# Lecture 04
# BLE Advertisement Deep Dive

Credit: Andy Mauragis

CS397/497 – Wireless Protocols for IoT

Branden Ghena – Spring 2024

Materials in collaboration with
Pat Pannuto (UCSD) and Brad Campbell (UVA)

# Announcements

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

- Everyone needs their own board and USB cable
  - I'll record which board is going to which student
  - You'll have to return them before the end of the quarter *or else*

  - Each *group* will end up with three among them
    - I'll do the pairing for remaining groups later today

- Wireshark lab due tonight!!
- BLE lab will be up tomorrow. Delayed a little by the eclipse

# Today's Goals

- Describe BLE advertising and scanning roles

- Deep dive into advertisements. Questions we might ask as researchers.
  - What are the real-world use cases of advertisements?

  - How much energy do advertisements take?

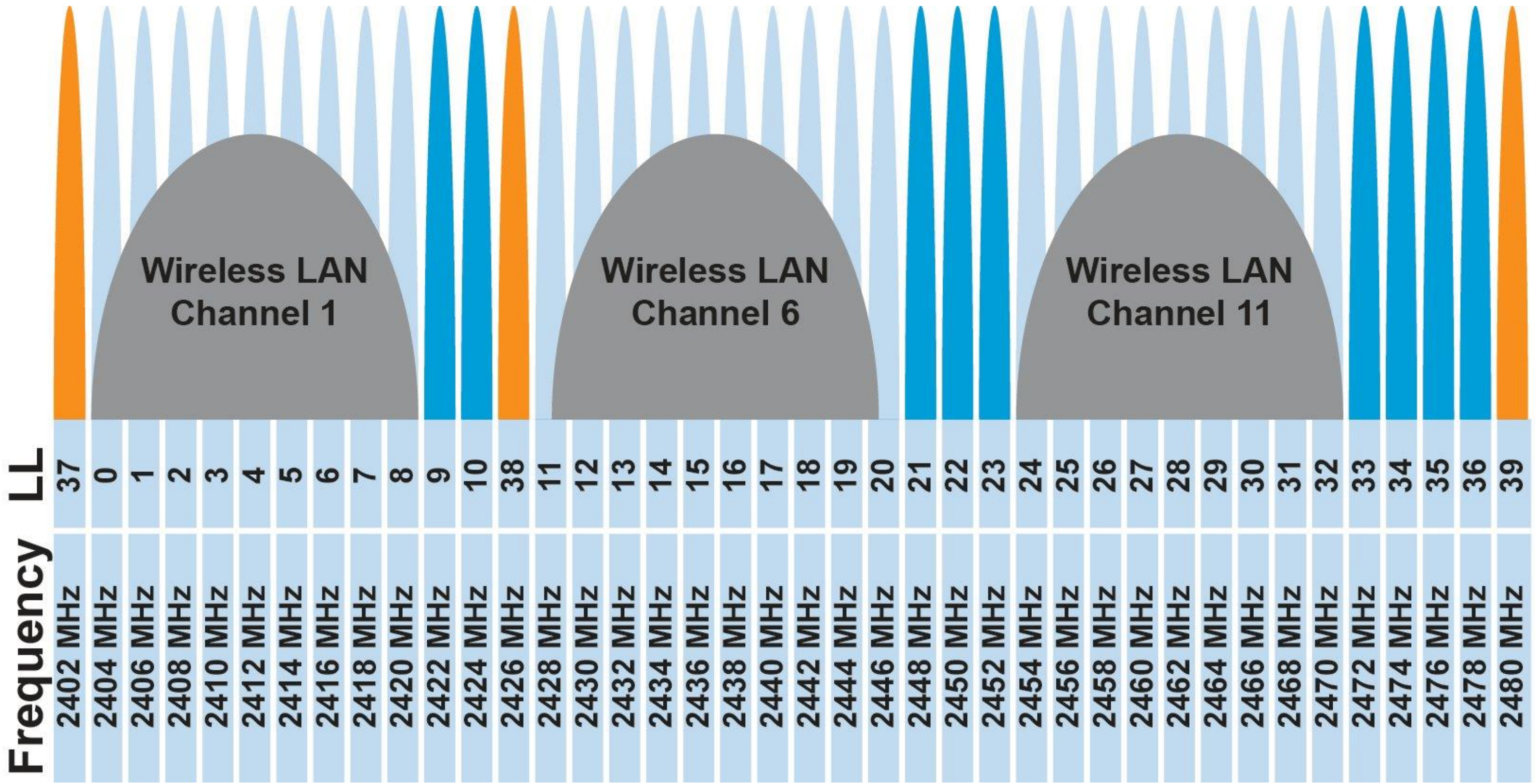
  - What is the probability of receiving a packet?
    - What is the probability of receiving data?

# Outline

- **BLE Layers**
  - **Physical Layer**
  - Link Layer
- BLE roles
  - Advertising
  - Scanning
- Communicating with advertisements
  - Advertisement Use Cases
  - Energy Use
  - Packet Collisions
  - Scan Responses

# BLE frequency

- 2.4 GHz carrier, Forty 2-MHz channels, 1 Mbps data rate
  - 37, 38, 39 for advertising
  - 0-36 for connection (FHSS)




**Why doesn’t BLE avoid WiFi altogether?**

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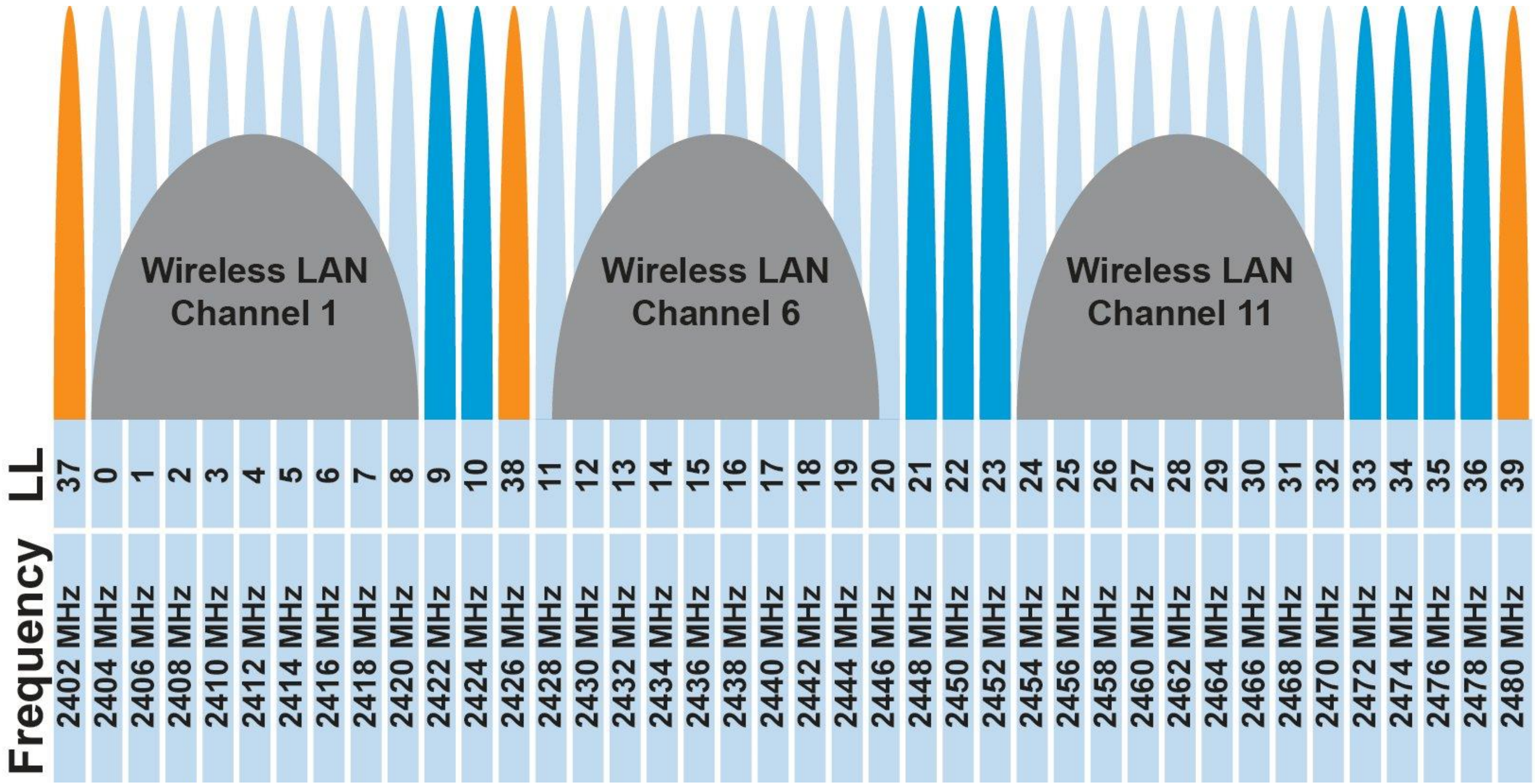


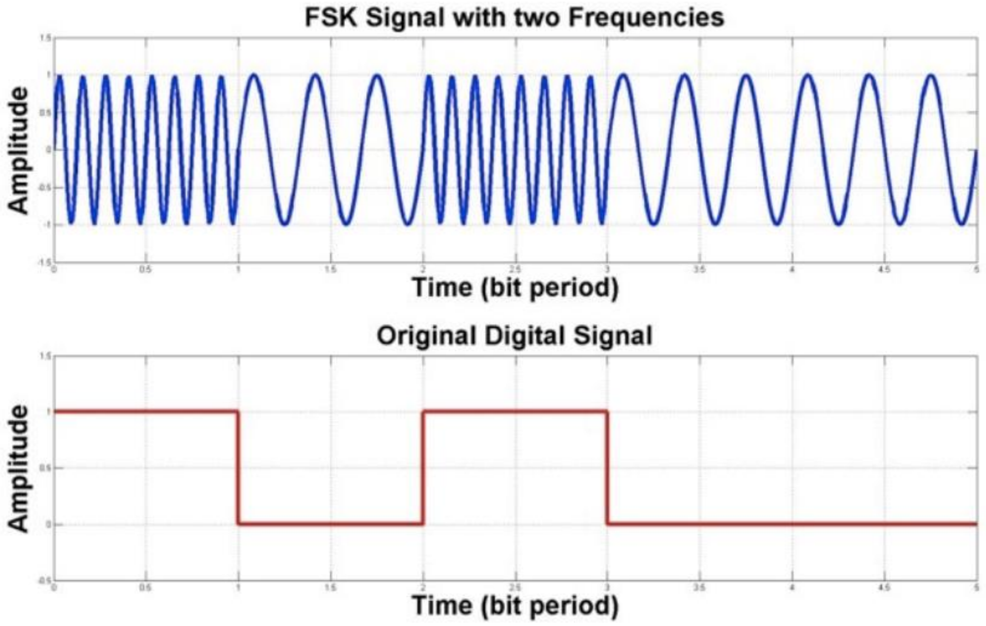

**Why doesn't BLE avoid WiFi altogether?**

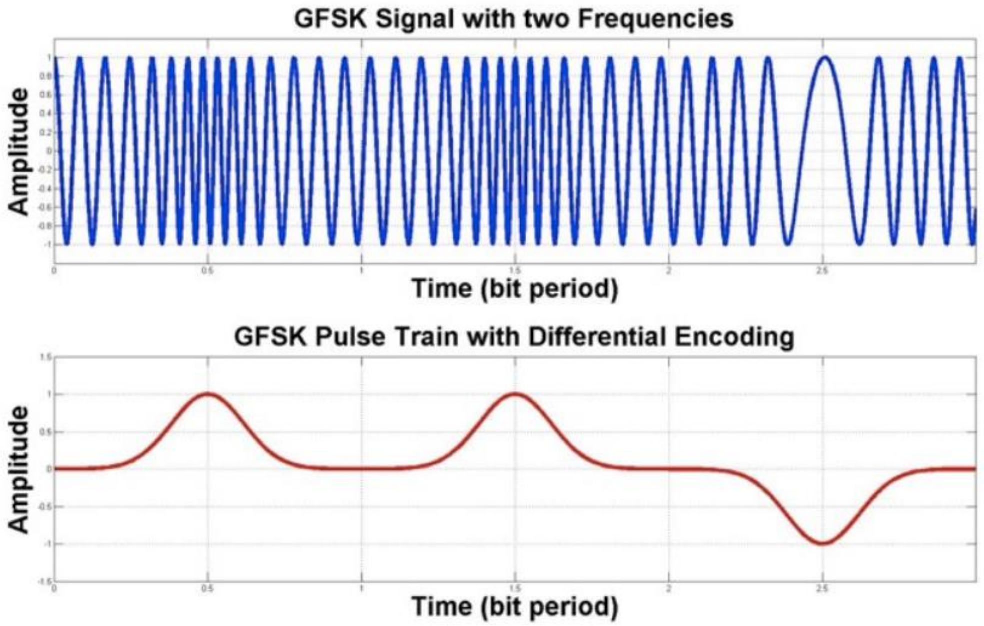
**Can't on 2.4 GHz**

**Wants 2.4 GHz for technology improvements**

# BLE modulation

- Gaussian Frequency-Shift Keying (GFSK)
  - Improvement on base Frequency-shift Keying
  - Smoother transitions between bits -> reduces nearby interference

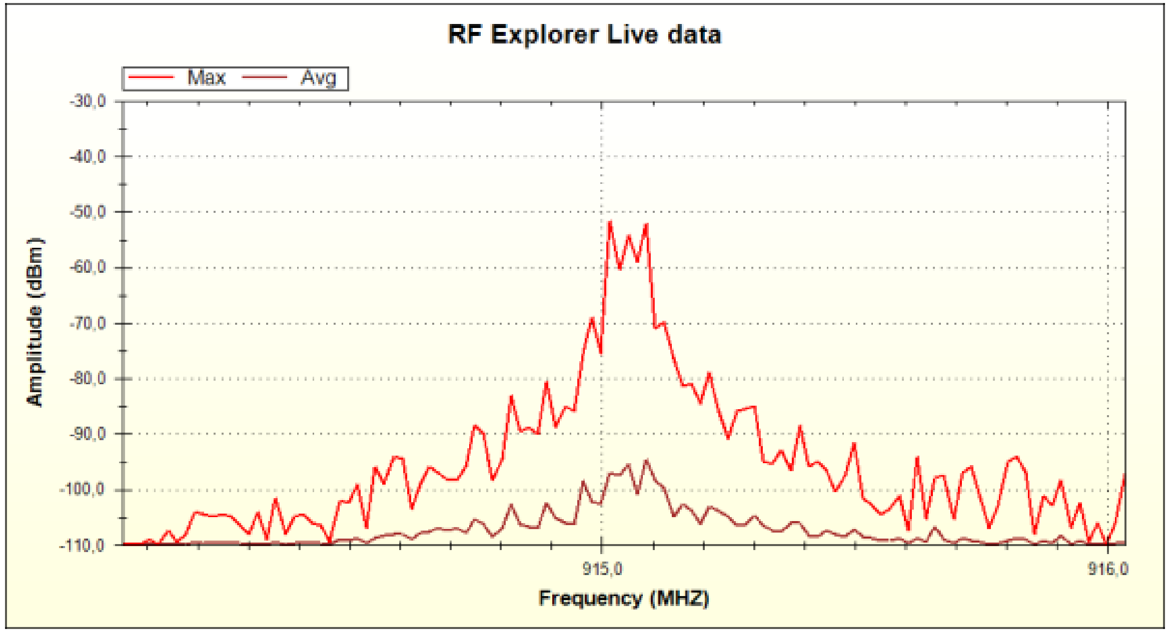


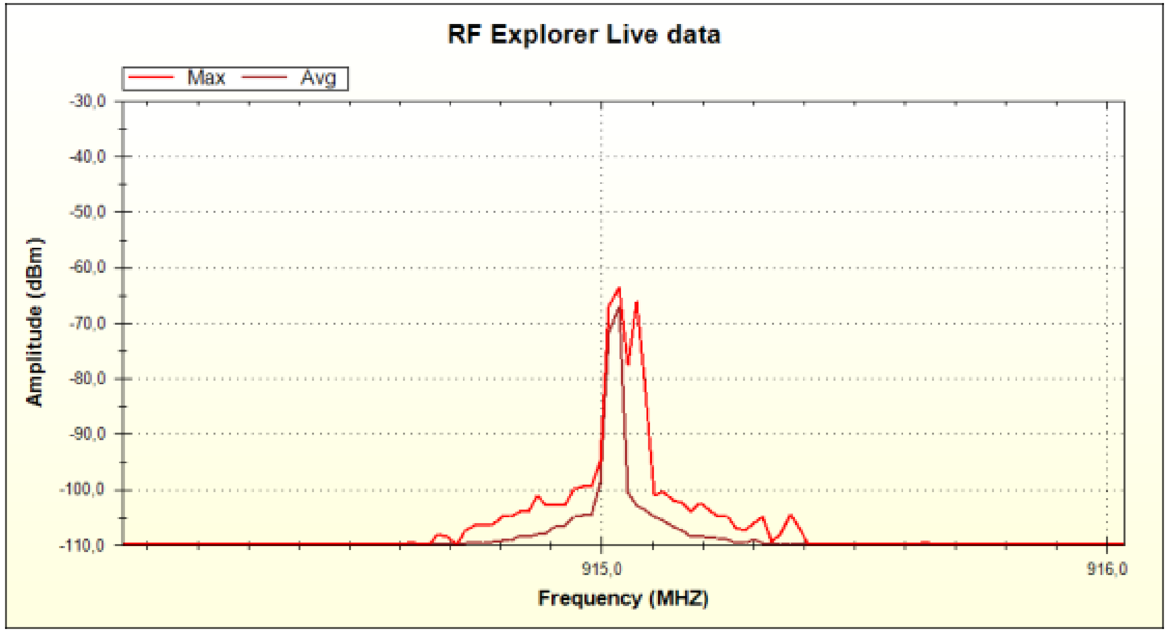



# Why use GFSK?

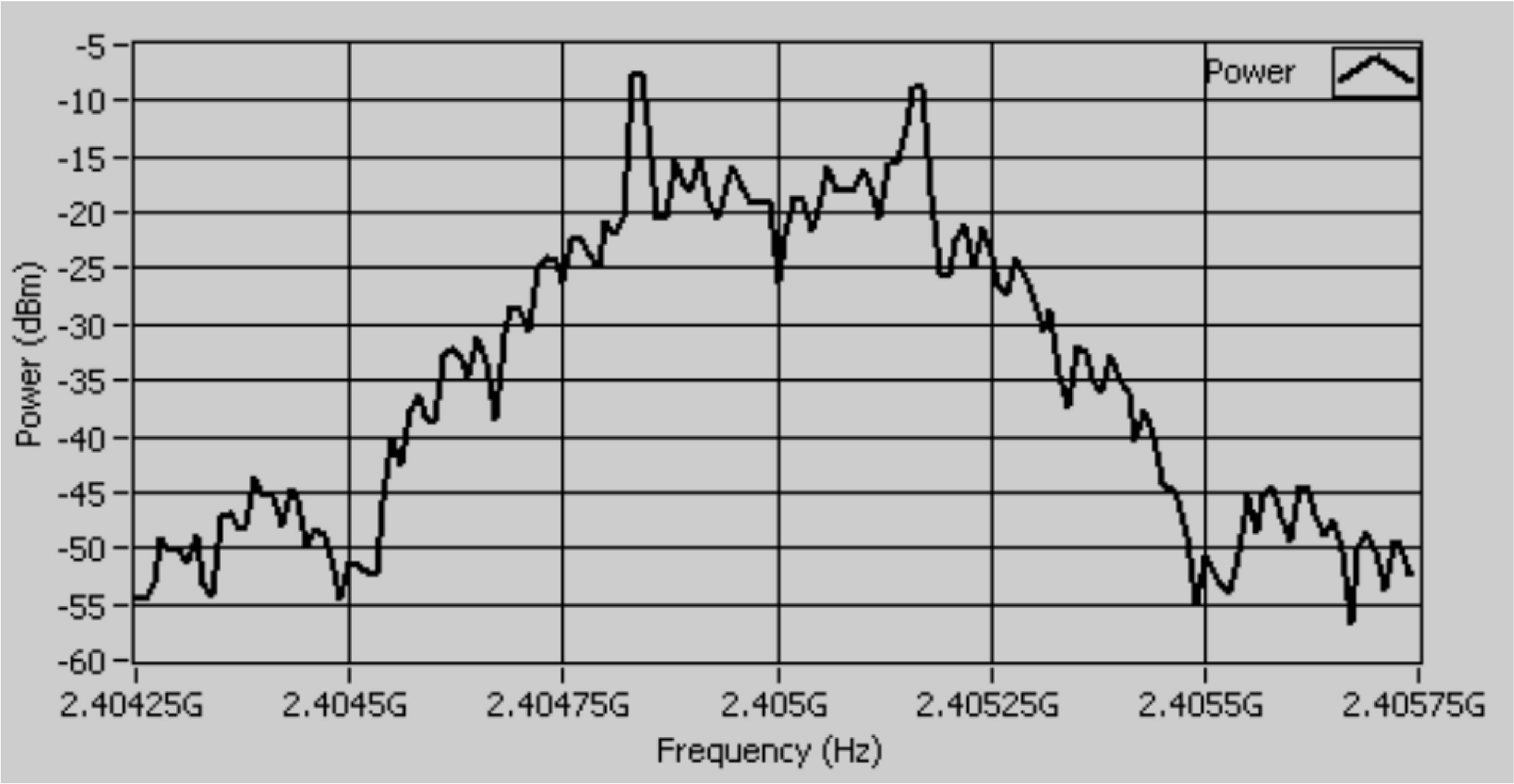
- Gaussian FSK lessens spectral leakage at the expense of some loss in intersymbol discriminability

- Translation: GFSK reduces bandwidth at the cost of bit errors



# An example from `good case` BLE hardware



# BLE signal strength

The requirements for a Bluetooth low energy radio are as follows:

| Feature | Value |
|---|---|
| Minimum TX power | 0.01 mW (-20 dBm) |
| Maximum TX power | 100 mW (20 dBm) |
| Minimum RX sensitivity | -70 dBm (BER 0.1%) |

The typical range for Bluetooth low energy radios is as follows:

| TX power | RX sensitivity | Antenna gain | Range |
|---|---|---|---|
| 0 dBm | -92 dBm | -5 dB | 160 meters |
| 10 dBm | -92 dBm | -5 dB | 295 meters |

The range to a smart phone is typically 0-50 meters due to limited RF performance of the phones.

- Remember nRF52840 capabilities
    - Transmit: up to 8 dBm
    - Receive sensitivity: -95 dBm

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  - **Link Layer**

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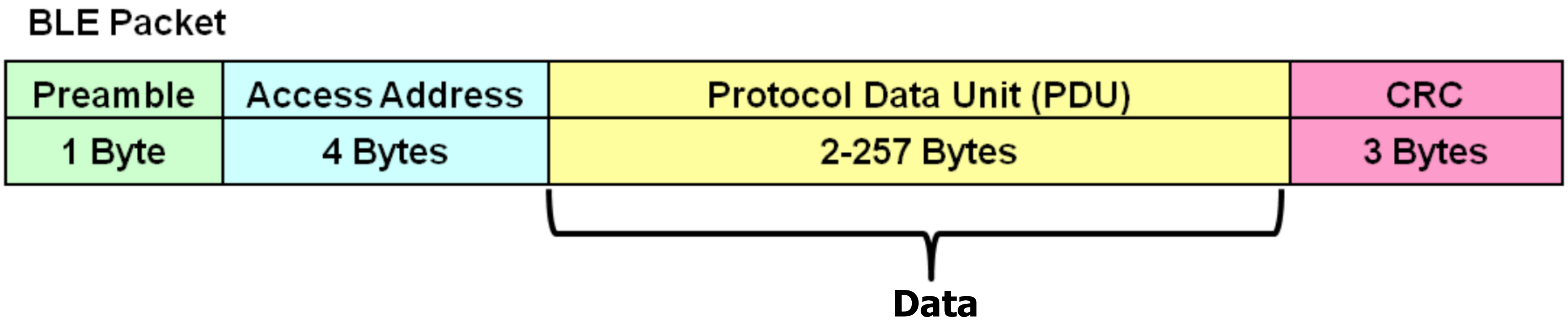
# Packet structure




- Same packet structure for both advertisements and connections
  - Fields are filled in little endian (the opposite of network byte order 😡)
- Access address unique for each connection (randomly chosen)
  - In Advertising always set to 0x8E89BED6

# Device addresses

- Public and private address forms
- Public
  - 48 bits: 24-bits of company ID, 24-bits of company assigned number
  - Literally the same MAC address scheme as Ethernet and WiFi
- Private
  - Top two MSbs specify type
    - 46 bits of random
    - 46 bits of hash of an identity key
- **Why have the two types?**

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- **Why have the two types?** **Privacy**

# Data whitening

- Avoid long series of repetitive bits (all zeros or all ones)
  - Would cause RF noise to be more focused in one direction
  - Radio hardware desires output to have zero DC-bias (or close to that)
  - Great example of the PHY and MAC being interwoven in wireless

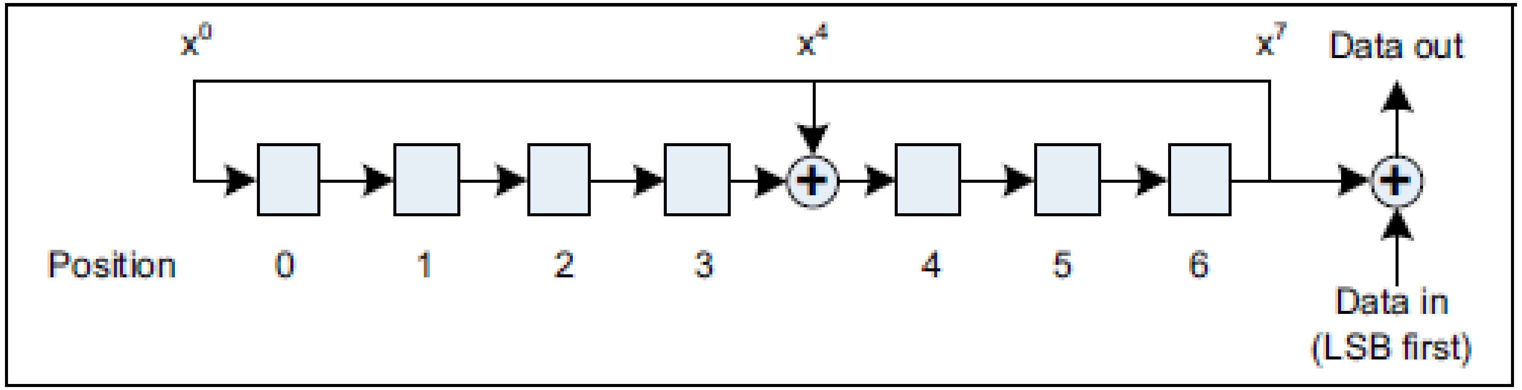


*Figure 3.3: The LFSR circuit to generate data whitening*

- I always forget this exists, since hardware usually handles it automatically

# Bit processing pipeline

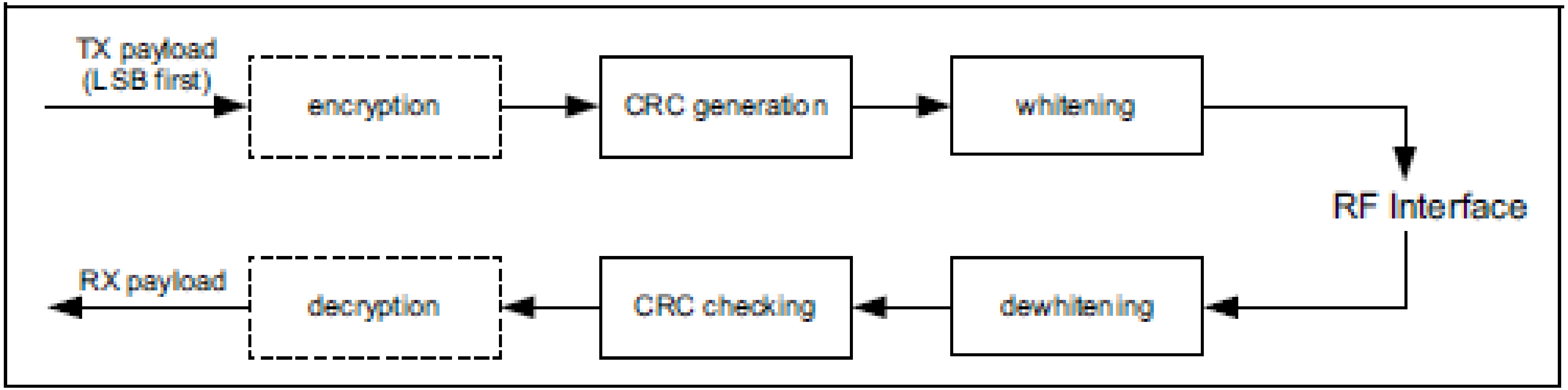


*Figure 3.1: Payload bit processes for the LE Uncoded PHYs*

# Break + Question

- With enough scanners, could you track BLE devices as they move?

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- With enough scanners, could you track BLE devices as they move?

  - Link Layer
    - Depends on how long they use a device address for
    - You can do a scan of BLE transmissions to find device addresses
    - Scans at multiple locations can detect when a device moves throughout an area
    - But if the device re-randomizes between two scanners, you can't follow it anymore
      - Re-randomizing at a scanner could be detectable…
      - Or if the user has more than one device with unsynchronized rotation schedules

# Break + Question

- With enough scanners, could you track BLE devices as they move?
  - Physical Layer
    - Fingerprint unique physical-layer imperfections in signals
    - Looking at things like amplitude and timing
    - 2022 paper out of UCSD explores this

## Evaluating Physical-Layer BLE Location Tracking Attacks on Mobile Devices

Hadi Givehchian*, Nishant Bhaskar*, Eliana Rodriguez Herrera, Héctor Rodrigo López Soto, Christian Dameff, Dinesh Bharadia, and Aaron Schulman

*UC San Diego*

***Abstract*—Mobile devices increasingly function as wireless tracking beacons. Using the Bluetooth Low Energy (BLE) protocol, mobile devices such as smartphones and smartwatches continuously transmit beacons to inform passive listeners about device locations for applications such as digital contact tracing for COVID-19, and even finding lost devices. These applications**

countermeasures by fingerprinting the device at a lower layer. Specifically, prior work has demonstrated that wireless transmitters have imperfections introduced in manufacturing that produce a unique physical-layer fingerprint for that device (e.g., Carrier Frequency Offset and I/Q Offset). Physical-layer

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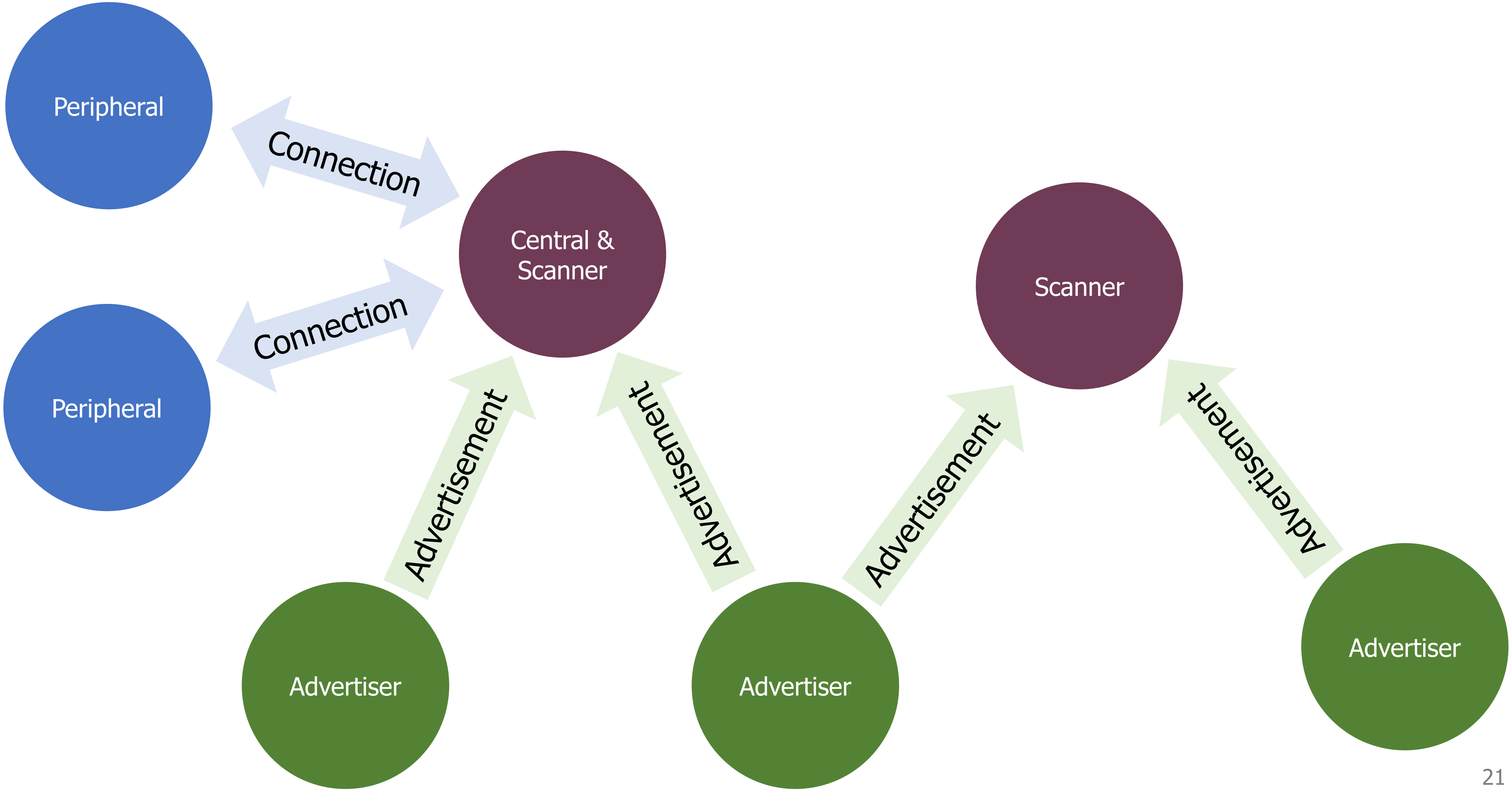
# BLE network topology



# 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

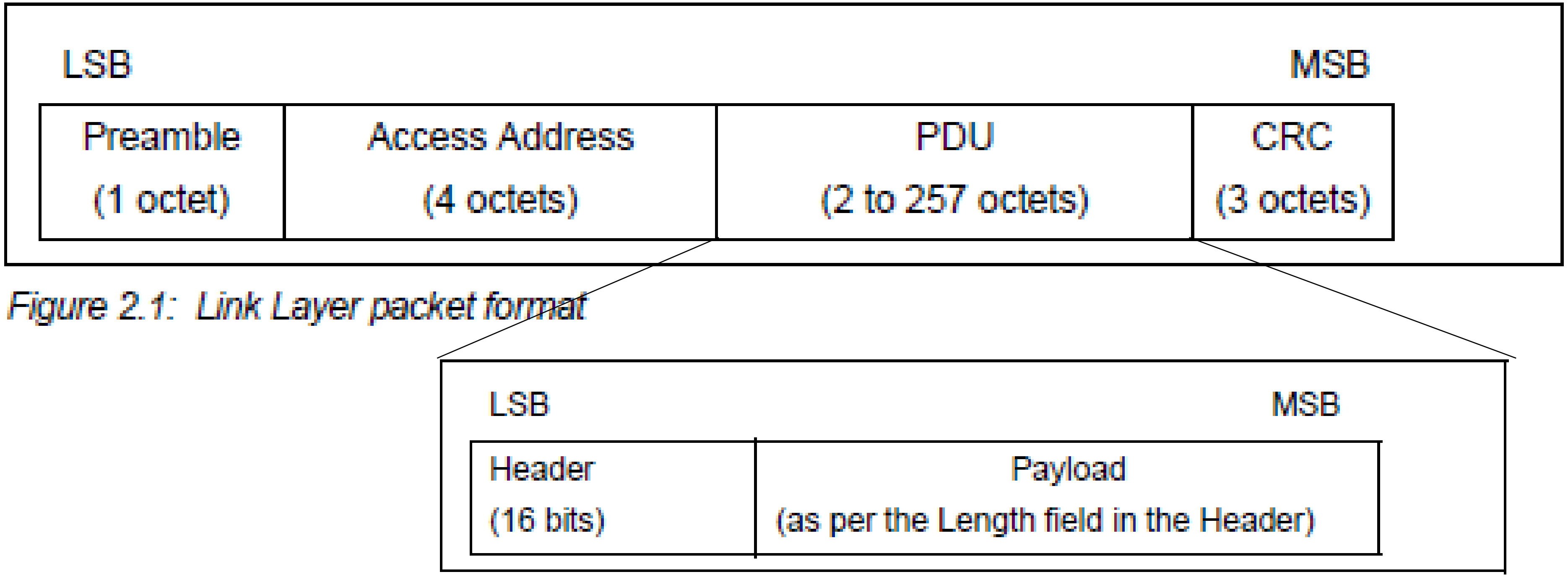



*Figure 2.1: Link Layer packet format*

*Figure 2.2: Advertising channel PDU*

# BLE advertising header

| LSB | MSB |
|---|---|
| Header (16 bits) | Payload (as per the Length field in the Header) |

*Figure 2.2: Advertising channel PDU*

| 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
  - Request for additional information
  - Just the two addresses: the scanner’s and the advertiser’s

| Payload | |
|---|---|
| ScanA (6 octets) | AdvA (6 octets) |

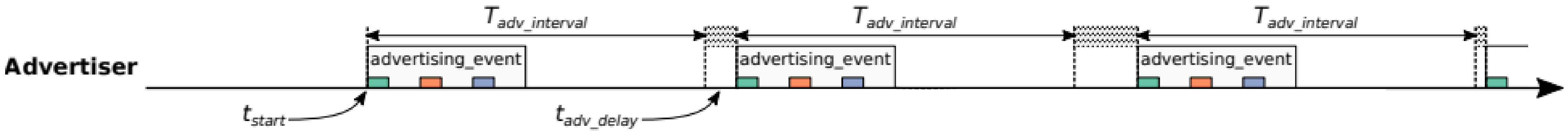
*Figure 2.8: SCAN_REQ PDU Payload*

- Scan response
  - Identical to an advertisement in structure but only occurs after a request
  - Usually has additional data not in the advertisement

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

*Figure 2.9: SCAN_RSP PDU payload*

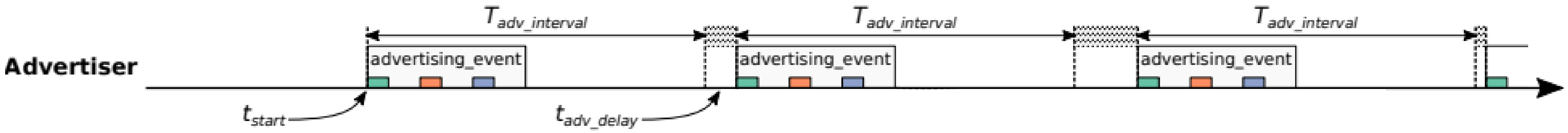
# Advertising timing




- 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

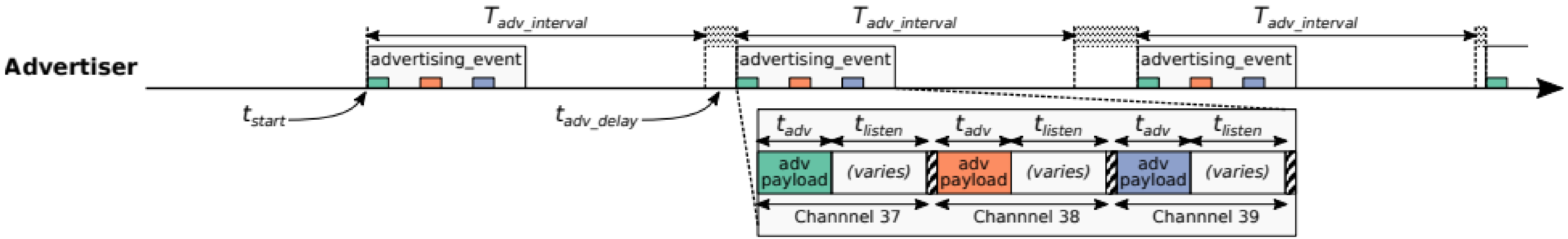
# Advertising timing




- 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

# 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

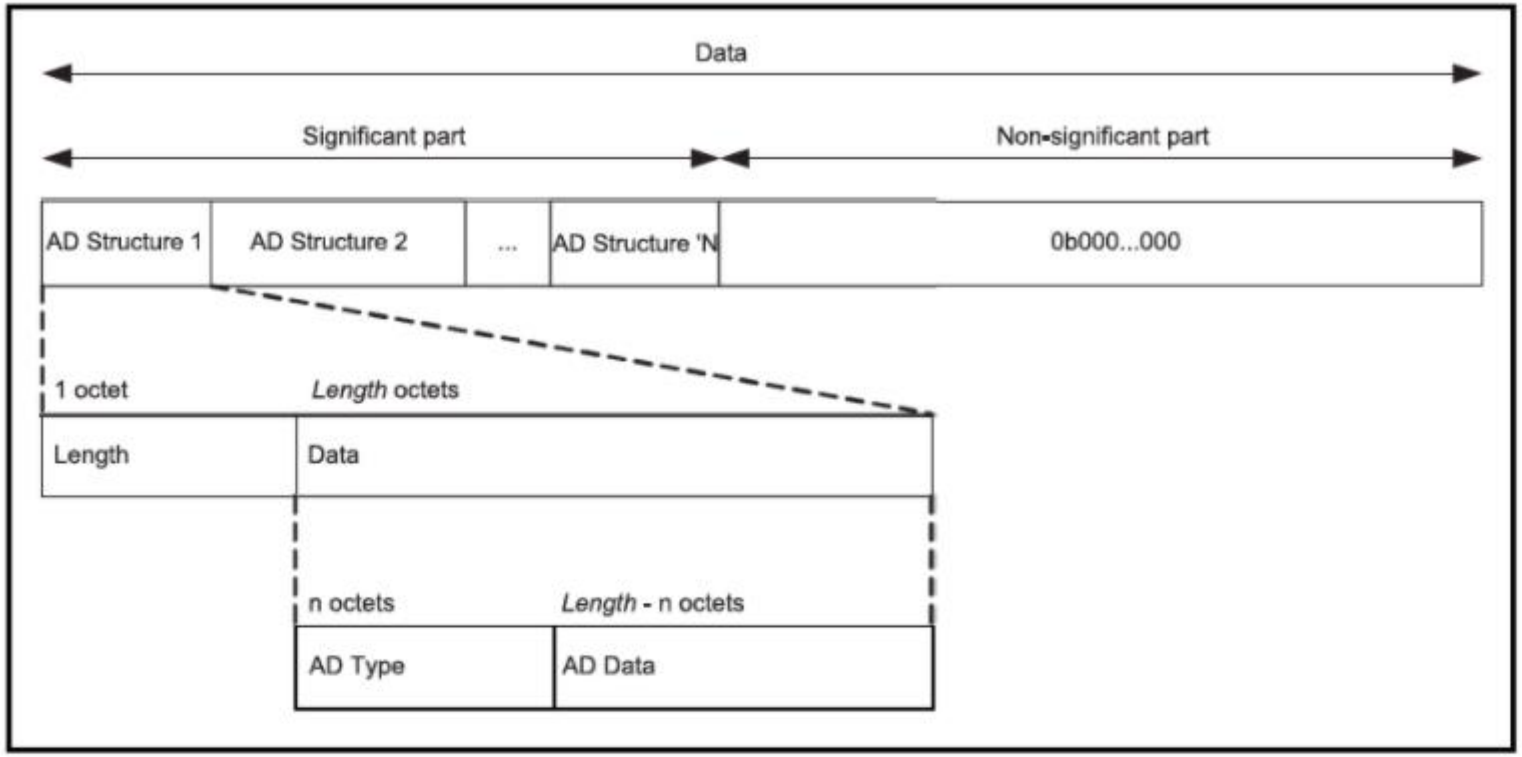



*Figure 11.1: Advertising and Scan Response data format*

# 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

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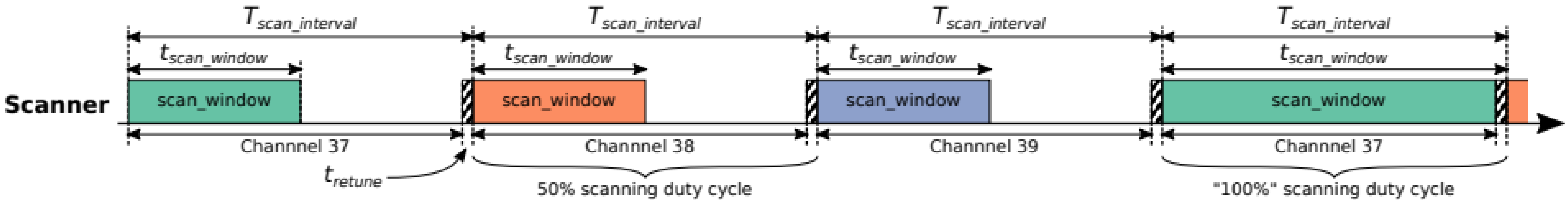
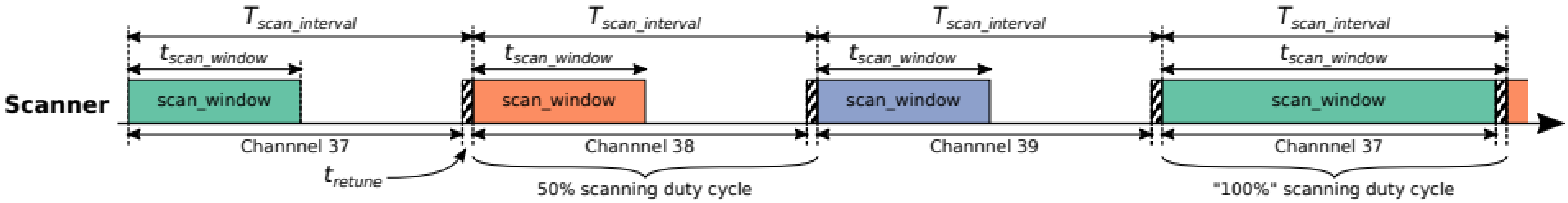
# Scanning Pattern




- 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

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

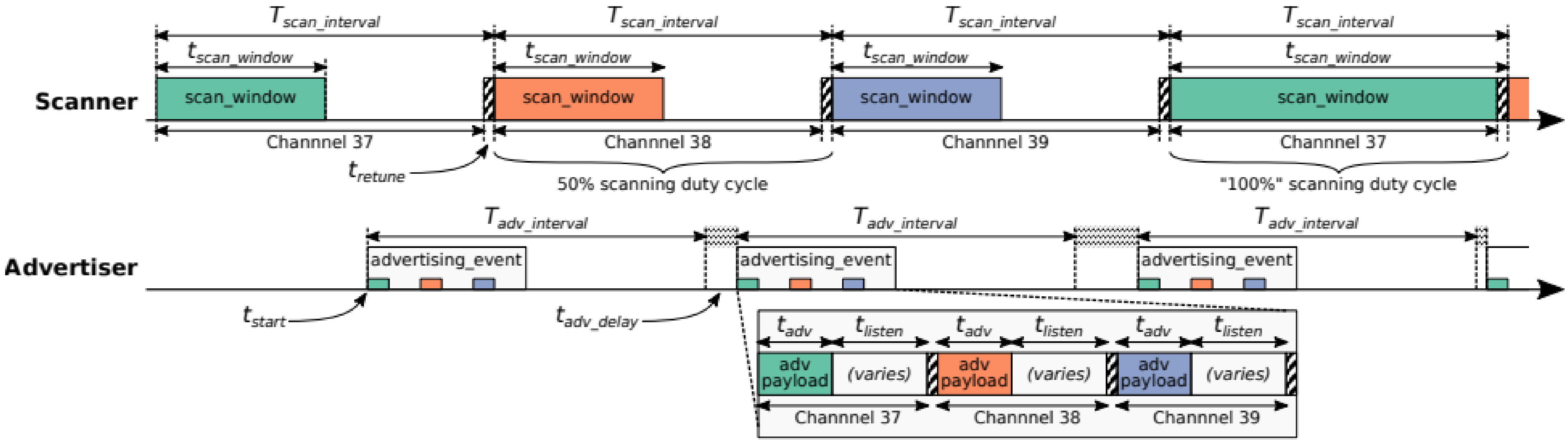
# A warning about scanning expectations

- 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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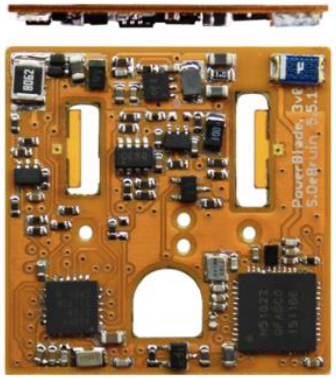
# Advertisements are sufficient for some applications


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



# 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)

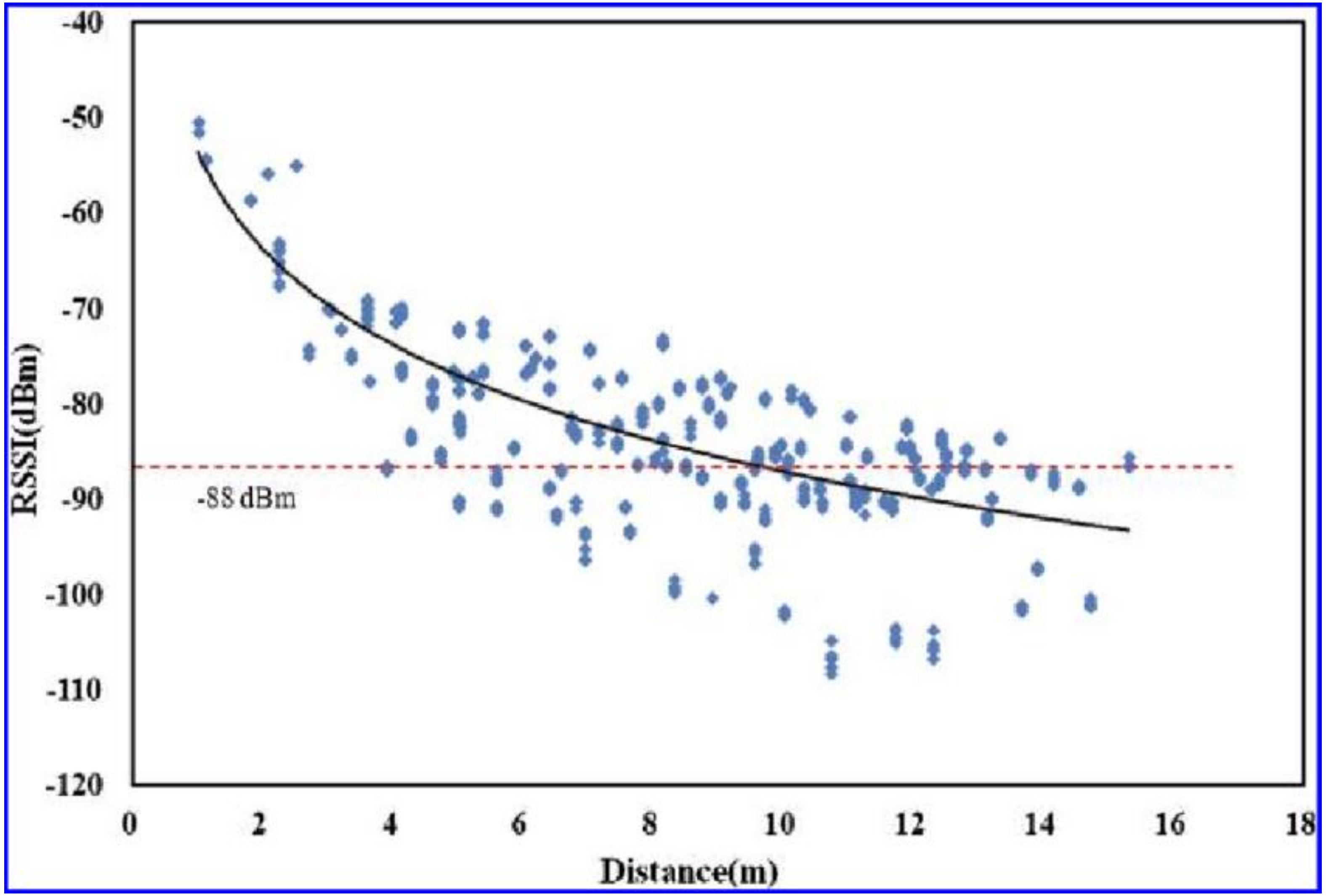
# Tracking


- Find devices nearby
  - Get a sense of distance to the device
- Find my X
  - Tile: find my keys
  - Apple: find my device (before UWB radios)
- 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

| 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 |

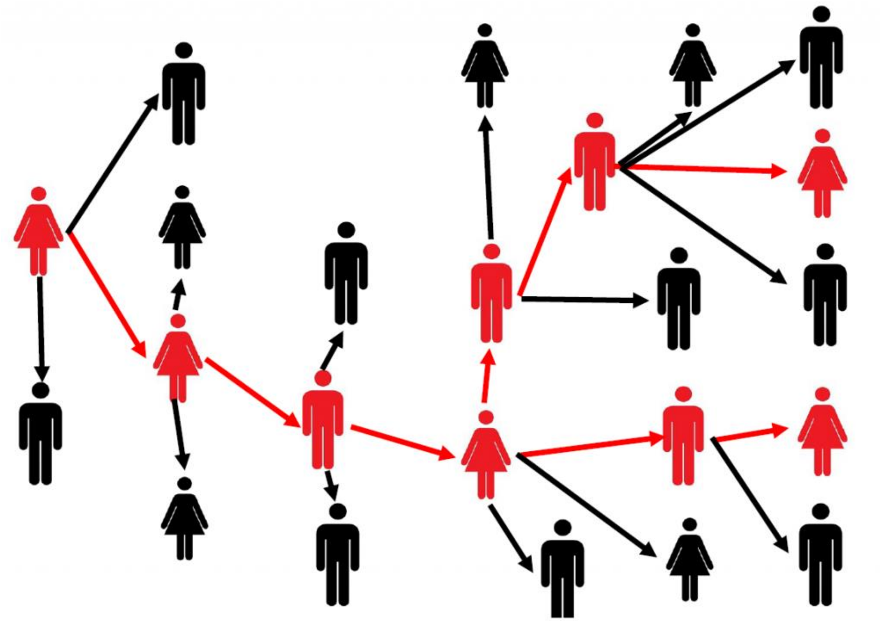
Martin, Jeremy, et al. "Handoff all your privacy–a review of apple's bluetooth low energy continuity protocol." *Proceedings on Privacy Enhancing Technologies* 2019.4 (2019): 34-53.

# 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.

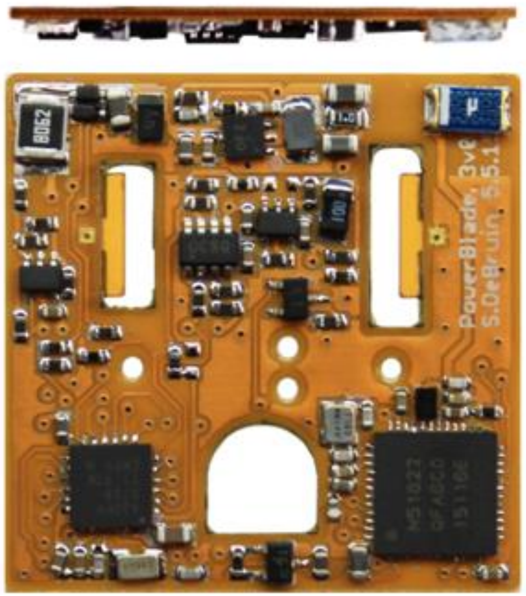
- Requires government/healthcare system interactions to determine when an identifier should be flagged as sick
  - 24 states (not Illinois) adopted this

- 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

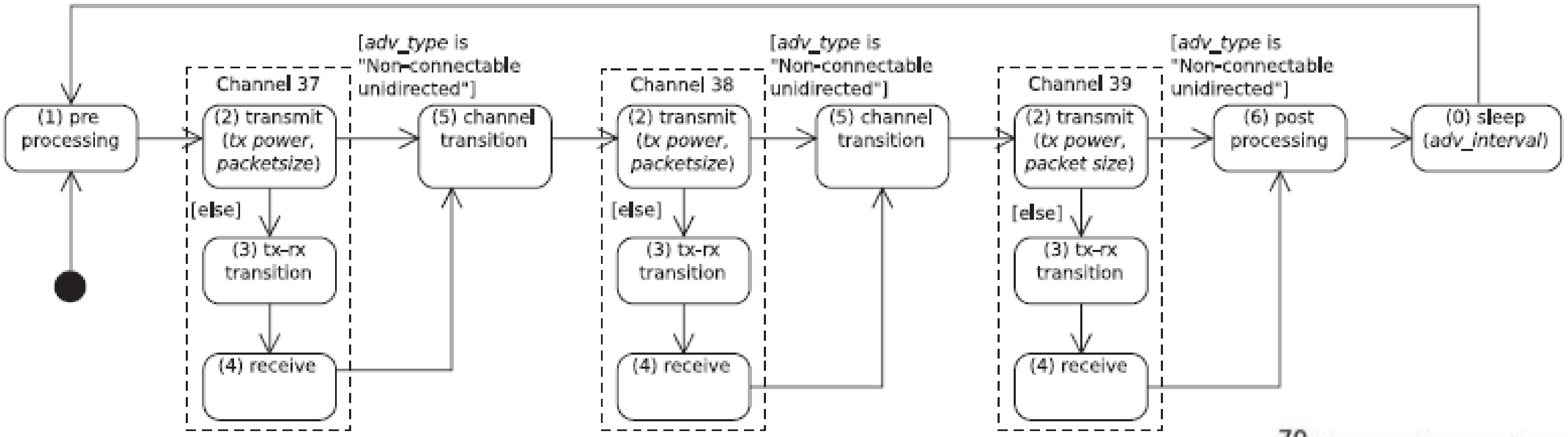
Schrader, Raphael, et al. "Advertising power consumption of bluetooth low energy systems." *2016 3rd International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS)*. IEEE, 2016.

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

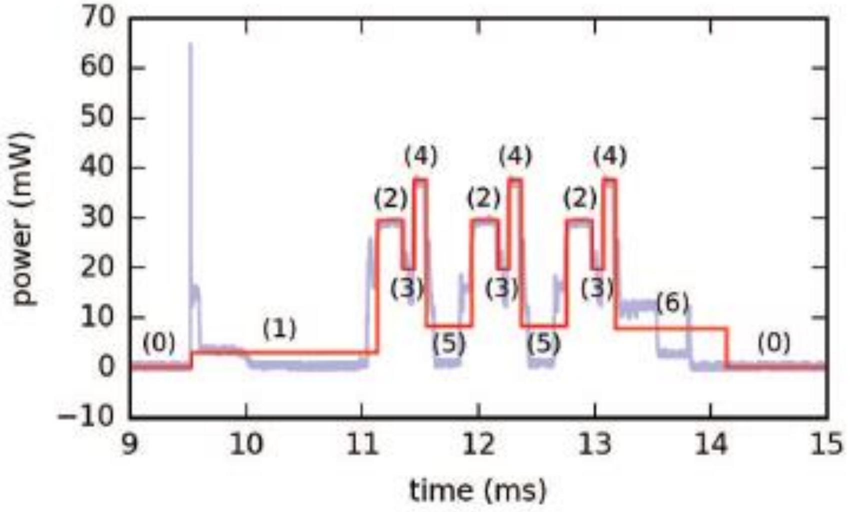
## Advertising Power Consumption of Bluetooth Low Energy Systems

Raphael Schrader, Thomas Ax, Christof Röhrig, Claus Fühner
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

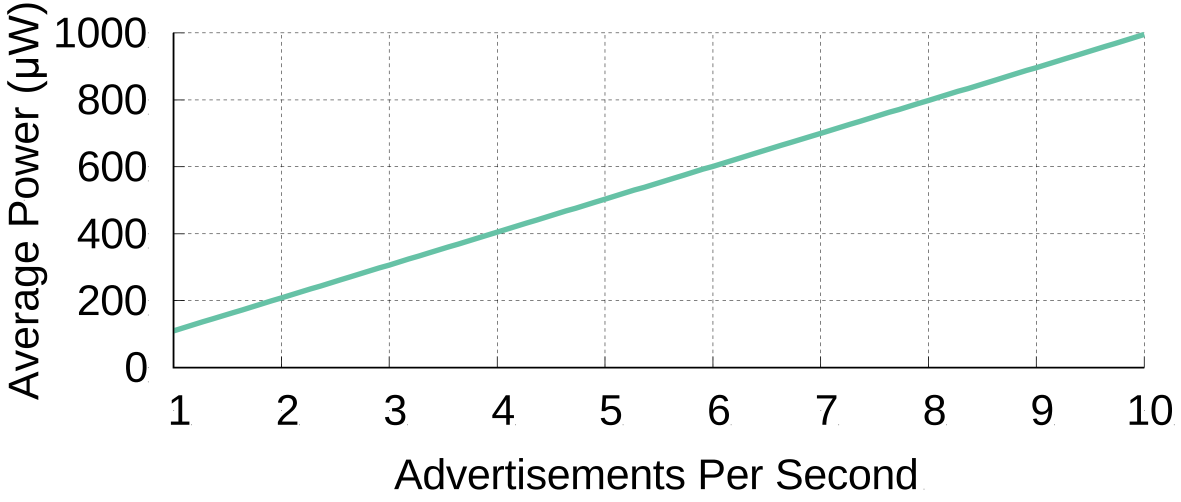
| Phase | Nordic nRF51 | | Nordic nRF52 | |
|---|---|---|---|---|
| | $T_i$ ($\sigma$) (µs) | $\overline{P_i}$ (mW) | $T_i$ ($\sigma$) (µs) | $\overline{P_i}$ (mW) |
| preprocessing | 951.8 (9.1) | 2.9 | 321.4 (8.9) | 2.7 |
| tx (4 dBm) | 72.4 (0.5) + $n_{\text{Bit}} \cdot 1/\text{Bit}$ | 45.4 | 13.2 (1.8) + $n_{\text{Bit}} \cdot 1/\text{Bit}$ | 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 | $T_{\text{advSleep}}$ | 0.0114 | $T_{\text{advSleep}}$ | 0.0058 |

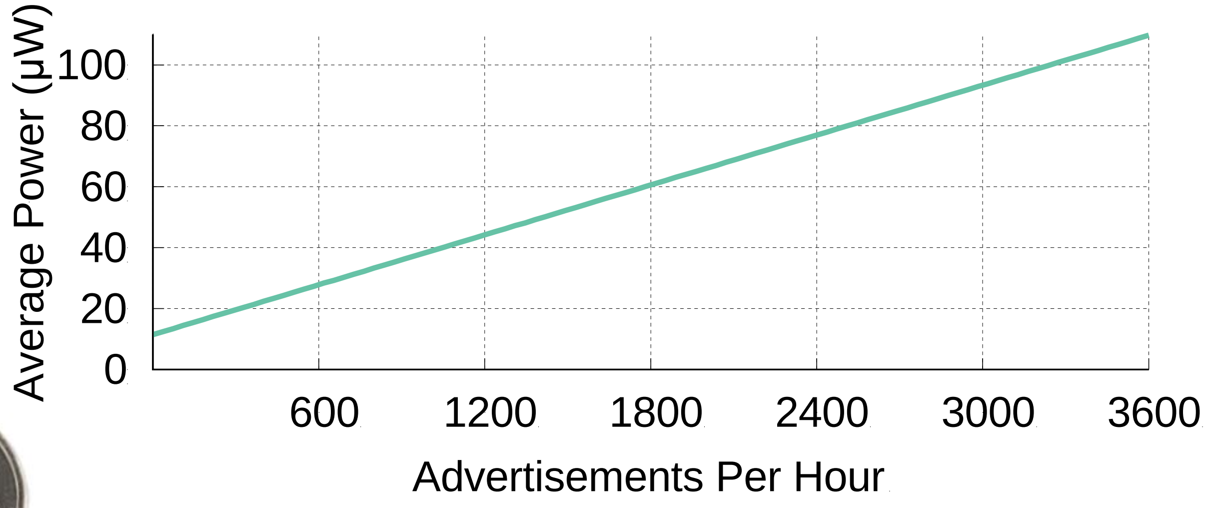
# How much energy does it cost to send data over advertisements?

- 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




# Break + Open Question

- How long does the lifetime of a BLE advertiser need to be?

# Outline

- BLE Layers
  - Physical Layer
  - Link Layer
- BLE roles
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  - Scanning
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  - **Packet Collisions**
  - Scan Responses

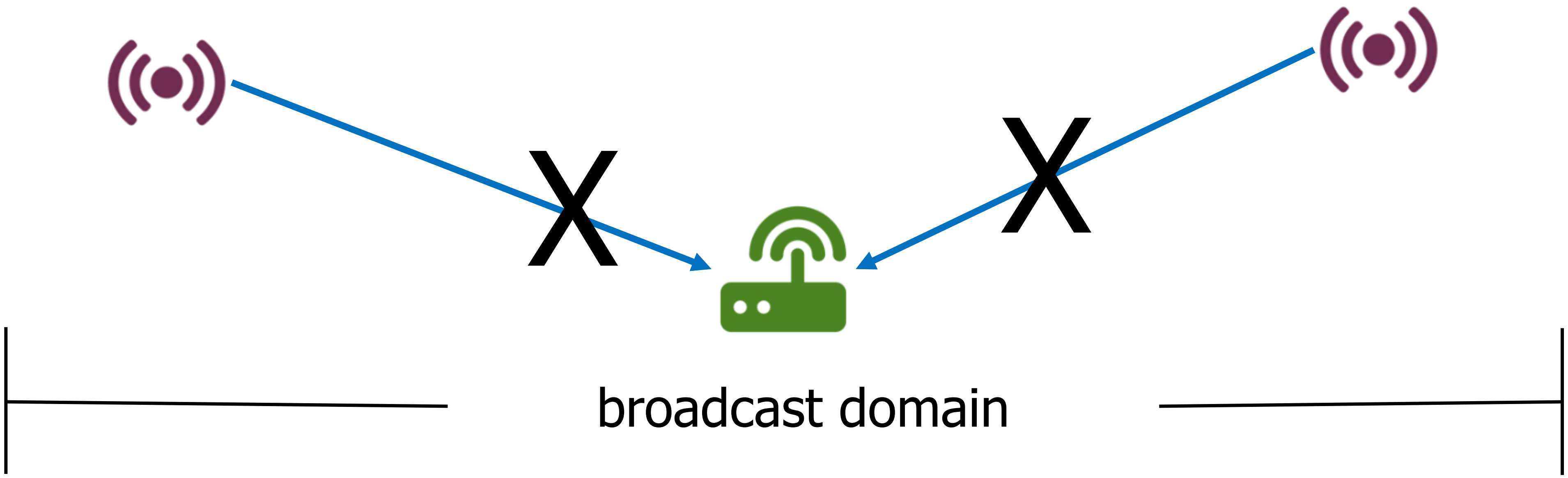
# Questions about network capability

- 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?

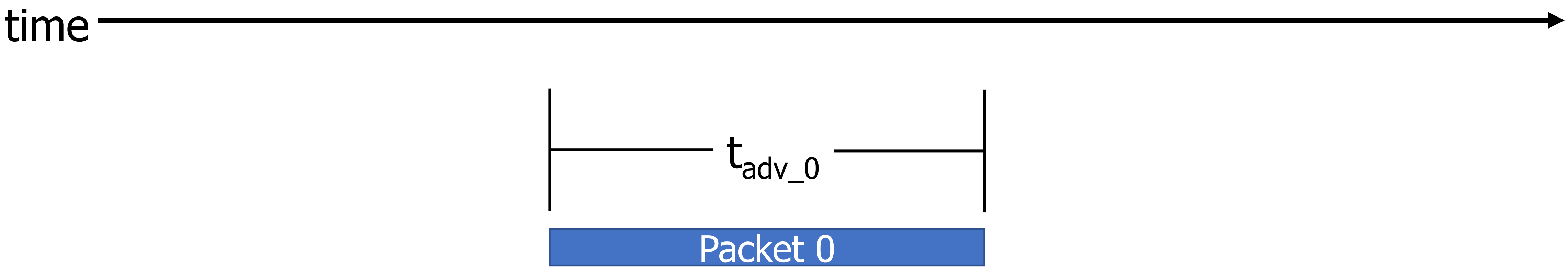
# What causes transmissions not to be received?

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).

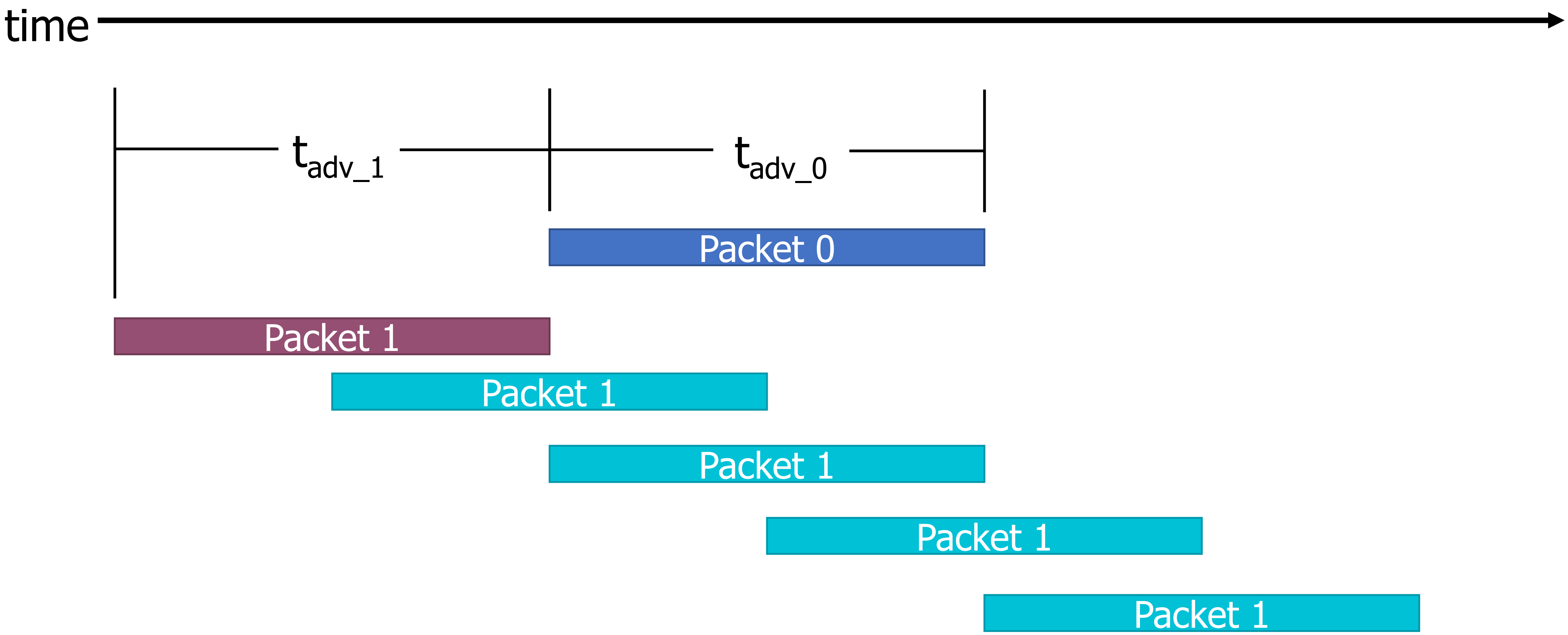


# What is the probability of a packet collision?




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).

# What is the probability of a packet collision?

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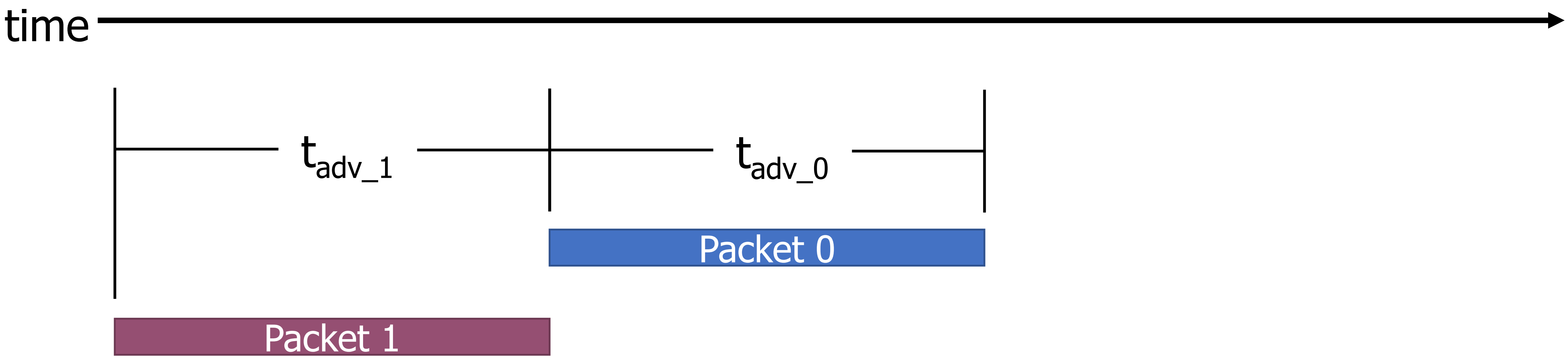
# What is the probability of a packet collision?




Probability of Collision $= \dfrac{Vulnerable\ Period}{Transmission\ Window} = \dfrac{t_{adv\_1} + t_{adv\_0}}{T_{adv\_interval} + \mathrm{E}(t_{adv\_delay})}$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# 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 (but difference is ~1%)

# 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

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

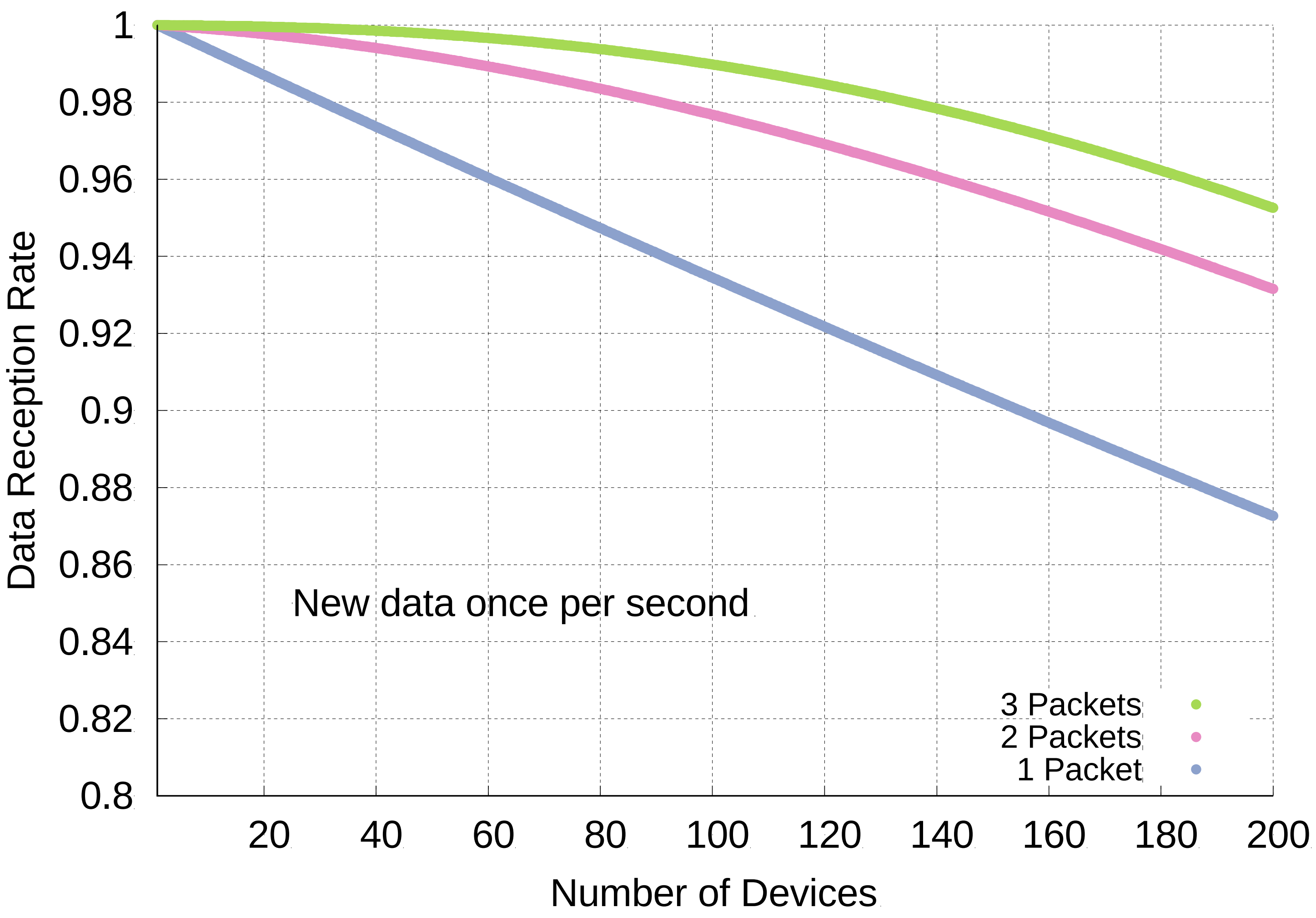
- Data Reception Rate
  - Probability that at least one of M redundant packets does not have a collision with any of N transmitting devices

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

# 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.

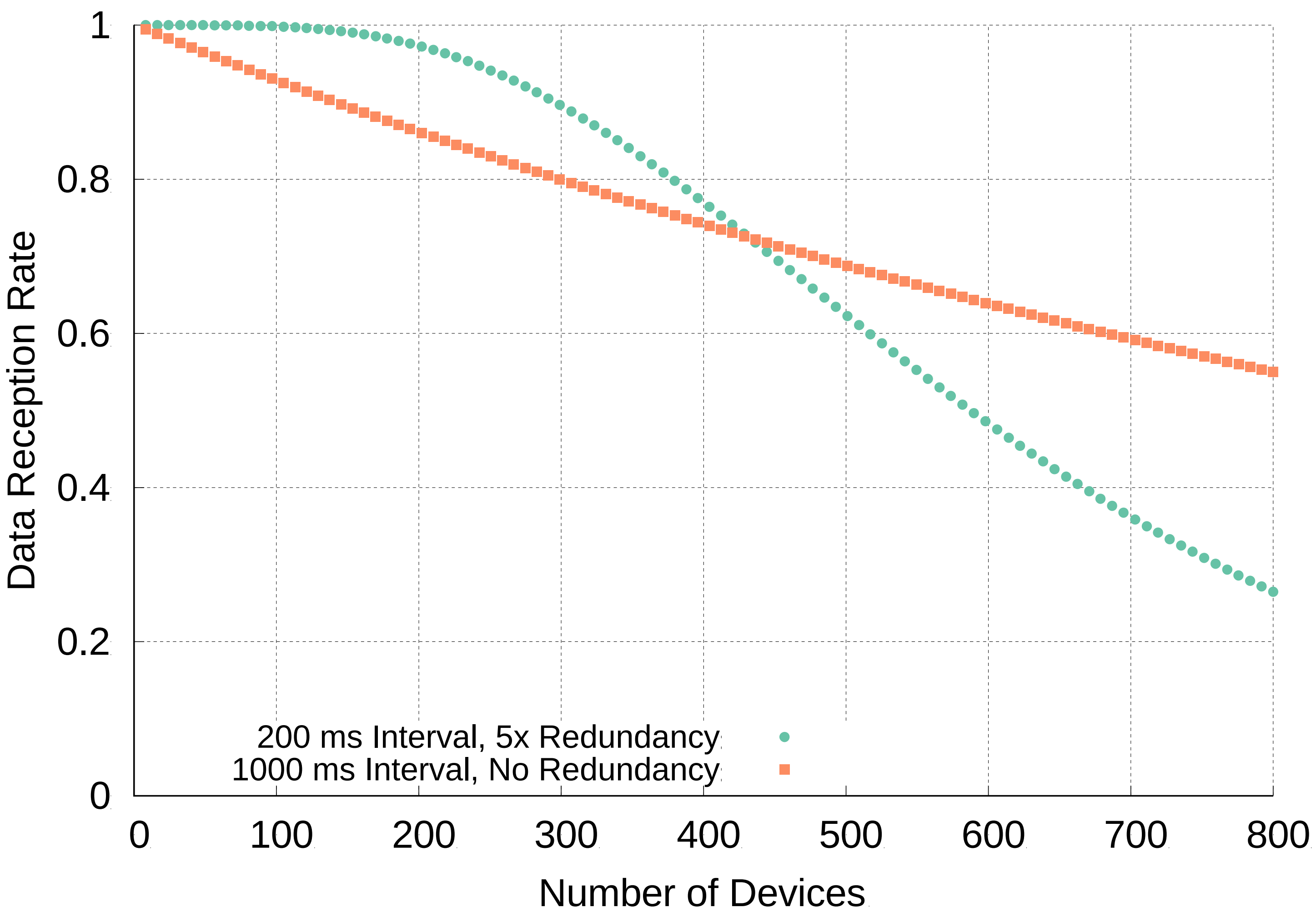
Design question:

- Send more packets to gain from redundancy?

  OR

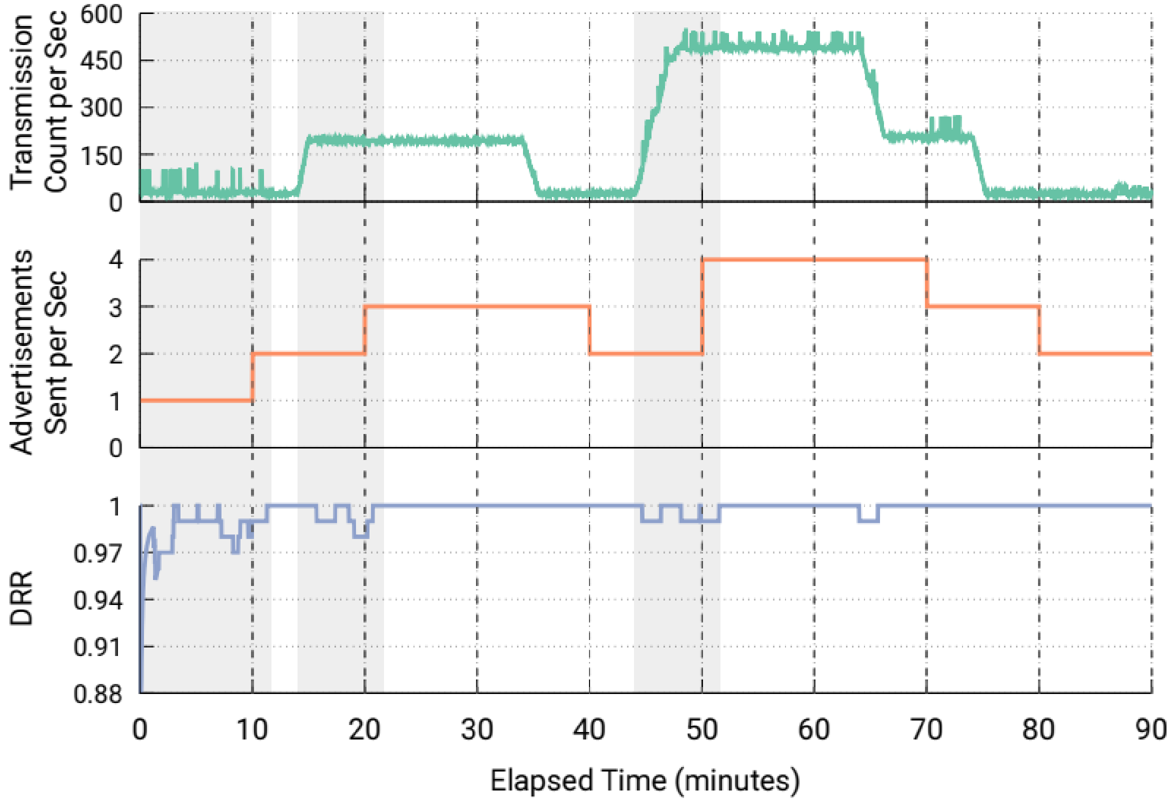
- Send less packets to reduce congestion?

The answer changes, but only with many devices.



# Automatic adaptation to advertising environment

- Devices could automatically adjust to the environment for best transmission rate




1. Scan and count how many unique devices are seen
2. Estimate DRR based on that traffic environment for redundancy from 1-10 packets per second
3. Choose the optimal result

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# 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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