ECEN 5823-001 / -001B

Internet of Things Embedded Firmware

Lecture #11

03 October 2017

Be Boulder.

University of Colorado Boulder

Agenda

- I2C temp sensor demo
- I2C temp sensor questions?
- Class announcements
- SPI tap sensor rubric
- Quiz 5 review
- Bluetooth Smart

Class Announcements

- Quiz #6 is due at 11:59pm on Sunday, October 8th, 2017
- I2C temp sensor assignment is due at 11:59pm on Saturday, October 7th, 2017

SPI tap sensor rubric

Question scoring. Max score is 5.0 pts.

a. Question 1:
   i. Energy mode: EM3 (0.4 pts)
   ii. Current LED0 off: < 175uA (0.7 pts)
      1. < 200uA (0.6 pts)
      2. < 300uA (0.4 pts)

b. Question 2:
   i. Energy mode: EM3 (0.4 pts)
   ii. Current LED0 off: < 310uA (0.6 pts)
      1. < 375uA (0.4 pts)
      2. < 450uA (0.2 pts)

c. Question 3:
   i. Energy mode: EM3 (0.4 pts)
   ii. Current LED0 off: < 175uA (0.7 pts)
      1. < 200uA (0.6 pts)
      2. < 300uA (0.4 pts)

d. Question 4:
   i. Current LED0 off: < 310uA (0.6 pts)
      1. < 375uA (0.4 pts)
      2. < 450uA (0.2 pts)
   ii. Current LED0 off: < 175uA (0.7 pts)
      1. < 200uA (0.6 pts)
      2. < 300uA (0.4 pts)

SPI tap sensor rubric

Functional code delivered per exercise. Max score is 5.0 pts.

a. Change the period to 9 secs (total of 1.0 pts)
   i. Does the period change to 9 seconds? (0.5 pts)
   ii. Does the on-time remain at 20mS? (0.5 pts)

b. Have they implemented a deterministic timing such as using TIMER0 to ensure that while enabling the BMA280 from SUSPEND to NORMAL it is guaranteed to meet timing independent of compiler optimization? (1.0 ps)

c. Does the TIMER0 work within another interrupt ISR, nested interrupts? Did they change the interrupt priority of TIMER0? (1.0 pt)

d. Does the BMA280 enable when the joy stick is pushed north? (0.5 pts)
   i. Can use energy profiler to verify

e. Does the BMA280 disable when the joy stick is pushed south? (0.5 pts)
   i. Can use energy profiler to verify

f. With the BMA280 enabled, does a double tap turn on LED1 (0.5 pts)

g. With the BMA280 enabled, does a single tap turn off LED1 (0.5 pts)

h. Submitting the assignment on time bonus (0.5 pts)

Quiz 5 review

To save energy, Bluetooth LE uses only 3 radio frequencies for discoverability out of the 40 radio channels.

- True
- False

Quiz 5 review

How long does it take a Bluetooth LE typically to make a connections?

- 200-500 milli seconds
- 200-500 micro seconds
- 2-4 seconds
- 2-4 milli seconds 

Quiz 5 review

Which Bluetooth LE term is most similar in functionality to a GATT Client?

- ○ GAP Peripheral
- ○ GAP Server
- ✓ GAP Central

Quiz 5 review

What are the key specifications in determining a coin-cell battery life in a BLE application?

- [x] The duty cycle of the active radio RX/TX
- [x] The duty cycle of the BLE device sleep mode
- [x] The peak current while the radio is in active transmitting
- [x] Internal resistance of the battery

Quiz 5 review

Which device is the primary power source in a BLE device while in sleep mode?

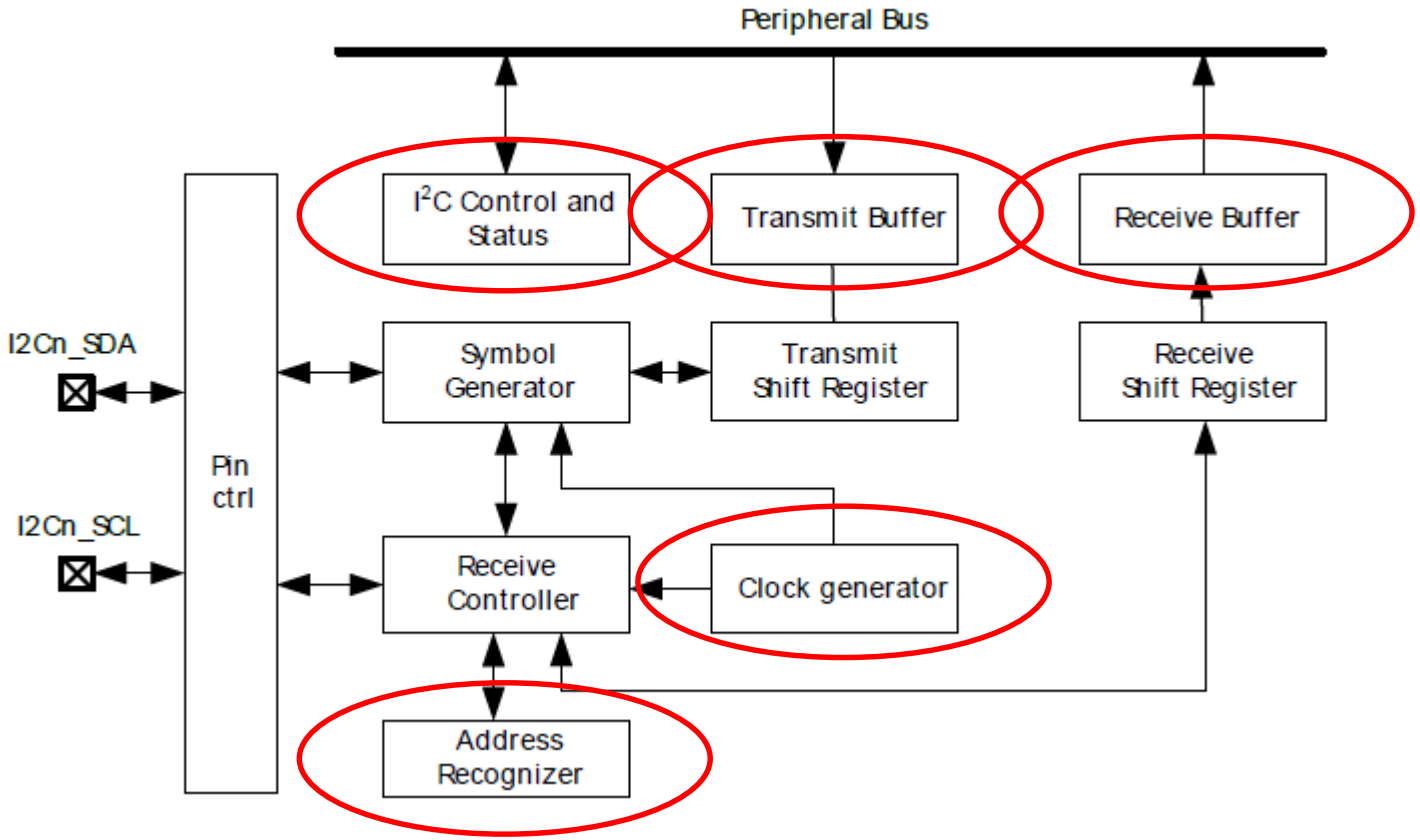
- The capacitance
- The coin-cell battery

Quiz 5 review

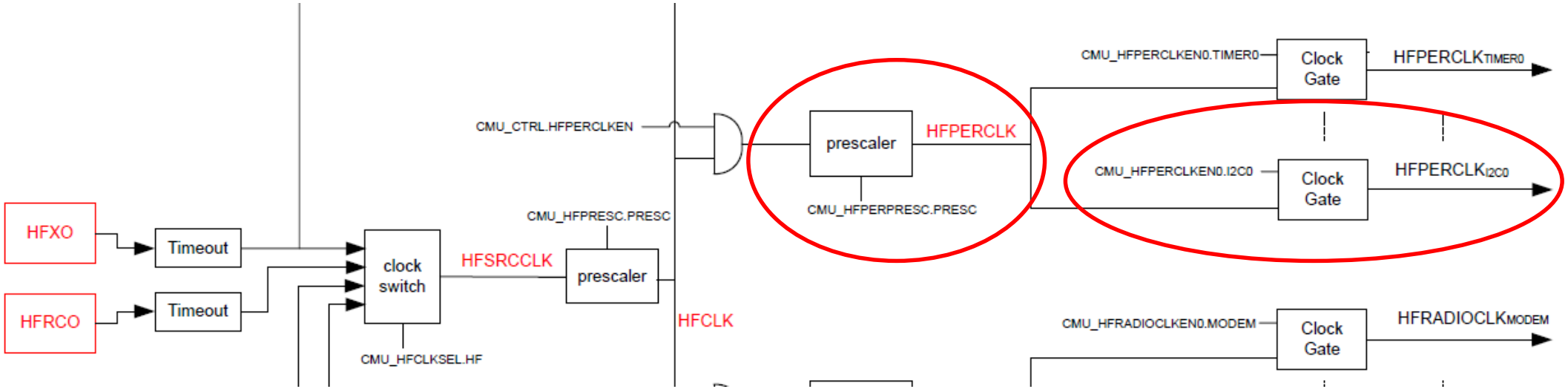
Using the Blue Gecko data sheet and reference manual, what would be the lowest sleep mode that the Blue Gecko could enter after enabling the I2C as an I2C slave and detect its I2C slave address after a successful BlockSleepMode()?

(Use the enumerations EM0, EM1, EM2, EM3, or EM4)

I2Cn peripheral block diagram



I2C



If the I2C clock input is the HFPEFCLK, how can it work done into EM3?

Quiz 5 review

Using the Blue Gecko data sheet and reference manual, what would be the lowest sleep mode that the Blue Gecko could enter after enabling the I2C as an I2C slave and detect its I2C slave address after a successful BlockSleepMode()?

(Use the enumerations EM0, EM1, EM2, EM3, or EM4)

(em3, EM3)

Quiz 5 review

In general, what is the preferred order of operation to enable an external device via Load Power Management using a GPIO pin as the power source?

4	Initialize, program, the external peripheral
1	Set GPIO power pin HIGH
3	Enable GPIO I//O pins
5	Enable Interrupts if used
2	Wait for power to stabilize and external device to boot

Quiz 5 review

In general, what is the preferred order of operation to disable an external device via Load Power Management using a GPIO pin as the power source?

3 Set GPIO power pin LOW

2 Disable GPIO I//O pins

1 Disable or turn off Interrupts if used

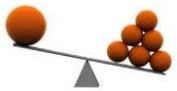
Quiz 5 review

What are the valid communication standards between different Bluetooth devices? (select all that apply)

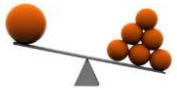
- [ ] Single-Mode to Classic in Bluetooth LE
- [x] Single-Mode to Single-Mode in Bluetooth LE
- [ ] Dual-Mode to Dual-Mode in Bluetooth LE
- [x] Classic to Dual-Mode in Bluetooth Classic

BLE: Asymmetric Design

- A major philosophy of the Bluetooth Low Energy Architecture



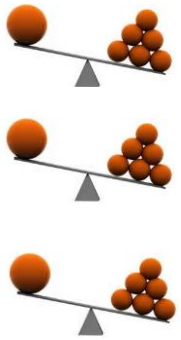
  - Devices with smaller energy sources be given less to do
  - Conversely, devices with larger energy sources be given more to do
- A fundamental assumption is the most resource-constraint device will be the one to which all others are optimized



  - Advertising is less energy consuming than scanning
  - A slave has less energy than a master
    - A master has to manage the piconet timing, the adaptive frequency hopping set, encryption, and many other complex procedures

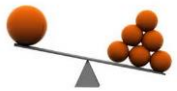
BLE: Asymmetric Design

- At the Generic Attribute Protocol Layer, the two type of devices are:
  - Client
    - Determines what data the server has and how to use it
    - The client sends request to the server for data
  - Server
    - The Server holds data
    - Similar to the slave at the Link Layer, the server just does what it is told
- The security architecture works on a key distribution scheme by which the slave device gives a key to the master device to remember
  - The burden is on the master to remember the bonding information, not the slave
- This implies the most resource-constraint device will want to be the advertisers, slaves, and servers
- Conversely, the devices with the most resources will be the scanners, masters, and clients

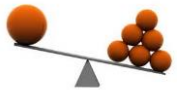


BLE: Asymmetric design

- Client-Server Architecture:
  - An IP address could have been specified to be given to each BLE device, but the simplest of IP stack takes more memory and energy than is desired on resourced constrained devices
    - The most resource-constraint device will be the one to which all others are optimized



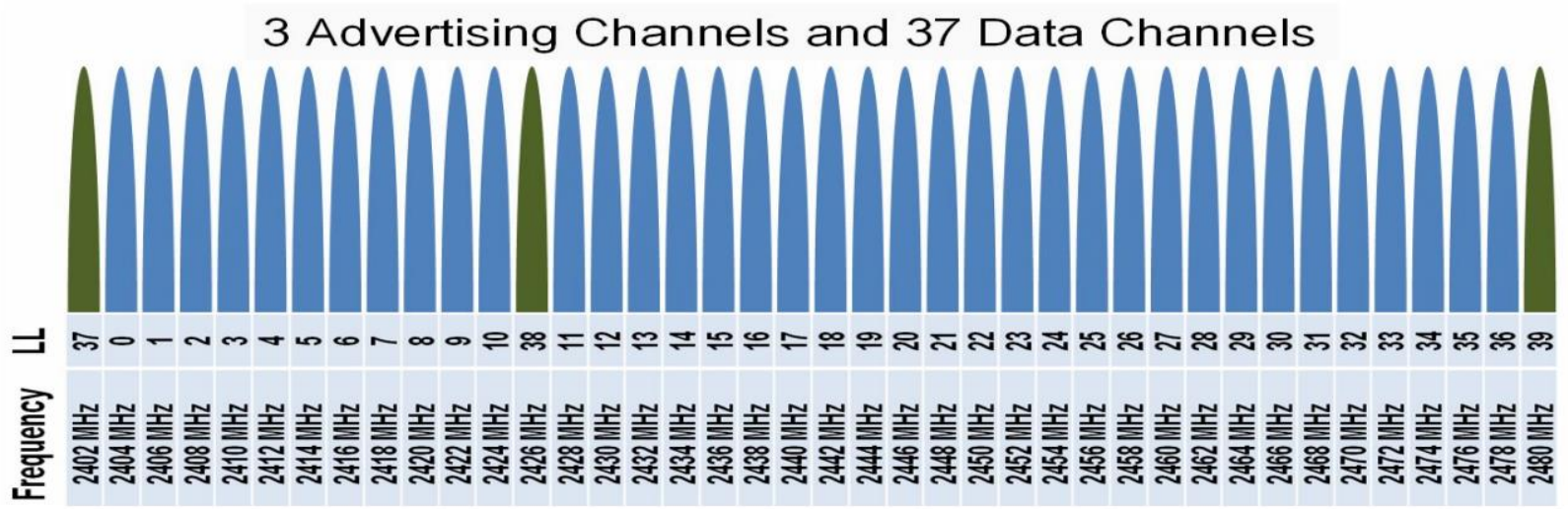
  - The client-server architecture makes possible smart gateways to connect the very efficient low-energy slaves to the internet
    - The client, the more resource abundant device, can connect and handle the IP protocol
    - While, the server is just the repository of data



  - Full Internet security can be provided between the client to the gateway where the gateway performs access control, firewall, and authorization of the client before granting access to anything beyond the gateway
    - These gateways, routers and access points, are proven technologies used today

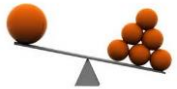
BLE: The Radio

- 2.4 GHz ISM band
- 1 Mbps GFSK
  - Larger modulation index than Bluetooth BR (which means better range)
- 40 Channels on 2 MHz spacing:



BLE: The Radio

- Adaptive Frequency Hopping (AFH):
  - A technology where only a subset of available frequencies are used
  - Robust by detecting sources of interference quickly, and adapting to avoid them in the future
  - Quickly recovers from dropped packets caused by interference quickly by hopping to a new channel
- Short Range and Low Power:
  - Transmit power should be kept as low as possible
  - Receive sensitivity should be relatively high to pick up the transmitted signals
  - Transmit power and Receive amplification should match the device resources appropriately
    - Dual-Mode devices with larger batteries can transmit at a higher power
    - Dual-Mode devices with larger batteries can increase the gain of the receiver



BLE: Adaptive Frequency Hopping

Another representations of the BLE Advertising and Data Channels

Table 7–3 Complete List of Advertising and Data Channels, the Link Layer Channel Number, and Center Frequency

Frequency (MHz)	LL Channel Number	Type	Frequency (MHz)	LL Channel Number	Type
2402	37	Adv	2442	18	Data
2404	0	Data	2444	19	Data
2406	1	Data	2446	20	Data
2408	2	Data	2448	21	Data
2410	3	Data	2450	22	Data
2412	4	Data	2452	23	Data
2414	5	Data	2454	24	Data
2416	6	Data	2456	25	Data
2418	7	Data	2458	26	Data
2420	8	Data	2460	27	Data
2422	9	Data	2462	28	Data
2424	10	Data	2464	29	Data
2426	38	Adv	2466	30	Data
2428	11	Data	2468	31	Data
2430	12	Data	2470	32	Data
2432	13	Data	2472	33	Data
2434	14	Data	2474	34	Data
2436	15	Data	2476	35	Data
2438	16	Data	2478	36	Data
2440	17	Data	2480	39	Adv

BLE: Adaptive Frequency Hopping Managing Interference and Coexistence

- WiFi access point typically use one of three 802.11 channels
- BLE Advertising channels are strategically placed to not be interfered by these WiFi channels (1, 6, and 11)
- Three advertising channels are designed into the BLE specification to provide robustness
- Without an effective advertising channel, BLE would not be an effective wireless network

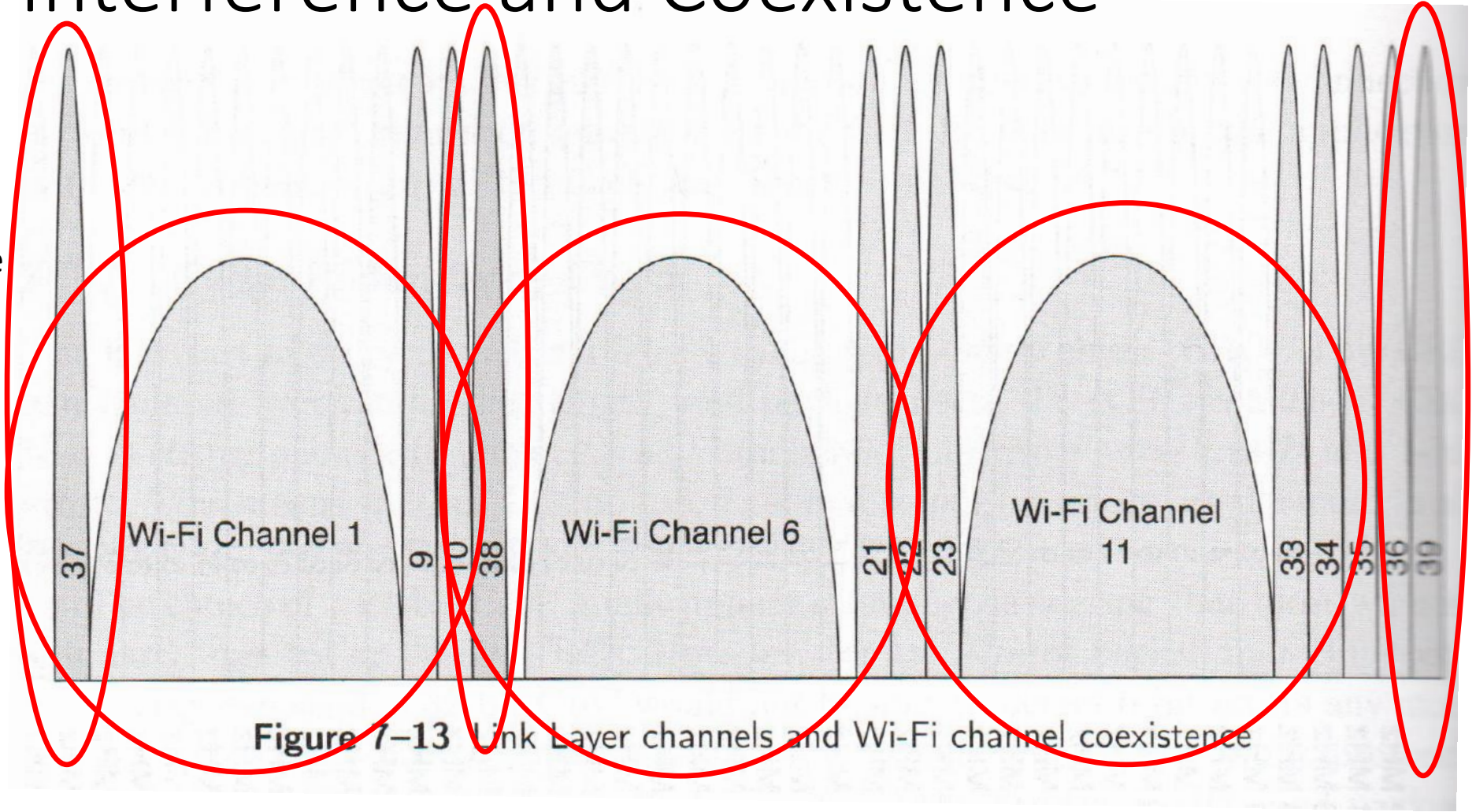


Figure 7–13 Link Layer channels and Wi-Fi channel coexistence

BLE: Frequency Hopping

- When in data connection, a frequency-hopping algorithm is used. Since there are 37 data channels which is a prime number, the hopping sequence is very simple
  - f_{n+1} = (f_n+hop) mod 37
  - The hop value can range from 5 to 16
  - This will result in every frequency be used with equal priority
- Notice, that the advertising channel numbers are greater than 37, so they will never be used in the data connection hop sequence

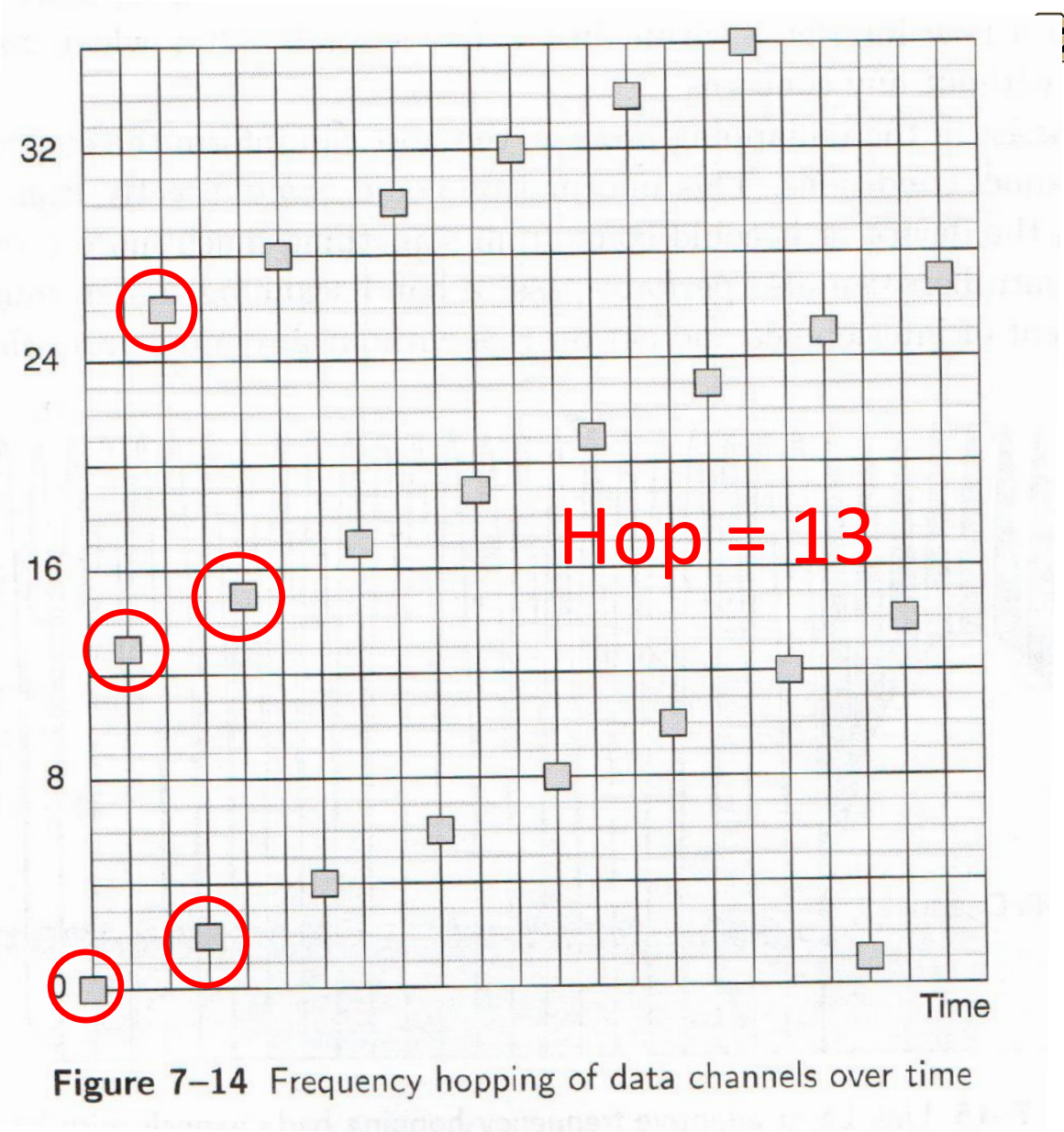


Figure 7–14 Frequency hopping of data channels over time

BLE: Adaptive Frequency Hopping

- Adaptive frequency hopping makes it possible for a given packet to be remapped from a known bad channel to a know good channel
- In the example to the right, the data channels 0-8 are known bad channels due to the WiFi Channel 1 interference
- Channels 0-8 should be remapped to channels 9-36

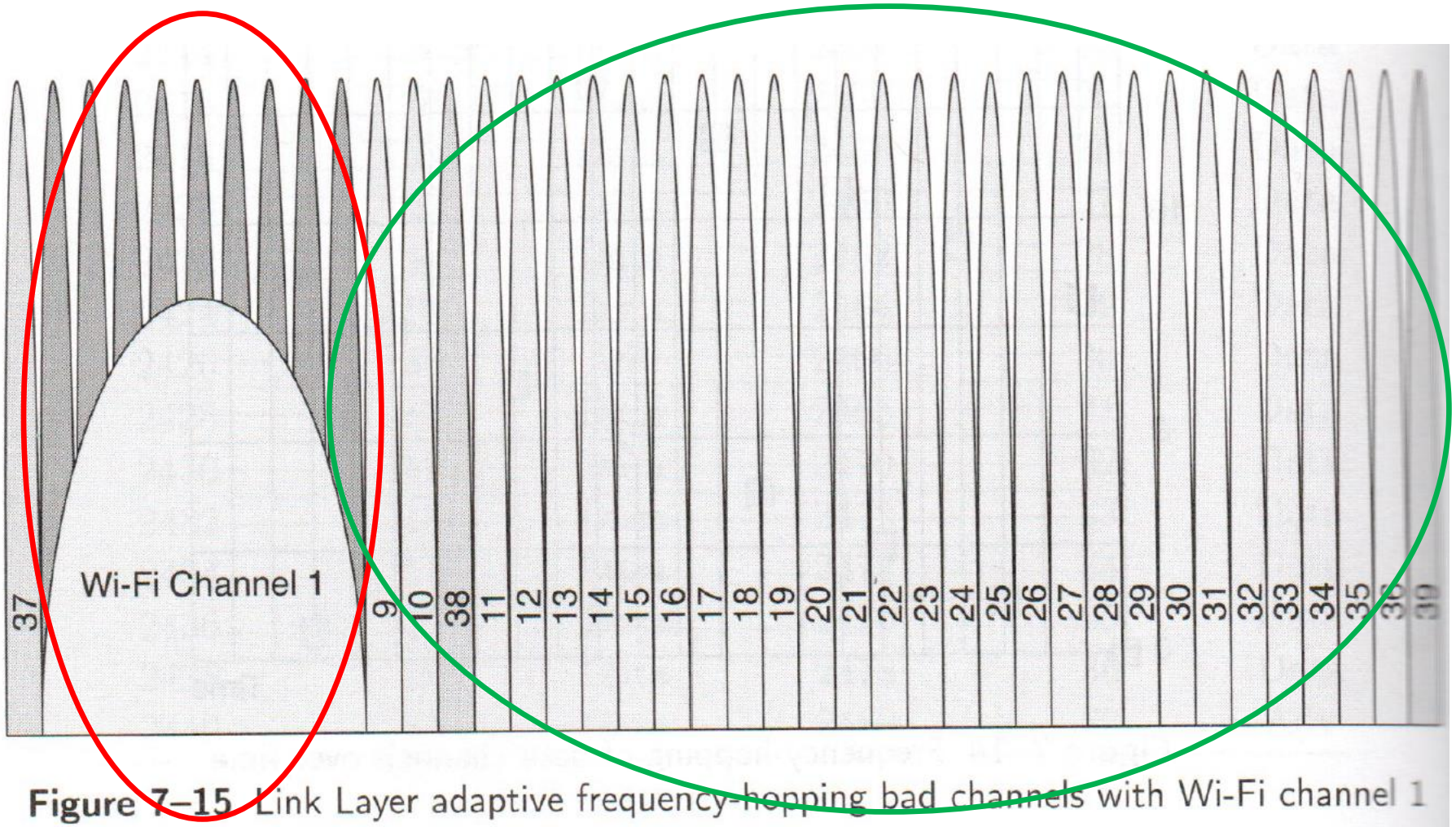


Figure 7–15 Link Layer adaptive frequency-hopping bad channels with Wi-Fi channel 1

BLE: Adaptive Frequency Hopping

Hop = 13

Table 7–4 An Example of Adaptive Frequency Channel Remapping

Original Channel	Good/Bad	Remapped Channel
0	Bad	9
13	Good	13
26	Good	26
2	Bad	11
15	Good	15
28	Good	28
4	Bad	13
17	Good	17
30	Good	30
6	Bad	15
19	Good	19
32	Good	32
8	Bad	17

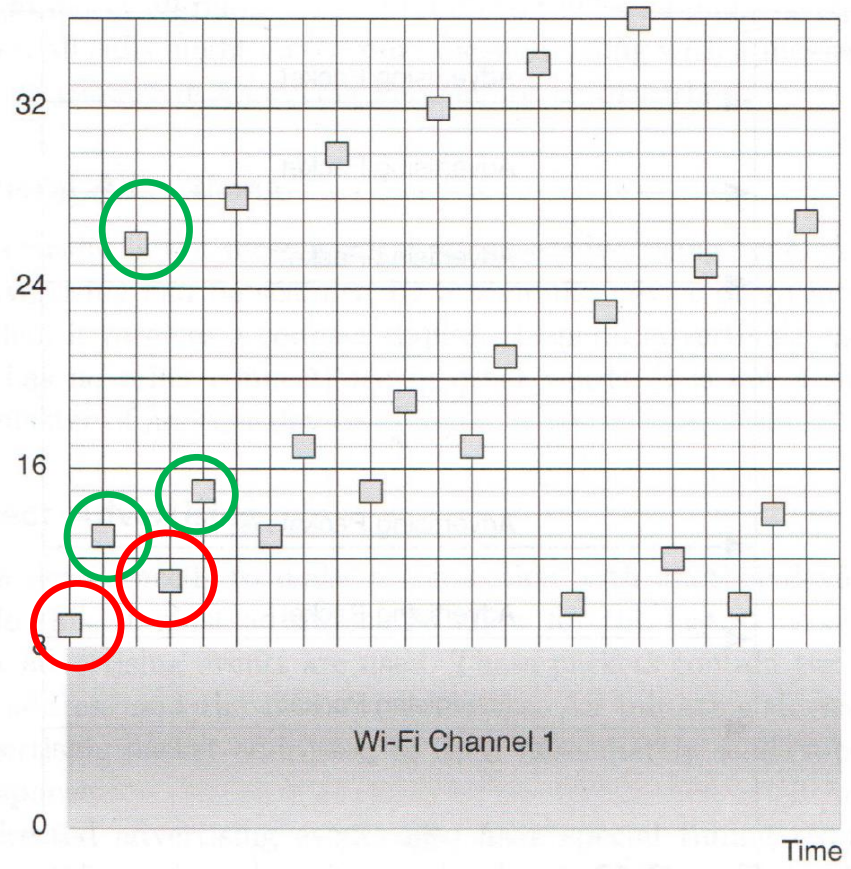


Figure 7–16 Adaptive frequency-hopping remapping

BLE: Time is Energy

Energy = Power x Time

- Optimizing a number of important and repetitive action is a must
  - Discovering devices
  - Connecting to devices
  - Sending data

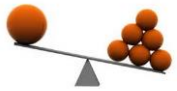
➢Reducing the time for these activities

➢Reduces the energy consumed for these activities

➢Lengthening the battery life

BLE: Time is Energy (Advertising)

- Advertising to be discovered requires a device to transmit a very short message 3 times per second and listen immediately afterwards if it wants to connect
- Three transmits are done, one per advertising frequency channel, for robustness.
  - If the advertising channels was just one frequency band, if that frequency became blocked or a lot of interference, devices would not be able to connect
  - If the number of channels was much higher than 3, such as 16, then the device would spend more time and energy by having its radio on 5x+
- Searching for a device that is transmitting requires the radio to be on a long period of time which requires more energy than the advertising device
  - Thus, the device that typically has more resources, larger battery, is listening and will become the master
  - The advertiser will normally be the smaller device with the smaller battery and become the slave

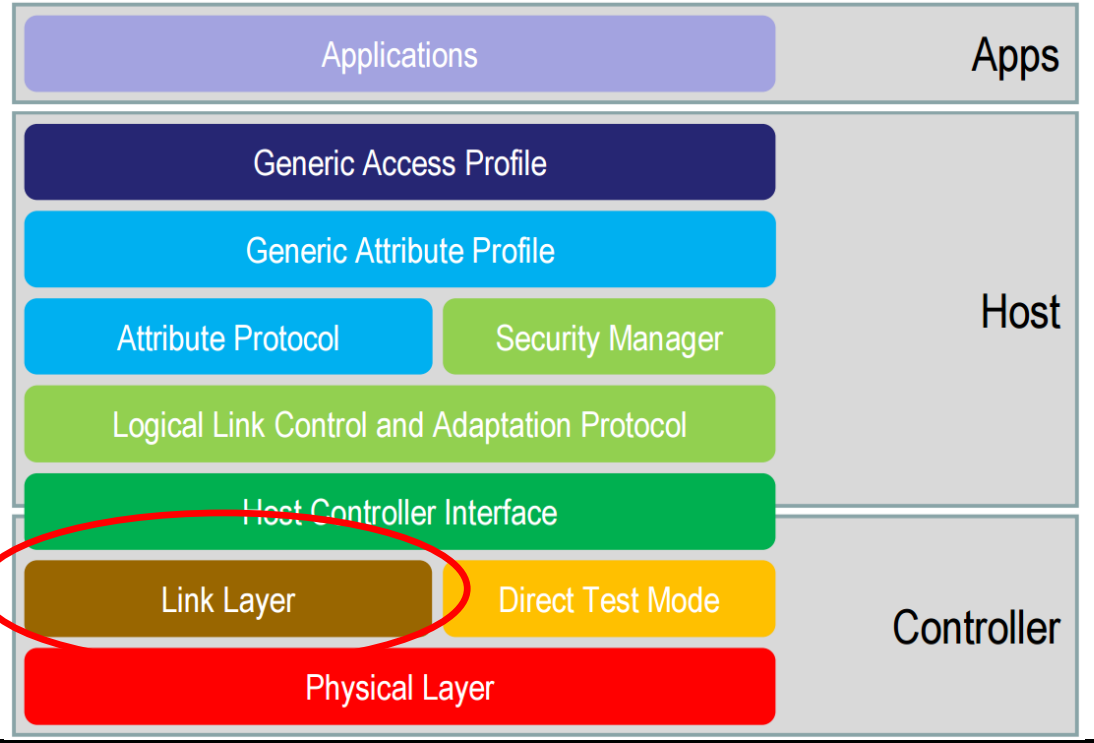


BLE: Time is Energy (Packet size)

- Short packets are good for three reasons:
  - Efficient encoding allows short packets to transmit as much as larger packets faster using less energy
  - Restricting the radio devices to only use short packets removes the requirement of constantly recalibrating the radio within the controller due to internally heating while the radio is operational
  - Short packets reduces peak power consumption which enables more energy to be taken out of the battery

BLE: Link Layer

- Two types of Link Layer Channels:
  - Advertising channels
    - Broadcast data
    - Advertise that they are connectable and discoverable
    - Scan
    - Initiate connections
  - Data channels
    - Only used once a connection has been established
    - And, only when data needs to flow



CSR: Bluetooth 4.0 Low Energy
http://chapters.comsoc.org/vancouver/BTLER3.pdf
Bluetooth Low Energy: The Developer's Handbook By Robin Heydon

BLE: Link Layer packet structure

- Basic packet structure is the same for both advertising channels and data channels
  - A minimum of 80 bits of addressing, header, and check information for every packet
- The packets are optimized to increase their robustness by using an 8-bit preamble that is sufficiently large to allow the receiver to synchronize bit timing and set the radio's automatic gain control
- A 32-bit access address that is fixed for advertising packets, but can be completely random and private for data packets
- An 8-bit header packet to describe the contents of the packet
- An 8-bit length field to describe the payload length
- 0-296 bit payload
- And, a 24-bit cyclic redundancy check (CRC) value to ensure that there are not bit errors in the received packet

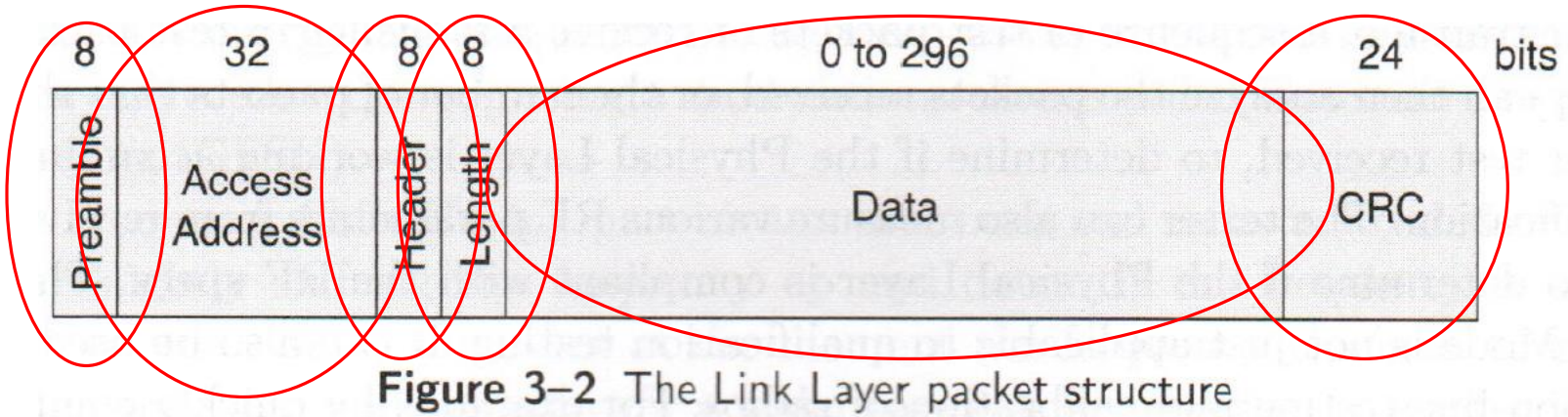
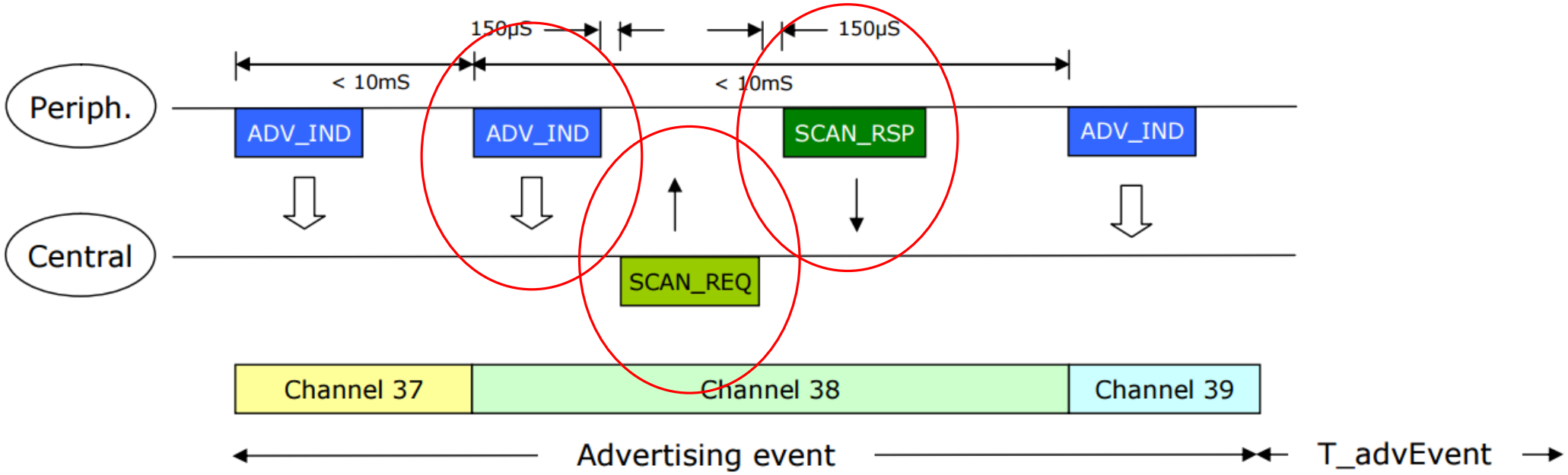


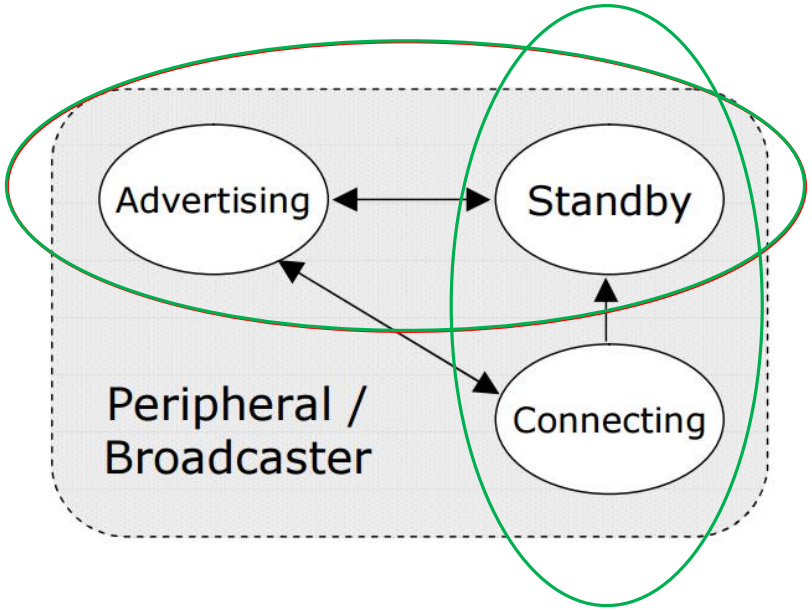
Figure 3–2 The Link Layer packet structure

BLE: Advertising

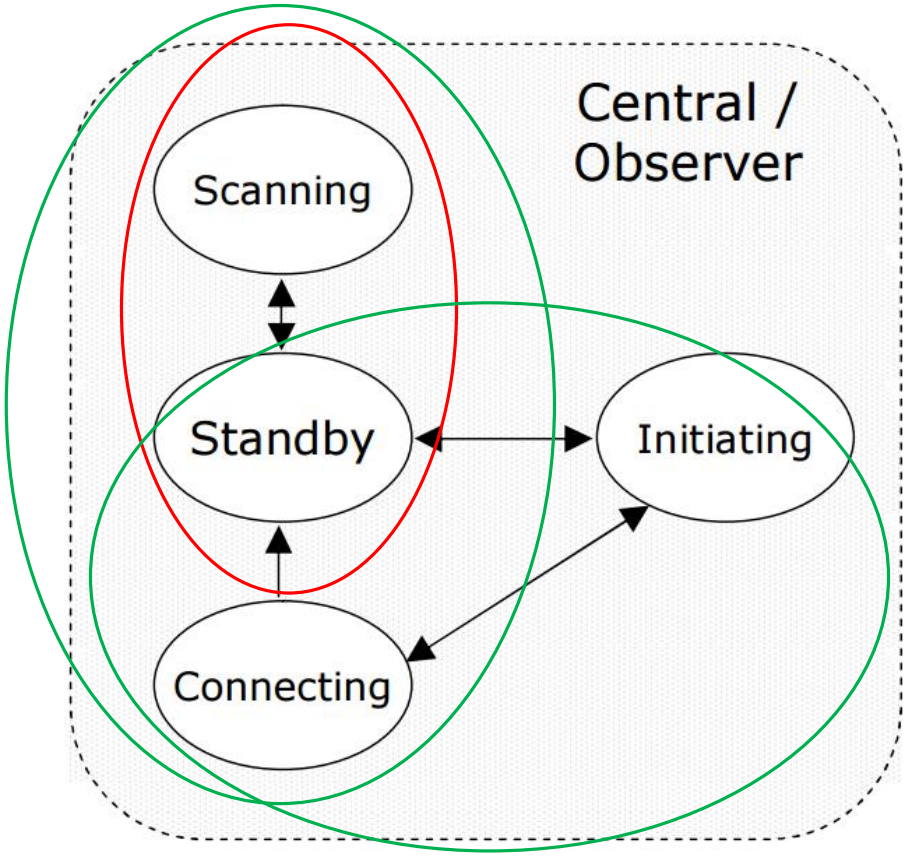


- Devices can advertise for a variety of reasons:
  - To broadcast promiscuously
  - To transmit signed data to a previously bonded device
  - To advertise their presence to a device wanting to connect
  - To reconnect asynchronously due to a local event

BLE: Advertising (Peripheral and Central States)

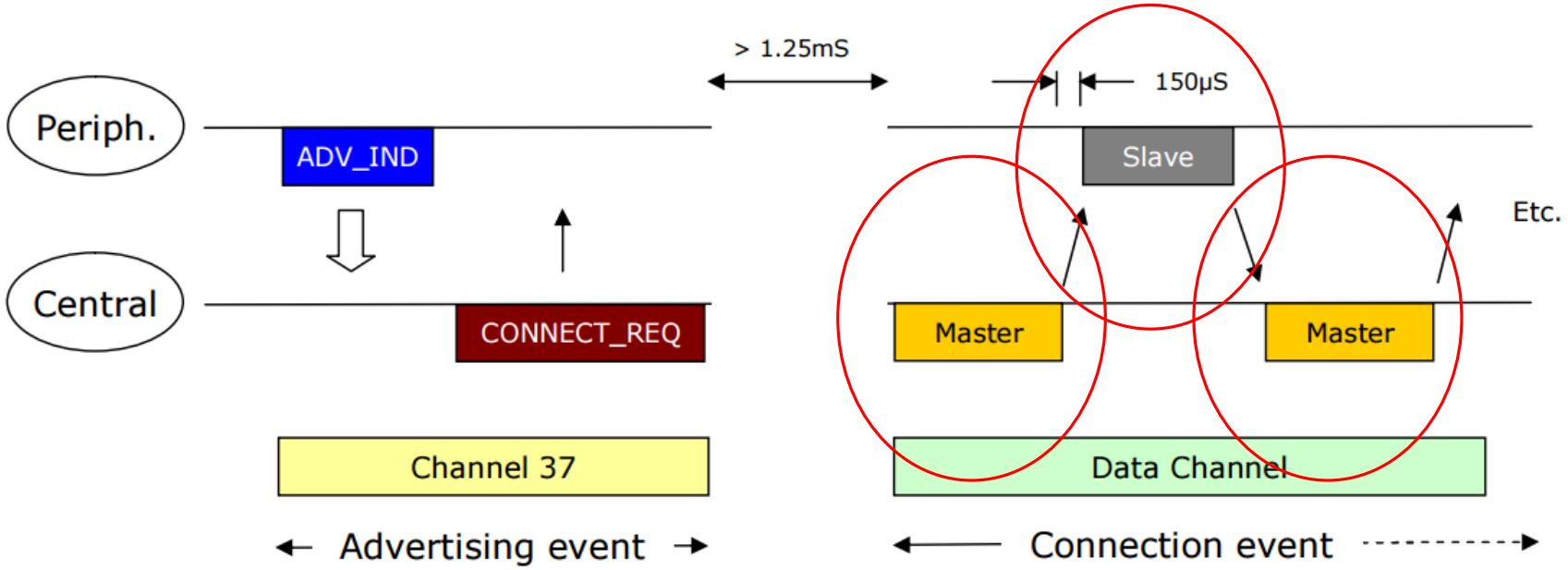


A Broadcaster cannot enter the Connecting state.



An Observer cannot enter the Initiating State.

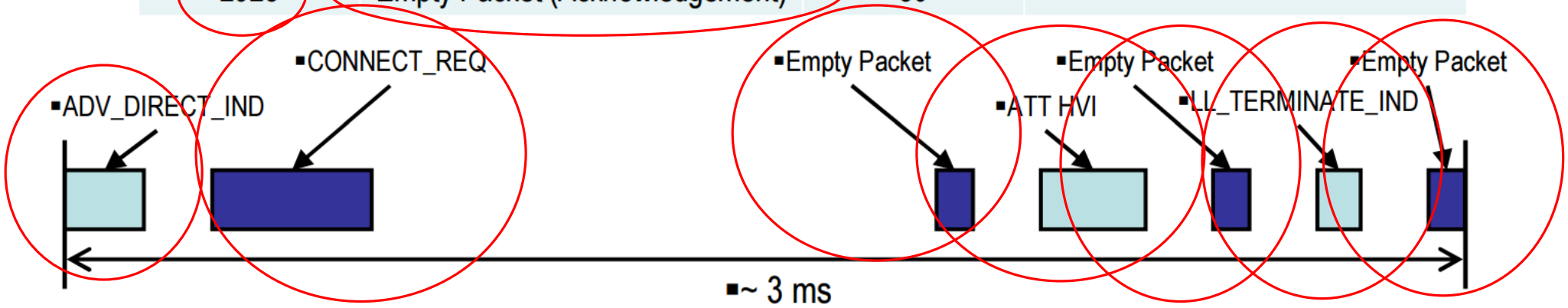
BLE: Data transactions



- Once a connection is made:
  - Master informs slave of hopping sequence and when to wake
  - All subsequent transactions are performed in the 37 data channels
  - Transactions can be encrypted
  - Both devices can go into deep sleep between transactions

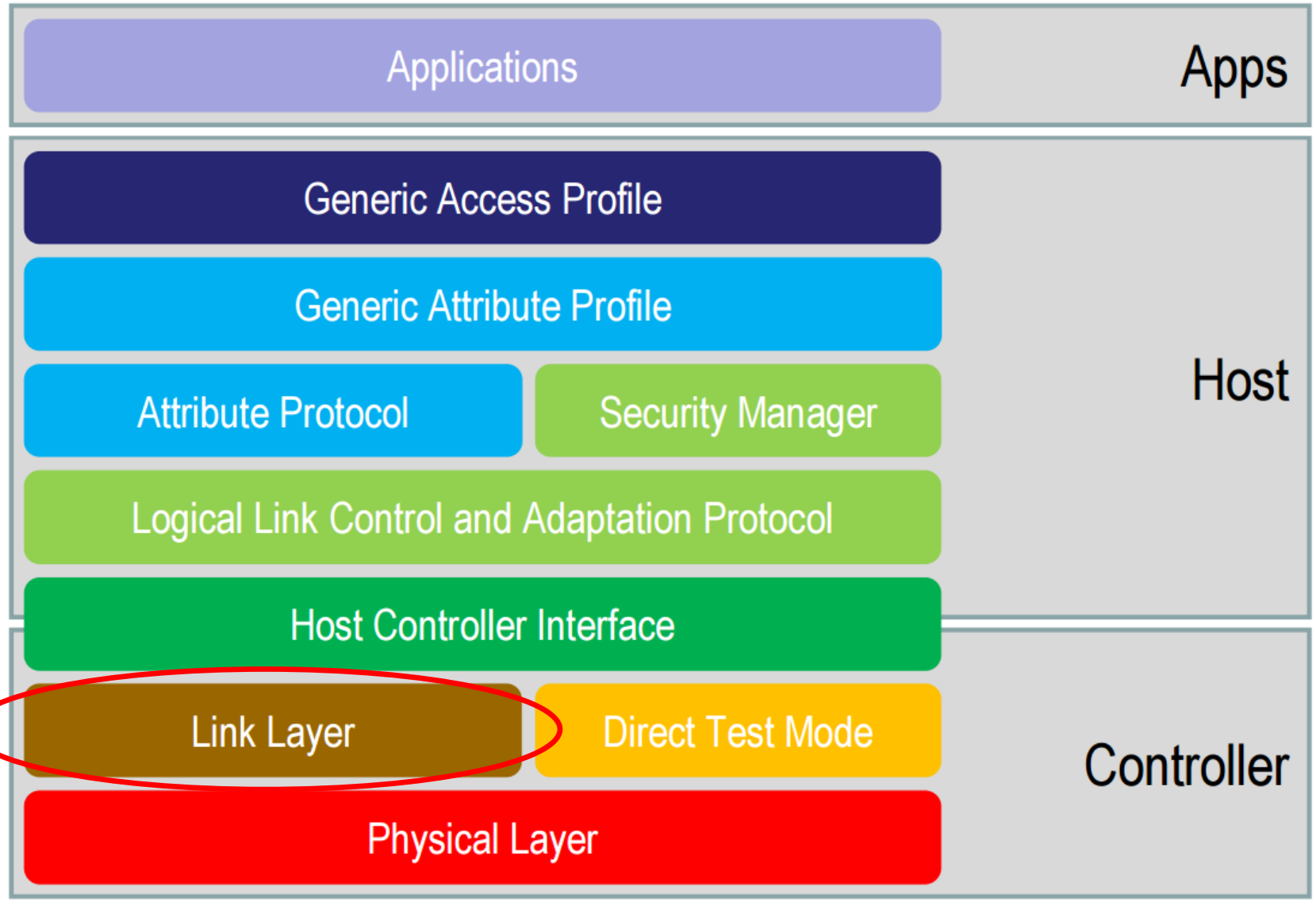
BLE – Minimum time for data transaction

Time (us)	Master Tx	Radio Active (us)	Slave Tx
0		176	ADV_DIRECT_IND
326	CONNECT_REQ	352	
1928	Empty Packet	80	
2158		144	Attribute Protocol Handle Value Indication
2452	Empty Packet (Acknowledgement)	80	
2682		96	LL_TERMINATE_IND
2928	Empty Packet (Acknowledgement)	80	



CSR: Bluetooth 4.0 Low Energy
http://chapters.comsoc.org/vancouver/BTLER3.pdf

BLE: Stack


Applications
Apps
Generic Access Profile
Generic Attribute Profile
Attribute Protocol
Security Manager
Logical Link Control and Adaptation Protocol
Host Controller Interface
Host
Link Layer
Direct Test Mode
Physical Layer
Controller

BLE: Optimizing for Low Power/Energy

- Primary methods to reducing power are:
  - Keeping the packets short
  - Using a high physical bit rate
  - Providing low overhead
  - Optimized acknowledgement scheme
  - Single-channel connection events
  - Using offline encryption (encrypting when the radio is off)
- Two types of power consumption that are critical for lower power consumption
  - Low peak-power consumption to optimize the use of button-cell batteries ($P=I^2R$)
  - Low power-per-application bit to enable a device to be used a long time sending a defined quantity of application data