CHALMERS
UNIVERSITY OF TECHNOLOGY

C A U
Kiel University
Christian-Albrechts-Universität zu Kiel

Concurrent Transmissions for Multi-Hop Bluetooth 5

Beshr Al Nahas
Chalmers

Simon Duquennoy
RISE SICS (now Yanzi)

Olaf Landsiedel
Chalmers, Kiel Uni.

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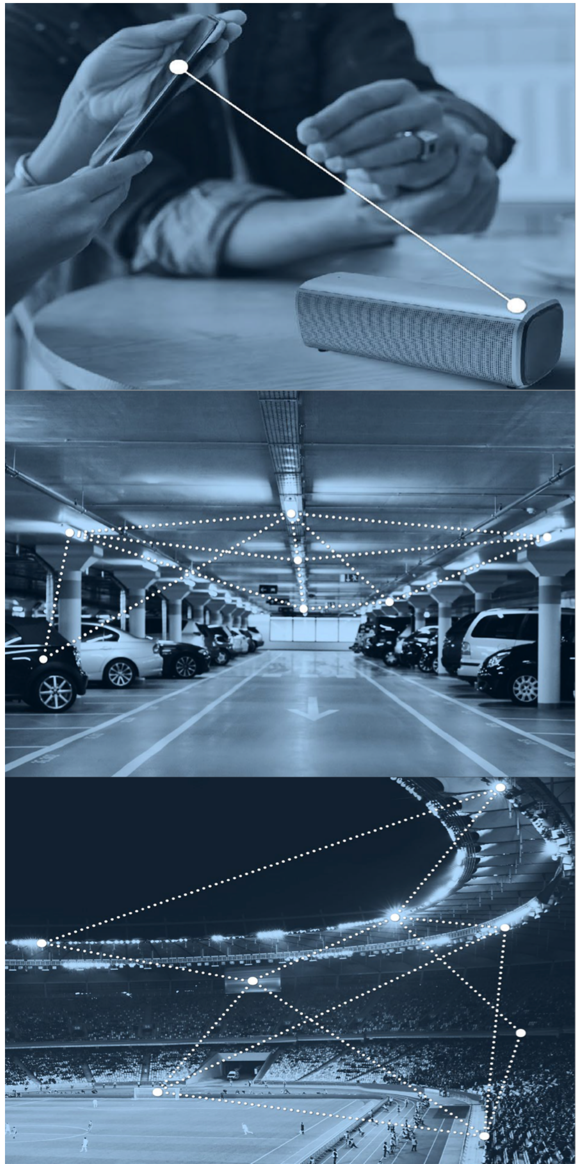
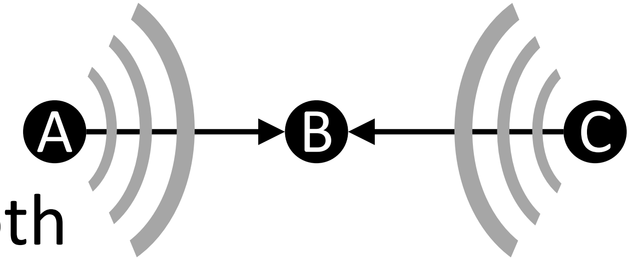
Motivation: Bluetooth as an IoT Enabler

- Bluetooth
  - 10 billion devices: each of you own multiple BLE devices
- IEEE 802.15.4
  - >20 years of IoT/WSN research
    - Impressive results with Glossy-style protocols: CT enables highly dependable dissemination
  - Market penetration? not impressive
- Can we use concurrent transmissions over Bluetooth?
  - While staying standard-compliant

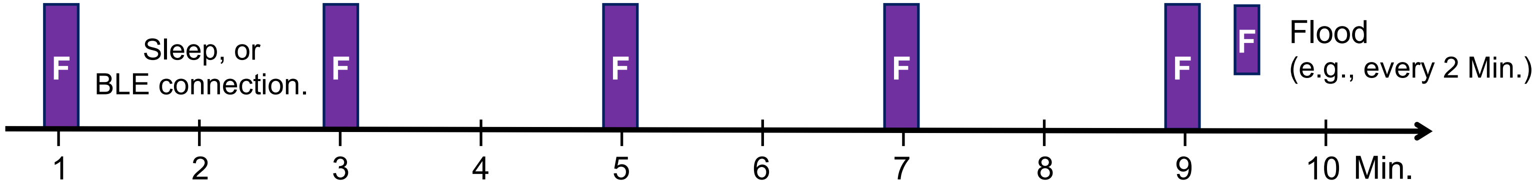


Contribution: CT + BlueFlood

- Feasibility study of concurrent transmissions over Bluetooth 5
  - Reliable when all send the same data



- BlueFlood: data dissemination for multi-hop Bluetooth
  - >99% end-to-end delivery, 0.1% duty-cycle for 1-second intervals
  - Up to 2 Mbps (compared to 250 Kbps with 802.15.4)
  - Receivable by unmodified mobile phones



- Open-source code, logs and processing scripts

Try me: github.com/iot-chalmers/BlueFlood

Outline

Motivation and summary

Background

- Bluetooth vs. 802.15.4
- Concurrent transmissions

Concurrent Transmissions over Bluetooth

Full system: BlueFlood

Evaluation

Conclusion

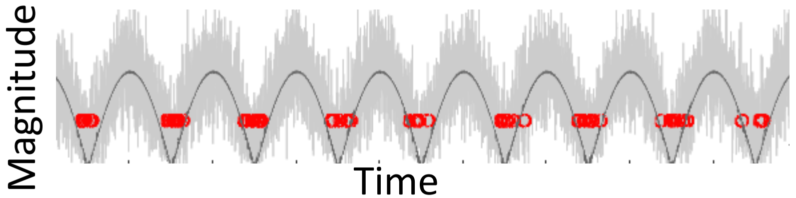
Background

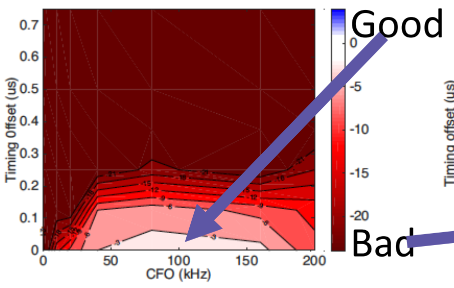
	Bluetooth	802.15.4
• **Topology**	Star - new: mesh	Multihop mesh
• **Energy**	Days - years	5-10 years
• **Bitrate**	2, 1, 0.5, 0.125 Mbps	0.25 Mbps
• **Coding**	-, -, 1:2, 1:8 Convolutional codes over 1 Mbps PHY	1:8 (2M chips: 0.25 Mb) DSSS
• **Symbol period**	0.5, 1, 1, 1 µs	1 µs
• **Modulation**	GFSK	OQPSK

Background: Doubts about CT applicability

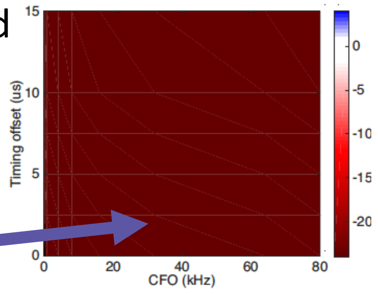
- Doubts about CT performance over Bluetooth [1], [2], [3]
  - Why: GFSK modulation + absence of DSSS
- Real life: Frequency offset (CFO), time offset, phase offset ➔ *beating* ➔ destructive interference
- Worst case: same power and opposite phase ➔ zero
- Classic 802.15.4e, 2.4 GHz, OQPSK with DSSS: sustains frequency offsets
- 802.15.4g, FSK: bad performance
  - Modulation is similar to Bluetooth

Beating [2]





802.15.4e [2]



FSK, similar to Bluetooth [2]

[1] M. Wilhelm et al., "On the Reception of Concurrent Transmissions in WSN". IEEE Trans. Wirel. Commun., 2014.
[2] C.-H. Liao et al., "Revisiting the So-Called Constructive Interference in Concurrent Transmission". IEEE LCN, 2016.
[3] A. Escobar, "Improving reliability and latency of Wireless Sensor Networks using Concurrent Transmissions", Automatisierungstechnik, 2019.

Outline

Motivation and summary

Background

Concurrent Transmissions over Bluetooth

- Feasibility study

Full system: BlueFlood

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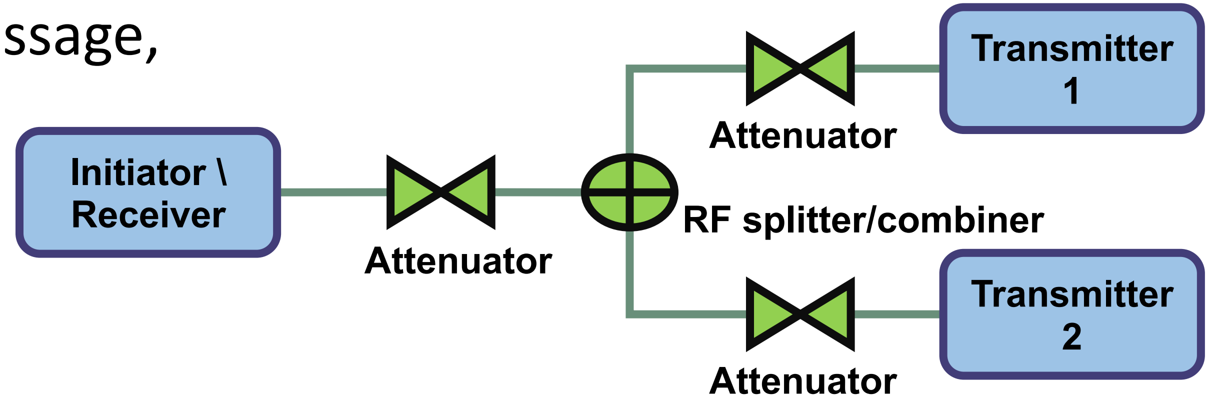
Concurrent Tx over Bluetooth PHY

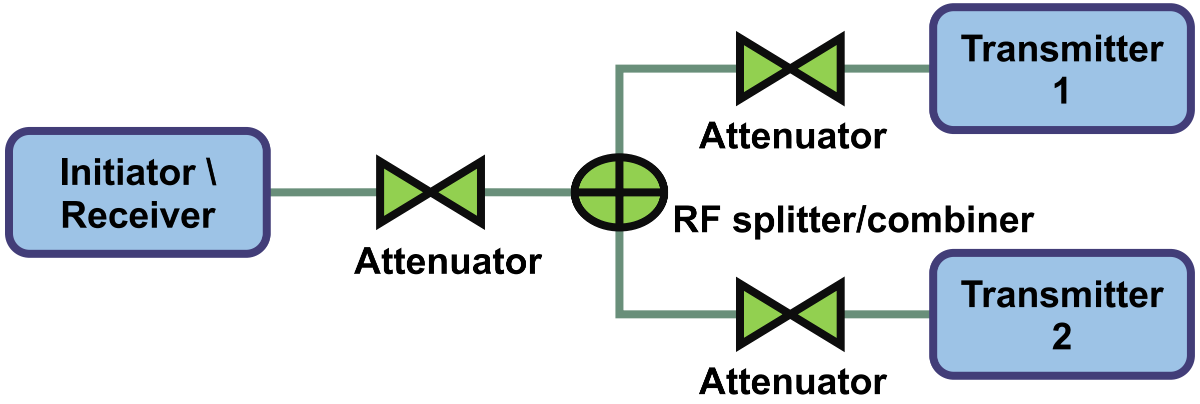
- **Goal**: *Characterize link quality degradation*
- **Experimental Setup**
  - **Reproducible**: 2 transmitters and 1 initiator, connected by RF cables
  - **Symmetric**: same cables, attenuators and nodes (nRF 52840)
- **Scenario**
  - Initiator sends one message, then listens. Repeat Periodically.
  - Transmitters synchronize on the message, then send concurrently



Concurrent Tx over Bluetooth

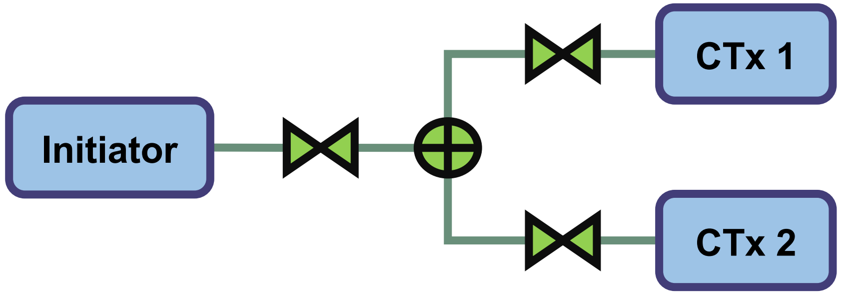
- **Goal:** *Characterize link quality degradation*

- **Systematic evaluation**
  - Tx power difference
  - Tx time desynchronization
  - Same vs. different payload
  - Different Bluetooth modes

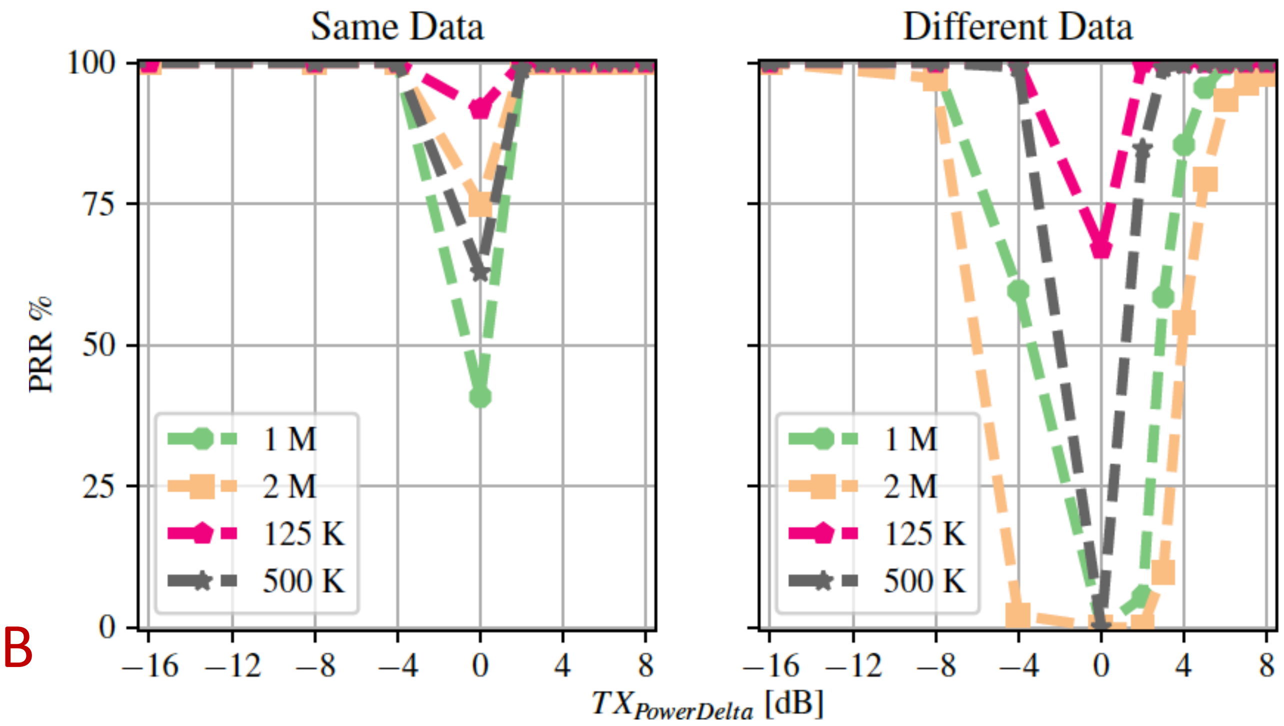


Concurrent Tx over Bluetooth

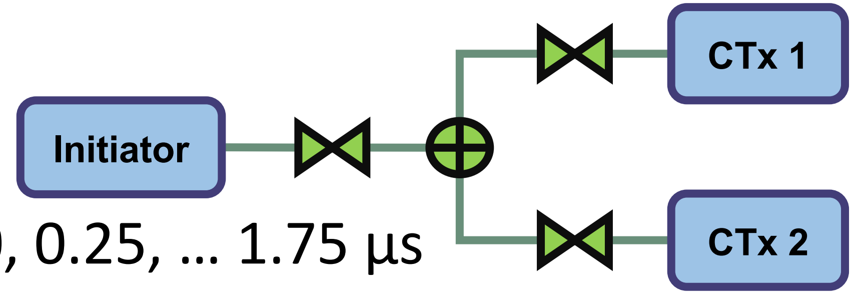
- CT in **different Tx power:** CTx1 in 0 dB; CTx2 in -16, -12, … 8 dB



- **Same data** CT is reliable if Tx power delta > 2 dB
- **The worst performance when both transmit at the same power**
- **➔ No constructive interference!**
- Rare to receive from different sources with the same power in deployments
- **Different Data CT** Tx power delta ≈ 8 dB

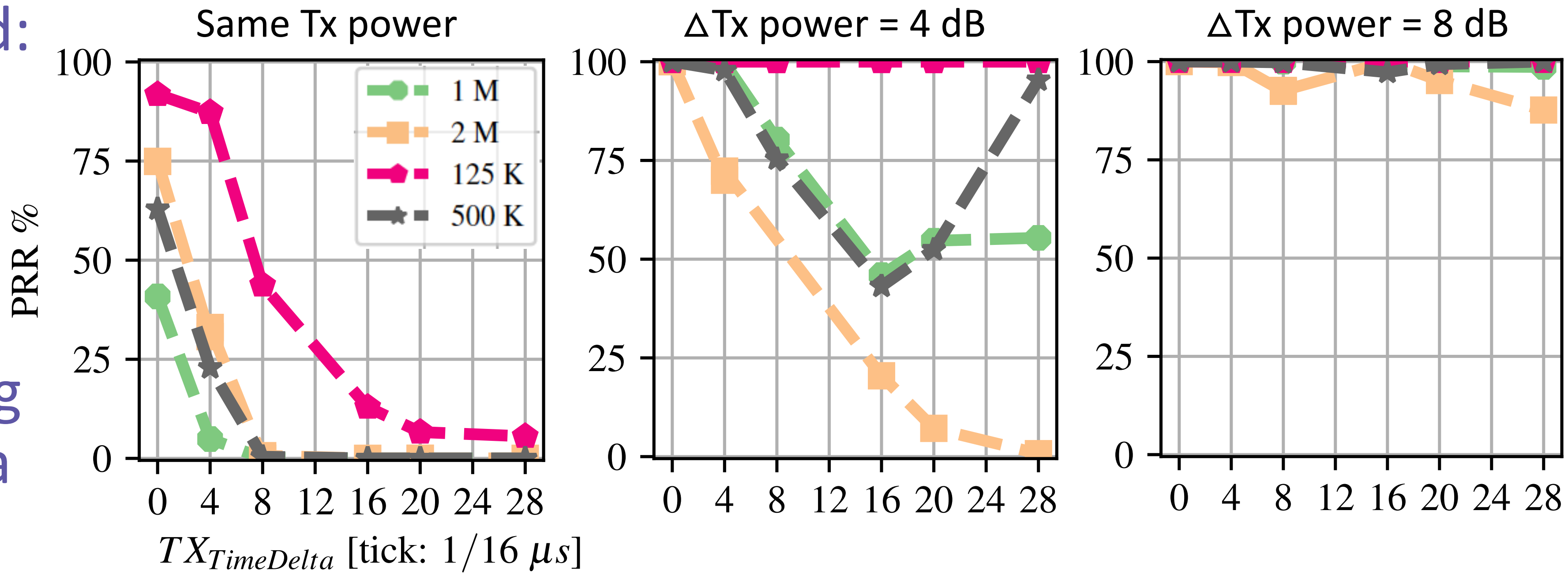


Concurrent Tx over Bluetooth



- **Tx time desynchronization**
  - **Experiment**: Controlled delay 0,4, … 28 ticks == 0, 0.25, … 1.75 µs
  - **Real sources of desync:** SW inaccuracy, drift, signal travel time, reflections, …

- **Sync** threshold: 0.25 μs
- **Timing is relaxed** with increasing Tx power delta



Outline

Motivation and summary

Background

Concurrent Transmissions over Bluetooth

Full system: BlueFlood

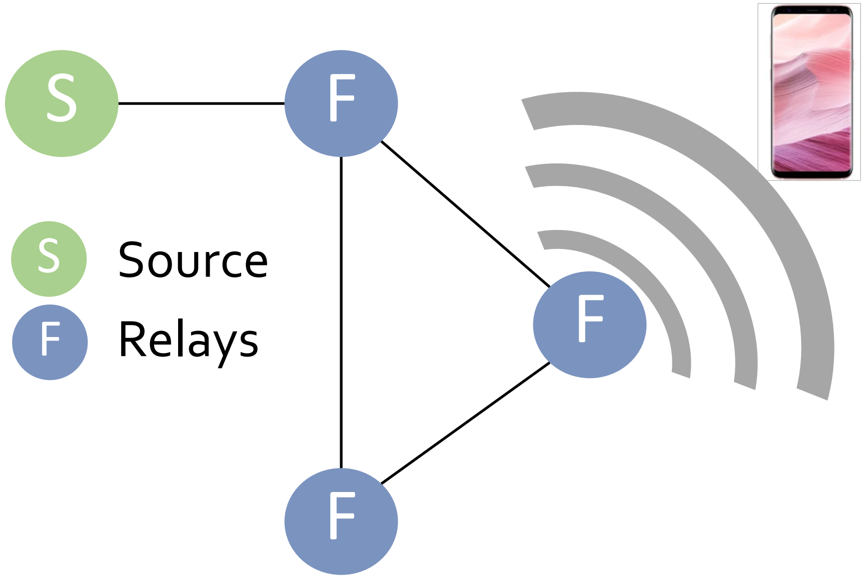
- Architecture
- Operation
- Implementation

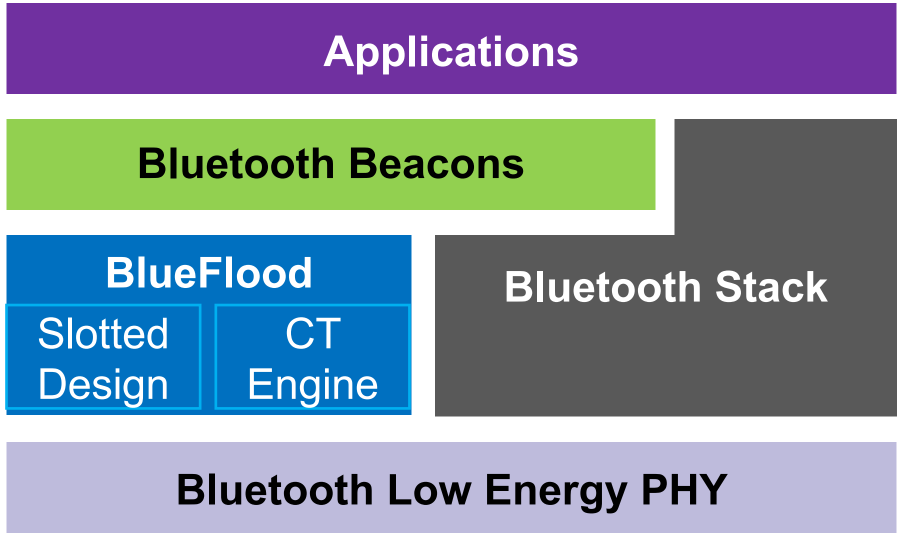
Evaluation

Conclusion

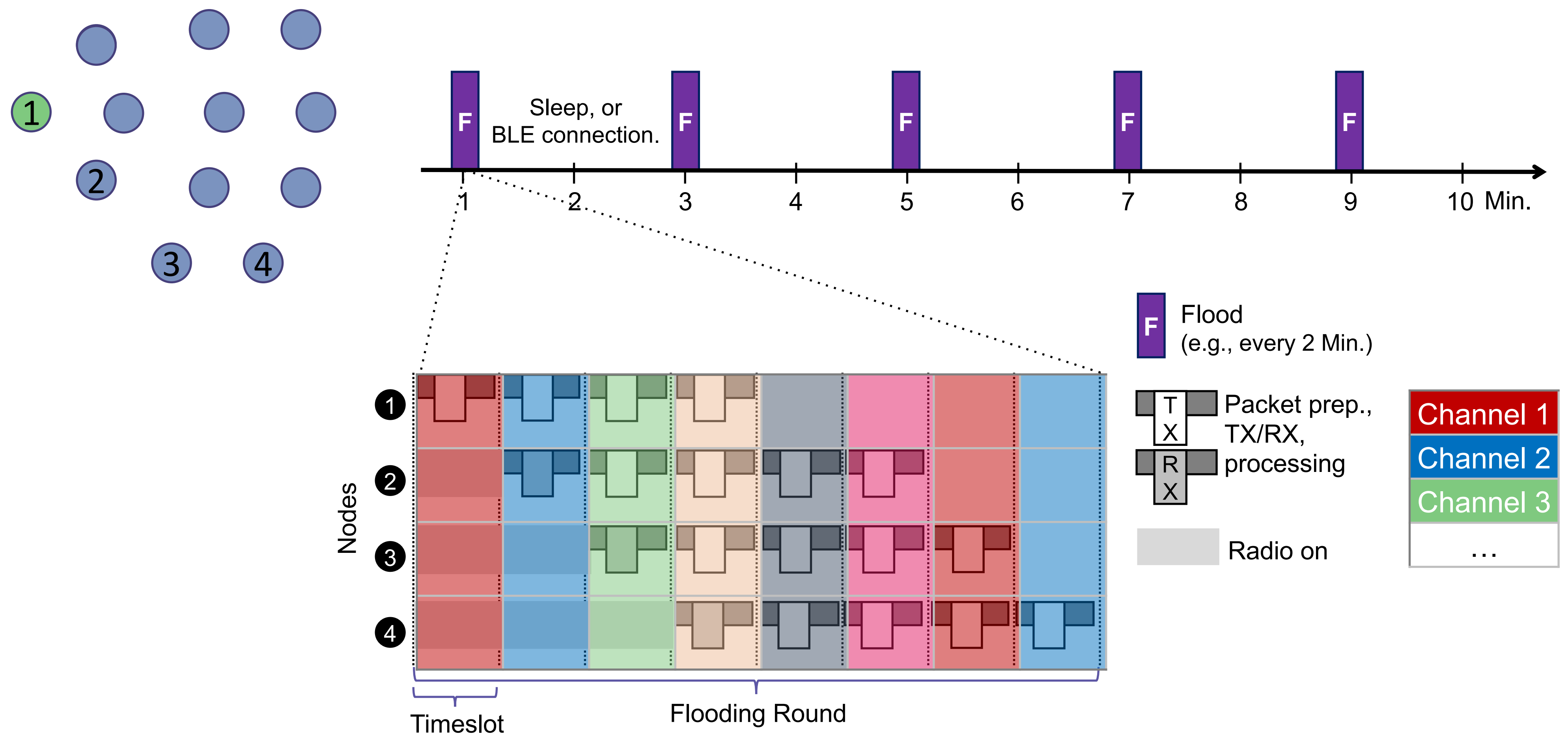
BlueFlood: System design

- Low power data dissemination
- Similar to the established CT protocols
  - Glossy, the dependability competition solutions
  - Flooding-based: No need for routing
  - Robust: Multichannel
- Floods non-connectable Bluetooth beacons
  - For example: iBeacon, Google beacons
  - Only BlueFlood nodes can participate in flooding
  - Receivable by unmodified mobile phones





BlueFlood: Operation



BlueFlood: Implementation

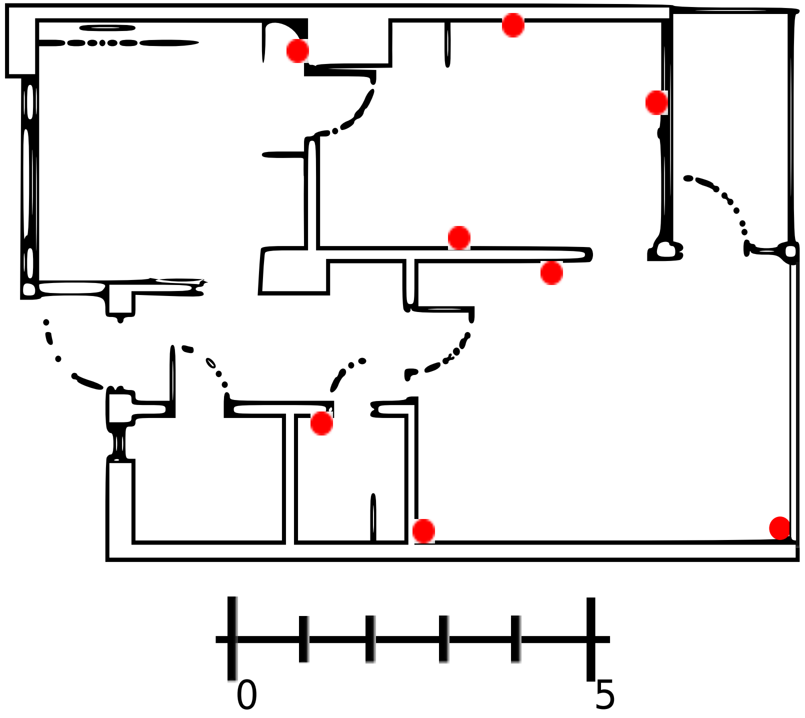
- Have you worked with Glossy code?
  - Clever but complex implementation, although simple protocol logic
- Modern platform; e.g., nRF 52840
  - Advanced SoC features make implementation easier

- Main protocol logic is a simple loop
  - Decide next slot operation; e.g., depending on received packet
  - Easy to modify transmission policy
- How: Make use of HW event wiring for precise timing of radio
  - No need for SW interaction between event cascades

Outline

Setup

- 8 nodes in 60 m^2 apartment: HW nRF 52840
  - ARM Cortex M4 64 MHz
  - RAM 64 KB, Flash 512 KB
  - Bluetooth modes: 2, 1, 0.5, 0.125 Mbps
- Metrics
  - Link quality: Packet reception ratio PRR per slot
  - End-to-end: Packet delivery ratio PDR
  - Latency: Average time to receive
- Parameters
  - Number of repetitions NTx = 4
  - Number of Channels NCh = 40

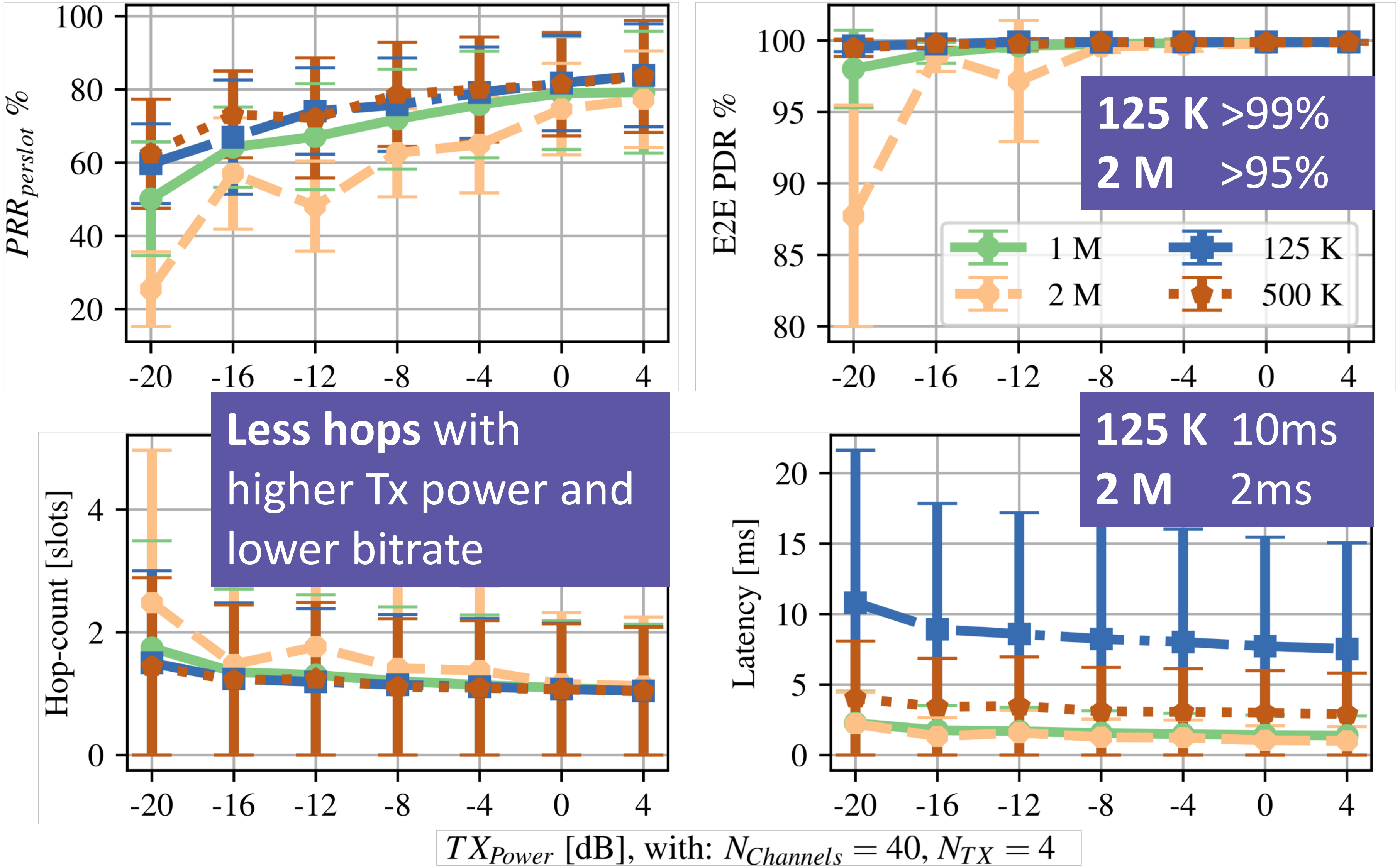


Evaluation

- Packet size
- Number of channels (NCh)
- Number of repetitions (NTx)
- **Transmission power (TxPower)**

Transmission power

- Link quality
- Reliability
- Hop-count
- Latency



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Concurrent Transmissions over Bluetooth

Full system: BlueFlood

Evaluation

Limitations & Conclusions

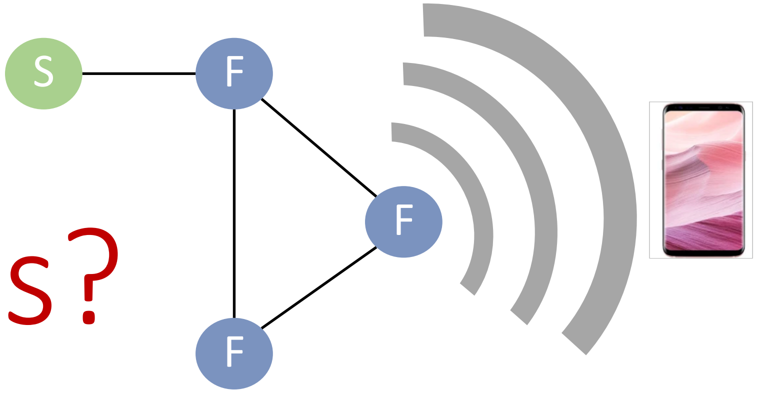
Limitations

- Feasibility study is limited to experimentation
  - Missing a physical-layer explanation of concurrent transmissions
- Small scale evaluation
  - Although indicative of the trend

Conclusions

- **Characterize** concurrent transmissions on Bluetooth
  - No constructive interference, but same data CT is feasible
- **BlueFlood**
  - Glossy-like fast data dissemination
  - Simple code, easy to modify transmission policy
- **Receive compatibility** with off-the-shelf devices
  - Flood standard beacons
- **Results**
  - Reliability: end-to-end > 99%
  - Latency: 2 ms – less than a single packet on 802.15.4
- **Open source** (BSD): *https://github.com/iot-chalmers/BlueFlood*

github.com/
iot-chalmers/BlueFlood



Thanks! Questions?

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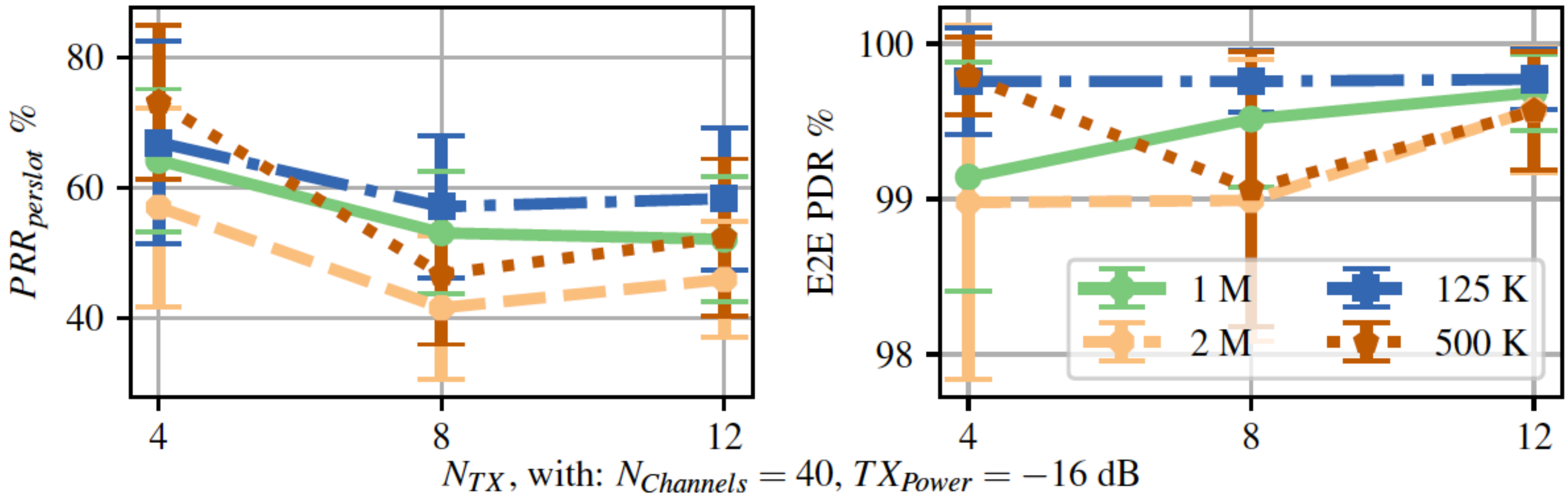
Number of repetitions (NTx)



Bluetooth 5 coded modes: 500K (C=2) and 125K (C=8). Symbol duration: 1µs

Preamble (10 bytes)	Coded Access Address (4 bytes)	CI	Term 1	PDU (N bytes)	CRC (3 bytes)	Term 2
10*8 = 80µs	4*8*8 = 256µs	16µs	24µs	N*8*C µs	24*C µs	3*C µs
Sent @125K with coding rate C=8 for both modes				Sent @500K or 125K		

Bluetooth 5 uncoded modes: 1M (symbol duration: s = 1µs) and 2M (s = 0.5)

Preamble (1 or 2 bytes)	Access Address (4 bytes)	PDU (N bytes)	CRC (3 bytes)
1*8 = 8µs	4*8*s µs	N*8*s µs	3*8*s µs

Bluetooth advertisement PDU

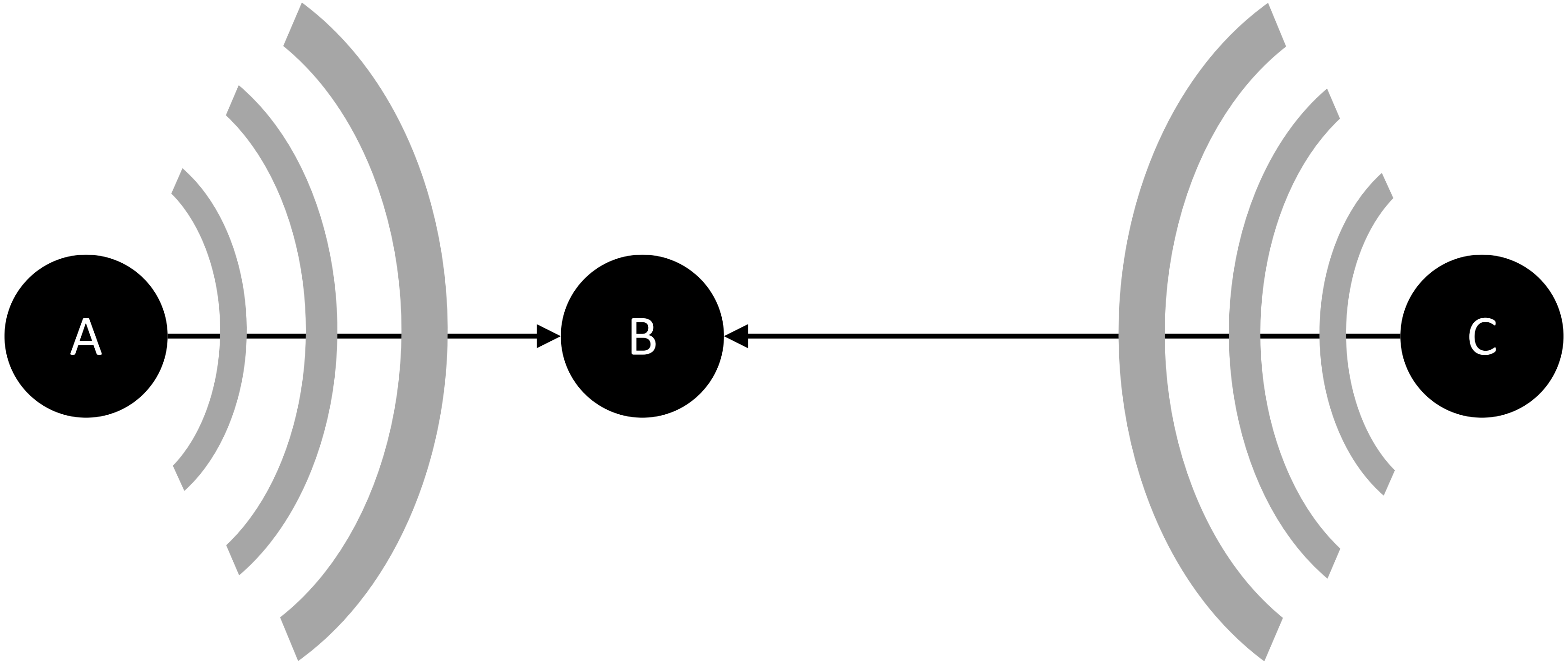
Header (2 bytes)	Advertiser Address (6 bytes)	Adverting Data

iBeacon frame

iBeacon Prefix (9 bytes)	UUID (16 bytes)	Major Num (2 bytes)	Minor Num (2 bytes)	TX Power (1 byte)

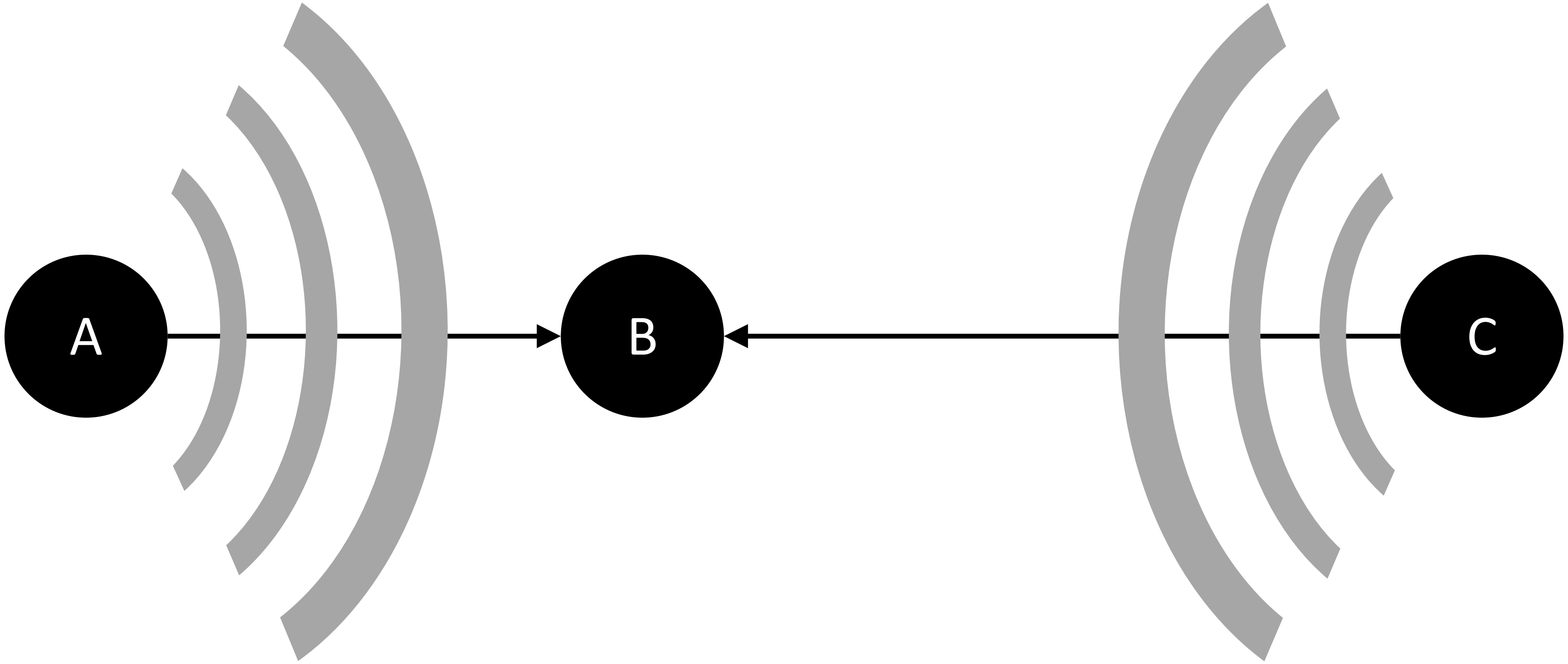
Concurrent Wireless Transmissions

(of the same data – synchronous flooding)



- Receive the colliding transmissions
- Glossy: Efficient flooding and time synchronization over 802.15.4
  - **Symbol overlap**: 802.15.4 @2.4GHz: 0.5 µs
  - Bluetooth?

Concurrent Wireless Transmissions
(of different data)



- Receive stronger signal of concurrent transmissions
  - Preambles overlap: 802.15.4 @2.4GHz: 5 bytes = **160 $\boldsymbol{\mu s}$**
  - Threshold: roughly **3dB**
  - Known as: Capture Effect