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**Using IEEE802.15.4e TSCH in an LLN context:
Overview, Problem Statement and Goals
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Abstract

This document describes the environment, problem statement, and goals for using the IEEE802.15.4e TSCH MAC protocol in the context of LLNs. The set of goals enumerated in this document form an initial set only.

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Table of Contents

1.	Introduction	2
2.	TSCH in the LLN Context	4
3.	Problems and Goals	5
3.1.	Network Formation	6
3.2.	Network Maintenance	6
3.3.	Multi-Hop Topology	7
3.4.	Routing and Timing Parents	7
3.5.	Resource Management	7
3.6.	Dataflow Control	8
3.7.	Deterministic Behavior	8
3.8.	Scheduling Mechanisms	8
3.9.	Secure Communication	9
4.	Acknowledgements	9
5.	References	9
5.1.	Normative References	9
5.2.	Informative References	9
5.3.	External Informative References	12
Appendix A.	TSCH Protocol Highlights	14
A.1.	Timeslots	14
A.2.	Slotframes	15
A.3.	Node TSCH Schedule	15
A.4.	Cells and Bundles	15
A.5.	Dedicated vs. Shared Cells	16
A.6.	Absolute Slot Number	16
A.7.	Channel Hopping	16
A.8.	Time Synchronization	17
A.9.	Power Consumption	18
A.10.	Network TSCH Schedule	18
A.11.	Join Process	18
A.12.	Information Elements	19
A.13.	Extensibility	19
Appendix B.	TSCH Gotchas	19
B.1.	Collision Free Communication	19
B.2.	Multi-Channel vs. Channel Hopping	19
B.3.	Cost of (continuous) Synchronization	20
B.4.	Topology Stability	20
B.5.	Multiple Concurrent Slotframes	20
	Authors' Addresses	21

[1. Introduction](#)

The IEEE802.15.4e standard [[IEEE802154e](#)] was published in 2012 as an amendment to the Medium Access Control (MAC) protocol defined by the IEEE802.15.4-2011 [[IEEE802154](#)] standard. The Timeslotted Channel Hopping (TSCH) mode of IEEE802.15.4e is the object of this document.

This document describes the main issues arising from the adoption of the IEEE802.15.4e TSCH in the LLN context, following the terminology defined in [[I-D.palattella-6tisch-terminology](#)].

TSCH was designed to "allow IEEE802.15.4 devices to support a wide range of industrial applications" [[IEEE802154e](#)]. At its core is a medium access technique which uses time synchronization to achieve ultra low-power operation and channel hopping to enable high reliability. This is very different from the "legacy" IEEE802.15.4 MAC protocol, and is therefore better described as a "redesign". TSCH does not amend the physical layer; i.e., it can operate on any IEEE802.15.4-compliant hardware.

IEEE802.15.4e can be seen as the latest generation of ultra-lower power and reliable networking solutions for LLNs. [[RFC5673](#)] discusses industrial applications, and highlights the harsh operating conditions as well as the stringent reliability, availability, and security requirements for an LLN to operate in an industrial environment. Commercial networking solutions are available today in which motes consume 10's of micro-amps on average [[CurrentCalculator](#)] with end-to-end packet delivery ratios over 99.999% [[doherty07channel](#)].

IEEE802.15.4e TSCH focuses on the MAC layer only. This clean layering allows for TSCH to fit under an IPv6 enabled protocol stack for LLNs, running 6LoWPAN [[RFC6282](#)], RPL [[RFC6550](#)] and CoAP [[I-D.ietf-core-coap](#)].

Bringing industrial-like performance into the LLN stack developed by the 6LoWPAN, ROLL and CORE working groups opens up new application domains for these networks. Sensors deployed in smart cities [[RFC5548](#)] will be able to be installed for years without needing battery replacement. "Umbrella" networks will interconnect smart elements from different entities in smart buildings [[RFC5867](#)]. Peel-and-stick switches will obsolete the need for costly conduits for lighting solutions in smart homes [[RFC5826](#)].

While [[IEEE802154e](#)] defines the mechanisms for a TSCH mote to communicate, it does not define the policies to build and maintain the communication schedule, match that schedule to the multi-hop paths maintained by RPL, adapt the resources allocated between neighbor nodes to the data traffic flows, enforce a differentiated treatment for data generated at the application layer and signalling

messages needed by 6LoWPAN and RPL to discover neighbors, react to topology changes, self-configure IP addresses, or manage keying material.

In other words, IEEE802.15.4e TSCH is designed to allow optimizations and strong customizations, simplifying the merging of TSCH with a protocol stack based on IPv6, 6LoWPAN, and RPL.

2. TSCH in the LLN Context

In many cases, to map the services required by the IP layer to the services provided by the link layer, an adaptation layer is used [[palattella12standardized](#)]. The 6LoWPAN working group started working in 2007 on specifications for transmitting IPv6 packets over IEEE802.15.4 networks [[RFC4919](#)]. Typically, low-power WPANs are characterized by small packet sizes, support for addresses with different lengths, low bandwidth, star and mesh topologies, battery powered devices, low cost, large number of devices, unknown node positions, high unreliability, and periods during which communication interfaces are turned off to save energy. Given these features, it is clear that the adoption of IPv6 on top of a Low-Power WPAN is not straightforward, but poses strong requirements for the optimization of this adaptation layer. For instance, due to the IPv6 default minimum MTU size (1280 bytes), an un-fragmented IPv6 packet is too large to fit in an IEEE802.15.4 frame. Moreover, the overhead due to the 40-byte long IPv6 header wastes the scarce bandwidth available at the PHY layer [[RFC4944](#)]. For these reasons, the 6LoWPAN working group has defined an effective adaptation layer [[RFC6568](#)]. Further issues encompass the auto-configuration of IPv6 addresses [[RFC2464](#)][[RFC6755](#)], the compliance with the recommendation on supporting link-layer subnet broadcast in shared networks [[RFC3819](#)], the reduction of routing and management overhead [[RFC6606](#)], the adoption of lightweight application protocols (or novel data encoding techniques), and the support for security mechanisms (confidentiality and integrity protection, device bootstrapping, key establishment, and management).

These features can run on top of TSCH. There are, however, important issues to solve, as highlighted in [Section 3](#).

Routing issues are challenging for 6LoWPAN, given the low-power and lossy radio-links, the battery-powered nodes, the multi-hop mesh topologies, and the frequent topology changes due to mobility. Successful solutions take into account the specific application requirements, along with IPv6 behavior and 6LoWPAN mechanisms [[palattella12standardized](#)]. The ROLL working group has defined RPL in [[RFC6550](#)]. RPL can support a wide variety of link layers, including ones that are constrained, potentially lossy, or typically

utilized in conjunction with host or router devices with very limited resources, as in building/home automation [[RFC5867](#)][RFC5826], industrial environments [[RFC5673](#)], and urban applications [[RFC5548](#)]. RPL is able to quickly build up network routes, distribute routing knowledge among nodes, and adapt to a changing topology. In a typical setting, nodes are connected through multi-hop paths to a small set of root devices, which are usually responsible for data collection and coordination. For each of them, a Destination Oriented Directed Acyclic Graph (DODAG) is created by accounting for link costs, node attributes/status information, and an Objective Function, which maps the optimization requirements of the target scenario. The topology is set up based on a Rank metric, which encodes the distance of each node with respect to its reference root, as specified by the Objective Function. Regardless of the way it is computed, the Rank monotonically decreases along the DODAG towards the destination, building a gradient. RPL encompasses different kinds of traffic and signalling information. Multipoint-to-Point (MP2P) is the dominant traffic in LLN applications. Data is routed towards nodes with some application relevance, such as the LLN gateway to the larger Internet, or to the core of private IP networks. In general, these destinations are the DODAG roots and act as data collection points for distributed monitoring applications. Point-to-Multipoint (P2MP) data streams are used for actuation purposes, where messages are sent from DODAG roots to destination nodes. Point-to-Point (P2P) traffic allows communication between two devices belonging to the same LLN, such as a sensor and an actuator. A packet flows from the source to the common ancestor of those two communicating devices, then downward towards the destination. RPL therefore has to discover both upward routes (i.e. from nodes to DODAG roots) in order to enable MP2P and P2P flows, and downward routes (i.e. from DODAG roots to nodes) to support P2MP and P2P traffic.

[Section 3](#) highlights the challenges that need to be addressed to use RPL on top of TSCH.

Several open-source initiatives have emerged around TSCH. The OpenWSN project [[OpenWSN](#)][OpenWSNETT] is an open-source implementation of a standards-based protocol stack, which aims at evaluating the applicability of TSCH to different applications. This implementation was used as the foundation for an IP for Smart Objects Alliance (IPSO) [[IPSO](#)] interoperability event in 2011. In the absence of a standardized scheduling mechanism for TSCH, a "slotted Aloha" schedule was used.

[3. Problems and Goals](#)

As highlighted in [Appendix A](#), TSCH is different for traditional low-power MAC protocols because of its scheduled nature. TSCH defines the mechanisms to execute a communication schedule, yet it is the entity that sets up that schedule which controls the topology of the network. This scheduling entity also controls the resources allocated to each link in that topology.

How this entity should operate is out of scope of TSCH. The remainder of this section highlights the problems this entity needs to address. For simplicity, we will refer to this entity by the generic name "6TiSCH". Note that the 6top sublayer, currently being defined in [[I-D.wang-6tsch-6top](#)], can be seen as an embodiment of this generic "6TiSCH".

Some of the issues 6TiSCH needs to target might overlap with the scope of other protocols (e.g., 6LoWPAN, RPL, and RSVP). In this case, it is entailed that 6TiSCH will profit from the services provided by other protocols to pursue these objectives.

[3.1.](#) Network Formation

6TiSCH needs to control the way the network is formed, including how new motes join, and how already joined motes advertise the presence of the network. 6TiSCH needs to:

1. Define the Information Elements to include in the Enhanced Beacons advertising the presence of the network.
2. For a new mote, define rules to process and filter received Enhanced Beacons.
3. Define the joining procedure. This includes a mechanism to assign a unique 16-bit address to a mote, and the management of initial keying material.
4. Define a mechanism to secure the joining process and the subsequent optional process of scheduling more communication links.

[3.2.](#) Network Maintenance

Once a network is formed, 6TiSCH needs to maintain the network's health, allowing for motes to stay synchronized. 6TiSCH needs to:

1. Manage each mote's time source neighbor.
2. Define a mechanism for a mote to update the join priority it announces in its Enhanced Beacon.

3. Schedule transmissions of Enhanced Beacons to advertise the presence of the network.

3.3. Multi-Hop Topology

RPL, given a weighted connectivity graph, determines multi-hop routes. 6TiSCH needs to:

1. Define a mechanism to gather topological information, which it can then feed to RPL.
2. Ensure that the TSCH schedule contains links along the multi-hop routes identified by RPL.
3. Where applicable, maintain independent sets of links to transport independent flows of data.

3.4. Routing and Timing Parents

At all times, a TSCH mote needs to have a time source neighbor it can synchronize to. 6TiSCH therefore needs to assign a time source neighbor to allow for correct operation of the TSCH network. A time source neighbors could, or not, be taken from the RPL routing parent set.

3.5. Resource Management

A link in a TSCH schedule is a "unit" of resource. The number of links to assign between neighbor motes needs to be appropriate for the size of the traffic flow. 6TiSCH needs to:

1. Define rules on when to create or delete a slotframe.
2. Define rules to determine the length of a slotframe, and the trigger to modify the length of a slotframe.
3. Define rules on when to add or delete links in a particular slotframe.
4. Define a mechanism for neighbor nodes to exchange information about their schedule and, if applicable, negotiate the addition/deletion of links.
5. Allow for an entity (e.g., a set of devices, a distributed protocol, a PCE, etc.) to take control of the schedule.

6. Define a set of metrics to evaluate the trade-off between latency, bandwidth and energy consumption achieved by a particular schedule.

[3.6.](#) Dataflow Control

TSCH defines mechanisms for a mote to signal it cannot accept an incoming packet. It does not, however, define the policy which determines when to stop accepting packets. 6TiSCH needs to:

1. Define a queueing policy for incoming and outgoing packets.
2. Manage the buffer space, and indicate to TSCH when to stop accepting incoming packets.
3. Handle transmissions that have failed. A transmission is declared failed when TSCH has retransmitted the packet multiple times, without receiving an acknowledgement. This covers both dedicated and shared links.

[3.7.](#) Deterministic Behavior

As highlighted in [[RFC5673](#)], in some applications, data is generated periodically and has a well understood data bandwidth requirement, which is deterministic and predictable. 6TiSCH needs to:

1. Ensure timely delivery of such data.
2. Provide a mechanism for such deterministic flows to coexist with bursty or infrequent traffic flows of different priorities.

[3.8.](#) Scheduling Mechanisms

Several scheduling mechanisms can be envisioned, and possibly coexist in the same network. For example, [[I-D.phinney-roll-rpl-industrial-applicability](#)] describe how the allocation of bandwidth can be optimized by an external Path Computation Element (PCE). Alternatively, two neighbor nodes can adapt the number of cells autonomously by monitoring the amount of traffic, and negotiating the allocation to extra cell when needed. This mechanism can be used to establish multi-hop paths in a fashion similar to RSVP. 6TiSCH needs to:

1. Provide a mechanism for two 6TiSCH devices to negotiate the allocation and deallocation of cells between them.
2. Provide a mechanism for device to monitor and manage the 6TiSCH capabilities of a node several hops away.

3. Define an mechanism for these different scheduling mechanisms to coexist in the same network.

[3.9. Secure Communication](#)

Given some keying material, TSCH defines mechanisms to encrypt and authenticate MAC frames. It does not define how this keying material is generated. 6TiSCH needs to:

1. Define the keying material and authentication mechanism needed by a new mote to join an existing network.
2. Define a mechanism to allow for the secure transfer of application data between neighbor motes.
3. Define a mechanism to allow for the secure transfer of signalling data between motes and 6TiSCH.

[4. Acknowledgements](#)

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Appendix A. TSCH Protocol Highlights

This appendix gives an overview of the key features of the IEEE802.15.4e Timeslotted Channel Hopping (TSCH) amendment. It makes no attempt at repeating the standard, but rather focuses on the following:

- o Concepts which are sufficiently different from traditional IEEE802.15.4 networking that they may need to be defined and presented precisely.
- o Techniques and ideas which are part of IEEE802.15.4e and which might be useful for the work of the 6TiSCH WG.

A.1. Timeslots

All motes in a TSCH network are synchronized. Time is sliced up into timeslots. A timeslot is long enough for a MAC frame of maximum size to be sent from mote A to mote B, and for mote B to reply with an acknowledgement (ACK) frame indicating successful reception.

The duration of a timeslot is not defined by the standard. With IEEE802.15.4-compliant radios operating in the 2.4GHz frequency band, a maximum-length frame of 127 bytes takes about 4ms to transmit; a shorter ACK takes about 1ms. With a 10ms slot (a typical duration), this leaves 5ms to radio turnaround, packet processing and security operations.

A.2. Slotframes

Timeslots are grouped into one or more slotframes. A slotframe continuously repeats over time. TSCH does not impose a slotframe size. Depending on the application needs, these can range from 10s to 1000s of timeslots. The shorter the slotframe, the more often a timeslot repeats, resulting in more available bandwidth, but also in a higher power consumption.

A.3. Node TSCH Schedule

A TSCH schedule instructs each mote what to do in each timeslot: transmit, receive or sleep. The schedule indicates, for each scheduled (transmit or receive) cell a channelOffset and the address of the neighbor to communicate with.

Once a mote obtains its schedule, it executes it:

- o For each transmit cell, the mote checks whether there is a packet in the outgoing buffer which matches the neighbor written in the schedule information for that timeslot. If there is none, the mote keeps its radio off for the duration of the timeslot. If there is one, the mote can ask for the neighbor to acknowledge it, in which case it has to listen for the acknowledgement after transmitting.
- o For each receive cell, the mote listens for possible incoming packets. If none is received after some listening period, it shuts down its radio. If a packet is received, addressed to the mote, and passes security checks, the mote can send back an acknowledgement.

How the schedule is built, updated and maintained, and by which entity, is outside of the scope of the IEEE802.15.4e standard.

A.4. Cells and Bundles

Assuming the schedule is well built, if mote A is scheduled to transmit to mote B at slotOffset 5 and channelOffset 11, mote B will be scheduled to receive from mote A at the same slotOffset and channelOffset.

A single element of the schedule characterized by a slotOffset and channelOffset, and reserved for mote A to transmit to mote B (or for mote B to receive from mote A) within a given slotframe, is called a "scheduled cell".

If there is a lot of data flowing from mote A to mote B, the schedule might contain multiple cells from A to B, at different times. Multiple cells scheduled to the same neighbor can be equivalent, i.e. the MAC layer sends the packet on whichever of these cells happens to show up first after the packet was put in the MAC queue. The union of all cells between two neighbors, A and B, is called a "bundle". Since the slotframe repeats over time (and the length of the slotframe is typically constant), each cell gives a "quantum" of bandwidth to a given neighbor. Modifying the number of equivalent cells in a bundle modifies the amount of resources allocated between two neighbors.

[A.5. Dedicated vs. Shared Cells](#)

By default, each scheduled transmit cell within the TSCH schedule is dedicated, i.e., reserved only for mote A to transmit to mote B. IEEE802.15.4e allows also to mark a cell as shared. In a shared cell, multiple motes can transmit at the same time, on the same frequency. To avoid contention, TSCH defines a back-off algorithm for shared cells.

A scheduled cell can be marked as both transmitting and receiving. In this case, a mote transmits if it has an appropriate packet in its output buffer, or listens otherwise. Marking a cell as [transmit,shared,receive] results in slotted-Aloha behavior.

[A.6. Absolute Slot Number](#)

TSCH defines a timeslot counter called Absolute Slot Number (ASN). When a new network is created, the ASN is initialized to 0; from then on, it increments by 1 at each timeslot. In detail:

$$\text{ASN} = (k \cdot S + t)$$

where k is the slotframe cycle (i.e., the number of slotframe repetitions since the network was started), S the slotframe size and t the slotOffset. A mote learns the current ASN when it joins the network. Since motes are synchronized, they all know the current value of the ASN, at any time. The ASN is encoded as a 5-byte number: this allows it to increment for hundreds of years (the exact value depends on the duration of a timeslot) without wrapping. The ASN is used to calculate the frequency to communicate on, and can be used for security-related operations.

[A.7. Channel Hopping](#)

For each scheduled cell, the schedule specifies a slotOffset and a channelOffset. In a well-built schedule, when mote A has a transmit

cell to mote B on channelOffset 5, mote B has a receive cell from mote A on the same channelOffset. The channelOffset is translated by both nodes into a frequency using the following function:

$$\text{frequency} = F \{(\text{ASN} + \text{channelOffset}) \bmod \text{nFreq}\}$$

The function F consists of a look-up table containing the set of available channels. The value nFreq (the number of available frequencies) is the size of this look-up table. There are as many channelOffset values as there are frequencies available (e.g. 16 when using IEEE802.15.4-compliant radios at 2.4GHz, when all channels are used). Since both motes have the same channelOffset written in their schedule for that scheduled cell, and the same ASN counter, they compute the same frequency. At the next iteration (cycle) of the slotframe, however, while the channelOffset is the same, the ASN has changed, resulting in the computation of a different frequency.

This results in "channel hopping": even with a static schedule, pairs of neighbors "hop" between the different frequencies when communicating. Channel hopping is a technique known to efficiently combat multi-path fading and external interference.

[A.8. Time Synchronization](#)

Because of the slotted nature of communication in a TSCH network, motes have to maintain tight synchronization. All motes are assumed to be equipped with clocks to keep track of time. Yet, because clocks in different motes drift with respect to one another, neighbor motes need to periodically re-synchronize.

Each mote needs to periodically synchronize its network clock to another mote, and it also provides its network time to its neighbors. It is up to the entity that manages the schedule to assign an adequate time source neighbor to each mote, i.e., to indicate in the schedule which of neighbor is its "time source neighbor". While setting the time source neighbor, it is important to avoid synchronization loops, which could result in the formation of independent clusters of motes.

TSCH adds timing information in all packets that are exchanged (both data and ACK frames). This means that neighbor motes can resynchronize to one another whenever they exchange data. In detail, in the IEEE 802.15.4e standard two methods are defined for allowing a device to synchronize in a TSCH network: (i) Acknowledgement-Based and (ii) Frame-Based synchronization. In both cases, the receiver calculates the difference in time between the expected time of frame arrival and its actual arrival. In Acknowledgement-Based synchronization, the receiver provides such information to the sender

mote in its acknowledgement. Thus, in this case, it is the sender mote that synchronizes to the clock of the receiver. In Frame-Based synchronization, the receiver uses the computed delta for adjusting its own clock. Therefore, it is the receiver mote that synchronizes to the clock of the sender.

Different synchronization policies are possible. Motes can keep synchronization exclusively by exchanging EBs. Motes can also keep synchronized by periodically sending valid frames to a time source neighbor and use the acknowledgement to resynchronize. Both method (or a combination thereof) are valid synchronization policies; which one to use depends on network requirements.

[A.9.](#) Power Consumption

There are only a handful of activities a mote can perform during a timeslot: transmit, receive, or sleep. Each of these operations has some energy cost associated to them, the exact value depending on the hardware used. Given the schedule of a mote, it is straightforward to calculate the expected average power consumption of that mote.

[A.10.](#) Network TSCH Schedule

The schedule defines entirely the synchronization and communication between motes. By adding/removing cells between neighbors, one can adapt a schedule to the needs of the application. Intuitive examples are:

- o Make the schedule "sparse" for applications where motes need to consume as little energy as possible, at the price of reduced bandwidth.
- o Make the schedule "dense" for applications where motes generate a lot of data, at the price of increased power consumption.
- o Add more cells along a multi-hop route over which many packets flow.

[A.11.](#) Join Process

Motes already part of the network can periodically send Enhanced Beacon (EB) frames to announce the presence the network. These contain information about the size of the timeslot used in the network, the current ASN, information about the slotframes and timeslots the beaconing mote is listening on, and a 1-byte join priority. Because of the channel hopping nature of TSCH, these EB frames are sent on all frequencies.

A mote wishing to join the network listens for EBs. Using the ASN and the other timing information of the EB, the new mote synchronizes to the network. Using the slotframe and link information from the EB, it knows how to contact the network.

The IEEE802.15.4e TSCH standard does not define the steps beyond this network "bootstrap".

[A.12.](#) Information Elements

TSCH introduces the concept of Information Elements (IEs). An information element is a list of Type-Length-Value containers placed at the end of the MAC header. A small number of types are defined for TSCH (e.g., the ASN in the EB is contained in an IE), and an unmanaged range is available for extensions.

A data bit in the MAC header indicates whether the frame contains IEs. IEs are grouped into Header IEs, consumed by the MAC layer and therefore typically invisible to the next higher layer, and Payload IEs, which are passed untouched to the next higher layer, possibly followed by regular payload. Payload IEs can therefore be used for the next higher layers of two neighbor motes to exchange information.

[A.13.](#) Extensibility

The TSCH standard is designed to be extensible. It introduces the mechanisms as "building block" (e.g., cells, bundles, slotframes, etc.), but leaves entire freedom to the upper layer to assemble those. The MAC protocol can be extended by defining new Header IEs. An intermediate layer can be defined to manage the MAC layer by defining new Payload IEs.

[Appendix B.](#) TSCH Gotchas

This section lists features of TSCH which we believe are important and beneficial to the work of 6TiSCH.

[B.1.](#) Collision Free Communication

TSCH allows one to design a schedule which yields collision-free communication. This is done by building the schedule with dedicated cells in such a way that at most one node can communicate with a specific neighbor in each slotOffset/channelOffset cell. Multiple pairs of neighbor motes can exchange data at the same time, but on different frequencies.

[B.2.](#) Multi-Channel vs. Channel Hopping

A TSCH schedule looks like a matrix of width "slotframe size", S , and of height "number of frequencies", n_{Freq} . For a scheduling algorithm, these can be considered atomic "units" to schedule. In particular, because of the channel hopping nature of TSCH, the scheduling algorithm should not worry about the actual frequency communication happens on, since it changes at each slotframe iteration.

[B.3.](#) Cost of (continuous) Synchronization

When there is traffic in the network, motes which are communicating implicitly re-synchronize using the data frames they exchange. In the absence of data traffic, motes are required to synchronize to their time source neighbor(s) periodically not to drift in time. If they have not been communicating for some time (typically 30s), motes can exchange an dummy data frame to re-synchronize. The frequency at which such messages need to be transmitted depends on the stability of the clock source, and on how "early" each mote starts listening for data (the "guard time"). Theoretically, with a 10ppm clock and a 1ms guard time, this period can be 100s. Assuming this exchange causes the mote's radio to be on for 5ms, this yields a radio duty cycle needed to keep synchronized of $5\text{ms}/100\text{s}=0.005\%$. While TSCH does requires motes to resynchronize periodically, the cost of doing so is very low.

[B.4.](#) Topology Stability

The channel hopping nature of TSCH causes links to be very "stable". Wireless phenomena such as multi-path fading and external interference impact a wireless link between two motes differently on each frequency. If a transmission from mote A to mote B fails, retransmitting on a different frequency has a higher likelihood of succeeding than retransmitting on the same frequency. As a result, even when some frequencies are "behaving bad", channel hopping "smoothes" the contribution of each frequency, resulting in more stable links, and therefore a more stable topology.

[B.5.](#) Multiple Concurrent Slotframes

The TSCH standard allows for multiple slotframes to coexist in a mote's schedule. It is possible that at some timeslot, a mote has multiple activities scheduled (e.g. transmit to mote B on slotframe 2, receive from mote C on slotframe 1). To handle this situation, the TSCH standard defines the following precedence rules:

1. Transmissions take precedence over receptions;

2. Lower slotframe identifiers take precedence over higher slotframe identifiers.

In the example above, the mote would transmit to mote B on slotframe 2.

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