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6TiSCH Minimal Scheduling Function (MSF)
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Abstract

This specification defines the 6TiSCH Minimal Scheduling Function (MSF). This Scheduling Function describes both the behavior of a node when joining the network, and how the communication schedule is managed in a distributed fashion. MSF builds upon the 6TiSCH Operation Sublayer Protocol (6P) and the Minimal Security Framework for 6TiSCH.

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 [RFC2119].

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on January 3, 2019.

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1. Introduction

The 6TiSCH Minimal Scheduling Function (MSF), defined in this specification, is a 6TiSCH Scheduling Function (SF). The role of an SF is entirely defined in [I-D.ietf-6tisch-6top-protocol]: it complements [I-D.ietf-6tisch-6top-protocol] by providing the rules of when to add/delete cells in the communication schedule. The SF defined in this document follows that definition, and satisfies all the requirements for an SF listed in Section 4.2 of [I-D.ietf-6tisch-6top-protocol].

MSF builds on top of the following specifications: the Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration [RFC8180], the 6TiSCH Operation Sublayer Protocol (6P) [I-D.ietf-6tisch-6top-protocol], and the Minimal Security Framework for 6TiSCH [I-D.ietf-6tisch-minimal-security].

MSF defines both the behavior of a node when joining the network, and how the communication schedule is managed in a distributed fashion. When a node running MSF boots up, it joins the network by following the 7 steps described in Section 4. The end state of the join process is that the node is synchronized to the network, has mutually authenticated to the network, has identified a preferred routing parent, has scheduled one default unicast cell to/from each of its neighbors. After the join process, the node can continuously add/delete/relocate cells, as described in Section 5. It does so for 3 reasons: to match the link-layer resources to the traffic, to handle changing parent, to handle a schedule collision.

MSF is designed to operate in a wide range of application domains. It is optimized for applications with regular upstream traffic (from the nodes to the root). Appendix C contains a performance evaluation of MSF.

This specification follows the recommended structure of an SF specification in Appendix A of [I-D.ietf-6tisch-6top-protocol], with the following adaptations:

- o We have reordered part of the sections, in particular to have the section on the node behavior at boot Section 4 appear early in this specification.
- o We added sections on the interface to the minimal 6TiSCH configuration Section 2, the use of the SIGNAL command Section 6, the MSF constants Section 14, the MSF statistics Section 15, the performance of MSF Appendix C.
- o This specification does not include an examples section.

2. Interface to the Minimal 6TiSCH Configuration

A node implementing MSF MUST implement the Minimal 6TiSCH Configuration [RFC8180], which defines the "minimal cell", a single shared cell providing minimal connectivity between the nodes in the network.

MSF uses the minimal cell to exchange the following packets:

1. Enhanced Beacons (EBs), defined by [IEEE802154-2015]. These are broadcast frames.
2. DODAG Information Objects (DIOs), defined by [RFC6550]. These are broadcast frames.

Because the minimal cell is SHARED, the back-off algorithm defined in [IEEE802154-2015] is used to resolve collisions. To ensure there is enough bandwidth available on the minimal cell, a node implementing MSF SHOULD enforce the following rules for broadcast frames:

1. send EBs on a portion of the minimal cells not exceeding 1/(3(N+1)), where N is the number of neighbors of the node.
2. send DIOs on a portion of the minimal cells not exceeding 1/(3(N+1)), where N is the number of neighbors of the node.

The RECOMMENDED behavior for sending EBs is to have a node send EBs with a probability of 1/(3(N+1)). The RECOMMENDED behavior for sending DIOs is to use a Trickle timer with rate-limiting.

Section 4.3 describes how to evaluate the number of neighbors during the joining process. After the joining process, how to evaluate the number of neighbors is implementation-specific.

As detailed in Section 2.2 of [I-D.ietf-6tisch-6top-protocol], MSF MUST schedule cells from Slotframe 1, while Slotframe 0 is used for traffic defined in the Minimal 6TiSCH Configuration. The length of Slotframe 0 and Slotframe 1 SHOULD be the same value. The default of SLOTFRAME_LENGTH is RECOMMENDED, although any value can be advertised in the EBs.

3. Autonomous Unicast Cells

MSF nodes MUST initialize Slotframe 1 with a set of default cells for unicast communication with their neighbors. These cells are referred to as 'autonomous cells', because they are maintained autonomously by each node. Each node has:

1. One cell to receive, at a [slotOffset,channelOffset] computed as a hash of the node's EUI64 (detailed next). The cell options for this cell are RX=1.
2. For each neighbor in the IPv6 neighbor table, one cell to transmit, at a [slotOffset,channelOffset] computed as a hash of the neighbor's EUI64 (detailed next). The cell options for this cell are TX=1, SHARED=1.

To compute a [slotOffset,channelOffset] from an EUI64 address, nodes MUST use the hash function SAX [SAX-DASFAA]. The coordinates are computed to distribute the cells across all 16 channel offsets, and all but the first time offsets of Slotframe 1. The first time offset is skipped to avoid colliding with the minimal cell in Slotframe 0. The slot coordinates derived from a given EUI64 address are computed as follows:

```
slotOffset(MAC) = 1 + hash(EUI64) % (length(Slotframe_1) - 1)
channelOffset(MAC) = hash(EUI64) % 16
```

Because of hash collisions, there are cases where one node has multiple cells scheduled at the same time offset and/or channel offset. Note that nodes have only one autonomous RX cell and potentially multiple TX cells. Hash collisions among a set of cells at a given time offset is resolved at run-time as follows:

1. The TX cell with the most packets in outgoing queue takes precedence.
2. If all TX cells have empty outgoing queues, the RX cell takes precedence.

Throughout the network lifetime, nodes MUST maintain the autonomous cells as follows:

1. The receive cell MUST always remain scheduled.
2. Whenever a new neighbor is discovered, add a transmit cell for it.
3. Whenever a new neighbor is removed, remove transmit cell that was assigned to it.
4. 6P CLEAR MUST NOT erase autonomous cells.

4. Node Behavior at Boot

This section details the behavior the node SHOULD follow from the moment it is switched on, until it has successfully joined the network. Section 4.1 details the start state; Section 4.9 details the end state. The other sections detail the 7 steps of the joining process. We use the term "pledge" and "joined node", as defined in [I-D.ietf-6tisch-minimal-security].

4.1. Start State

A node implementing MSF MUST implement the Minimal Security Framework for 6TiSCH [I-D.ietf-6tisch-minimal-security]. As a corollary, this means that a pledge, before being switched on, is pre-configured with the Pre-Shared Key (PSK) for joining, as well as any other configuration detailed in [I-D.ietf-6tisch-minimal-security].

4.2. Step 1 - Choosing Frequency

When switched on, the pledge SHOULD randomly choose a frequency among the available frequencies, and start listening for EBs on that frequency.

4.3. Step 2 - Receiving EBs

Upon receiving the first EB, the pledge SHOULD continue listening for additional EBs to learn:

1. the number of neighbors N in its vicinity
2. which neighbor to choose as a Join Proxy (JP) for the joining process

While the exact behavior is implementation-specific, the RECOMMENDED behavior is to follow [RFC8180], and listen until EBs sent by NUM_NEIGHBOURS_TO_WAIT nodes (defined in [RFC8180]) have been received.

During this step, the pledge MAY synchronize to any EB it receives from the network it wishes to join. How to decide whether an EB originates from a node from the network it wishes to join is implementation-specific, but MAY involve filtering EBs by the PAN ID field it contains, the presence and contents of the IE defined in [I-D.richardson-6tisch-join-enhanced-beacon], or the key used to authenticate it.

The decision of which neighbor to use as a JP is implementation-specific, and discussed in [I-D.ietf-6tisch-minimal-security].

4.4. Step 3 - Setting up Autonomous Unicast Cells

After joining, nodes MUST set up their autonomous unicast cells, as described in Section 3. This enables unicast communication in Slotframe 1, until more cells are added with 6P as defined in Section 5.

4.5. Step 4 - Join Request/Response

As per [I-D.ietf-6tisch-minimal-security], after having selected a JP, the pledge sends a Join Request to its JP. Because no dedicated cells are in place at this point, this happens on the autonomous unicast cell. The JP then forwards the Join Request to the JRC, possibly over multiple hops. When forwarding this Join Request, a node MUST use a unicast cell (autonomous or dedicated) it has with its preferred parent. How dedicated cells are installed is detailed in Section 5.

As per [I-D.ietf-6tisch-minimal-security], the JRC sends back a Join Response to the pledge, through the JP. When forwarding this Join Response, a node MUST use a unicast (autonomous or dedicated) cell it has with its child (not the minimal cell).

As per [I-D.ietf-6tisch-minimal-security], after receiving the Join Response, the pledge learns the keying material used in the network, as well as other configurations, and becomes a "joined node".

4.6. Step 5 - Acquiring a RPL rank

Because it has learned the link-layer keying material used in the network, the joined node can now decrypt the DIO packets sent by its neighbors. Per [RFC6550], the joined node receives DIOs, computes its own rank, and selects a preferred parent.

4.7. Step 6 - Send EBs and DIOs

The node SHOULD start sending EBs and DIOs on the minimal cell, while following the transmit rules for broadcast frames from Section 2.

4.8. Step 7 - Neighbor Polling

The node SHOULD send some form of keep-alive messages to all its neighbors it has unicast cells with. The Keep-Alive (KA) mechanism is detailed in [RFC7554]. It uses the keep-alive messages to its preferred parent to stay synchronized. It uses the keep-alive messages to its children (with which it has a unicast cell to) to ensure the child is still reachable. The RECOMMENDED period for sending keep-alive messages is KA_PERIOD.

If the keep-alive message to a child fails at the link layer (i.e. the maximum number of link-layer retries is reached), the node SHOULD declare the child as unreachable. This can happen for example when the child node is switched off.

When a neighbor is declared unreachable, the node MUST remove all dedicated cells with that neighbor from its own schedule. In addition, it MAY issue a 6P CLEAR to that neighbor (which can fail at the link-layer). If the node has autonmous cells to the unreachable neighbor those cells will be removed following the procedure described in Section 3.

4.9. End State

For a new node, the end state of the joining process is:

- it is synchronized to the network
- it is using the link-layer keying material it learned through the secure joining process
- it has identified its preferred routing parent
- it has a set of autonomous unicast cells to/from its neighbors
- it is periodically sending DIOs, potentially serving as a router for other nodes' traffic
- it is periodically sending EBs, potentially serving as a JP for new joining nodes

5. Rules for Adding/Deleting Cells

Once a node has joined the 6TiSCH network, it adds/deletes/relocates cells with its preferred parent for three reasons:

- to match the link-layer resources to the traffic between the node and its preferred parent (Section 5.1)
- to handle switching preferred parent (Section 5.2)
- to handle a schedule collision (Section 5.3)

5.1. Adapting to Traffic

A node implementing MSF MUST implement the behavior described in this section.

In order to handle transient traffic bursts, MSF uses the [IEEE802154-2015] frame pending bit (page 152, Section 7.2.1.3). By setting the bit, a node can transmit a series of packets to a given neighbor in consecutive time offsets. The next paragraphs define how to handle longer-term fluctuations in traffic, using 6P.

The goal of MSF is to manage the communication schedule in the 6TiSCH schedule in a distributed manner. For a node, this translates into monitoring the current usage of the cells it has to its preferred parent:

- If the node determines that the number of link-layer frames it is attempting to exchange with its preferred parent per unit of time is larger than the capacity offered by the TSCH unicast cells (dedicated and autonmous cells) it has scheduled with it, the node triggers a 6P Transaction with its preferred parent to add dedicated cells to the TSCH schedule of both nodes.
- If the traffic is lower than the capacity, the node triggers a 6P Transaction with its preferred parent to delete dedicated cells from the TSCH schedule of both nodes.

From the join process, the node already has a set of autonmous unicast cells, as defined in Section 3. The autonomous cells MUST NOT be removed by 6P, so that there always exists a unicast cell between a node and its preferred parent, even if no frames are being exchanged between them. Autonomous cells are used indistinguishably together with dedicated cells, for broadcast or unicast traffic with the target neighbor. The procedure to remove autonomous cells is described in Section 3.

Adding/removing/relocating cells involves exchanging frames that contain 6P commands. All 6P frames MUST be sent on the unicast cells (and not the minimal cell).

The node MUST maintain the following counters for its preferred parent:

NumCellsPassed: Counts the number of unicast cells (dedicated and autonmous cells) that have passed since the counter was initialized. This counter is initialized at 0. Each time the TSCH state machine indicates that the current cell is a unicast cell to the preferred parent, NumCellsPassed is incremented by exactly 1, regardless of whether the cell is used to transmit/ receive a frame.

NumCellsUsed: Counts the number of unicast cells that have been used. This counter is initialized at 0. NumCellsUsed is incremented by exactly 1 when, during a unicast cell to the preferred parent, either of the following happens:

  * The node sends a frame to its preferred parent. The counter increments regardless of whether a link-layer acknowledgment was received or not.
  * The node receives a frame from its preferred parent.

Implementors MAY choose to create the same counters for each neighbor, and add them as additional statistics in the neighbor table.

The counters are used as follows:

1. Both NumCellsPassed and NumCellsUsed are initialized to 0 when the node boots.
2. When the value of NumCellsPassed reaches MAX_NUMCELLS:

    * If NumCellsUsed > LIM_NUMCELLSUSED_HIGH, trigger 6P to add a single cell to the preferred parent
    * If NumCellsUsed < LIM_NUMCELLSUSED_LOW, trigger 6P to remove a single cell to the preferred parent
    * Reset both NumCellsPassed and NumCellsUsed to 0 and go to step 2.

5.2. Switching Parent

A node implementing MSF MUST implement the behavior described in this section.

Part of its normal operation, the RPL routing protocol can have a node switch preferred parents. The procedure for switching from the old preferred parent to the new preferred parent is:

1. the node counts the number of dedicated (unicast but not autonomous) cells it has per slotframe to the old preferred parent
2. the node triggers one or more 6P ADD commands to schedule the same number of dedicated cells to the new preferred parent
3. when that successfully completes, the node issues a 6P CLEAR command to its old preferred parent

5.3. Handling Schedule Collisions

A node implementing MSF SHOULD implement the behavior described in this section. The "MUST" statements in this section hence only apply if the node implements schedule collision handling.

Since scheduling is entirely distributed, there is a non-zero probability that two pairs of nearby neighbor nodes schedule a cell at the same [slotOffset,channelOffset] location in the TSCH schedule. In that case, data exchanged by the two pairs may collide on that cell. We call this case a "schedule collision".

The node MUST maintain the following counters for each cell to its preferred parent:

NumTx: Counts the number of transmission attempts on that cell. Each time the node attempts to transmit a frame on that cell, NumTx is incremented by exactly 1.

NumTxAck: Counts the number of successful transmission attempts on that cell. Each time the node receives an acknowledgment for a transmission attempt, NumTxAck is incremented by exactly 1.

Implementors MAY choose to maintain the same counters for each cell in the schedule.

Since both NumTx and NumTxAck are initialized to 0, we necessarily have NumTxAck <= NumTx. We call Packet Delivery Ratio (PDR) the ratio NumTxAck/NumTx; and represent it as a percentage. A cell with PDR=50% means that half of the frames transmitted are not acknowledged (and need to be retransmitted).

Each time the node switches preferred parent (or during the join process when the node selects a preferred parent for the first time), both NumTx and NumTxAck MUST be reset to 0. They increment over time, as the schedule is executed and the node sends frames to its preferred parent. When NumTx reaches 256, both NumTx and NumTxAck MUST be divided by 2. That is, for example, from NumTx=256 and NumTxAck=128, they become NumTx=128 and NumTxAck=64. This operation does not change the value of the PDR, but allows the counters to keep incrementing.

The key for detecting a schedule collision is that, if a node has several cells to the same preferred parent, all cells should exhibit the same PDR. A cell which exhibits a PDR significantly lower than the others indicates than there are collisions on that cell.

Every HOUSEKEEPINGCOLLISION_PERIOD, the node executes the following steps:

1. It computes, for each dedicated cell with its preferred parent (not for the autonomous cell), that cell’s PDR.
2. Any cell that hasn’t yet had NumTx divided by 2 since it was last reset is skipped in steps 3 and 4. This avoids triggering cell relocation when the values of NumTx and NumTxAck are not statistically significant yet.
3. It identifies the cell with the highest PDR.
4. For each other cell, it compares its PDR against that of the cell with the highest PDR. If it’s less than RELOCATE_PDRTHRES, it triggers the relocation of that cell using a 6P RELOCATE command.

6. 6P SIGNAL command

The 6P SIGNAL command is not used by MSF.

7. Scheduling Function Identifier

The Scheduling Function Identifier (SFID) of MSF is IANA_6TISCH_SFID_MSF.

8. Rules for CellList

MSF uses 2-step 6P Transactions exclusively. 6P Transactions are only initiated by a node towards it preferred parent. As a result, the cells to put in the CellList of a 6P ADD command, and in the candidate CellList of a RELOCATE command, are chosen by the node initiating the 6P Transaction. In both cases, the same rules apply:

- The CellList SHOULD contain 5 or more cells.
- Each cell in the CellList MUST have a different slotOffset value.
- For each cell in the CellList, the node MUST NOT have any scheduled cell on the same slotOffset.
- The slotOffset value of any cell in the CellList MUST NOT be the same as the slotOffset of the minimal cell (slotOffset=0).
- The slotOffset of a cell in the CellList SHOULD be randomly and uniformly chosen among all the slotOffset values that satisfy the restrictions above.
- The channelOffset of a cell in the CellList SHOULD be randomly and uniformly chosen in [0..numFrequencies], where numFrequencies represents the number of frequencies a node can communicate on.

9. 6P Timeout Value

The 6P Timeout is not a constant value. It is calculated as (1/C)*(1/PDR)*SIXP_TIMEOUT_SEC_FACTOR, where:

- C represents the number of cells per second scheduled to that neighbor
- PDR represents the average PDR of those cells
- SIXP_TIMEOUT_SEC_FACTOR is a security factor, a constant

10. Rule for Ordering Cells

Cells are ordered slotOffset first, channelOffset second.

The following sequence is correctly ordered (each element represents the [slottOffset,channelOffset] of a cell in the schedule):

[1,3],[1,4],[2,0],[5,3],[6,0],[6,3],[7,9]

11. Meaning of the Metadata Field

The Metadata field is not used by MSF.

12. 6P Error Handling

Section 6.2.4 of [I-D.ietf-6tisch-6top-protocol] lists the 6P Return Codes. Figure 1 lists the same error codes, and the behavior a node implementing MSF SHOULD follow.

Code	RECOMMENDED behavior
RC_SUCCESS	nothing
RC_EOL	nothing
RC_ERR	quarantine
RC_RESET	quarantine
RC_ERR_VERSION	quarantine
RC_ERR_SFID	quarantine
RC_ERR_SEQNUM	clear
RC_ERR_CELLLIST	clear
RC_ERR_BUSY	waitretry
RC_ERR_LOCKED	waitretry

Figure 1: Recommended behavior for each 6P Error Code.

The meaning of each behavior from Figure 1 is:

nothing: Indicates that this Return Code is not an error. No error handling behavior is triggered.

clear: Abort the 6P Transaction. Issue a 6P CLEAR command to that neighbor (this command may fail at the link layer). Remove all cells scheduled with that neighbor from the local schedule. Keep that node in the neighbor and routing tables.

quarantine: Same behavior as for "clear". In addition, remove the node from the neighbor and routing tables. Place the node’s identifier in a quarantine list for QUARANTINE_DURATION. When in quarantine, drop all frames received from that node.

waitretry: Abort the 6P Transaction. Wait for a duration randomly and uniformly chosen in [WAITDURATION_MIN,WAITDURATION_MAX]. Retry the same transaction.

13. Schedule Inconsistency Handling

The behavior when schedule inconsistency is detected is explained in Figure 1, for 6P Return Code RC_ERR_SEQNUM.

14. MSF Constants

Figure 2 lists MSF Constants and their RECOMMENDED values.

Name	RECOMMENDED value
KA_PERIOD	10 s
LIM_NUMCELLSUSED_HIGH	75 %
LIM_NUMCELLSUSED_LOW	25 %
HOUSEKEEPINGCOLLISION_PERIOD	1 min
RELOCATE_PDRTHRES	50 %
SIXP_TIMEOUT_SEC_FACTOR	3 x
SLOTFRAME_LENGTH	101 slots
QUARANTINE_DURATION	5 min
WAITDURATION_MIN	30 s
WAITDURATION_MAX	60 s

Figure 2: MSF Constants and their RECOMMENDED values.

15. MSF Statistics

Figure 3 lists MSF Statistics and their RECOMMENDED width.

Name	RECOMMENDED width
NumCellsPassed	1 byte
NumCellsUsed	1 byte
NumTx	1 byte
NumTxAck	1 byte

Figure 3: MSF Statistics and their RECOMMENDED width.

16. Security Considerations

MSF defines a series of "rules" for the node to follow. It triggers several actions, that are carried out by the protocols defined in the following specifications: the Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration [RFC8180], the 6TiSCH Operation Sublayer Protocol (6P) [I-D.ietf-6tisch-6top-protocol], and the Minimal Security Framework for 6TiSCH [I-D.ietf-6tisch-minimal-security]. In particular, MSF does not define a new protocol or packet format.

MSF relies entirely on the security mechanisms defined in the specifications listed above.

17. IANA Considerations

17.1. MSF Scheduling Function Identifiers

This document adds the following number to the "6P Scheduling Function Identifiers" sub-registry, part of the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry, as defined by [I-D.ietf-6tisch-6top-protocol]:

SFID	Name	Reference
IANA_6TISCH_SFID_MSF	Minimal Scheduling Function (MSF)	RFCXXXX (NOTE:this)

Figure 4: IETF IE Subtype ’6P’.

18. References

18.1. Normative References

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[RFC8180] Vilajosana, X., Ed., Pister, K., and T. Watteyne, "Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration", BCP 210, RFC 8180, DOI 10.17487/RFC8180, May 2017, <https://www.rfc-editor.org/info/rfc8180>.

18.2. Informative References

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[SAX-DASFAA] Ramakrishna, M. and J. Zobel, "Performance in Practice of String Hashing Functions", DASFAA , 1997.

Appendix A. Contributors

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Appendix B. Implementation Status

This section records the status of known implementations of the protocol defined by this specification at the time of posting of this Internet-Draft, and is based on a proposal described in [RFC6982]. The description of implementations in this section is intended to assist the IETF in its decision processes in progressing drafts to RFCs. Please note that the listing of any individual implementation here does not imply endorsement by the IETF. Furthermore, no effort has been spent to verify the information presented here that was supplied by IETF contributors. This is not intended as, and must not be construed to be, a catalog of available implementations or their features. Readers are advised to note that other implementations may exist.

According to [RFC6982], "this will allow reviewers and working groups to assign due consideration to documents that have the benefit of running code, which may serve as evidence of valuable experimentation and feedback that have made the implemented protocols more mature. It is up to the individual working groups to use this information as they see fit".

OpenWSN: MSF is being implemented in the OpenWSN project [OpenWSN] under a BSD open-source license. The authors of this document are collaborating with the OpenWSN community to gather feedback about the status and performance of the protocols described in this document. Results from that discussion will appear in this section in future revision of this specification. More information about this implementation at http://www.openwsn.org/.

6TiSCH simulator The 6TiSCH simulator is a Python-based high-level simulator on which MSF is being implemented. More information at https://bitbucket.org/6tisch/simulator/.

Appendix C. Performance Evaluation

The performance of MSF may be published as companion documents to this specification, possibly under the form a applicability statements.

Appendix D. [TEMPORARY] Changelog

- draft-chang-6tisch-msf-02
  - Added autonomous cell.
- draft-chang-6tisch-msf-01
  - When neighbor is unreachable, sending a CLEAR command was a MUST, now a MAY.

    * Fixing 6P Timeout calculation.
    * Clearer text for "Handling Schedule Collisions" section.
    * Typos.
    * Input from Yasuyuki Tanaka's review (https://www.ietf.org/mail-archive/web/6tisch/current/msg05723.html).

- draft-chang-6tisch-msf-00

    * Initial submission.

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6TiSCH Operation Sublayer Protocol (6P)
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Abstract

This document defines the IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) Operation Sublayer (6top) Protocol (6P), which enables distributed scheduling in 6TiSCH networks. 6P allows neighbor nodes to add/delete TSCH cells to one another. 6P is part of the 6TiSCH Operation Sublayer (6top), the next higher layer to the IEEE Std 802.15.4 TSCH medium access control layer. The 6top layer terminates the 6top Protocol defined in this document, and runs one or more 6top Scheduling Function(s). A 6top Scheduling Function (SF) decides when to add/delete cells, and triggers 6P Transactions. This document lists the requirements for an SF, but leaves the definition of SFs out of scope.

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.

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This Internet-Draft will expire on December 22, 2018.

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1. Introduction

All communication in a IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) network is orchestrated by a schedule [RFC7554]. The schedule is composed of cells, each identified by a [slotOffset,channelOffset]. This specification defines the 6TiSCH Operation Sublayer (6top) Protocol (6P), terminated by the 6TiSCH Operation sublayer (6top). 6P allows a node to communicate with a neighbor node to add/delete TSCH cells to one another. This results in distributed schedule management in a 6TiSCH network. The 6top layer terminates the 6top Protocol, and runs one or more 6top Scheduling Functions (SFs) that decide when to add/delete cells and trigger 6P Transactions. The SF is out of scope of this document but this document defines the requirements for an SF.

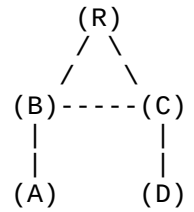

Figure 1: A simple 6TiSCH network.

The example network depicted in Figure 1 is used to describe the interaction between nodes. We consider the canonical case where node "A" issues 6P requests to node "B". We keep this example throughout

this document. Throughout the document, node A always represents the node that issues a 6P request; node B the node that receives this request.

We consider that node A monitors the communication cells it has in its schedule to node B:

- If node A determines that the number of link-layer frames it is sending to node B per unit of time exceeds the capacity offered by the TSCH cells it has scheduled to node B, it triggers a 6P Transaction with node B to add one or more cells to the TSCH schedule of both nodes.
- If the traffic is lower than the capacity, node A triggers a 6P Transaction with node B to delete one or more cells in the TSCH schedule of both nodes.
- Node A MAY also monitor statistics to determine whether collisions are happening on a particular cell to node B. If this feature is enabled, node A communicates with node B to "relocate" the cell which undergoes collisions to a different [slotOffset,channelOffset] location in the TSCH schedule.

This results in distributed schedule management in a 6TiSCH network.

The 6top Scheduling Function (SF) defines when to add/delete a cell to a neighbor. Different applications require different SFs, so the SF is left out of scope of this document. Different SFs are expected to be defined in future companion specifications. A node MAY implement multiple SFs and run them at the same time. At least one SF MUST be running. The SFID field contained in all 6P messages allows a node to invoke the appropriate SF on a per-6P Transaction basis.

Section 2 describes the 6TiSCH Operation Sublayer (6top). Section 3 defines the 6top Protocol (6P). Section 4 provides guidelines on how to define an SF.

2. 6TiSCH Operation Sublayer (6top)

As depicted in Figure 2, the 6TiSCH Operation Sublayer (6top) is the next higher layer to the IEEE Std 802.15.4 TSCH medium access control (MAC) layer [IEEE802154]. We use "802.15.4" as a short version of "IEEE Std 802.15.4" in this document.

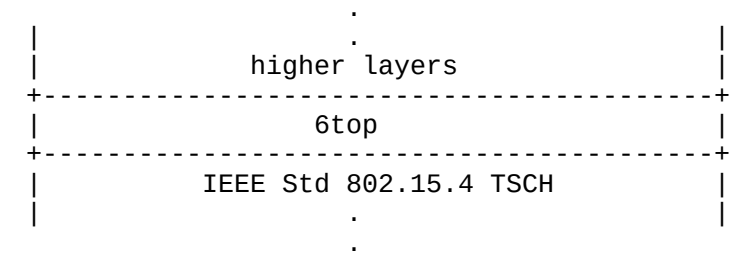

Figure 2: The 6top sublayer in the protocol stack.

The roles of the 6top sublayer are to:

- Terminate the 6top Protocol (6P), which allows neighbor nodes to communicate to add/delete cells to one another.
- Run one or multiple 6top Scheduling Functions (SFs), which define the rules that decide when to add/delete cells.

2.1. Hard/Soft Cells

Each cell in the schedule is either "hard" or "soft":

- a soft cell can be read, added, deleted or updated by 6top.
- a hard cell is read-only for 6top.

In the context of this specification, all the cells used by 6top are soft cells. Hard cells can be used for example when "hard-coding" a schedule [RFC8180].

2.2. Using 6P with the Minimal 6TiSCH Configuration

6P MAY be used alongside the Minimal 6TiSCH Configuration [RFC8180]. In this case, it is RECOMMENDED to use 2 slotframes, as depicted in Figure 3:

- Slotframe 0 is used for traffic defined in the Minimal 6TiSCH Configuration. In Figure 3, Slotframe 0 is 5 slots long, but it can be shorter or longer.
- 6P allocates cells from Slotframe 1. In Figure 3, Slotframe 1 is 10 slots long, but it can be shorter or longer.

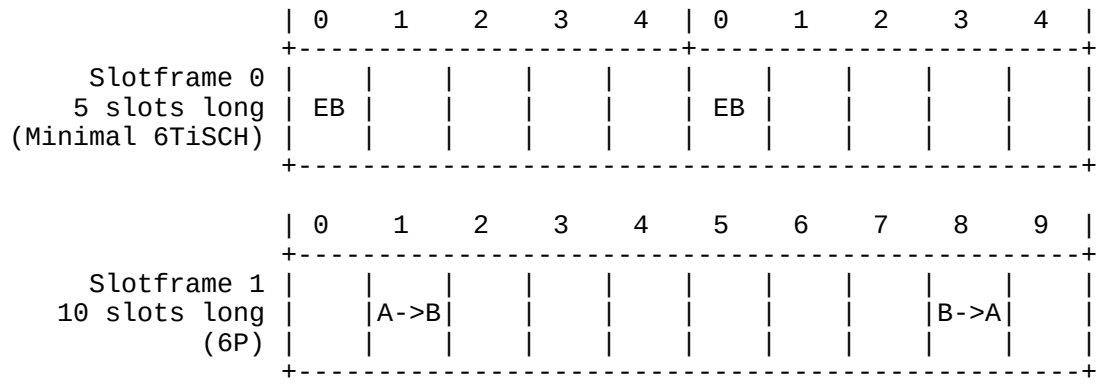

Figure 3: 2-slotframe structure when using 6P alongside the Minimal 6TiSCH Configuration.

The Minimal 6TiSCH Configuration cell SHOULD be allocated from a slotframe of higher priority than the slotframe used by 6P for dynamic cell allocation. This way, dynamically allocated cells cannot "mask" the cells used by the Minimal 6TiSCH Configuration. 6top MAY support additional slotframes; how to use additional slotframes is out of scope for this document.

3. 6top Protocol (6P)

The 6top Protocol (6P) enables two neighbor nodes to add/delete/relocate cells in their TSCH schedule. Conceptually, two neighbor nodes "negotiate" the location of the cells to add, delete, or relocate in their TSCH schedule.

3.1. 6P Transactions

We call "6P Transaction" a complete negotiation between two neighbor nodes. A particular 6P Transaction is executed between two nodes as a result of an action triggered by one SF. For a 6P Transaction to succeed, both nodes must use the same SF to handle the particular transaction. A 6P Transaction starts when a node wishes to add/delete/relocate one or more cells with one of its neighbors. A 6P Transaction ends when the cell(s) have been added/deleted/relocated in the schedule of both nodes, or when the 6P Transaction has failed.

6P messages exchanged between nodes A and B during a 6P Transaction SHOULD be exchanged on non-shared unicast cells ("dedicated" cells) between A and B. If no dedicated cells are scheduled between nodes A and B, shared cells MAY be used.

Keeping consistency between the schedules of the two neighbor nodes is important. A loss of consistency can cause loss of connectivity. One example is when node A has a transmit cell to node B, but node B does not have the corresponding reception cell. To verify consistency, neighbor nodes maintain a Sequence Number (SeqNum). Neighbor nodes exchange the SeqNum as part of each 6P Transaction to detect a possible inconsistency. This mechanism is explained in Section 3.4.6.2.

An implementation MUST include a mechanism to associate each scheduled cell with the SF that scheduled it. This mechanism is implementation-specific and out of scope of this document.

A 6P Transaction can consist of 2 or 3 steps. A 2-step transaction is used when node A selects the cells to be allocated. A 3-step transaction is used when node B selects the cells to be allocated. An SF MUST specify whether to use 2-step transactions, 3-step transactions, or both.

We illustrate 2-step and 3-step transactions using the topology in Figure 1.

3.1.1. 2-step 6P Transaction

Figure 4 shows an example 2-step 6P Transaction. In a 2-step transaction, node A selects the candidate cells. Several elements are left out to simplify understanding.

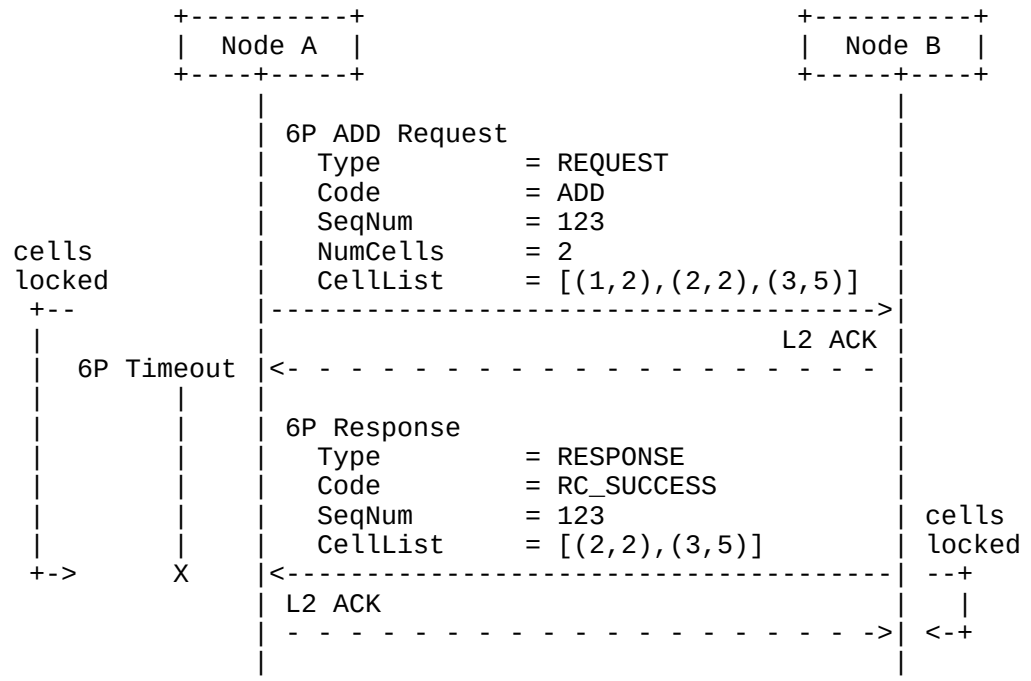

Figure 4: An example 2-step 6P Transaction.

In this example, the 2-step transaction occurs as follows:

1. The SF running on node A determines that 2 extra cells need to be scheduled to node B.
2. The SF running on node A selects candidate cells for node B to choose from. Node A MUST select at least as many candidate cells as the number of cells to add. Here, node A selects 3 candidate cells. Node A locks those candidate cells in its schedule until it receives a 6P response.
3. Node A sends a 6P ADD Request to node B, indicating it wishes to add 2 cells (the "NumCells" value), and specifying the list of 3 candidate cells (the "CellList" value). Each cell in the CellList is a [slotOffset,channelOffset] tuple. This 6P ADD Request is link-layer acknowledged by node B (labeled "L2 ACK" in Figure 4).
4. After having successfully sent the 6P ADD Request (i.e. receiving the link-layer acknowledgment), node A starts a 6P Timeout to abort the 6P Transaction in case no response is received from node B.
5. The SF running on node B selects 2 out of the 3 cells from the CellList of the 6P ADD Request. Node B locks those cells in its schedule until the transmission is successful (i.e. node B

receives a link-layer ACK from node A). Node B sends back a 6P Response to node A, indicating the cells it has selected. The response is link-layer acknowledged by node A.

6. Upon completion of this 6P Transaction, 2 cells from A to B have been added to the TSCH schedule of both nodes A and B.
7. An inconsistency in the schedule can happen if the 6P Timeout expires when the 6P Response is in the air, if the last link-layer ACK for the 6P Response is lost, or if one of the nodes is power cycled during the transaction. 6P provides an inconsistency detection mechanism described in Section 3.4.6.1 to cope with such situations.

3.1.2. 3-step 6P Transaction

Figure 5 shows an example 3-step 6P Transaction. In a 3-step transaction, node B selects the candidate cells. Several elements are left out to simplify understanding.

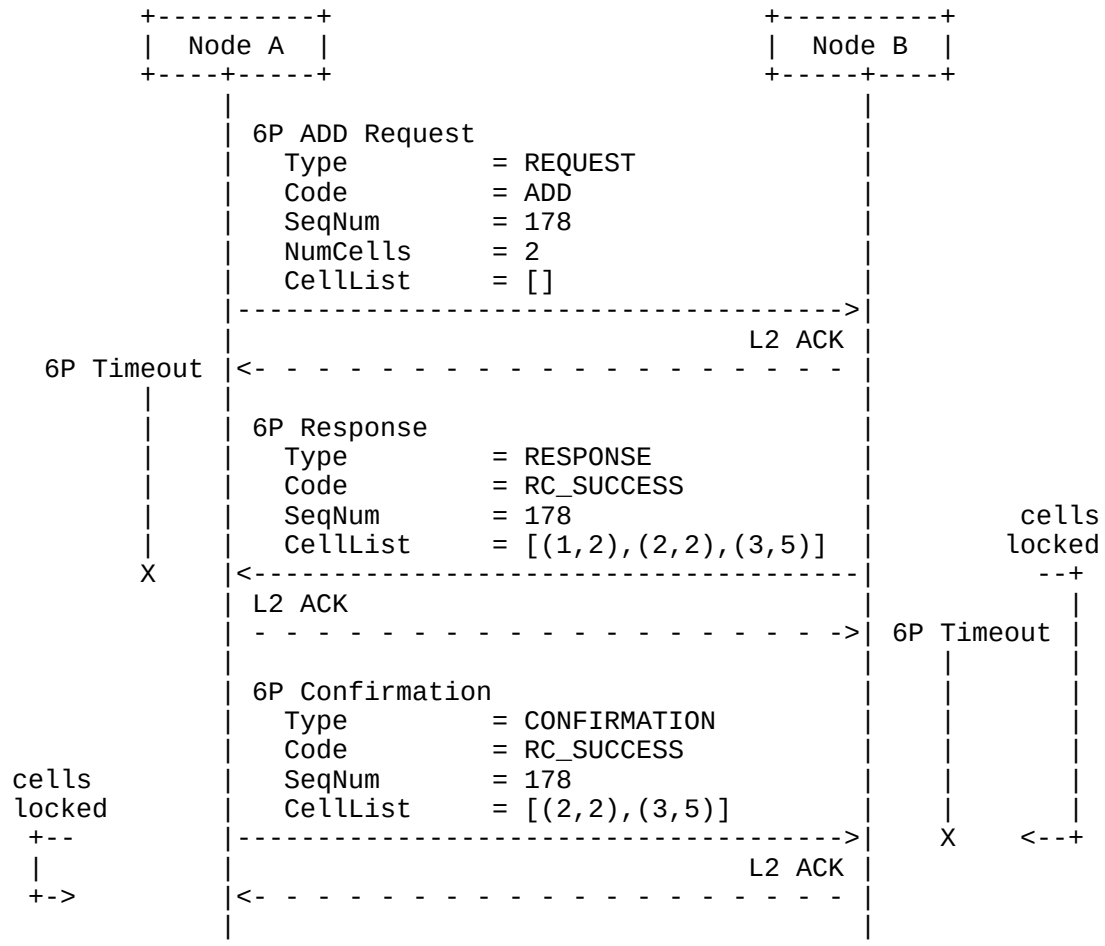

Figure 5: An example 3-step 6P Transaction.

In this example, the 3-step transaction occurs as follows:

1. The SF running on node A determines that 2 extra cells need to be scheduled to node B. The SF uses a 3-step transaction, so it does not select candidate cells.
2. Node A sends a 6P ADD Request to node B, indicating it wishes to add 2 cells (the "NumCells" value), with an empty "CellList". This 6P ADD Request is link-layer acknowledged by node B.
3. After having successfully sent the 6P ADD Request, node A starts a 6P Timeout to abort the transaction in case no 6P Response is received from node B.
4. The SF running on node B selects 3 candidate cells, and locks them. Node B sends back a 6P Response to node A, indicating the

3 cells it has selected. The response is link-layer acknowledged by node A.

5. After having successfully sent the 6P Response, node B starts a 6P Timeout to abort the transaction in case no 6P Confirmation is received from node A.
6. The SF running on node A selects 2 cells from the CellList field in the 6P Response, and locks those. Node A sends back a 6P Confirmation to node B, indicating the cells it selected. The confirmation is link-layer acknowledged by node B.
7. Upon completion of the 6P Transaction, 2 cells from A to B have been added to the TSCH schedule of both nodes A and B.
8. An inconsistency in the schedule can happen if the 6P Timeout expires when the 6P Confirmation is in the air, if the last link-layer ACK for the 6P Confirmation is lost, or if one of the nodes is power cycled during the transaction. 6P provides an inconsistency detection mechanism described in Section 3.4.6.1 to cope with such situations.

3.2. Message Format

3.2.1. 6top Information Element (IE)

6P messages travel over a single hop. 6P messages are carried as payload of an 802.15.4 Payload Information Element (IE) [IEEE802154]. The messages are encapsulated within the Payload IE Header. The Group ID is set to the IETF IE value defined in [RFC8137]. The content is encapsulated by a SubType ID, as defined in [RFC8137].

Since 6P messages are carried in IEs, IEEE bit/byte ordering applies. Bits within each field in the 6top IE are numbered from 0 (leftmost and least significant) to k-1 (rightmost and most significant), where the length of the field is k bits. Fields that are longer than a single octet are copied to the packet in the order from the octet containing the lowest numbered bits to the octet containing the highest numbered bits (little endian).

This document defines the "6top IE", a SubType of the IETF IE defined in [RFC8137], with subtype ID IANA_6TOP_SUBIE_ID. The SubType Content of the "6top IE" is defined in Section 3.2.2. The length of the "6top IE" content is variable.

3.2.2. Generic 6P Message Format

All 6P messages follow the generic format shown in Figure 6.

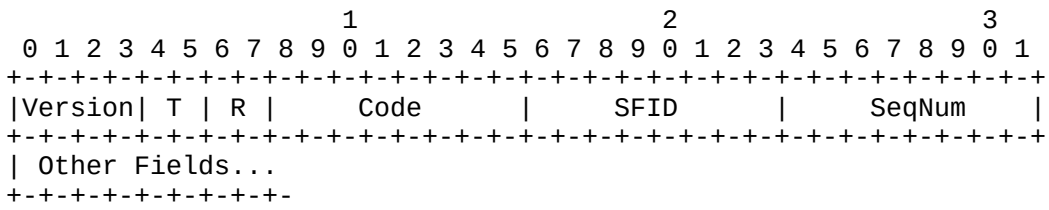

Figure 6: Generic 6P Message Format.

6P Version (Version): The version of the 6P protocol. Only version 0 is defined in this document. Future specifications may define further versions of the 6P protocol.

Type (T): Type of message. The message types are defined in Section 6.2.2.

Reserved (R): Reserved bits. These two bits SHOULD be set to zero when sending the message, and MUST be ignored upon reception.

Code: The Code field contains a 6P Command Identifier when the 6P message is of Type REQUEST. Section 6.2.3 lists the 6P command identifiers. The Code field contains a 6P return code when the 6P message is of Type RESPONSE or CONFIRMATION. Section 6.2.4 lists the 6P return codes. The same return codes are used in both 6P Response and 6P Confirmation messages.

6top Scheduling Function Identifier (SFID): The identifier of the SF to use to handle this message. The SFID is defined in Section 4.1.

SeqNum: Sequence number associated with the 6P Transaction, used to match the 6P Request, 6P Response and 6P Confirmation of the same 6P Transaction. The value of SeqNum MUST be different at each new 6P Request issued to the same neighbor and using the same SF. The SeqNum is also used to ensure consistency between the schedules of the two neighbors. Section 3.4.6 details how the SeqNum is managed.

Other Fields: The list of other fields and how they are used is detailed in Section 3.3.

6P Requests, 6P Response and 6P Confirmation messages for a same transaction MUST share the same Version, SFID and SeqNum values.

Future versions of the 6P Message SHOULD maintain the format of the 6P Version, Type and Code fields for backward compatibility.

3.2.3. 6P CellOptions

An 8-bit 6P CellOptions bitmap is present in the following 6P requests: ADD, DELETE, COUNT, LIST, RELOCATE. The format and meaning of this field MAY be redefined by the SF; the routine that parses this field is therefore associated with a specific SF.

- In the 6P ADD request, the 6P CellOptions bitmap is used to specify what type of cell to add.
- In the 6P DELETE request, the 6P CellOptions bitmap is used to specify what type of cell to delete.
- In the 6P RELOCATE request, the 6P CellOptions bitmap is used to specify what type of cell to relocate.
- In the 6P COUNT and the 6P LIST requests, the 6P CellOptions bitmap is used as a selector of a particular type of cells.

The content of the 6P CellOptions bitmap applies to all elements in the CellList field. The possible values of the 6P CellOptions are: TX = 1 (resp. 0) refers to macTxType = TRUE (resp. FALSE) in the macLinkTable of 802.15.4 [IEEE802154]. RX = 1 (resp. 0) refers to macRxType = TRUE (resp. FALSE) in the macLinkTable of 802.15.4. S = 1 (resp. 0) refers to macSharedType = TRUE (resp. FALSE) in the macLinkTable of 802.15.4. Section 6.2.6 contains the format of the 6P CellOptions bitmap, unless redefined by the SF. Figure 7 contains the meaning of the 6P CellOptions bitmap for the 6P ADD, DELETE, RELOCATE requests, unless redefined by the SF. Figure 8 contains the meaning of the 6P CellOptions bitmap for the 6P COUNT, LIST requests, unless redefined by the SF.

Note: assuming node A issues the 6P command to node B.

CellOptions Value	The type of cells B adds/deletes/relocates to its schedule when receiving a 6P ADD/DELETE/RELOCATE Request from A.
TX=0,RX=0,S=0	Invalid combination. RC_ERR is returned.
TX=1,RX=0,S=0	add/delete/relocate RX cells at B (TX cells at A)
TX=0,RX=1,S=0	add/delete/relocate TX cells at B (RX cells at A)
TX=1,RX=1,S=0	add/delete/relocate TX|RX cells at B (and at A)
TX=0,RX=0,S=1	Invalid combination. RC_ERR is returned.
TX=1,RX=0,S=1	add/delete/relocate RX|SHARED cells at B (TX|SHARED cells at A)
TX=0,RX=1,S=1	add/delete/relocate TX|SHARED cells at B (RX|SHARED cells at A)
TX=1,RX=1,S=1	add/delete/relocate TX|RX|SHARED cells at B (and at A)

Figure 7: Meaning of the 6P CellOptions bitmap for the 6P ADD, DELETE, RELOCATE requests.

Note: assuming node A issues the 6P command to node B.

CellOptions Value	The type of cells B selects from its schedule when receiving a 6P COUNT or LIST Request from A, from all the cells B has scheduled with A
TX=0,RX=0,S=0	all cells
TX=1,RX=0,S=0	all cells marked as RX only
TX=0,RX=1,S=0	all cells marked as TX only
TX=1,RX=1,S=0	all cells marked as TX and RX only
TX=0,RX=0,S=1	all cells marked as SHARED (regardless of TX, RX)
TX=1,RX=0,S=1	all cells marked as RX and SHARED only
TX=0,RX=1,S=1	all cells marked as TX and SHARED only
TX=1,RX=1,S=1	all cells marked as TX and RX and SHARED

Figure 8: Meaning of the 6P CellOptions bitmap for the 6P COUNT, LIST requests.

The CellOptions is an opaque set of bits, sent unmodified to the SF. The SF MAY redefine the format and meaning of the CellOptions field.

3.2.4. 6P CellList

A CellList field MAY be present in a 6P ADD Request, a 6P DELETE Request, a 6P RELOCATE Request, a 6P Response, or a 6P Confirmation. It is composed of a concatenation of zero, one or more 6P Cells as defined in Figure 9. The content of the CellOptions field specifies the options associated with all cells in the CellList. This necessarily means that the same options are associated with all cells in the CellList.

A 6P Cell is a 4-byte field, its default format is:

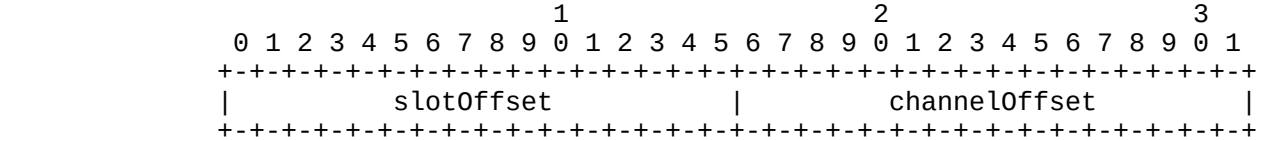

Figure 9: 6P Cell Format.

slotOffset: The slot offset of the cell.
channelOffset: The channel offset of the cell.

The CellList is an opaque set of bytes, sent unmodified to the SF. The length of the CellList field is implicit, and determined by the IE Length field of the Payload IE header as defined in 802.15.4. The SF MAY redefine the format of the CellList field; the routine that parses this field is therefore associated with a specific SF.

3.3. 6P Commands and Operations

3.3.1. Adding Cells

Cells are added by using the 6P ADD command. The Type field (T) is set to REQUEST. The Code field is set to ADD. Figure 10 defines the format of a 6P ADD Request.

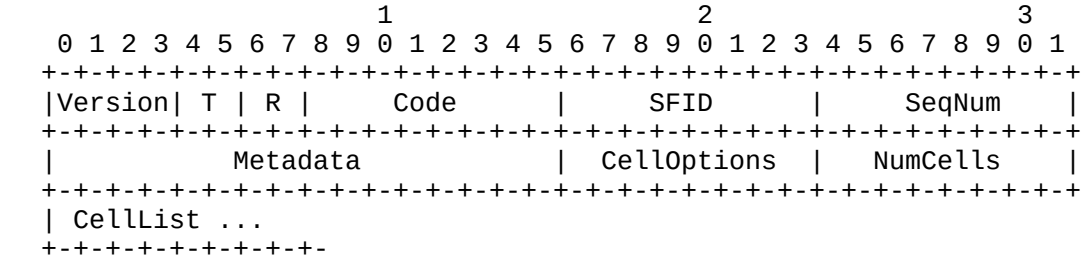

Figure 10: 6P ADD Request Format.

Metadata: Used as extra signaling to the SF. The contents of the Metadata field is an opaque set of bytes passed unmodified to the SF. The meaning of this field depends on the SF, and is out of scope of this document. For example, Metadata can specify in which slotframe to add the cells.
CellOptions: Indicates the options to associate with the cells to be added. If more than one cell is added (NumCells>1), the same options are associated with each one. This necessarily means that, if node A needs to add multiple cells with different options, it needs to initiate multiple 6P ADD Transactions.
NumCells: The number of additional cells node A wants to schedule to node B.
CellList: A list of 0 or multiple candidate cells. Its length is implicit and determined by the Length field of the Payload IE header.

Figure 11 defines the format of a 6P ADD Response and Confirmation.

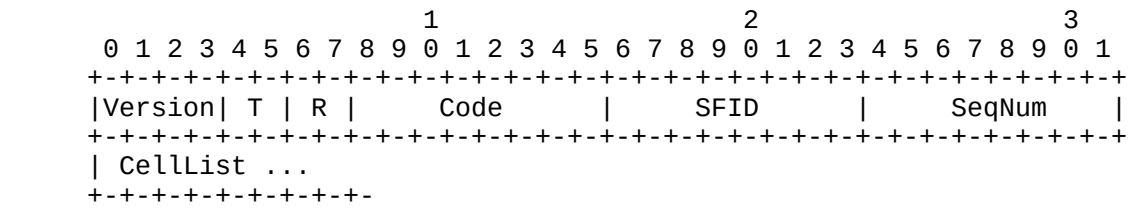

Figure 11: 6P ADD Response and Confirmation Formats.

CellList: A list of 0 or more 6P Cells.

Consider the topology in Figure 1 where the SF on node A decides to add NumCells cells to node B.

Node A's SF selects NumCandidate cells from its schedule. These are cells that are candidates to be scheduled with node B. The CellOptions field specifies the type of these cells. NumCandidate MUST be larger or equal to NumCells. How many cells node A selects (NumCandidate) and how that selection is done is specified in the SF and out of scope of this document. Node A sends a 6P ADD Request to node B which contains the CellOptions, the value of NumCells, and a selection of NumCandidate cells in the CellList. In case the NumCandidate cells do not fit in a single packet, this operation MUST be split into multiple independent 6P ADD Requests, each for a subset of the number of cells that eventually need to be added. In case of a 3-step transaction, the SF is responsible for ensuring that the returned candidate CellList fits into the 6P Response.

Upon receiving the request, node B checks whether the cellOptions are set to a valid value as noted by Figure 7. If this is not the case, a Response with code RC_ERR is returned. If the cells in the received CellList in node B is smaller than NumCells, Node B MUST return a 6P Response with RC_ERR_CELLLIST code. Otherwise, node B's SF verifies which of the cells in the CellList it can install in node B's schedule, following the specified CellOptions field. How that selection is done is specified in the SF and out of scope of this document. The verification can succeed (NumCells cells from the CellList can be used), fail (none of the cells from the CellList can be used), or partially succeed (fewer than NumCells cells from the CellList can be used). In all cases, node B MUST send a 6P Response with return code set to RC_SUCCESS, and which specifies the list of cells that were scheduled following the CellOptions field. That can contain NumCells elements (succeed), 0 elements (fail), or between 0 and NumCells elements (partially succeed).

Upon receiving the response, node A adds the cells specified in the CellList according to the CellOptions field.

3.3.2. Deleting Cells

Cells are deleted by using the 6P DELETE command. The Type field (T) is set to REQUEST. The Code field is set to DELETE. Figure 12 defines the format of a 6P DELETE Request.

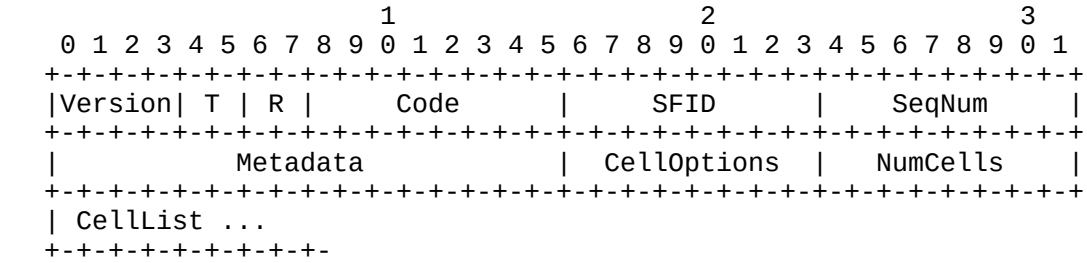

Figure 12: 6P DELETE Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1. Its format is the same as that in the 6P ADD command, but its content could be different.

CellOptions: Indicates the options that need to be associated to the cells to delete. Only cells matching the CellOptions can are deleted.

NumCells: The number of cells from the specified CellList the sender wants to delete from the schedule of both sender and receiver.

CellList: A list of 0 or more 6P Cells. Its length is determined by the Length field of the Payload IE header.

Figure 13 defines the format of a 6P DELETE Response and Confirmation.

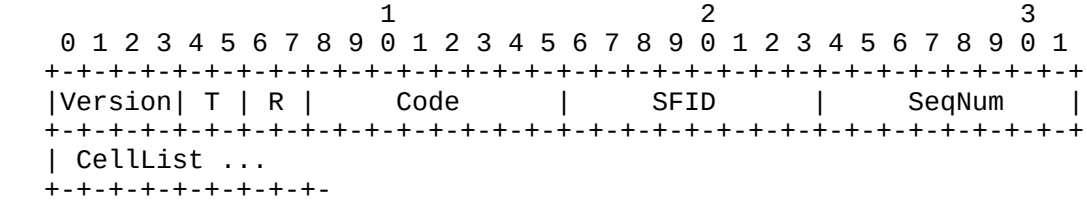

Figure 13: 6P DELETE Response and Confirmation Formats.

CellList: A list of 0 or more 6P Cells.

The behavior for deleting cells is equivalent to that of adding cells except that:

- The nodes delete the cells they agree upon rather than adding them.
- All cells in the CellList MUST already be scheduled between the two nodes and MUST match the CellOptions field. If node A puts cells in its CellList that are not already scheduled between the two nodes and match the CellOptions field, node B MUST reply with a RC_ERR_CELLLIST return code.
- The CellList in a 6P Request (2-step transaction) or 6P Response (3-step transaction) MUST either be empty, contain exactly NumCells cells, or more than NumCells cells. The case where the CellList is not empty but contains fewer than NumCells cells is not supported. RC_ERR_CELLLIST code MUST be returned when the CellList contains fewer than NumCells cells. If the CellList is empty, the SF on the receiving node SHOULD choose NumCells cells with the sender from its schedule, which match the CellOption field, and delete them. If the CellList contains more than NumCells cells, the SF on the receiving node chooses exactly NumCells cells from the CellList to delete.

3.3.3. Relocating Cells

Cell relocation consists in moving a cell to a different [slotOffset,channelOffset] location in the schedule. The Type field (T) is set to REQUEST. The Code is set to RELOCATE. Figure 14 defines the format of a 6P RELOCATE Request.

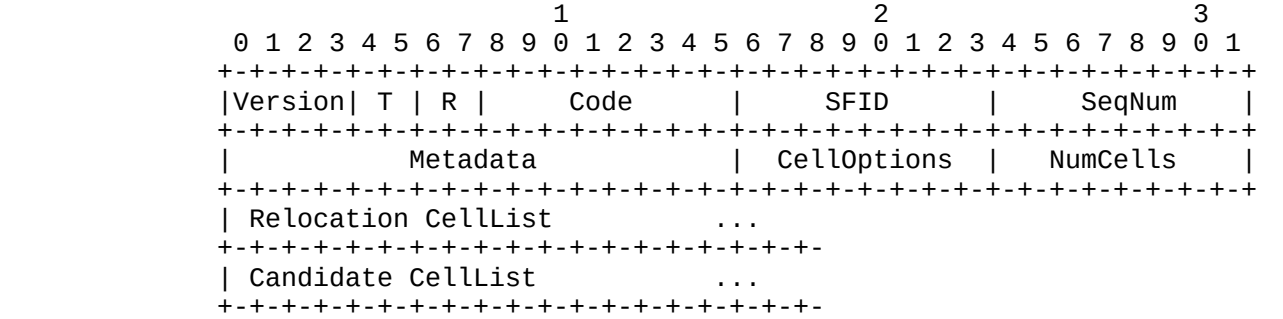

Figure 14: 6P RELOCATE Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1.
CellOptions: Indicates the options that need to be associated with cells to be relocated.
NumCells: The number of cells to relocate, which MUST be equal or greater than 1.
Relocation CellList: The list of NumCells 6P Cells to relocate.
Candidate CellList: A list of NumCandidate candidate cells for node B to pick from. NumCandidate MUST be 0, equal to NumCells, or

greater than NumCells. Its length is determined by the Length field of the Payload IE header.

In a 2-step 6P RELOCATE Transaction, node A specifies both the cells it needs to relocate, and the list of candidate cells to relocate to. The Relocation CellList MUST contain exactly NumCells entries. The Candidate CellList MUST contain at least NumCells entries (NumCandidate>=NumCells).

In a 3-step 6P RELOCATE Transaction, node A specifies only the cells it needs to relocate, but not the list of candidate cells to relocate to. The Candidate CellList MUST therefore be empty.

Figure 15 defines the format of a 6P RELOCATE Response and Confirmation.

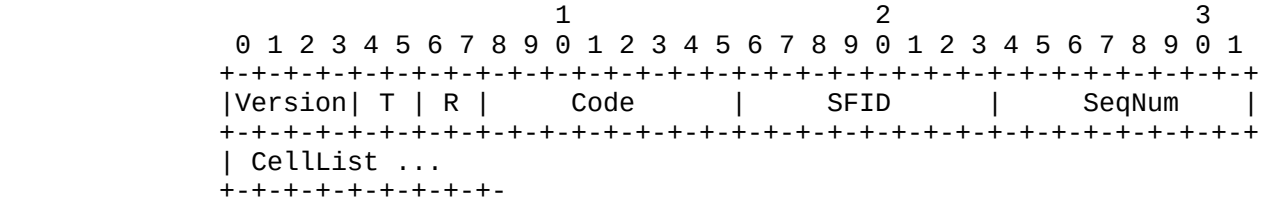

Figure 15: 6P RELOCATE Response and Confirmation Formats.

CellList: A list of 0 or more 6P Cells.

Node A's SF wants to relocate NumCells cells. Node A creates a 6P RELOCATE Request, and indicates the cells it wants to relocate in the Relocation CellList. It also selects NumCandidate cells from its schedule as candidate cells to relocate the cells to, and puts those in the Candidate CellList. The CellOptions field specifies the type of the cell(s) to relocate. NumCandidate MUST be larger or equal to NumCells. How many cells it selects (NumCandidate) and how that selection is done is specified in the SF and out of scope of this document. Node A sends the 6P RELOCATE Request to node B.

Upon receiving the request, Node B checks if the length of the Candidate CellList is larger or equal to NumCells. Node B's SF verifies that all the cells in the Relocation CellList are scheduled with node A, and are associate the options specified in the CellOptions field. If either check fails, node B MUST send a 6P Response to node A with return code RC_ERR_CELLLIST. If both checks pass, node B's SF verifies which of the cells in the Candidate CellList it can install in its schedule. How that selection is done is specified in the SF and out of scope of this document. That verification on Candidate CellList can succeed (NumCells cells from

the Candidate CellList can be used), fail (none of the cells from the Candidate CellList can be used) or partially succeed (fewer than NumCells cells from the Candidate CellList can be used). In all cases, node B MUST send a 6P Response with return code set to RC_SUCCESS, and which specifies the list of cells that will be re-scheduled following the CellOptions field. That can contain NumCells elements (succeed), 0 elements (fail), between 0 and NumCells elements (partially succeed). If N < NumCells cells appear in the CellList, this means the first N cells in the Relocation CellList have been relocated, the remainder have not.

Upon receiving the response with Code RC_SUCCESS, node A relocates the cells specified in Relocation CellList of its RELOCATE Request to the new locations specified in the CellList of the 6P Response, in the same order. In case the received return code is RC_ERR_CELLLIST, the transaction is aborted and no cell is relocated. In case of a 2-step transaction, Node B relocates the selected cells upon receiving the link-layer ACK for the 6P Response. In case of a 3-step transaction, Node B relocates the selected cells upon receiving the 6P Confirmation.

The SF SHOULD NOT relocate all cells between two nodes at the same time, which might result in the schedules of both nodes diverging significantly.

Figure 16 shows an example of a successful 2-step 6P RELOCATION Transaction.

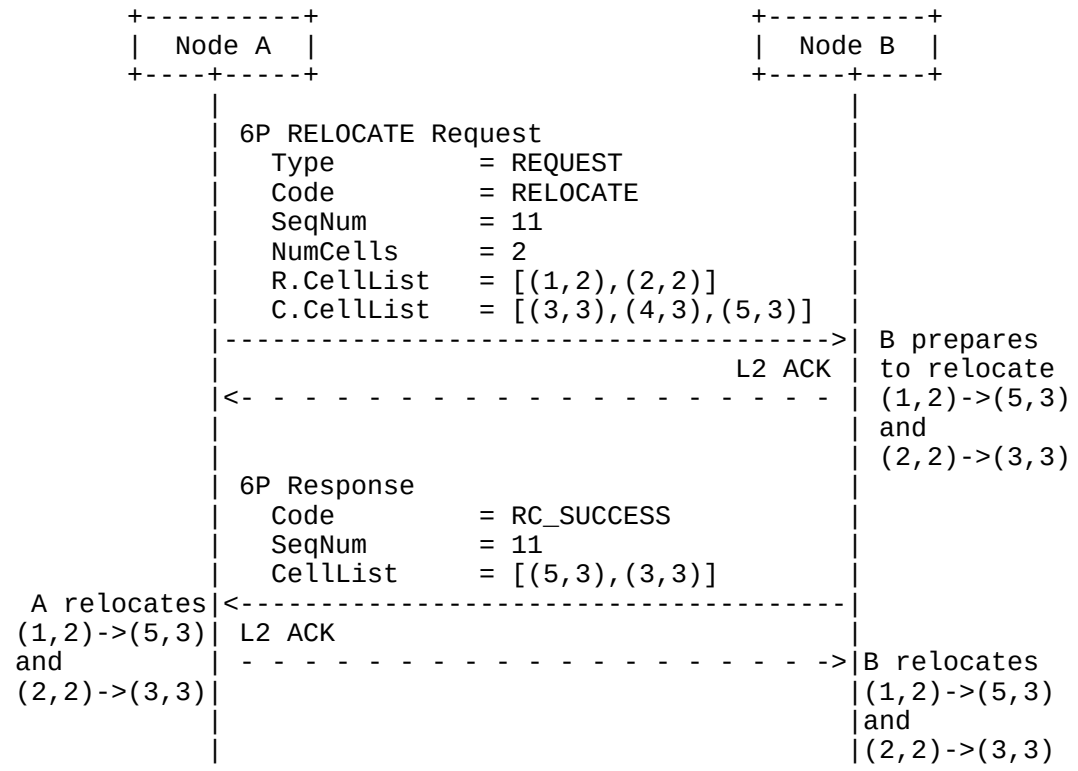

Figure 16: Example of a successful 2-step 6P RELOCATION Transaction.

Figure 17 shows an example of a partially successful 2-step 6P RELOCATION Transaction.

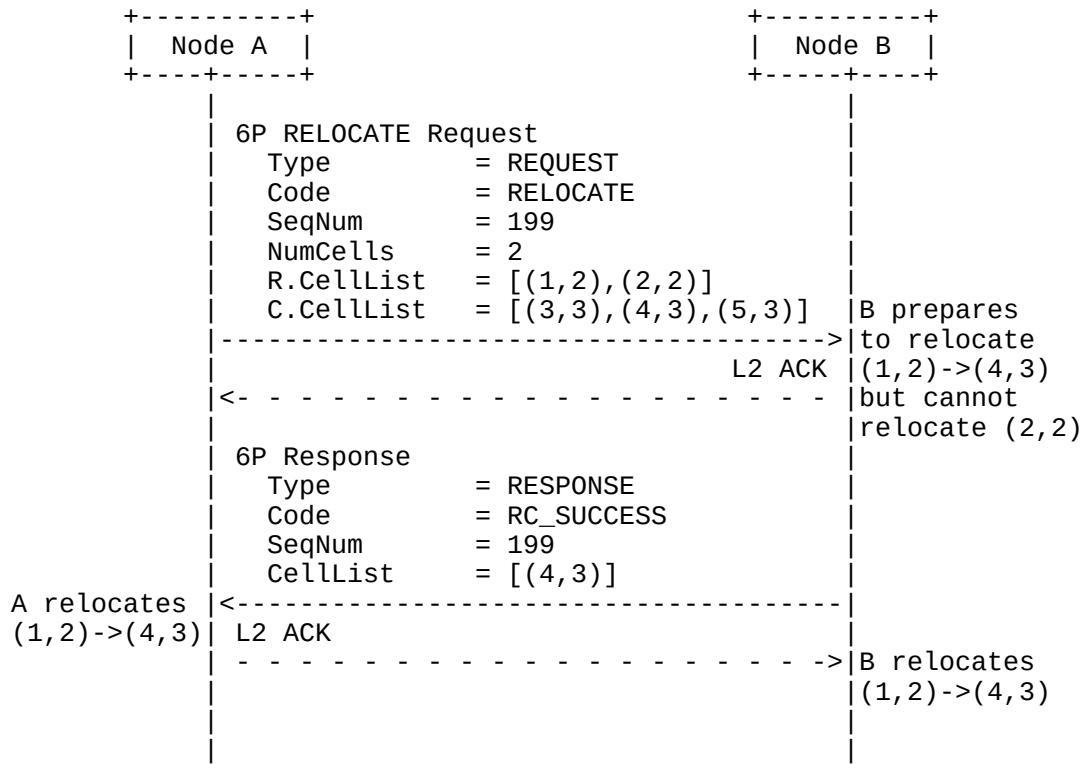

Figure 17: Example of a partially successful 2-step 6P RELOCATION Transaction.

Figure 18 shows an example of a failed 2-step 6P RELOCATION Transaction.

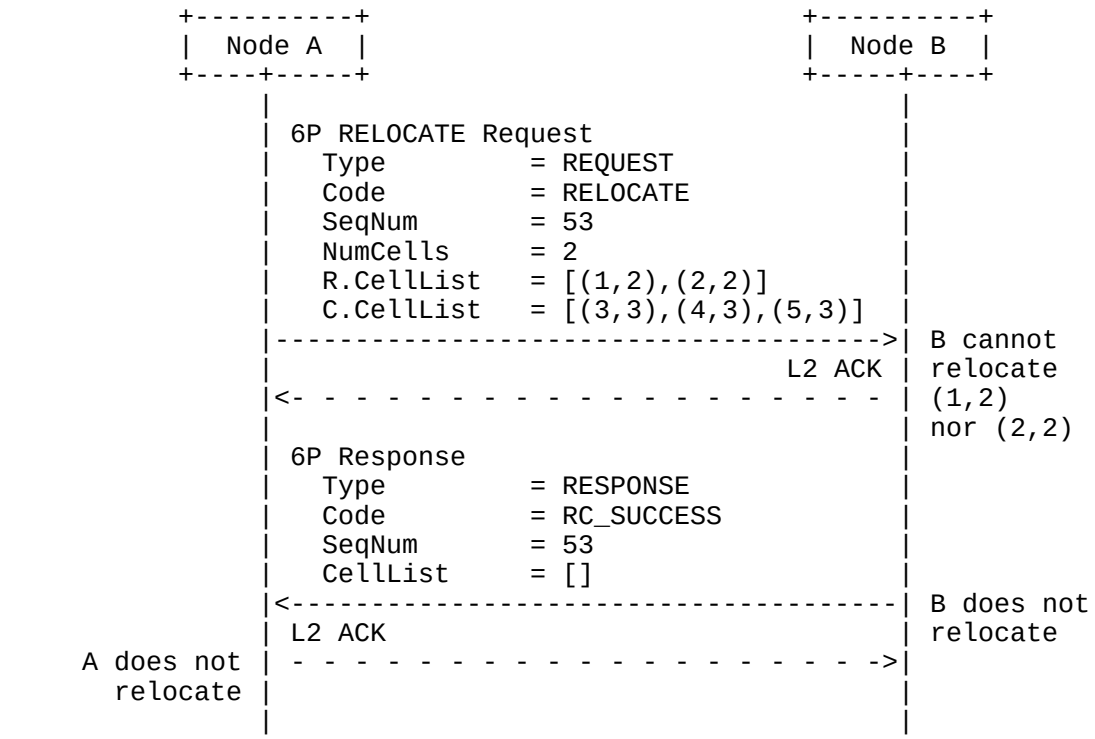

Figure 18: Failed 2-step 6P RELOCATION Transaction Example.

Figure 19 shows an example of a successful 3-step 6P RELOCATION Transaction.

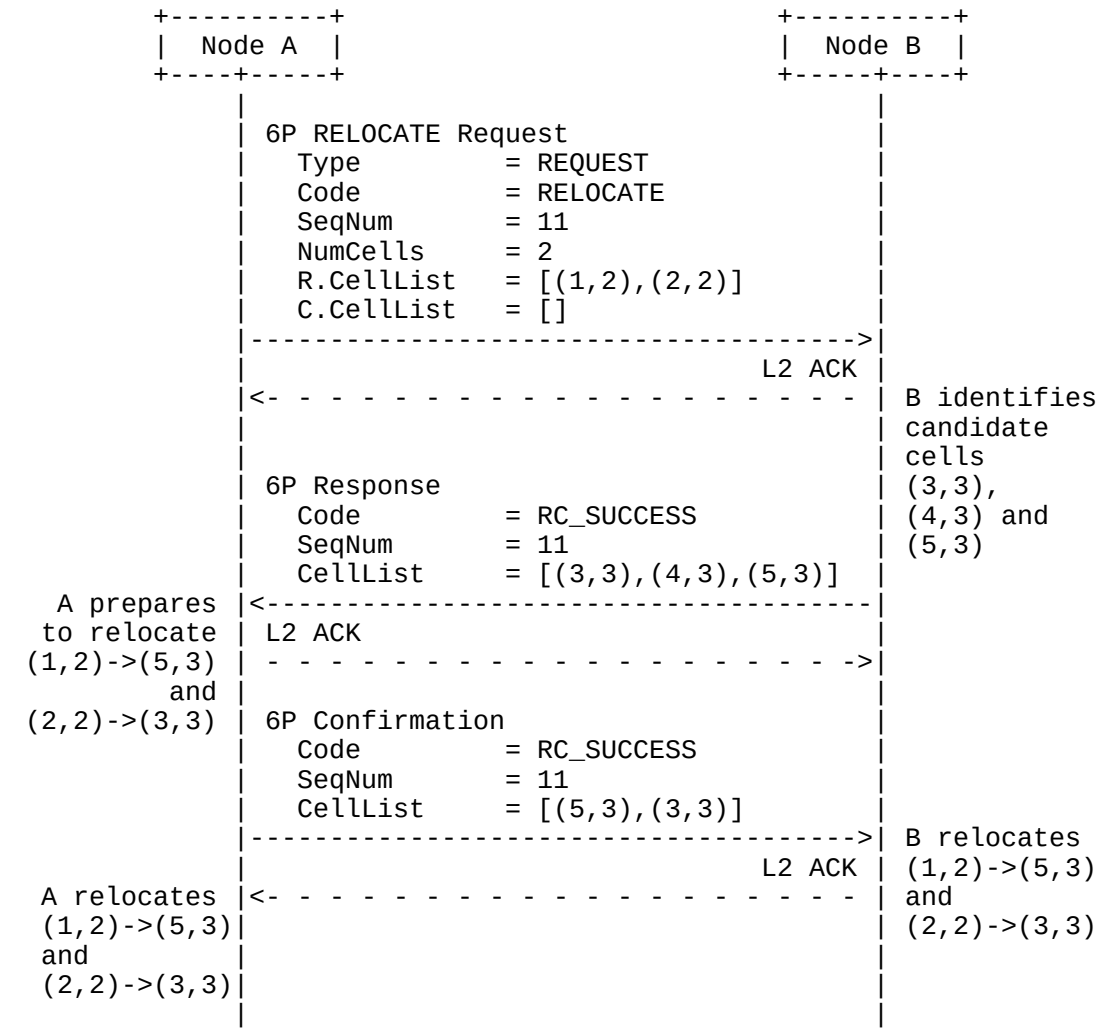

Figure 19: Example of a successful 3-step 6P RELOCATION Transaction.

3.3.4. Counting Cells

To retrieve the number of scheduled cells node A has with B, node A issues a 6P COUNT command. The Type field (T) is set to REQUEST. The Code field is set to COUNT. Figure 20 defines the format of a 6P COUNT Request.

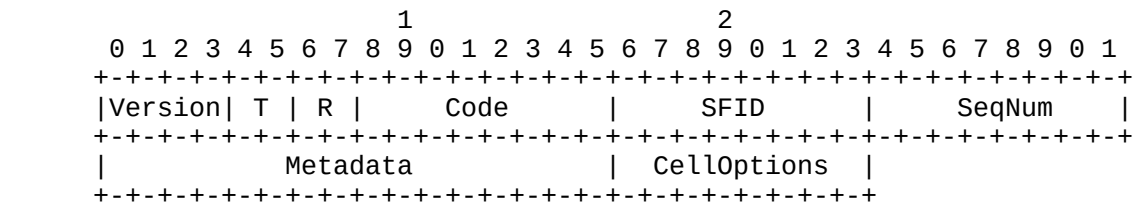

Figure 20: 6P COUNT Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1. Its format is the same as that in the 6P ADD command, but its content could be different.
CellOptions: Specifies which type of cell to be counted.

Figure 21 defines the format of a 6P COUNT Response.

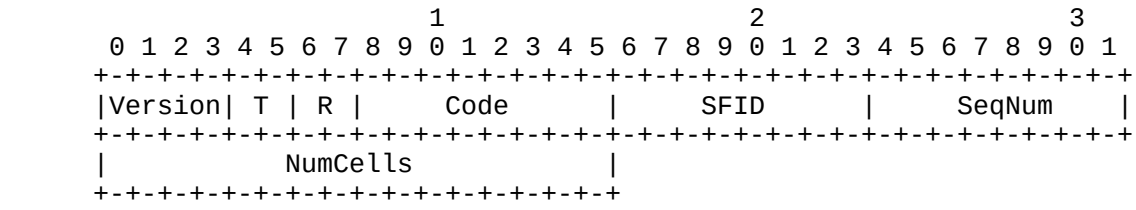

Figure 21: 6P COUNT Response Format.

NumCells: The number of cells which correspond to the fields of the request.

Node A issues a COUNT command to node B, specifying some cell options. Upon receiving the 6P COUNT request, node B goes through its schedule and counts the number of cells scheduled with node A in its own schedule which match the cell options in the CellOptions field of the request. Section 3.2.3 details the use of the CellOptions field.

Node B issues a 6P response to node A with return code set to RC_SUCCESS, and with NumCells containing the number of cells that match the request.

3.3.5. Listing Cells

To retrieve a list of scheduled cells node A has with node B, node A issues a 6P LIST command. The Type field (T) is set to REQUEST. The Code field is set to LIST. Figure 22 defines the format of a 6P LIST Request.

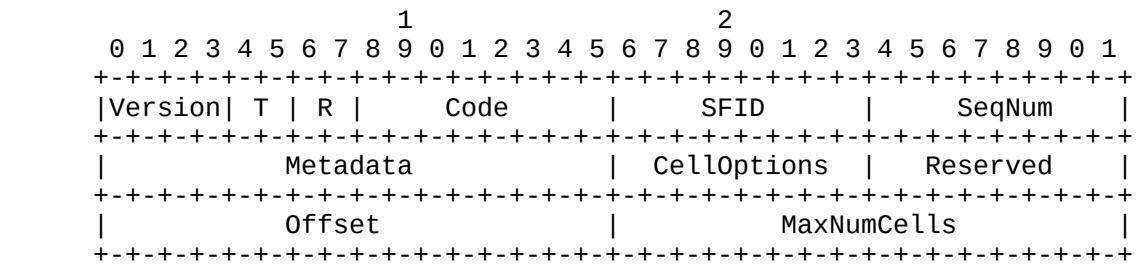

Figure 22: 6P LIST Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1. Its format is the same as that in the 6P ADD command, but its content could be different.

CellOptions: Specifies which type of cell to be listed.

Reserved: Reserved bits. These bits SHOULD be set to zero when sending the message, and MUST be ignored upon reception.

Offset: The Offset of the first scheduled cell that is requested. The mechanism assumes cells are ordered according to a rule defined in the SF. The rule MUST always order the cells in the same way.

MaxNumCells: The maximum number of cells to be listed. Node B MAY return fewer than MaxNumCells cells, for example if MaxNumCells cells do not fit in the frame.

Figure 23 defines the format of a 6P LIST Response.

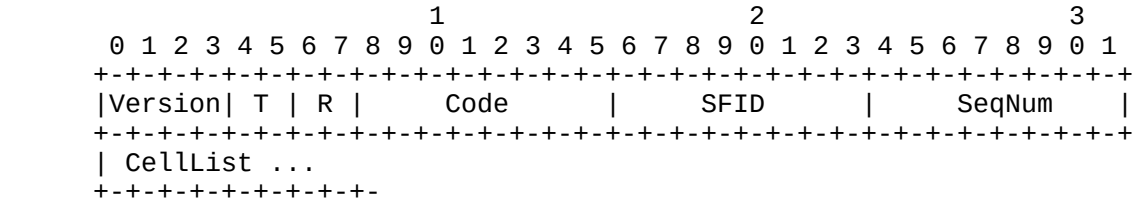

Figure 23: 6P LIST Response Format.

CellList: A list of 0 or more 6P Cells.

When receiving a LIST command, node B returns the cells scheduled with A in its schedule that match the CellOptions field as specified in Section 3.2.3.

When node B receives a LIST request, the returned CellList in the 6P Response contains between 0 and MaxNumCells cells, starting from the specified offset. Node B SHOULD include as many cells as fit in the frame. If the response contains the last cell, Node B MUST set the

Code field in the response to RC_EOL ("End of List", as per Figure 38), indicating to Node A that there no more cells that match the request. Node B MUST return at least one cell, unless the specified Offset is beyond the end of B's cell list in its schedule. If node B has fewer than Offset cells that match the request, node B returns an empty CellList and a Code field set to RC_EOL.

3.3.6. Clearing the Schedule

To clear the schedule between nodes A and B (for example after a schedule inconsistency is detected), node A issues a CLEAR command. The Type field (T) is set to 6P Request. The Code field is set to CLEAR. Figure 24 defines the format of a 6P CLEAR Request.

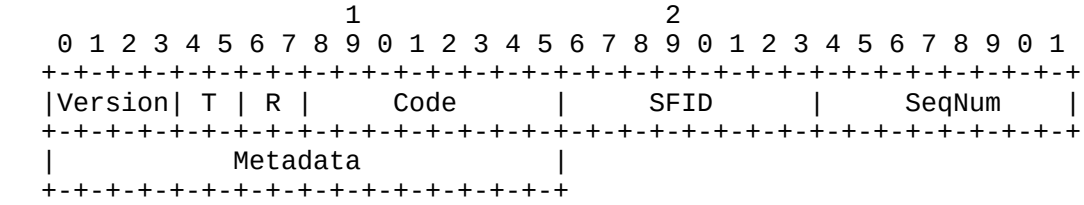

Figure 24: 6P CLEAR Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1. Its format is the same as that in the 6P ADD command, but its content could be different.

Figure 25 defines the format of a 6P CLEAR Response.

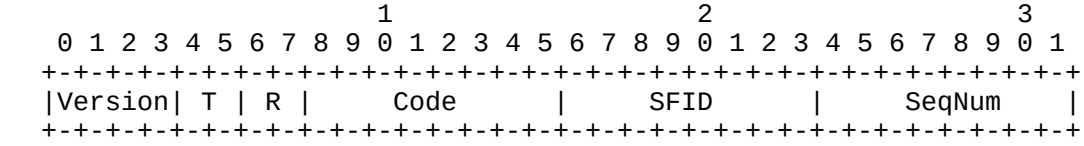

Figure 25: 6P CLEAR Response Format.

When a 6P CLEAR command is issued from node A to node B, both nodes A and B MUST remove all the cells scheduled between them. That is, node A MUST remove all the cells scheduled with node B, and node B MUST remove all the cells scheduled with node A. In a 6P CLEAR command, the SeqNum MUST NOT be checked. In particular, even if the request contains a SeqNum value that would normally cause node B to detect a schedule inconsistency, the transaction MUST NOT be aborted. Upon 6P CLEAR completion, the value of SeqNum MUST be reset to 0.

The return code to a 6P CLEAR command SHOULD be RC_SUCCESS unless the operation cannot be executed. When the CLEAR operation cannot be executed, the return code MUST be set to RC_RESET.

3.3.7. Generic Signaling Between SFs

The 6P SIGNAL message allows the SF implementations on two neighbor nodes to exchange generic commands. The payload in a received SIGNAL message is an opaque set of bytes passed unmodified to the SF. The length of the payload is determined through the length field of the Payload IE Header. How the generic SIGNAL command is used is specified by the SF, and outside the scope of this document. The Type field (T) is set to REQUEST. The Code field is set to SIGNAL. Figure 26 defines the format of a 6P SIGNAL Request.

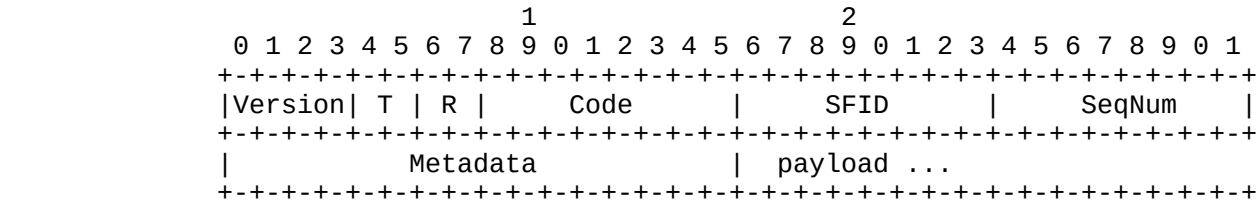

Figure 26: 6P SIGNAL Request Format.

Metadata: Same usage as for the 6P ADD command, see Section 3.3.1. Its format is the same as that in the 6P ADD command, but its content could be different.

Figure 27 defines the format of a 6P SIGNAL Response.

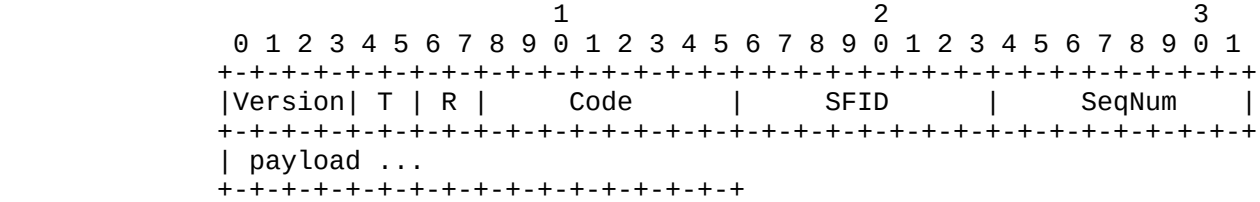

Figure 27: 6P SIGNAL Response Format.

3.4. Protocol Functional Details

3.4.1. Version Checking

All messages contain a Version field. If multiple Versions of the 6P protocol have been defined (in future specifications for Version values different from 0), a node MAY implement multiple protocol

versions at the same time. When a node receives a 6P message with a Version number it does not implement, the node MUST reply with a 6P Response with a return code field set to RC_ERR_VERSION. The format of this 6P Response message MUST be compliant with Version 0 and MUST be supported by all future versions of the protocol. This ensures that, when node B sends a 6P Response to node A indicating it does not implement the 6P version in the 6P Request, node A can successfully parse that response.

When a node supports a version number received in a 6P Request message, the Version field in the 6P Response MUST be the same as the Version field in the corresponding 6P Request. Similarly, in a 3-step transaction, the Version field in the 6P Confirmation MUST match that of the 6P Request and 6P Response of the same transaction.

3.4.2. SFID Checking

All messages contain an SFID field. A node MAY support multiple SFs at the same time. When receiving a 6P message with an unsupported SFID, a node MUST reply with a 6P Response with return code of RC_ERR_SFID. The SFID field in the 6P Response MUST be the same as the SFID field in the corresponding 6P Request. In a 3-step transaction, the SFID field in the 6P Confirmation MUST match that of the 6P Request and the 6P Response of the same transaction.

3.4.3. Concurrent 6P Transactions

Only a single 6P Transaction between two neighbors, in a given direction, can take place at the same time. That is, a node MUST NOT issue a new 6P Request to a given neighbor before the previous 6P Transaction it initiated has finished (possibly timed out). If a node receives a 6P Request from a given neighbor before having sent the 6P Response to the previous 6P Request from that neighbor, it MUST send back a 6P Response with a return code of RC_RESET (as per Figure 38) and discard this ongoing second transaction. A node receiving a RC_RESET code MUST abort the second transaction and consider it never happened (i.e. reverting changes to the schedule or SeqNum done by this transaction).

Nodes A and B MAY support having two transactions going on at the same time, one in each direction. Similarly, a node MAY support concurrent 6P Transactions with different neighbors. In this case, the cells involved in an ongoing 6P Transaction MUST be "locked" until the transaction finishes. For example, in Figure 1, node C can have a different ongoing 6P Transaction with nodes B and R. In case a node does not have enough resources to handle concurrent 6P Transactions from different neighbors it MUST reply with a 6P Response with return code RC_ERR_BUSY (as per Figure 38). In case

the requested cells are locked, it MUST reply to that request with a 6P Response with return code RC_ERR_LOCKED (as per Figure 38). The node receiving RC_ERR_BUSY or a RC_ERR_LOCKED MAY implement a retry mechanism, defined by the SF.

3.4.4. 6P Timeout

A timeout occurs when the node that successfully sent a 6P Request does not receive the corresponding 6P Response within an amount of time specified by the SF. In a 3-step transaction, a timeout also occurs when a node sending the 6P Response does not receive a 6P Confirmation. When a timeout occurs, the transaction MUST be canceled at the node where the timeout occurs. The value of the 6P Timeout should be larger than the longest possible time it takes to receive the 6P Response or Confirmation. The value of the 6P Timeout hence depends on the number of cells scheduled between the neighbor nodes, the maximum number of link-layer retransmissions, etc. The SF MUST determine the value of the timeout. The value of the timeout is out of scope of this document.

3.4.5. Aborting a 6P Transaction

In case the receiver of a 6P Request fails during a 6P Transaction and is unable to complete it, it SHOULD reply to that Request with a 6P Response with return code RC_RESET. Upon receiving this 6P Response, the initiator of the 6P Transaction MUST consider the 6P Transaction as failed.

Similarly, in the case of 3-step transaction, when the receiver of a 6P Response fails during the 6P Transaction and is unable to complete it, it MUST reply to that 6P Response with a 6P Confirmation with return code RC_RESET. Upon receiving this 6P Confirmation, the sender of the 6P Response MUST consider the 6P Transaction as failed.

3.4.6. SeqNum Management

The SeqNum is the field in the 6top IE header used to match Request, Response and Confirmation. The SeqNum is used to detect and handle duplicate commands (Section 3.4.6.1) and schedule inconsistencies (Section 3.4.6.2). Each node remembers the last used SeqNum for each neighbor. That is, a node stores as many SeqNum values as it has neighbors. In case of supporting multiple SFs at a time, a SeqNum value is maintained per SF and per neighbor. In the remainder of this section, we describe the use of SeqNum between two neighbors; the same happens for each other neighbor, independently.

When a node resets or after a CLEAR transaction, it MUST reset SeqNum to 0. The 6P Response and 6P Confirmation for a transaction MUST use

the same SeqNum value as that in the Request. After every transaction, the SeqNum MUST be incremented by exactly 1.

Specifically, if node A receives the link-layer acknowledgment for its 6P Request, it commits to incrementing the SeqNum by exactly 1 after the 6P Transaction ends. This ensure that, at the next 6P Transaction where it sends a 6P Request, 6P Request will have a different SeqNum.

Similarly, a node B increments the SeqNum by exactly 1 after having received the link-layer acknowledgment for the 6P Response (2-step 6P Transaction), or after having sent the link-layer acknowledgment for the 6P Confirmation (3-step 6P Transaction) .

When a node B receives a 6P Request from node A with SeqNum equal to 0, it checks the stored SeqNum for A. If A is a new neighbor, the stored SeqNum in B will be 0. The transaction can continue. If the stored SeqNum for A in B is different than 0, a potential inconsistency is detected. In this case, B MUST return RC_ERR_SEQNUM with SeqNum=0. The SF of node A MAY decide what to do next, as described in Section 3.4.6.2.

The SeqNum MUST be implemented as a lollipop counter: it rolls over from 0xFF to 0x01 (not to 0x00). This is used to detect a neighbor reset. Figure 28 lists the possible values of the SeqNum.

Value	Meaning
0x00	Clear or After device Reset
0x01-0xFF	Lollipop Counter values

Figure 28: Possible values of the SeqNum.

3.4.6.1. Detecting and Handling Duplicate 6P Messages

All 6P commands are link-layer acknowledged. A duplicate message means that a node receives a second 6P Request, Response or Confirmation. This happens when the link-layer acknowledgment is not received, and a link-layer retransmission happens. Duplicate messages are normal and unavoidable.

Figure 29 shows an example 2-step transaction in which Node A receives a duplicate 6P Response.

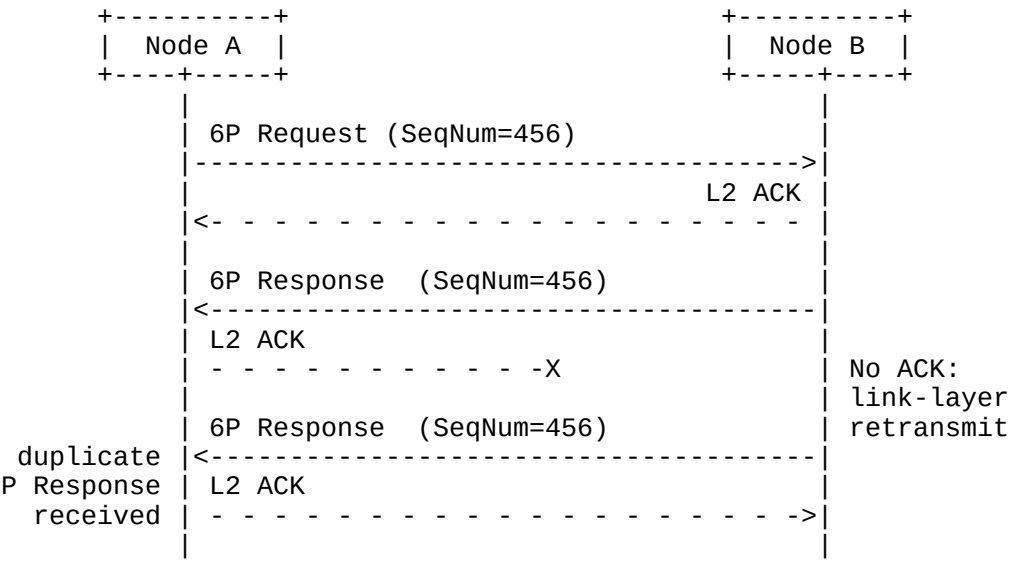

Figure 29: Example duplicate 6P message.

Figure 30 shows example 3-step transaction in which Node A receives a out-of-order duplicate 6P Response after having sent a 6P Confirmation.

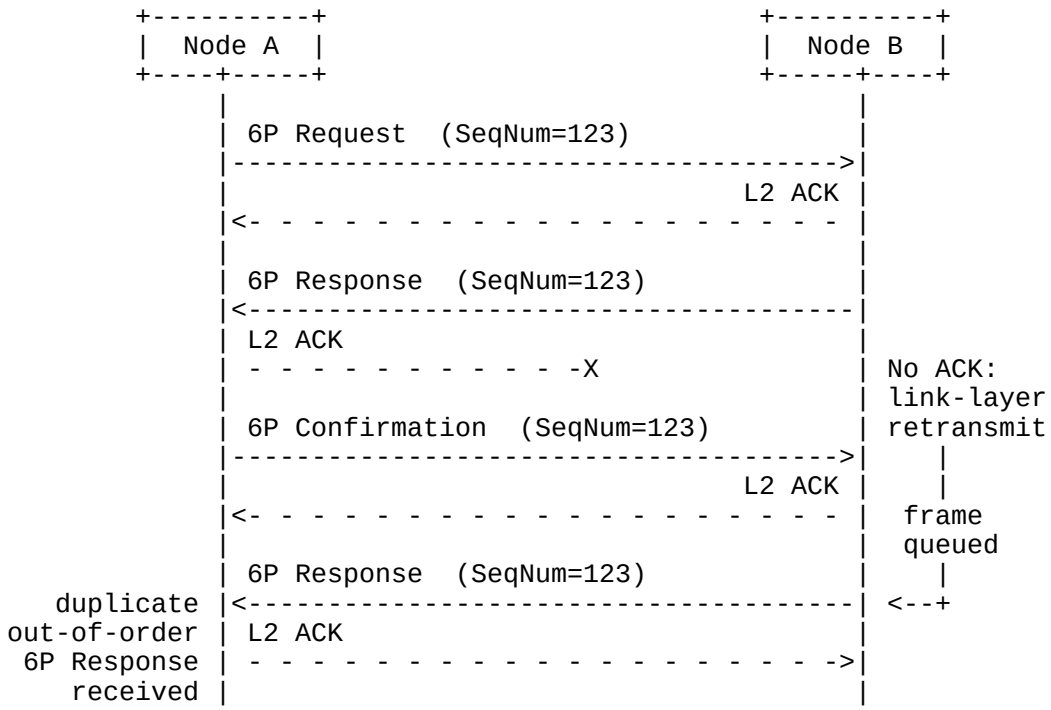

Figure 30: Example out-of-order duplicate 6P message.

A node detects a duplicate 6P message when it has the same SeqNum and type as the last frame received from the same neighbor. When receiving a duplicate 6P message, a node MUST send a link-layer acknowledgment, but MUST silently ignore the 6P message at the 6top sublayer.

3.4.6.2. Detecting and Handling a Schedule Inconsistency

A schedule inconsistency happens when the schedules of nodes A and B are inconsistent. For example, when node A has a transmit cell to node B, but node B does not have the corresponding receive cell, and therefore isn't listening to node A on that cell. A schedule inconsistency results in loss of connectivity.

The SeqNum field, which is present in each 6P message, is used to detect an inconsistency. The SeqNum field increments by 1 at each message, as detailed in Section 3.4.6. A node computes the expected SeqNum field for the next 6P Transaction. If a node receives a 6P Request with a SeqNum value that is not the expected one, it has detected an inconsistency.

There are at least 2 cases in which a schedule inconsistency happens.

The first case is when a node loses state, for example when it is power cycled (turned off, then on). In that case, its SeqNum value is reset to 0. Since the SeqNum is a lollipop counter, its neighbor detects an inconsistency at the next 6P transaction. This is illustrated in Figure 31 and Figure 32.

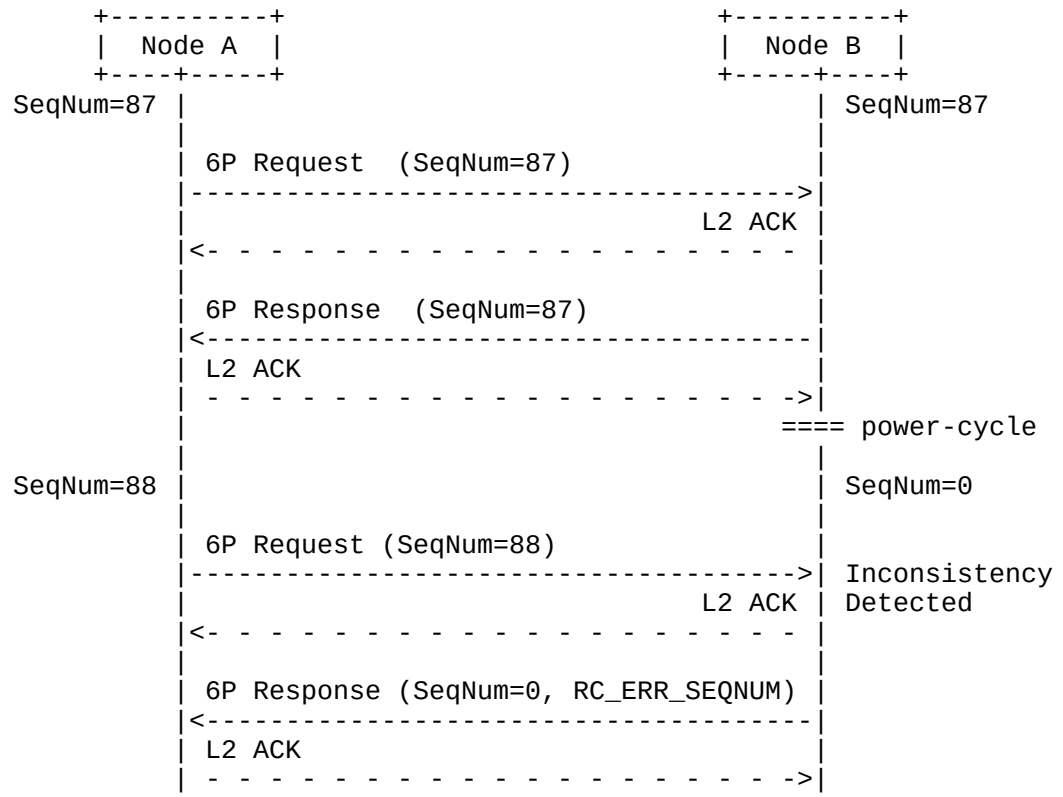

Figure 31: Example of inconsistency because of node B reset. Detected by node B

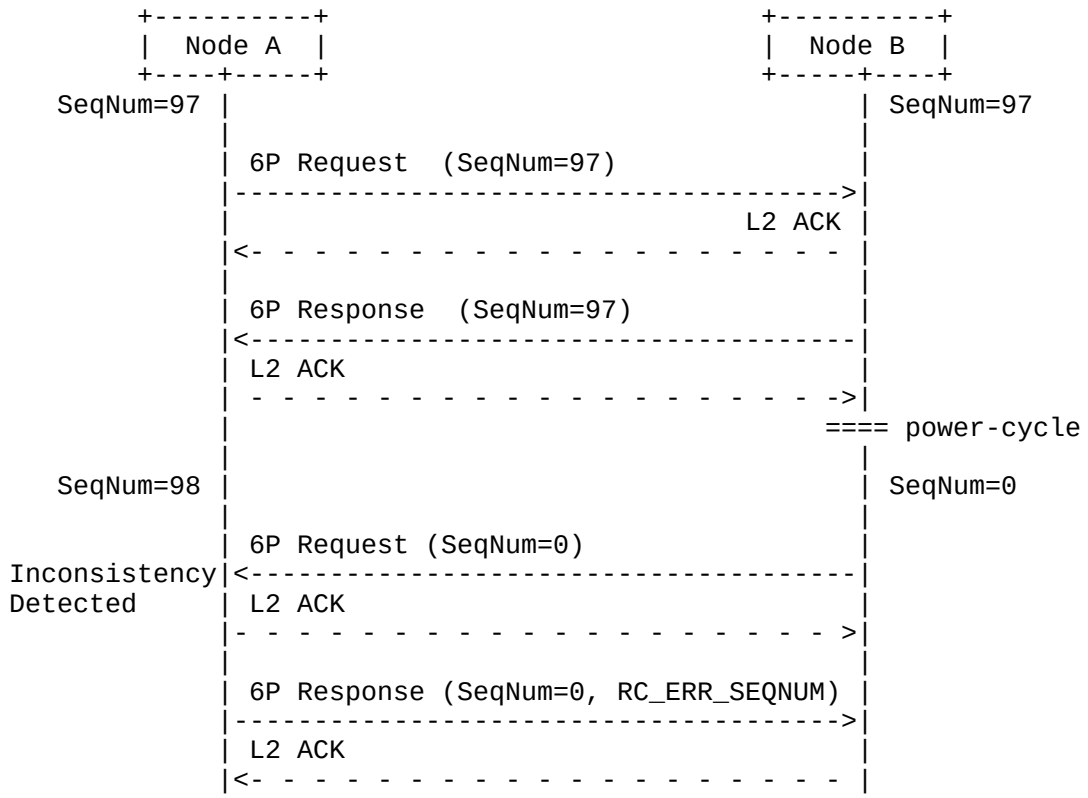

Figure 32: Example of inconsistency because node B resets. Detected by node A

The second case is when the maximum number of link-layer retransmissions is reached on the 6P Response of a 2-step transaction (or equivalently on a 6P Confirmation of a 3-step transaction). This is illustrated in Figure 33.

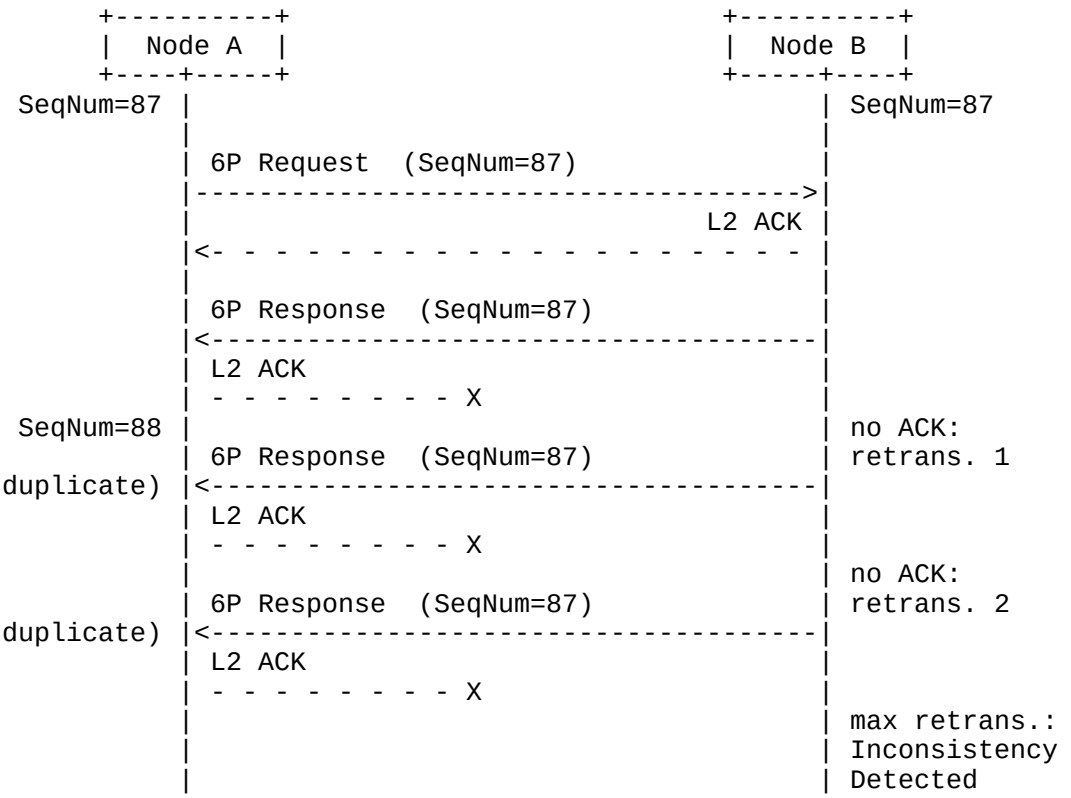

Figure 33: Example inconsistency because of maximum link-layer retransmissions (here 2).

In both cases, node B detects the inconsistency.

If the inconsistency is detected during a 6P Transaction (Figure 31), the node that has detected it MUST send back a 6P Response or 6P Confirmation with an error code of RC_ERR_SEQNUM. In this 6P Response or 6P Confirmation, the SeqNum field MUST be set to the value of the sender of the message (0 in the example in Figure 31).

The SF of the node which has detected the inconsistency MUST define how to handle the inconsistency. A first possibility is to issue a 6P CLEAR request to clear the schedule, and rebuild. A second possibility is to issue a 6P LIST request to retrieve the schedule. A third possibility is to internally "roll-back" the schedule. How to handle an inconsistency is out of scope of this document. The SF defines how to handle an inconsistency.

3.4.7. Handling Error Responses

A return code marked as Yes in the "Is Error" column in Figure 38 indicates an error. When a node receives a 6P Response or 6P Confirmation with an error, it MUST consider the 6P Transaction as failed. In particular, if this was a response to a 6P ADD, DELETE or RELOCATE Request, the node MUST NOT add, delete or relocate any of the cells involved in this 6P Transaction. Similarly, a node sending a 6P Response or a 6P Confirmation with an error code MUST NOT add, delete, relocate any cells as part of that 6P Transaction. If a node receives an unrecognized return code the 6P Transaction MUST be considered as failed. In particular, in a 3 step 6P Transaction, a 6P Response with an unrecognized return code MUST be responded with a 6P Confirmation with return code RC_ERR and consider the transaction as failed. Defining what to do after an error has occurred is out of scope of this document. The SF defines what to do after an error has occurred.

3.5. Security

6P messages MUST be secured through link-layer security. This is possible because 6P messages are carried as Payload IEs.

4. Requirements for 6top Scheduling Functions (SF) Specification

4.1. SF Identifier (SFID)

Each SF has a 1-byte identifier. Section 6.2.5 defines the rules for applying for an SFID.

4.2. Requirements for an SF specification

The specification for an SF

- MUST specify an identifier for that SF.
- MUST specify the rule for a node to decide when to add/delete one or more cells to a neighbor.
- MUST specify the rule for a Transaction source to select cells to add to the CellList field in the 6P ADD Request.
- MUST specify the rule for a Transaction destination to select cells from CellList to add to its schedule.
- MUST specify a value for the 6P Timeout, or a rule/equation to calculate it.
- MUST specify the rule for ordering cells.
- MUST specify a meaning for the "Metadata" field in the 6P ADD Request.
- MUST specify the SF behavior of a node when it boots.
- MUST specify how to handle a schedule inconsistency.

- MUST specify what to do after an error has occurred (either the node sent a 6P Response with an error code, or received one).
- MUST specify the list of statistics to gather. Example statistics include the number of transmitted frames to each neighbor. In case the SF requires no statistics to be gathered, the specific of the SF MUST explicitly state so.

- SHOULD clearly state the application domain the SF is created for.
- SHOULD contain examples which highlight normal and error scenarios.
- SHOULD contain a list of current implementations, at least during the I-D state of the document, per [RFC6982].
- SHOULD contain a performance evaluation of the scheme, possibly through references to external documents.
- SHOULD define the format of the SIGNAL command payload and its use.

- MAY redefine the format of the CellList field.
- MAY redefine the format of the CellOptions field.
- MAY redefine the meaning of the CellOptions field.

5. Security Considerations

6P messages are carried inside 802.15.4 Payload Information Elements (IEs). Those Payload IEs are encrypted and authenticated at the link layer through CCM* [CCM-Star]. 6P benefits from the same level of security as any other Payload IE. The 6P protocol does not define its own security mechanisms. In particular, although a key management solution is out of scope of this document, the 6P protocol will benefit for the key management solution used in the network. This is relevant as security attacks such as forgery and misattribution attacks become more damaging when a single key is shared amongst a group of more than 2 participants.

The 6P protocol does not provide protection against DOS attacks. Example attacks include, not sending confirmation messages in 3-step transaction, and sending wrongly formatted requests. These cases SHOULD be handled by an appropriate policy, such as rate-limiting or time-limited blacklisting the attacker after several attempts. The effect on the overall network is mostly localized to those two nodes, as communication happens in dedicated cells.

6. IANA Considerations

6.1. IETF IE Subtype '6P'

This document adds the following number to the "IEEE Std 802.15.4 IETF IE subtype IDs" registry defined by [RFC8137]:

Value	Subtype ID	Reference
<TBD>	SUBID_6TOP	RFCXXXX

Figure 34: IETF IE Subtype SUBID_6TOP.

6.2. 6TiSCH parameters sub-registries

This section defines sub-registries within the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry, hereafter referred to as the "6TiSCH parameters" registry. Each sub-registry is described in a subsection.

6.2.1. 6P Version Numbers

The name of the sub-registry is "6P Version Numbers".

A Note included in this registry should say: "In the 6top Protocol (6P) [RFCXXXX] there is a field to identify the version of the protocol. This field is 4 bits in size."

Each entry in the sub-registry must include the Version in the range 0-15, and a reference to the 6P version's documentation.

The initial entry in this sub-registry is as follows:

Version	Reference
0	RFCXXXX

Figure 35: 6P Version Numbers.

All other Version Numbers are Unassigned.

The IANA policy for future additions to this sub-registry is "IETF Review or IESG Approval" as described in [RFC8126].

6.2.2. 6P Message Types

The name of the sub-registry is "6P Message Types".

A note included in this registry should say: "In the 6top Protocol (6P) version 0 [RFCXXXX], there is a field to identify the type of message. This field is 2 bits in size."

Each entry in the sub-registry must include the Type in range b00-b11, the corresponding Name, and a reference to the 6P message type's documentation.

Initial entries in this sub-registry are as follows:

Type	Name	Reference
b00	REQUEST	RFCXXXX
b01	RESPONSE	RFCXXXX
b10	CONFIRMATION	RFCXXXX

Figure 36: 6P Message Types.

All other Message Types are Reserved.

The IANA policy for future additions to this sub-registry is "IETF Review or IESG Approval" as described in [RFC8126].

6.2.3. 6P Command Identifiers

The name of the sub-registry is "6P Command Identifiers".

A Note included in this registry should say: "In the 6top Protocol (6P) version 0 [RFCXXXX], there is a Code field which is 8 bits in size. In a 6P Request, the value of this Code field is used to identify the command."

Each entry in the sub-registry must include an Identifier in the range 0-255, the corresponding Name, and a reference to the 6P command identifier's documentation.

Initial entries in this sub-registry are as follows:

Identifier	Name	Reference
0	Reserved	
1	ADD	RFCXXXX
2	DELETE	RFCXXXX
3	RELOCATE	RFCXXXX
4	COUNT	RFCXXXX
5	LIST	RFCXXXX
6	SIGNAL	RFCXXXX
7	CLEAR	RFCXXXX
8-254	Unassigned	
255	Reserved	

Figure 37: 6P Command Identifiers.

The IANA policy for future additions to this sub-registry is "IETF Review or IESG Approval" as described in [RFC8126].

6.2.4. 6P Return Codes

The name of the sub-registry is "6P Return Codes".

A Note included in this registry should say: "In the 6top Protocol (6P) version 0 [RFCXXXX], there is a Code field which is 8 bits in size. In a 6P Response or 6P Confirmation, the value of this Code field is used to identify the return code."

Each entry in the sub-registry must include a Code in the range 0-255, the corresponding Name, the corresponding Description, and a reference to the 6P return code’s documentation.

Initial entries in this sub-registry are as follows:

Code	Name	Description	Is Error?
0	RC_SUCCESS	operation succeeded	No
1	RC_EOL	end of list	No
2	RC_ERR	generic error	Yes
3	RC_RESET	critical error, reset	Yes
4	RC_ERR_VERSION	unsupported 6P version	Yes
5	RC_ERR_SFID	unsupported SFID	Yes
6	RC_ERR_SEQNUM	schedule inconsistency	Yes
7	RC_ERR_CELLLIST	cellList error	Yes
8	RC_ERR_BUSY	busy	Yes
9	RC_ERR_LOCKED	cells are locked	Yes

Figure 38: 6P Return Codes.

All other Message Types are Unassigned.

The IANA policy for future additions to this sub-registry is "IETF Review or IESG Approval" as described in [RFC8126].

6.2.5. 6P Scheduling Function Identifiers

6P Scheduling Function Identifiers.

A Note included in this registry should say: "In the 6top Protocol (6P) version 0 [RFCXXXX], there is a field to identify the scheduling function to handle the message. This field is 8 bits in size."

Each entry in the sub-registry must include an SFID in the range 0-255, the corresponding Name, and a reference to the 6P Scheduling Function's documentation.

Initial entries in this sub-registry are as follows:

SFID	Name	Reference
0	Minimal Scheduling Function (MSF)	draft-chang-6tisch-msf

Figure 39: SF Identifiers (SFID).

All other Message Types are Unassigned.

The IANA policy for future additions to this sub-registry depends on the value of the SFID, as defined in Figure 40. These specifications must follow the guidelines of Section 4.

Range	Registration Procedures
0-127	IETF Review or IESG Approval
128-255	Expert Review

Figure 40: SF Identifier (SFID): Registration Procedure.

6.2.6. 6P CellOptions bitmap

The name of the sub-registry is "6P CellOptions bitmap".

A Note included in this registry should say: "In the 6top Protocol (6P) version 0 [RFCXXXX], there is an optional CellOptions field which is 8 bits in size."

Each entry in the sub-registry must include a bit position in the range 0-7, the corresponding Name, and a reference to the bit's documentation.

Initial entries in this sub-registry are as follows:

bit	Name	Reference
0	TX (Transmit)	RFCXXXX
1	RX (Receive)	RFCXXXX
2	SHARED	RFCXXXX
3-7	Reserved	

Figure 41: 6P CellOptions bitmap.

All other Message Types are Reserved.

The IANA policy for future additions to this sub-registry is "IETF Review or IESG Approval" as described in [RFC8126].

7. References

7.1. Normative References

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[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <https://www.rfc-editor.org/info/rfc2119>.

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Appendix A. Recommended Structure of an SF Specification

The following section structure for a SF document is RECOMMENDED:

- Introduction
- Scheduling Function Identifier
- Rules for Adding/Deleting Cells
- Rules for CellList
- 6P Timeout Value
- Rule for Ordering Cells
- Meaning of the Metadata Field
- Node Behavior at Boot
- Schedule Inconsistency Handling
- 6P Error Handling
- Examples
- Implementation Status
- Security Considerations
- IANA Considerations

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6TiSCH Experimental Scheduling Function (SFX)
draft-ietf-6tisch-6top-sfx-01

Abstract

This document defines a Scheduling Function called "Experimental Scheduling Function" (SFX). SFX dynamically adapts the number of scheduled cells between neighbor nodes, based on the amount of currently allocated cells and the neighbor nodes' cell requirements. Neighbor nodes negotiate in a distributed neighbor-to-neighbor basis the number of cell(s) to be added/deleted. SFX uses the 6P signaling messages to add/delete cells in the schedule. This function selects the candidate cells from the schedule, defines which cells will be added/deleted and triggers the allocation/deallocation process.

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 https://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 September 6, 2018.

Table of Contents

1. Introduction

This document defines a Scheduling Function using the 6P protocol [I-D.ietf-6tisch-6top-protocol], called "Experimental Scheduling Function" (SFX). SFX is designed to offer a number of functionalities to be usable in a wide range of applications. SFX defines two algorithms: the Scheduling Algorithm which defines the number of cells to allocate/delete between two neighbors, and the Relocation Algorithm defines when to relocate a cell.

To synthesize, a node running SFX determines when to add/delete cells in a three-step process:

1. It waits for a triggering event (Section 5.1).
2. It applies the Cell Estimation Algorithm (CEA) for a particular neighbor to determine how many cells are required to that neighbor (Section 5.2).
3. It applies the Allocation Policy to compare the number of required cells to the number of already scheduled cells, and determines the number of cells to add/delete (Section 5.3).

SFX addresses the requirements for a scheduling function listed in Section 5.2 from [I-D.ietf-6tisch-6top-protocol], and follows the recommended outline listed in Section 5.3 of [I-D.ietf-6tisch-6top-protocol]. This document follows the terminology defined in [I-D.ietf-6tisch-terminology].

2. Scheduling Function Identifier

The Scheduling Function Identifier (SFID) of SFX is IANA_6TISCH_SFID_SFX.

3. Allocated and Used Cells

An allocated cell is assigned as a TX, RX or Shared cell on the schedule, as a reserved resource. This reservation does not imply that a packet will be transmitted during the scheduled cell time. A used cell is a cell where a packet has been transmitted during the scheduled cell time on the last slotframe.

4. Overprovisioning

Overprovisioning is the action and effect of increasing a value representing an amount of resources. In the case of SFX, overprovisioning is done as a provision to reduce traffic variability effects on packet loss, to the expense of artificially allocating a number of cells.

5. Scheduling Algorithm

A number of TX cells must be allocated between neighbor nodes in order to enable data transmission among them. A portion of these allocated cells will be used by neighbors, while the remaining cells can be over-provisioned to handle unanticipated increases in cell requirements. The Scheduling Algorithm collects the cell allocation/deallocation requests from the neighbors and the number of cells which are currently under usage. First, the Cell Estimation Algorithm calculates the number of required cells and second, the calculated number is transferred to the Allocation Policy. In order to reduce consumption, this algorithm is triggered only when there is a change on the number of used cells from a particular node.

5.1. SFX Triggering Events

We RECOMMEND SFX to be triggered by the following event: if there is a change on the number of used cells towards any of the neighbors. The exact mechanism of when SFX is triggered is implementation-specific.

5.2. SFX Cell Estimation Algorithm

The Cell Estimation Algorithm takes into account the number of currently used cells to the neighbor. This allows the algorithm to estimate a new number of cells to be scheduled to the neighbor. As a consequence, the Cell Estimation Algorithm for SFX follows the steps described below:

1. Collect the current number of used cells to the neighbor.
2. Calculate the new number of cells to be scheduled to the neighbor by adding the current number of used cells plus an OVERPROVISION number of cells.
3. Transfer the request to the allocation policy as REQUIREDCELLS.
4. Return to step 1 and wait for a triggering event.

The Cell Estimation Algorithm is depicted in Figure 1. The OVERPROVISION parameter is calculated as a percentage of the number of currently scheduled cells to the neighbor. OVERPROVISION is added to the amount of used cells to the neighbor to reduce the probability of packet loss given a sudden growth on the number of used cells to the neighbor. The OVERPROVISION value is implementation-specific. A value of OVERPROVISION equal to zero leads to queue growth and possible packet loss. In this case, there are no overprovisioned cells where a sudden growth on the number of cells can absorbed and detected.

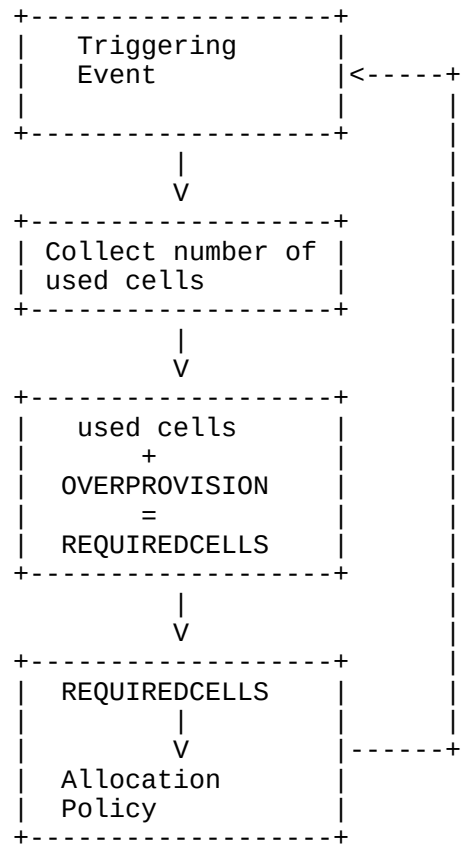

Figure 1: The SFX Estimation Algorithm

5.3. SFX Allocation Policy

The "Allocation Policy" is the set of rules used by SFX to decide when to add/delete cells to a particular neighbor to satisfy the cell requirements.

SFX uses the following parameters:

SCHEDULEDCELLS: The number of cells scheduled from the current node to a particular neighbor.

REQUIREDCELLS: The number of cells calculated by the Cell Estimation Algorithm from the current node to that neighbor.

SFXTHRESH: Threshold parameter introducing cell over-provisioning in the allocation policy. It is a non-negative value expressed as a number of cells. The definition of this value is implementation-

specific. A setting of SFXTHRESH>0 causes the node to allocate at least SFXTHRESH cells to each of its' neighbors.

The SFX allocation policy compares REQUIREDCELLS with SCHEDULEDCELLS and decides to add/delete cells taking into account SFXTHRESH. This is illustrated in Figure 2. The number of cells to be added/deleted is out of the scope of this document and it is implementation-dependent.

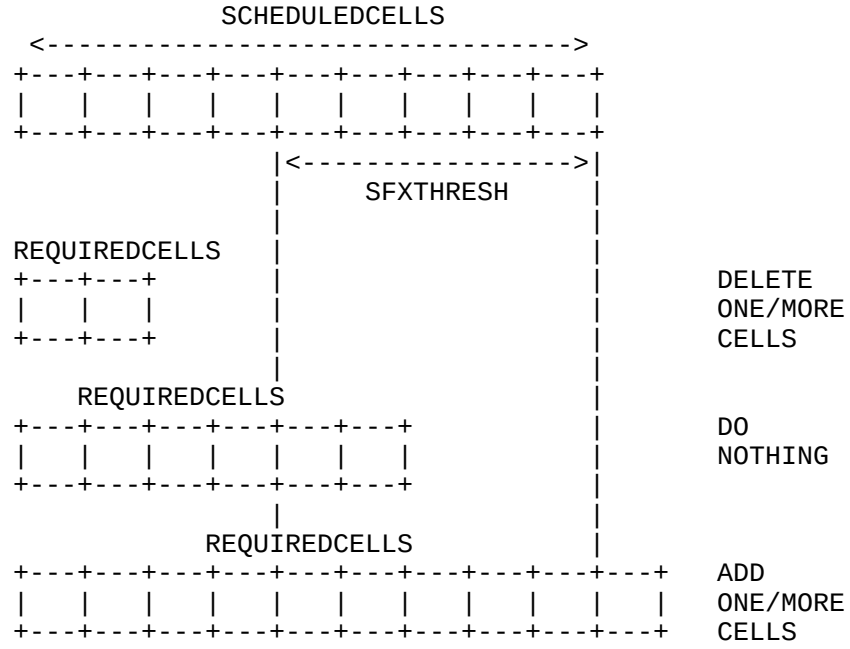

Figure 2: The SFX Allocation Policy

1. If REQUIREDCELLS<(SCHEDULEDCELLS-SFXTHRESH), delete one or more cells.
2. If (SCHEDULEDCELLS-SFXTHRESH)<=REQUIREDCELLS<=SCHEDULEDCELLS, do nothing.
3. If SCHEDULEDCELLS<REQUIREDCELLS, add one or more cells.

When SFXTHRESH equals 0, any discrepancy between REQUIREDCELLS and SCHEDULEDCELLS triggers an action to add/delete cells. Positive values of SFXTHRESH reduce the number of 6P Transactions. The number of cells to add or delete is implementation-specific.

6. Rules for CellList

There are two methods to define the CellList. The Whitelist method fills the CellList with the number of proposed cells to the neighbor. The Blacklist method fills the CellList with the cells which cannot be used by the neighbor. The rule to select the method is implementation-specific. When issuing a 6top ADD Request, SFX executes the following sequence:

Whitelist case:

The Transaction Source node prepares the CellList field by selecting randomly the required cells, verifying that the slot offset is not occupied and choose channelOffset randomly for each cell.
The Transaction Destination node goes through the cells in the CellList in order, verifying whether there are no slotOffset conflicts.

Blacklist case:

The Transaction Source node prepares the CellList field by building a list of currently scheduled cells into the CellList. The Transaction Destination node selects randomly the required cells from the unallocated cells on the schedule, verifying that the slot offset is not occupied from the ones on the CellList.

SFX does not include any transaction retry process. If the transaction is not successful, SFX will be retriggered on the next slotframe if the number of used cells changes.

7. 6P Timeout Value

The timeout value is implementation-specific. The timeout value MAY be different for each transaction and each neighbor. The timeout range is from 0 to 128. The timeout MUST be added as an 7-bit on the Metadata header to the neighbor. There is no measurement unit associated to the timeout value. If the timeout expires, the node issues a RESET return code will be issued to the neighbor. SFX has no retry policy. Timeout examples are depicted on Figure 3 and Figure 4.

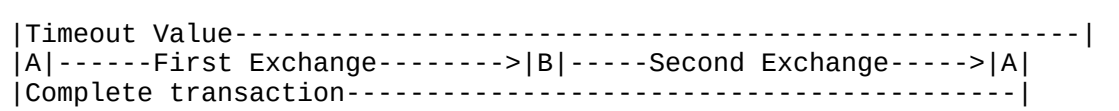

Figure 3: Example Transaction where the timeout does not expire

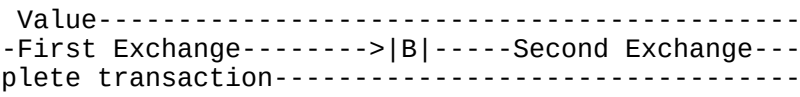

Figure 4: Example Transaction where the timeout expires

8. Meaning of Metadata Information

The Metadata 16-bit field is used as follows:

BITS 0-7 [SLOTFRAME] are used to identify the slotframe number
BITS 8-14 [TIMEOUT] represents the Timeout value
BIT 15 [WBLIST] is used to indicate that the CellList provided is a Whitelist (value=0) or a Blacklist (value=1).

9. Node Behavior at Boot

In order to define a known state after the node is restarted, a CLEAR command is issued to each of the neighbor nodes to enable a new allocation process and at least a SFXTHRESH number of cells MUST be allocated to each of the neighbors.

10. Cell Type

SFX uses the TX (Transmission) cell type only, thus defining celloptions as TX=0, RX=1 and S=0 according to section 4.2.6 of [I-D.ietf-6tisch-6top-protocol].

11. SFX Statistics

Packet Delivery Rate (PDR) is calculated per cell, as the percentage of acknowledged packets, for the last 10 packet transmission attempts. There is no retransmission policy on SFX.

12. Relocating Cells

Allocated cells may experience packet loss from different sources, such as noise, interference or cell collision (after the same cell is allocated by other nodes in range on the network).

SFX uses Packet Delivery Rate (PDR) statistics to monitor the currently allocated cells for cell relocation (by changing their slotOffset and/or channelOffset). When the PDR of one or more softcells is below PDR_THRESHOLD, SFX relocates each of the cell(s) to a number of available cells selected randomly. PDR_THRESHOLD is out of the scope of this document and it is implementation-dependent.

13. Forced Cell Deletion Policy

When all the cells are scheduled, we need a policy to free cells, for example, under alarm conditions, or if a node disappears from the neighbor list. The action to follow this condition is out of scope of this document and it is implementation-dependent.

14. 6P Error Handling

A node implementing SFX handles a 6P Response depending on the Return Code it contains:

RC_SUCCESS:
: If the number of elements in the CellList is the number of cells specified in the NumCells field of the 6P ADD Request, the operation is complete. The node does not take further action. If the number of elements in the CellList is smaller (possibly 0) than the number of cells specified in the NumCells field of the 6P ADD Request, the neighbor has received the request, but less than NumCells of the cells in the CellList were allocated. In that case, the node MAY retry immediately with a different CellList if the amount of storage space permits, or build a new (random) CellList.

RC_EOL:
: If an LIST command is issued and the RC_EOL is received, the node MUST understand what is specified on Section 3.3.5 of [I-D.ietf-6tisch-6top-protocol].

RC_ERR_VER:
: The node MUST NOT retry immediately. The node MAY add the neighbor node to a blacklist. The node MAY retry to contact this neighbor later.

RC_ERR_SFID:
: The node MUST NOT retry immediately. The node MAY add the neighbor node to a blacklist. The node MAY retry to contact this neighbor later.

RC_ERR_SEQNUM:
: The node MUST issue a CLEAR command to the neighbor.

RC_ERR_BUSY:
: Wait for a timeout and restart the scheduling process.

RC_ERR_CELLLIST:
: Wait for a timeout and restart the scheduling process.

RC_ERR_LOCKED:
: Wait for a timeout and restart the scheduling process.

RC_RESET:
: Abort 6P Transaction.

RC_ERR:
: Abort 6P Transaction. The node MAY retry to contact this neighbor later.

15. Experimental requirements

In order to evaluate the performance of this draft, we propose the following experimental work:

1. Define values for OVERPROVISION, SFXTHRESH and ranges to the number of cells to Add or Delete after the Allocation Policy is applied for typical use cases.
2. Analyze the scheduling stability (in terms of oscillation) and the hysteresis effect on scheduling using SFX. A tradeoff shall be found between the reactivity of the algorithm facing new scheduling requirements and the number of overprovisioned cells.
3. Define the PDR value below the Average which is most effective for blacklisting cells and a method to whitelist cells. Analyze the stability and long-term behavior of this algorithm.
4. Measure the distribution of cell scheduling delay (including the time taken by 6P) to estimate timeouts for different type of transactions.

16. Security Considerations

SFX is defined as an algorithm designed to efficiently fulfill bandwidth requirements between neighbour nodes and does not define a new protocol SFX uses the Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration standardized on [RFC8180] and the 6top Protocol (6P): [I-D.ietf-6tisch-6top-protocol]. SFX relies on the security framework described on [I-D.ietf-6tisch-minimal-security].

17. IANA Considerations

17.1. SFX Scheduling Function Identifiers

This document provide a new element to the "6P Scheduling Function Identifiers" sub-registry, which is part of the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry, as defined by [I-D.ietf-6tisch-6top-protocol]. This Subtype is defined on figure Figure 5

SFID	Name	Reference
IANA_6TISCH_SFID_SFX	Experimental Scheduling Function (SFX)	RFCXXXX (NOTE:this)

Figure 5: IETF IE Subtype ’6P’

18. Acknowledgments

Thanks to Kris Pister for his contribution in designing the default Bandwidth Estimation Algorithm. Thanks to Qin Wang and Thomas

Watteyne for their support in defining the interaction between SFX and the 6top sublayer.

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19. References

19.1. Normative References

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July 08, 2019

6tisch Zero-Touch Secure Join protocol
draft-ietf-6tisch-dtsecurity-zerotouch-join-04

Abstract

This document describes a Zero-touch Secure Join (ZSJ) mechanism to enroll a new device (the "pledge") into a IEEE802.15.4 TSCH network using the 6tisch signaling mechanisms. The resulting device will obtain a domain specific credential that can be used with either 802.15.9 per-host pair keying protocols, or to obtain the network-wide key from a coordinator. The mechanism describe here is an augmentation to the one-touch mechanism described in [I-D.ietf-6tisch-minimal-security], and is a profile of the constrained voucher mechanism [I-D.ietf-anima-constrained-voucher].

Status of This Memo

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1. Introduction

Enrollment of new nodes into LLNs present unique challenges. The constrained nodes has no user interfaces, and even if they did, configuring thousands of such nodes manually is undesireable from a human resources issue, as well as the difficulty in getting consistent results.

This document is about a standard way to introduce new nodes into a 6tisch network that does not involve any direct manipulation of the nodes themselves. This act has been called "zero-touch" provisioning, and it does not occur by chance, but requires coordination between the manufacturer of the node, the service operator running the LLN, and the installers actually taking the devices out of the shipping boxes.

The mechanism described in [I-D.ietf-anima-bootstrapping-keyinfra] has been adapted in [I-D.ietf-anima-constrained-voucher] to produce a protocol that is suited for constrained devices and constrained networks such as 6tisch. The above document/protocol is referred by by it's acronym: BRSKI and constrained-BRSKI. The pronounciation of which is "brew-ski", a common north american slang for beer with a

pseudo-polish ending. This constrained protocol is called Zero-touch Secure Join.

This document is a profile of [I-D.ietf-anima-constrained-voucher]. It uses COSE signatures of CBOR voucher [RFC8366] artifacts, and it uses [I-D.selander-ace-cose-ecdhe] as a Lightweight authenticated key exchange protocol.

[I-D.ietf-anima-constrained-voucher] has options for CMS signatures of CBOR vouchers, and for using DTLS. The protocol described in this document does not make use those options.

Like [I-D.ietf-anima-bootstrapping-keyinfra], the networks which are in scope for this protocol are deployed by a professional operator. The deterministic mechanisms which have been designed into 6tisch have been created to satisfy the operational needs of industrial settings where such an operator exists.

This document builds upon the "one-touch" provisioning described in [I-D.ietf-6tisch-minimal-security], reusing the OSCOAP Join Request mechanism when appropriate, but preceeding it with the EDHOC key agreement protocol.

As a second option, a certificate may be deployed using the constrained version of [RFC7030] EST described in [I-D.ietf-ace-coap-est].

Otherwise, this document follows BRSKI with the following high-level changes:

- HTTP is replaced with CoAP.
- TLS (HTTPS) is replaced with EDHOC/OSCOAP+CoAP
- the domain-registrar anchor certificate is replaced with a Raw Public Key (RPK) using [RFC7250].
- the PKCS7 signed JSON voucher format is replaced with COSE signature
- the GRASP discovery mechanism for the Proxy is replaced with an announcement in the Enhanced Beacon [I-D.richardson-6tisch-join-enhanced-beacon]
- the TCP circuit proxy mechanism is not used. The CoAP based stateless proxy mechanism described in [I-D.ietf-6tisch-minimal-security] section 7.1 is used.

- real time clocks are assumed to be unavailable, so expiry dates in ownership vouchers are never used

- nonce-full vouchers are encouraged, but off-line nonce-less operation is also supported, however, the resulting vouchers would have infinite life.

802.1AR Client certificates are retained, but optionally are specified by reference rather than value (Work in Progress).

It is expected that the back-end network operator infrastructure would be able to bootstrap ANIMA BRSKI-type devices over ethernet, while also being able bootstrap 6tisch devices over 802.15.4 with few changes.

1.1. Prior Bootstrapping Approaches

Constrained devices as used in industrial control systems are usually installed (or replaced) by technicians with expertise in the equipment being serviced, not in secure enrollment of devices.

Devices therefore are typically pre-configured in advance, marked for a particular factory, assembly line, or even down to the specific machine. It is not uncommon for manufacturers to have a unique product (stock keeping unit -SKU) for each customer as the part will be loaded with customer specifc security configuration. The resulting customer-specific parts are hard to inventory and very expensive to provide spares for. Should a part be delivered to the wrong customer, determining the reason for inability to configure is difficult and time consuming.

End-user actions to configure the part at the time of installation, aside from being error prone, also suffer from requiring a part that has a user interface.

1.2. Terminology

In this document, the key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" are to be interpreted as described in BCP 14, RFC 2119 [RFC2119] and indicate requirement levels for compliant STuPiD implementations.

The reader is expected to be familiar with the terms and concepts defined in [I-D.ietf-6tisch-terminology], [RFC7252], [I-D.ietf-core-object-security], [I-D.ietf-anima-bootstrapping-keyinfra] and [I-D.ietf-anima-constrained-voucher]. The following terms are

imported: drop ship, imprint, enrollment, pledge, join proxy, ownership voucher, and join registrar/coordinator (JRC). The following terms are repeated here for readability, but this document is not authoritative for their definition:

pledge the prospective device, which has the identity provided to at the factory. Neither the device nor the network knows if the device yet knows if this device belongs with this network.

Joined Node the prospective device, after having completing the join process, often just called a Node.

Join Proxy (JP): a stateless relay that provides connectivity between the pledge and the join registrar/coordinator.

Join Registrar/Coordinator (JRC): central entity responsible for authentication and authorization of joining nodes.

Audit Token A signed token from the manufacturer authorized signing authority indicating that the bootstrapping event has been successfully logged. This has been referred to as an "authorization token" indicating that it authorizes bootstrapping to proceed.

Ownership Voucher A signed voucher from the vendor vouching that a specific domain "owns" the new entity as defined in [I-D.ietf-anima-voucher].

MIC manufacturer installed certificate. An [ieee802-1AR] identity. Not to be confused with a (cryptographic) "Message Integrity Check"

1.3. Scope of solution

The solution described in this document is appropriate to enrolling between hundreds to hundreds of thousands of diverse devices into a network without any prior contact with the devices. The devices could be shipped by the manufacturer directly to the customer site without ever being seen by the operator of the network. As described in BRSKI, in the audit-mode of operation the device will be claimed by the first network that sees it. In the tracked owner mode of operation, sales channel integration provides a strong connection that the operator of the network is the legitimate owner of the device.

BRSKI describes a more general, more flexible approach for bootstrapping devices into an ISP or Enterprise network.

[I-D.ietf-6tisch-minimal-security] provides an extremely streamlined approach to enrolling from hundreds to thousands of devices into a network, provided that a unique secret key can be installed in each device.

1.4. Leveraging the new key infrastructure / next steps

In constrained networks, it is unlikely that an ACP be formed. This document does not preclude such a thing, but it is not mandated.

The resulting secure channel SHOULD be used just to distribute network-wide keys using a protocol such as [I-D.ietf-6tisch-minimal-security].

As a more complex, but but more secure alternative the resulting secure channel MAY be instead used to do an enrollment of an LDevID as in BRSKI. The resulting certificate is used to do per-pair keying such as described by {{ieee802159}.

XXX - this document does not yet provide a way to signal which mode the pledge should do.

1.4.1. Key Distribution Process

In addition to being used for the initial enrollment process, the secure channel SHOULD be kept open to use for network rekeying. The CoJP protocol described in [I-D.ietf-6tisch-minimal-security] includes a mechanism for rekeys in section 8.4.3.1.

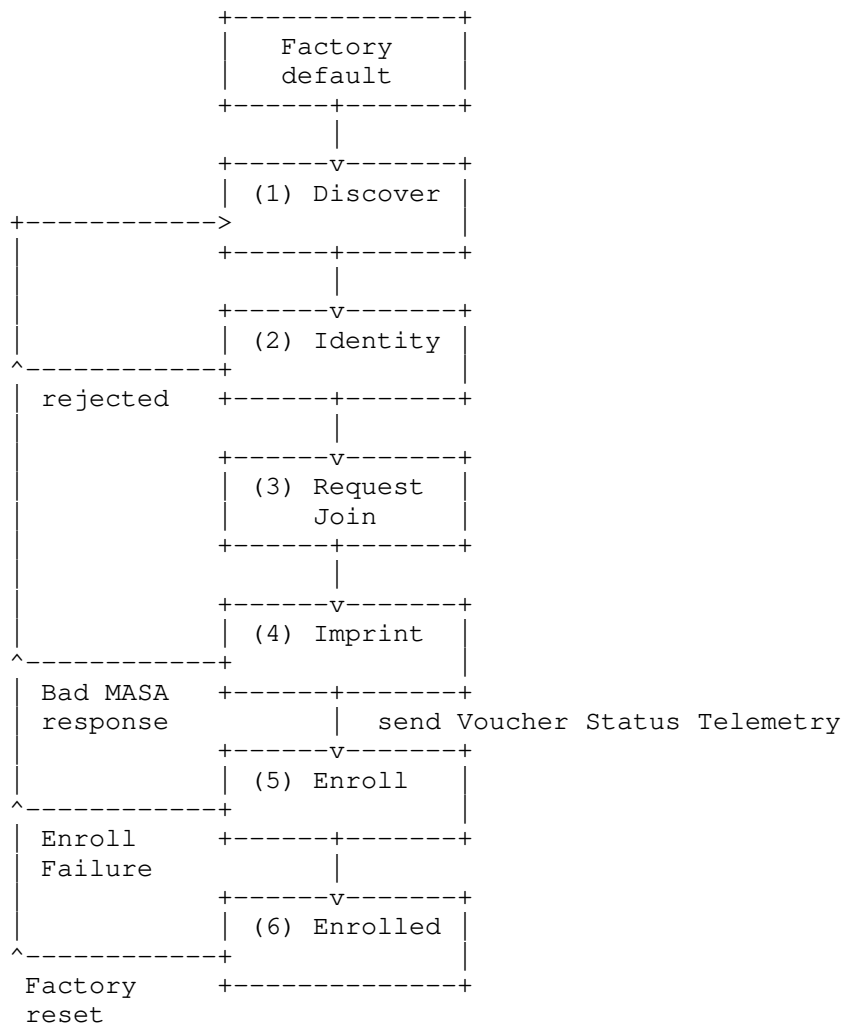
2. Architectural Overview

Section 2 of BRSKI has a diagram with all of the components shown together. There are no significant changes to the diagram.

The use of a circuit proxy is not desireable. The CoAP based stateless proxy mechanism described in [I-D.ietf-6tisch-minimal-security] section 7.1 MUST be used.

2.1. Behavior of a Pledge

The pledge goes through a series of steps which are outlined here at a high level.



State descriptions for the pledge are as follows:

1. Discover a communication channel to a Registrar. This is done by listening for beacons as described by [I-D.richardson-anima-6join-discovery]

2. Identify itself. This is done by presenting an X.509 IDevID credential to the discovered Registrar (via the Proxy) in the EDHOC handshake. The certificate MAY be presented by reference. (The Registrar credentials are only provisionally accepted at this time).

The registrar identifies itself using a raw public key, while the the pledge identifies itself to the registrar using an IDevID credential.

3. Requests to Join the discovered Registrar. A unique nonce SHOULD be included ensuring that any responses can be associated with this particular bootstrapping attempt.

4. Imprint on the Registrar. This requires verification of the vendor service (MASA) provided voucher. A voucher contains sufficient information for the Pledge to complete authentication of a Registrar. The voucher is signed by the vendor (MASA) using a raw public key, previously installed into the pledge at manufacturing time.

5. Optionally Enroll. By accepting the domain specific information from a Registrar, and by obtaining a domain certificate from a Registrar using a standard enrollment protocol, e.g. Enrollment over Secure Transport (EST) [RFC7030].

6. The Pledge is now a member of, and can be managed by, the domain and will only repeat the discovery aspects of bootstrapping if it is returned to factory default settings.

2.2. Secure Imprinting using Vouchers

As in BRSKI, there is a voucher mechanism based upon [RFC8366]. The format and cryptographic mechansim of the constrained vouchers is described in detail in [I-D.ietf-anima-constrained-voucher].

COSE signed vouchers and voucher-requests are MANDATORY.

2.3. Initial Device Identifier

The essential component of the zero-touch operation is that the pledge is provisioned with an 802.1AR (PKIX) certificate installed during the manufacturing process.

It is expected that constrained devices will use a signature algorithm corresponding to the hardware acceleration that they have, if they have any. The anticipated initial algorithms are the ECDSA P-256 (secp256v1). Newer devices SHOULD begin to appear using EdDSA curves using the 25519 curves.

The manufacturer will always know what algorithms are available in the Pledge, and will use an appropriate one. The other components that need to evaluate the IDevID (the Registrar and MASA) are expected to support all common algorithms.

The JRC is expected to be an easily updated appliance that can learn about new algorithms with a regular maintenance cycle.

There are a number of simplications detailed later on in this document designed to eliminate the need for an ASN.1 parser in the pledge.

The pledge should consider it's 802.1AR certificate to be an opaque blob of bytes, to be inserted into protocols at appropriate places. The pledge SHOULD have access to the underlying public and private keys in the most useable native format for computation.

The pledge MUST have the public key of the MASA built in a manufacturer time. This protocol optimizes for network bandwidth, and does not transfer the public key or certificate chain used to validate the voucher in-band.

This is a seemingly identical requirement as for BRSKI, but rather than being an abstract trust anchor that can be augmented with a certificate chain, the pledge MUST be provided with the Raw Public Key that the MASA will use to sign vouchers for that pledge.

This use of a direct key has drawbacks, section Section 9.1 addresses some of them with some operational suggestions.

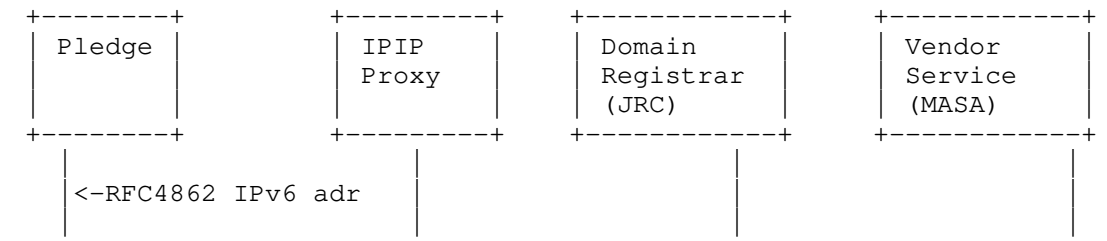
BRSKI places some clear requirements upon the contents of the IDevID, but leaves the exact origin of the voucher serial-number open. This document restricts the process to being the hwSerialNum OCTET STRING. As CWT can handle binary formats, no base64 encoding is necessary.

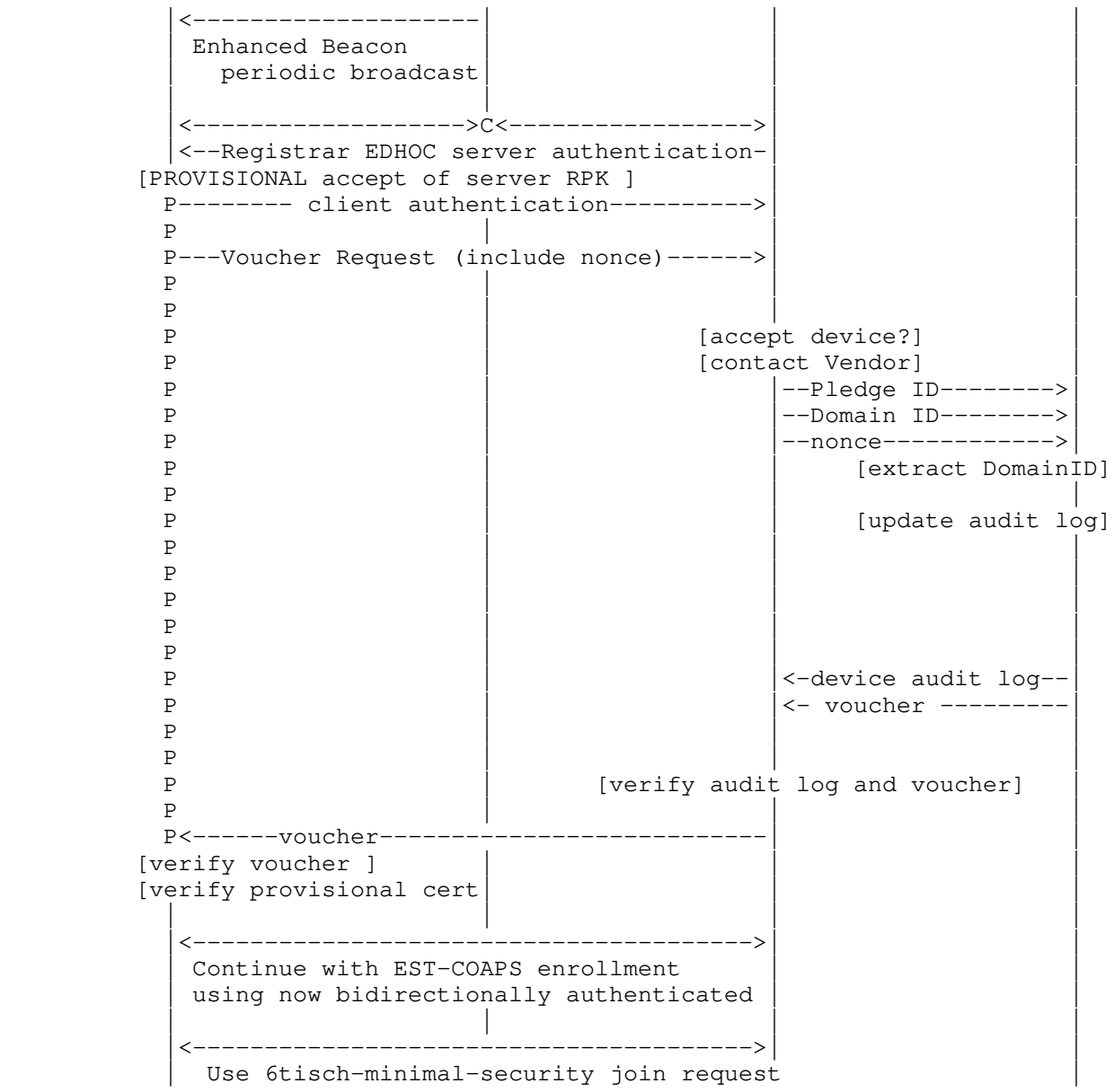
The MASA-URL extension MANDATORY. The inclusion of a MUD URL [RFC8520] is strongly recommended.

EDNOTE: here belongs text about sending only a reference to the IDevID rather than the entire certificate

2.4. Protocol Flow

This diagram from BRSKI is reproduced with some edits:





Noteable changes are:

1. no IPv4 support/options.

2. no mDNS steps, 6tisch only uses Enhanced Beacon

3. nonce-full option is always mandatory

2.5. Architectural Components

The bootstrap process includes the following architectural components:

2.5.1. Pledge

The Pledge is the device which is attempting to join. Until the pledge completes the enrollment process, it has network connectivity only to the Proxy.

2.5.2. Stateless IPIP Join Proxy

The stateless CoAP provides CoAP connectivity between the pledge and the registrar. The stateless CoAP proxy mechanism is described in [I-D.ietf-6tisch-minimal-security].

2.5.3. Domain Registrar

The Domain Registrar (having the formal name Join Registrar/ Coordinator (JRC)), operates as a CMC Registrar, terminating the CoAP-EST and BRSKI connections. The Registrar is manually configured or distributed with a list of trust anchors necessary to authenticate any Pledge device expected on the network. The Registrar communicates with the Vendor supplied MASA to establish ownership.

The JRC is typically located on the 6LBR/DODAG root, but it may be located elsewhere, provided IP level connectivity can be established. The 6LBR may also provide a proxy or relay function to connect to the actual registrar in addition to the IPIP proxy described above. The existence of such an additional proxy is a private matter, and this documents assumes without loss of generality that the registrar is co-located with the 6LBR.

2.5.4. Manufacturer Service

The Manufacturer Service provides two logically seperate functions: the Manufacturer Authorized Signing Authority (MASA), and an ownership tracking/auditing function. This function is identical to that used by BRSKI, except that a different format voucher is used.

2.6. Certificate Time Validation

2.6.1. Lack of realtime clock

For the constrained situation it is assumed that devices have no real time clock. These nodes do have access to a monotonically increasing clock that will not go backwards in the form of the Absolute Sequence Number. Synchronization to the ASN is required in order to transmit/receive data and most nodes will maintain it in hardware.

The heuristic described in BRSKI under this section SHOULD be applied if there are dates in the COSE format voucher.

Voucher requests SHOULD include a nonce. For devices intended for off-line deployment, the vouchers will have been generated in advance and no nonce-ful operation will not be possible.

2.7. Cloud Registrar

In 6tisch, the pledge never has network connectivity until it is enrolled, so no alternate registrar is ever possible.

2.8. Determining the MASA to contact

There are no changes from BRSKI: the IDevID provided by the pledge will contain a MASA URL extension.

3. Voucher-Request artifact

The voucher-request artifact is defined in [I-D.ietf-anima-constrained-voucher] section 6.1.

For the 6tisch ZSJ protocol defined in this document, only COSE signed vouchers as described in [I-D.ietf-anima-constrained-voucher] section 6.3.2 are supported.

4. Proxying details (Pledge - Proxy - Registrar)

The voucher-request artifact is defined in [I-D.ietf-anima-constrained-voucher].

The 6tisch use of the constrained version differs from the non-constrained version in two ways:

1. it does not include the proximity-registrar-cert, but rather uses the proximity-registrar-subjet-public-key-info entry. This accomodates the use of a raw public key to identify the registrar.

2. the pledge uses the proximity-registrar-subject-public-key-info to verify the raw public key for the JRC.

An appendix of [I-D.ietf-anima-constrained-voucher] shows example requests and responses.

5. Proxy details

The role of the Proxy is to facilitate communication. In the constrained situation the proxy needs to be stateless as there is very little ram in constrained nodes, and none can be allocated to keep state for an unlimited number of potential pledges.

5.1. Pledge discovery of Proxy

In BRSKI, the pledge discovers the proxy via use of a GRASP M_FLOOD messages sent by the proxy. In 6tisch ZSJ, the existence of the proxy is announced by the Enhanced Beacon message described in [I-D.richardson-6tisch-enrollment-enhanced-beacon]. The proxy as described by [I-D.ietf-6tisch-minimal-security] section 10 is to be used in an identical fashion when EDHOC and OSCOAP are used.

5.2. HTTPS proxy connection to Registrar

HTTPS connections are not used between the Pledge, Proxy and Registrar. The Proxy relays CoAP packets and does not interpret or terminate CoAP connections.

HTTPS is still used between the Registrar and MASA!

5.3. Proxy discovery of Registrar

In BRSKI, the proxy autonomically discovers the Registrar by listening for GRASP messages.

In the constrained network, the proxies are optionally configured with the address of the JRC by the Join Response in in [I-D.ietf-6tisch-minimal-security] section 9.3.2. (As described in that section, the address of the registrar otherwise defaults to be that of the DODAG root)

Whether or not a 6LR will announce itself as a possible Join Proxy is outside the scope of this document.

6. Protocol Details (Pledge - Registrar - MASA)

BRSKI is specified to run over HTTPS. This document respecifies it to run over CoAP with either DTLS or EDHOC-provided OSCOAP security.

BRSKI introduces the concept of a provisional state for EST.

[I-D.ietf-ace-coap-est] specifies that CoAP specifies the use of CoAP Block-Wise Transfer ("Block") [RFC7959] to fragment EST messages at the application layer.

As in [I-D.ietf-ace-coap-est], support for Observe CoAP options [RFC7641] with BRSKI is not supported in the current BRSKI/EST message flows.

Observe options could be used by the server to notify clients about a change in the cacerts or csr attributes (resources) and might be an area of future work.

Redirection as described in [RFC7030] section 3.2.1 is NOT supported.

6.1. BRSKI-EST (D)TLS establishment details

6tisch ZSJ does not use TLS. The connection is CoAP with EDHOC security.

6.1.1. BRSKI-EST CoAP estasblishment details

The details in the BRSKI document apply directly to use of DTLS.

The registrar SHOULD authenticate itself with a raw public key. A 256 bit ECDSA raw public key is RECOMMENDED. Pledges SHOULD support EDDSA keys if they contain hardware that supports doing so efficiently.

TBD: the Pledge needs to signal what kind of Raw Public Key it supports before the Registrar sends its ServerCertificate. Can SNI be used to do this?

The pledge SHOULD authenticate itself with the built-in IDevID certificate as a ClientCertificate.

6.1.2. BRSKI-EST CoAP/EDHOC estasblishment details

[I-D.selander-ace-cose-ecdhe] details how to use EDHOC. The EDHOC description identifiers a party U (the initiator), and a party V. The Pledge is the party U, and the JRC is the party V.

The communication from the Pledge is via CoAP via the Join Proxy. The Join proxy relays traffic to the JRC, and using the mechanism described in [I-D.ietf-6tisch-minimal-security] section 5.1. This is designed so that the Join Proxy does not need to know if it is performing the one-touch enrollment described in [I-D.ietf-6tisch-minimal-security] or the zero-touch enrollment protocol described in this document. A network could consist of a mix of nodes of each type.

As generating ephemeral keys is expensive for a low-resource Pledge, the use of a common E_U by the Pledge for multiple enrollment attempts (should the first turn out to be the wrong network) is encouraged.

The first communication detailed in [I-D.ietf-ace-coap-est] is to query the "/.well-known/core" resource to request the Link for EST. This is where the initial CoAP request is to sent.

The JRC MAY replace it's E_V ephermal key on a periodic basis, or even for every communication session.

The Pledge's ID_U is the Pledge's IDevID. It is transmitted in an x5bag [I-D.schaad-cose-x509]. An x5u (URL) MAY be used. An x5t (hash) MAY also be used and would be the smallest, but the Registrar may not know where to find the Pledge's IDevID unless the JRC has been preloaded will all the IDevIDs via out-of-band mechanism. It is impossible for the Pledge to know if the JRC has been loaded in such a way so x5t is discouraged for general use.

The JRC's ID_V is the JRC's Raw Public Key. It is transmitted as a key in COSE's YYY parameter.

The initial Mandatory to Implement (MTI) of an HKDF of SHA2-256, an AEAD based upon AES-CCM-16-64-128, a signature verification of TBD:BBBB, and signature generation of TBD:BBBB. The Pledge proposes a set of algorithms that it supports, and Pledge need not support more than one combination.

JRCs are expected to run on non-constrained servers, and are expected to support the above initial as MTI, and any subsequent ones that become common.

A JRC SHOULD support all available algorithms for a significant amount of time.

Even when algorithms become weak or suspect, it is likely that it will still have to perform secure join for older devices. A JRC that responds to such an older device might not in the end accept the

device into the network, but it is important that it be able to audit the event and communicate the event to an operator.

While EDHOC supports sending additional data in the message_3, in the constrained network situation, it is anticipated that the size of the this message will already be large, and no additional data is to be sent.

A COAP confirmable message SHOULD be used.

[I-D.ietf-6tisch-minimal-security] section 6 details how to setup OSCORE context given a shared key derived by EDHOC.

The registrar SHOULD authenticate itself with a raw public key.

The pledge SHOULD authenticate itself with the built-in IDevID certificate.

6.2. Pledge Requests Voucher from the Registrar

The voucher request and response as defined by BRSKI is modified slightly.

In order to simplify the pledge, the use of a certificate (and chain) for the Registrar is not supported. Instead the newly defined proximity-registrar-subject-public-key-info must contain the (raw) public key info for the Registrar. It MUST be byte for byte identical to that which is transmitted by the Registrar during the TLS ServerCertificate handshake.

BRSKI mandates that all voucher requests be signed.

6.3. Registrar Requests Voucher from MASA

There are no change from BRSKI, as this step is between two non-constrained devices.

The format of the voucher-request and voucher response is COSE, which implies changes to both the Registrar and the MASA, but semantically the content is the same.

The manufacturer will know what algorithms are supported by the pledge, and will issue a 406 (Conflict) error to the Registrar if the Registar's public key format is not supported by the pledge. It is however, too late for the Registar to use a different key, but at least it can log a reason for a failure.

It is likely that the ZSJ-BRSKI-EST connection has already failed, and this step is never reached.

6.3.1. MASA renewal of expired vouchers

There are assumed to be no useful real-time clocks on constrained devices, so all vouchers are in effect infinite duration. Pledges will use nonces for freshness, and a request for a new voucher with a new voucher for the same Registrar is not unusual.

A token-bucket system SHOULD be used such that no more than 24 vouchers are issued per-day, but more than one voucher can be issued in a one hour period. Tokens should not accumulate for more than one day.

6.3.2. MASA verification of voucher-request signature consistency

The voucher-request is signed by the Registrar using it's Raw Public Key. There is no additional certificate authority to sign this key. The MASA MAY have this key via sales-channel integration, but in most cases it will be seeing the key for the first time.

XXX-should the TLS connection from Registrar to MASA have a ClientCertificate? If so, then should it use the same Public Key? Or a different one?

6.3.3. MASA authentication of registrar (certificate)

IDEA: The MASA SHOULD pin the Raw Public Key (RPK) to the IP address that was first used to make a request with it. Should the RPK <-> IP address relationship be 1:1, 1:N, N:1? Should we take IP address to mean, "IP subnet", essentially the IPv4/24, and IPv6/64? The value of doing is about DDoS mitigation?

Should above mapping be on a per-Pledge basis?

6.3.4. MASA revocation checking of registrar (certificate)

As the Registrar has a Raw Public Key as an identity, there is no meaningful standard revocation checking that can be done. The MASA SHOULD have a blacklist table, and a way to add entries, but this process is out of scope.

6.3.5. MASA verification of pledge prior-signed-voucher-request

The Registrar will put the signed pledge voucher-request into it's voucher-request as 'prior-signed-voucher-request'. The MASA can

verify the signature from the Pledge using the MASA's copy of the Pledge's IDevID public key.

6.3.6. MASA pinning of registrar

When the MASA creates a voucher, it puts the Registrar's Raw Public Key into the 'pinned-domain-subject-public-key-info' leaf of the voucher.

The MASA does not include the 'pinned-domain-cert' field in such vouchers.

6.3.7. MASA nonce handling

Use of nonces is highly RECOMMENDED, but there are situations where not all components are connected at the same time in which the nonce will not be present.

There are no significant changes from BRSKI.

6.4. MASA Voucher Response

As exaplained in [I-D.ietf-anima-constrained-voucher] section 6.3.2, when a voucher is returned by the MASA to the JRC, a public key or certificate container that will verify the voucher SHOULD also be returned.

In order to do this, the MASA MAY return a multipart/related return, within that body, two items SHOULD be returned:

1. An application/voucher-cose+cbor body.

2. An application/TBD:SOMETHING containing a Raw Public Key.

A MASA is not obligated to return the public key, and MAY return only the application/voucher-cose+cbor object. In that case, the JRC will be unable to validate it, and will have to just audit the contents.

6.4.1. Pledge voucher verification

The Pledge receives the voucher from the Registrar over it's CoAP connection. It verifies the signature using the MASA anchor built in, as in the BRSKI case.

6.4.2. Pledge authentication of provisional TLS connection

The BRSKI process uses the pinned-domain-cert field of the voucher to validate the registrar's ServerCertificate. In the ZeroTouch case, the voucher will contain a pinned-domain-subject-public-key-info field containing the raw public key of the certificate. It should match, byte-to-byte with the raw public key ServerCertificate.

6.5. Pledge Voucher Status Telemetry

The voucher status telemetry report is communicated from the pledge to the registrar over CoAP channel. The shortened URL is as described in table QQQ.

6.6. Registrar audit log request

There are no changes to the Registrar audit log request.

6.6.1. MASA audit log response

There are no changes to the MASA audit log response.

6.6.2. Registrar audit log verification

There are no changes to how the Registrar verifies the audit log.

6.6.3. EST CSR Attributes

In 6tisch, no Autonomic Control Plane will be created, so none of the criteria for SubjectAltname found in [I-D.ietf-anima-autonomic-control-plane] apply.

The CSR Attributes request SHOULD NOT be performed.

6.6.4. EST Client Certificate Request

6tisch will use a certificate to:

1. to authenticate an 802.15.9 key agreement protocol.

2. to terminate an incoming DTLS or EDHOC key agreement as part of application data protection.

It is recommended that the requested subjectAltName contain only the [RFC4514] hwSerialNum.

6.6.5. Enrollment Status Telemetry

There are no changes to the status telemetry between Registrar and MASA.

6.6.6. Multiple certificates

Multiple certificates are not supported.

6.6.7. EST over CoAP

This document and [I-D.ietf-ace-coap-est] detail how to run EST over CoAP.

6.7. Use of Secure Transport for Minimal Join

Rather than bootstrap to a public key infrastructure, the secure channel MAY instead be for the minimal security join process described in [I-D.ietf-6tisch-minimal-security].

The desire to do a minimal-security join process is signaled by the Registrar in it's voucher-request by including a 'join-process' value of 'minimal'. The MASA copies this value into the voucher that is creates, and also logs this to the audit log.

When the secure channel was created with EDHOC, then the keys setup by EDHOC are simply used by OSCORE exactly as if they had been Pre-Shared. The keys derived by EDHOC SHOULD be stored by both Registrar and Pledge as their long term key should the join process need to be repeated.

7. IANA Considerations

No specific requests are made

8. Privacy Considerations

[I-D.ietf-6lo-privacy-considerations] details a number of privacy considerations important in Resource Constrained nodes. There are two networks and three sets of constrained nodes to consider. They are: 1. the production nodes on the production network. 2. the new pledges, which have yet to enroll, and which are on a join network. 3. the production nodes which are also acting as proxy nodes.

8.1. Privacy Considerations for Production network

The details of this are out of scope for this document.

8.2. Privacy Considerations for New Pledges

New Pledges do not yet receive Router Advertisements with PIO options, and so configure link-local addresses only based upon layer-2 addresses using the normal SLAAC mechanisms described in [RFC4191].

These link-local addresses are visible to any on-link eavesdropper (who is synchronized to the same Join Assistant), so regardless of what is chosen they can be seen. This link-layer traffic is encapsulated by the Join Proxy into IPIP packets and carried to the JRC. The traffic SHOULD never leave the operator's network, will be kept confidential by the layer-2 keys inside the LLN. As no outside traffic can enter the join network, to do any ICMP scanning as described in [I-D.ietf-6lo-privacy-considerations].

The join process described herein requires that some identifier meaningful to the network operator be communicated to the JRC. The join request with this object occurs within a secured CoAP channel, although the link-local address configured by the pledge will be visible in either the CoAP stateless proxy option (section 5.1 of [I-D.ietf-6tisch-minimal-security]), or in the equivalent DTLS stateless proxy option (reference TBD).

This need not be a manufacturer created EUI-64 as assigned by IEEE; it could be another value with higher entropy and less interesting vendor/device information. Regardless of what is chosen, it can be used to track where the device attaches.

For most constrained device, network attachment occurs very infrequently, often only once in their lifetime, so tracking opportunities may be rare. Once connected, the long 8-byte EUI64 layer-2 address is usually replaced with a short JRC assigned 2-byte address.

Additionally, during the enrollment process, a DTLS connection or EDHOC connection will be created. TLS1.3 will keep contents of the certificates transmitted private while TLS 1.2 will not. If the client certificate can be observed, then the device identity will be visible to passive observers in the 802.11AR IDevID certificate that is sent.

Even when TLS 1.3 is used, an active attacker could collect the information by creating a rogue proxy.

The use of a manufacturer assigned EUI64 (whether derived from IEEE assignment or created through another process during manufacturing time) is encouraged.

8.2.1. EUI-64 derived address for join time IID

The IID used in the link-local address used during the join process be a vendor assigned EUI-64. After the join process has concluded, the device SHOULD be assigned a unique randomly generated long address, and a unique short address (not based upon the vendor EUI-64) for use at link-layer address. At that point, all layer-3 content is encrypted by the layer-2 key.

9. Security Considerations

TBD

9.1. Security of MASA voucher signing key(s)

TBD

10. Acknowledgements

Kristofer Pister helped with many non-IETF references.

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Minimal Security Framework for 6TiSCH
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Abstract

This document describes the minimal framework required for a new device, called "pledge", to securely join a 6TiSCH (IPv6 over the TSCH mode of IEEE 802.15.4e) network. The framework requires that the pledge and the JRC (join registrar/coordinator, a central entity), share a symmetric key. How this key is provisioned is out of scope of this document. Through a single CoAP (Constrained Application Protocol) request-response exchange secured by OSCORE (Object Security for Constrained RESTful Environments), the pledge requests admission into the network and the JRC configures it with link-layer keying material and other parameters. The JRC may at any time update the parameters through another request-response exchange secured by OSCORE. This specification defines the Constrained Join Protocol and its CBOR (Concise Binary Object Representation) data structures, and configures the rest of the 6TiSCH communication stack for this join process to occur in a secure manner. Additional security mechanisms may be added on top of this minimal framework.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on January 30, 2020.

Table of Contents

1. Introduction

This document defines a "secure join" solution for a new device, called "pledge", to securely join a 6TiSCH network. The term "secure join" refers to network access authentication, authorization and parameter distribution, as defined in [I-D.ietf-6tisch-terminology]. The Constrained Join Protocol (CoJP) defined in this document handles parameter distribution needed for a pledge to become a joined node. Authorization mechanisms are considered out of scope. Mutual authentication during network access is achieved through the use of a secure channel, as configured by this document. This document also specifies a configuration of different layers of the 6TiSCH protocol stack that reduces the Denial of Service (DoS) attack surface during the join process.

This document presumes a 6TiSCH network as described by [RFC7554] and [RFC8180]. By design, nodes in a 6TiSCH network [RFC7554] have their radio turned off most of the time, to conserve energy. As a consequence, the link used by a new device for joining the network has limited bandwidth [RFC8180]. The secure join solution defined in this document therefore keeps the number of over-the-air exchanges to a minimum.

The micro-controllers at the heart of 6TiSCH nodes have a small amount of code memory. It is therefore paramount to reuse existing protocols available as part of the 6TiSCH stack. At the application layer, the 6TiSCH stack already relies on CoAP [RFC7252] for web transfer, and on OSCORE [I-D.ietf-core-object-security] for its end-to-end security. The secure join solution defined in this document therefore reuses those two protocols as its building blocks.

CoJP is a generic protocol that can be used as-is in all modes of IEEE Std 802.15.4, including the Time-Slotted Channel Hopping (TSCH) mode 6TiSCH is based on. CoJP may as well be used in other (low-power) networking technologies where efficiency in terms of communication overhead and code footprint is important. In such a case, it may be necessary to define configuration parameters specific to the technology in question, through companion documents. The overall process described in Section 4 and the configuration of the stack is specific to 6TiSCH.

CoJP assumes the presence of a Join Registrar/Coordinator (JRC), a central entity. The configuration defined in this document assumes that the pledge and the JRC share a secret cryptographic key, called PSK (pre-shared key). The PSK is used to configure OSCORE to provide a secure channel to CoJP. How the PSK is installed is out of scope of this document: this may happen during the provisioning phase or by a key exchange protocol that may precede the execution of CoJP.

When the pledge seeks admission to a 6TiSCH network, it first synchronizes to it, by initiating the passive scan defined in [IEEE802.15.4]. The pledge then exchanges CoJP messages with the JRC; these messages can be forwarded by nodes already part of the 6TiSCH network, called Join Proxies. The messages exchanged allow the JRC and the pledge to mutually authenticate, based on the properties provided by OSCORE. They also allow the JRC to configure the pledge with link-layer keying material, short identifier and other parameters. After this secure join process successfully completes, the joined node can interact with its neighbors to request additional bandwidth using the 6top Protocol [RFC8480] and start sending application traffic.

2. Terminology

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 BCP14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

The reader is expected to be familiar with the terms and concepts defined in [I-D.ietf-6tisch-terminology], [RFC7252], [I-D.ietf-core-object-security], and [RFC8152].

The specification also includes a set of informative specifications using the Concise data definition language (CDDL) [I-D.ietf-cbor-cddl].

The following terms defined in [I-D.ietf-6tisch-terminology] are used extensively throughout this document:

- pledge
- joined node
- join proxy (JP)
- join registrar/coordinator (JRC)

- enhanced beacon (EB)
- join protocol
- join process

The following terms defined in [RFC8505] are also used throughout this document:

- 6LoWPAN Border Router (6LBR)
- 6LoWPAN Node (6LN)

The term "6LBR" is used interchangeably with the term "DODAG root" defined in [RFC6550], assuming the two entities are co-located, as recommended by [I-D.ietf-6tisch-architecture].

The term "pledge", as used throughout the document, explicitly denotes non-6LBR devices attempting to join the network using their IEEE Std 802.15.4 network interface. The device that attempts to join as the 6LBR of the network and does so over another network interface is explicitly denoted as the "6LBR pledge". When the text equally applies to the pledge and the 6LBR pledge, the "(6LBR) pledge" form is used.

In addition, we use generic terms "pledge identifier" and "network identifier". See Section 3.

The terms "secret key" and "symmetric key" are used interchangeably.

3. Provisioning Phase

The (6LBR) pledge is provisioned with certain parameters before attempting to join the network, and the same parameters are provisioned to the JRC. There are many ways by which this provisioning can be done. Physically, the parameters can be written into the (6LBR) pledge using a number of mechanisms, such as a JTAG interface, a serial (craft) console interface, pushing buttons simultaneously on different devices, over-the-air configuration in a Faraday cage, etc. The provisioning can be done by the vendor, the manufacturer, the integrator, etc.

Details of how this provisioning is done is out of scope of this document. What is assumed is that there can be a secure, private conversation between the JRC and the (6LBR) pledge, and that the two devices can exchange the parameters.

Parameters that are provisioned to the (6LBR) pledge include:

- pledge identifier. The pledge identifier identifies the (6LBR) pledge. The pledge identifier MUST be unique in the set of all pledge identifiers managed by a JRC. The pledge identifier uniqueness is an important security requirement, as discussed in Section 9. The pledge identifier is typically the globally unique 64-bit Extended Unique Identifier (EUI-64) of the IEEE Std 802.15.4 device, in which case it is provisioned by the hardware manufacturer. The pledge identifier is used to generate the IPv6 addresses of the (6LBR) pledge and to identify it during the execution of the join protocol. For privacy reasons (see Section 10), it is possible to use a pledge identifier different from the EUI-64. For example, a pledge identifier may be a random byte string, but care needs to be taken that such a string meets the uniqueness requirement.

- Pre-Shared Key (PSK). A secret cryptographic key shared between the (6LBR) pledge and the JRC. The JRC additionally needs to store the pledge identifier bound to the given PSK. Each (6LBR) pledge MUST be provisioned with a unique PSK. The PSK SHOULD be a cryptographically strong key, at least 128 bits in length, indistinguishable by feasible computation from a random uniform string of the same length. How the PSK is generated and/or provisioned is out of scope of this specification. This could be done during a provisioning step or companion documents can specify the use of a key agreement protocol. Common pitfalls when generating PSKs are discussed in Section 9.

- Optionally, a network identifier. The network identifier identifies the 6TiSCH network. The network identifier MUST be carried within Enhanced Beacon (EB) frames. Typically, the 16-bit Personal Area Network Identifier (PAN ID) defined in [IEEE802.15.4] is used as the network identifier. However, PAN ID is not considered a stable network identifier as it may change during network lifetime if a collision with another network is detected. Companion documents can specify the use of a different network identifier for join purposes, but this is out of scope of this specification. Provisioning the network identifier is RECOMMENDED. However, due to operational constraints, the network identifier may not be known at the time when the provisioning is done. In case this parameter is not provisioned to the pledge, the pledge attempts to join one advertised network at a time, which significantly prolongs the join process. This parameter MUST be provisioned to the 6LBR pledge.

- Optionally, any non-default algorithms. The default algorithms are specified in Section 7.3.3. When algorithm identifiers are not exchanged, the use of these default algorithms is implied.

Additionally, the 6LBR pledge that is not co-located with the JRC needs to be provisioned with:

- Global IPv6 address of the JRC. This address is used by the 6LBR pledge to address the JRC during the join process. The 6LBR pledge may also obtain the IPv6 address of the JRC through other available mechanisms, such as DHCPv6, GRASP, mDNS, the use of which is out of scope of this document. Pledges do not need to be provisioned with this address as they discover it dynamically through CoJP.

4. Join Process Overview

This section describes the steps taken by a pledge in a 6TiSCH network. When a pledge seeks admission to a 6TiSCH network, the following exchange occurs:

1. The pledge listens for an Enhanced Beacon (EB) frame [IEEE802.15.4]. This frame provides network synchronization information, and tells the device when it can send a frame to the node sending the beacons, which acts as a Join Proxy (JP) for the pledge, and when it can expect to receive a frame. The Enhanced Beacon provides the L2 address of the JP and it may also provide its link-local IPv6 address.

2. The pledge configures its link-local IPv6 address and advertises it to the JP using Neighbor Discovery. This step may be omitted if the link-local address has been derived from a known unique interface identifier, such as an EUI-64 address.

3. The pledge sends a Join Request to the JP in order to securely identify itself to the network. The Join Request is forwarded to the JRC.

4. In case of successful processing of the request, the pledge receives a Join Response from the JRC (via the JP). The Join Response contains configuration parameters necessary for the pledge to join the network.

From the pledge's perspective, joining is a local phenomenon - the pledge only interacts with the JP, and it needs not know how far it is from the 6LBR, or how to route to the JRC. Only after establishing one or more link-layer keys does it need to know about the particulars of a 6TiSCH network.

The join process is shown as a transaction diagram in Figure 1:

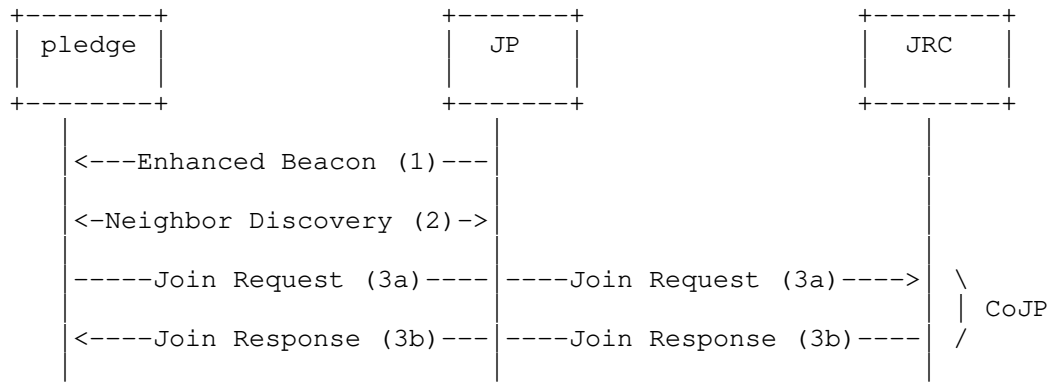

Figure 1: Overview of a successful join process.

As other nodes in the network, the 6LBR node may act as the JP. The 6LBR may in addition be co-located with the JRC.

The details of each step are described in the following sections.

4.1. Step 1 - Enhanced Beacon

The pledge synchronizes to the network by listening for, and receiving, an Enhanced Beacon (EB) sent by a node already in the network. This process is entirely defined by [IEEE802.15.4], and described in [RFC7554].

Once the pledge hears an EB, it synchronizes to the joining schedule using the cells contained in the EB. The pledge can hear multiple EBs; the selection of which EB to use is out of the scope for this document, and is discussed in [RFC7554]. Implementers should make use of information such as: what network identifier the EB contains, the value of the Join Metric field within EBs, whether the source link-layer address of the EB has been tried before, what signal strength the different EBs were received at, etc. In addition, the pledge may be pre-configured to search for EBs with a specific network identifier.

If the pledge is not provisioned with the network identifier, it attempts to join one network at a time, as described in Section 8.1.1.

Once the pledge selects the EB, it synchronizes to it and transitions into a low-power mode. It follows the schedule information contained in the EB which indicates the slots that the pledge may use for the join process. During the remainder of the join process, the node that has sent the EB to the pledge acts as the JP.

At this point, the pledge may proceed to step 2, or continue to listen for additional EBs.

4.2. Step 2 - Neighbor Discovery

The pledge forms its link-local IPv6 address based on the interface identifier, as per [RFC4944]. The pledge MAY perform the Neighbor Solicitation / Neighbor Advertisement exchange with the JP, as per Section 5.6 of [RFC8505]. The pledge and the JP use their link-local IPv6 addresses for all subsequent communication during the join process.

Note that Neighbor Discovery exchanges at this point are not protected with link-layer security as the pledge is not in possession of the keys. How JP accepts these unprotected frames is discussed in Section 5.

4.3. Step 3 - Constrained Join Protocol (CoJP) Execution

The pledge triggers the join exchange of the Constrained Join Protocol (CoJP). The join exchange consists of two messages: the Join Request message (Step 3a), and the Join Response message conditioned on the successful security processing of the request (Step 3b).

All CoJP messages are exchanged over a secure end-to-end channel that provides confidentiality, data authenticity and replay protection. Frames carrying CoJP messages are not protected with link-layer security when exchanged between the pledge and the JP as the pledge is not in possession of the link-layer keys in use. How JP and pledge accept these unprotected frames is discussed in Section 5. When frames carrying CoJP messages are exchanged between nodes that have already joined the network, the link-layer security is applied according to the security configuration used in the network.

4.3.1. Step 3a - Join Request

The Join Request is a message sent from the pledge to the JP, and which the JP forwards to the JRC. The pledge indicates in the Join Request the role it requests to play in the network, as well as the identifier of the network it requests to join. The JP forwards the Join Request to the JRC on the existing links. How exactly this happens is out of scope of this document; some networks may wish to dedicate specific link layer resources for this join traffic.

4.3.2. Step 3b - Join Response

The Join Response is sent by the JRC to the pledge, and is forwarded through the JP. The packet containing the Join Response travels from the JRC to the JP using the operating routes in the network. The JP delivers it to the pledge. The JP operates as the application-layer proxy.

The Join Response contains different parameters needed by the pledge to become a fully operational network node. These parameters include the link-layer key(s) currently in use in the network, the short address assigned to the pledge, the IPv6 address of the JRC needed by the pledge to operate as the JP, among others.

4.4. The Special Case of the 6LBR Pledge Joining

The 6LBR pledge performs Section 4.3 of the join process described above, just as any other pledge, albeit over a different network interface. There is no JP intermediating the communication between the 6LBR pledge and the JRC, as described in Section 6. The other steps of the described join process do not apply to the 6LBR pledge. How the 6LBR pledge obtains an IPv6 address and triggers the execution of the CoJP protocol is out of scope of this document.

5. Link-layer Configuration

In an operational 6TiSCH network, all frames MUST use link-layer frame security [RFC8180]. The IEEE Std 802.15.4 security attributes MUST include frame authenticity, and MAY include frame confidentiality (i.e. encryption).

The pledge does not initially do any authenticity check of the EB frames, as it does not possess the link-layer key(s) in use. The pledge is still able to parse the contents of the received EBs and synchronize to the network, as EBs are not encrypted [RFC8180].

When sending frames during the join process, the pledge sends unencrypted and unauthenticated frames. The JP accepts these unsecured frames for the duration of the join process. This behavior may be implemented by setting the "secExempt" attribute in the IEEE Std 802.15.4 security configuration tables. How the JP learns whether the join process is ongoing is out of scope of this specification.

When the pledge initially synchronizes to the network, it has no means of verifying the authenticity of EB frames. As an attacker can craft a frame that looks like a legitimate EB frame, this opens up a DoS vector, as discussed in Section 9.

5.1. Distribution of Time

Nodes in a 6TiSCH network keep a global notion of time known as the absolute slot number (ASN). ASN is used in the construction of the link-layer nonce, as defined in [IEEE802.15.4]. The pledge initially synchronizes to the EB frame sent by the JP, and uses the value of the ASN found in the TSCH Synchronization Information Element. At the time of the synchronization, the EB frame can neither be authenticated nor its freshness verified. During the join process, the pledge sends frames that are unprotected at the link-layer and protected end-to-end instead. The pledge does not obtain the time information as the output of the join process as this information is local to the network and may not be known at the JRC.

This enables an attack on the pledge where the attacker replays to the pledge legitimate EB frames obtained from the network and acts as a man-in-the-middle between the pledge and the JP. The EB frames will make the pledge believe that the replayed ASN value is the current notion of time in the network. By forwarding the join traffic to the legitimate JP, the attacker enables the pledge to join the network. Under different conditions relating to the reuse of the pledge's short address by the JRC or its attempt to rejoin the network, this may cause the pledge to reuse the link-layer nonce in the first frame it sends protected after the join process is completed.

For this reason, all frames originated at the JP and destined to the pledge during the join process MUST be authenticated at the link-layer using the key that is normally in use in the network. Link-layer security processing at the pledge for these frames will fail as the pledge is not yet in possession of the key. The pledge acknowledges these frames without link-layer security, and JP accepts the unsecured acknowledgment due to the secExempt attribute set for the pledge. The frames should be passed to the upper layer for processing using the promiscuous mode of [IEEE802.15.4] or another appropriate mechanism. When the upper layer processing is completed and the link-layer keys are configured, the upper layer MUST trigger the security processing of the corresponding frame. Once the security processing of the frame carrying the Join Response message is successful, the current ASN kept locally at the pledge SHALL be declared as valid.

6. Network-layer Configuration

The pledge and the JP SHOULD keep a separate neighbor cache for untrusted entries and use it to store each other's information during the join process. Mixing neighbor entries belonging to pledges and nodes that are part of the network opens up the JP to a DoS attack,

as the attacker may fill JP's neighbor table and prevent the discovery of legitimate neighbors.

Once the pledge obtains link-layer keys and becomes a joined node, it is able to securely communicate with its neighbors, obtain the network IPv6 prefix and form its global IPv6 address. The joined node then undergoes an independent process to bootstrap its neighbor cache entries, possibly with a node that formerly acted as a JP, following [RFC8505]. From the point of view of the JP, there is no relationship between the neighbor cache entry belonging to a pledge and the joined node that formerly acted as a pledge.

The pledge does not communicate with the JRC at the network layer. This allows the pledge to join without knowing the IPv6 address of the JRC. Instead, the pledge communicates with the JP at the network layer using link-local addressing, and with the JRC at the application layer, as specified in Section 7.

The JP communicates with the JRC over global IPv6 addresses. The JP discovers the network IPv6 prefix and configures its global IPv6 address upon successful completion of the join process and the obtention of link-layer keys. The pledge learns the IPv6 address of the JRC from the Join Response, as specified in Section 8.1.2; it uses it once joined in order to operate as a JP.

As a special case, the 6LBR pledge is expected to have an additional network interface that it uses in order to obtain the configuration parameters from the JRC and start advertising the 6TiSCH network. This additional interface needs to be configured with a global IPv6 address, by a mechanism that is out of scope of this document. The 6LBR pledge uses this interface to directly communicate with the JRC using global IPv6 addressing.

The JRC can be co-located on the 6LBR. In this special case, the IPv6 address of the JRC can be omitted from the Join Response message for space optimization. The 6LBR then MUST set the DODAGID field in the RPL DIOs [RFC6550] to its IPv6 address. The pledge learns the address of the JRC once joined and upon the reception of the first RPL DIO message, and uses it to operate as a JP.

6.1. Identification of Unauthenticated Traffic

The traffic that is proxied by the Join Proxy (JP) comes from unauthenticated pledges, and there may be an arbitrary amount of it. In particular, an attacker may send fraudulent traffic in an attempt to overwhelm the network.

When operating as part of a [RFC8180] 6TiSCH minimal network using distributed scheduling algorithms, the traffic from unauthenticated pledges may cause intermediate nodes to request additional bandwidth. An attacker could use this property to cause the network to overcommit bandwidth (and energy) to the join process.

The Join Proxy is aware of what traffic originates from unauthenticated pledges, and so can avoid allocating additional bandwidth itself. The Join Proxy implements a data cap on outgoing join traffic through CoAP's congestion control mechanism. This cap will not protect intermediate nodes as they can not tell join traffic from regular traffic. Despite the data cap implemented separately on each Join Proxy, the aggregate join traffic from many Join Proxies may cause intermediate nodes to decide to allocate additional cells. It is undesirable to do so in response to the traffic originated at unauthenticated pledges. In order to permit the intermediate nodes to avoid this, the traffic needs to be tagged. [RFC2597] defines a set of per-hop behaviors that may be encoded into the Diffserv Code Points (DSCPs). Based on the DSCP, intermediate nodes can decide whether to act on a given packet.

6.1.1. Traffic from JP to JRC

The Join Proxy SHOULD set the DSCP of packets that it produces as part of the forwarding process to AF43 code point (See Section 6 of [RFC2597]). A Join Proxy that does not set the DSCP on traffic forwarded should set it to zero so that it is compressed out.

A Scheduling Function (SF) running on 6TiSCH nodes SHOULD NOT allocate additional cells as a result of traffic with code point AF43. Companion SF documents SHOULD specify how this recommended behavior is achieved.

6.1.2. Traffic from JRC to JP

The JRC SHOULD set the DSCP of join response packets addressed to the Join Proxy to AF42 code point. AF42 has lower drop probability than AF43, giving this traffic priority in buffers over the traffic going towards the JRC.

Due to the convergecast nature of the DODAG, the 6LBR links are often the most congested, and from that point down there is progressively less (or equal) congestion. If the 6LBR paces itself when sending join response traffic then it ought to never exceed the bandwidth allocated to the best effort traffic cells. If the 6LBR has the capacity (if it is not constrained) then it should provide some buffers in order to satisfy the Assured Forwarding behavior.

Companion SF documents SHOULD specify how traffic with code point AF42 is handled with respect to cell allocation. In case the recommended behavior described in this section is not followed, the network may become prone to the attack discussed in Section 6.1.

7. Application-level Configuration

The CoJP join exchange in Figure 1 is carried over CoAP [RFC7252] and the secure channel provided by OSCORE [I-D.ietf-core-object-security]. The (6LBR) pledge acts as a CoAP client; the JRC acts as a CoAP server. The JP implements CoAP forward proxy functionality [RFC7252]. Because the JP can also be a constrained device, it cannot implement a cache.

The pledge designates a JP as a proxy by including the Proxy-Scheme option in CoAP requests it sends to the JP. The pledge also includes in the requests the Uri-Host option with its value set to the well-known JRC's alias, as specified in Section 8.1.1.

The JP resolves the alias to the IPv6 address of the JRC that it learned when it acted as a pledge, and joined the network. This allows the JP to reach the JRC at the network layer and forward the requests on behalf of the pledge.

7.1. Statelessness of the JP

The CoAP proxy defined in [RFC7252] keeps per-client state information in order to forward the response towards the originator of the request. This state information includes at least the CoAP token, the IPv6 address of the client, and the UDP source port number. Since the JP can be a constrained device that acts as a CoAP proxy, memory limitations make it prone to a Denial-of-Service (DoS) attack.

This DoS vector on the JP can be mitigated by making the JP act as a stateless CoAP proxy, where "state" encompasses the information related individual pledges. The JP can wrap the state it needs to keep for a given pledge throughout the network stack in a "state object" and include it as a CoAP token in the forwarded request to the JRC. The JP may use the CoAP token as defined in [RFC7252], if the size of the serialized state object permits, or use the extended CoAP token defined in [I-D.ietf-core-stateless], to transport the state object. Since the CoAP token is echoed back in the response, the JP is able to decode the state object and configure the state needed to forward the response to the pledge. The information that the JP needs to encode in the state object to operate in a fully stateless manner with respect to a given pledge is implementation specific.

It is RECOMMENDED that the JP operates in a stateless manner and signals the per-pledge state within the CoAP token, for every request it forwards into the network on behalf of unauthenticated pledges. When operating in a stateless manner, the security considerations from [I-D.ietf-core-stateless] apply and the type of the CoAP message that the JP forwards on behalf of the pledge MUST be non-confirmable (NON), regardless of the message type received from the pledge. The use of a non-confirmable message by the JP alleviates the JP from keeping CoAP message exchange state. The retransmission burden is then entirely shifted to the pledge. A JP that operates in a stateless manner still needs to keep congestion control state with the JRC, see Section 9. Recommended values of CoAP settings for use during the join process, both by the pledge and the JP, are given in Section 7.2.

Note that in some networking stack implementations, a fully (per-pledge) stateless operation of the JP may be challenging from the implementation's point of view. In those cases, the JP may operate as a statefull proxy that stores the per-pledge state until the response is received or timed out, but this comes at a price of a DoS vector.

7.2. Recommended Settings

This section gives RECOMMENDED values of CoAP settings during the join process.

Name	Default Value: Pledge	Default Value: JP
ACK_TIMEOUT	10 seconds	(10 seconds)
ACK_RANDOM_FACTOR	1.5	(1.5)
MAX_RETRANSMIT	4	(4)

Recommended CoAP settings. Values enclosed in () have no effect when JP operates in a stateless manner.

These values may be configured to values specific to the deployment. The default values have been chosen to accommodate a wide range of deployments, taking into account dense networks.

The PROBING_RATE value at the JP is controlled by the join rate parameter, see Section 8.4.2. Following [RFC7252], the average data rate in sending to the JRC must not exceed PROBING_RATE. For

security reasons, the average data rate SHOULD be measured over a rather short window, e.g. ACK_TIMEOUT, see Section 9.

7.3. OSCORE

Before the (6LBR) pledge and the JRC start exchanging CoAP messages protected with OSCORE, they need to derive the OSCORE security context from the provisioned parameters, as discussed in Section 3.

The OSCORE security context MUST be derived as per Section 3 of [I-D.ietf-core-object-security].

- the Master Secret MUST be the PSK.
- the Master Salt MUST be the empty byte string.
- the ID Context MUST be set to the pledge identifier.
- the ID of the pledge MUST be set to the empty byte string. This identifier is used as the OSCORE Sender ID of the pledge in the security context derivation, since the pledge initially acts as a CoAP client.
- the ID of the JRC MUST be set to the byte string 0x4a5243 ("JRC" in ASCII). This identifier is used as the OSCORE Recipient ID of the pledge in the security context derivation, as the JRC initially acts as a CoAP server.
- the Algorithm MUST be set to the value from [RFC8152], agreed out-of-band by the same mechanism used to provision the PSK. The default is AES-CCM-16-64-128.
- the Key Derivation Function MUST be agreed out-of-band by the same mechanism used to provision the PSK. Default is HKDF SHA-256 [RFC5869].

Since the pledge's OSCORE Sender ID is the empty byte string, when constructing the OSCORE option, the pledge sets the k bit in the OSCORE flag byte, but indicates a 0-length kid. The pledge transports its pledge identifier within the kid context field of the OSCORE option. The derivation in [I-D.ietf-core-object-security] results in OSCORE keys and a common IV for each side of the conversation. Nonces are constructed by XOR'ing the common IV with the current sequence number. For details on nonce and OSCORE option construction, refer to [I-D.ietf-core-object-security].

Implementations MUST ensure that multiple CoAP requests, including to different JRCs, are properly incrementing the sequence numbers, so

that the same sequence number is never reused in distinct requests. The pledge typically sends requests to different JRCs if it is not provisioned with the network identifier and attempts to join one network at a time. Failure to comply will break the security guarantees of the Authenticated Encryption with Associated Data (AEAD) algorithm because of nonce reuse.

This OSCORE security context is used for initial joining of the (6LBR) pledge, where the (6LBR) pledge acts as a CoAP client, as well as for any later parameter updates, where the JRC acts as a CoAP client and the joined node as a CoAP server, as discussed in Section 8.2. Note that when the (6LBR) pledge and the JRC change roles between CoAP client and CoAP server, the same OSCORE security context as initially derived remains in use and the derived parameters are unchanged, for example Sender ID when sending and Recipient ID when receiving (see Section 3.1 of [I-D.ietf-core-object-security]). A (6LBR) pledge is expected to have exactly one OSCORE security context with the JRC.

7.3.1. Replay Window and Persistency

Both (6LBR) pledge and the JRC MUST implement a replay protection mechanism. The use of the default OSCORE replay protection mechanism specified in Section 3.2.2 of [I-D.ietf-core-object-security] is RECOMMENDED.

Implementations MUST ensure that mutable OSCORE context parameters (Sender Sequence Number, Replay Window) are stored in persistent memory. A technique that prevents reuse of sequence numbers, detailed in Appendix B.1.1 of [I-D.ietf-core-object-security], MUST be implemented. Each update of the OSCORE Replay Window MUST be written to persistent memory.

This is an important security requirement in order to guarantee nonce uniqueness and resistance to replay attacks across reboots and rejoins. Traffic between the (6LBR) pledge and the JRC is rare, making security outweigh the cost of writing to persistent memory.

7.3.2. OSCORE Error Handling

Errors raised by OSCORE during the join process MUST be silently dropped, with no error response being signaled. The pledge MUST silently discard any response not protected with OSCORE, including error codes.

Such errors may happen for a number of reasons, including failed lookup of an appropriate security context (e.g. the pledge attempting to join a wrong network), failed decryption, positive replay window

lookup, formatting errors (possibly due to malicious alterations in transit). Silently dropping OSCORE messages prevents a DoS attack on the pledge where the attacker could send bogus error responses, forcing the pledge to attempt joining one network at a time, until all networks have been tried.

7.3.3. Mandatory to Implement Algorithms

The mandatory to implement AEAD algorithm for use with OSCORE is AES-CCM-16-64-128 from [RFC8152]. This is the algorithm used for securing IEEE Std 802.15.4 frames, and hardware acceleration for it is present in virtually all compliant radio chips. With this choice, CoAP messages are protected with an 8-byte CCM authentication tag, and the algorithm uses 13-byte long nonces.

The mandatory to implement hash algorithm is SHA-256 [RFC4231]. The mandatory to implement key derivation function is HKDF [RFC5869], instantiated with a SHA-256 hash. See Appendix B for implementation guidance when code footprint is important.

8. Constrained Join Protocol (CoJP)

The Constrained Join Protocol (CoJP) is a lightweight protocol over CoAP [RFC7252] and a secure channel provided by OSCORE [I-D.ietf-core-object-security]. CoJP allows the (6LBR) pledge to request admission into a network managed by the JRC, and for the JRC to configure the pledge with the parameters necessary for joining the network, or advertising it in the case of 6LBR pledge. The JRC may update the parameters at any time, by reaching out to the joined node that formerly acted as a (6LBR) pledge. For example, network-wide rekeying can be implemented by updating the keying material on each node.

This section specifies how the CoJP messages are mapped to CoAP and OSCORE, CBOR data structures carrying different parameters, transported within CoAP payload, and the parameter semantics and processing rules.

CoJP relies on the security properties provided by OSCORE. This includes end-to-end confidentiality, data authenticity, replay protection, and a secure binding of responses to requests.

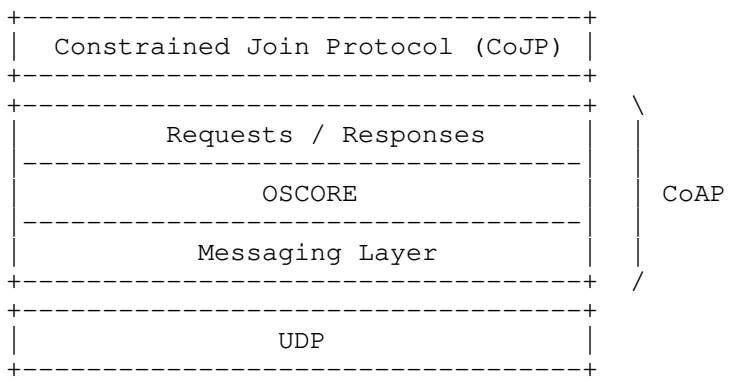

Figure 2: Abstract layering of CoJP.

When a (6LBR) pledge requests admission to a given network, it undergoes the CoJP join exchange that consists of:

- the Join Request message, sent by the (6LBR) pledge to the JRC, potentially proxied by the JP. The Join Request message and its mapping to CoAP is specified in Section 8.1.1.

- the Join Response message, sent by the JRC to the (6LBR) pledge, if the JRC successfully processes the Join Request using OSCORE and it determines through a mechanism that is out of scope of this specification that the (6LBR) pledge is authorized to join the network. The Join Response message is potentially proxied by the JP. The Join Response message and its mapping to CoAP is specified in Section 8.1.2.

When the JRC needs to update the parameters of a joined node that formerly acted as a (6LBR) pledge, it executes the CoJP parameter update exchange that consists of:

- the Parameter Update message, sent by the JRC to the joined node that formerly acted as a (6LBR) pledge. The Parameter Update message and its mapping to CoAP is specified in Section 8.2.1.

- the Parameter Update Response message, sent by the joined node to the JRC in response to the Parameter Update message to signal successful reception of the updated parameters. The Parameter Update Response message and its mapping to CoAP is specified in Section 8.2.2.

The payload of CoJP messages is encoded with CBOR [RFC7049]. The CBOR data structures that may appear as the payload of different CoJP messages are specified in Section 8.4.

8.1. Join Exchange

This section specifies the messages exchanged when the (6LBR) pledge requests admission and configuration parameters from the JRC.

8.1.1. Join Request Message

The Join Request message that the (6LBR) pledge sends SHALL be mapped to a CoAP request:

- The request method is POST.
- The type is Confirmable (CON).
- The Proxy-Scheme option is set to "coap".
- The Uri-Host option is set to "6tisch.arpa". This is an anycast type of identifier of the JRC that is resolved to its IPv6 address by the JP or the 6LBR pledge.
- The Uri-Path option is set to "j".
- The OSCORE option SHALL be set according to [I-D.ietf-core-object-security]. The OSCORE security context used is the one derived in Section 7.3. The OSCORE kid context allows the JRC to retrieve the security context for a given pledge.
- The payload is a Join_Request CBOR object, as defined in Section 8.4.1.

Since the Join Request is a confirmable message, the transmission at (6LBR) pledge will be controlled by CoAP's retransmission mechanism. The JP, when operating in a stateless manner, forwards this Join Request as a non-confirmable (NON) CoAP message, as specified in Section 7. If the CoAP at (6LBR) pledge declares the message transmission as failure, the (6LBR) pledge SHOULD attempt to join the next advertised 6TiSCH network. See Section 7.2 for recommended values of CoAP settings to use during the join exchange.

If all join attempts to advertised networks have failed, the (6LBR) pledge SHOULD signal to the user the presence of an error condition, through some out-of-band mechanism.

8.1.2. Join Response Message

The Join Response message that the JRC sends SHALL be mapped to a CoAP response:

- The response Code is 2.04 (Changed).

- The payload is a Configuration CBOR object, as defined in Section 8.4.2.

8.2. Parameter Update Exchange

During the network lifetime, parameters returned as part of the Join Response may need to be updated. One typical example is the update of link-layer keying material for the network, a process known as rekeying. This section specifies a generic mechanism when this parameter update is initiated by the JRC.

At the time of the join, the (6LBR) pledge acts as a CoAP client and requests the network parameters through a representation of the "/j" resource, exposed by the JRC. In order for the update of these parameters to happen, the JRC needs to asynchronously contact the joined node. The use of the CoAP Observe option for this purpose is not feasible due to the change in the IPv6 address when the pledge becomes the joined node and obtains a global address.

Instead, once the (6LBR) pledge receives and successfully validates the Join Response and so becomes a joined node, it becomes a CoAP server. The joined node exposes the "/j" resource that is used by the JRC to update the parameters. Consequently, the JRC operates as a CoAP client when updating the parameters. The request/response exchange between the JRC and the (6LBR) pledge happens over the already-established OSCORE secure channel.

8.2.1. Parameter Update Message

The Parameter Update message that the JRC sends to the joined node SHALL be mapped to a CoAP request:

- The request method is POST.

- The type is Confirmable (CON).

- The Uri-Path option is set to "j".

- The OSCORE option SHALL be set according to [I-D.ietf-core-object-security]. The OSCORE security context used is the one derived in Section 7.3. When a joined node receives a request with the Sender ID set to 0x4a5243 (ID of the JRC), it is able to correctly retrieve the security context with the JRC.

- The payload is a Configuration CBOR object, as defined in Section 8.4.2.

The JRC has implicit knowledge on the global IPv6 address of the joined node, as it knows the pledge identifier that the joined node used when it acted as a pledge, and the IPv6 network prefix. The JRC uses this implicitly derived IPv6 address of the joined node to directly address CoAP messages to it.

In case the JRC does not receive a response to a Parameter Update message, it attempts multiple retransmissions, as configured by the underlying CoAP retransmission mechanism triggered for confirmable messages. Finally, if the CoAP implementation declares the transmission as failure, the JRC may consider this as a hint that the joined node is no longer in the network. How the JRC decides when to stop attempting to contact a previously joined node is out of scope of this specification but security considerations on the reuse of assigned resources apply, as discussed in Section 9.

8.2.2. Parameter Update Response Message

The Parameter Update Response message that the joined node sends to the JRC SHALL be mapped to a CoAP response:

- The response Code is 2.04 (Changed).
- The payload is empty.

8.3. Error Handling

8.3.1. CoJP CBOR Object Processing

CoJP CBOR objects are transported within both CoAP requests and responses. This section describes handling in case certain CoJP CBOR object parameters are not supported by the implementation or their processing fails. See Section 7.3.2 for the handling of errors that may be raised by the underlying OSCORE implementation.

When such a parameter is detected in a CoAP request (Join Request message, Parameter Update message), a Diagnostic Response message MUST be returned. A Diagnostic Response message maps to a CoAP response and is specified in Section 8.3.2.

When a parameter that cannot be acted upon is encountered while processing a CoJP object in a CoAP response (Join Response message), a (6LBR) pledge SHOULD reattempt to join. In this case, the (6LBR) pledge SHOULD include the Unsupported Configuration CBOR object within the Join Request object in the following Join Request message. The Unsupported Configuration CBOR object is self-contained and enables the (6LBR) pledge to signal any parameters that the implementation of the networking stack may not support. A (6LBR)

pledge MUST NOT attempt more than MAX_RETRANSMIT number of attempts to join if the processing of the Join Response message fails each time. If COJP_MAX_JOIN_ATTEMPTS number of attempts is reached without success, the (6LBR) pledge SHOULD signal to the user the presence of an error condition, through some out-of-band mechanism.

8.3.2. Diagnostic Response Message

The Diagnostic Response message is returned for any CoJP request when the processing of the payload failed. The Diagnostic Response message is protected by OSCORE as any other CoJP protocol message.

The Diagnostic Response message SHALL be mapped to a CoAP response:

- The response Code is 4.00 (Bad Request).
- The payload is an Unsupported Configuration CBOR object, as defined in Section 8.4.5, containing more information about the parameter that triggered the sending of this message.

8.3.3. Failure Handling

The Parameter Update exchange may be triggered at any time during the network lifetime, which may span several years. During this period, it may occur that a joined node or the JRC experience unexpected events such as reboots or complete failures.

This document mandates that the mutable parameters in the security context are written to persistent memory (see Section 7.3.1) by both the JRC and pledges (joined nodes). As the joined node (pledge) is typically a constrained device that handles the write operations to persistent memory in a predictable manner, the retrieval of mutable security context parameters is feasible across reboots such that there is no risk of AEAD nonce reuse due to reinitialized Sender Sequence numbers, or of a replay attack due to the reinitialized replay window. JRC may be hosted on a generic machine where the write operation to persistent memory may lead to unpredictable delays due to caching. In case of a reboot event at JRC occurring before the cached data is written to persistent memory, the loss of mutable security context parameters is likely which consequently poses the risk of AEAD nonce reuse.

In the event of a complete device failure, where the mutable security context parameters cannot be retrieved, it is expected that a failed joined node is replaced with a new physical device, using a new pledge identifier and a PSK. When such a failure event occurs at the JRC, it is possible that the static information on provisioned pledges, like PSKs and pledge identifiers, can be retrieved through

available backups. However, it is likely that the information about joined nodes, their assigned short identifiers and mutable security context parameters is lost. If this is the case, during the process of JRC reinitialization, the network administrator MUST force through out-of-band means all the networks managed by the failed JRC to rejoin, through e.g. the reinitialization of the 6LBR nodes and freshly generated dynamic cryptographic keys and other parameters that have influence on the security properties of the network.

In order to recover from such a failure event, the reinitialized JRC can trigger the renegotiation of the OSCORE security context through the procedure described in Appendix B.2 of [I-D.ietf-core-object-security]. Aware of the failure event, the reinitialized JRC responds to the first join request of each pledge it is managing with a 4.01 Unauthorized error and a random nonce. The pledge verifies the error response and then initiates the CoJP join exchange using a new OSCORE security context derived from an ID Context consisting of the concatenation of two nonces, one that it received from the JRC and the other that the pledge generates locally. After verifying the join request with the new ID Context and the derived OSCORE security context, the JRC should consequently take action in mapping the new ID Context with the previously used pledge identifier. How JRC handles this mapping is implementation specific.

The described procedure is specified in Appendix B.2 of [I-D.ietf-core-object-security] and is RECOMMENDED in order to handle the failure events or any other event that may lead to the loss of mutable security context parameters. The length of nonces exchanged using this procedure SHOULD be at least 8 bytes.

The procedure does require both the pledge and the JRC to have good sources of randomness. While this is typically not an issue at the JRC side, the constrained device hosting the pledge may pose limitations in this regard. If the procedure outlined in Appendix B.2 of [I-D.ietf-core-object-security] is not supported by the pledge, the network administrator MUST take action in reprovisioning the concerned devices with freshly generated parameters, through out-of-band means.

8.4. CoJP Objects

This section specifies the structure of CoJP CBOR objects that may be carried as the payload of CoJP messages. Some of these objects may be received both as part of the CoJP join exchange when the device operates as a (CoJP) pledge, or the parameter update exchange, when the device operates as a joined (6LBR) node.

8.4.1. Join Request Object

The Join_Request structure is built on a CBOR map object.

The set of parameters that can appear in a Join_Request object is summarized below. The labels can be found in the "CoJP Parameters" registry Section 11.1.

- role: The identifier of the role that the pledge requests to play in the network once it joins, encoded as an unsigned integer. Possible values are specified in Table 1. This parameter MAY be included. In case the parameter is omitted, the default value of 0, i.e. the role "6TiSCH Node", MUST be assumed.

- network identifier: The identifier of the network, as discussed in Section 3, encoded as a CBOR byte string. When present in the Join_Request, it hints to the JRC the network that the pledge is requesting to join, enabling the JRC to manage multiple networks. The pledge obtains the value of the network identifier from the received EB frames. This parameter MUST be included in a Join_Request object regardless of the role parameter value.

- unsupported configuration: The identifier of the parameters that are not supported by the implementation, encoded as an Unsupported_Configuration object described in Section 8.4.5. This parameter MAY be included. If a (6LBR) pledge previously attempted to join and received a valid Join Response message over OSCORE, but failed to act on its payload (Configuration object), it SHOULD include this parameter to facilitate the recovery and debugging.

The CDDL fragment that represents the text above for the Join_Request follows.

```
Join_Request = {
    ? 1 : uint,                       ; role
    ? 5 : bstr,                       ; network identifier
    ? 8 : Unsupported_Configuration   ; unsupported configuration
}
```

Name	Value	Description	Reference
6TiSCH Node	0	The pledge requests to play the role of a regular 6TiSCH node, i.e. non-6LBR node.	[[this document]]
6LBR	1	The pledge requests to play the role of 6LoWPAN Border Router (6LBR).	[[this document]]

Table 1: Role values.

8.4.2. Configuration Object

The Configuration structure is built on a CBOR map object. The set of parameters that can appear in a Configuration object is summarized below. The labels can be found in "CoJP Parameters" registry Section 11.1.

- link-layer key set: An array encompassing a set of cryptographic keys and their identifiers that are currently in use in the network, or that are scheduled to be used in the future. The encoding of individual keys is described in Section 8.4.3. The link-layer key set parameter MAY be included in a Configuration object. When present, the link-layer key set parameter MUST contain at least one key. When a pledge is joining for the first time and receives this parameter, before sending the first outgoing frame secured with a received key, the pledge needs to successfully complete the security processing of an incoming frame. To do so, the pledge can wait to receive a new frame, or it can store an EB frame that it used to find the JP and use it for immediate security processing upon reception of the key set. This parameter is also used to implement rekeying in the network. How the keys are installed and used differs for the 6LBR and other (regular) nodes, and this is explained in Section 8.4.3.1 and Section 8.4.3.2.

- short identifier: a compact identifier assigned to the pledge. The short identifier structure is described in Section 8.4.4. The short identifier parameter MAY be included in a Configuration object.

- JRC address: the IPv6 address of the JRC, encoded as a byte string, with the length of 16 bytes. If the length of the byte string is different from 16, the parameter MUST be discarded. If the JRC is not co-located with the 6LBR and has a different IPv6

address than the 6LBR, this parameter MUST be included. In the special case where the JRC is co-located with the 6LBR and has the same IPv6 address as the 6LBR, this parameter MAY be included. If the JRC address parameter is not present in the Configuration object, this indicates that the JRC has the same IPv6 address as the 6LBR. The joined node can then discover the IPv6 address of the JRC through network control traffic. See Section 6.

- blacklist: An array encompassing a list of pledge identifiers that are blacklisted by the JRC, with each pledge identifier encoded as a byte string. The blacklist parameter MAY be included in a Configuration object. When present, the array MUST contain zero or more byte strings encoding pledge identifiers. The joined node MUST silently drop any link-layer frames originating from the pledge identifiers enclosed in the blacklist parameter. When this parameter is received, its value MUST overwrite any previously set values. This parameter allows the JRC to configure the node acting as a JP to filter out traffic from misconfigured or malicious pledges before their traffic is forwarded into the network. If the JRC decides to remove a given pledge identifier from a blacklist, it omits the pledge identifier in the blacklist parameter value it sends next.

- join rate: Average data rate of join traffic forwarded into the network that should not be exceeded when a joined node operates as a JP, encoded as an unsigned integer in bytes per second. The join rate parameter MAY be included in a Configuration object. This parameter allows the JRC to configure different nodes in the network to operate as JP, and act in case of an attack by throttling the rate at which JP forwards unauthenticated traffic into the network. When this parameter is present in a Configuration object, the value MUST be used to set the PROBING_RATE of CoAP at the joined node for communication with the JRC. In case this parameter is set to zero, a joined node MUST silently drop any join traffic coming from unauthenticated pledges. In case this parameter is omitted, the value of positive infinity SHOULD be assumed. Node operating as a JP MAY use another mechanism that is out of scope of this specification to configure PROBING_RATE of CoAP in the absence of join rate parameter from the Configuration object.

The CDDL fragment that represents the text above for the Configuration follows. Structures Link_Layer_Key and Short_Identifier are specified in Section 8.4.3 and Section 8.4.4.

```
   Configuration = {
       ? 2 : [ +Link_Layer_Key ],   ; link-layer key set
       ? 3 : Short_Identifier,      ; short identifier
       ? 4 : bstr,                  ; JRC address
       ? 6 : [ *bstr ],             ; blacklist
       ? 7 : uint                   ; join rate
   }
```

Name	Label	CBOR type	Description	Reference
role	1	unsigned integer	Identifies the role parameter	[[this document]]
link-layer key set	2	array	Identifies the array carrying one or more link-level cryptographic keys	[[this document]]
short identifier	3	array	Identifies the assigned short identifier	[[this document]]
JRC address	4	byte string	Identifies the IPv6 address of the JRC	[[this document]]
network identifier	5	byte string	Identifies the network identifier parameter	[[this document]]
blacklist	6	array	Identifies the blacklist parameter	[[this document]]
join rate	7	unsigned integer	Identifier the join rate parameter	[[this document]]
unsupported configuration	8	array	Identifies the unsupported configuration parameter	[[this document]]

Table 2: CoJP parameters map labels.

8.4.3. Link-Layer Key

The Link_Layer_Key structure encompasses the parameters needed to configure the link-layer security module: the key identifier; the value of the cryptographic key; the link-layer algorithm identifier

and the security level and the frame types that it should be used with, both for outgoing and incoming security operations; and any additional information that may be needed to configure the key.

For encoding compactness, the Link_Layer_Key object is not enclosed in a top-level CBOR object. Rather, it is transported as a sequence of CBOR elements, some being optional.

The set of parameters that can appear in a Link_Layer_Key object is summarized below, in order:

- key_id: The identifier of the key, encoded as a CBOR unsigned integer. This parameter MUST be included. If the decoded CBOR unsigned integer value is larger than the maximum link-layer key identifier, the key is considered invalid. In case the key is considered invalid, the key MUST be discarded and the implementation MUST signal the error as specified in Section 8.3.1.

- key_usage: The identifier of the link-layer algorithm, security level and link-layer frame types that can be used with the key, encoded as an integer. This parameter MAY be included. Possible values and the corresponding link-layer settings are specified in IANA "CoJP Key Usage" registry (Section 11.2). In case the parameter is omitted, the default value of 0 from Table 3 MUST be assumed.

- key_value: The value of the cryptographic key, encoded as a byte string. This parameter MUST be included. If the length of the byte string is different than the corresponding key length for a given algorithm specified by the key_usage parameter, the key MUST be discarded and the implementation MUST signal the error as specified in Section 8.3.1.

- key_addinfo: Additional information needed to configure the link-layer key, encoded as a byte string. This parameter MAY be included. The processing of this parameter is dependent on the link-layer technology in use and a particular keying mode.

To be able to decode the keys that are present in the link-layer key set, and to identify individual parameters of a single Link_Layer_Key object, the CBOR decoder needs to differentiate between elements based on the CBOR type. For example, a uint that follows a byte string signals to the decoder that a new Link_Layer_Key object is being processed.

The CDDL fragment that represents the text above for the Link_Layer_Key follows.

```
Link_Layer_Key = (
      key_id            : uint,
    ? key_usage         : int,
      key_value         : bstr,
    ? key_addinfo       : bstr,
)
```

Name	Value	Algorithm	Description	Reference
6TiSCH-K1K2-ENC-MIC32	0	IEEE802154-AES-CCM-128	Use MIC-32 for EBs, ENC-MIC-32 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K1K2-ENC-MIC64	1	IEEE802154-AES-CCM-128	Use MIC-64 for EBs, ENC-MIC-64 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K1K2-ENC-MIC128	2	IEEE802154-AES-CCM-128	Use MIC-128 for EBs, ENC-MIC-128 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K1K2-MIC32	3	IEEE802154-AES-CCM-128	Use MIC-32 for EBs, DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K1K2-MIC64	4	IEEE802154-AES-CCM-128	Use MIC-64 for EBs, DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K1K2-MIC128	5	IEEE802154-AES-CCM-128	Use MIC-128 for EBs, DATA and ACKNOWLEDGMEN	[[this document]]

			T.	
6TiSCH-K1-MIC32	6	IEEE802154-AES-CCM-128	Use MIC-32 for EBs.	[[this document]]
6TiSCH-K1-MIC64	7	IEEE802154-AES-CCM-128	Use MIC-64 for EBs.	[[this document]]
6TiSCH-K1-MIC128	8	IEEE802154-AES-CCM-128	Use MIC-128 for EBs.	[[this document]]
6TiSCH-K2-MIC32	9	IEEE802154-AES-CCM-128	Use MIC-32 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K2-MIC64	10	IEEE802154-AES-CCM-128	Use MIC-64 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K2-MIC128	11	IEEE802154-AES-CCM-128	Use MIC-128 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K2-ENC-MIC32	12	IEEE802154-AES-CCM-128	Use ENC-MIC-32 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K2-ENC-MIC64	13	IEEE802154-AES-CCM-128	Use ENC-MIC-64 for DATA and ACKNOWLEDGMENT.	[[this document]]
6TiSCH-K2-ENC-MIC128	14	IEEE802154-AES-CCM-128	Use ENC-MIC-128 for DATA and ACKNOWLEDGMENT.	[[this document]]

Table 3: Key Usage values.

8.4.3.1. Rekeying of (6LoWPAN) Border Routers (6LBR)

When the 6LoWPAN Border Router (6LBR) receives the Configuration object containing a link-layer key set, it MUST immediately install and start using the new keys for all outgoing traffic, and remove any old keys it has installed from the previous key set after a delay of COJP_REKEYING_GUARD_TIME has passed. This mechanism is used by the JRC to force the 6LBR to start sending traffic with the new key. The decision is taken by the JRC when it has determined that the new key has been made available to all (or some overwhelming majority) of nodes. Any node that the JRC has not yet reached at that point is either non-functional or in extended sleep such that it will not be reached. To get the key update, such node needs to go through the join process anew.

8.4.3.2. Rekeying of regular (6LoWPAN) Nodes (6LN)

When a regular 6LN node receives the Configuration object with a link-layer key set, it MUST install the new keys. The 6LN will use both the old and the new keys to decrypt and authenticate any incoming traffic that arrives based upon the key identifier in the packet. It MUST continue to use the old keys for all outgoing traffic until it has detected that the network has switched to the new key set.

The detection of network switch is based upon the receipt of traffic secured with the new keys. Upon reception and successful security processing of a link-layer frame secured with a key from the new key set, a 6LN node MUST then switch to sending outgoing traffic using the keys from the new set for all outgoing traffic. The 6LN node MUST remove any old keys it has installed from the previous key set after a delay of COJP_REKEYING_GUARD_TIME has passed after it starts using the new key set.

Sending of traffic with the new keys signals to other downstream nodes to switch to their new key, and the affect is that there is a ripple of key updates in outward concentric circles around each 6LBR.

8.4.3.3. Use in IEEE Std 802.15.4

When Link_Layer_Key is used in the context of [IEEE802.15.4], the following considerations apply.

Signaling of different keying modes of [IEEE802.15.4] is done based on the parameter values present in a Link_Layer_Key object.

- Key ID Mode 0x00 (Implicit, pairwise): key_id parameter MUST be set to 0. key_addinfo parameter MUST be present. key_addinfo parameter MUST be set to the link-layer address(es) of a single peer with whom the key should be used. Depending on the configuration of the network, key_addinfo may carry the peer's long link-layer address (i.e. pledge identifier), short link-layer address, or their concatenation with the long address being encoded first. Which address is carried is determined from the length of the byte string.

- Key ID Mode 0x01 (Key Index): key_id parameter MUST be set to a value different than 0. key_addinfo parameter MUST NOT be present.

- Key ID Mode 0x02 (4-byte Explicit Key Source): key_id parameter MUST be set to a value different than 0. key_addinfo parameter MUST be present. key_addinfo parameter MUST be set to a byte string, exactly 4 bytes long. key_addinfo parameter carries the Key Source parameter used to configure [IEEE802.15.4].

- Key ID Mode 0x03 (8-byte Explicit Key Source): key_id parameter MUST be set to a value different than 0. key_addinfo parameter MUST be present. key_addinfo parameter MUST be set to a byte string, exactly 8 bytes long. key_addinfo parameter carries the Key Source parameter used to configure [IEEE802.15.4].

In all cases, key_usage parameter determines how a particular key should be used in respect to incoming and outgoing security policies.

For Key ID Modes 0x01 - 0x03, parameter key_id sets the "secKeyIndex" parameter of [IEEE802.15.4] that is signaled in all outgoing frames secured with a given key. The maximum value key_id can have is 254. The value of 255 is reserved in [IEEE802.15.4] and is therefore considered invalid.

Key ID Mode 0x00 (Implicit, pairwise) enables the JRC to act as a trusted third party and assign pairwise keys between nodes in the network. How JRC learns about the network topology is out of scope of this specification, but could be done through 6LBR - JRC signaling for example. Pairwise keys could also be derived through a key agreement protocol executed between the peers directly, where the authentication is based on the symmetric cryptographic material provided to both peers by the JRC. Such a protocol is out of scope of this specification.

Implementations MUST use different link-layer keys when using different authentication tag (MIC) lengths, as using the same key with different authentication tag lengths might be unsafe. For

example, this prohibits the usage of the same key for both MIC-32 and MIC-64 levels. See Annex B.4.3 of [IEEE802.15.4] for more information.

8.4.4. Short Identifier

The Short_Identifier object represents an identifier assigned to the pledge. It is encoded as a CBOR array object, containing, in order:

- identifier: The short identifier assigned to the pledge, encoded as a byte string. This parameter MUST be included. The identifier MUST be unique in the set of all identifiers assigned in a network that is managed by a JRC. In case the identifier is invalid, the decoder MUST silently ignore the Short_Identifier object.

- lease_time: The validity of the identifier in hours after the reception of the CBOR object, encoded as a CBOR unsigned integer. This parameter MAY be included. The node MUST stop using the assigned short identifier after the expiry of the lease_time interval. It is up to the JRC to renew the lease before the expiry of the previous interval. The JRC updates the lease by executing the Parameter Update exchange with the node and including the Short_Identifier in the Configuration object, as described in Section 8.2. In case the lease expires, the node SHOULD initiate a new join exchange, as described in Section 8.1. In case this parameter is omitted, the value of positive infinity MUST be assumed, meaning that the identifier is valid for as long as the node participates in the network.

The CDDL fragment that represents the text above for the Short_Identifier follows.

```
Short_Identifier = [
      identifier        : bstr,
    ? lease_time        : uint
]
```

8.4.4.1. Use in IEEE Std 802.15.4

When Short_Identifier is used in the context of [IEEE802.15.4], the following considerations apply.

The identifier MUST be used to set the short address of IEEE Std 802.15.4 module. When operating in TSCH mode, the identifier MUST be unique in the set of all identifiers assigned in multiple networks that share link-layer key(s). If the length of the byte string corresponding to the identifier parameter is different than 2, the

identifier is considered invalid. The values 0xfffe and 0xffff are reserved by [IEEE802.15.4] and their use is considered invalid.

The security properties offered by the [IEEE802.15.4] link-layer in TSCH mode are conditioned on the uniqueness requirement of the short identifier (i.e. short address). The short address is one of the inputs in the construction of the nonce, which is used to protect link-layer frames. If a misconfiguration occurs, and the same short address is assigned twice under the same link-layer key, the loss of security properties is eminent. For this reason, practices where the pledge generates the short identifier locally are not safe and are likely to result in the loss of link-layer security properties.

The JRC MUST ensure that at any given time there are never two same short identifiers being used under the same link-layer key. If the lease_time parameter of a given Short_Identifier object is set to positive infinity, care needs to be taken that the corresponding identifier is not assigned to another node until the JRC is certain that it is no longer in use, potentially through out-of-band signaling. If the lease_time parameter expires for any reason, the JRC should take into consideration potential ongoing transmissions by the joined node, which may be hanging in the queues, before assigning the same identifier to another node.

8.4.5. Unsupported Configuration Object

The Unsupported_Configuration object is encoded as a CBOR array, containing at least one Unsupported_Parameter object. Each Unsupported_Parameter object is a sequence of CBOR elements without an enclosing top-level CBOR object for compactness. The set of parameters that appear in an Unsupported_Parameter object is summarized below, in order:

- code: Indicates the capability of acting on the parameter signaled by parameter_label, encoded as an integer. This parameter MUST be included. Possible values of this parameter are specified in the IANA "CoJP Unsupported Configuration Code Registry" (Section 11.3).

- parameter_label: Indicates the parameter. This parameter MUST be included. Possible values of this parameter are specified in the label column of the IANA "CoJP Parameters" registry (Section 11.1).

- parameter_addinfo: Additional information about the parameter that cannot be acted upon. This parameter MUST be included. In case the code is set to "Unsupported", parameter_addinfo gives additional information to the JRC. If the parameter indicated by

parameter_label cannot be acted upon regardless of its value, parameter_addinfo MUST be set to null, signaling to the JRC that it SHOULD NOT attempt to configure the parameter again. If the pledge can act on the parameter, but cannot configure the setting indicated by the parameter value, the pledge can hint this to the JRC. In this case, parameter_addinfo MUST be set to the value of the parameter that cannot be acted upon following the normative parameter structure specified in this document. For example, it is possible to include only a subset of the link-layer key set object, signaling the keys that cannot be acted upon, or the entire key set that was received. In case the code is set to "Malformed", parameter_addinfo MUST be set to null, signaling to the JRC that it SHOULD NOT attempt to configure the parameter again.

The CDDL fragment that represents the text above for Unsupported_Configuration and Unsupported_Parameter objects follows.

```
Unsupported_Configuration = [
       + parameter           : Unsupported_Parameter
]

Unsupported_Parameter = (
         code                : int,
         parameter_label     : int,
         parameter_addinfo   : nil / any
)
```

Name	Value	Description	Reference
Unsupported	0	The indicated setting is not supported by the networking stack implementation.	[[this document]]
Malformed	1	The indicated parameter value is malformed.	[[this document]]

Table 4: Unsupported Configuration code values.

8.5. Recommended Settings

This section gives RECOMMENDED values of CoJP settings.

Name	Default Value
COJP_MAX_JOIN_ATTEMPTS	4
COJP_REKEYING_GUARD_TIME	12 seconds

Recommended CoJP settings.

The COJP_REKEYING_GUARD_TIME value SHOULD take into account possible retransmissions at the link layer due to imperfect wireless links.

9. Security Considerations

Since this document uses the pledge identifier to set the ID Context parameter of OSCORE, an important security requirement is that the pledge identifier is unique in the set of all pledge identifiers managed by a JRC. The uniqueness of the pledge identifier ensures unique (key, nonce) pairs for AEAD algorithm used by OSCORE. It also allows the JRC to retrieve the correct security context, upon the reception of a Join Request message. The management of pledge identifiers is simplified if the globally unique EUI-64 is used, but this comes with privacy risks, as discussed in Section 10.

This document further mandates that the (6LBR) pledge and the JRC are provisioned with unique PSKs. The PSK is used to set the OSCORE Master Secret during security context derivation. This derivation process results in OSCORE keys that are important for mutual authentication of the (6LBR) pledge and the JRC. Should an attacker come to know the PSK, then a man-in-the-middle attack is possible.

Many vendors are known to use unsafe practices when generating and provisioning PSKs. The use of a single PSK shared among a group of devices is a common pitfall that results in poor security. In this case, the compromise of a single device is likely to lead to a compromise of the entire batch, with the attacker having the ability to impersonate a legitimate device and join the network, generate bogus data and disturb the network operation. As a reminder, recall the well-known problem with Bluetooth headsets with a "0000" pin. Additionally, some vendors use methods such as scrambling or hashing of device serial numbers or their EUI-64 to generate "unique" PSKs. Without any secret information involved, the effort that the attacker needs to invest into breaking these unsafe derivation methods is quite low, resulting in the possible impersonation of any device from the batch, without even needing to compromise a single device. The use of cryptographically secure random number generators to generate

the PSK is RECOMMENDED, see [NIST800-90A] for different mechanisms using deterministic methods.

The JP forwards the unauthenticated join traffic into the network. A data cap on the JP prevents it from forwarding more traffic than the network can handle. The data cap can be configured by the JRC by including a join rate parameter in the Join Response and it is implemented through the CoAP's PROBING_RATE setting. The use of a data cap at a JP forces attackers to use more than one JP if they wish to overwhelm the network. Marking the join traffic packets with a non-zero DSCP allows the network to carry the traffic if it has capacity, but encourages the network to drop the extra traffic rather than add bandwidth due to that traffic.

The shared nature of the "minimal" cell used for the join traffic makes the network prone to a DoS attack by congesting the JP with bogus traffic. Such an attacker is limited by its maximum transmit power. The redundancy in the number of deployed JPs alleviates the issue and also gives the pledge a possibility to use the best available link for joining. How a network node decides to become a JP is out of scope of this specification.

At the beginning of the join process, the pledge has no means of verifying the content in the EB, and has to accept it at "face value". In case the pledge tries to join an attacker's network, the Join Response message will either fail the security check or time out. The pledge may implement a temporary blacklist in order to filter out undesired EBs and try to join using the next seemingly valid EB. This blacklist alleviates the issue, but is effectively limited by the node's available memory. Note that this temporary blacklist is different from the one communicated as part of the CoJP Configuration object as it helps pledge fight a DoS attack. These bogus beacons prolong the join time of the pledge, and so the time spent in "minimal" [RFC8180] duty cycle mode. The blacklist communicated as part of the CoJP Configuration object helps JP fight a DoS attack by a malicious pledge.

10. Privacy Considerations

The join solution specified in this document relies on the uniqueness of the pledge identifier in the set of all pledge identifiers managed by a JRC. This identifier is transferred in clear as an OSCORE kid context. The use of the globally unique EUI-64 as pledge identifier simplifies the management but comes with certain privacy risks. The implications are thoroughly discussed in [RFC7721] and comprise correlation of activities over time, location tracking, address scanning and device-specific vulnerability exploitation. Since the join process occurs rarely compared to the network lifetime, long-

term threats that arise from using EUI-64 as the pledge identifier are minimal. In addition, the Join Response message contains a short address which is assigned by the JRC to the (6LBR) pledge. The assigned short address SHOULD be uncorrelated with the long-term pledge identifier. The short address is encrypted in the response. Once the join process completes, the new node uses the short addresses for all further layer 2 (and layer-3) operations. This reduces the aforementioned privacy risks as the short layer-2 address (visible even when the network is encrypted) is not traceable between locations and does not disclose the manufacturer, as is the case of EUI-64. However, an eavesdropper with access to the radio medium during the join process may be able to correlate the assigned short address with the extended address based on timing information with a non-negligible probability. This probability decreases with an increasing number of pledges joining concurrently.

11. IANA Considerations

Note to RFC Editor: Please replace all occurrences of "[[this document]]" with the RFC number of this specification.

This document allocates a well-known name under the .arpa name space according to the rules given in [RFC3172]. The name "6tisch.arpa" is requested. No subdomains are expected. No A, AAAA or PTR record is requested.

11.1. CoJP Parameters Registry

This section defines a sub-registry within the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry with the name "Constrained Join Protocol Parameters Registry".

The columns of the registry are:

Name: This is a descriptive name that enables an easier reference to the item. It is not used in the encoding.

Label: The value to be used to identify this parameter. The label is an integer.

CBOR type: This field contains the CBOR type for the field.

Description: This field contains a brief description for the field.

Reference: This field contains a pointer to the public specification for the field, if one exists.

This registry is to be populated with the values in Table 2.

The amending formula for this sub-registry is: Different ranges of values use different registration policies [RFC8126]. Integer values from -256 to 255 are designated as Standards Action. Integer values from -65536 to -257 and from 256 to 65535 are designated as Specification Required. Integer values greater than 65535 are designated as Expert Review. Integer values less than -65536 are marked as Private Use.

11.2. CoJP Key Usage Registry

This section defines a sub-registry within the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry with the name "Constrained Join Protocol Key Usage Registry".

The columns of this registry are:

Name: This is a descriptive name that enables easier reference to the item. The name MUST be unique. It is not used in the encoding.

Value: This is the value used to identify the key usage setting. These values MUST be unique. The value is an integer.

Algorithm: This is a descriptive name of the link-layer algorithm in use and uniquely determines the key length. The name is not used in the encoding.

Description: This field contains a description of the key usage setting. The field should describe in enough detail how the key is to be used with different frame types, specific for the link-layer technology in question.

Reference: This contains a pointer to the public specification for the field, if one exists.

This registry is to be populated with the values in Table 3.

The amending formula for this sub-registry is: Different ranges of values use different registration policies [RFC8126]. Integer values from -256 to 255 are designated as Standards Action. Integer values from -65536 to -257 and from 256 to 65535 are designated as Specification Required. Integer values greater than 65535 are designated as Expert Review. Integer values less than -65536 are marked as Private Use.

11.3. CoJP Unsupported Configuration Code Registry

This section defines a sub-registry within the "IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) parameters" registry with the name "Constrained Join Protocol Unsupported Configuration Code Registry".

The columns of this registry are:

Name: This is a descriptive name that enables easier reference to the item. The name MUST be unique. It is not used in the encoding.

Value: This is the value used to identify the diagnostic code. These values MUST be unique. The value is an integer.

Description: This is a descriptive human-readable name. The description MUST be unique. It is not used in the encoding.

Reference: This contains a pointer to the public specification for the field, if one exists.

This registry is to be populated with the values in Table 4.

The amending formula for this sub-registry is: Different ranges of values use different registration policies [RFC8126]. Integer values from -256 to 255 are designated as Standards Action. Integer values from -65536 to -257 and from 256 to 65535 are designated as Specification Required. Integer values greater than 65535 are designated as Expert Review. Integer values less than -65536 are marked as Private Use.

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Appendix A. Example

Figure 3 illustrates a successful join protocol exchange. The pledge instantiates the OSCORE context and derives the OSCORE keys and nonces from the PSK. It uses the instantiated context to protect the Join Request addressed with a Proxy-Scheme option, the well-known host name of the JRC in the Uri-Host option, and its EUI-64 as pledge identifier and OSCORE kid context. Triggered by the presence of a Proxy-Scheme option, the JP forwards the request to the JRC and sets the CoAP token to the internally needed state. The JP has learned the IPv6 address of the JRC when it acted as a pledge and joined the network. Once the JRC receives the request, it looks up the correct context based on the kid context parameter. The OSCORE data authenticity verification ensures that the request has not been

modified in transit. In addition, replay protection is ensured through persistent handling of mutable context parameters.

Once the JP receives the Join Response, it authenticates the state within the CoAP token before deciding where to forward. The JP sets its internal state to that found in the token, and forwards the Join Response to the correct pledge. Note that the JP does not possess the key to decrypt the CBOR object (configuration) present in the payload. The Join Response is matched to the Join Request and verified for replay protection at the pledge using OSCORE processing rules. In this example, the Join Response does not contain the IPv6 address of the JRC, the pledge hence understands the JRC is co-located with the 6LBR.

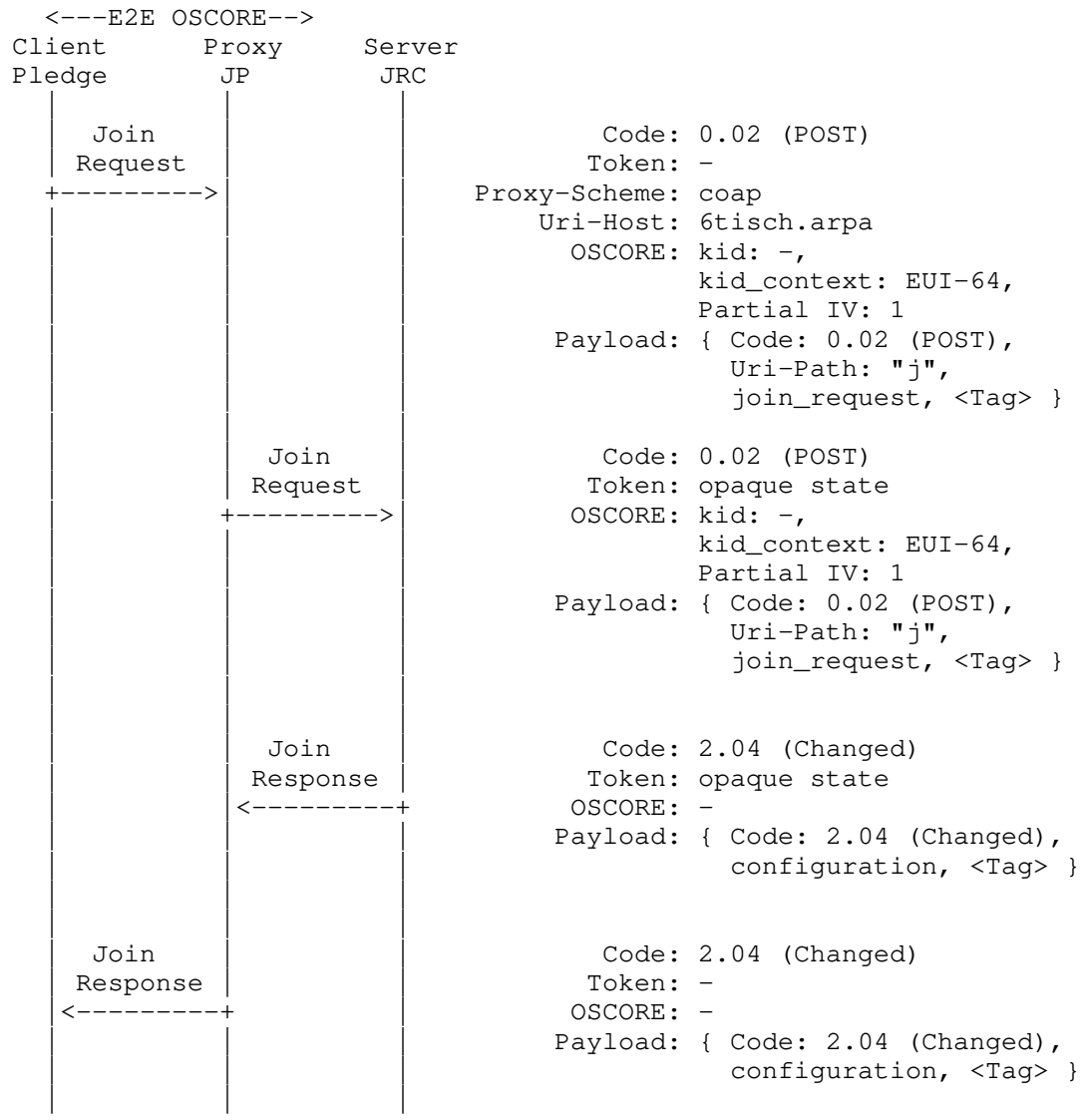

Figure 3: Example of a successful join protocol exchange. { ... } denotes authenticated encryption, <Tag> denotes the authentication tag.

Where the join_request object is:

```
join_request:
{
    5 : h'cafe' / PAN ID of the network pledge is attempting to join /
}
```

Since the role parameter is not present, the default role of "6TiSCH Node" is implied.

The join_request object encodes to h'a10542cafe' with a size of 5 bytes.

And the configuration object is:

```
configuration:
{
    2 : [           / link-layer key set /
          1,        / key_id /
          h'e6bf4287c2d7618d6a9687445ffd33e6' / key_value /
        ],
    3 : [           / short identifier /
          h'af93'   / assigned short address /
        ]
}
```

Since the key_usage parameter is not present in the link-layer key set object, the default value of "6TiSCH-K1K2-ENC-MIC32" is implied. Since key_addinfo parameter is not present and key_id is different than 0, Key ID Mode 0x01 (Key Index) is implied. Similarly, since the lease_time parameter is not present in the short identifier object, the default value of positive infinity is implied.

The configuration object encodes to

h'a202820150e6bf4287c2d7618d6a9687445ffd33e6038142af93' with a size of 26 bytes.

Appendix B. Lightweight Implementation Option

In environments where optimizing the implementation footprint is important, it is possible to implement this specification without having the implementations of HKDF [RFC5869] and SHA [RFC4231] on constrained devices. HKDF and SHA are used during the OSCORE security context derivation phase. This derivation can also be done by the JRC or a provisioning device, on behalf of the (6LBR) pledge during the provisioning phase. In that case, the derived OSCORE security context parameters are written directly into the (6LBR) pledge, without requiring the PSK be provisioned to the (6LBR) pledge.

The use of HKDF to derive OSCORE security context parameters ensures that the resulting OSCORE keys have good security properties, and are unique as long as the input for different pledges varies. This specification ensures the uniqueness by mandating unique pledge identifiers and a unique PSK for each (6LBR) pledge. From the AEAD nonce reuse viewpoint, having a unique pledge identifier is a sufficient condition. However, as discussed in Section 9, the use of a single PSK shared among many devices is a common security pitfall. The compromise of this shared PSK on a single device would lead to the compromise of the entire batch. When using the implementation/ deployment scheme outlined above, the PSK does not need to be written to individual pledges. As a consequence, even if a shared PSK is used, the scheme offers the same level of security as in the scenario where each pledge is provisioned with a unique PSK.

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M. Richardson
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July 18, 2017

Enabling secure network join in RPL networks
draft-richardson-6tisch-roll-join-priority-00

Abstract

[I-D.richardson-6tisch-join-enhanced-beacon] defines a method by which a potential [I-D.ietf-6tisch-minimal-security] can announce itself as a available for new Pledges to Join a network. The announcement includes a priority for join. This document provides a mechanism by which a RPL DODAG root can disable join announcements, or adjust the base priority for join operation.

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/.

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This Internet-Draft will expire on January 19, 2018.

Copyright Notice

Table of Contents

1. Introduction

[RFC7554] describes the use of the time-slotted channel hopping (TSCH) mode of [ieee802154]. [I-D.ietf-6tisch-minimal-security] and [I-D.ietf-6tisch-dtsecurity-secure-join] describe mechanisms by which a new node (the "pledge)" can use a friendly router as a Join Proxy. [I-D.richardson-6tisch-join-enhanced-beacon] describes an extension to the 802.15.4 Enhanced Beacon that is used by a Join Proxy to announce its existence such that Pledges can find them.

It has become clear that not every routing member of the mesh ought to announce itself as a Join Proxy. There are a variety of local reasons by which a 6LR might not want to provide the Join Proxy function. They include available battery power, already committed network bandwidth, and also total available memory available for Join proxy neighbor cache slots.

There are other situations where the operator of the network would like to selective enable or disable the join process in a particular DODAG.

As the join process involves permitting unencrypted traffic into the best effort part of a (TSCH) network, it would be better to have the join process off when no new nodes are expected.

A network operator might also be able to recognize when certain parts of the network are overloaded and can not accomodate additional join traffic, and it would like to adjust the join priority among all nodes in the subtree of a congested link.

This document describes an RPL DIO option that can be used to announce a minimum join priority.

1.1. Terminology

In this document, the key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" are to be interpreted as described in BCP 14, RFC 2119 [RFC2119] and indicate requirement levels for compliant STuPiD implementations.

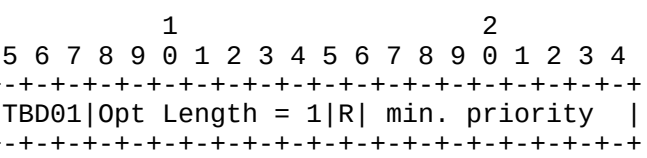
In addition, the terminology of [I-D.ietf-6tisch-terminology] and from [I-D.ietf-anima-voucher] are used.

2. Protocol Definition

The following option is defined to transmission in the DIO issued by the DODAG root. It may also be added by a router on part of the sub-tree as a result of some (out of scope for this document) management function.

6LRs that see this DIO Option SHOULD increment the minimum priority if they observe congestion on the channel used for join traffic. (TODO: how much? Do we need to standardize this?)

A 6LR which would otherwise be willing to act as a Join Proxy, will examine the minimum priority field, and to that number, add any additional local consideration (such as upstream congestion). The resulting priority, if less than 0x7f should enable the Join Proxy function.



min.priority a 7 bit field which provides a base value for the Enhanced Beacon Join priority. A value of 0x7f (127) disables the Join Proxy function entirely.

R a reserved bit that SHOULD be set to 0 by senders, and MUST be ignored by receivers. The reserved bit SHOULD be copied to options created.

3. Security Considerations

As per [RFC7416], RPL control frames either run over a secured layer 2, or use the [RFC6550] Secure DIO methods. This option can be placed into either a "clear" (layer-2 secured) DIO, or a layer-3 Secure DIO. As such this option will have both integrity and confidentiality mechanisms applied to it.

A malicious node (that was part of the RPL control plane) could see these options and could, based upon the observed minimal join priority signal a confederate that it was a good time to send malicious join traffic.

A malicious node (that was part of the RPL control plane) could also send DIOs with a different minimal join priority which would cause downstream mesh routers to change their Join Proxy behaviour. Lower minimal priorities would cause downstream nodes to accept more pledges than the network was expecting, and higher minimal priorities cause the join process to stall.

The use of layer-2 or layer-3 security for RPL control messages prevents the above two attacks.

4. Privacy Considerations

There are no new privacy issues caused by this extension.

5. IANA Considerations

Allocate a new number TBD01 from Registry RPL Control Message Options. This entry should be called Minimum Join Priority.

6. Acknowledgements

none so far.

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7.2. Informative References

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Appendix A. Change history

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Scheduling Function One (SF1): hop-by-hop Scheduling with RSVP-TE in 6tisch Networks
draft-satish-6tisch-6top-sf1-04

Abstract

This document defines a 6top Scheduling Function called "Scheduling Function One" (SF1) to reserve, label and schedule the end-to-end resources hop-by-hop through the Resource ReserVation Protocol - Traffic Engineering (RSVP-TE). SF1 uses the 6P signaling messages with a global TrackID to add or delete the cells in L2-bundles of isolated traffic flows.

Table of Contents

1. Introduction

Scheduling Function Zero (SF0) [I-D.ietf-6tisch-6top-sf0] enables on-the-fly cell scheduling (ADD/DELETE) between one-hop neighbors for aggregated (best-effort) traffic flows. In other words, all the instances from nodeA to nodeB in Figure 1 are scheduled in a single L3-bundle (IP link).

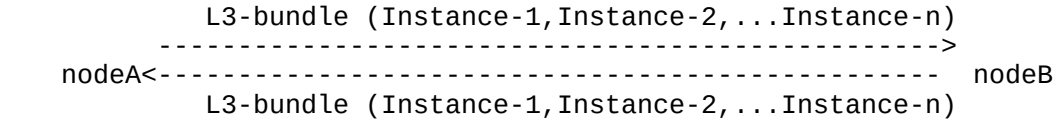


Figure 1: L3-bundle for aggregated traffic flows over one-hop with SF0.

Some applications (e.g. Industrial M2M) require end-to-end dedicated L2-bundles to support control/data streams for time-critical applications [I-D.ietf-detnet-use-cases]. For such applications, the sender can reserve a dedicated track to the receiver for each isolated instance. A track is actually a succession of paired L2-bundles (a receive bundle at the downstream node and a transmit bundle at the upstream node), which is identified by a global TrackID. Per-instance L2-bundles need to be scheduled hop-by-hop in between sender and receiver [I-D.ietf-6tisch-architecture]. In addition, cells in the scheduled end-to-end track of each instance may have to be dynamically adapted for bursty time-critical traffic flows. With one-hop based SF0 cell scheduling, it is difficult to schedule dedicated end-to-end cells for isolated traffic flows. Moreover, global bandwidth estimation through Resource Reservation protocol is required for bandwidth allocation in multi-hop cell scheduling. This draft specifies a Scheduling Function One (SF1) to schedule end-to-end dedicated L2-bundles for each instance, and to dynamically adapt the cells in already scheduled L2-bundles through RSVP-TE (see Figure 2).

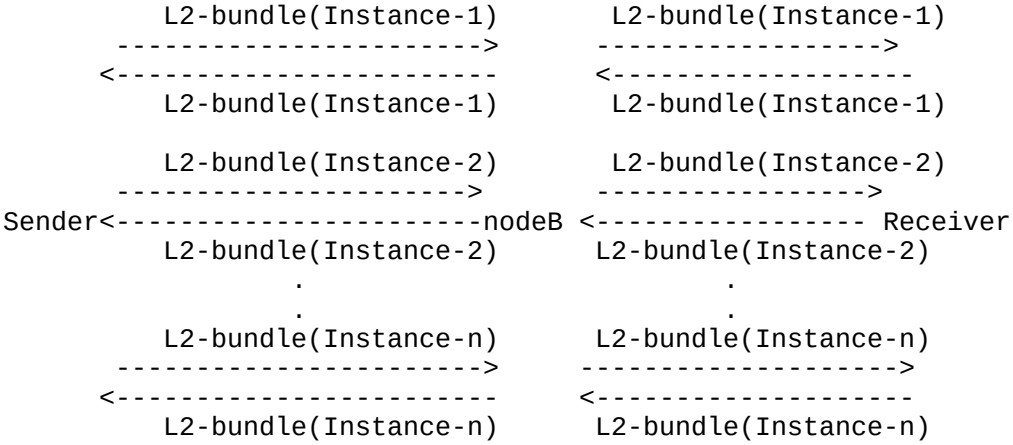


Figure 2: Dedicated L2-bundles for end-to-end isolated traffic flows with SF1

2. Operation of Scheduling Function One (SF1)

SF1 is a combination of RSVP-TE and 6P (the 6top protocol [I-D.ietf-6tisch-6top-protocol]). According to the bandwidth and QoS requirements of traffic flows, SF1 can schedule, reserve and label L2-bundles of cells at each hop, build up an end-to-end track identified by a global TrackID, and dynamically adapt the cells in an existing track.

Using SF1, the Sender determines when to reserve end-to-end resources. The following events may trigger the use of SF1:

o The Sender has an outgoing bandwidth requirement for a new instance to transmit data to Receiver.

o The Sender has a new outgoing bandwidth requirement for an existing instance to transmit data to Receiver.

In both cases, distributed RSVP-TE is used to provide end-to-end resource reservations along with scheduling operations. The outcome of RSVP-TE is a label switching path (LSP) [RFC3209]. In the context of this draft, a track is actually an LSP, in which the label at each hop is associated to the reserved cells. And the TrackID is equivalent to the LSP_ID.

2.1. End-to-end Operation

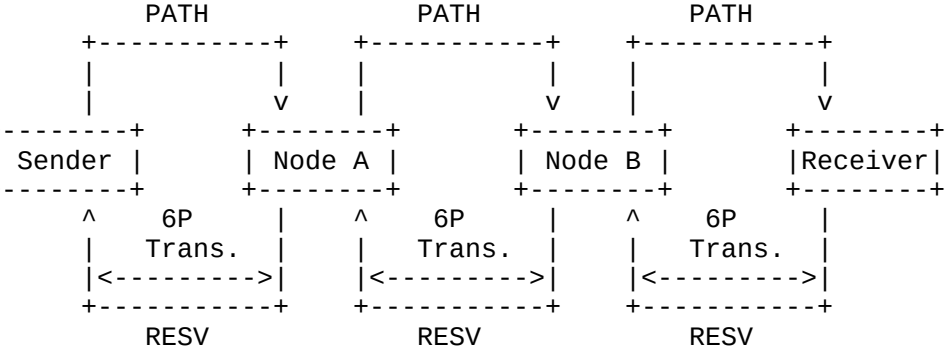


Figure 3: End-to-end Operation in SF1

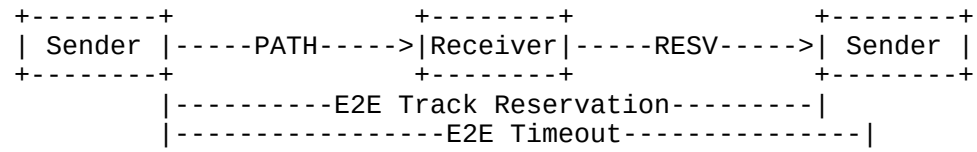


Figure 4: End-to-end timeout in SF1

It is assumed that an end-to-end route path is already available, for instance by using AODV-RPL [I-D.ietf-roll-aodv-rpl] routing. To initiate the track reservation, the sender sends the RSVP-PATH message to the receiver along the route. The PATH message describes the characteristics of the traffic flow and gathers information along the route to help the receiver(s) construct an appropriate reservation request [RFC2205]. Upon arrival of the PATH message, the receiver sends an RSVP-RESV message upstream to the sender. At each hop, the cells to be reserved are negotiated between 2 neighbors with the help of 6P transactions. If one-hop reservation succeeds, the downstream node assigns a label, which is associated to the selected cells, to the upstream node. And the label is also associated to the track whose TrackID is encapsulated in the FILTER_SPEC of the RESV message. If one-hop reservation fails at an intermediate node, the node SHOULD send a ResvErr message to the receiver and all the nodes along the downstream route to tear down the reserved resources. When the RESV message arrives at the sender before the end-to-end timeout, an end-to-end track is built successfully. If no RESV message is received at the sender when timeout, the track reservation fails.

The end-to-end data transmission is achieved through Track Forwarding [I-D.ietf-6tisch-architecture] that can be seen as a G-MPLS operation in which the explicit label at each hop is associated to an implicit label, i.e., the reserved cells. When transmitting data, the sender identifies the track to be used based on Sender and Receiver IP addresses and RPLInstanceID of the packet. At each hop, the packet is transmitted using the reserved L2-bundle of cells on this track.

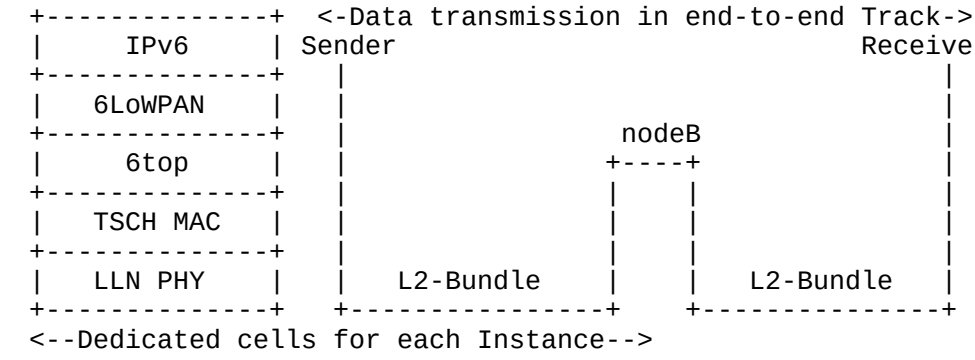


Figure 5: Track Forwarding

2.2. One-hop Operation

Upon arrival of the PATH message at an application receiver, the SENDER_TSPEC and ADSPEC objects are utilized to select the resource reservation parameters in FLOWSPEC of the RESV message. Since RSVP provides receiver initiated resource reservation setup, the scheduling operation proceeds upstream from receiver to sender. In 6P the resources are represented as cells, thus the bandwidth can be interpreted as the number of cells, and the QoS can be interpreted as the constraints on cells, e.g. the priority of slotframe, the slotOffset and channelOffset of cells. Therefore, the bandwidth and QoS parameters in FLOWSPEC need to be mapped to number and constraints of cells in the 6P transaction.

In this document, when there are two neighbor nodes, the upstream node is named Node A, and the downstream node is named Node B. If Node B is the receiver, the cell reservation is initiated by the arrival of a PATH message. If node B is an intermediate node, the reservation is initiated by the arrival of an RESV message from downstream. The cell reservation begins with 6P transactions, which can be 3-step or 2-step [I-D.ietf-6tisch-6top-protocol]. The operation of RESV message with these two kinds of transactions is specified as follows.

2.2.1. 3-step transaction

As illustrated in Figure 6, Node B first determines whether it can provide enough qualified cells to receive traffic from Node A, according to the parameters in FLOWSPEC. If not, Node B SHOULD send a ResvErr message. Otherwise, Node B transmits a 6P Request message to Node A with the slotFrame_ID in the metadata field. The type of the Request message (ADD or DELETE) is decided by comparing the the required cells and the currently reserved cells. In a 3-step

transaction, the "CellList" field in the 6P request SHOULD be empty. The timeout for the 6P transaction is as defined in [I-D.ietf-6tisch-6top-protocol]. Node A checks the associated slotframe and proposes a candidate CellList. Then a 6P Response message is sent back to Node B. If Node B is able to select expected number of cells in this candidate CellList, it sends an RESV message to Node A, in which the 6P Confirmation message indicating the selected cells is encapsulated as the 6P OPERATION object, and the label is assigned as defined in Section 3.2. Otherwise, the Node B can choose to initiate another 6P transaction on another slotframe which can fulfill the QoS requirement. If all the 6P transactions fail, Node B SHOULD send a ResvErr message all the way to the receiver to tear down all the reserved resources. When the RESV message arrives at Node A, the L2-bundle between Node A and Node B is installed.

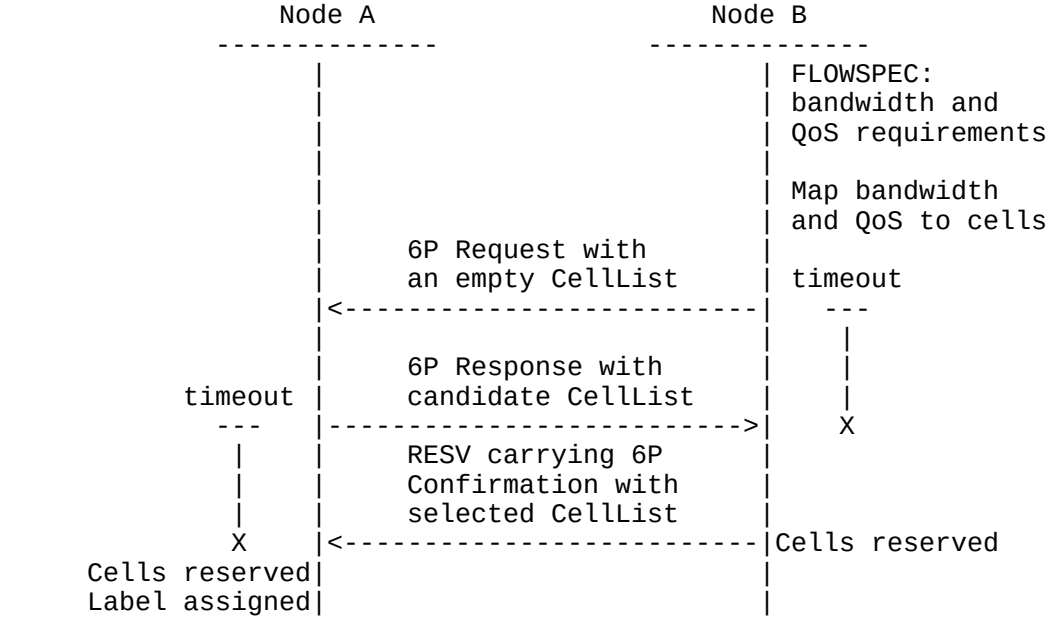


Figure 6: Operation of RESV message with 3-step transaction.

2.2.2. 2-step transaction

As illustrated in Figure 7, Node B SHOULD provide a candidate CellList which can fulfill the requirements in the 6P Request message, then Node A sends back the 6P Response message with a selected CellList. If the number of cells in the selected CellList is what Node B expects, Node B sends an RESV message to Node A including an assigned label and without the 6P OPERATION object. The

error handling mechanism is the same as in the 3-step transaction fashion.

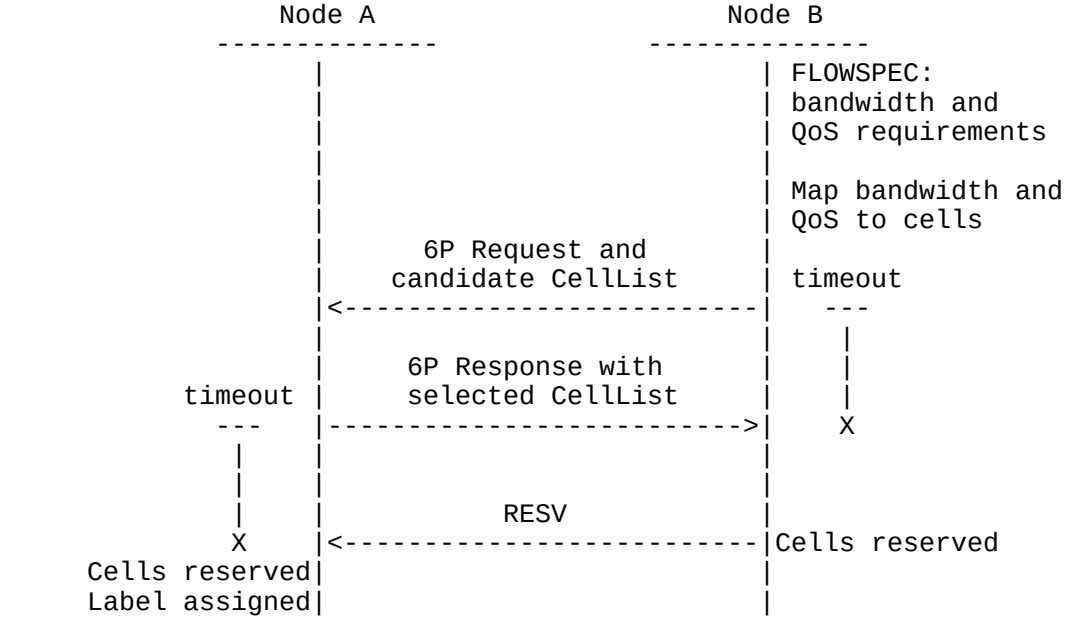


Figure 7: Operation of RESV message with 2-step transaction.

2.3. Reroute and Bandwidth Increase mechanism

Whenever the sender needs to establish a new tunnel that can maintain resource reservations without double counting (at any particular intermediate node) the resources with an existing tunnel, then the "RSVP reroute mechanism" is initiated [RFC3209]. With this operation, bandwidth can be increased or decreased end-to-end in the tunnel. The detailed explanation of the reroute mechanism is explained in [RFC3209].

2.4. Error Codes

The detailed explanation of PathErr and ResvErr with different ERROR_SPEC to handle Scheduling and 6P operation errors will be described in later specification.

3. Message Format

3.1. RSVP-PATH message

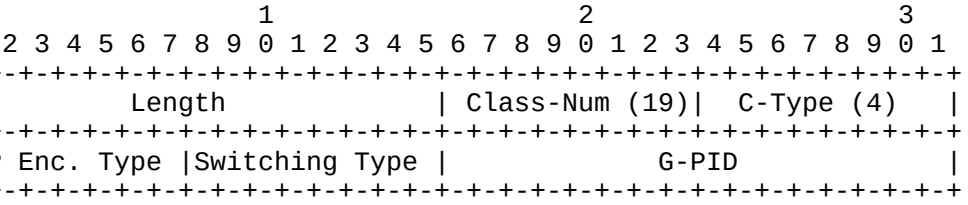
The basic RSVP-PATH message [RFC2205] is used to carry the "Sender Traffic Specification" along with "characterization parameters" from sender to receiver. Since RSVP treats objects as opaque data, it is permissible to use another protocol element (e.g. GMPLS, 6P, SF1) as an object in a RSVP-PATH message.

The format of the PATH message that supports 6tisch scheduling capabilities (6P and SF1) is as follows:

```
<Path Message> ::=    <Common Header> [ <INTEGRITY> ]
                      [ [<MESSAGE_ID_ACK> | <MESSAGE_ID_NACK> ] ... ]
                      [ <MESSAGE_ID> ]
                      <SESSION> <RSVP_HOP>
                      <TIME_VALUES>
                      [ <EXPLICIT_ROUTE> ]
                      <LABEL_REQUEST>
                      [ <SF1 OPERATION REQUEST> ]
                      [ <6P OPERATION REQUEST> ]
                      [ <SESSION_ATTRIBUTE> ]
                      [ <NOTIFY_REQUEST> ]
                      [ <ADMIN_STATUS> ]
                      [ <POLICY_DATA> ... ]
                      <sender descriptor>

  <sender descriptor> ::=  <SENDER_TEMPLATE> <SENDER_TSPEC>
                           [ <ADSPEC> ]
                           [ <RECORD_ROUTE> ]
```

The format of the Generalized Label Request Object in PATH message is:



The Generalized Label Request describes the requirement of communication characteristics to support the 6TiSCH-LSP being requested. The Generalized Label Request object is set by the ingress node (6LR), transparently passed by transit nodes, and used by the egress node (6LR).

1. LSP Encoding Type (8 bits): Indicates the encoding of the LSP being requested.

Value	Type
TBD	Timeslot

2. Switching Type (8 bits): Indicates the type of switching that should be performed on a particular link.

Value	Type
100	Time-Division-Multiplex (TDM) Capable

3. G-PID (8 bits): An identifier of the payload carried by an LSP, i.e., an identifier of the client layer of that LSP.

Value	Type	Technology
TBD	Wireless PAN (802.15.4)	TSCH

"SF1 OPERATION REQUEST" and "6P OPERATION REQUEST" are added in the PATH message to check for 6tisch scheduling capabilities within the intermediate nodes from sender to receiver. The "Timeslot Switching Capability" (TSC) is used as an implicit label to switch the cell at intermediate nodes [RFC3473]. "LABEL_REQUEST" in path message should be set to "Timeslot Switching Capability". If an intermediate node does not support the TSC or "6P transactions" or "SF1 operation" then it MUST send a "PathErr" message back to application. At the sender, the combination of sender and receiver IP addresses and the RPLInstanceID is mapped to a 16-bit identifier. The sender uses this identifier as the Track ID, and encapsulates it in the SENDER_TEMPLATE.

3.2. RSVP-RESV message

The basic RSVP-RESV messages [RFC2205] are transmitted upstream from receiver to sender to provide resource reservation as well as label distribution. In this specification, hop-by-hop scheduling is extended to support both resource reservation and label distribution. The current specification is only defined for unicast point-to-point traffic flows, i.e., Fixed Filter (FF) reservation style.

The format of the RESV message that supports 6tisch scheduling capabilities (6P and SF1) is as follows:

```
<Resv Message> ::= <Common Header> [ <INTEGRITY> ]
                         [ [<MESSAGE_ID_ACK> | <MESSAGE_ID_NACK> ] ... ]
                         [ <MESSAGE_ID> ]
                         <SESSION> <RSVP_HOP>
                         <TIME_VALUES>
                         [ <6P OPERATION> ]
                         [ <RESV_CONFIRM> ]  [ <SCOPE> ]
                         [ <NOTIFY_REQUEST> ]
                         [ <ADMIN_STATUS> ]
                         [ <POLICY_DATA> ... ]
                         <STYLE> <flow descriptor list>

     <flow descriptor list> ::= <FF flow descriptor>
     <FF flow descriptor> ::= [ <FLOWSPEC> ] <FILTER_SPEC> <LABEL>
     [ <RECORD_ROUTE> ]
```

The 6P OPERATION object encapsulates the 6P message. The tuple (slotFrame_ID, CellList) indicating the reserved cells is mapped to a 32-bit unsigned integer, which is used as the label to be assigned to the upstream node. The format of the LABEL object (in the flow descriptor) conforms to the Type 1 Label defined in [RFC3473].

4. Scheduling Function Identifier

The Scheduling Function Identifier (SFID) of SF1 is IANA_SFID_SF1(TBD).

5. IANA Considerations

IANA is requested to allocate a new Scheduling Function (IANA_SFID_SF1) from the SF space of Scheduling Functions defined in [I-D.ietf-6tisch-6top-sf0]

6. Security Considerations

TODO

7. References

7.1. References

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7.2. Informative References

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