGI, that MUST be less than 0xFF, as its Join Priority (JP) in its IEEE802.15.4e Extended Beacons (EB). We'll note that the JP is now specified between 0 and 0x3F leaving 2 bit sin the octet unused in the IEEE802.15.4e 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.7.4. Scheduling 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.7.5. Packet Marking and HandlingThubert, Watteyne & AssiExpires August 16, 2014 [Page 16]

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)7.6. Distributing the reservation of timeslots 6TiSCH expects a high degree of scalability together with a distributed routing functionality based on the RPL routing protocol. 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 link abstraction is implemented as a bundle of cells; 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 an abstract channel usage/distribution (CUD) matrix of timeslots within its interference domain. 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 CUD 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 chunks is the basic unit of ownership that is used in that process. Thubert, Watteyne & Assi Expires August 16, 2014

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 scheduled can be preconfigured or learnt by a node when joining the network. Regardless, the schedule remains unchanged after the node has joined a network. The Routing Protocol for LLNs (RPL) is used on the resulting network. This "minimal" scheduling mechanism that implements this paradigm is detailed in [I-D.ietf-6tisch-minimal].8.2. Neighbor-to-neighbor Scheduling In the simplest instantiation of a 6TiSCH network described in Section 8.1, 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 emissions will be destroyed. If the size is configured to allow for peak emissions, energy is be wasted idle listening.

In the most efficient instantiation of a 6TiSCH network, the size of the bundles that implement the links may be changed dynamically in order to adapt to the need of end-to-end flows routed by RPL. An optional On-The-Fly (OTF) component may be used to monitor bandwidth usage and perform requests for dynamic allocation by the 6top sublayer. The OTF 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. The 6top sublayer [I-D.wang-6tisch-6top-sublayer] defines a protocol for neighbor nodes to reserve soft cells to one another. Because this reservation is done without global knowledge of the schedule of nodes in the LLN, scheduling collisions are possible. 6top defines a monitoring process which continuously tracks the packet delivery ratio of soft cells. It uses these statistics to trigger the relocation of a soft cell in the schedule, using a negotiation protocol between the neighbors nodes communicating over that cell. Monitoring and relocation is done in the 6top layer. For the upper layer, the connection between two neighbor nodes appears as a 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.8.3. Remote Monitoring and Schedule ManagementThubert, Watteyne & AssiExpires August 16, 2014

top interface document [I-D.wang-6tisch-6top-interface] specifies the generic data model that can be used to monitor and manage resources at the 6top sublayer. Abstract methods are suggested for use by a management entity in the device. The data model also enables remote control operations on the 6top sublayer. Being able to interact with the 6top sublayer of a node multiple hops away can be used for monitoring, scheduling, or a combination of both. The architecture supports variations on the deployment model, and focuses on the flows rather than whether there is a proxy or a translational operation on the way.

[I-D.sudhaakar-6tisch-coap] defines an mapping of 6top's set of commands described in [I-D.wang-6tisch-6top-interface] to CoAP resources. This allows an entity to interact with the 6top layer of a node that is multiple hops away in a RESTful fashion. [I-D.sudhaakar-6tisch-coap] defines a basic set CoAP resources and associated RESTful access methods (GET/PUT/POST/DELETE). The payload

(body) of the CoAP messages is encoded using the CBOR format. The draft also defines the concept of "profiles" to allow for future or specific extensions, as well as a mechanism for a CoAP client to discover the profiles installed on a node. 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 an external device monitoring the overall state of the network (e.g. NME). The architecture allows for different types of interactions between this CoAP client and a node in the network:8.4. Hop-by-hop Scheduling A node can reserve a track 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 similar to [RFC2119] and [RFC5974]. The protocol for a node to trigger hop-by-hop scheduling is not yet defined.9. Centralized vs. Distributed Routing 6TiSCH supports a mixed model of centralized routes and distributed routes. Centralized routes can for example be computed by an entity such as a PCE. Distributed routes are computed by the RPL routing protocol.Thubert, Watteyne & AssiExpires August 16, 20

may inject routes in the Routing Tables of the 6TiSCH routers. In either case, each route is associated with a topology that is indexed by an RPLInstanceID, as defined in RPL [RFC6550]. RPL and PCE rely on shared sources to define Global and Local RPLInstanceIDs. It is possible for centralized and distributed routing to share a same topology. In this case, centralized routes have precedence over distributed routes in case of conflict. Inside the 6TiSCH domain, the flow label is used to indicate the topology that must be used for routing. The associated Routing Tables are discussed in [I-D.thubert-roll-flow-label].10. IANA Considerations This specification does not require IANA action.11.

Security Considerations This specification is not found to introduce new security threat.12. Acknowledgements13. References13.1. Normative References [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, March 1997. [RFC2460] Deering, S.E. and R.M. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, December 1998. [RFC3444] Pras, A. and J. Schoenwaelder, "On the Difference between Information Models and Data Models", RFC 3444, January 2003. [RFC4080] Hancock, R., Karagiannis, G., Loughney, J. and S. Van den Bosch, "Next Steps in Signaling (NSIS): Framework", RFC 4080, June 2005. [RFC4291] Hinden, R. and S. Deering, "IP Version 6 Addressing Architecture", RFC 4291, February 2006. [RFC4861] Narten, T., Nordmark, E., Simpson, W. and H. Soliman, "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861, September 2007. [RFC4862] Thomson, S., Narten, T. and T. Jinmei, "IPv6 Stateless Address Autoconfiguration", RFC 4862, September 2007. Thubert, Watteyne & Assi Expires August 16, 2014 [Page 21]

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