Lecture 04
BLE Advertisement Deep Dive

CS397/497 – Wireless Protocols for IoT

Branden Ghena – Winter 2021

Northwestern

Announcements

- I updated the Project Proposal link on canvas with additional information about your proposal
  - https://canvas.northwestern.edu/courses/133790/assignments/841765

- Reminder: due end-of-day on the 1st
  - Come talk to me in office hours about your project *before* then if you've got questions or concerns
  - Also feel free to post project ideas on campuswire

Today's Goals

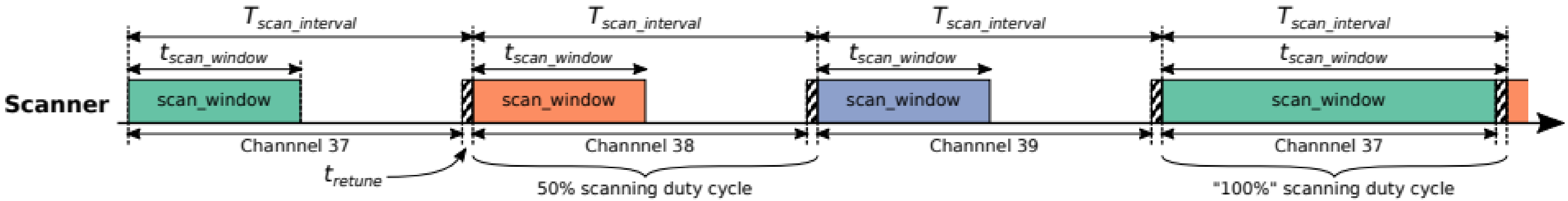
- Describe BLE scanning role

- Deep dive into advertisements. Questions we might ask as researchers.
  - How much energy do advertisements take?
  - What is the probability of receiving a packet?
    - What is the probability of receiving data?
  - What are the real-world use cases of advertisements?

Outline

- **BLE roles**
  - Advertising
  - **Scanning**
- Energy Use
- Packet Collisions
- Advertisement Use Cases

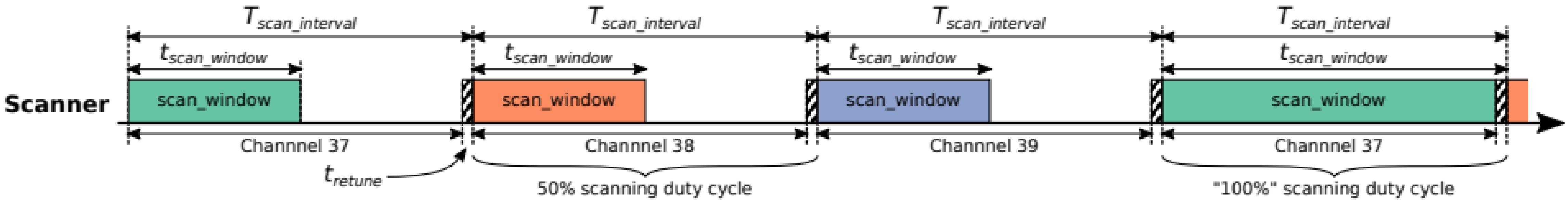
Scanning Pattern



- Iterate through channels, listening for advertisements
  - $T_{scan\_interval}$ controls rate at which channels are changes
  - T_{scan_window} controls duty cycle of listening

- **Why listen at a low duty cycle?**

Scanning Pattern

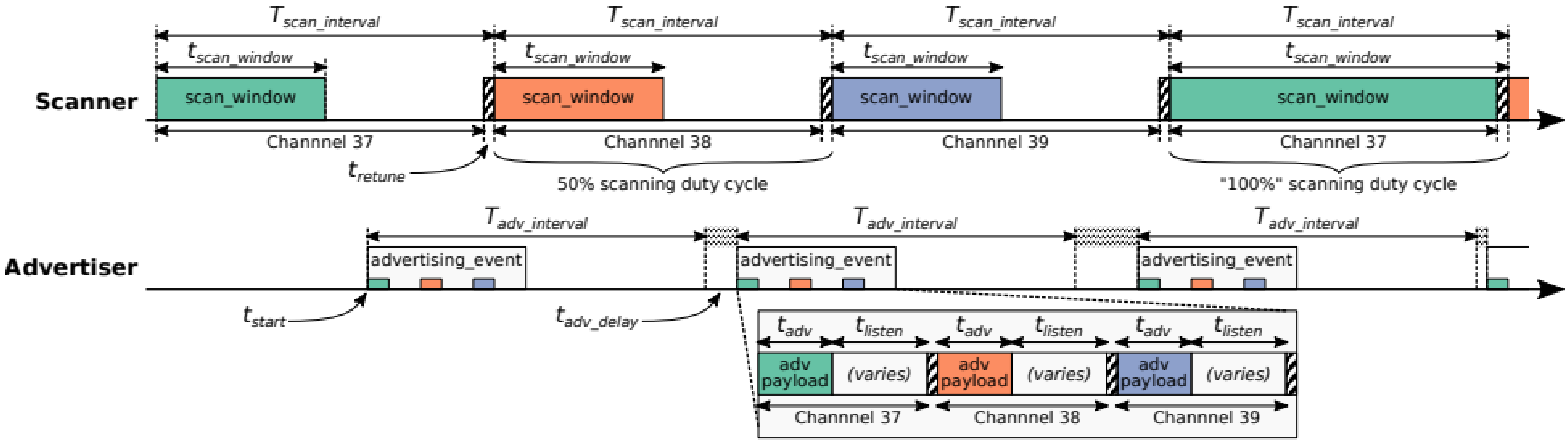


- Iterate through channels, listening for advertisements
  - $T_{scan\_interval}$ controls rate at which channels are changes
  - T_{scan_window} controls duty cycle of listening

- **Why listen at a low duty cycle?** **Save energy**

Putting it all together

- Advertisements are received when the channel of the scan window and the channel of the advertisement overlap in time (and space)



A warning about scanning expectations

- Scanners will NOT receive 100% of packets sent
  - Even ignoring range issues

- Packets are lost due to (in roughly descending order):
  - Duty cycle
  - Sharing 2.4 GHz antenna with WiFi
  - Retune period after each scanning interval
  - Dropped packets in the receive software
  - Packet collisions

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Paper: power measurements of BLE advertisements

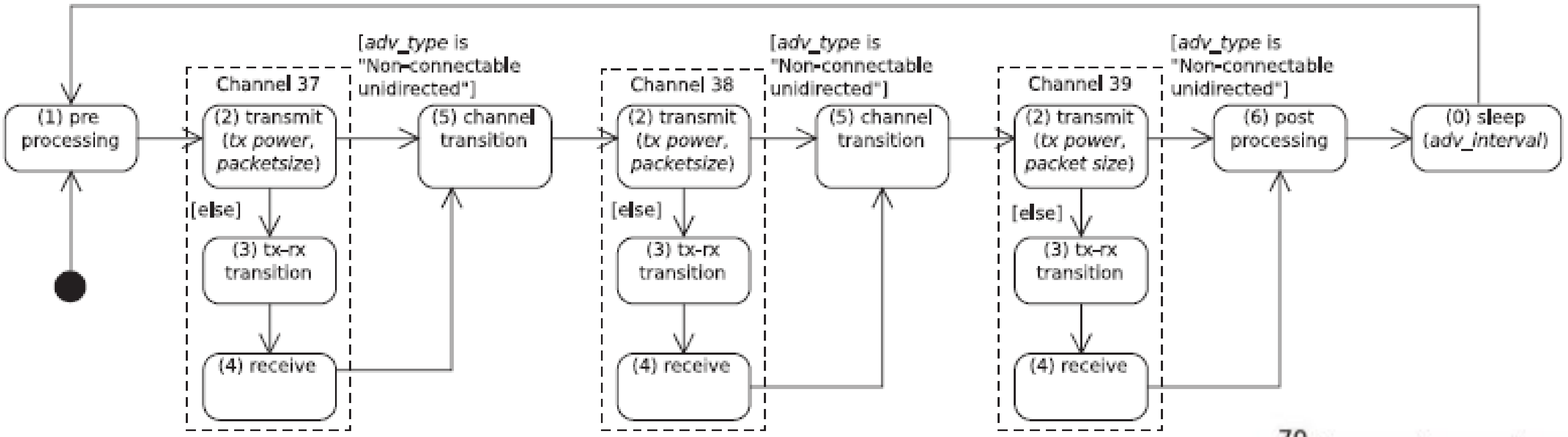
Schrader, Raphael, et al. "Advertising power consumption of bluetooth low energy systems." *2016 3rd International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS)*. IEEE, 2016.

The 3rd IEEE International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems
26-27 September 2016, Offenburg, Germany

Advertising Power Consumption of Bluetooth Low Energy Systems

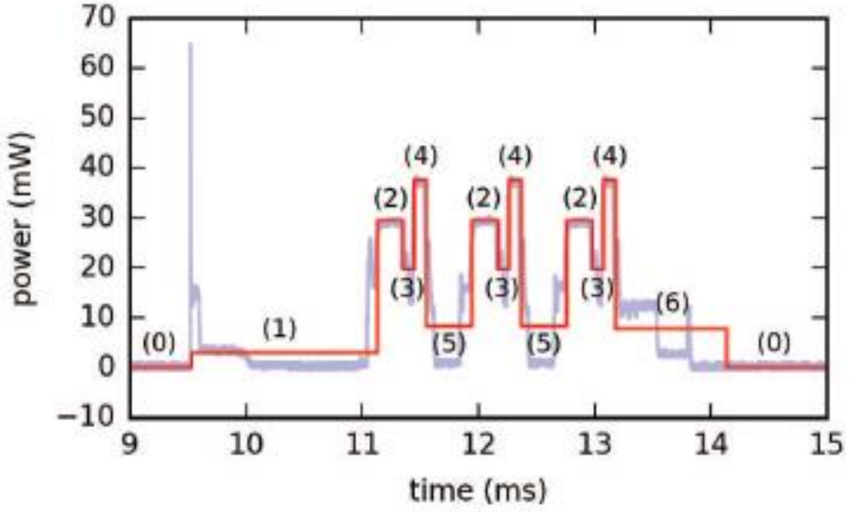
Raphael Schrader, Thomas Ax, Christof Röhrig, Claus Fühner
Fachhochschule Dortmund
Fachbereich Informatik
Email: claus.fuehner@fh-dortmund.de

Energy model for BLE advertisements



- Is this valuable?
  - Is this surprising?

- Does this seem accurate?
  - When does it apply?



Measurements of Power Use

- Power use and duration (energy)
  - nRF51 (nRF51822)
  - nRF52 (nRF52832)

- Does this seem accurate?
  - What conditions are the tests performed under?

TABLE II
SoC-Dependent Model Parameters from Measurements

Phase	Nordic nRF51		Nordic nRF52	
	T_i (σ) (µs)	$\overline{P_i}$ (mW)	T_i (σ) (µs)	$\overline{P_i}$ (mW)
preprocessing	951.8 (9.1)	2.9	321.4 (8.9)	2.7
tx (4 dBm)	72.4 (0.5) + $n_{Bit} \cdot 1/Bit$	45.4	13.2 (1.8) + $n_{Bit} \cdot 1/Bit$	46.2
tx (0 dBm)		29.5		33.2
tx (-4 dBm)		25.8		27.5
tx (-8 dBm)		23.2		25.3
tx (-12 dBm)		21.1		23.6
tx (-16 dBm)		19.8		22.6
tx (-20 dBm)		18.9		21.6
tx-rx transit.	94.7 (0.6)	19.6	130.6 (2.0)	15.9
rx	104.3 (1.5)	37.6	73.0 (3.9)	32.4
channel transit.	390.4 (0.9)	8.4	432.3 (4.47)	7.3
postprocessing	961.8 (156.9)	7.7	321.4 (32.2)	10.2
sleep	$T_{advSleep}$	0.0114	$T_{advSleep}$	0.0058

Overall thoughts on the paper?

- Any additional thoughts?

- Grad students: is this a *good* paper?
  - And how are you defining good?

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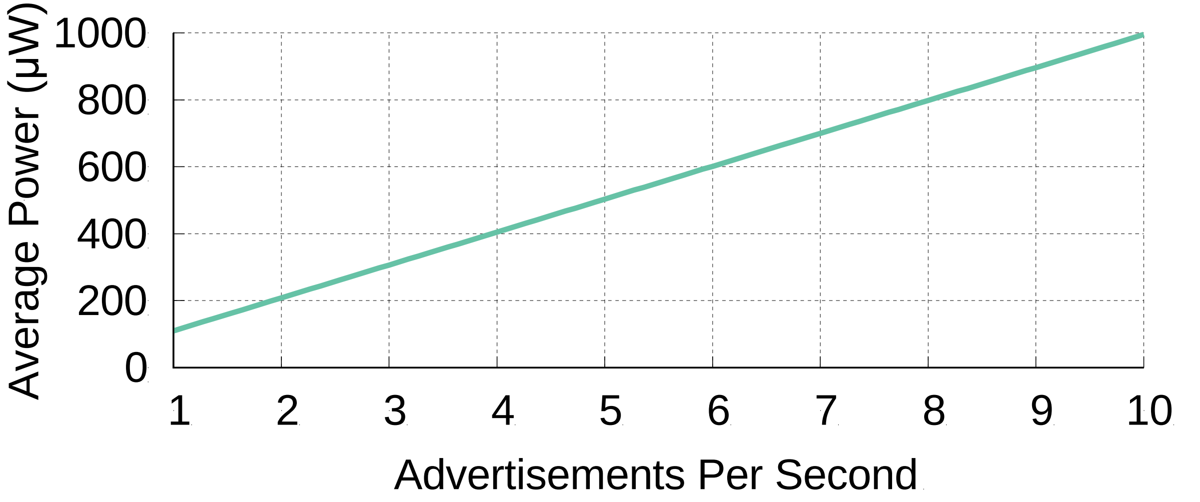
- Note: I think this would make an excellent class project.
  - ~70-80% of this would be sufficient for a good grade.

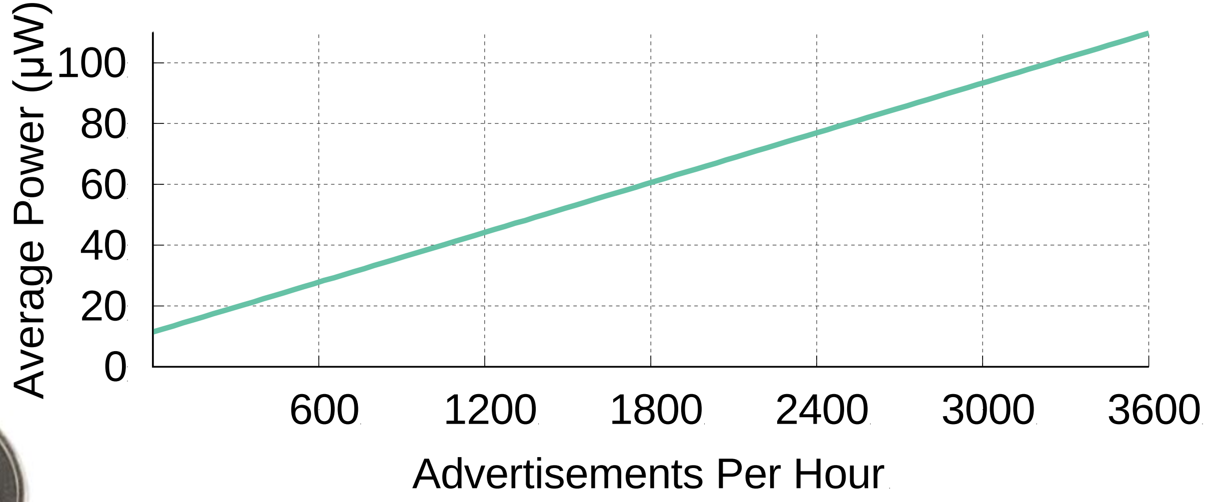
How much energy does it cost to send data over advertisements?

- Configuration
  - nRF51822 microcontroller
  - Maximum payload size
  - +4 dBm transmit power
  - Connectable advertisement
  - Sleep power 11 μW

- One packet per second example:
  - 110 μW average
  - ~270 days on a CR2032

- One packet per minute example:
  - 13 μW average
  - ~2250 days on a CR2032





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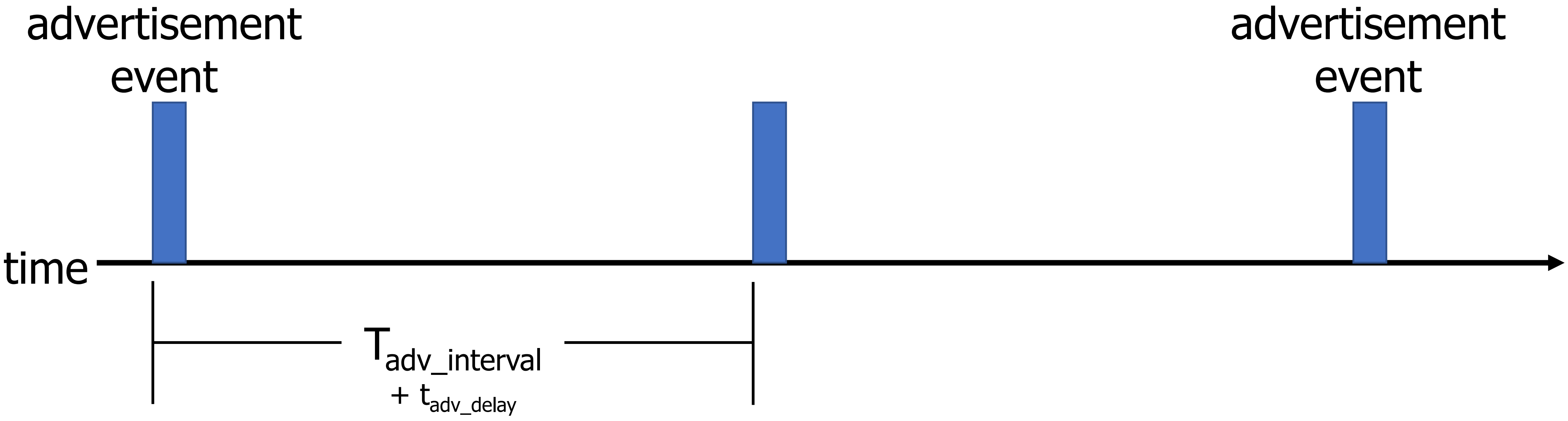
- Advertisement Use Cases

Questions about network capability

- What are the odds that a transmitted advertisement will be received?
  - Packet reception rate
- If M redundant advertisements are sent instead, what are the odds that at least one are received?
  - Data reception rate
- How do these odds vary with number of devices, advertising interval, and packet size?

BLE advertisements are periodic, broadcast transmissions.

- Advertisement events occur periodically ($T_{adv\_interval}$: 20 ms–10 s).
- Random delay appended before each transmission (t_{adv_delay}: 0–10 ms).
- Data payload of up to 31 bytes.

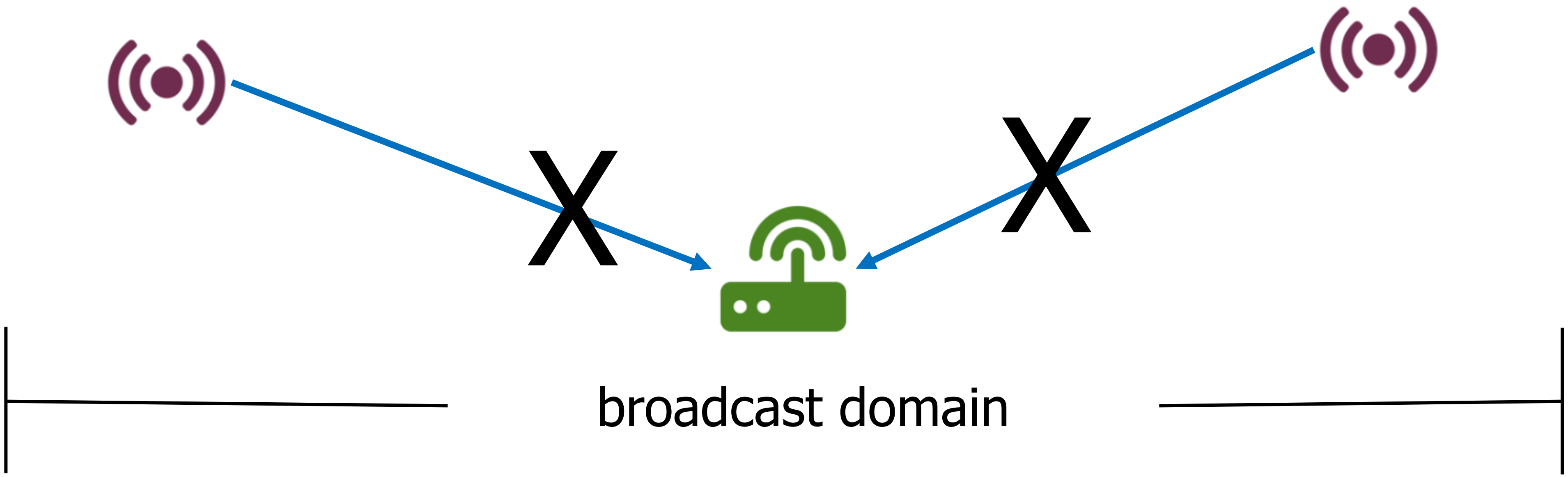


Bluetooth SIG. Bluetooth Core Specification 4.2. (2014).

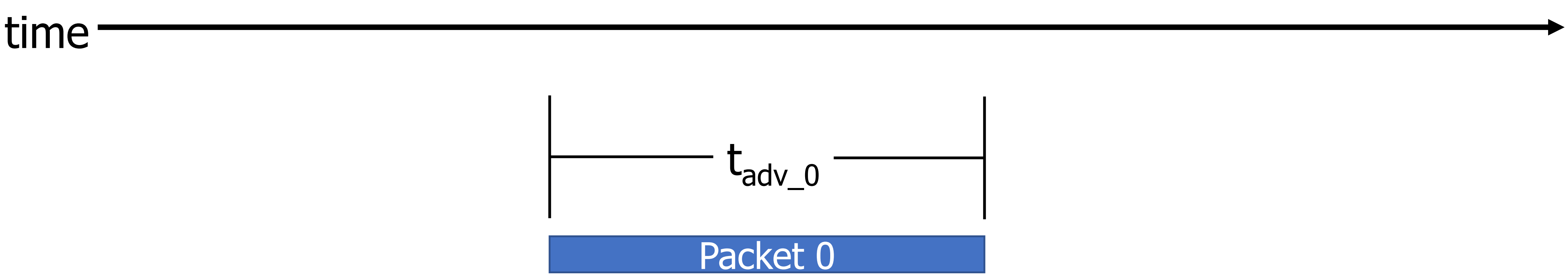
What causes transmissions not to be received?

1. Not within range of the gateway.
    - Or various other losses within the gateway itself

2. Two devices try to send at the same time (packet collision).



What is the probability of a packet collision?



Jeon, Wha Sook, et al. "Performance analysis of neighbor discovery process in bluetooth low-energy networks." (IEEE Transactions on Vehicular Technology, 2016).
Perez-Diaz de Cerio, David, et al. "Analytical and experimental performance evaluation of BLE neighbor discovery process including non-idealities of real chipsets." (Sensors, 2017).

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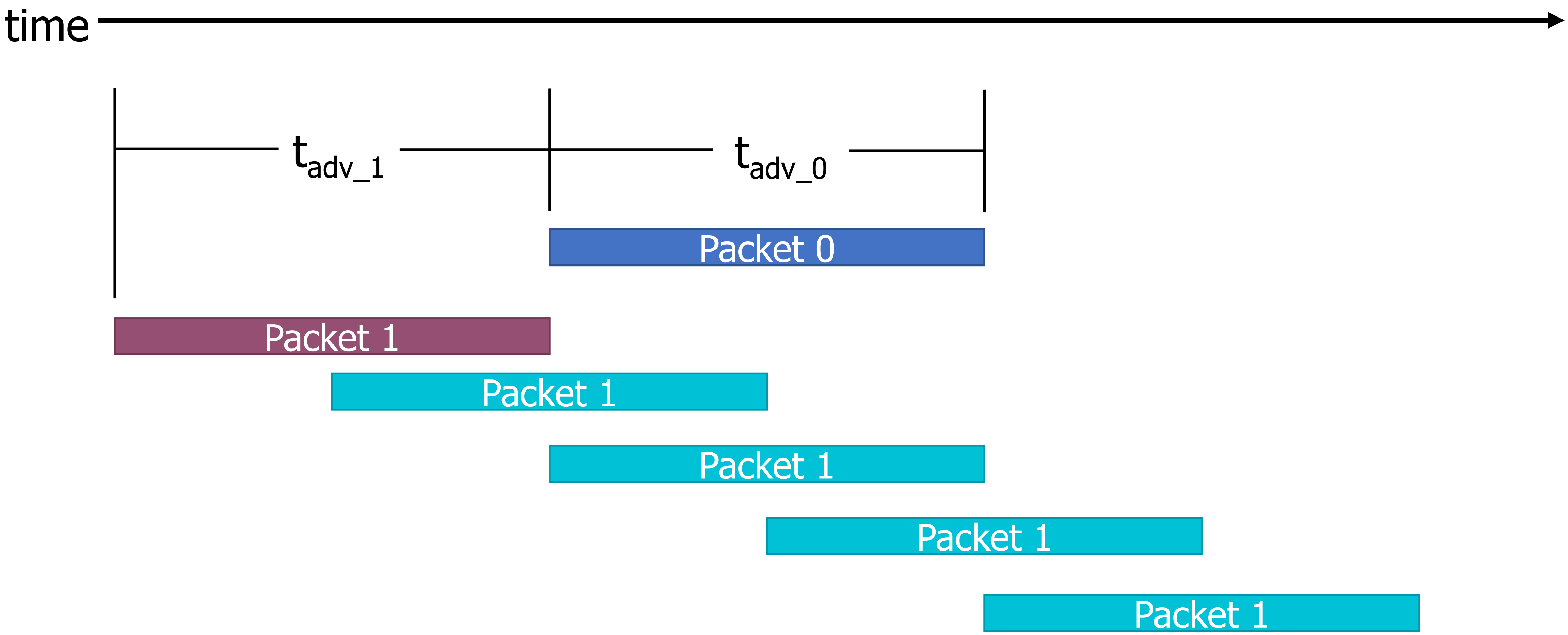

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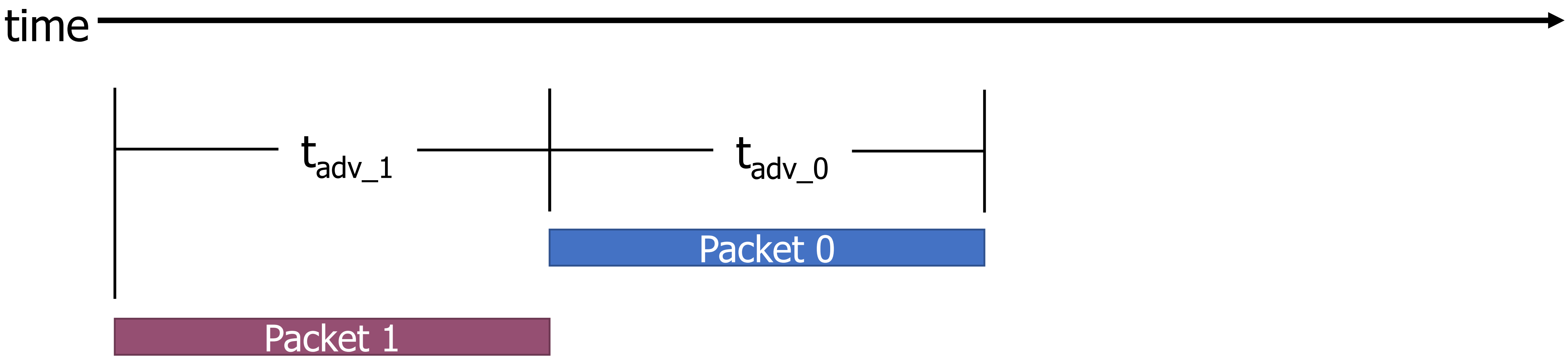

$$\text{Probability of Collision} = \frac{Vulnerable\ Period}{Transmission\ Window} = \frac{t_{adv\_1} + t_{adv\_0}}{T_{adv\_interval} + \mathrm{E}(t_{adv\_delay})}$$

Jeon, Wha Sook, et al. "Performance analysis of neighbor discovery process in bluetooth low-energy networks." (IEEE Transactions on Vehicular Technology, 2016).
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How do we determine reception rate?

With redundancy, we care about data reception instead of packet reception.

Naïve model:

- $Packet\ Reception\ Rate = 1 - (Probability\ of\ Collision)$
- $Data\ Reception\ Rate = 1 - (Probability\ of\ Collision)^{Number\ of\ Packets}$

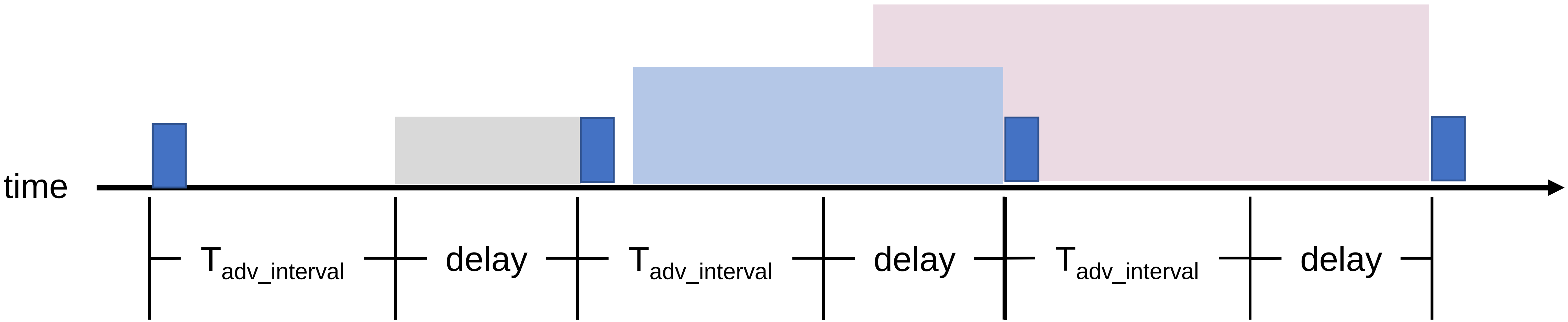
Data Reception Assumption: repeat packet collisions are independent.

- True for any arbitrary selection of two BLE devices
- False for two devices that have recently collided

When are transmissions from two devices independent?

Assumption is *true* for any BLE device that has been advertising for some time

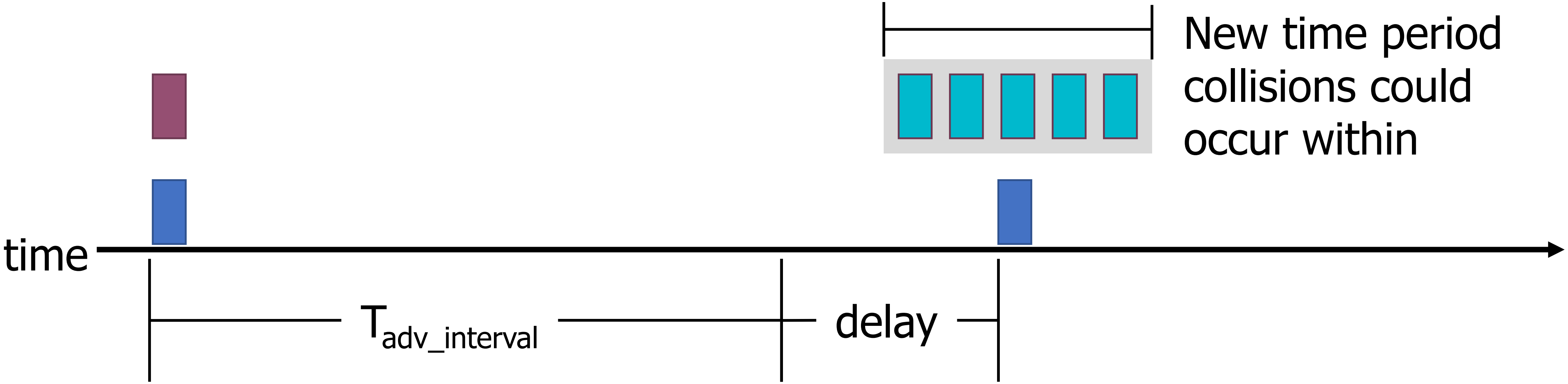
- Sum of random delays grows the uncertainty of transmission.
- Applied to periodic transmissions, any point in interval becomes equally likely.
  - Range of 1x delay, 2x delay, 3x delay, until it wraps



When are transmissions from two devices NOT independent?

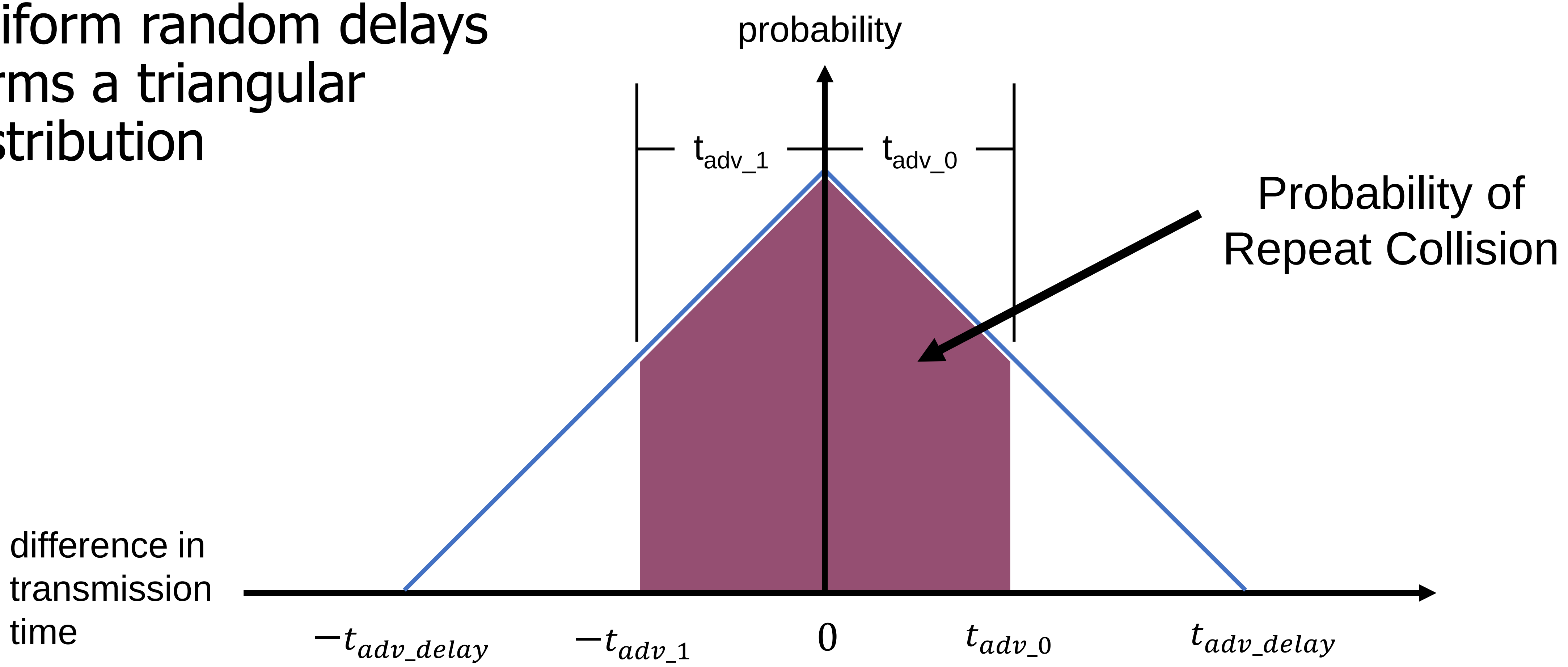
Independence assumption is *false* for two BLE devices that have recently collided.

- If $T_{adv\_interval}$ is identical, next transmissions with be close in time.
- Collision is determined by difference of random delays.
- Further repeat collisions have the same probability of occurrence.



Calculating probability of a repeat collision

- Difference of two uniform random delays forms a triangular distribution

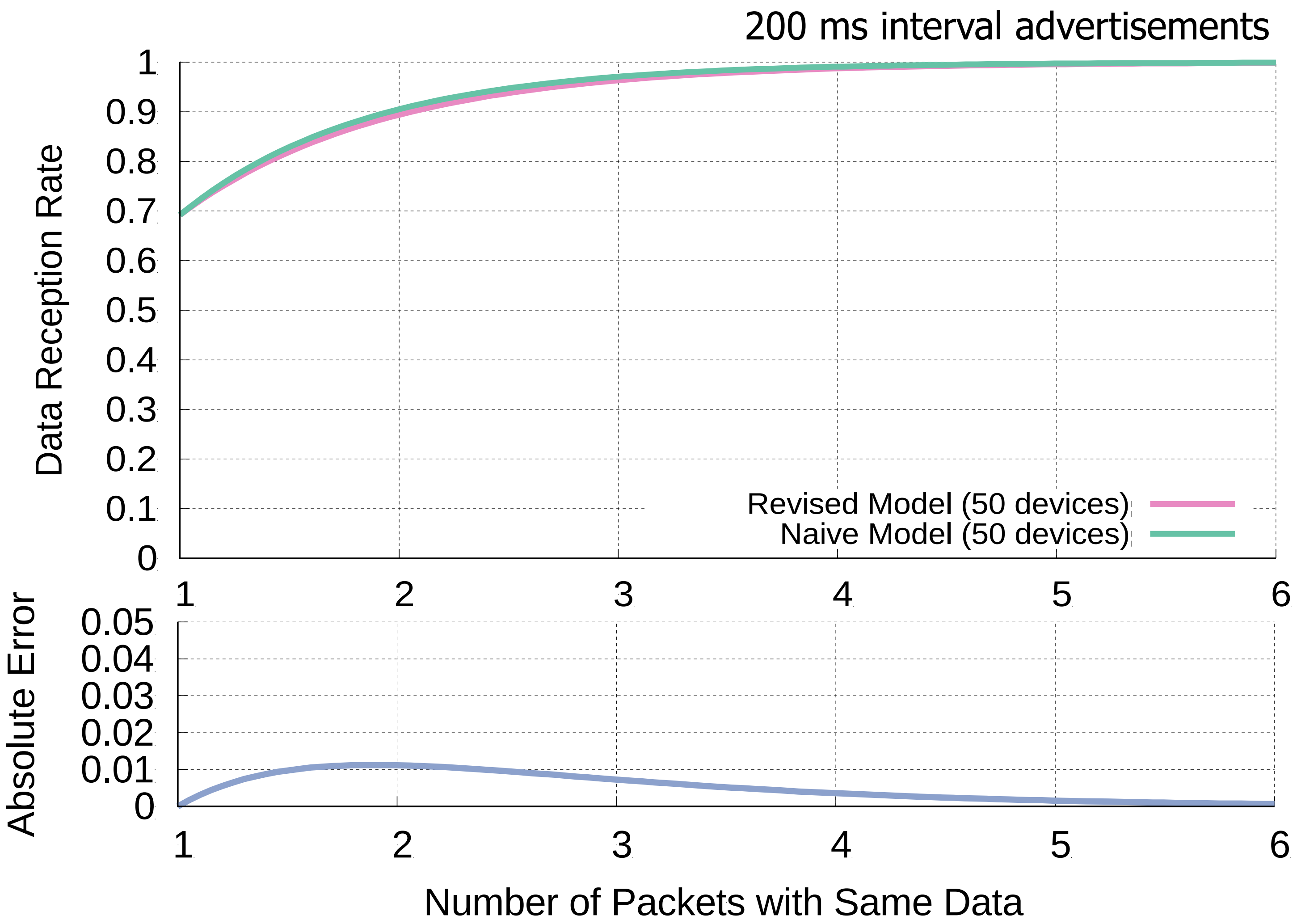


Important lesson: spend time on things that are important

How important was accounting for repeat collisions?

Maximum error is about a 1% change in Data Reception Rate.

This is due to size of delay 10 ms compared to size of transmission ~300 μs.



Equations for modeling data transmissions

- Packet Reception Rate
  - Probability that at the transmitted packet does not have a collision with any of N transmitting devices

$$\text{PRR} = (1 - \frac{2 * tad_v}{T_{adv\_interval} + \text{E}[ta_{dv\_delay}]})^{N-1}$$

- Data Reception Rate
  - Probability that at least one of M redundant packets does not have a collision with any of N transmitting devices

$$\text{DRR} = 1 - \left(1 - \left(1 - \frac{2 * t_{adv}}{T_{adv\_interval} + \text{E}[tad_{v\_delay}]}\right)^{N-1}\right)^{M}$$

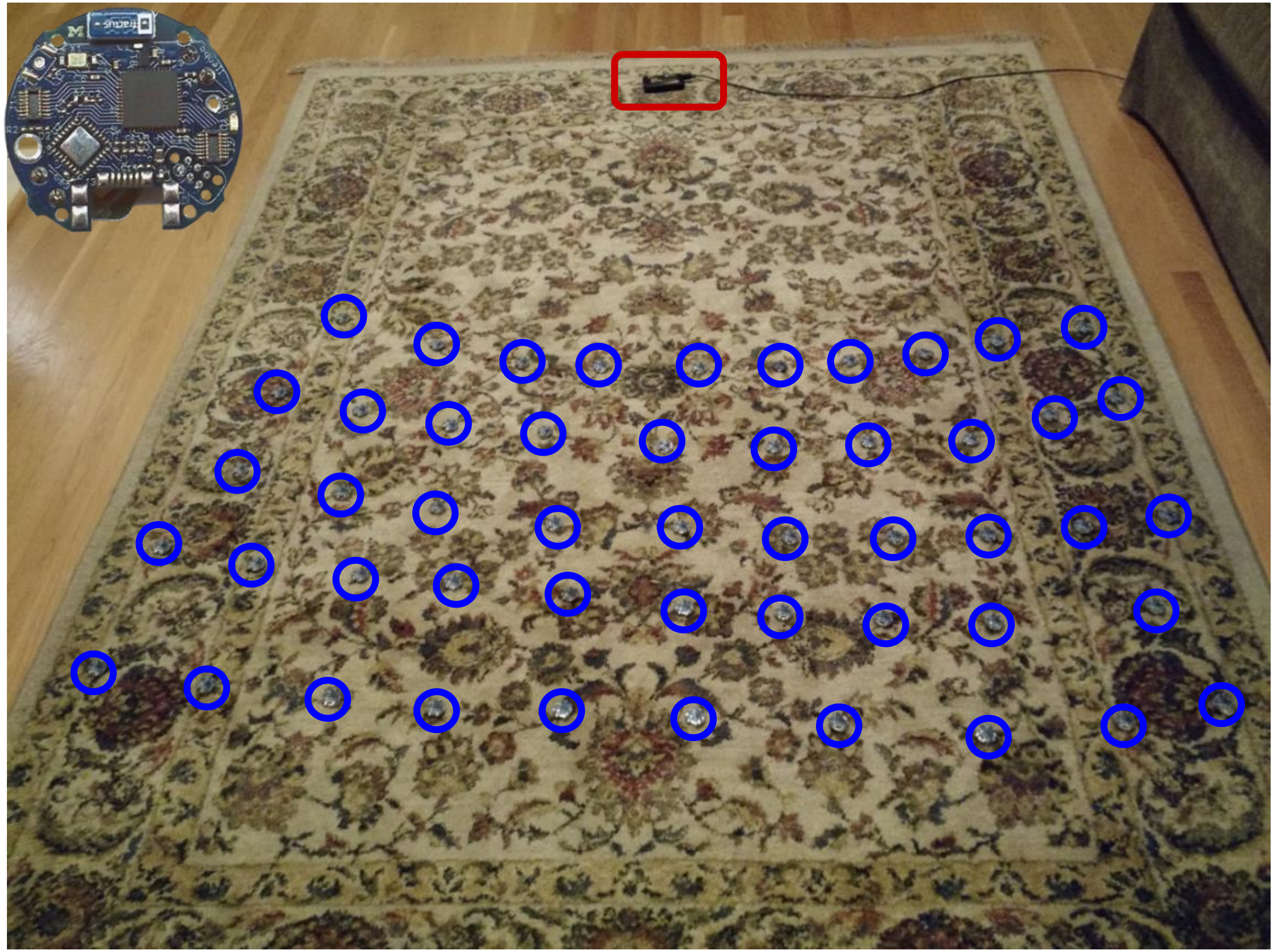
Is the model valid?

Empirical testing setup:

- 50 devices
- 1 meter from scanner
- 5-10 cm apart

Transmit monotonically increasing sequence numbers.

Sweep number of devices and advertising intervals.

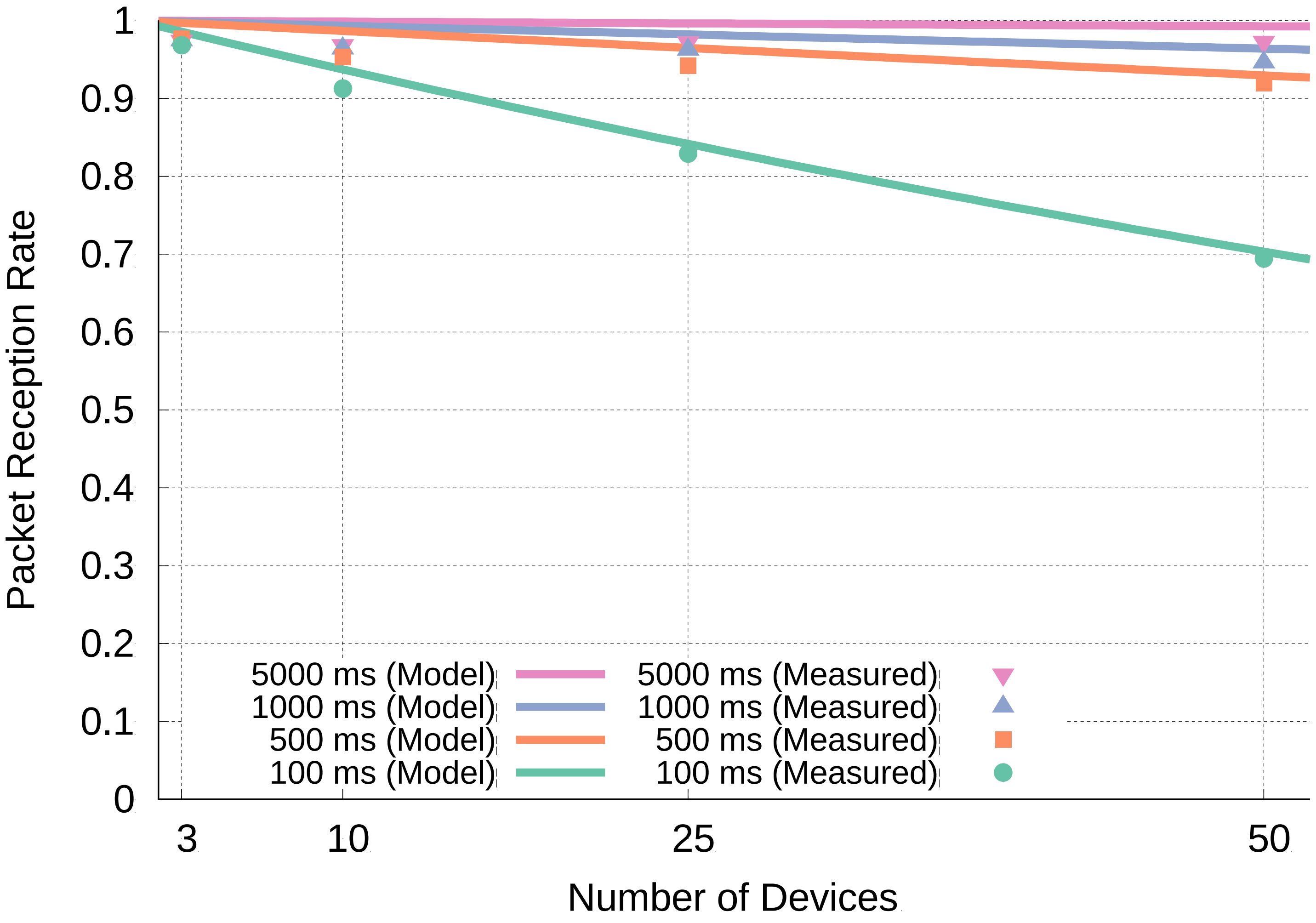


The model is accurate across advertisement rates and deployment sizes.

Accuracy is fairly consistent across intervals.

The model consistently overestimates the measured PRR values.

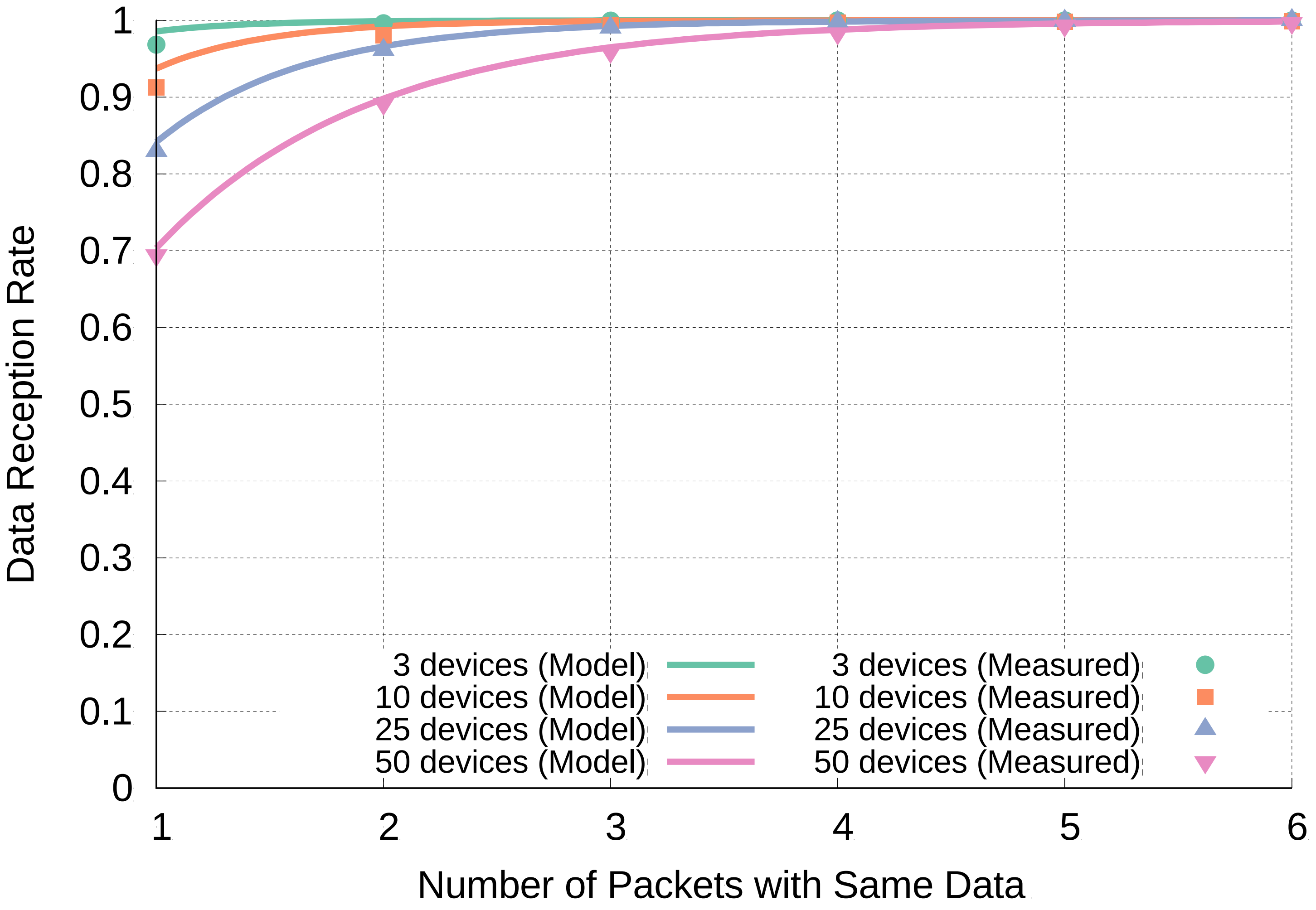
The effect could be due to RF interference.



The model accurately accounts for redundancy as well.

The same dataset can be used to measure the effect of redundancy by grouping sets of sequence numbers.

The model again slightly overestimates, but error reduces quickly as DRR approaches 100%.



What questions can we answer with a collision model?

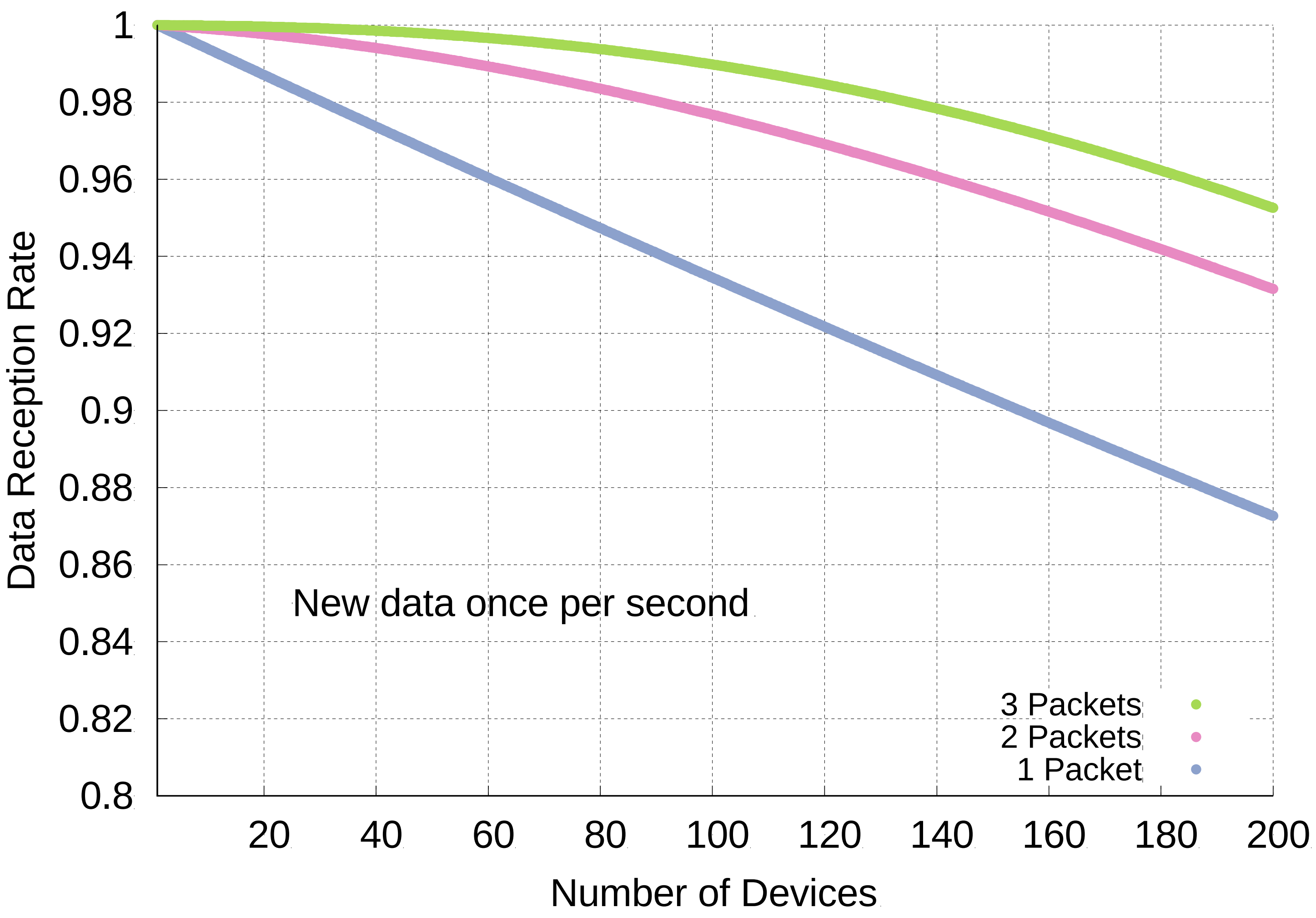
- Original questions
  - What are the odds that a transmitted advertisement will be received?
  - If M redundant advertisements are sent instead, what are the odds that at least one are received?
  - How do these odds vary with number of devices, advertising interval, and packet size?

- Additional questions
  - Can redundancy make advertisements reliable?
  - Is it better to transmit often for high redundancy or rarely for less congestion?

Redundancy results in high DRR even with many devices.

In this example, a sensor has new data once per second and sends it in 1-3 packets.

Even without redundancy, data reception rates never fall below 87% even with 200 devices in a deployment, assuming no interference.



Redundancy is (normally) better than less congestion.

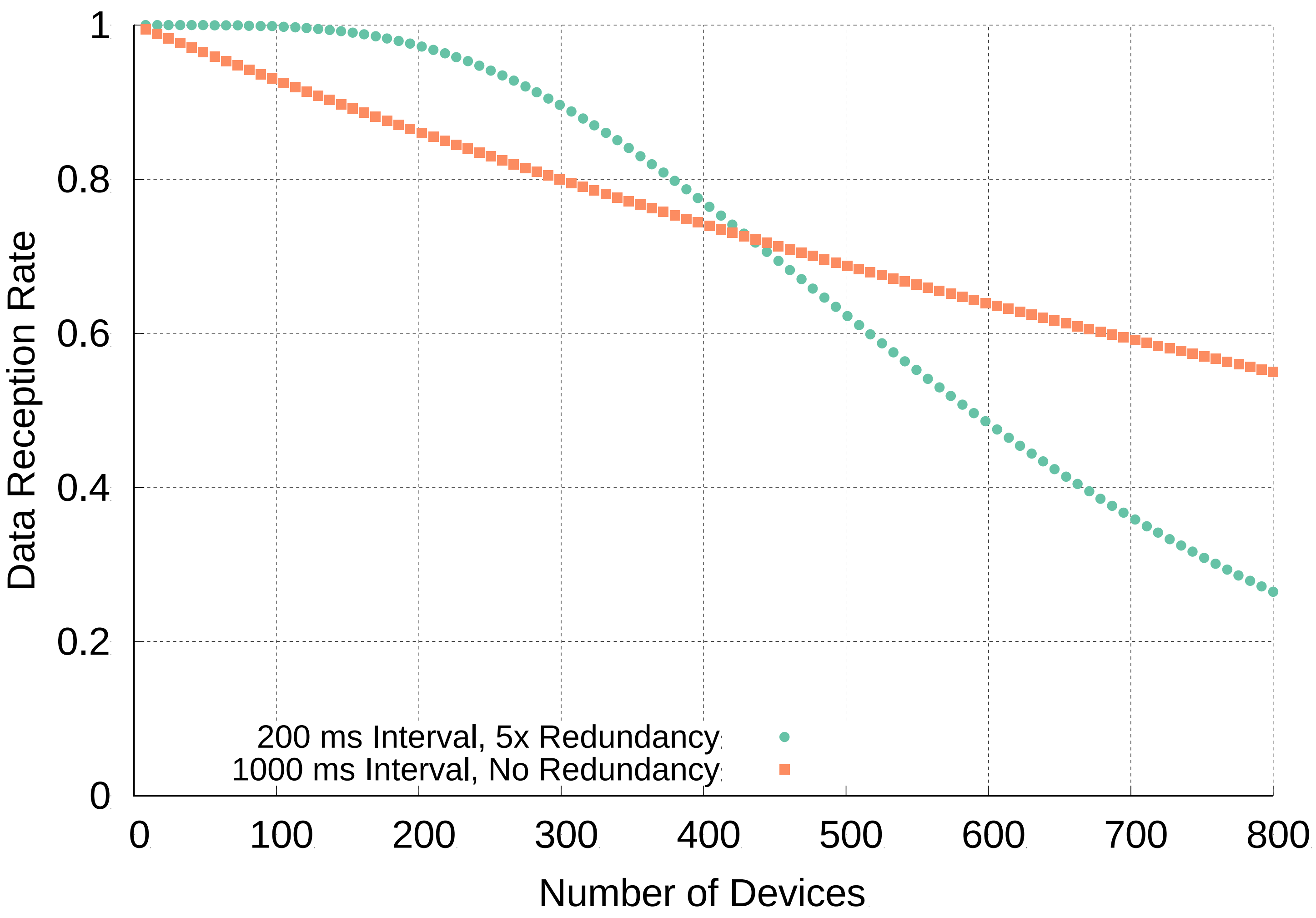
Design question:

- Send more packets to gain from redundancy?

  OR

- Send less packets to reduce congestion?

The answer changes, but only with many devices.



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- **Advertisement Use Cases**

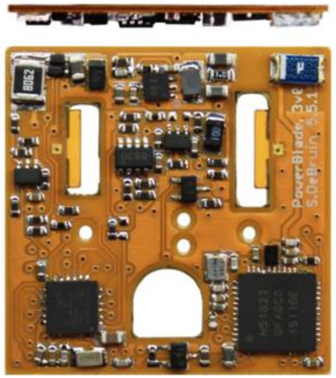
Advertisements are already being used for communication.

BLE advertisements are uncoordinated, broadcast messages designed for discovery.

- Devices are being deployed using advertisements.
  1. Beacons – iBeacon
  2. Tracking – Tile
  3. Local communication – Apple Continuity
  4. Sensor deployments – PowerBlade

iBeacon

Eddystone



Beacons

- Advertising with advertisements!

- Web of Things
  - Real-world tags that broadcast virtual-world identifiers

- iBeacon and Eddystone
  - Formats for sending URLs and device identifiers
  - Use existing BLE fields (Service Data and Manufacturer-Specific Data)

Tracking

- Find devices nearby
  - Get a sense of distance to the device

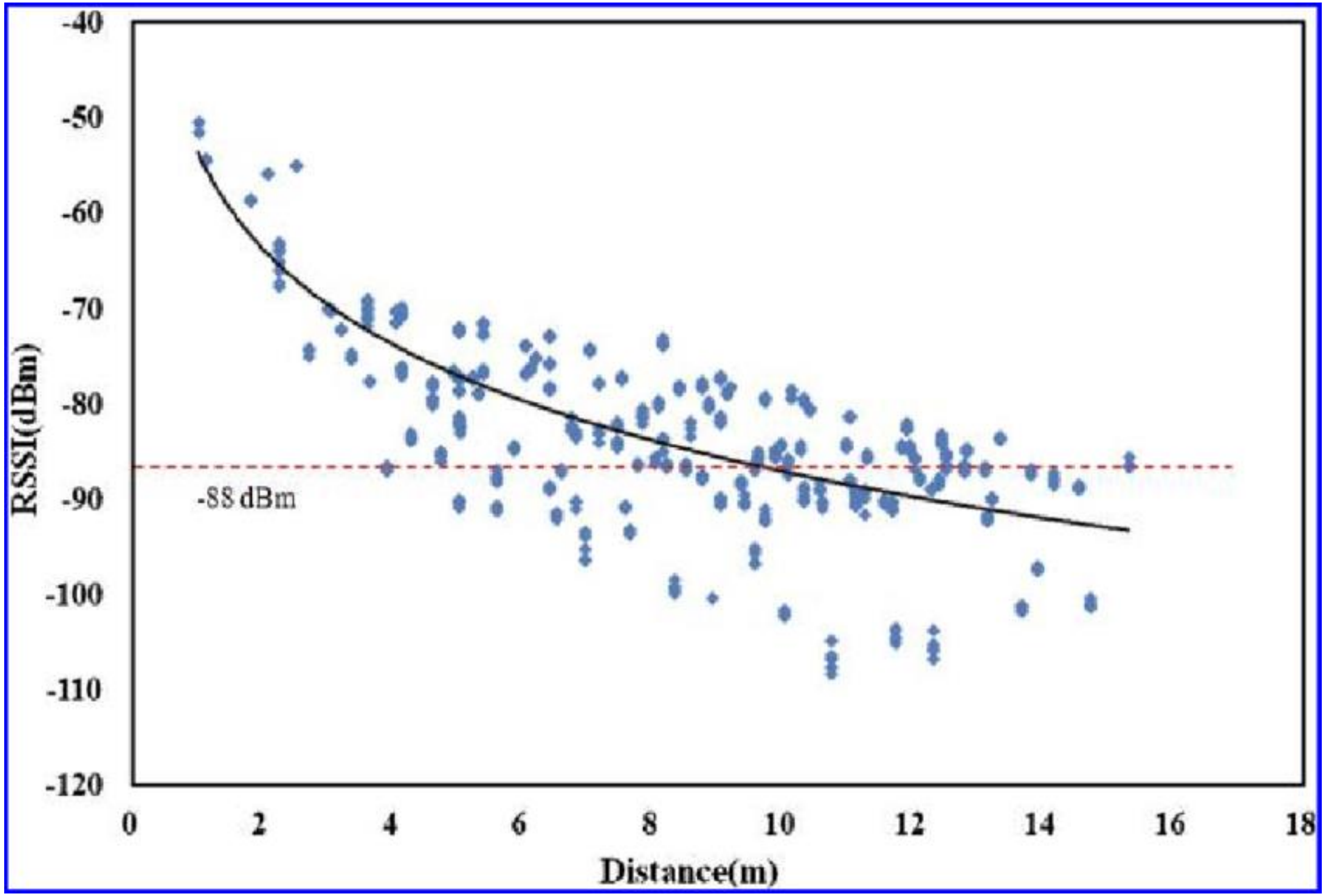
- Find my X
  - Tile: find my keys
  - Apple: find my device

- Uses TX power level field
  - Lists the transmitted power of the device
  - Pathloss = TX power – RSSI (all in dBm)

Problem with RSSI-based distance – not accurate

- Pathloss is NOT only due to distance

- RSSI is way worse at this than you hope it would be



Citation: literally everyone has made this figure at some point

Local communication

- Communication with only *nearby* devices

- Apple Continuity

0 – 7	8 – 15	16 – 23	24 – 31
Access Address - 0x8E89BED6			
Packet Header			
Advertising Address - xx:xx:xx:xx:xx:xx			
Length / Type - 0x01 / Flags (Optional)			Length
Type - 0xFF	Company ID - 0x004C		Apple Type
Apple Length	Variable Length Apple Data		Apple Type
Apple Length	Variable Length Apple Data		

Table 1. Advertisement Frames

		Test 1	Test 2
		Count	
Address Type	Public	26	57
	Random	726	1,518
Company ID†	Apple	692	1296
	Microsoft	30	201
	Garmin	2	9
	Samsung	0	3
	All Others	2	9

† Randomized Devices Only

Type	Value
Watch Connection	11
Handoff	12
Wi-Fi Settings	13
Instant Hotspot	14
Wi-Fi Join Network	15
Nearby	16

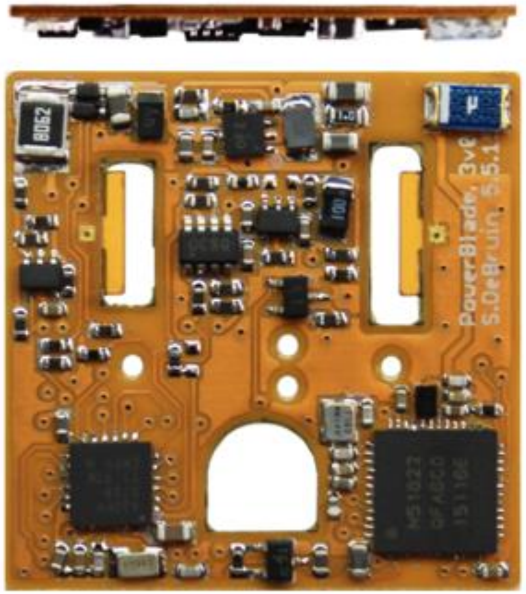
Table 3. Action Codes

Type	Description
1	iOS recently updated
3	Locked Screen
7	Transition Phase
10	Locked Screen, Inform Apple Watch
11	Active User
13	Unknown
14	Phone Call or Facetime

Martin, Jeremy, et al. "Handoff all your privacy–a review of apple's bluetooth low energy continuity protocol." *Proceedings on Privacy Enhancing Technologies* 2019.4 (2019): 34-53.

Sensor deployments

- Report data so gateways and users can retrieve it simultaneously
  - Easy introspection during a deployment
  - Satisfy users' curiosity
- Ignore difficult questions about networking
  - Just broadcast the data!



DeBruin, Samuel, et al. "Powerblade: A low-profile, true-power, plug-through energy meter." *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*. 2015.

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- **Bonus: Scan Responses**

Scan requests/responses seem intriguing

- Why not send most data in scan responses instead of advertisements?
  - Theoretically could reduce energy costs
- Scan we use scan requests as a form of acknowledgement?
  - Could relieve need for redundant transmissions
- Problem: scan requests/responses don’t work all that well

Scan Requests and Responses are broken

- Goal: provide a little extra advertisement data on demand

- Problem: exponential backoff for lost messages
  - If there is a request without a response, scanners assume collision with another scanner and exponentially back off from requesting
  - But collisions are far more likely between a device and a scanner, which should not have back off
  - Result is that scan requests will occur far less frequently than expected
  - Instead, just send additional advertisements with different data

Kravets, Robin, Albert F. Harris III, and Roy Want. "Beacon trains: blazing a trail through dense BLE environments." *Proceedings of the Eleventh ACM Workshop on Challenged Networks*. 2016.

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