Lecture 04
BLE Advertisement Deep Dive

CS397/497 – Wireless Protocols for IoT

Branden Ghena – Spring 2022

Materials in collaboration with Pat Pannuto (UCSD)

Northwestern

Announcements

- Reminder – Lab1: Wireshark
  - Due Thursday by 11:59 pm
  - Late policy: 50% of points if submitted within a week of deadline

- Project Proposals
  - Due next week Friday (04/22) by 11:59 pm
  - Added details about what to include on Canvas assignment
    - Submit PDF to Gradescope

- Hardware for labs
  - I have some! I'll pass out after class today/Thursday

Today's Goals

- Describe BLE advertising and scanning roles

- 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?

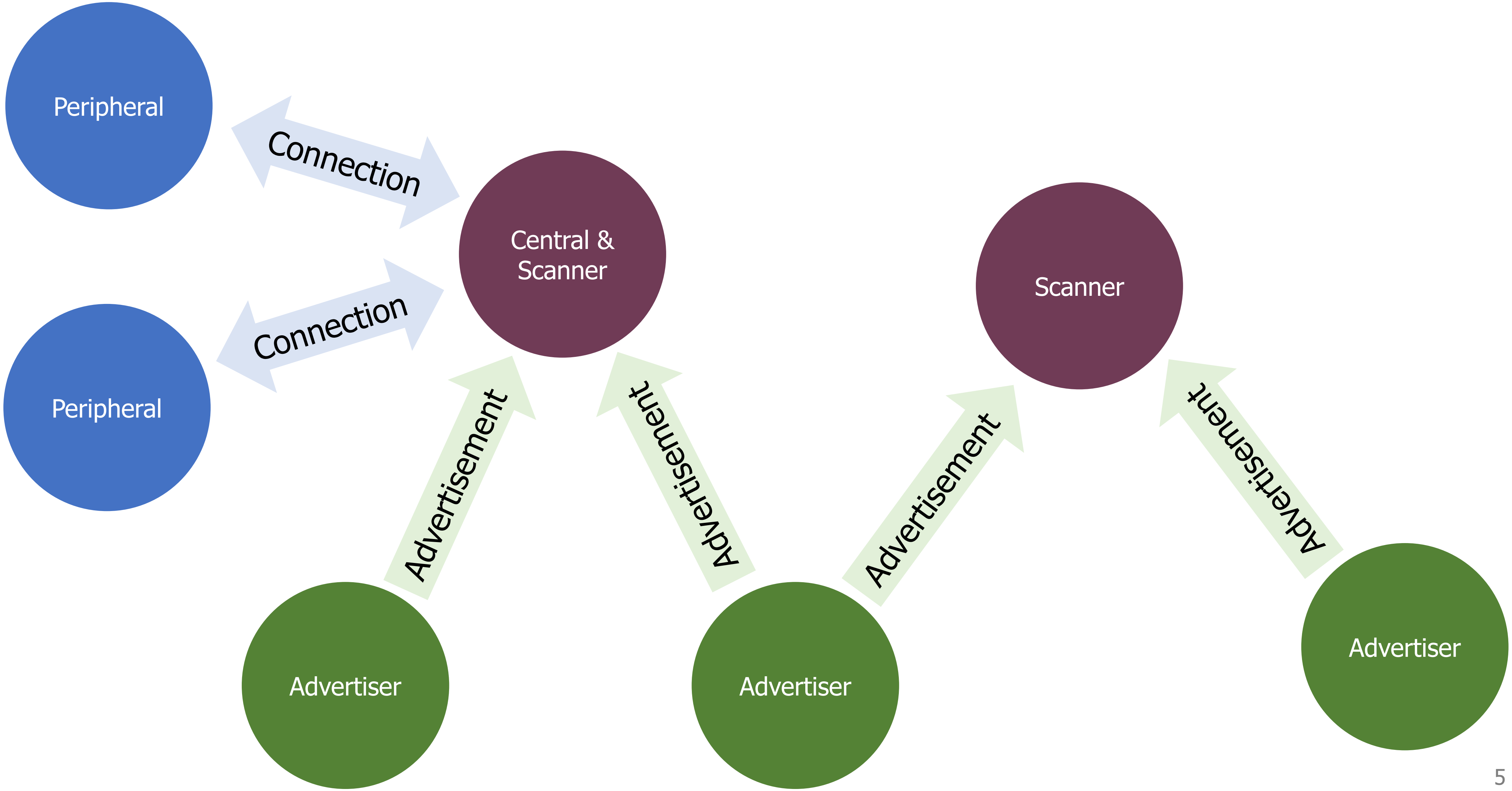
  - What are the real-world use cases of advertisements?

Outline

- **BLE roles**
  - **Advertising**
  - Scanning

- Communicating with advertisements
  - Advertisement Use Cases
  - Energy Use
  - Packet Collisions

BLE network topology



Advertising

- BLE discovery mechanism
    - Make nearby devices aware of advertiser’s existence
    - Communicate some information from or about advertiser
    - Traditional purpose is to enable connections, but this is also useful for general communication

- Advertisements
    - Periodic broadcast messages with data
- Scan Requests/Responses
    - Scanner sends responses after getting a request
        - Only occurs when scanner is listening
    - Almost literally “bonus advertisement data”

Advertising packet layering

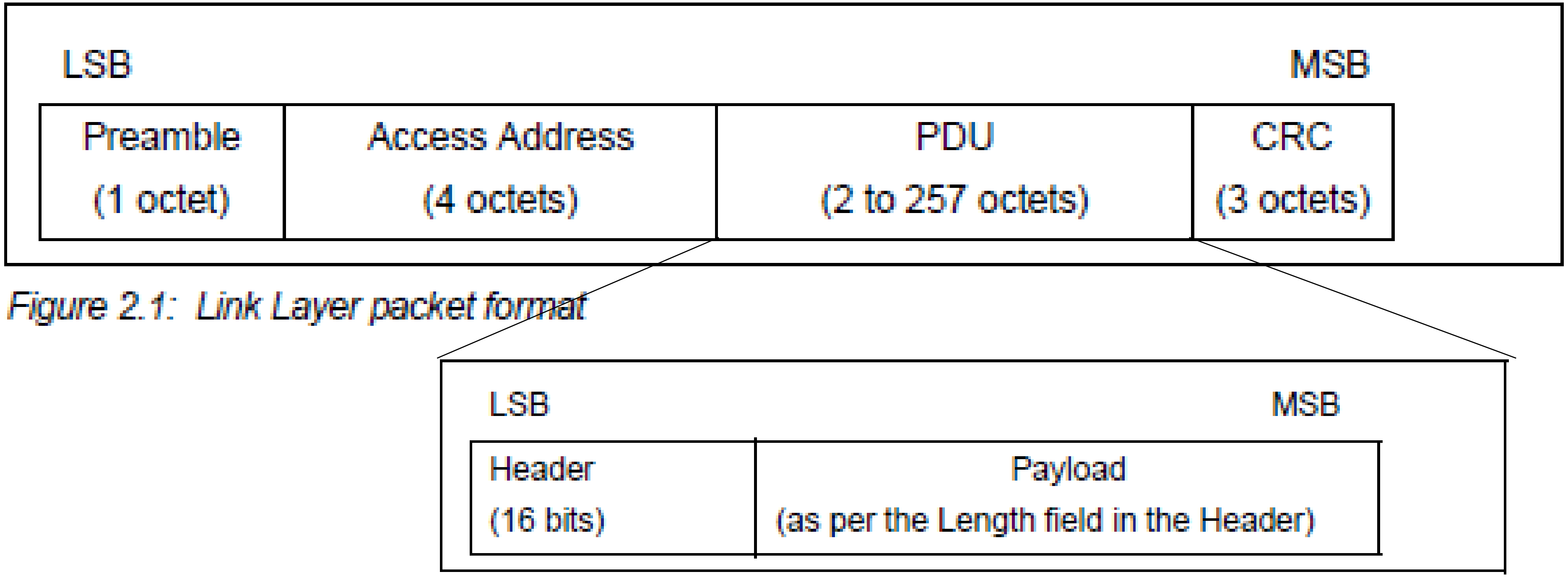


Figure 2.1: Link Layer packet format

Figure 2.2: Advertising channel PDU

BLE advertising header

LSB					MSB
PDU Type (4 bits)	RFU (2 bits)	TxAdd (1 bit)	RxAdd (1 bit)	Length (6 bits)	RFU (2 bits)

Figure 2.3: Advertising channel PDU Header

PDU Type $b_3b_2b_1b_0$	Packet Name
0000	ADV_IND
0001	ADV_DIRECT_IND
0010	ADV_NONCONN_IND
0011	SCAN_REQ
0100	SCAN_RSP
0101	CONNECT_REQ
0110	ADV_SCAN_IND
0111-1111	Reserved

Table 2.1: Advertising channel PDU Header's PDU Type field encoding

- ADV_IND
  - Advertisement
  - Allows connections and scan requests
- ADV_NONCONN_IND
  - Advertisement
  - No connections or scan requests
- ADV_SCAN_IND
  - Advertisement
  - No connections but allows scan requests
- SCAN_REQ
  - Scan request
- SCAN_RSP
  - Scan response

Advertisement payloads

Payload	
AdvA (6 octets)	AdvData (0-31 octets)

- AdvA – address of the advertiser
  - TxAdd bit from header specifies if this is a “public” or “random” address

- Remaining up to 31 bytes are available for use

- Putting it all together, up to 47 bytes total:

BLE Packet

		Advertising PDU			
Preamble 1 Byte	Access Address 4 Bytes	Header 2 Bytes	Advertiser Address 6 Bytes	Advertiser Data (Payload) 0-31 Bytes	CRC 3 Bytes

Scan Requests and Responses

- Scan request
  - Just the two addresses: the scanner’s and the advertiser’s

Payload	
ScanA (6 octets)	AdvA (6 octets)

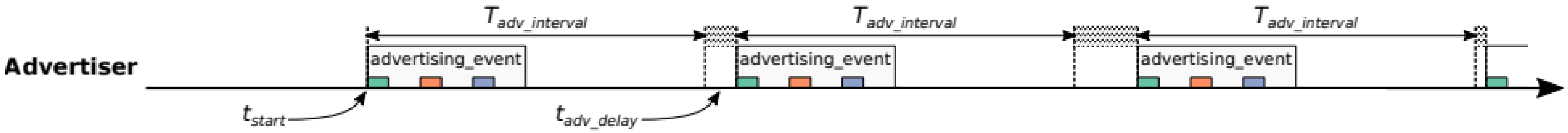
Figure 2.8: SCAN_REQ PDU Payload

- Scan response
  - Identical to an advertisement
  - But only occurs after a request

Payload	
AdvA (6 octets)	ScanRspData (0-31 octets)

Figure 2.9: SCAN_RSP PDU payload

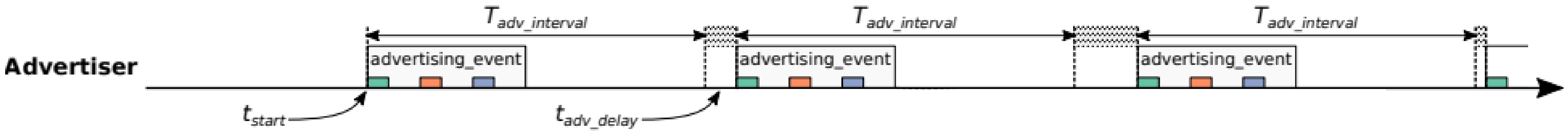
Advertising timing



- Advertising Events occur periodically [20ms – 10.24 s] (or longer)
  - Plus a random delay after each instance [0-10ms]
  - **Why?**

- User picks the rate as a tradeoff of energy and discovery latency

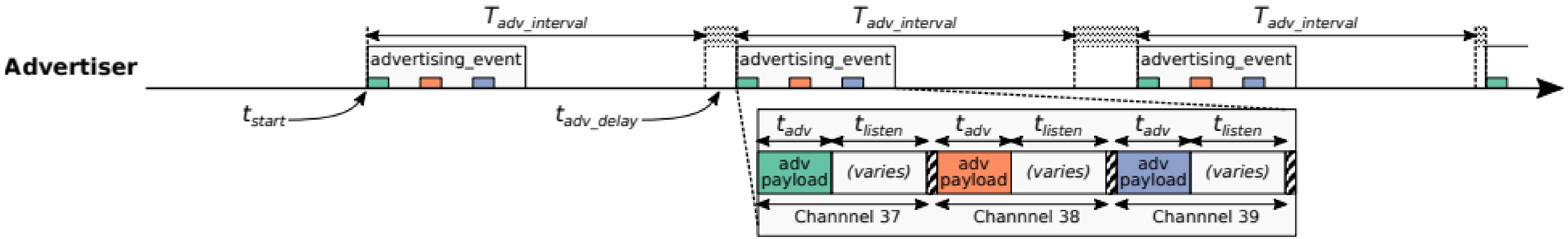
Advertising timing



- Advertising Events occur periodically [20ms – 10.24 s] (or longer)
  - Plus a random delay after each instance [0-10ms]
  - **Why? Avoid repeat collisions**

- User picks the rate as a tradeoff of energy and discovery latency

Advertising event



- Three transmissions, one on each advertising channel
  - Always in the same order

- Transmission, followed by listening window on that same channel
  - Requests will be sent >=150 us (Inter-Frame Spacing, IFS) after Tx
  - Followed by a retune to the next channel frequency
- This short listen window is the magic “low energy” part

Preserving energy in communication

- Most energy is spent listening
  - This is due primarily to how long listening durations are compared to transmissions

- Example: maximum-sized BLE transmission:
  - 8 bits/byte * 47 bytes = 376 bits at 1 Mbps = 0.376 ms transmitting
  - So listening for an entire second is >2500 times longer
  - But listening for only 0.376 ms requires sub-ms synchronization, which itself costs energy to manage…
  - Instead, when advertising, nRF radios listen for ~0.200 ms, only after a transmission

Payload of an advertisement

- What do you stick in the BLE payload anyways?
  - Theoretically whatever you want, but that isn’t very compatible
  - Point is to specify capabilities of the advertiser

- Desire: specify payloads in such a way that all scanners can interpret what they mean about the device
  - This is different from traditional internet packets
  - Broadcasts are for _anyone_ to hear, not a specific server/application

- Which fields are or aren’t present is device-specific
  - A lot more possible fields than will really be used on any device

TLV Format

- Type – Length – Value (Wikipedia)
  - Actually, BLE does the length part first
  - Scanner can hop through length/type pairs to find what interests it

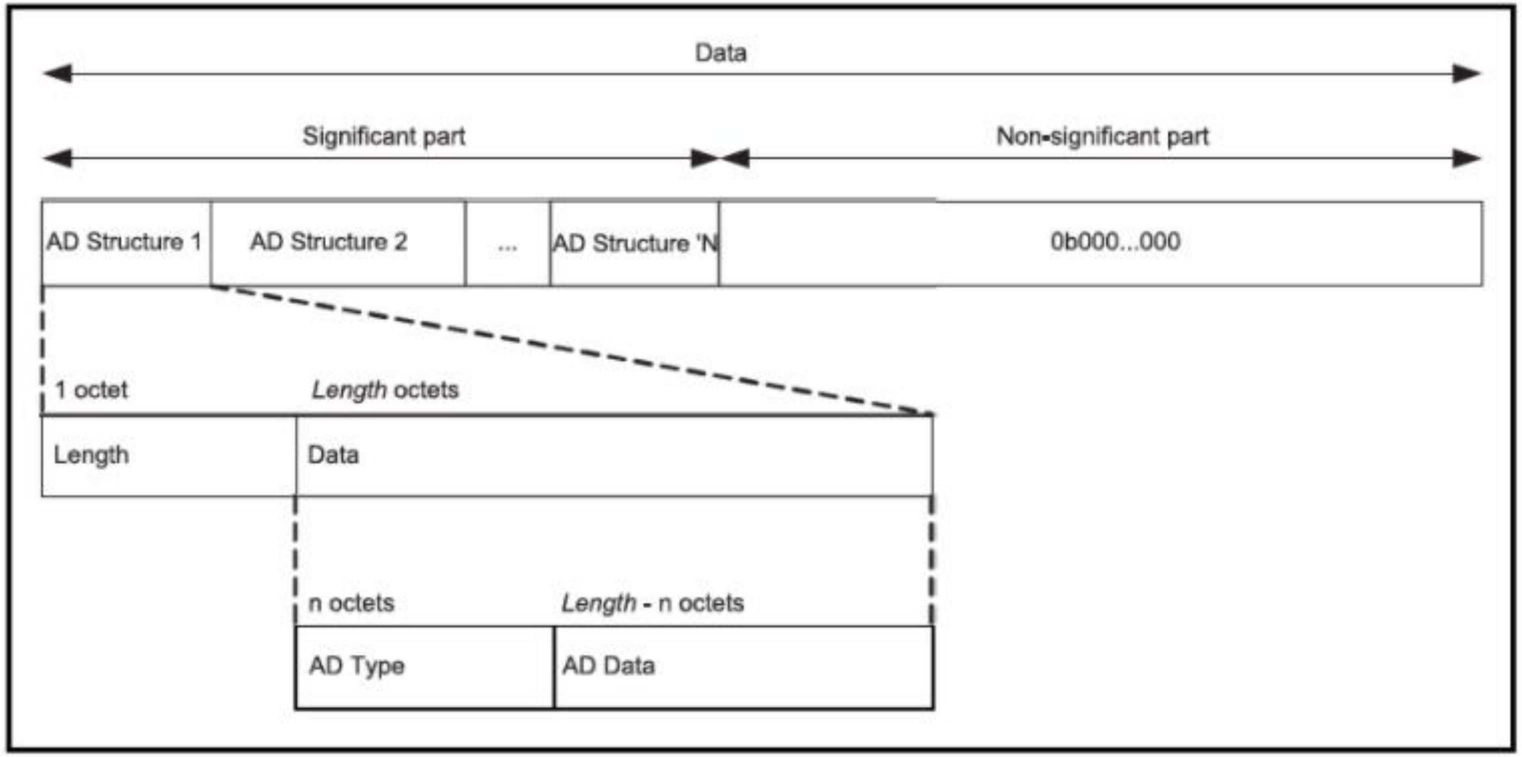


Figure 11.1: Advertising and Scan Response data format

Payload types

- Listed in the Core Specification Supplement [Supplement v9]
  - Each might have their own considerations about AD Data format

- Flags (supported modes: BLE and Bluetooth) required by Apple?
- Name
- Service UUID
- TX Power Level
- Manufacturer-specific data
- And about twenty others

Outline

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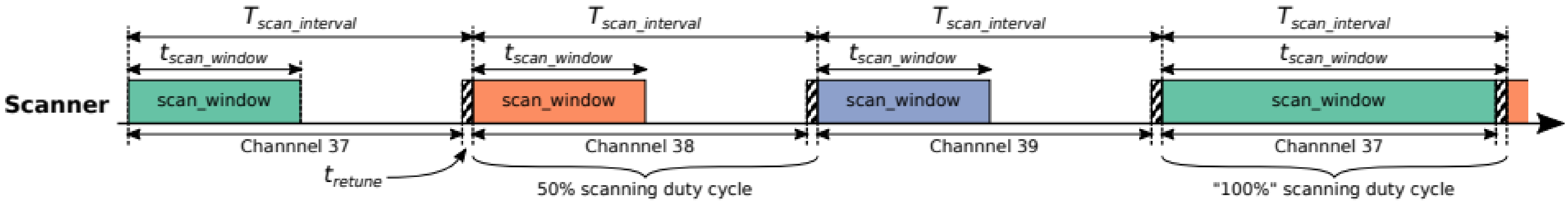
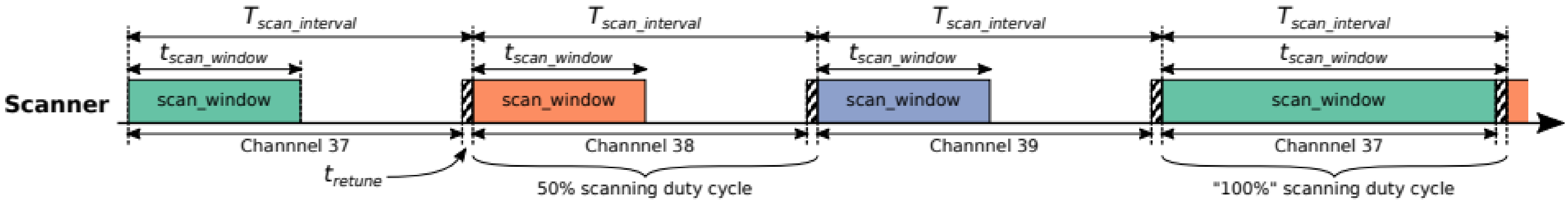
Scanning Pattern



- 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**

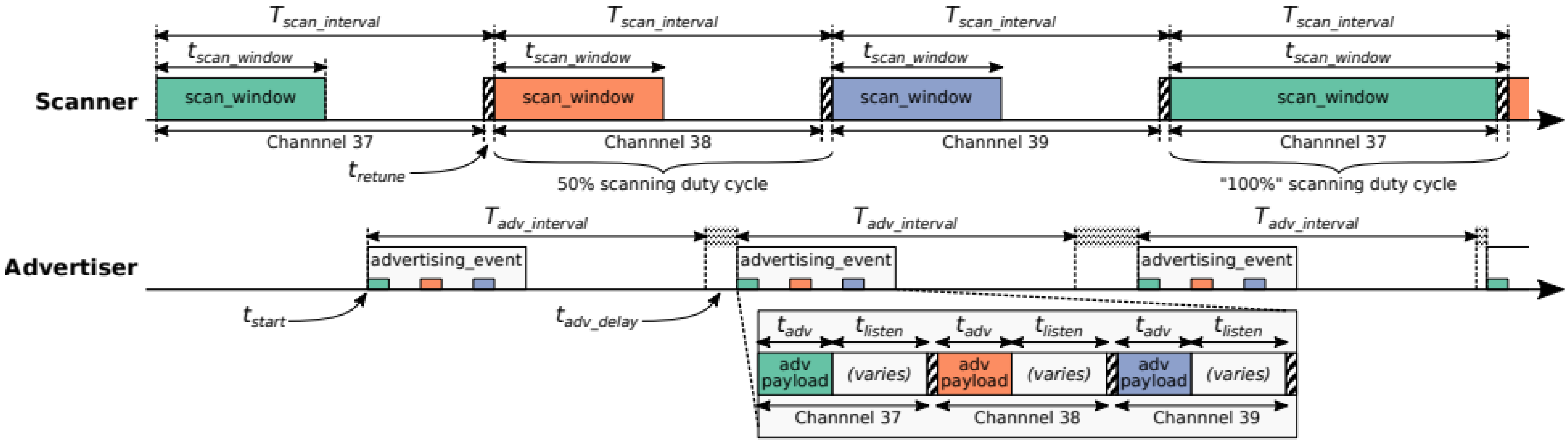
A warning about scanning expectations

- 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

Break + 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)



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Advertisements are already being used for communication.

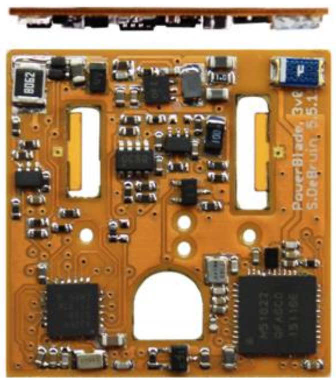
BLE advertisements are uncoordinated, broadcast messages designed for discovery.

iBeacon

Eddystone

Devices are being deployed using advertisements.

1. Beacons – iBeacon
2. Tracking – Tile
3. Local communication – Apple Continuity
4. Sensor deployments – PowerBlade



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

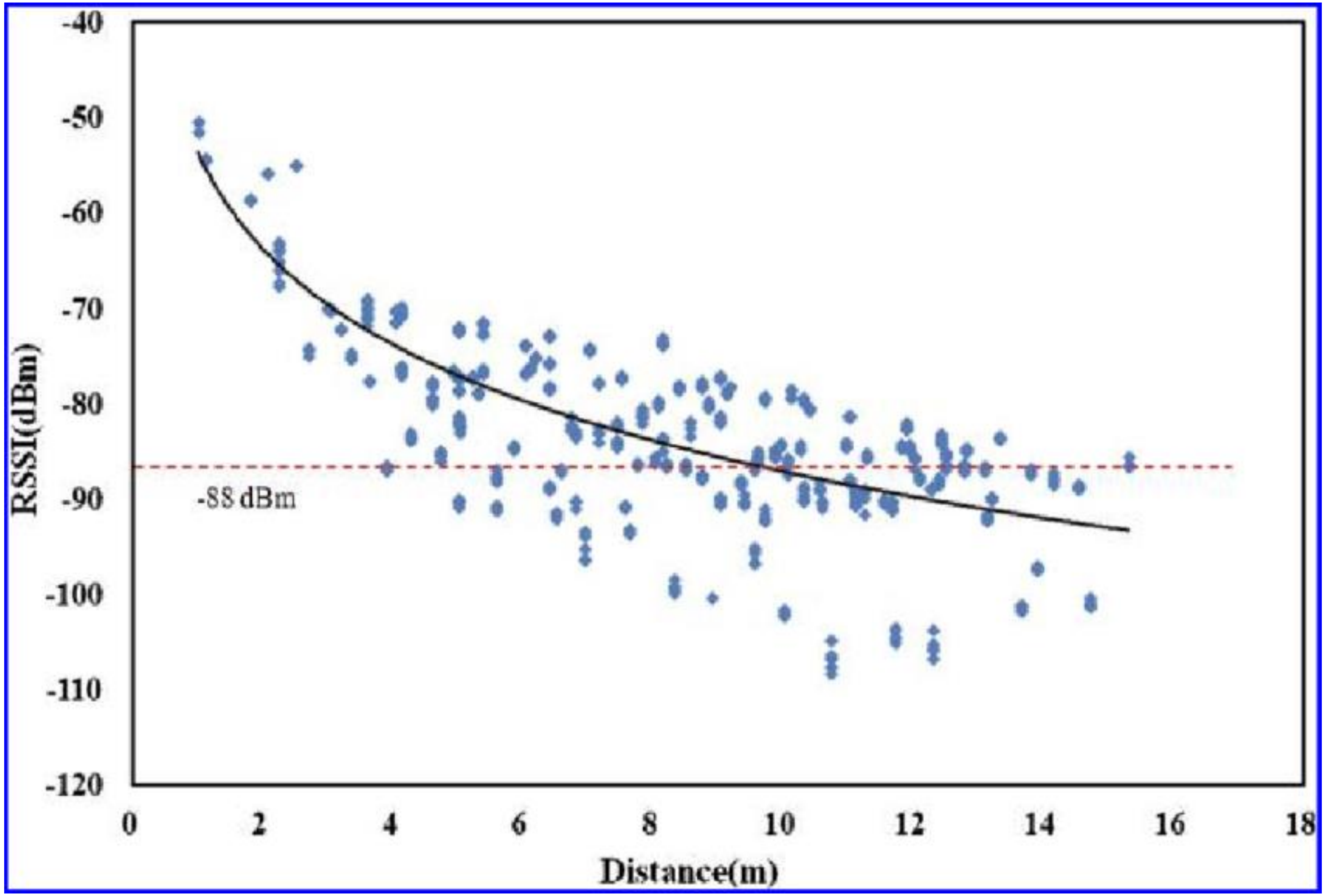
- Find my X
  - Tile: find my keys
  - Apple: find my device

- 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: Apple Continuity

- Communication with only *nearby* devices

- Apple Continuity

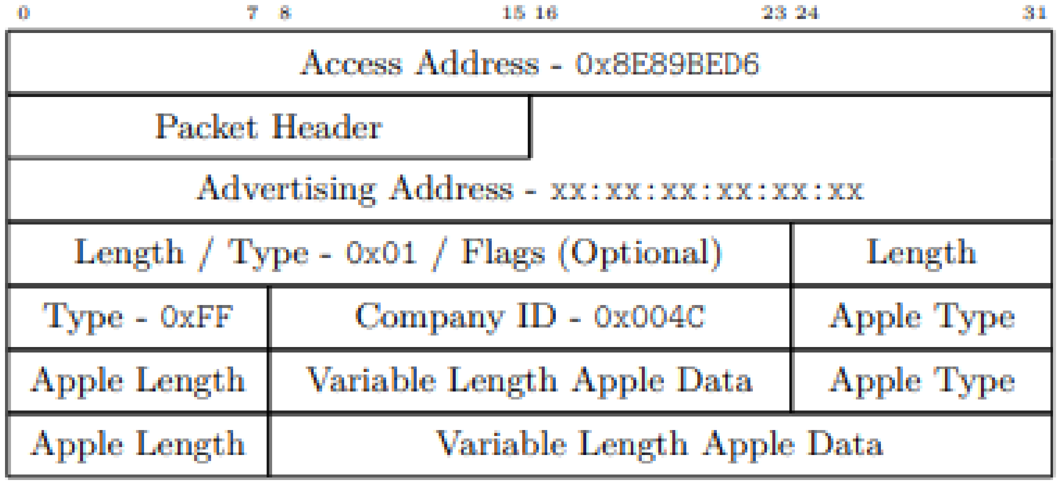


Table 1. Advertisement Frames

		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

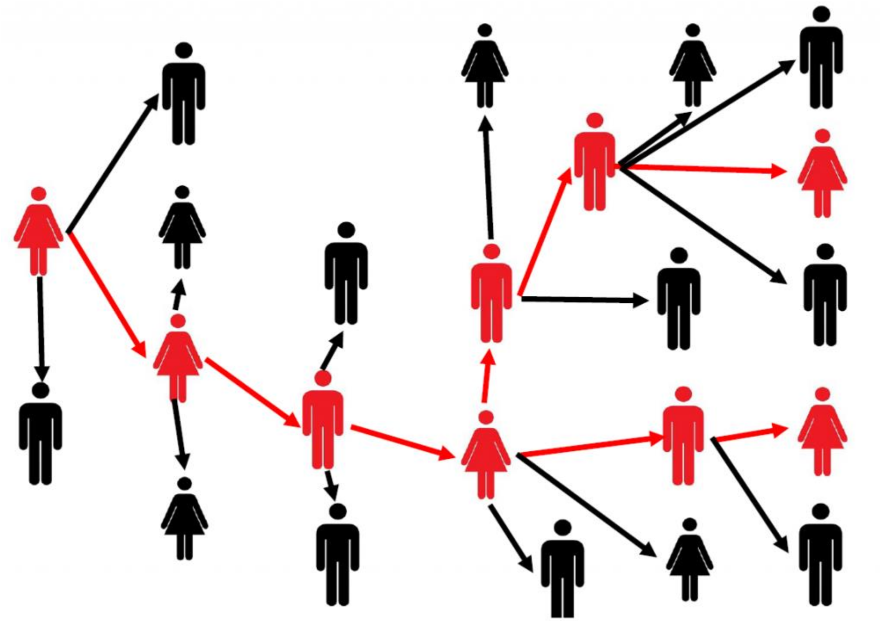
Martin, Jeremy, et al. "Handoff all your privacy–a review of apple's bluetooth low energy continuity protocol." *Proceedings on Privacy Enhancing Technologies* 2019.4 (2019): 34-53.

Local Communication: Exposure Notifications

- Apple and Google collaboration to use phones for contact tracing
  - Smartphone constantly broadcasts identifier.
  - Periodically, each smartphone listens for broadcasts around it.
  - Check list of identifiers to see if you've been around someone who is sick.

- Requires government/healthcare system interactions to determine when an identifier should be flagged as sick
  - 24 states (not Illinois) adopted this

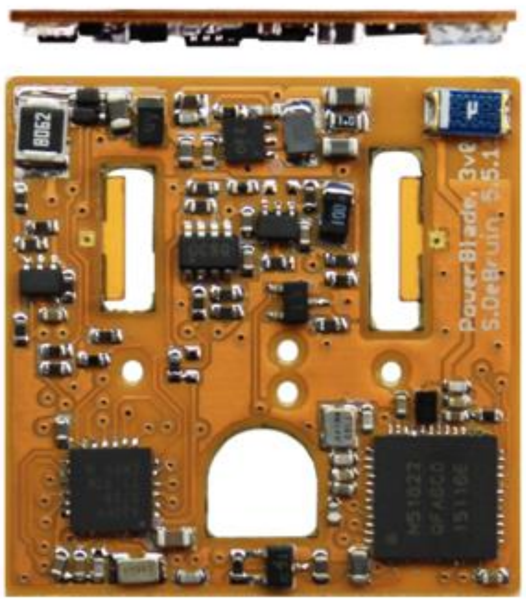
- Implemented at OS level in background



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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Paper: power measurements of BLE advertisements

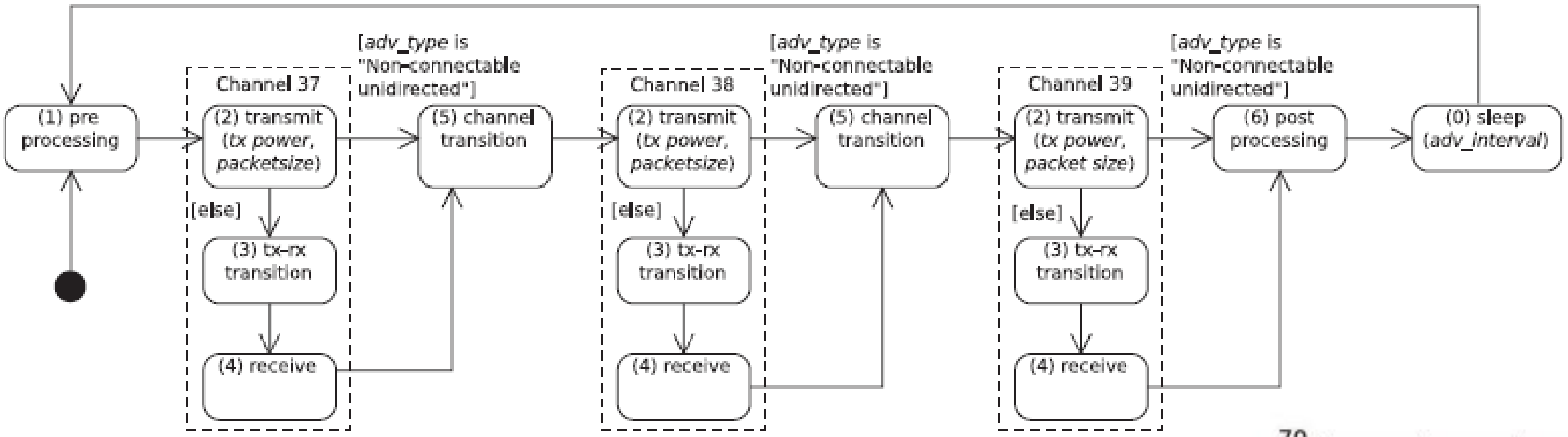
Schrader, Raphael, et al. "Advertising power consumption of bluetooth low energy systems." *2016 3rd International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS)*. IEEE, 2016.

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

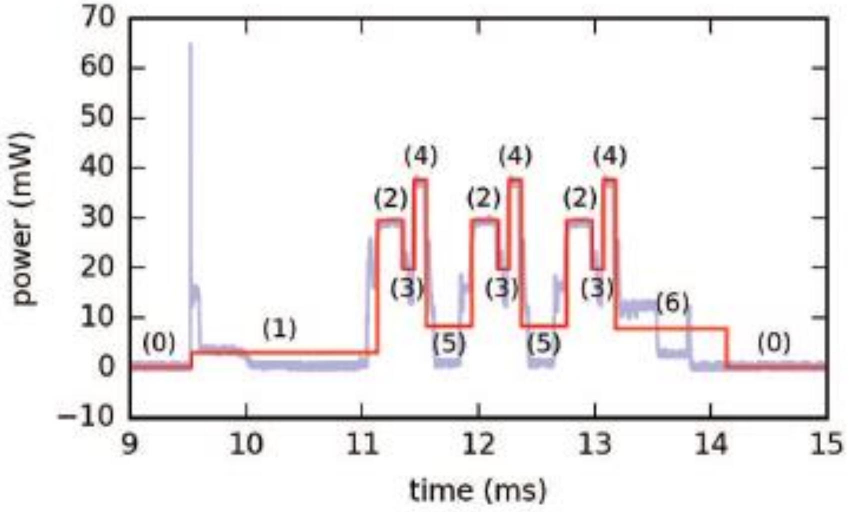
Advertising Power Consumption of Bluetooth Low Energy Systems

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

Energy model for BLE advertisements



- Creates a set of states and metrics for how much power each uses and for what duration
  - power * duration = energy



Measurements of Power Use

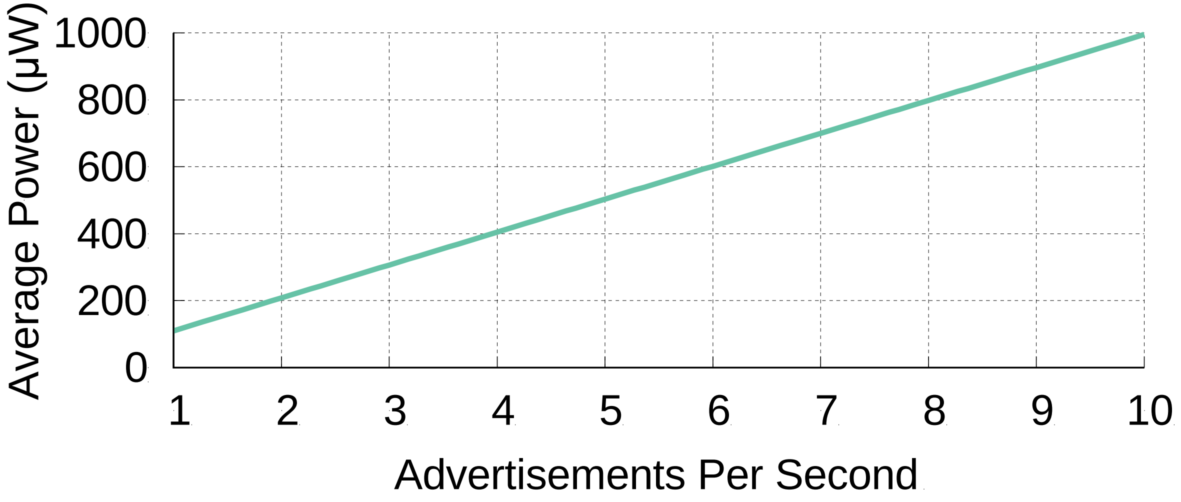
- Power use and duration (energy)
  - nRF51 (nRF51822)
  - nRF52 (nRF52832)

TABLE II
SoC-DEPENDENT MODEL PARAMETERS FROM MEASUREMENTS

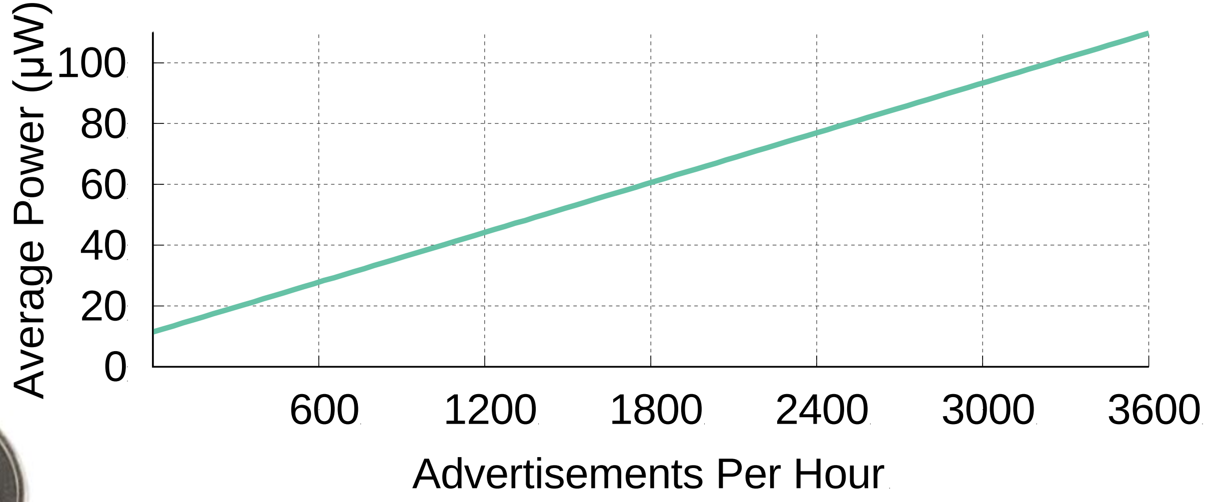
Phase	Nordic nRF51		Nordic nRF52	
	T_i (σ) (µs)	$\overline{P_i}$ (mW)	T_i (σ) (µs)	$\overline{P_i}$ (mW)
preprocessing	951.8 (9.1)	2.9	321.4 (8.9)	2.7
tx (4 dBm)	72.4 (0.5) + $n_{Bit} \cdot 1/Bit$	45.4	13.2 (1.8) + $n_{Bit} \cdot 1/Bit$	46.2
tx (0 dBm)		29.5		33.2
tx (-4 dBm)		25.8		27.5
tx (-8 dBm)		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

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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Questions about network capability

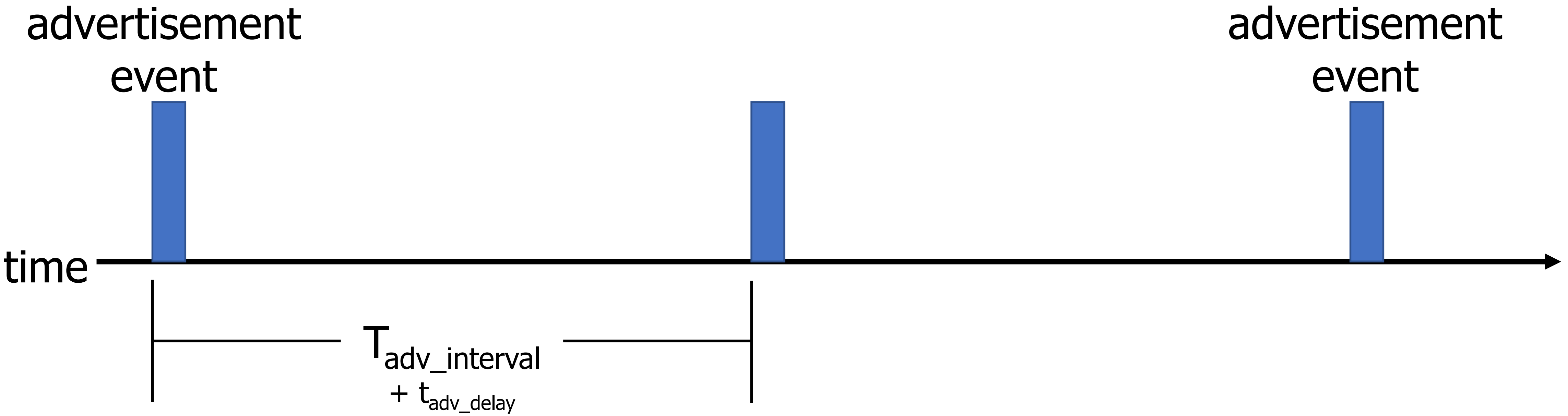
- What are the odds that a transmitted advertisement will be received?
  - Packet reception rate

- 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.

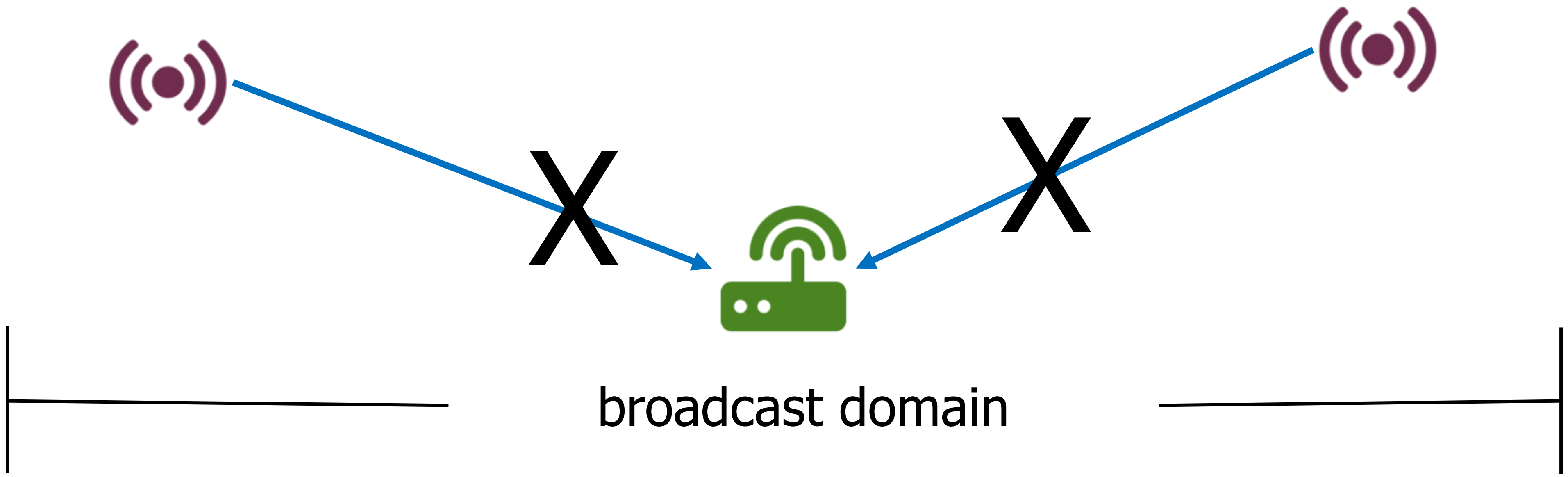


Bluetooth SIG. Bluetooth Core Specification 4.2. (2014).

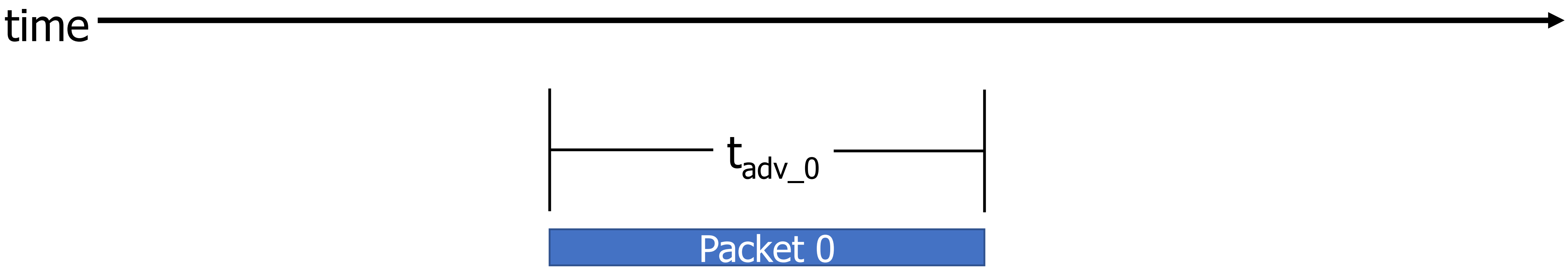
What causes transmissions not to be received?

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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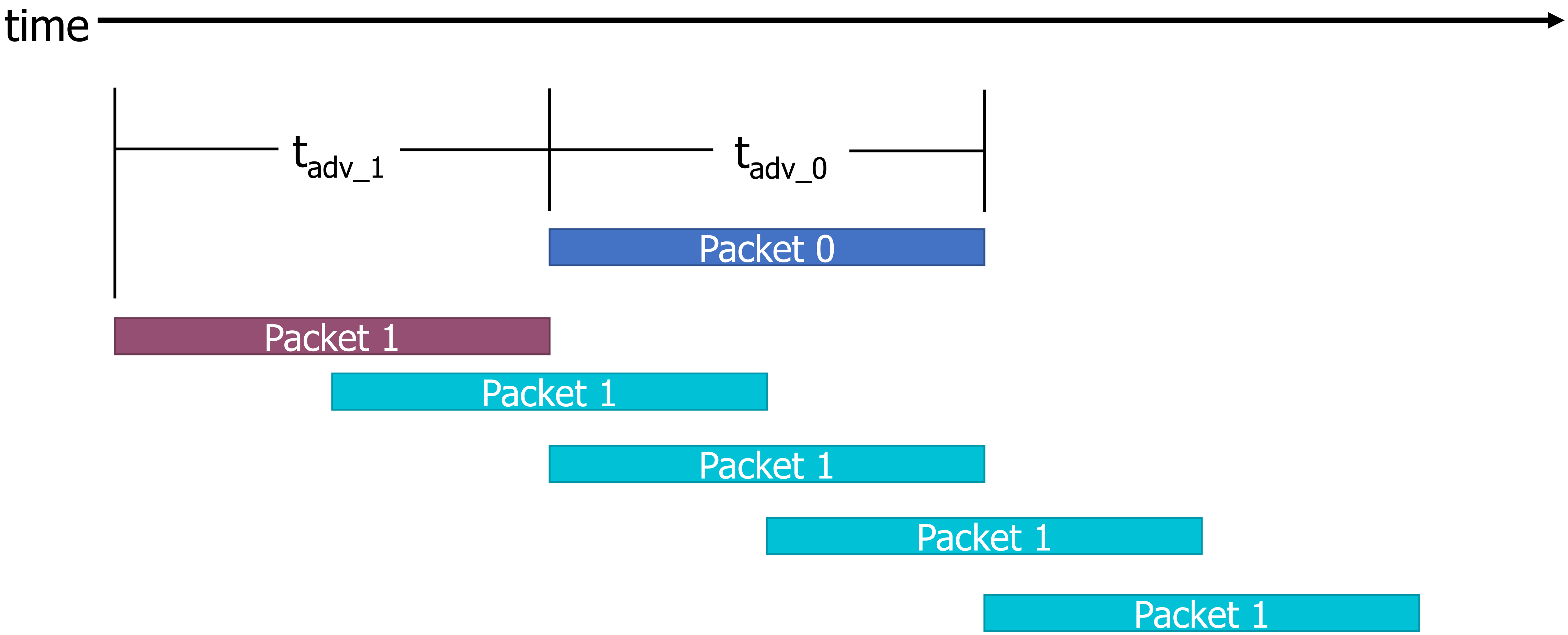

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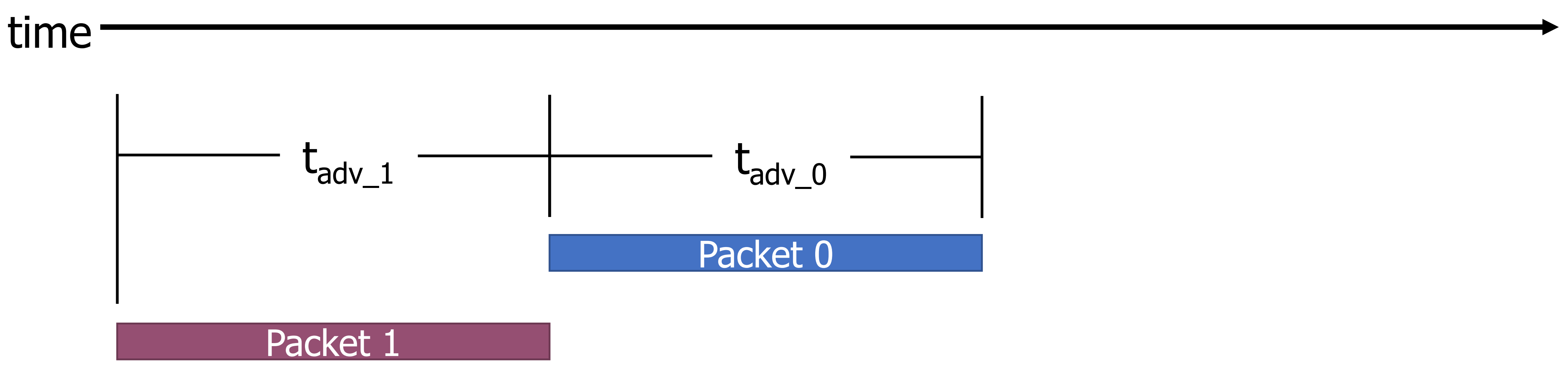


$$\text{Probability of Collision} = \frac{\textit{Vulnerable Period}}{\textit{Transmission Window}} = \frac{t_{adv\_1} + t_{adv\_0}}{T_{adv\_interval} + \mathrm{E}(t_{adv\_delay})}$$

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

Break + Determine Probability of Multiple Failures

- Given:
  - Probability of Collision

- Determine:
  - Probability of Reception for data sent redundantly across `M` packets

Break + Determine Probability of Multiple Failures

- Given:
  - Probability of Collision

- Determine:
  - Probability of Reception for data sent redundantly across `M` packets

  - i.e., what are the odds that **at least one** of the packets doesn't collide

  - 1 – (Probability of Collision^M)
    - $(P_c)^M$ = Probability that all of them collide
    - 1-that = Probability that NOT all of them collide

How do we determine reception rate?

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

Naïve model:

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

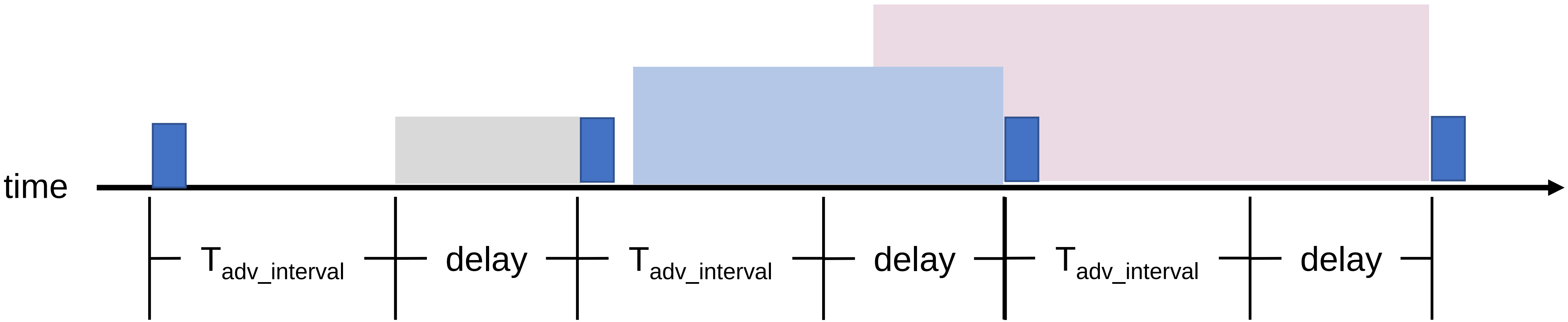
Data Reception Assumption: repeat packet collisions are independent.

- 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

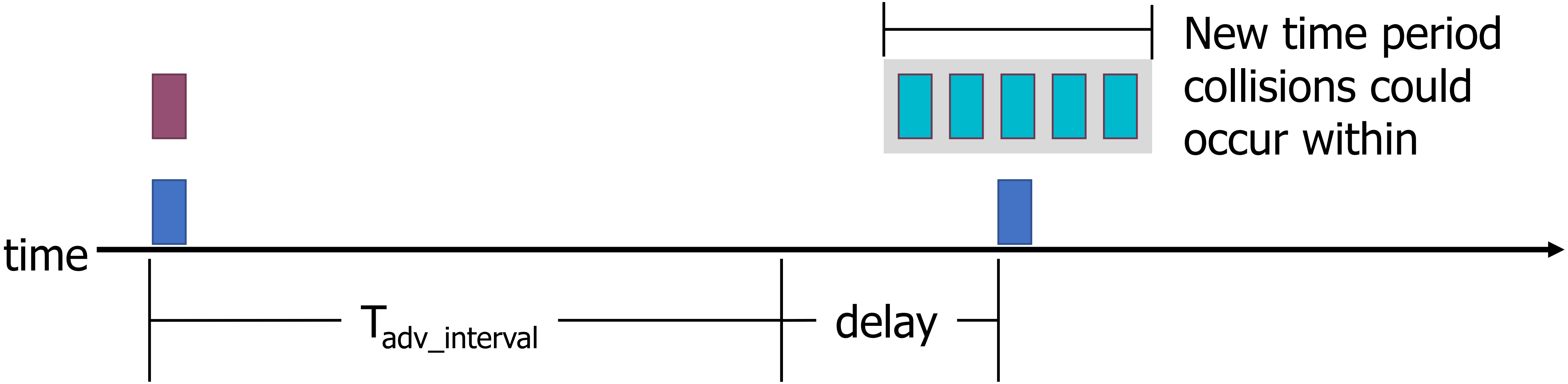
- Sum of random delays grows the uncertainty of transmission.
- Applied to periodic transmissions, any point in interval becomes equally likely.
  - Range of 1x delay, 2x delay, 3x delay, until it wraps



When are transmissions from two devices NOT independent?

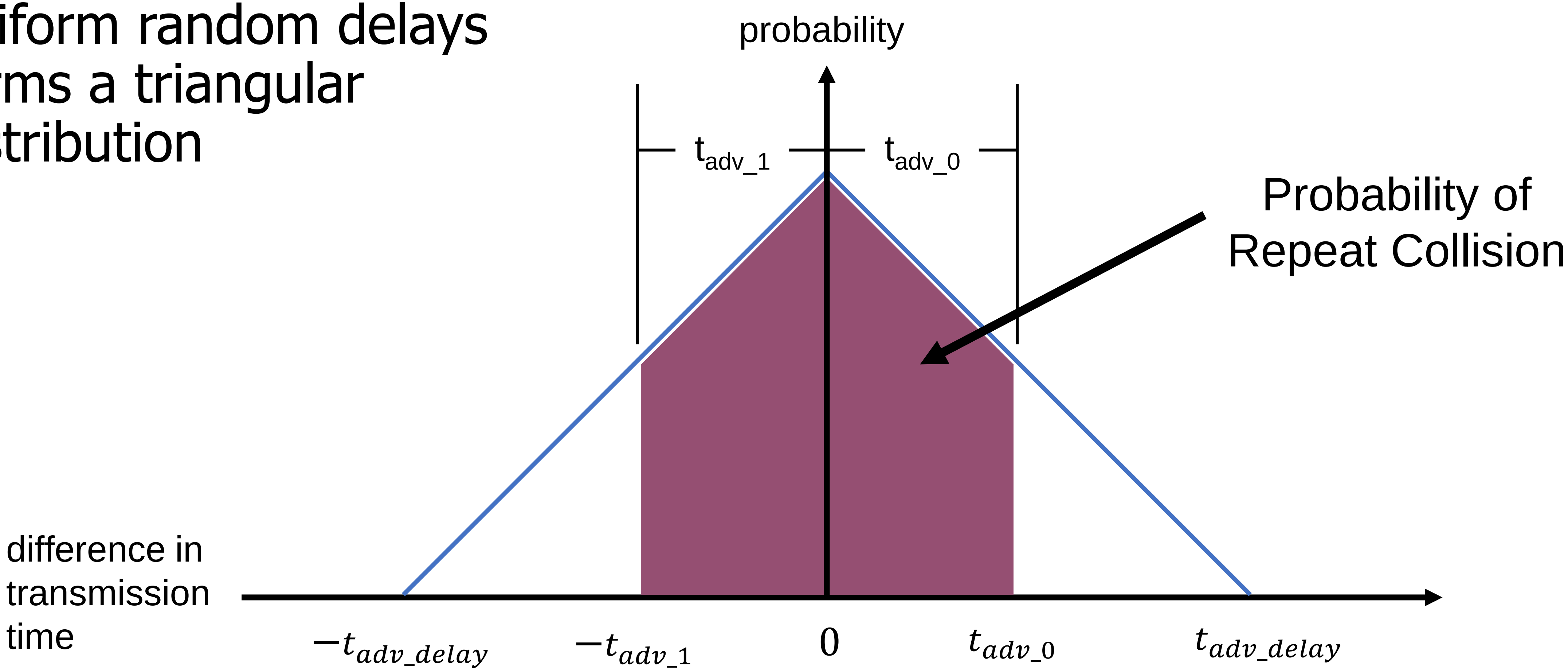
Independence assumption is *false* for two BLE devices that have recently collided.

- 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

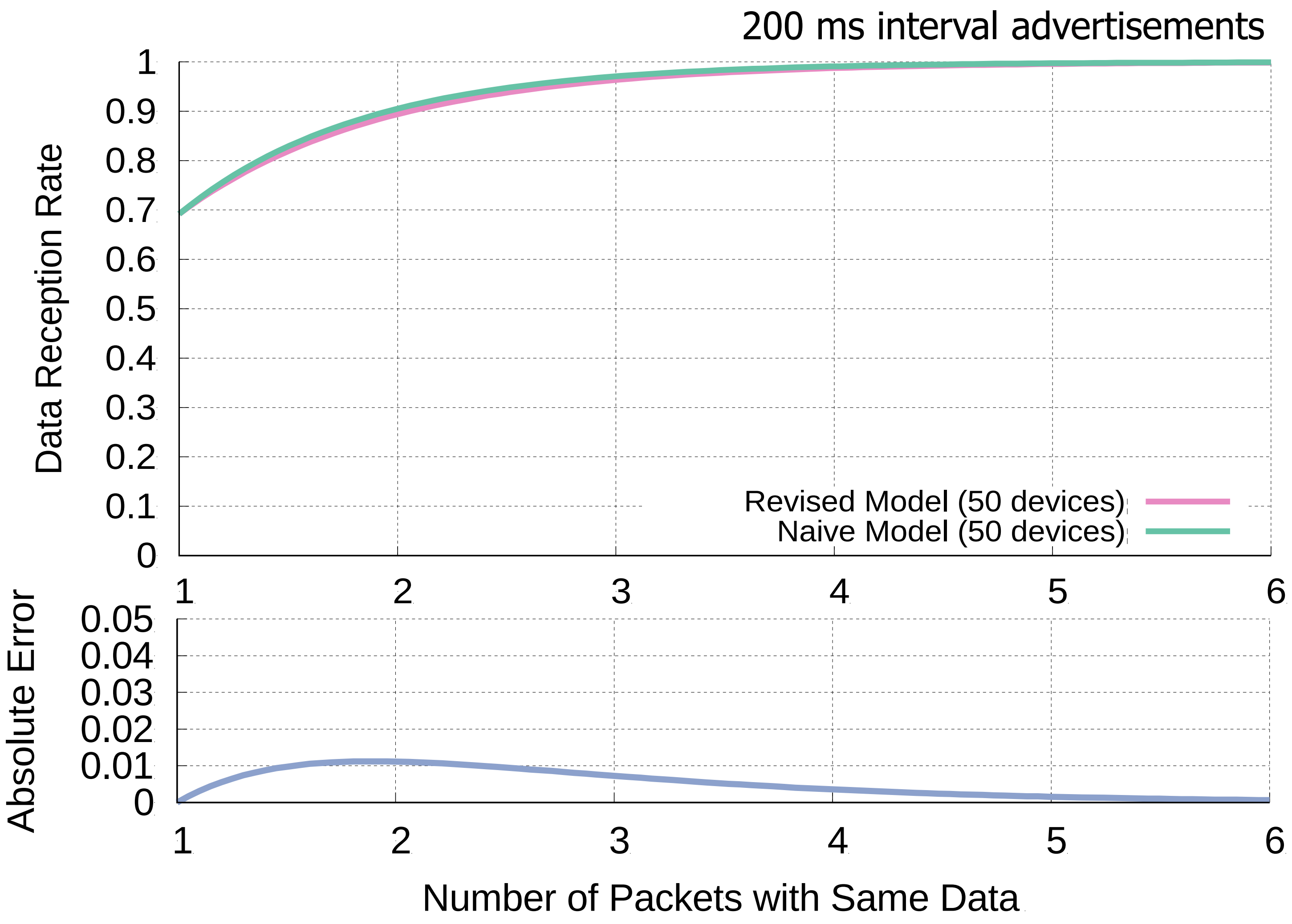


Important lesson: spend time on things that are important

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

$$\mathrm{PRR} = (1 - \frac{2*tadv}{T_{adv\_interval} + \mathrm{E}[tadv_{\_delay}]})^{N-1}$$

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

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

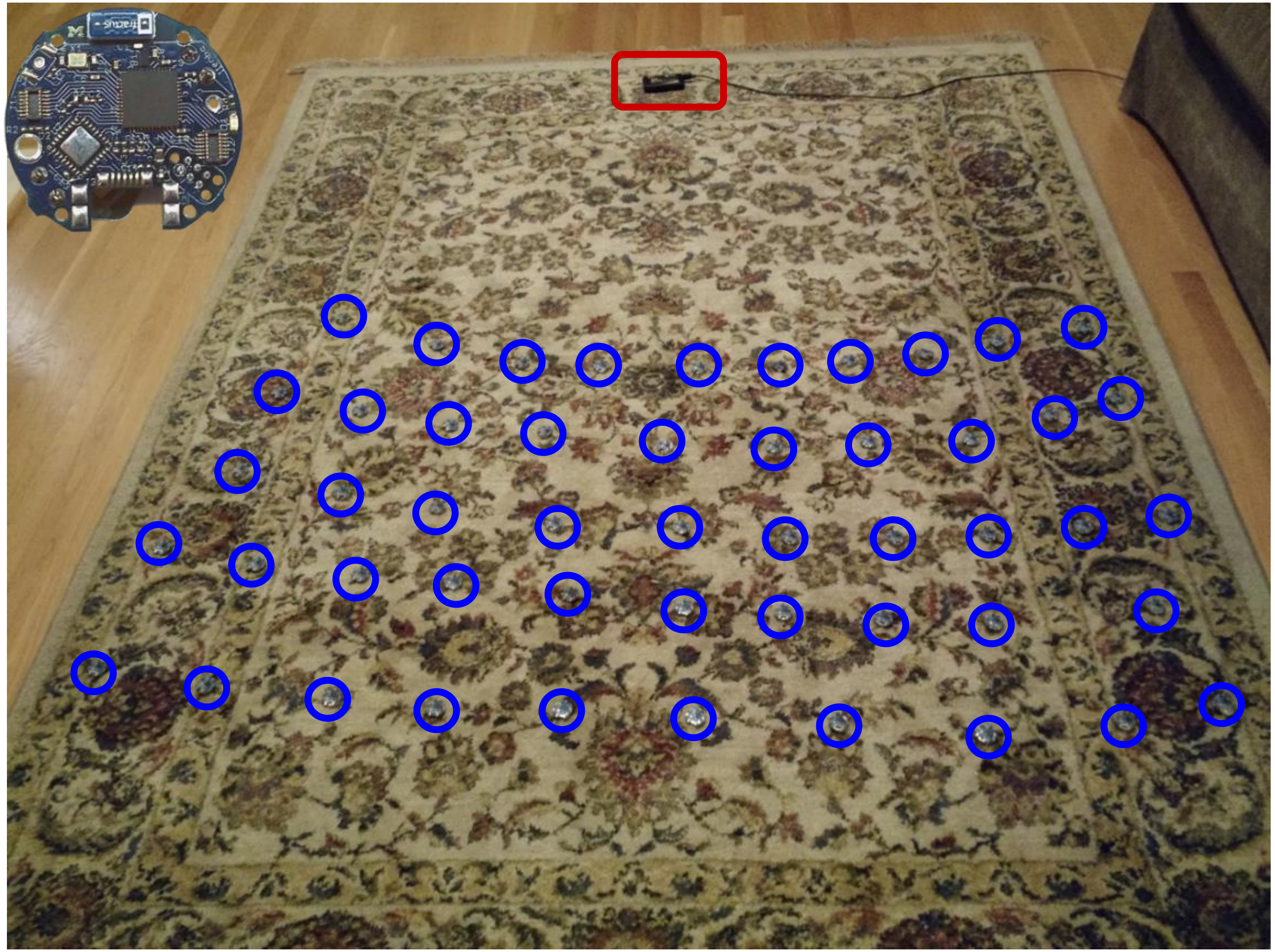
Is the model valid?

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.

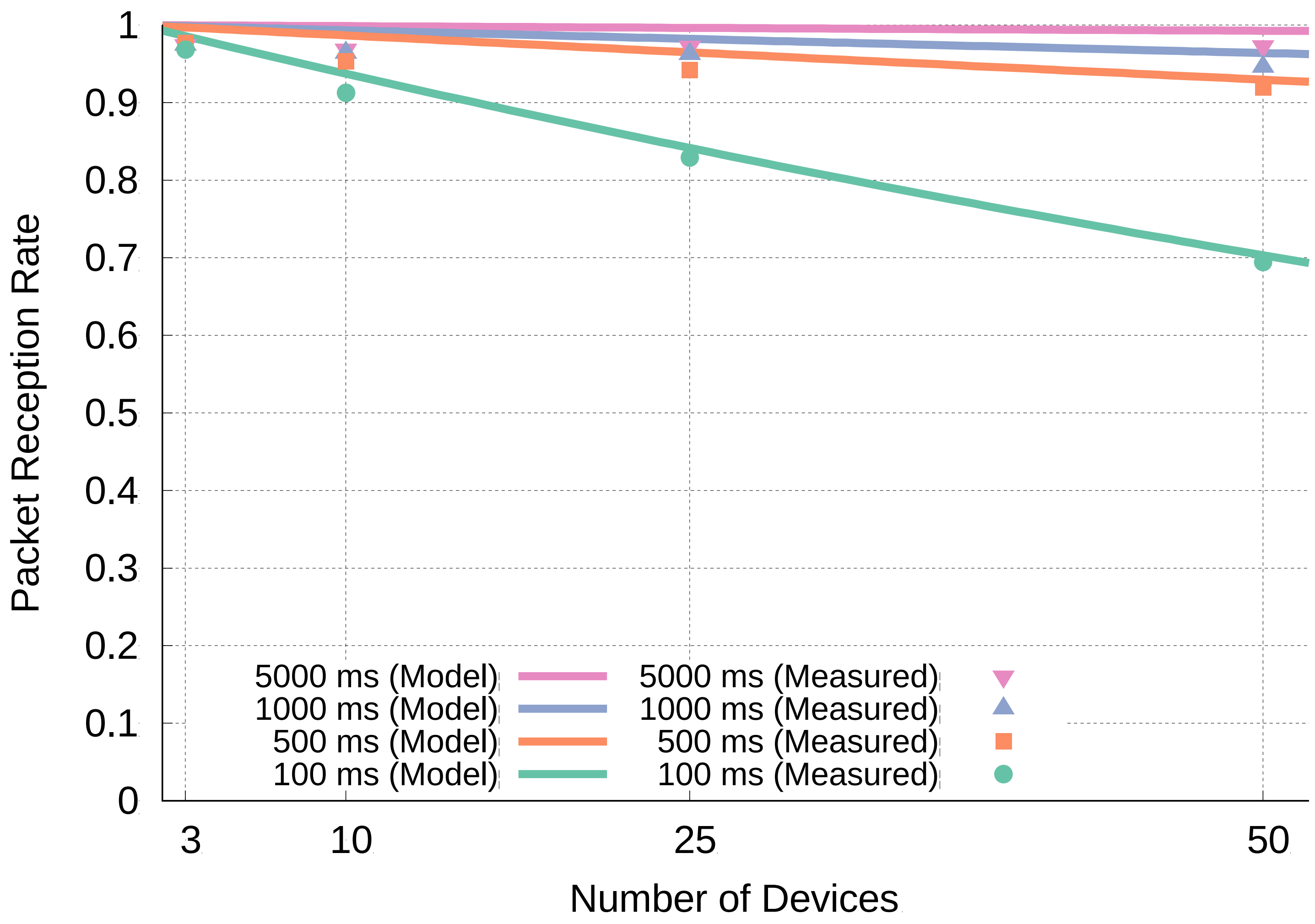


The model is accurate across advertisement rates and deployment sizes.

Accuracy is fairly consistent across intervals.

The model consistently overestimates the measured PRR values.

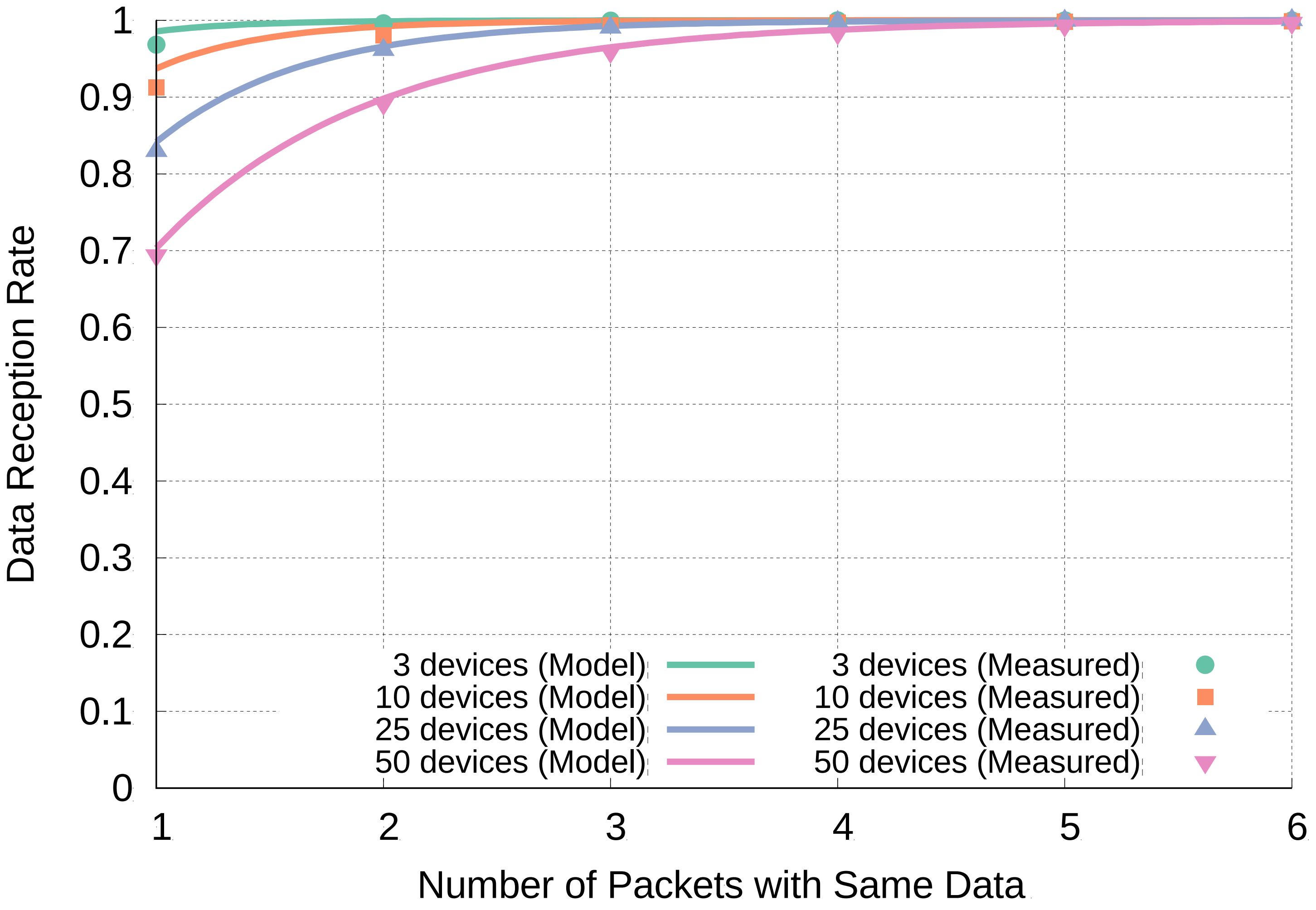
The effect could be due to RF interference.



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?

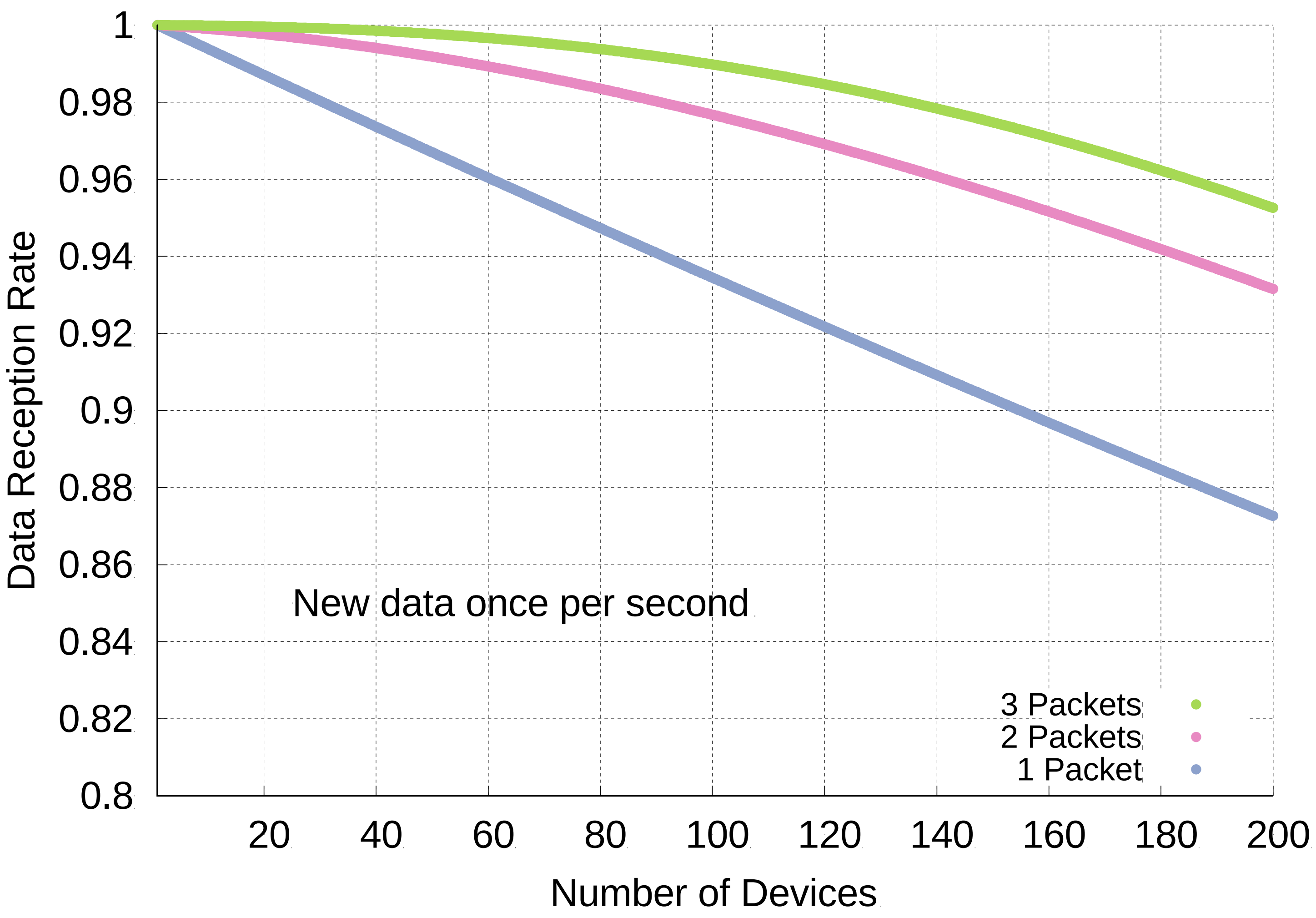
- Original questions
  - What are the odds that a transmitted advertisement will be received?
  - If M redundant advertisements are sent instead, what are the odds that at least one are received?
  - How do these odds vary with number of devices, advertising interval, and packet size?

- 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.

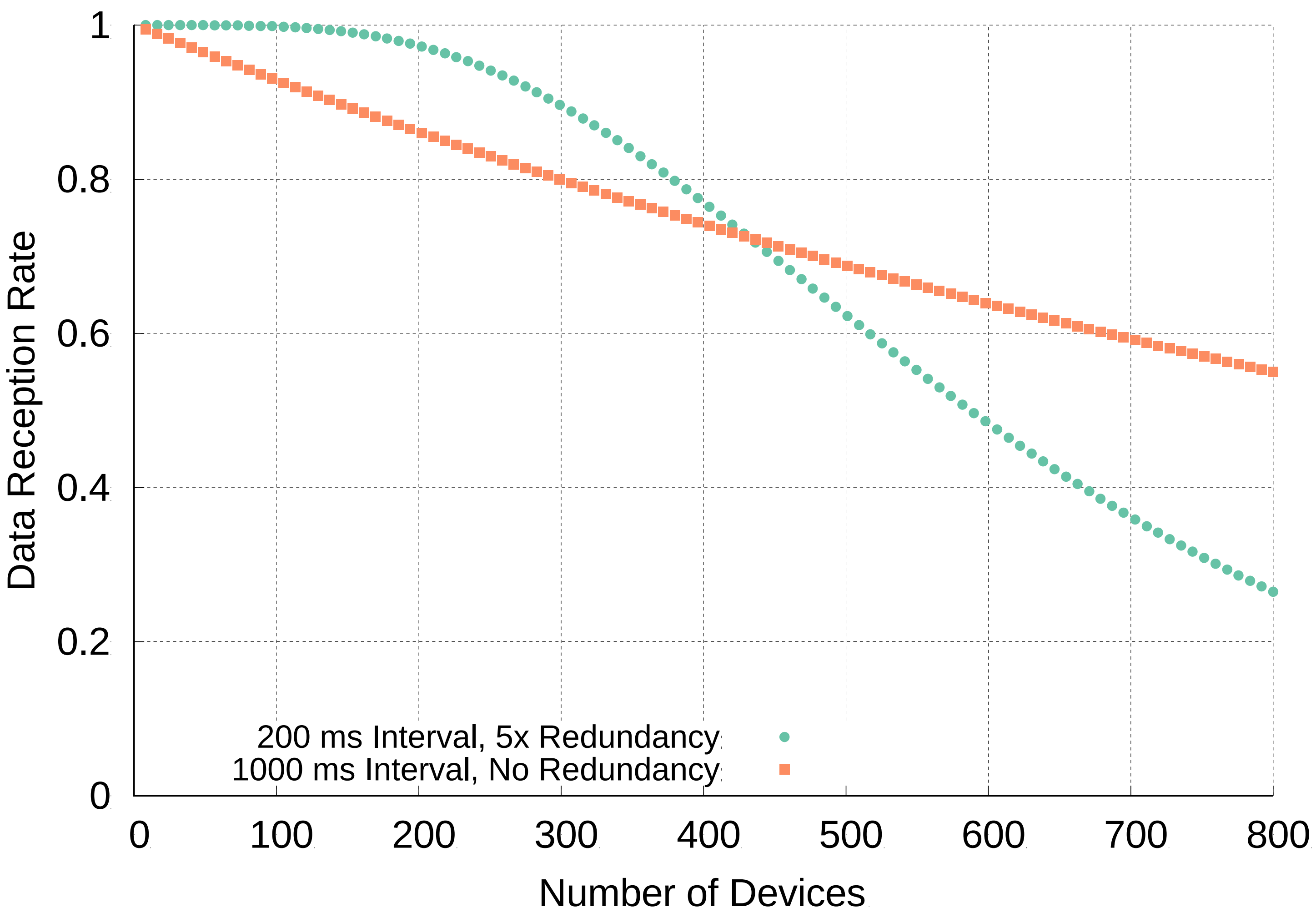
Design question:

- Send more packets to gain from redundancy?

  OR

- Send less packets to reduce congestion?

The answer changes, but only with many devices.



Outline

- BLE roles
  - Advertising
  - Scanning

- Communicating with advertisements
  - Advertisement Use Cases
  - Energy Use
  - Packet Collisions
  - **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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