TOSHIBA

6TiSCH++ with Bluetooth 5 and Concurrent Transmissions

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Scope of Disclosure	Whom it may concern
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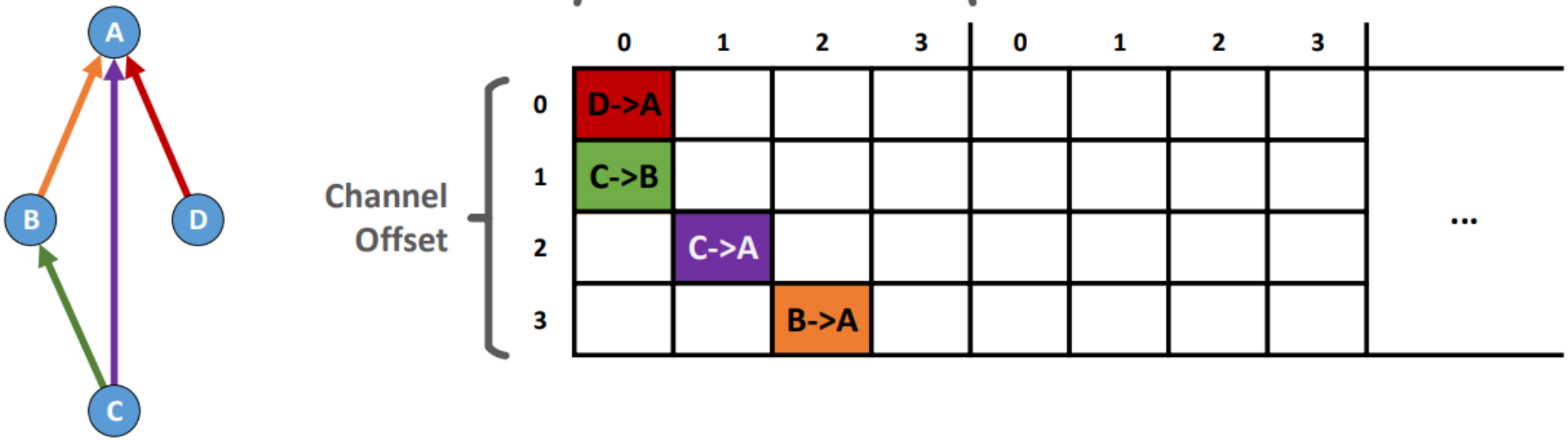
Contents

IETF 6TiSCH

IETF 6TiSCH defines mechanisms to create and disseminate scheduling for the TSCH (Time Slotted Channel Hopping) MAC layer introduced in IEEE 802.15.4-2015



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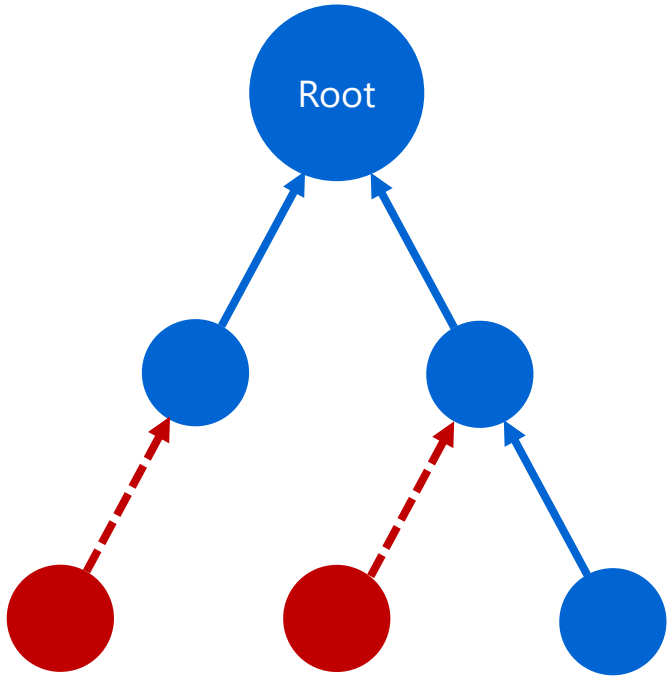
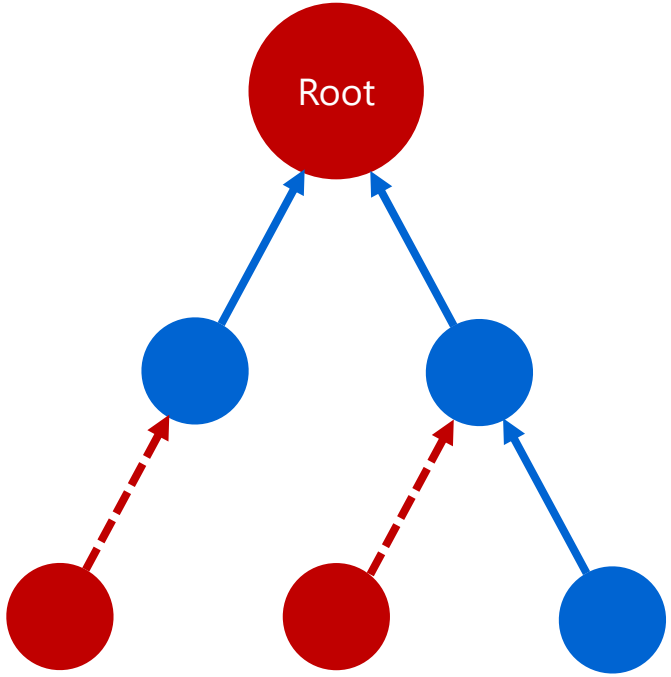


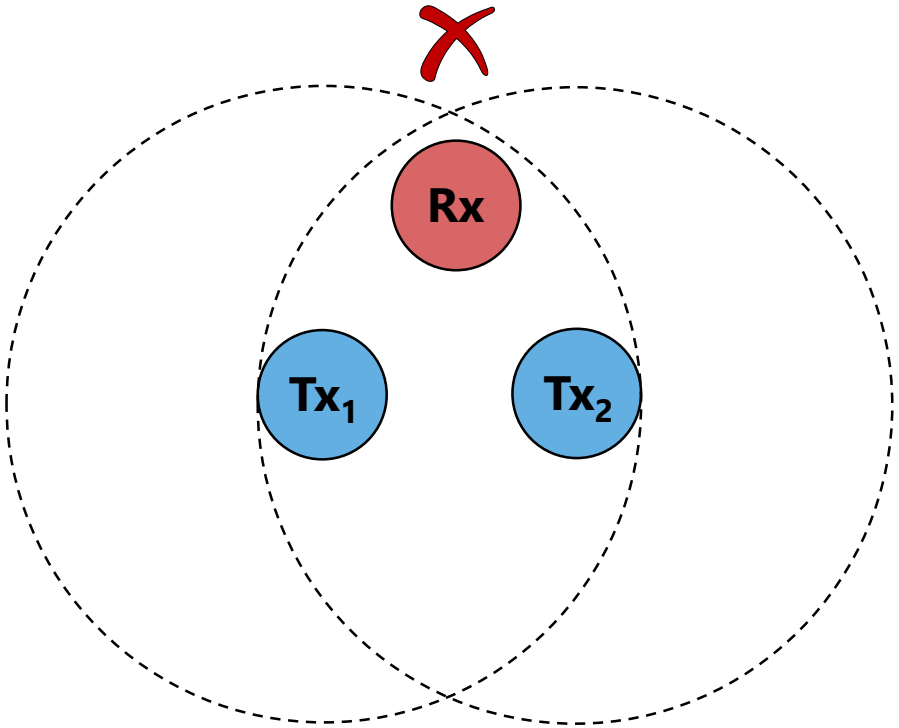
Distributed Scheduling



Centralized Scheduling

Concurrent Transmissions and Synchronous Flooding

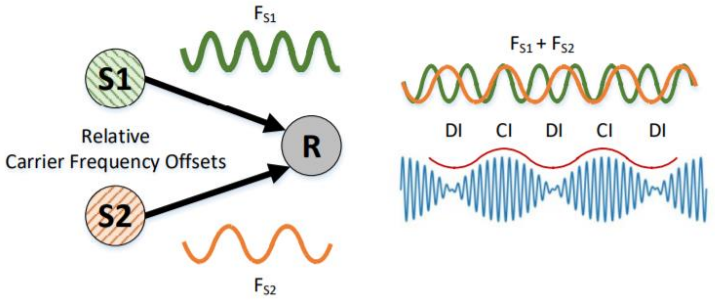
Usually when two nodes transmit at the same time, they will cause destructive interference and **COLLIDE** at the receiver, meaning both transmissions fail.



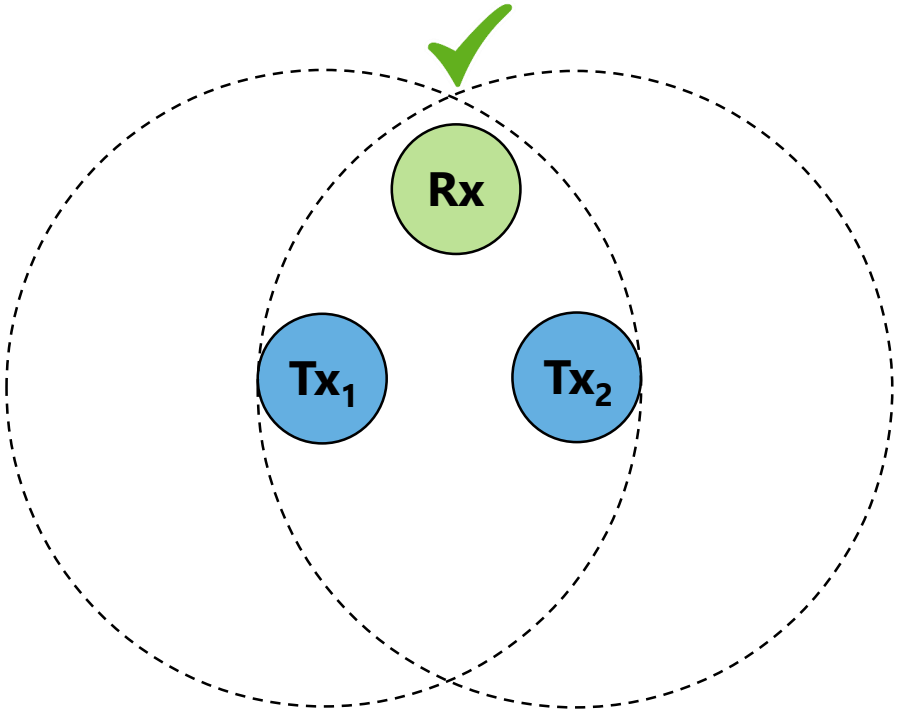
Concurrent Transmissions and Synchronous Flooding

Concurrent Transmissions **SOLVE** this using two Physical layer properties present in FSK modulated systems…

1) Non-Destructive Interference



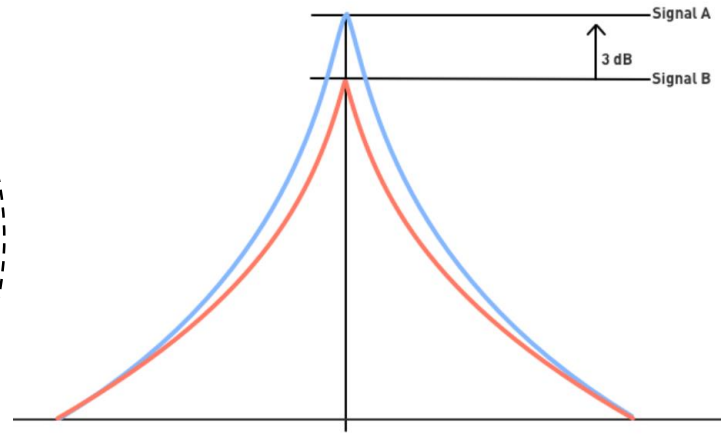
… allows nodes to simultaneously send the SAME DATA when they are WELL-SYNCHRONIZED.



<=1/2 chip period

ΔP >threshold

2) Capture Effect



… allows nodes to COMPETE to send DIFFERENT DATA.

Concurrent Transmissions and Synchronous Flooding

1. SYNCHRONIZE

- Nodes scan for floods sent by a root *R* (timesync)
- Nodes sync to T_0 (i.e. the time ref. of node *R)* using…
  - Packet length (e.g. 8B)
  - On-air PHY time (e.g. 250kbps)
  - The TX slot on which is received

2. SLEEP

- Nodes know the time of the next TX and sleep in-between.

3. WAKEUP + HOP

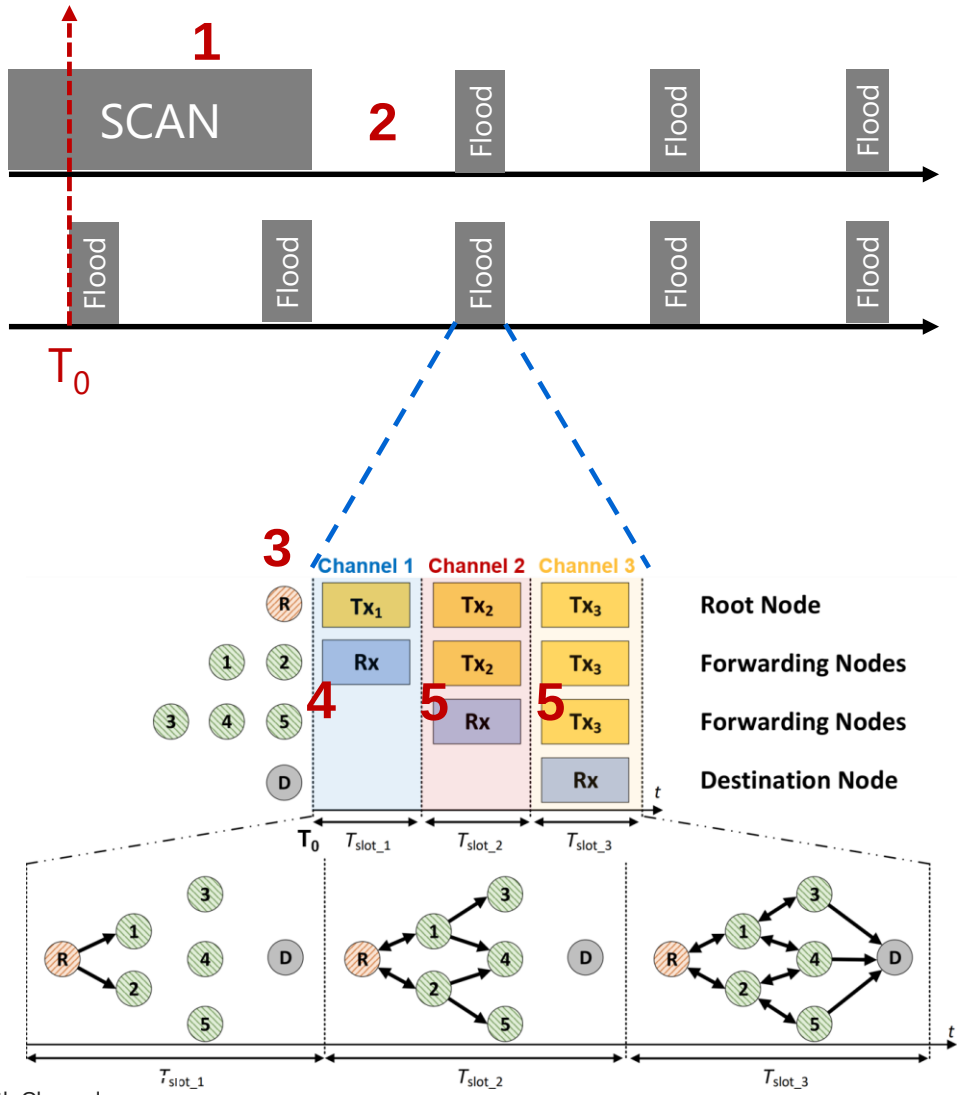
- Nodes wake up in time for the next flood
- A pseudo-random key generates the hopping schedule
- Nodes hop channel at each TX slot *(T_0 + (length * rate))*

4. RECEIVE

- **IF** a node RXs it **IMMEDATELY** determines how far along the flood is using a counter * the on-air packet PHY time.

5. TRANSMIT

- The nodes continue to synchronously schedule transmissions on each slot until the end of the flood.



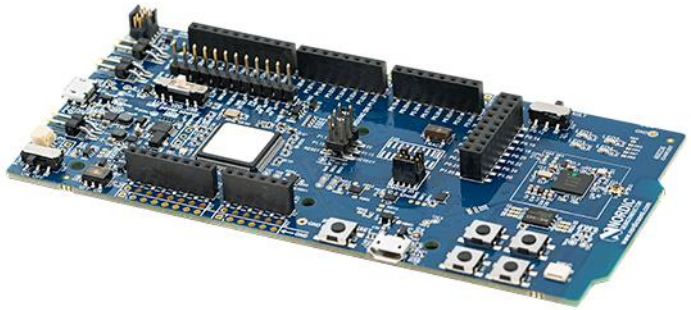
[1] Lim, Roman, Reto Da Forno, Felix Sutton, and Lothar Thiele. "Competition: Robust Flooding using Back-to-Back Synchronous Transmissions with Channel-Hopping." In *EWSN*, pp. 270-271. 2017.

Single-Radio Multi-Protocol SoCs

The Nordic nRF52840 supports multiple 2.4GHz physical layers on a **SINGLE-RADIO**.

- 16 MHz triggered Programmable Peripheral Interconnect (PPI) channels.
  - Radio is a peripheral off the core.
  - Makes timing + synchronization much easier!

- 5 Available Physical Layers (+ proprietary Nordic)
  - BLE 2 Mbit/s (Uncoded)
  - BLE 1 Mbit/s (Uncoded)
  - BLE 500 Kbit/s (S=2)
  - BLE 125 Kbit/s (S=8)
  - IEEE 802.15.4 (256 Kbit/s with DSSS)



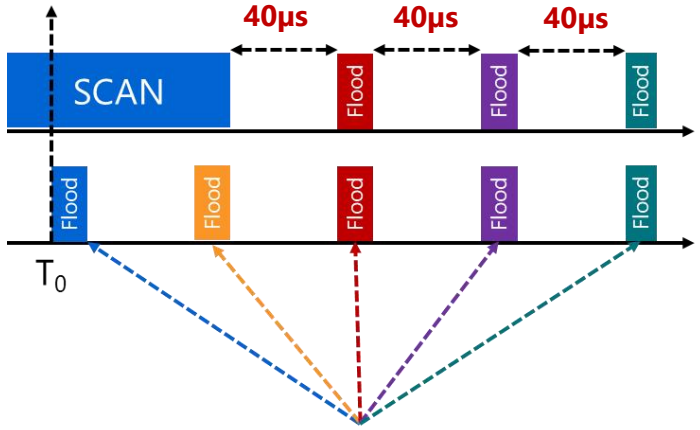
IMPORTANT: Only takes 40µs to switch PHY layer!!! (i.e., the radio ramp up time)

Single-Radio Multi-Protocol SoCs

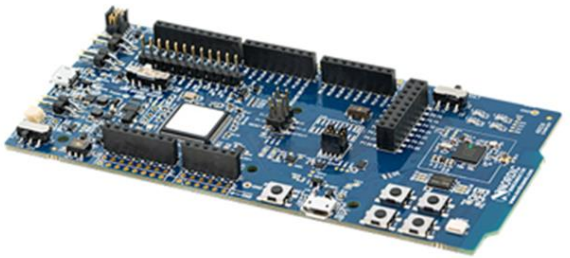
1. Different physical layers support CT-based flooding in different ways [2] - e.g., higher data rate PHYs can support OTA firmware updates.

2. If nodes are well-synchronized and follow a known schedule, there is very little overhead to switching the physical layer.

PHY	Advantage
BLE 2M	High data rates.
BLE 125K	Longer range.
BLE 500K	Support Concurrent Transmissions under interference.
IEEE 802.15.4	



40µs to switch PHY layer!



[2] M. Baddeley, CA. Boano, A. Escobar-Molero, Y. Liu, X. Ma, U. Raza, M. Schuß, and A. Stanoev, *"The Impact of the Physical Layer on the Performance of Concurrent Transmissions,"* in IEEE International Conference on Network Protocols (ICNP) May. 2020

The 6TiSCH++ Approach

1. MAC Layer

Address weaknesses in IETF 6TiSCH by leveraging the strengths of CT-based Synchronous Flooding.

Synchronization | ***Association*** | ***Downward Routes***

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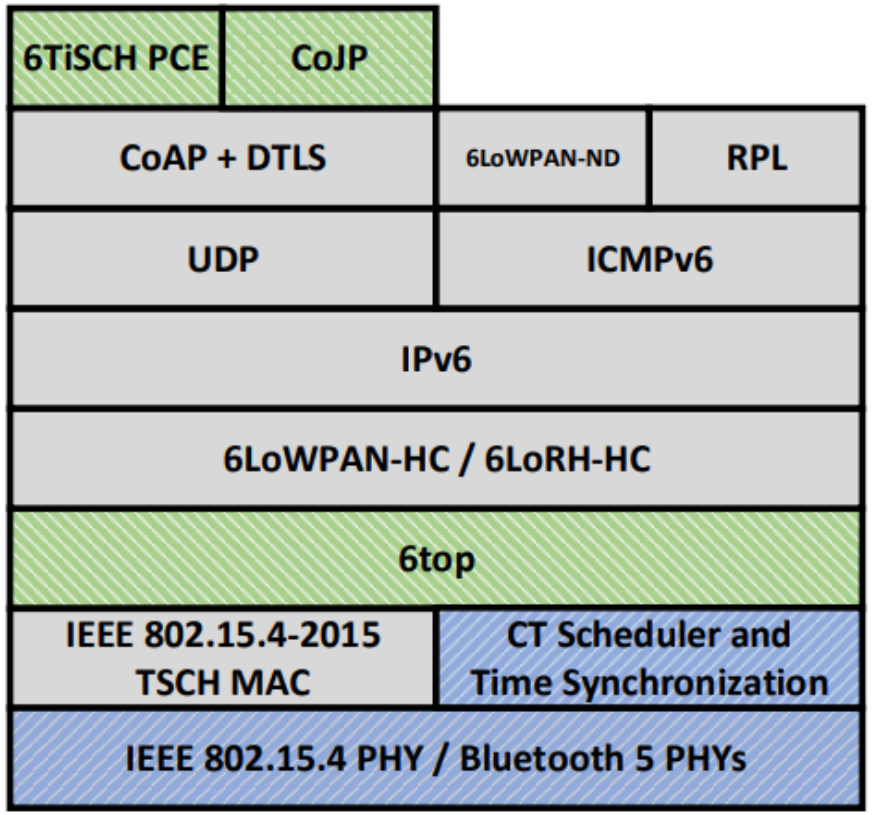
2. PHY Layer

Take advantage of modern *single-radio, multi-protocol* SoCs by switching the PHY at runtime to tailor the CT-based Synchronous Flooding depending on the application/network conditions.

High Data-Rates | ***Long-Range*** | ***CT Reliability***



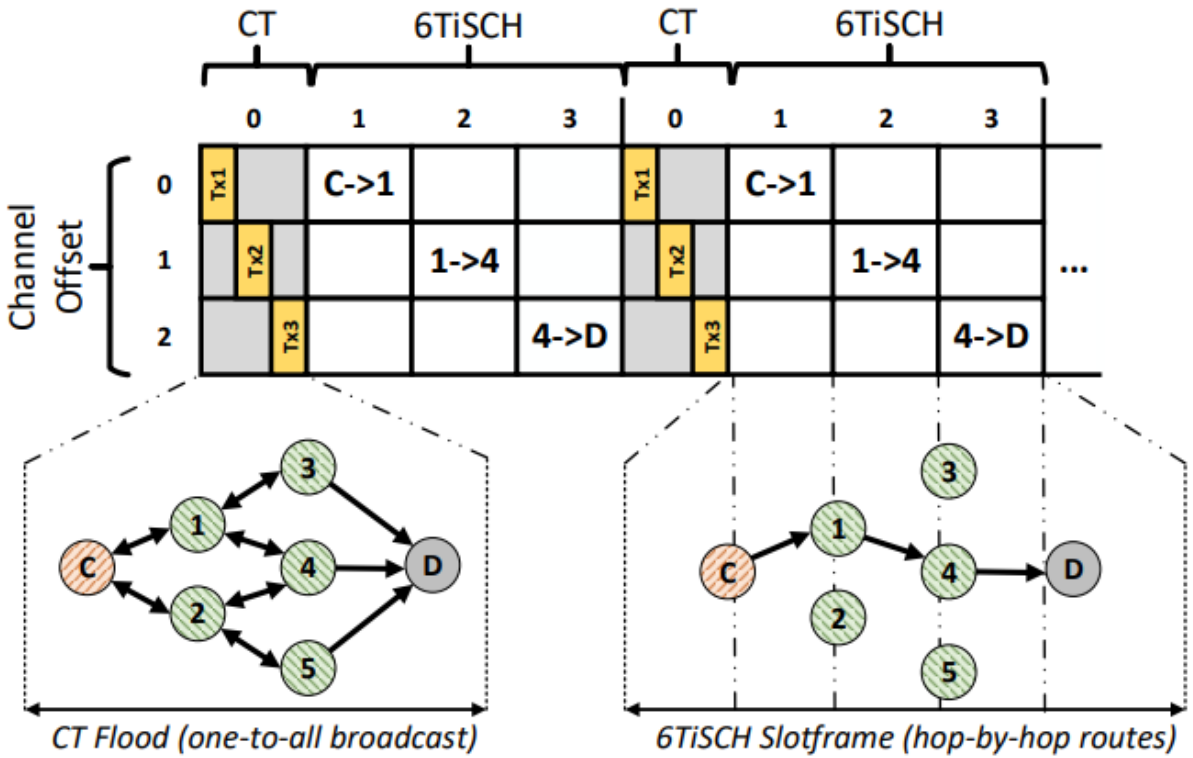
6TiSCH++: Switching the MAC Layer at Runtime

CT-based Synchronous Flooding is rather amenable to the 6TiSCH Standard…

1. **Synchronicity**. CT-based flooding protocols are highly synchronous + deterministic.

2. **Time-Bounded**. CT floods are bounded in time. You know when they are going to end. This fits neatly into the TSCH SlotFrame structure.

3. **Standard Compliant.** 6TiSCH defines immutable hard-cells, as well as negotiable soft-cells.

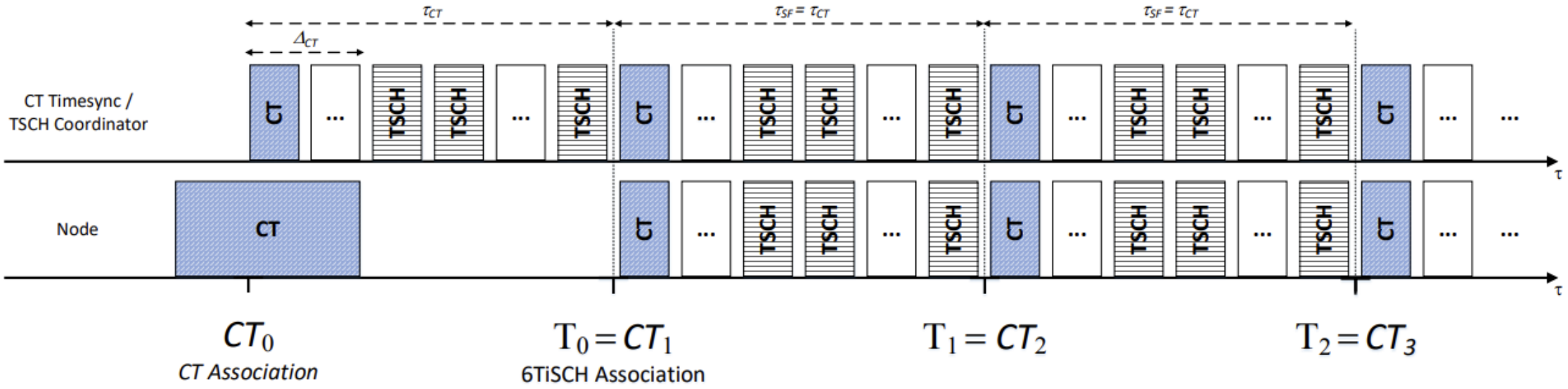


6TiSCH++: Switching the PHY Layer at Runtime

Recent research has shown the effectiveness of Bluetooth-based Synchronous Flooding protocols [3].

- Uncoded PHYs provide higher data rates (e.g., 2Mbps) than IEEE 802.15.4 OQPSK-DSSS
- Coded long-range PHY option (125Kbps)

Switching the PHY at runtime allows us to take advantage of these BLE PHYs whilst still supporting standard IEEE 802.15.4-based 6TiSCH.



[3] Al Nahas, Beshr, Simon Duquennoy, and Olaf Landsiedel. "Concurrent Transmissions for Multi-Hop Bluetooth 5." In *EWSN*, pp. 130-141. 2019.

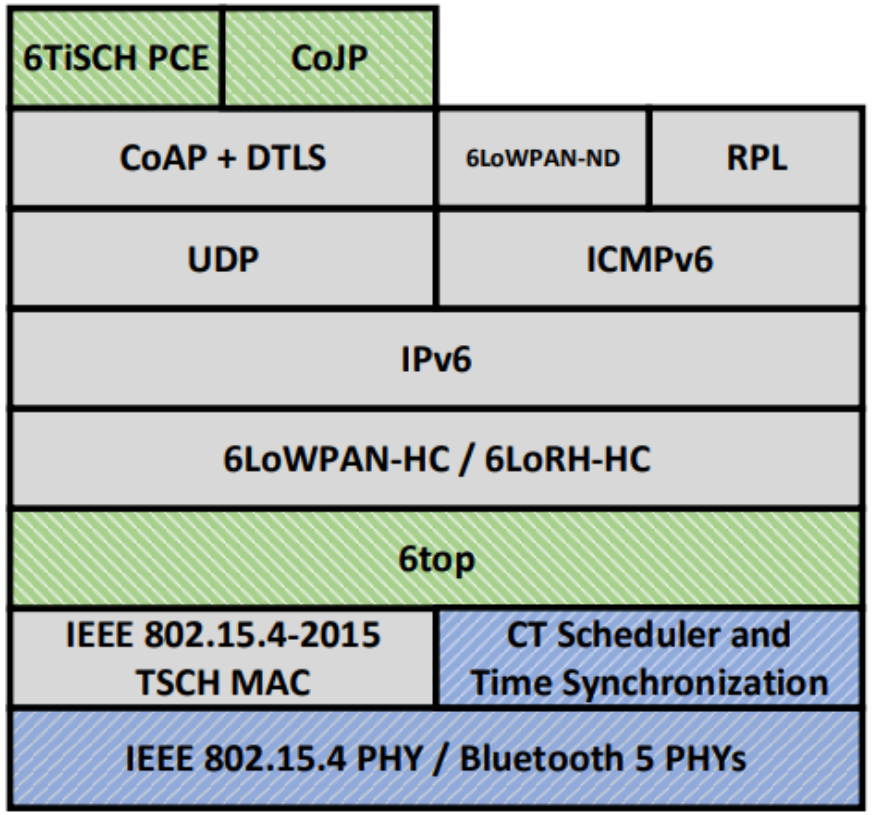
6TiSCH++: What precisely does it do?

1. Provide callbacks for switching between Bluetooth-based CT flooding and IEEE 802.15.4 TSCH at runtime.

2. Use 6TiSCH Minimal to reserve hard cells depending on the CT flood duration.
   - # of transmissions *X* on-air PHY duration.

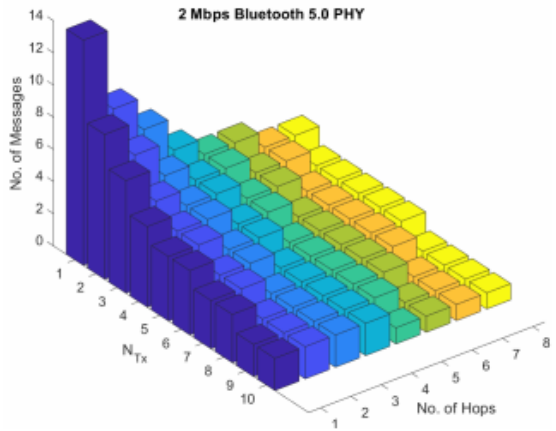
3. Periodically broadcast 6TiSCH EBs through CT floods.
   - Network-wide, *highly-accurate* synchronization.
   - Removes need for KA messaging.

4. Send RPL DAO-ACKs through CT floods.
   - Technique previously demonstrated in [4].
   - Significantly reduces the signaling overhead involved in establishing *downwards* RPL routing.

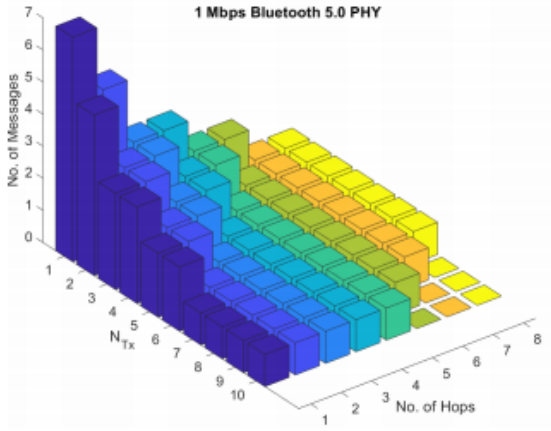


[4] Istomin, Timofei, Oana Iova, Gian Pietro Picco, and Csaba Kiraly. "Route or flood? Reliable and efficient support for downward traffic in RPL." *ACM Transactions on Sensor Networks (TOSN)* 16, no. 1 (2019): 1-41.

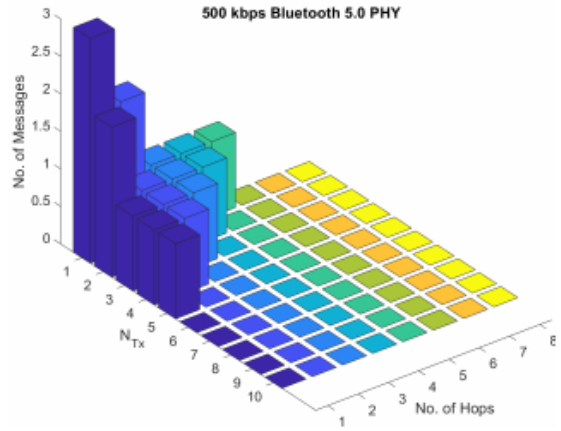
Simulating BT5-based CT Scalability within a 10ms 6TiSCH Slot



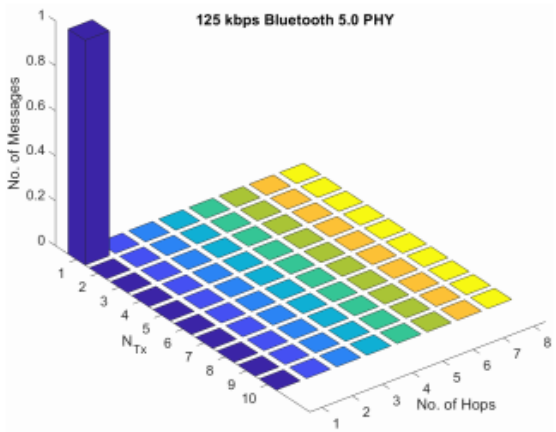
(a)

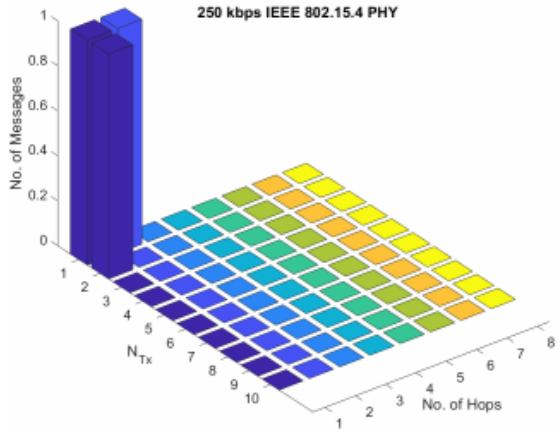


(b)



(c)





Testbed Evaluation on D-Cube

A Mesh Benchmarking Testbed from TU Graz, Austria.

You may remember D-Cube from the Dependability Competition at previous editions of EWSN…

… and many others!

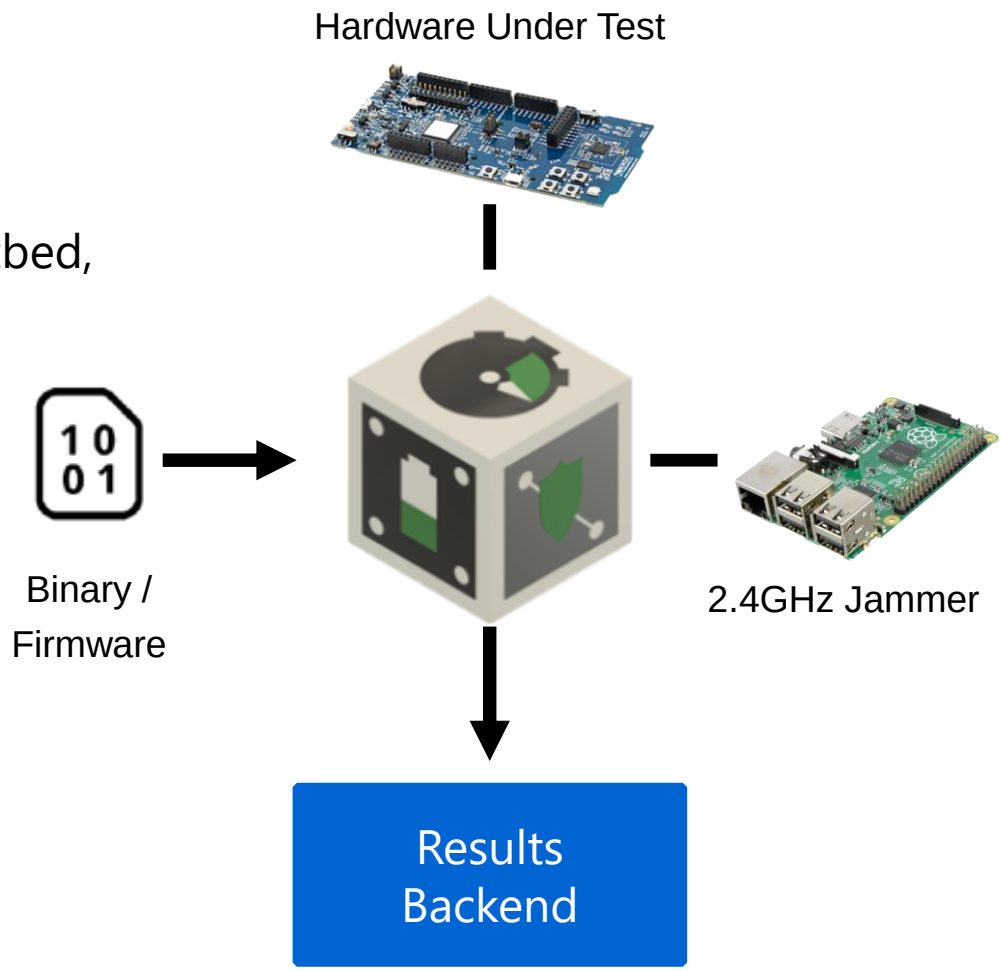
Testbed Evaluation on D-Cube

A Mesh Benchmarking Testbed from TU Graz, Austria.

- D-Cube hardware is essentially an **adapter** that allows **unobtrusive testing + jamming** of mesh protocols:

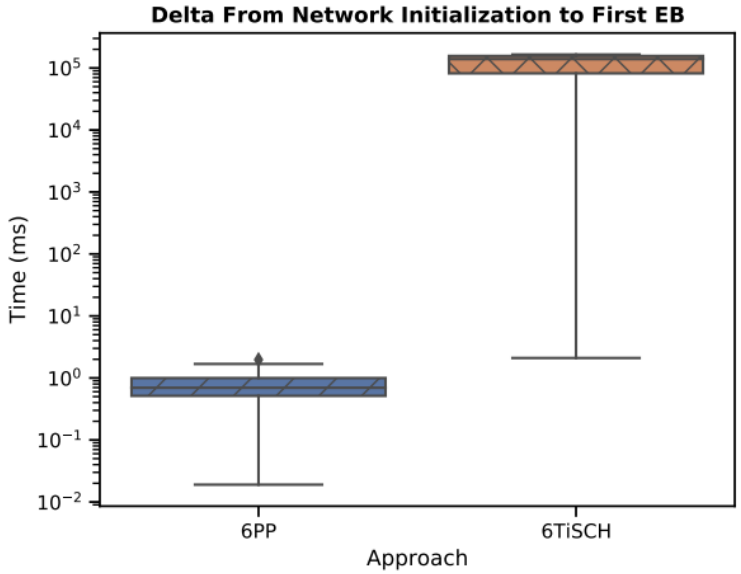
- It manages sending and receiving messages across the testbed, and **automatically** measures
  - The **power** consumed by the device under test
  - The **latency** of received messages
  - The **reliability** of sent messages

- These metrics are then…
  - **Collected** by the D-Cube hardware
  - **Analyzed** in a backend system

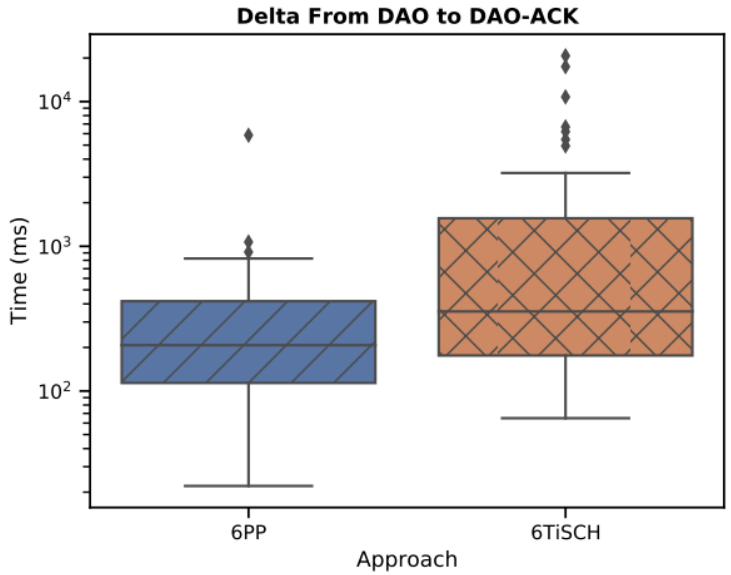


Testbed Evaluation on D-Cube: Association and Route Establishment

1. Time taken for all nodes to associate to the network.
   - In 6TiSCH++ EBs are disseminated using CT-based flooding protocols.
   - KA messages are no longer needed.



2. Time taken for all nodes to establish a *downwards* RPL route.
   - RPL DAO-ACKs are also disseminated using CT-based flooding protocols.



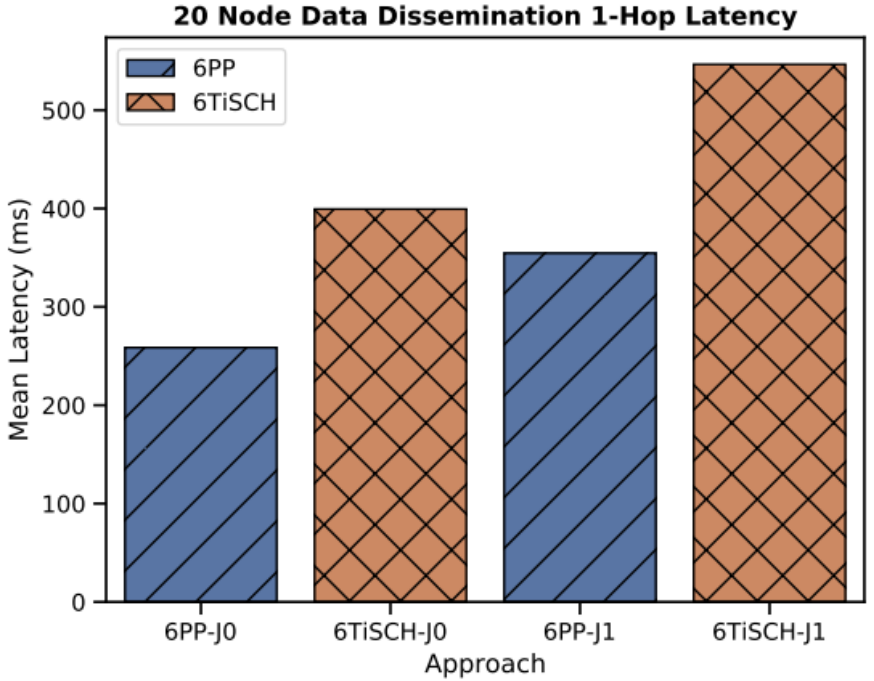
Testbed Evaluation on D-Cube: Reduced Control Signalling

Dense Data Dissemination Scenario:

- 20-node data dissemination (broadcast).
- Both *with (J1)* and *without (J0)* D-Cube generated narrowband interference.
- Periodic data generation (5s).
- 64B messaging (sent over 6TiSCH).

The reduction of control signaling in 6TiSCH++ (eliminating KAs + dependable EBs and DAO-ACKs) frees up the TSCH SlotFrame for application traffic.

- Significantly lower latency (42% without interference and 37% with)
- Improved reliability under interference.



Approach	Reliability (%)	Mean Latency (ms)
6PP (No Interf.)	100	250.60
6TiSCH (No Interf.)	100	403.96
6PP (With Interf.)	99.54	329.58
6TiSCH (With Interf.)	98.63	527.64

What Next?

6TiSCH++ explores how BT5-based Concurrent Transmissions can address weaknesses in the IETF 6TiSCH standard. Specifically, 6TiSCH++ demonstrates:

1. Fast, highly-reliable synchronization and (re)authentication.

2. Reliable, low-latency 6TiSCH and RPL centralized control signaling.

3. Viability of switching the radio PHY at runtime.

Questions?

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