TOSHIBA

The Impact of the Physical Layer on the Performance of Concurrent Transmissions

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1. *Bristol Research and Innovation Lab (BRIL), Toshiba Europe, UK*
2. *Institute of Technical Informatics, Graz University of Technology, Austria*
3. *RedNodeLabs UG, Germany*
4. *College of Engineering, Nanjing Agricultural University, China*
5. *Shanghai Advanced Research Institute (SARI), Chinese Academy of Sciences, China*

Toshiba Europe Ltd.
16/10/20

Scope of Disclosure	Whom it may concern
Head of Information Owner Section	**Mahesh Sooriyabandara (mahesh@toshiba-bril.com)**

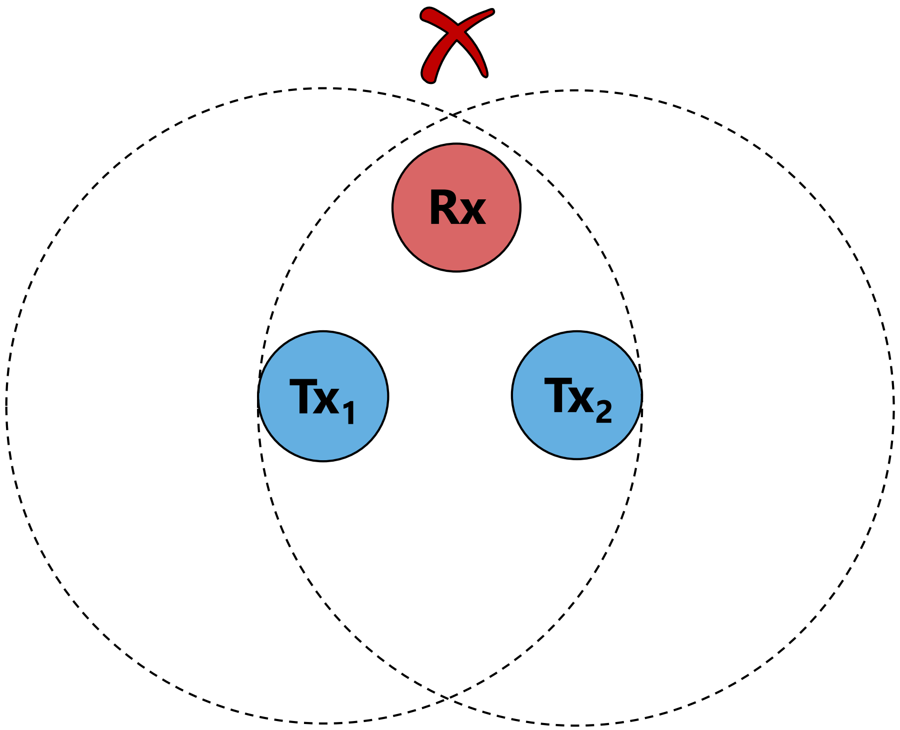
Contents

01

The PHY Layer Properties of Concurrent Transmissions

What are Concurrent Transmissions (CTs)?

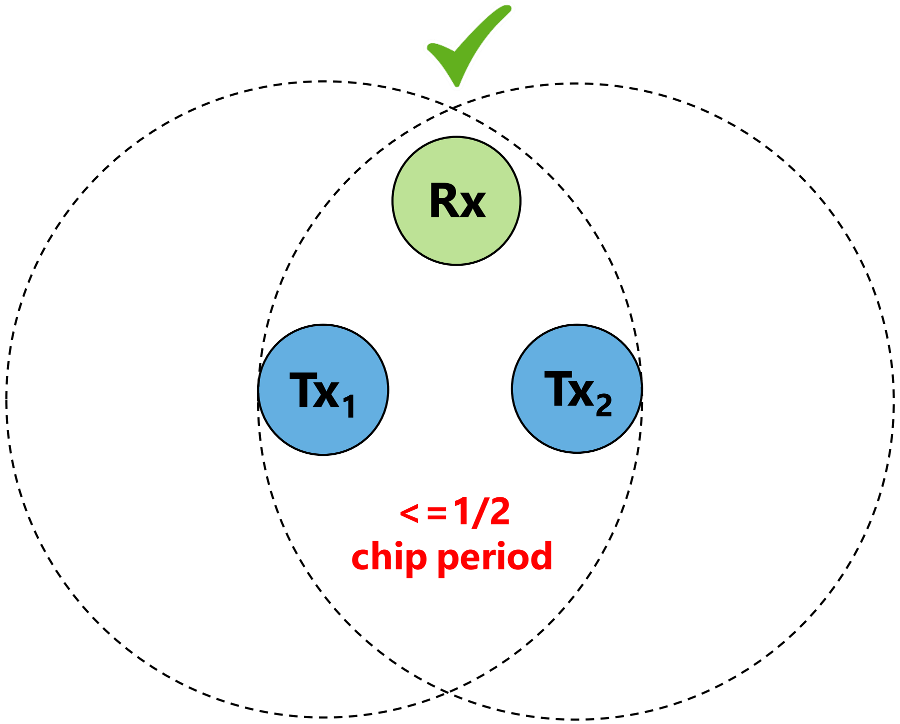
Usually when two nodes Tx at the same time, they will collide at the receiver.



Concurrent Transmissions is the technique of allowing highly synchronized devices to transmit at the same time.

What are Concurrent Transmissions (CTs)?

If nodes are well-synchronised the transmission can be reliably demodulated
($<0.5\mu$s for IEEE 802.15.4)

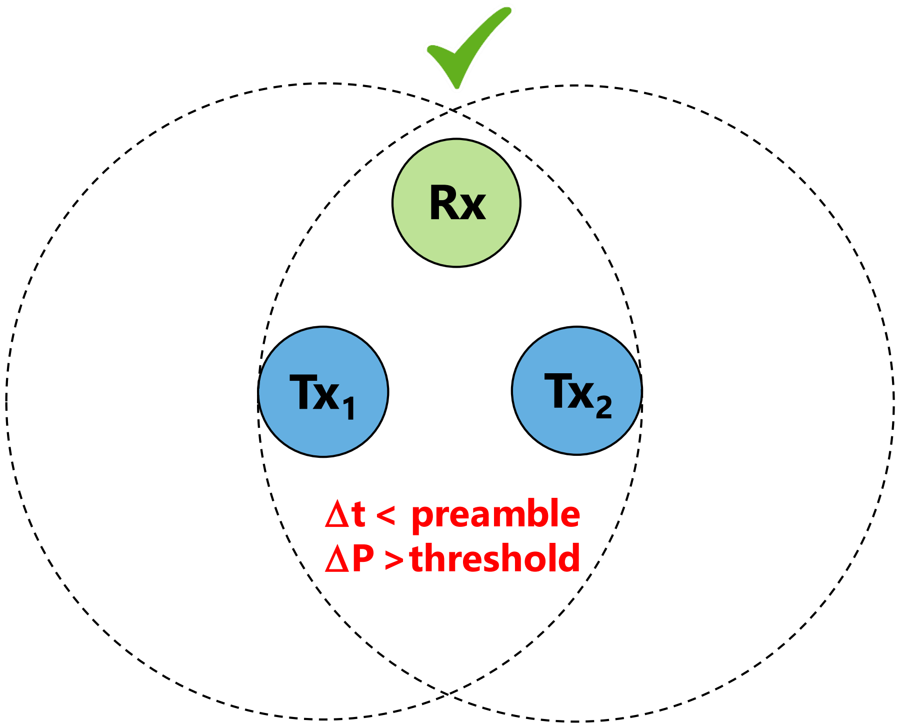


They benefit from (1) non-destructive interference when nodes are HIGHLY synchronized and send the SAME data. This has previously been attributed to so-called "Constructive Interference" [1]

1. Ferrari, F., Zimmerling, M., Thiele, L. and Saukh, O., 2011, April. Efficient network flooding and time synchronization with glossy. In *Proceedings of the 10th ACM/IEEE International Conference on Information Processing in Sensor Networks* (pp. 73-84). IEEE.

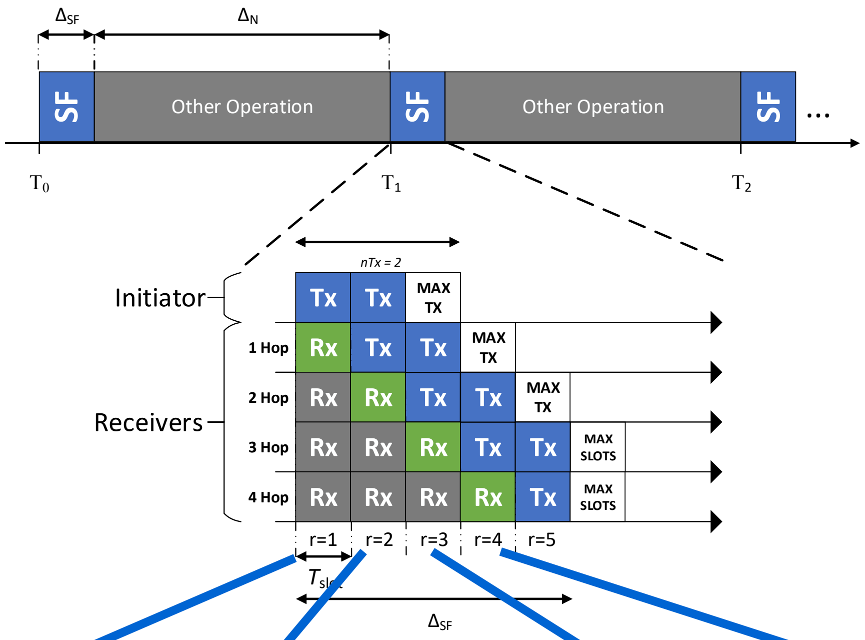
What are Concurrent Transmissions (CTs)?

Frequency modulated transmissions can benefit from the capture effect.
(ΔP >~3dB in IEEE 802.15.4)



Subsequent studies have shown that CT also benefits from (2) the Capture Effect when nodes send either the SAME or DIFFERENT data.

CT-based Flooding Protocols



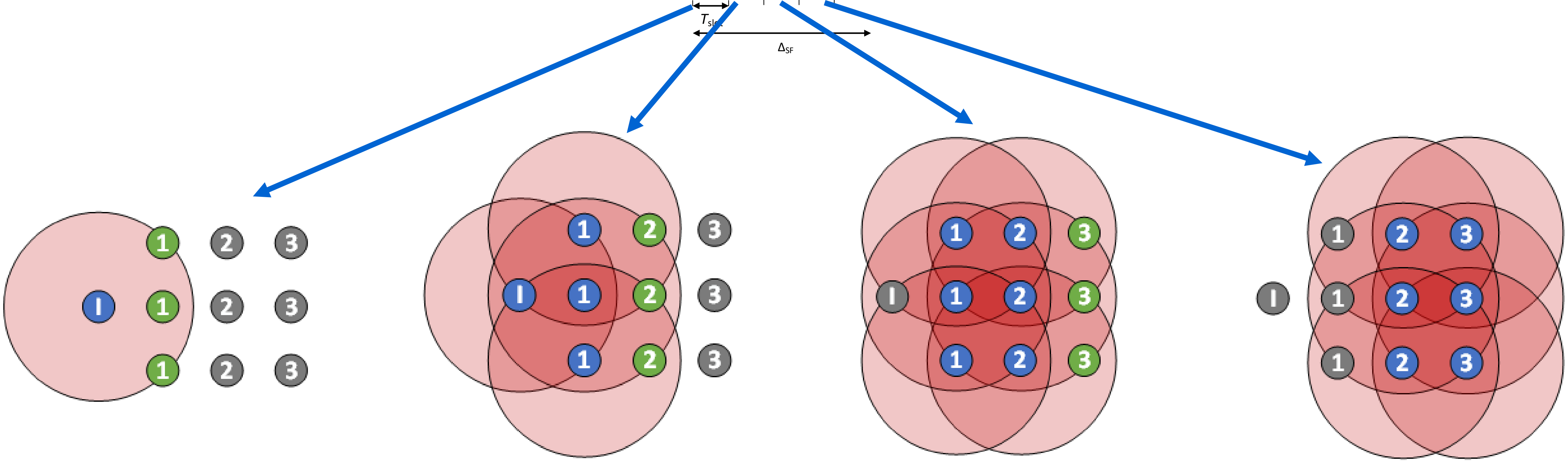
Synchronous Flooding (SF) allows the network to reliably send a packet across the mesh with minimal latency, using aggressive spatial, temporal and frequency diversity.

Extremely high reliability.

- Even under external network interference such as WiFi.

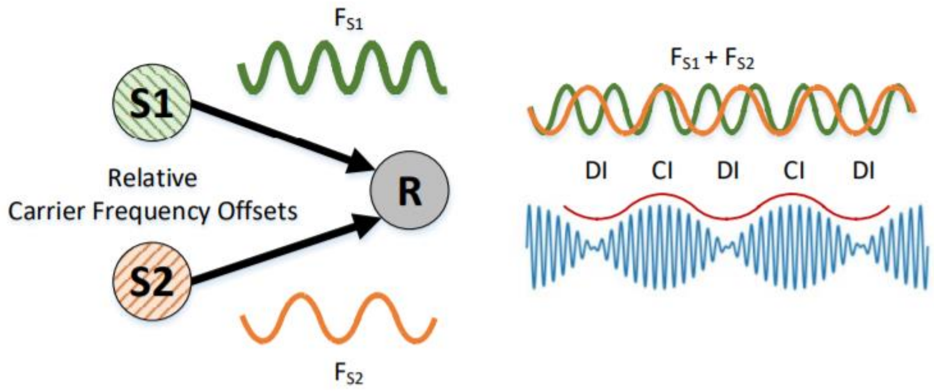
Minimal bounds on latency.

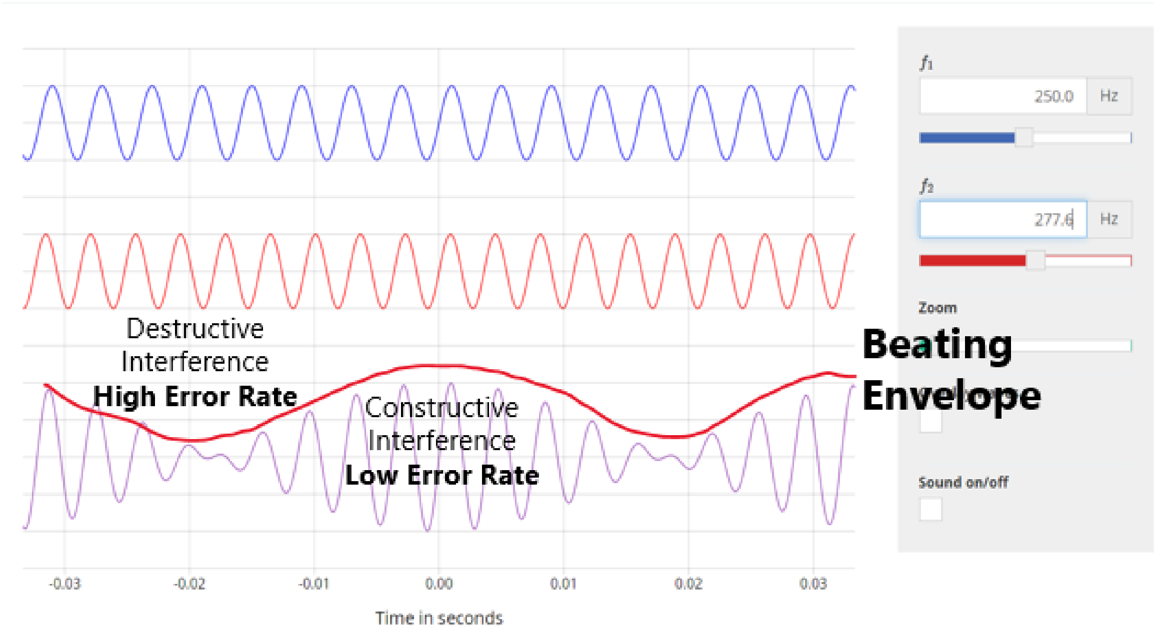
- Eliminates delays caused by scheduling algorithms or backoff mechanisms.



The Importance of the Beating Effect in Concurrent Transmissions

Concurrent Transmissions aren't just Capture Effect + "Constructive Interference"! They are also a big wibbly wobbly ball of Beating Effect (and multipath).



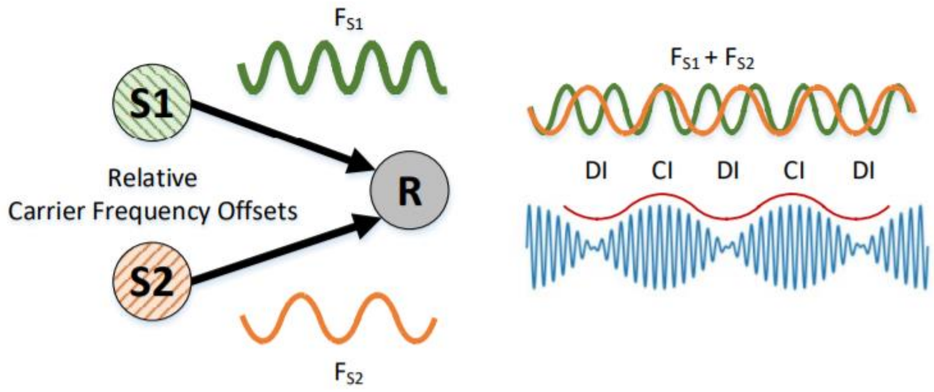


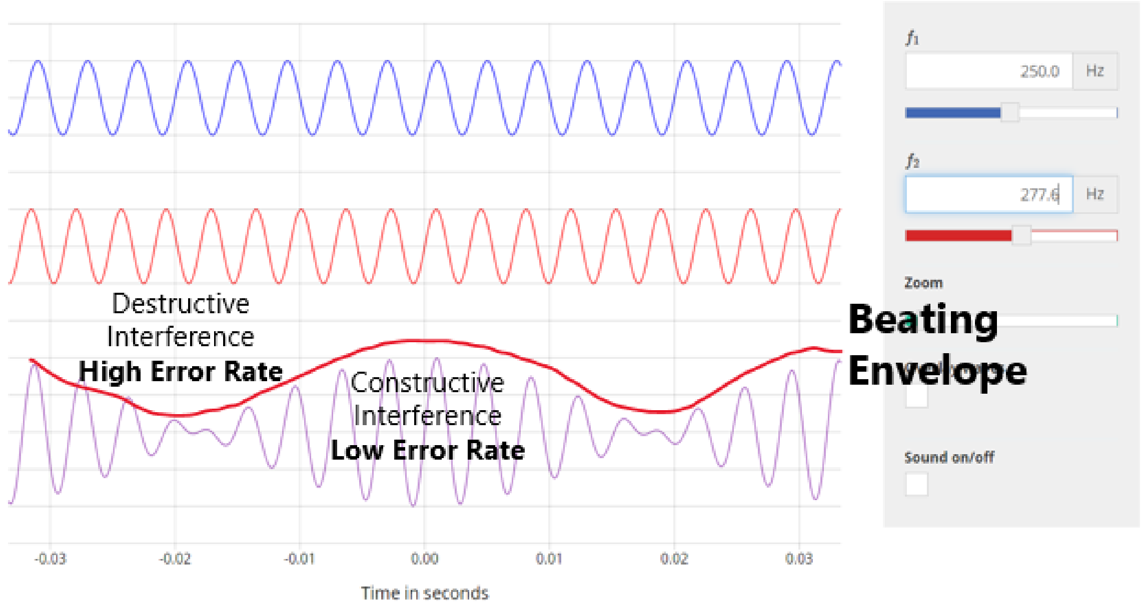
The effect of CFO-induced beating in CTs has been mentioned in a number of previous works:

1. Yamashita, Y., Tashiro, Y., Suzuki, M., Hase, Y. and Morikawa, H., 2013, November. Understanding the effects of carrier frequency difference in concurrent transmission. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems* (pp. 1-2).
2. C.-H. Liao, Y. Katsumata, M. Suzuki, and H. Morikawa. Revisiting the So-Called Constructive Interference in Concurrent Transmission. In Proc. of the Conf. on Local Computer Networks (IEEE LCN), 2016
3. Escobar-Molero, A., 2019. Improving reliability and latency of wireless sensor networks using concurrent transmissions. *at-Automatisierungstechnik*, *67*(1), pp.42-50.
4. Al Nahas, B., Duquennoy, S. and Landsiedel, O., 2019, February. Concurrent Transmissions for Multi-Hop Bluetooth 5. In *EWSN* (pp. 130-141).

The Importance of the Beating Effect in Concurrent Transmissions

Errors in the manufacturing process cause subtle variations in the Carrier Frequency Offsets of radio oscillators, resulting in a sinusoidal envelope of BOTH *constructive* AND *destructive* interference across the packet.





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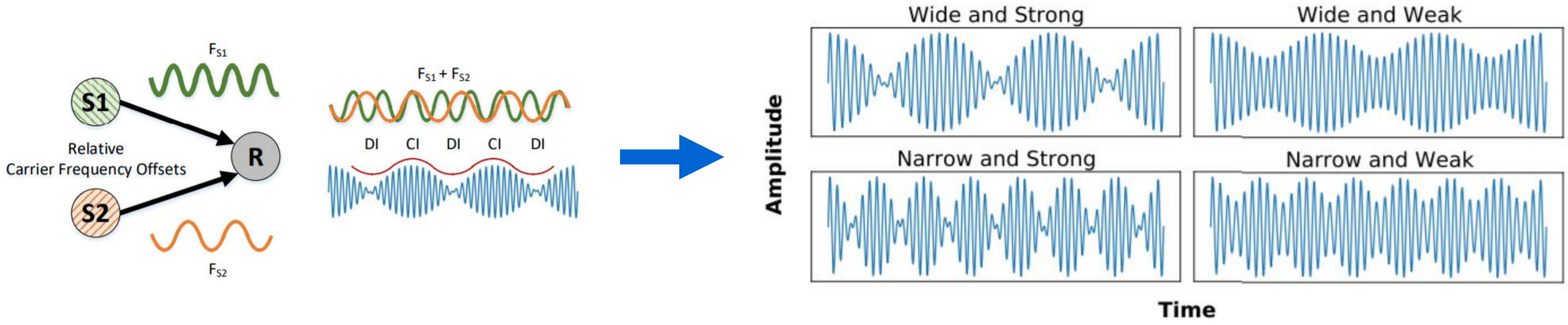
The Importance of the Beating Effect in Concurrent Transmissions

We categorize this beating envelope in terms of it's periodic negative effect on the underlying concurrent transmission…

Width - (Wide/Narrow)
Strength - (Strong/Weak)



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02

Concurrent Transmissions and Multi-PHY Low-Power Wireless Chipsets

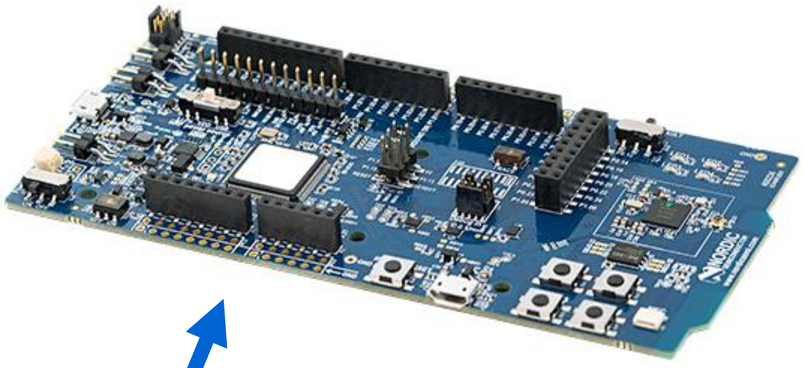
Concurrent Transmissions over Multiple Physical Layers

Recently it's been shown that CT-based protocols also work over the Bluetooth 5 physical layers (as well as IEEE 802.15.4)[1] …

IEEE 802.15.4 OQPSK-DSSS:
- 250 Kbps

BLE 5 Uncoded PHYs:
- 1 Mbps
- 2 Mbps

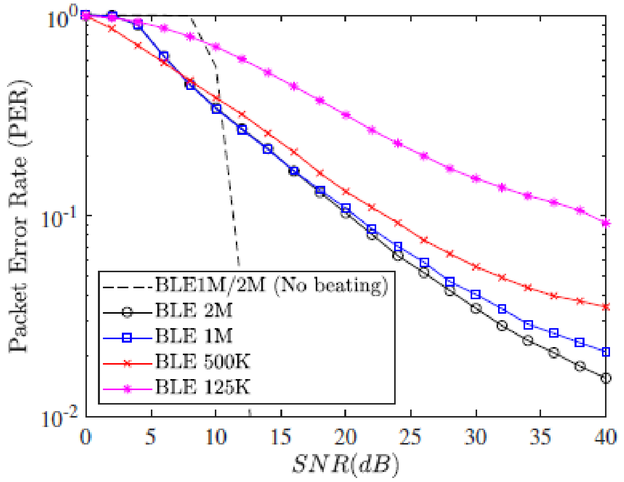
BLE 5 Coded PHYs:
- 500 Kbps (S=2)
- 125 Kbps (S=8)



Modern chipsets (such as the **Nordic nRF52840**) are capable of switching between IEEE 802.15.4 and the Bluetooth PHYs in real-time, **with no additional radio overhead.**

1. Al Nahas, B., Duquennoy, S. and Landsiedel, O., 2019, February. Concurrent Transmissions for Multi-Hop Bluetooth 5. In *EWSN* (pp. 130-141).

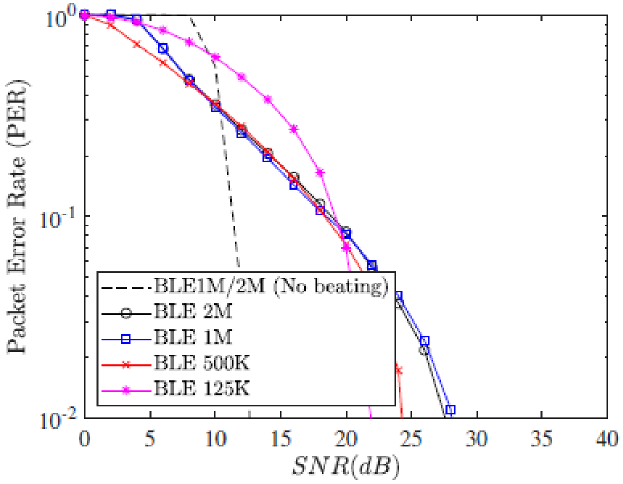
Concurrent Transmissions over Multiple Physical Layers



2CT, RFO=500Hz ΔP=0dB

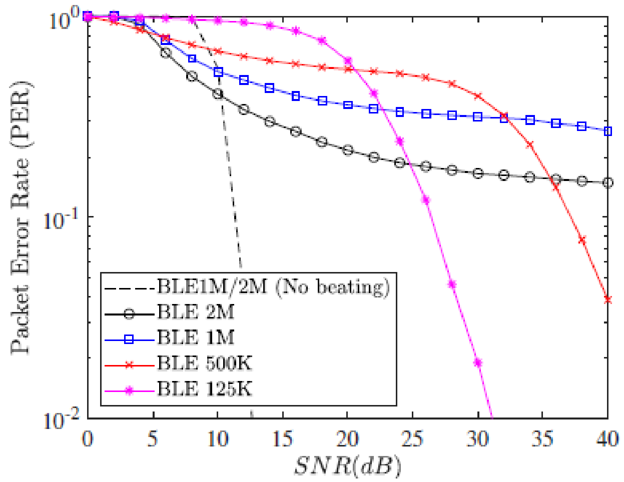
*Simulations model a non-coherent BFSK receiver

Importantly, the choice of PHY layer has a huge impact on the CT performance under different signal strength, noise (SNR), and Relative Carrier Frequency Offset (RFO) conditions…

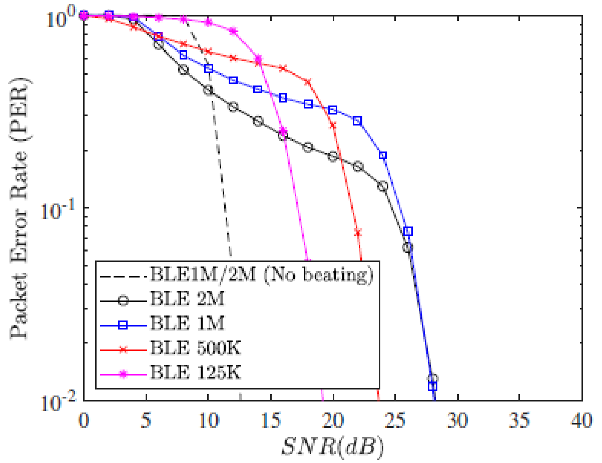


2CT, RFO=500Hz ΔP=1dB

2CT, RFO=10kHz ΔP=0dB



2CT, RFO=10kHz ΔP=1dB



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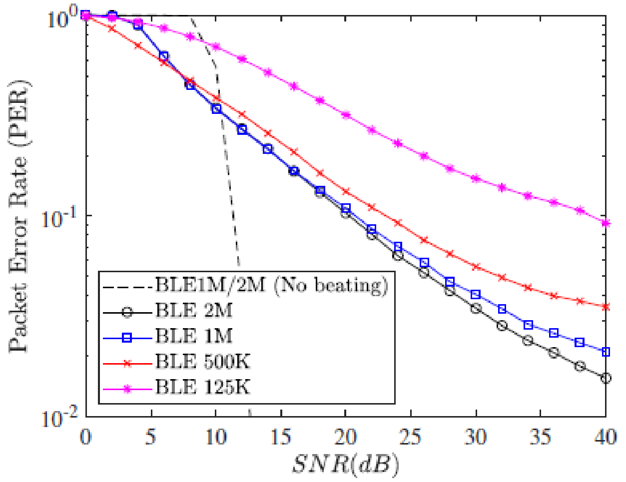
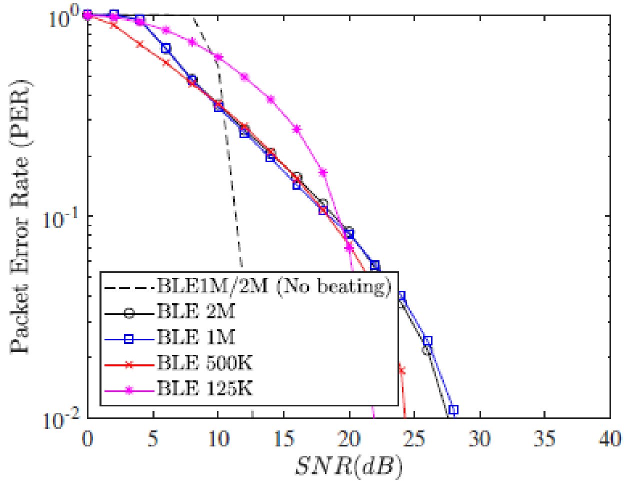


2CT, RFO=500Hz ΔP=0dB



2CT, RFO=500Hz ΔP=1dB

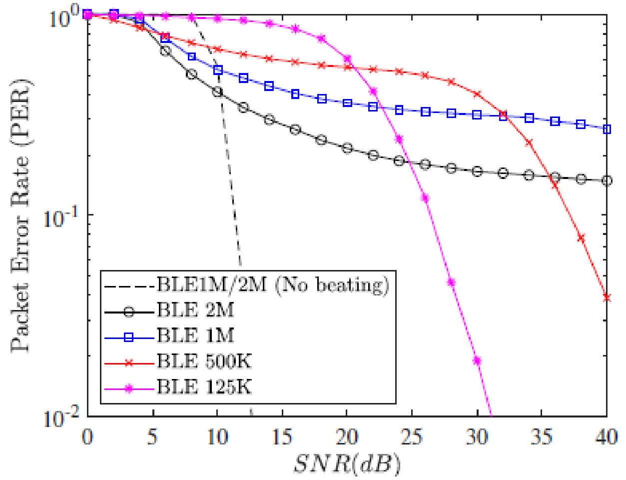
< RFO

< Power Delta

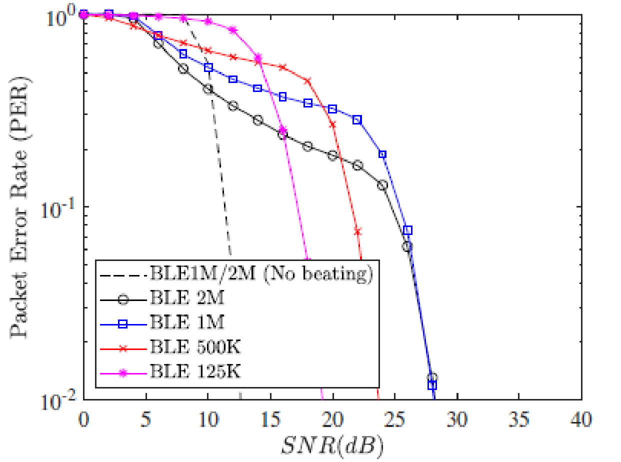
> Power Delta

> RFO

2CT, RFO=10kHz ΔP=0dB



2CT, RFO=10kHz ΔP=1dB



Concurrent Transmissions over Multiple Physical Layers

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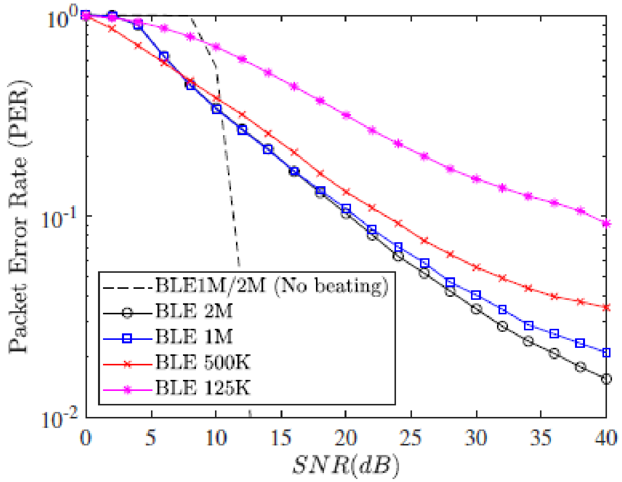

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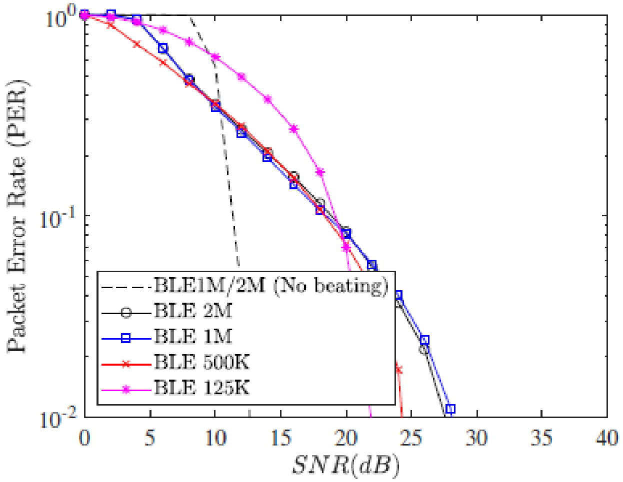
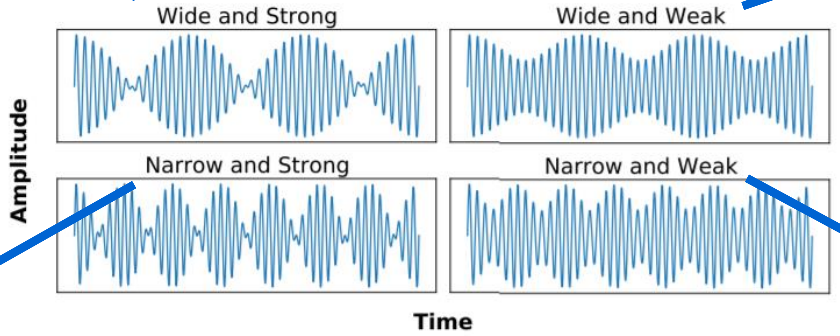


2CT, RFO=500Hz ΔP=1dB



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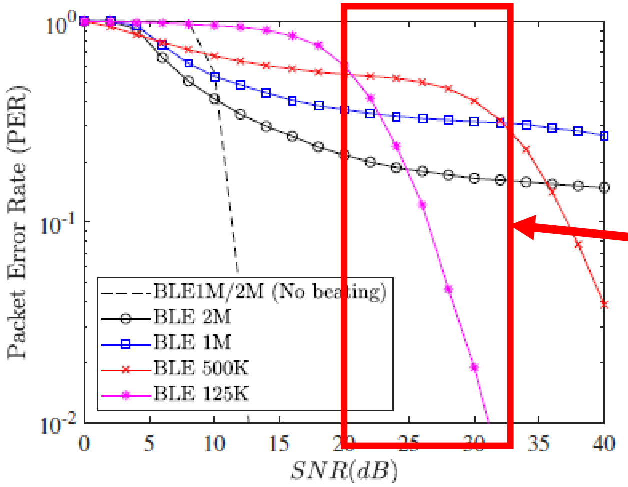

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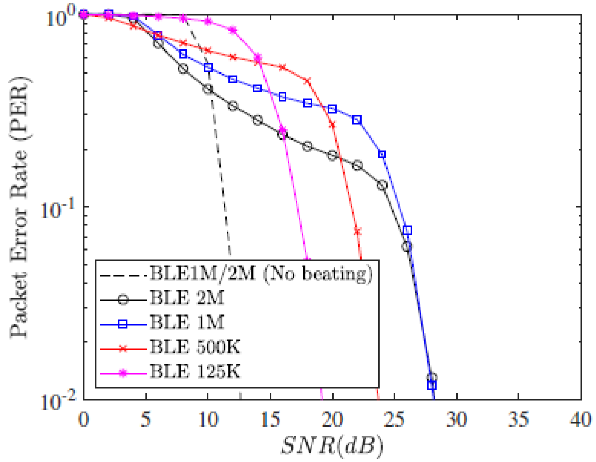


For example, under *narrow* and *strong* beating when there is <u>low noise</u> (SNR>20dB), the coded BLE 500K should be (surprisingly) the **worst** performing PHY!

Some Questions…

To date there has been no extensive experimental study examining how CT-based protocols perform across multiple different physical layers in a real-world environment. Specifically…

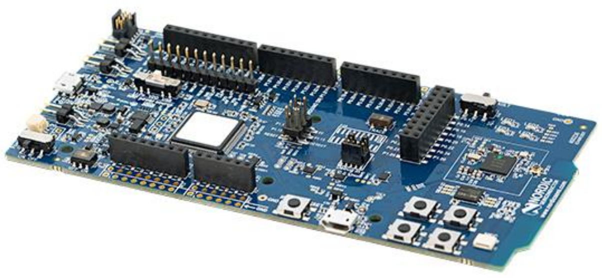
1. How does beating, which is closely linked to the PHY layer, impact CT protocols?
2. On a network level, how do CT protocols perform across the different PHY layers?
3. Are there any properties or observations that we can take advantage of?

D-CUBE Testbed

- Why did we need a testbed?
  - 1’000s jobs
  - 1’000s hours
  - 100s GB of raw logs
  - Experimental Setup
    - Many possible layouts
    - 1000s node combinations
  - Job scheduling
    - Can queue many 100s of job runs for an experiment (“Post and pray”)
    - Operational times protect yourself and neighbours from 2.4GHz interference
  - Results collection
    - Basic results are automatically generated (latency / reliability / energy)
    - APIs allow easy collection of raw data
  - **Easy collaboration with partners! (Toshiba, TU Graz, SARI, RedNodeLabs)**

D-Cube nRF52840-DK Setup

- 16 MHz triggered PPI channels
  - Makes timing concurrent transmissions much easier!
- 5 Physical Layers (+ proprietary Nordic)
  - BLE 2 Mbit/s (Uncoded)
  - BLE 1 Mbit/s (Uncoded)
  - BLE 500 Kbit/s (1M + S=2)
  - BLE 125 Kbit/s (1M + S=8)
  - IEEE 802.15.4 (256 Kbit/s with DSSS)
- Tx Power
  - -40 dBm to +8 dBm (Experiments were run at 0 dBm)

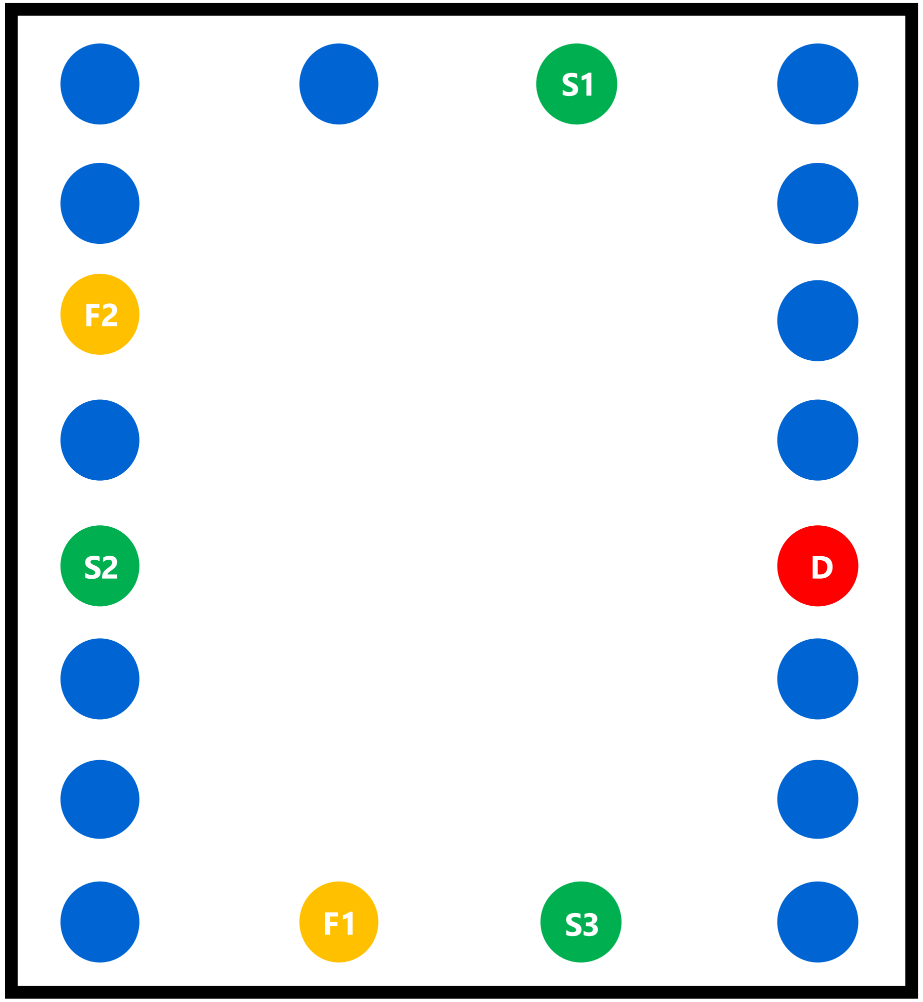


03

Experimental Analysis: The Impact of the Beating Effect on 1-Hop CT Performance

Beating Effect: Experimental Setup

- 1 Hop Scenario
  - All nodes in single room, mostly line-of-sight.
  - 3 different initiating layouts (S1, S2, S3)
  - 1 Destination (D)
  - All other nodes can act as Concurrent Transmitters

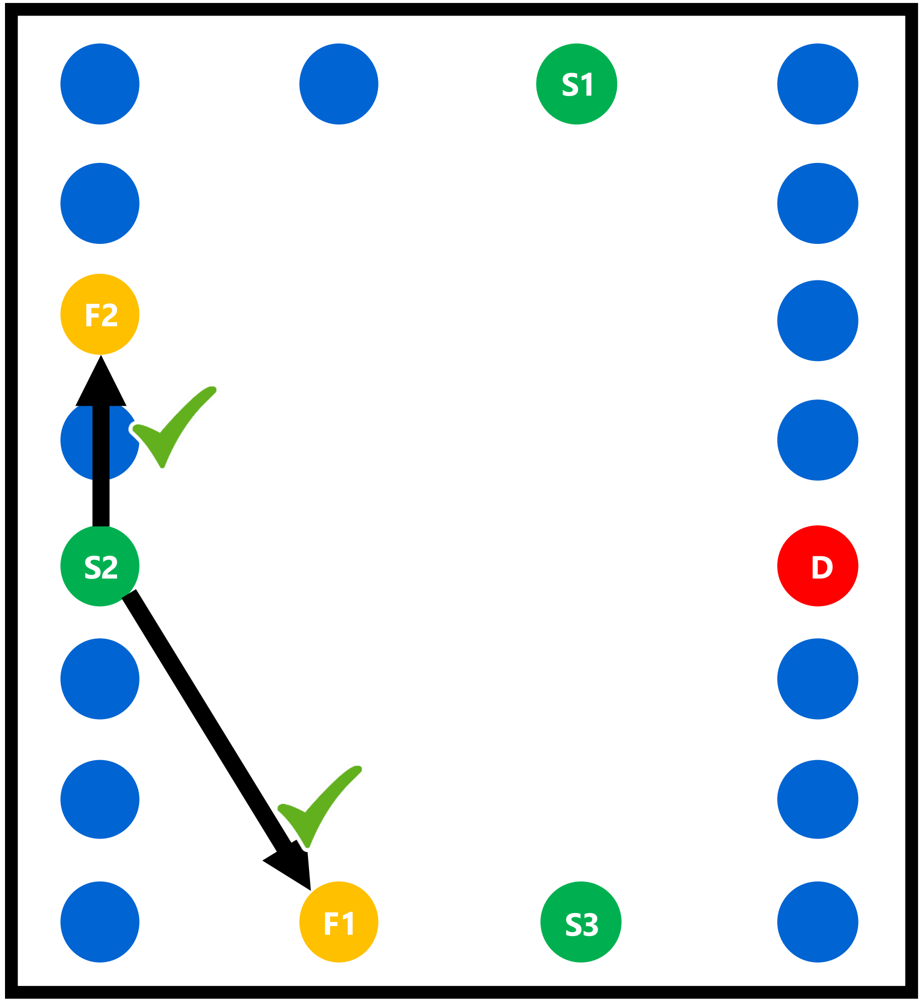


Beating Effect: Experimental Setup

- 1 Hop Scenario
  - All nodes in single room, mostly line-of-sight
  - 3 different initiating layouts (S1, S2, S3)
  - 1 Destination (D)
  - All other nodes can act as Concurrent Transmitters

- Example …
  1. **S2 synchronises F2 and F2**
  2. **S2, F1, and F2 concurrently Tx to D**

	TS1	TS2	TS3
S2	**Tx**		…
F1	✓		…
F2	✓		…
D			…

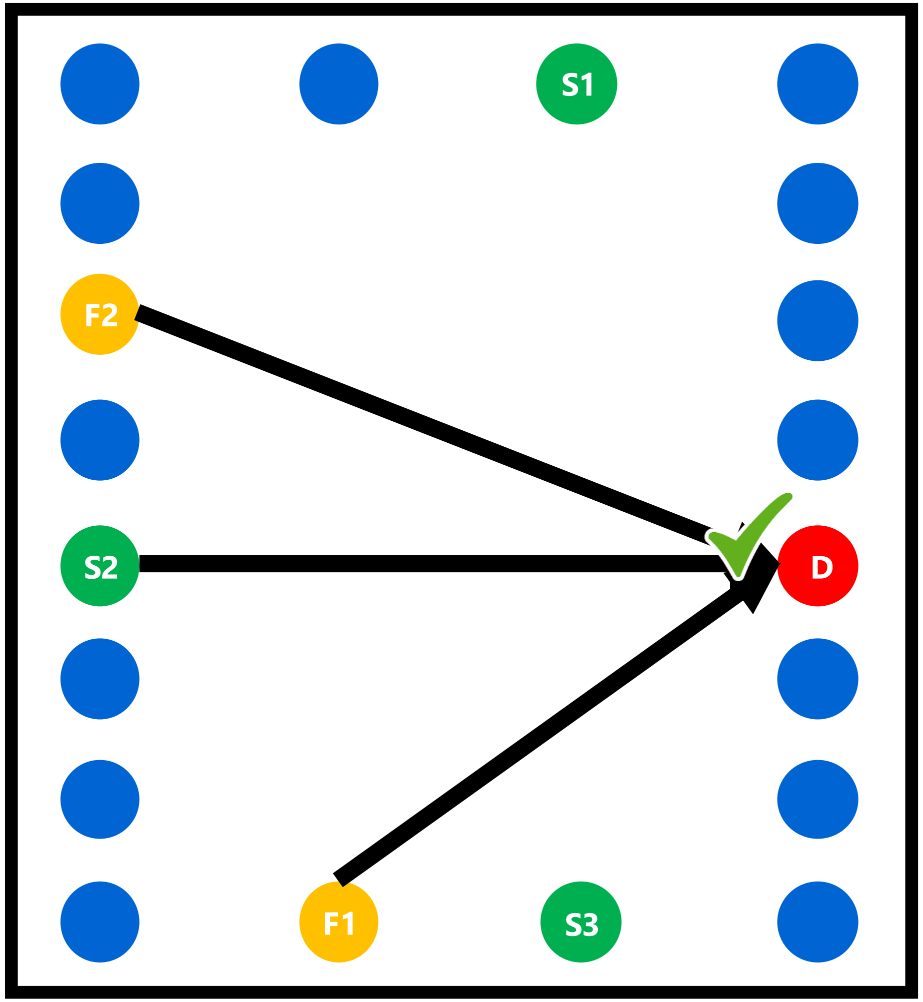


Beating Effect: Experimental Setup

- 1 Hop Scenario
  - All nodes in single room, mostly LoS
  - 3 different initiating layouts (S1, S2, S3)
  - 1 Destination (D)
  - All other nodes can act as Concurrent Transmitters

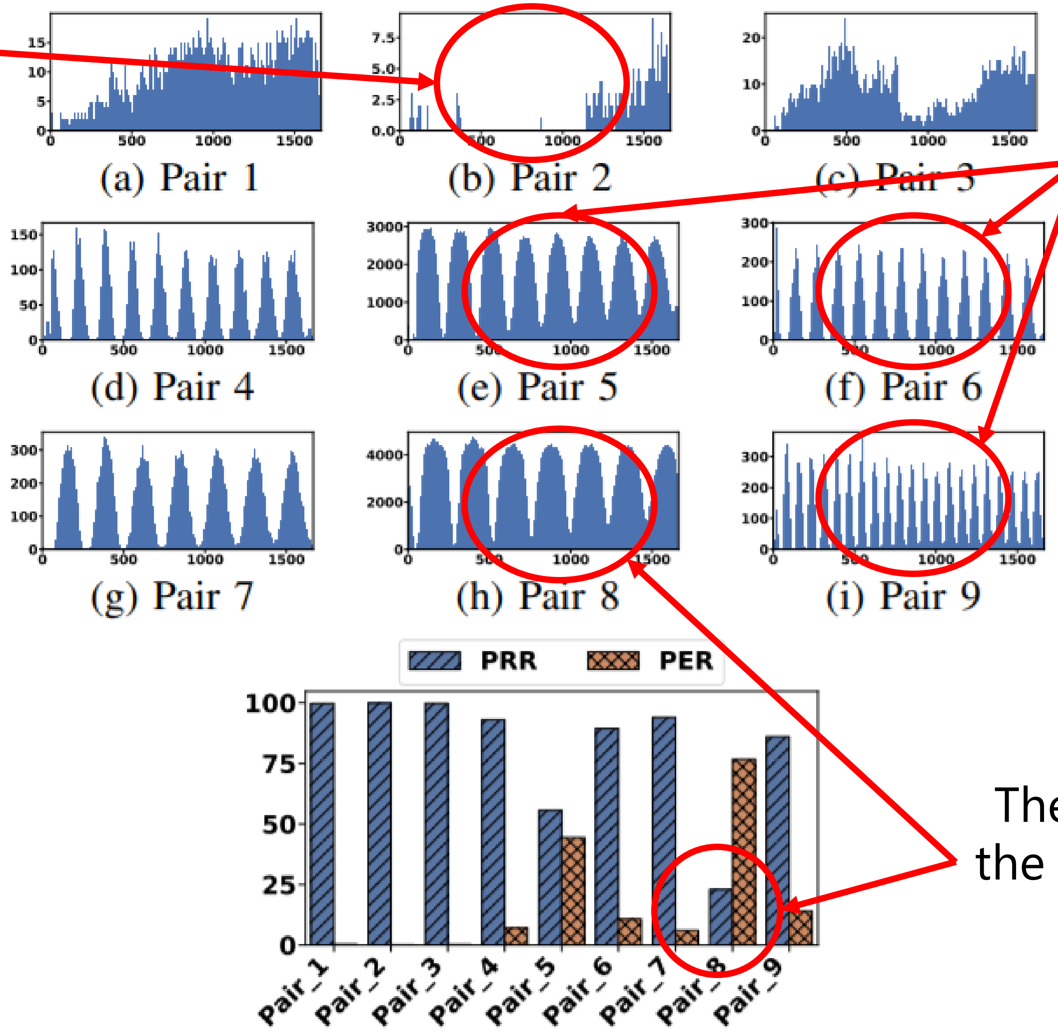
- Example (CT 3)…
  1. S2 synchronises F2 and F2
  2. **S2, F1, and F2 concurrently Tx to D**

	TS1	TS2	TS3
S2	**Tx**	**Tx**	**…**
F1	✓	**Tx**	**…**
F2	✓	**Tx**	**…**
D	✗	✓	**…**



Beating Effect: Different CT Pairs

In some cases practically no beating frequency is seen.



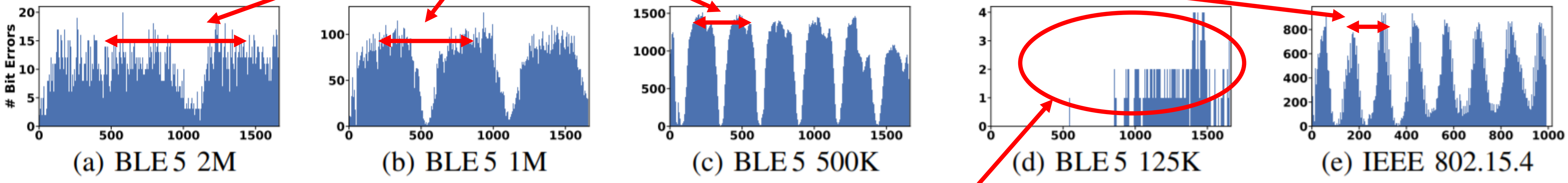
(j) PRR and PER for all pairs

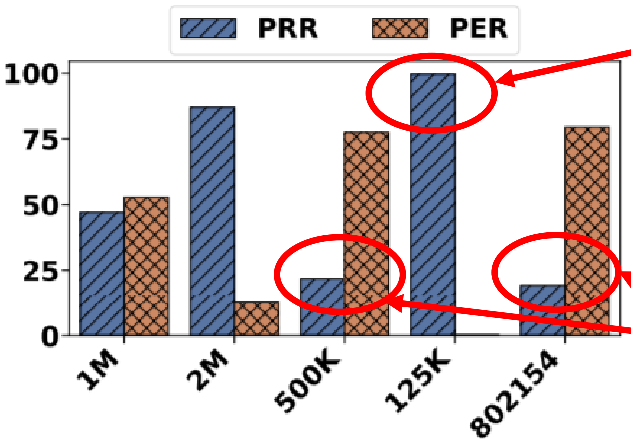
Different device pairs experience different beating frequencies due to different Relative Carrier Frequency Offsets (RFOs)

The strength and narrowness of the beating can have a significant impact on CT reliability!

Beating Effect: Different PHY Layers

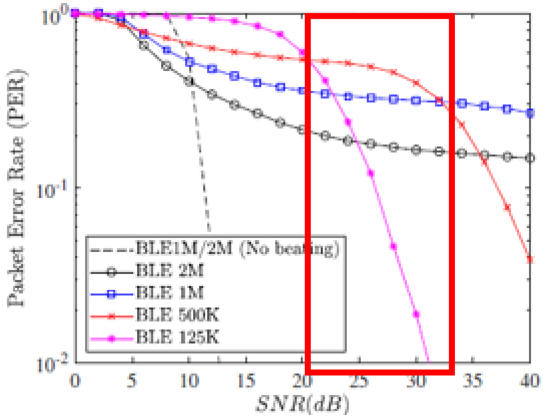
Consistent beating frequency across all PHYs for same node pair (~2kHz).





BLE 125K coding is <u>extremely</u> robust against *strong* and *wide* beating

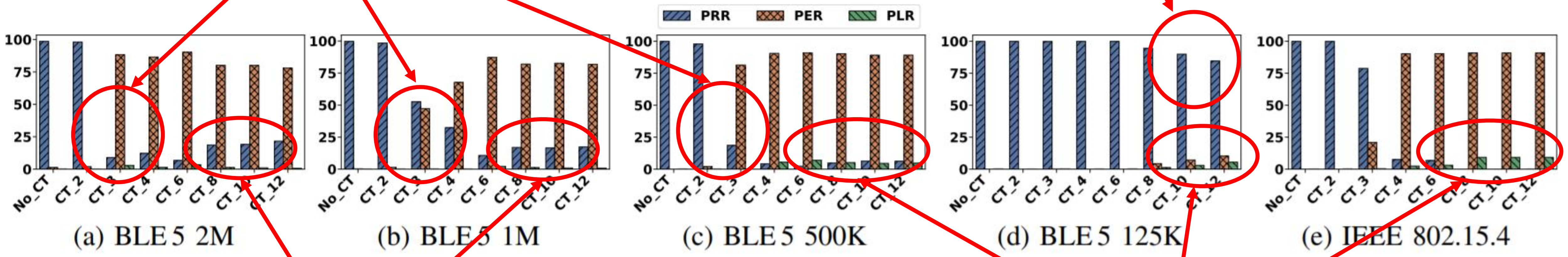
Surprisingly, the other coded PHYs don't perform well! This is consistent with modelling of Narrow and Strong beating conditions under low noise.



Beating Effect: # Concurrent Transmitters

Reliability drops rapidly on most PHYs after 2/3 CTs

BLE 125K can survive high-density CT scenarios! (at the cost of extremely long transmission times)



On uncoded PHYS reliability increases at higher densities. Likely as the received signal becomes a big ball of multipath.

At higher densities coded PHYs begin to experience packet losses (i.e. the preamble is never heard).

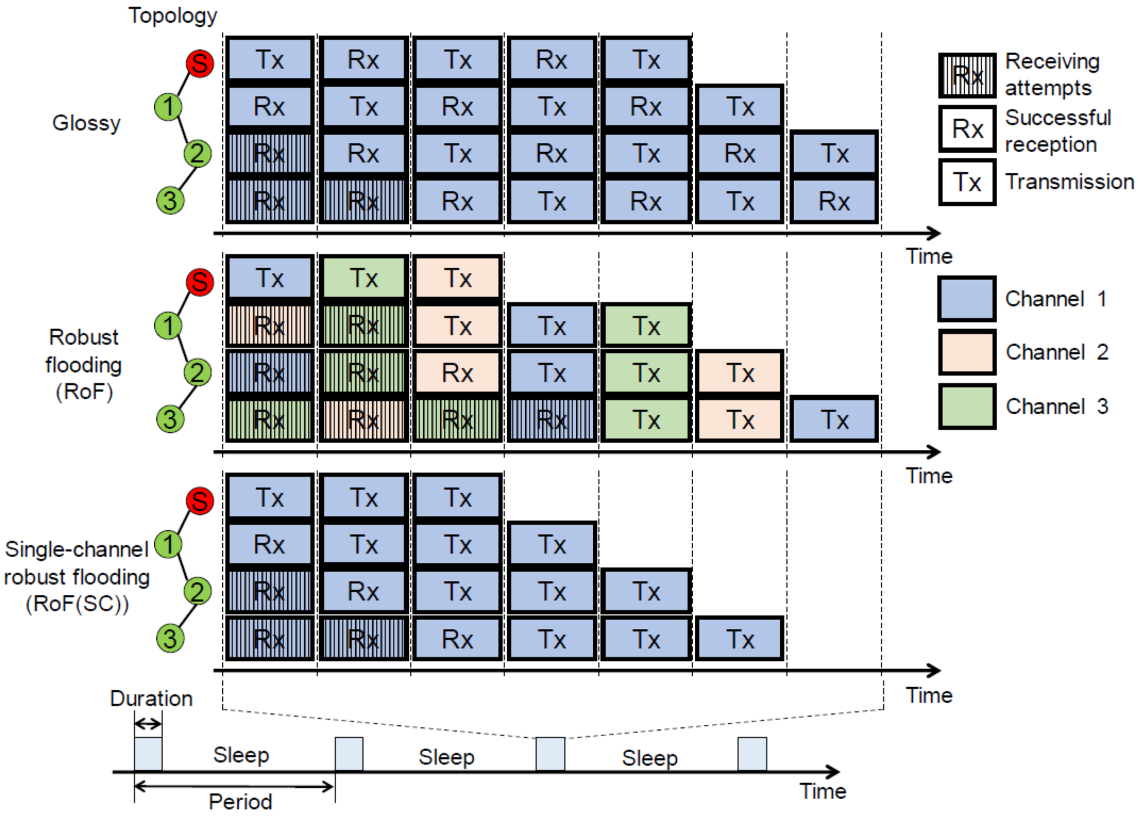
04

Experimental Analysis: Network-Wide CT Performance over Different PHYs

Network-Wide CT Performance over Different PHYs

Comparison of 2 different CT *primitives* often used as the basis for more complex protocols.

1. Glossy[1]
2. Robust Flooding[2] (Channel Hopping)
3. Robust Flooding[2] (Single Channel)



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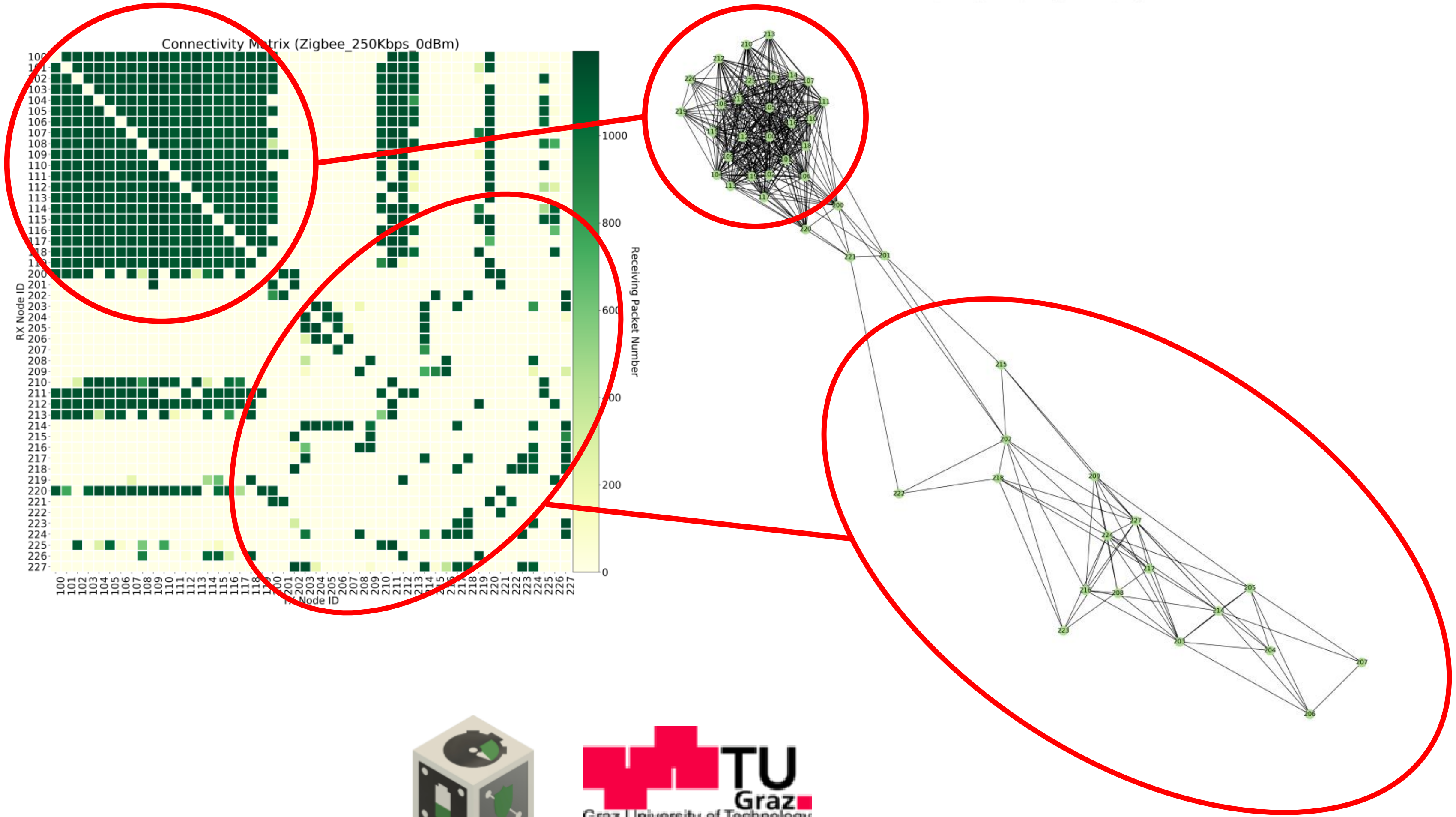
2. Lim, R., Da Forno, R., Sutton, F. and Thiele, L., 2017, February. Competition: Robust Flooding using Back-to-Back Synchronous Transmissions with Channel-Hopping. In *EWSN* (pp. 270-271).

Network-Wide CT Performance over Different PHYs

D-Cube is a challenging low-power wireless testbed with both *dense* and *sparse* network areas. This makes it ideal for testing the benefits of CT protocols over different PHY options.



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Network-Wide CT Performance over Different PHYs

One-to-All Data Dissemination (Broadcast) Scenario

3 Protocols:
- Glossy
- RoF (Single Channel)
- RoF (Channel Hopping)

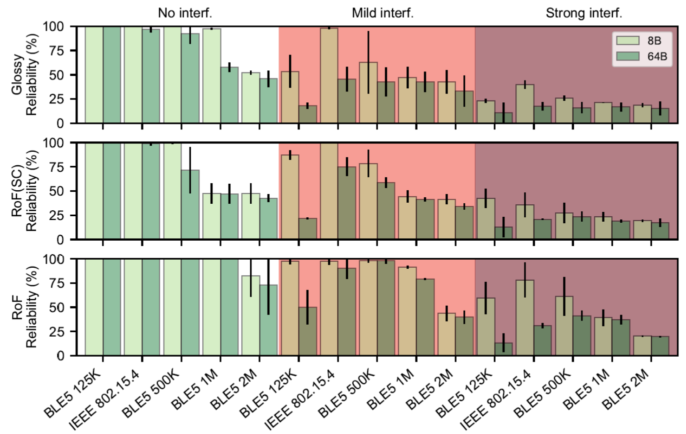
3 External Interference Scenarios:
- No Interference
- Mild Interference
- Strong (WiFi) Interference

5 PHY Options:
- BLE 2M
- BLE 1M
- BLE 500K
- BLE 125K
- IEEE 802.15.4

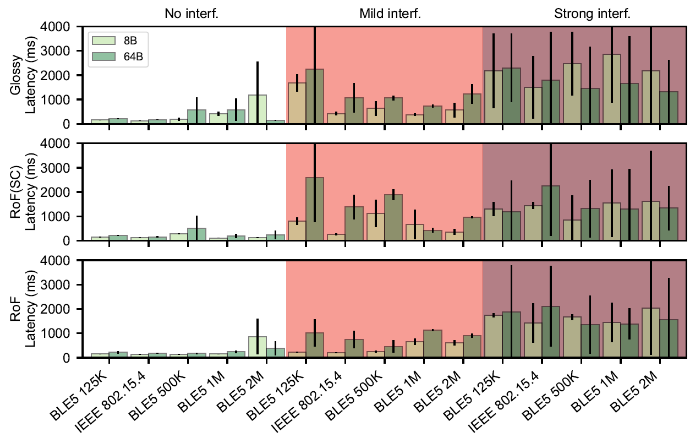
3 Performance Metrics:
- End-to-End Reliability
- End-to-End Latency
- Energy Per-Node

2 Packet Lengths:
- Short (8B)
- Long (64B)

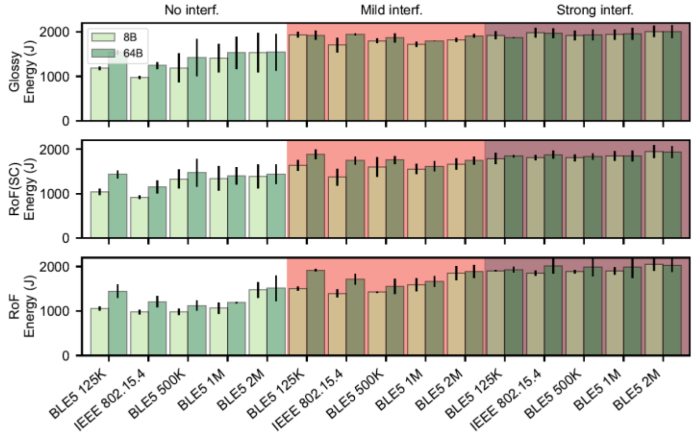
End-to-End Reliability



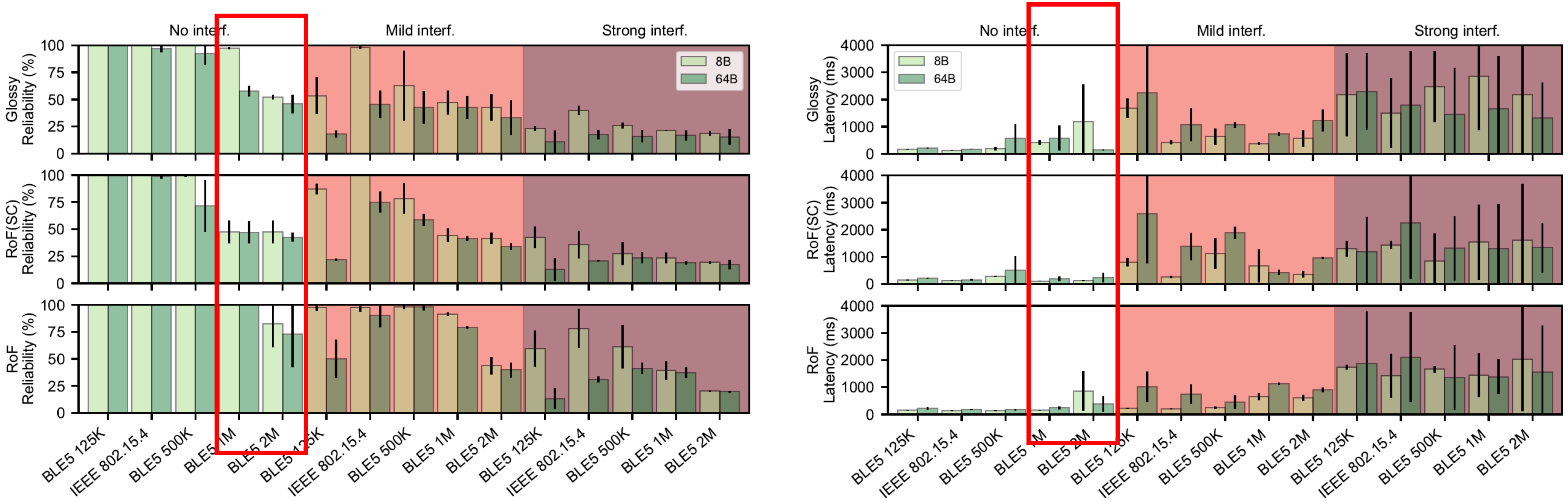
End-to-End Latency



Energy Per-Node

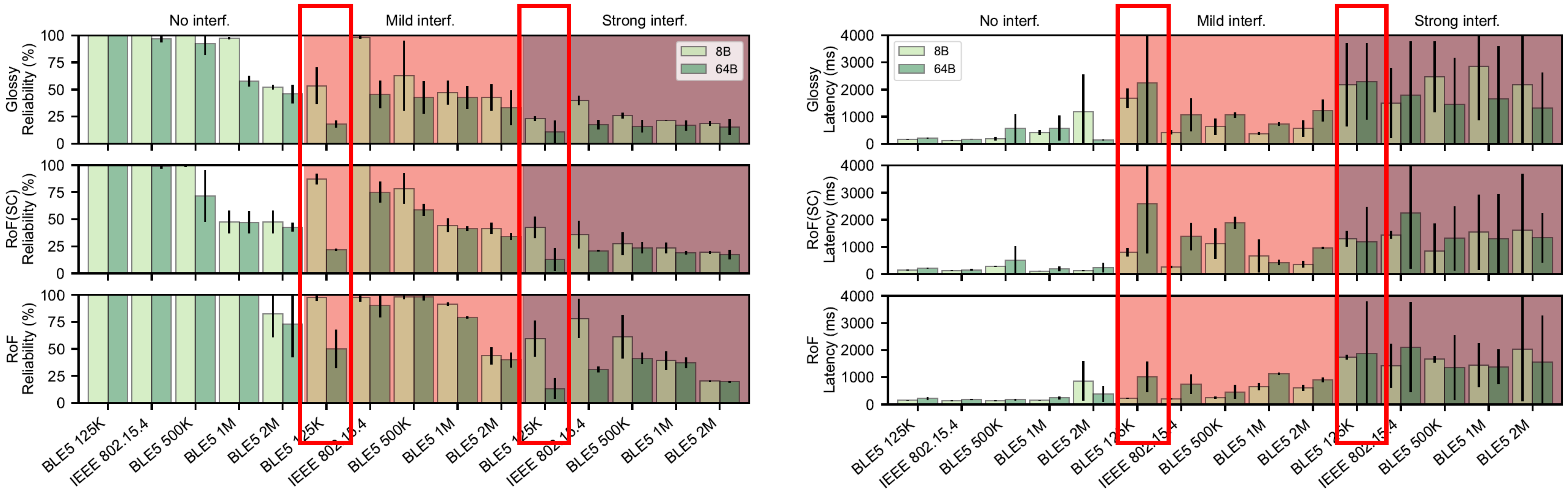


Network-Wide CT Performance over Different PHYs



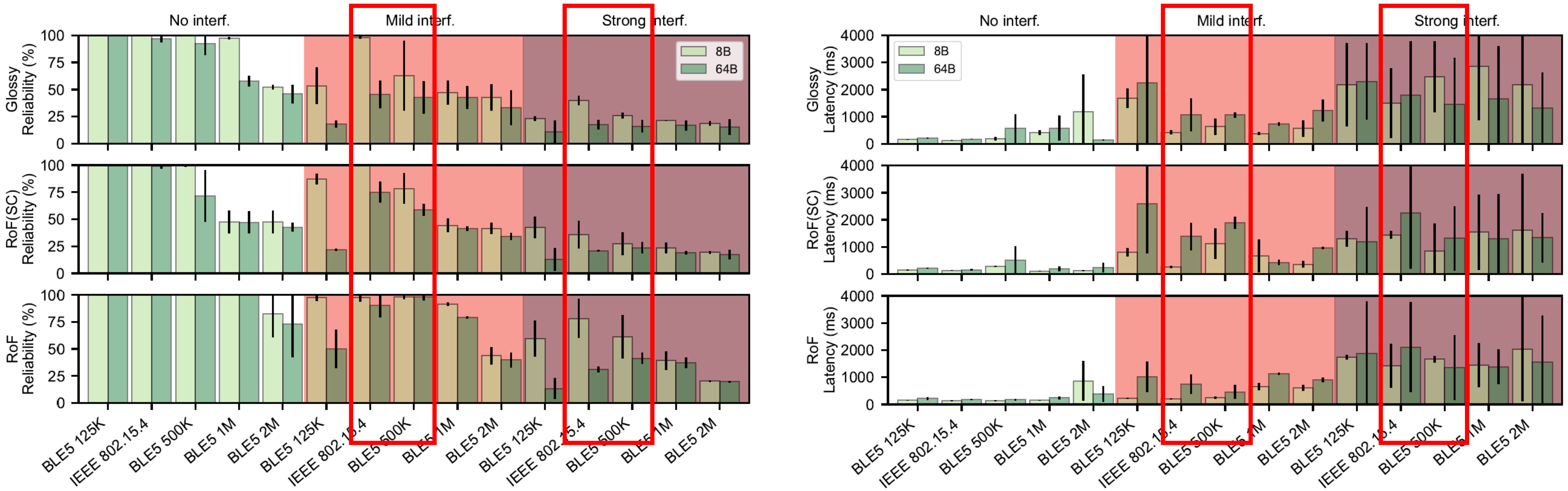
CT Protocols over uncoded PHYs struggle even WITHOUT external network interference (aka D-Cube Jamming).

Network-Wide CT Performance over Different PHYs



BLE 125K performs surprisingly poorly under external interference. Particularly with larger packet sizes!

Network-Wide CT Performance over Different PHYs



BLE 500K and IEEE 802.15.4 perform well
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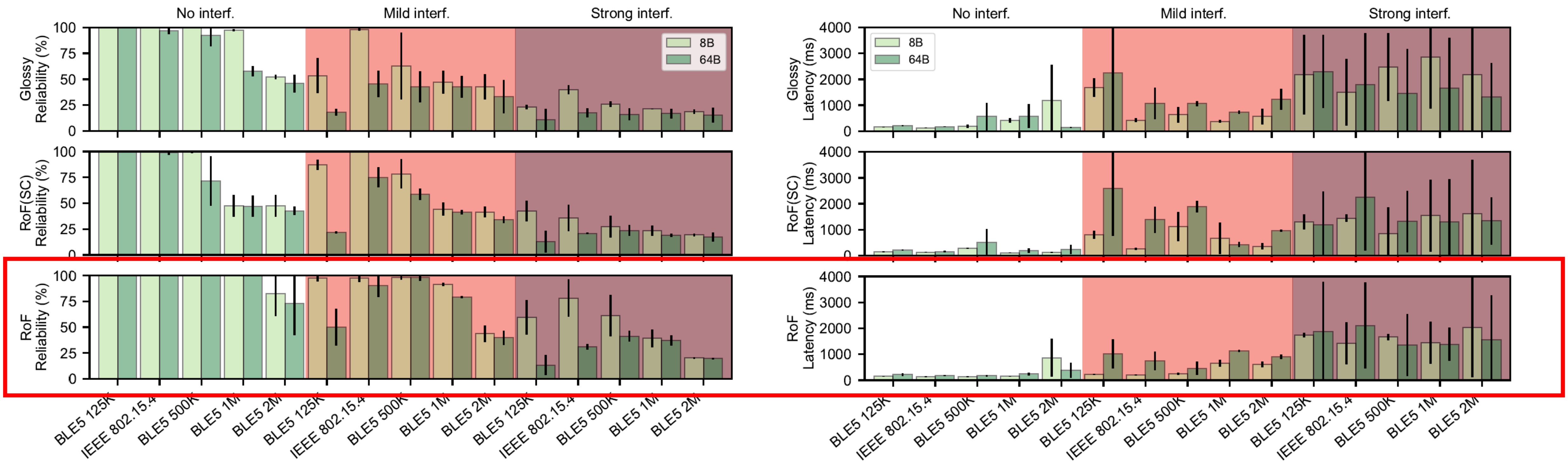

Time-triggered transmissions and channel hopping in Robust Flooding (RoF) produce significant gains over other CT primitives.

05

Recommendations for the Design of Multi-PHY CT Protocols

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BLE 5 1M	↗	↘	↘	↘
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(*) The choice of PHY to cope with beating should also be made based on the application's latency, energy, and RF range requirements.

A handy "Cheat Sheet" for the design of multi-PHY CT protcocols!

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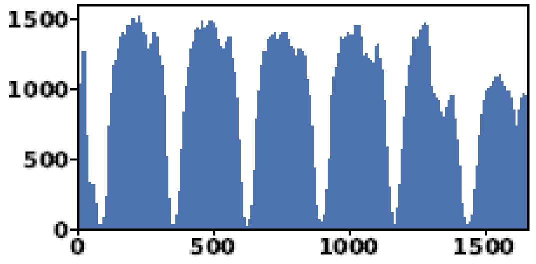
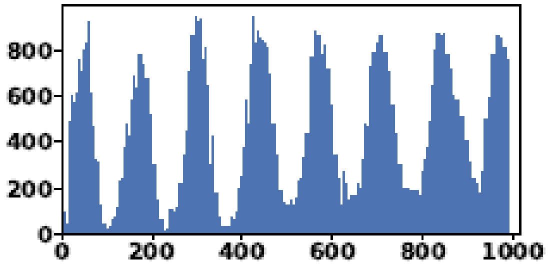
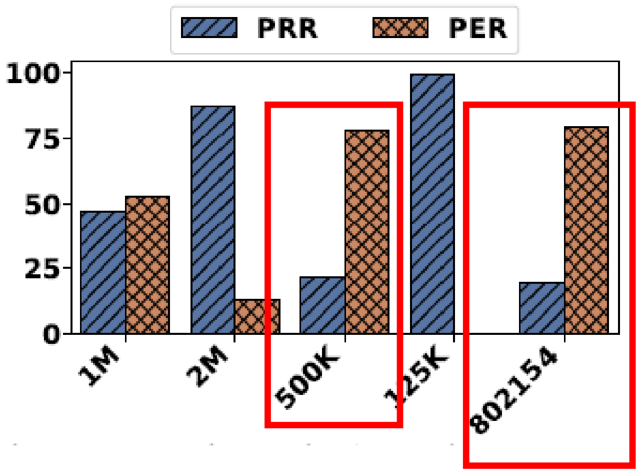


(c) BLE 5 500K



(e) IEEE 802.15.4



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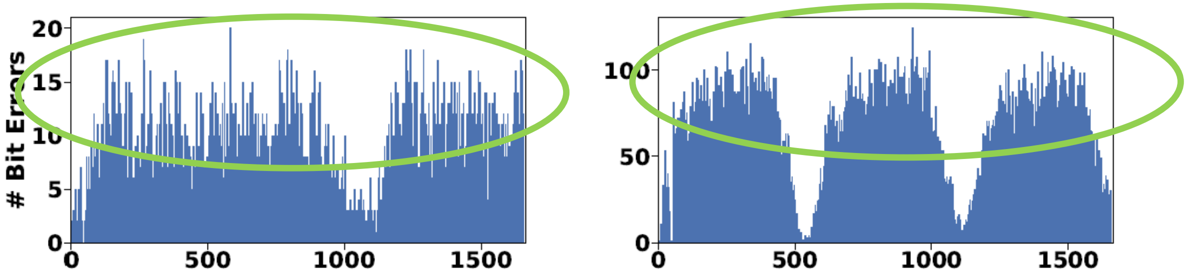
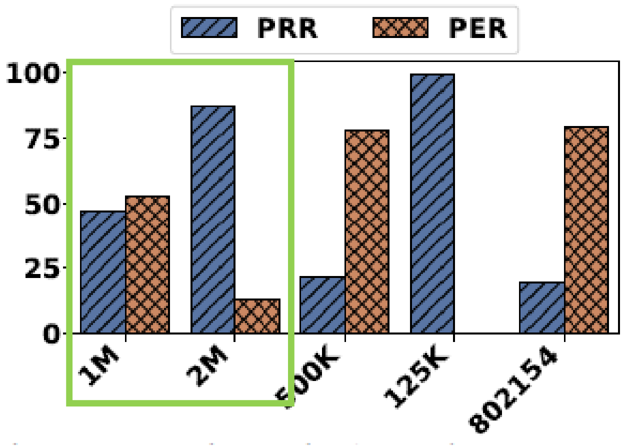


(a) BLE 5 2M (b) BLE 5 1M



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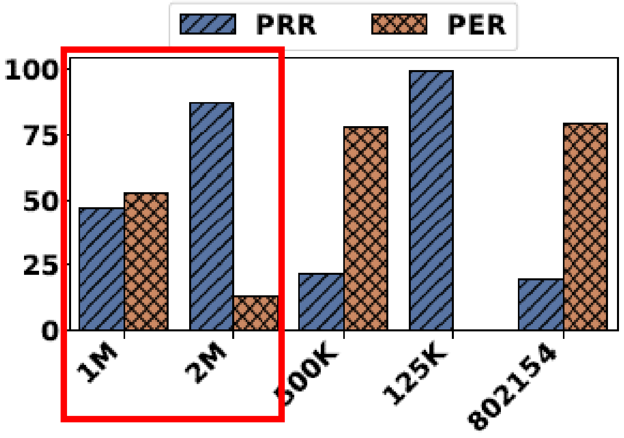

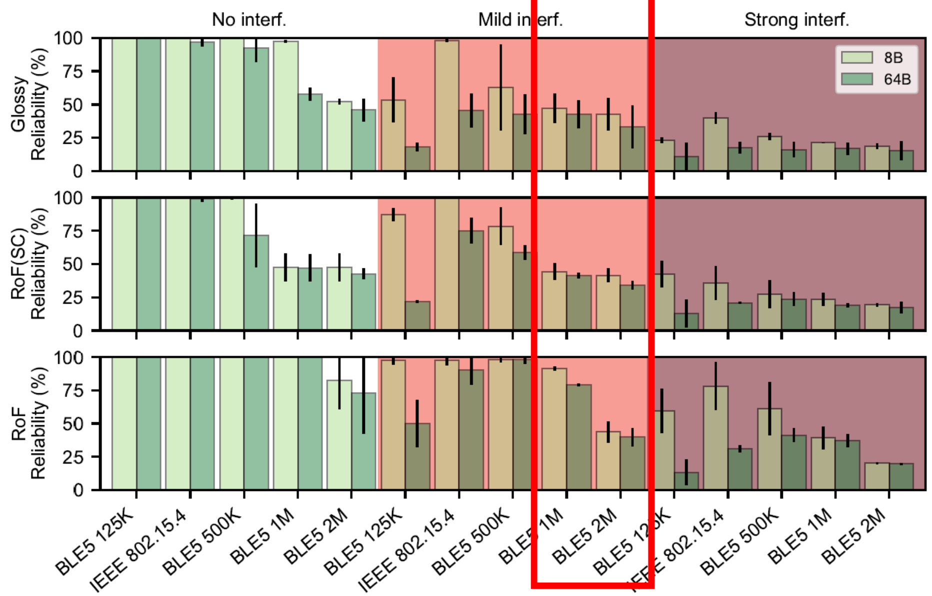

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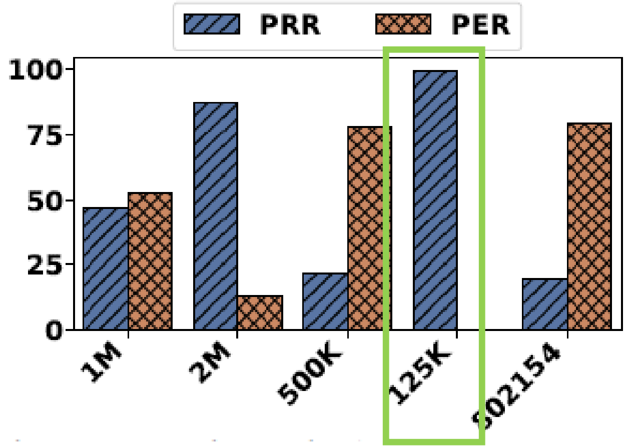

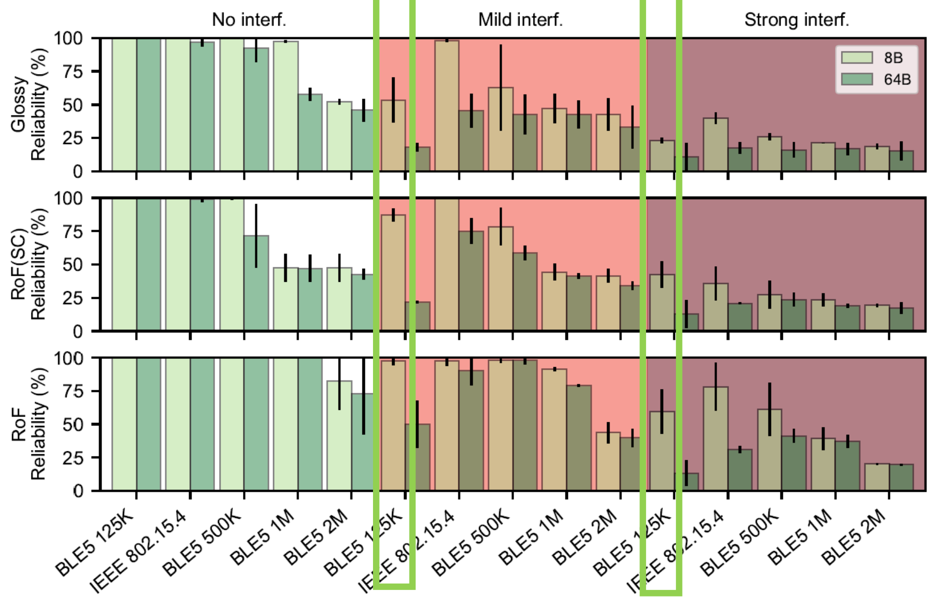

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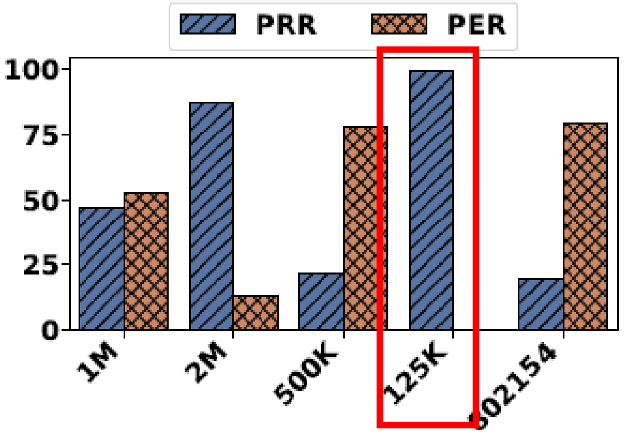

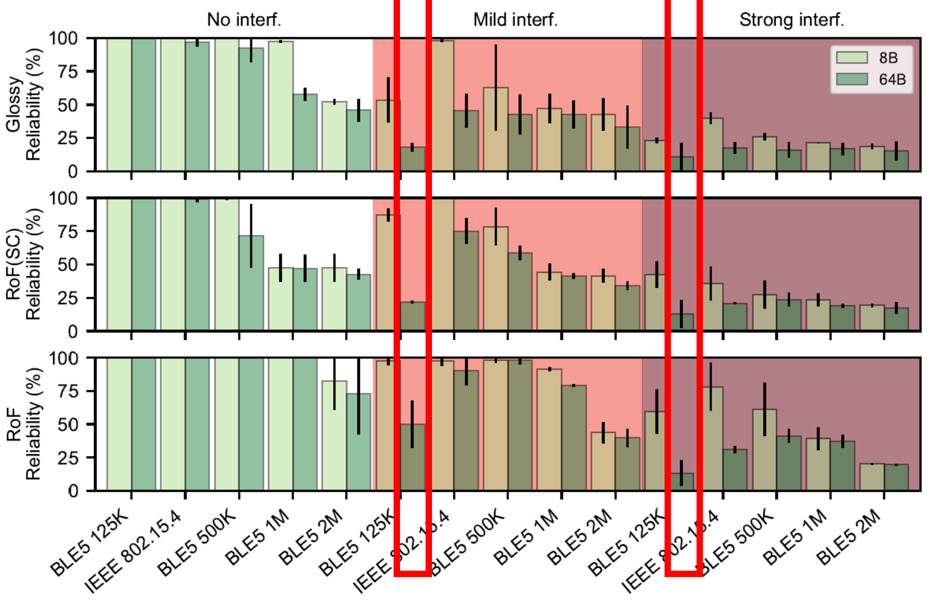

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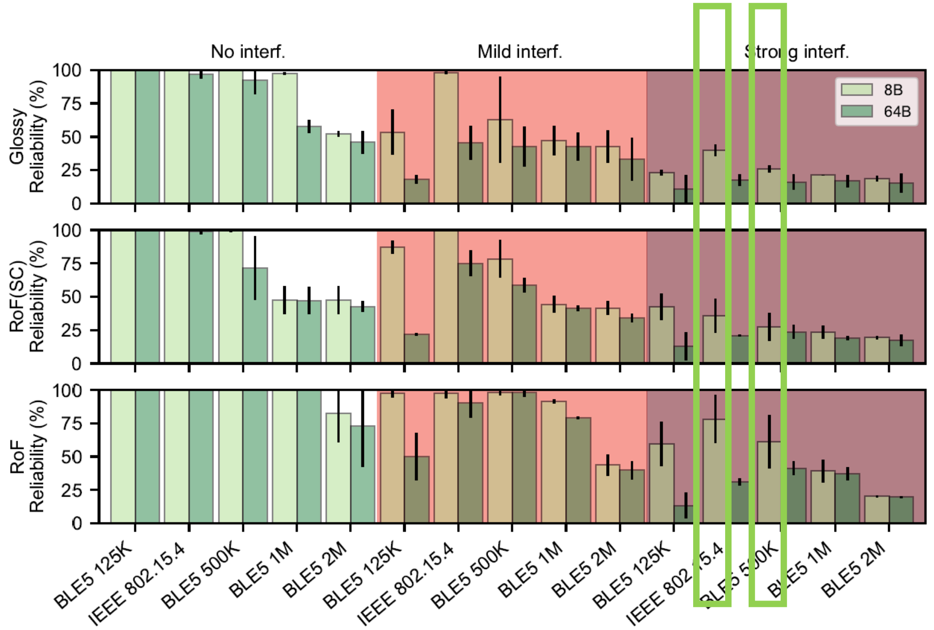

Questions?

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