ECEN 5823-001 / -001B

Internet of Things Embedded Firmware

Lecture #12

05 October 2017

How to get the ADC current requirement lower?

- First, must meet the system requirements
  - Match the input range to the reference which results in highest resolution
  - Two options:
    - VBGR and attenuate the input voltage in half
    - Or, use VDD / ADD external references
  - Which option above do you think will be lower power?
- Second, minimize what is not required
  - The Joy Stick is a resistor divider circuit of limited tolerance and speed
  - How can you minimize the analog circuit speed?
    - Set the bias current to its lowest setting, 0xff
    - For highest accuracy when using a VBGR-derived internal bandgap reference source, GPBIASACC in ADCn_BIASPROG should be cleared to 0. This will allow the ADC to enable high-accuracymode from the bias circuitry during conversions. When AVDD or an external pin reference option is used, software should set GPBIASACC in ADCn_BIASPROG to 1 to conserve energy.

Agenda

- I2C temp sensor demo
- I2C temp sensor questions?
- Class announcements
- 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
- Mid-term will be held in class on Thursday, October 19th, at 6:30pm in class
  - For on campus students, you must be in class for the exam
  - For distant learners, the mid-term will be due by 11:59pm on Saturday, October 21st, 2017
- There will be no homework assignment or quiz the week of October 16th

Mid-Term

- October 19th, 2017
  - For the distant learners, the Mid-Term will be available from October 19th at 6:30pm to Saturday the 21st at 11:59pm
- Will be administered by D2L
  - 75 minute time limit for the Mid-term
  - 5 minutes time limit for the bonus section
  - 1 attempt
- Open book, but not open people

Mid-Term

- Material covered will include:
  - All the readings from the first day of class
  - All the lectures through Thursday, October 12th, 2017
  - All assignments
- Questions:
  - 33 questions that will represent 100% of the mid-term
    - Question pool will be over 100 questions
  - 10 bonus questions each worth 1 point
    - Comprised of a random selection from the first 7 week quiz questions (roughly 150 questions in the question library)

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

BLE: Short Packets

- Low power designer dilemma:
  - To make a radio more stable, more circuity is required that increases cost and power consumption
  - The BLE radio solves this dilemma by making the packet length significantly small that heating effects are minimized
    - The heating effect does not require a very long packet to cause this heating problem
    - The 3 millisecond packets in Bluetooth Classic are long enough to cause this heating issue
  - The BLE specifications take into account the physical properties of the semiconductor that are used to create the radios
  - The goal is to keep packets no more than a few hundredths of milliseconds in length to prevent any semiconductor heating problems
    - Resulting in no requirement for calibration or stabilization circuitry for the radio

BLE: Short Packets

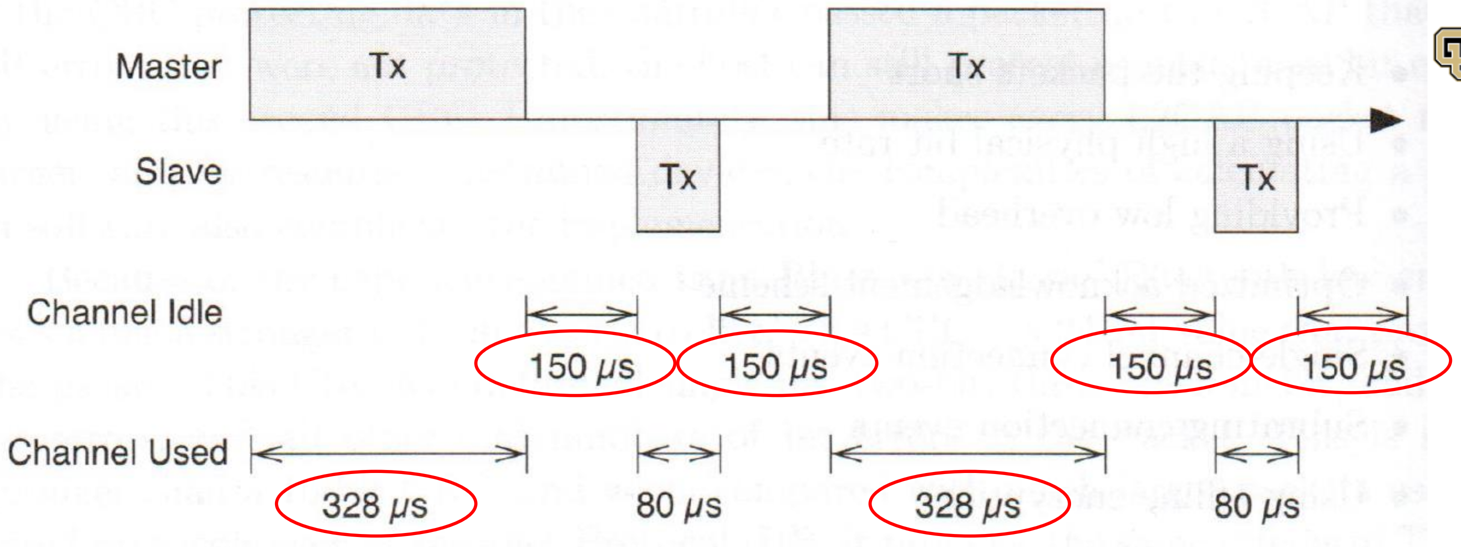


Figure 7–31 Short packets

- The packets are short enough that any drift of the frequency due to heating will not be outside the BLE radio specifications
  - The longest packet in an Advertising Event is 378uS
  - The longest packet in a Connection Event is 328uS
- To further reduce the issue of silicon heating, the specification requires a 150uS gap between "very long" packets to enable the silicon to cool down between packets
  - Removing the requirement of calibrating of the frequencies between transmitting and receiving or receiving and transmitting packets.

BLE: Short Packets

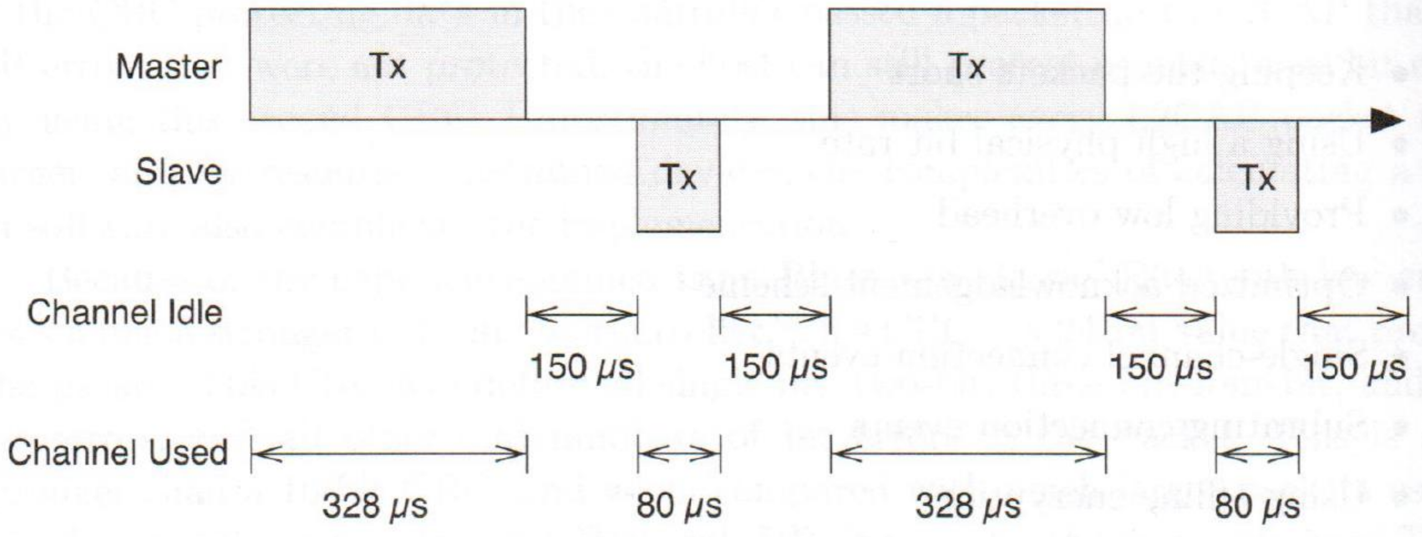


Figure 7–31 Short packets

- The addition of a 150uS cool down periods reduces the maximum duty cycle of transmitting data in one direction on an encrypted link
  - $\frac{maximum\ size\ packet + acknowledge\ packet}{total\ time\ to\ send\ and\ acknowledge\ data}$
  - $\frac{(328+80)}{(328+150+80+150)} = \frac{408}{708} = \sim 58\%$

Reducing bandwidth

- 58% is a very low duty cycle for wireless technology
  - For example, Bluetooth classic is 72% (Increase packet length and time has more effect on the numerator than the denominator)

BLE: High Bit Rate

- CMOS technology is optimized for gates that do not change state since in digital systems, most gates do not change state
  - Running a 2.4GHz oscillator used for the radio modulation is contrary to what CMOS is optimized, thus consuming a significant amount of energy
  - Since basic technology of the CMOS semiconductor defines a base amount of current/energy for the radio, the efficiency of the modulated signal becomes significant.
    - The quicker that a given amount of data can be transmit, the more efficient the radio
    - The BLE radio is designed for 1Msps transmit rates
    - If BLE could only transmit 250Ksps, the radio power would be 4x
  - Note, modulations schemes that are more complex and transmit data at higher data rates can result in more power/energy due to the complexity of the radio

BLE: Low Overhead

- As discussed, the short the packet, the more energy efficient the radio
  - Reducing the time that the radio is enabled and the time generating the 2.4GHz oscillator
  - BLE overhead includes:
    - Preamble
    - Access address
    - Header
    - Length
    - CRC
    - And optional MIC value

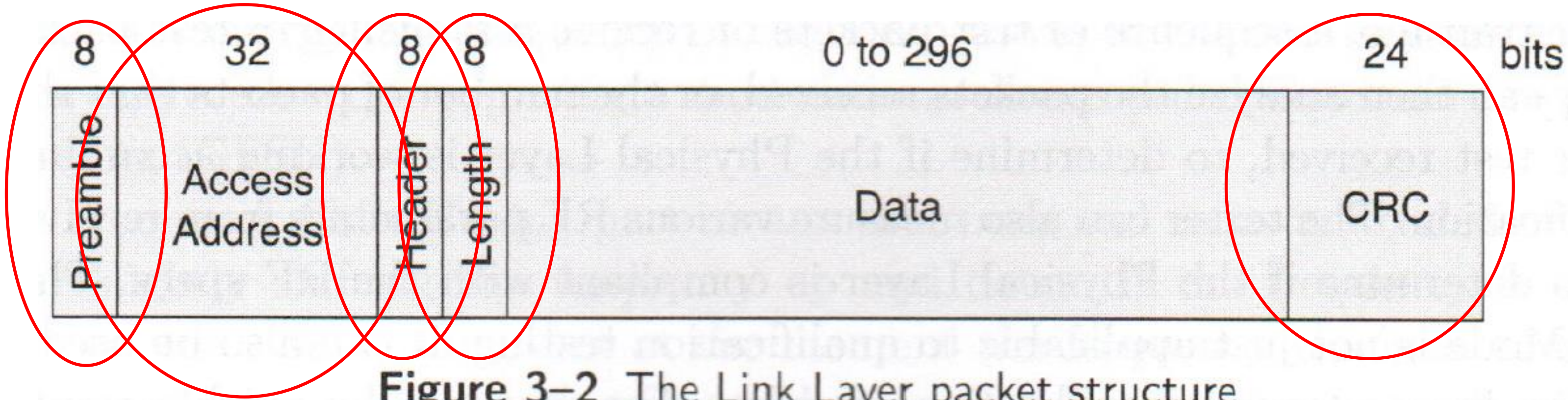


Figure 3–2 The Link Layer packet structure

BLE: Overhead

- Efficiency is measured as:
  - For an unencrypted packet, size of the application data compared with the total packet size required to transmit the application data
  - For an encrypted packet, the efficiency is lower, primarily because of the additional 4 octets of MIC included in each packet

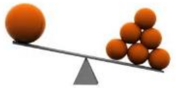
- Compared to other low energy radio technologies, the BLE efficiency is very good
  - For example, ZigBee has a packet overhead of 15 to 31 octets compared to BLE's 10 for unencrypted
  - With ZigBee transmitting 4x slower physical data rates than BLE, a short 4 octet application data in ZigBee could require up to 10 times more energy to transmit than BLE

Table 7–6 The Overhead for Application Data

Packet Type	Application Data Size (octets)	Overhead (octets)	Efficiency (%)
Unencrypted	4	10	29%
Unencrypted	8	10	44%
Unencrypted	16	10	62%
Unencrypted	27	10	73%
Encrypted	4	14	22%
Encrypted	8	14	36%
Encrypted	16	14	53%
Encrypted	27	14	66%

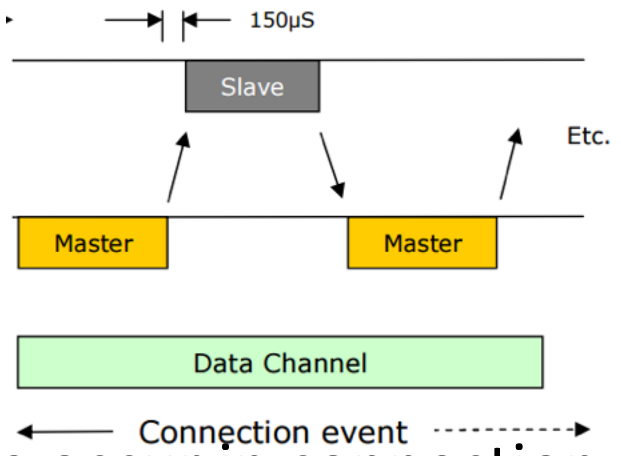
BLE: Acknowledgement Scheme

- The Link Layer acknowledgement scheme does not require an acknowledgement of a packet to be performed or even delivered immediately
  - This non-requirement of an acknowledgement is a departure from Bluetooth Classic
  - In Bluetooth Classic, the receiver must acknowledge the packet at the next opportunity it has to transmit
    - If the acknowledgement is not received immediately, the receiver must signal a negative acknowledgement in the next transmit packet



  - In BLE, every packet sent can acknowledge the last packet transmitted, even if this was transmitted some time ago
    - The BLE scheme enables the transmit acknowledgement to occur when convenient such as when it is ready to transmit for some other reason or allow it to finish transmitting a large amount of data quickly

BLE: Single-Channel Connection Events



- All communication between a master and a slave occur in connection events
  - A connection event is a packet transmitted by the master, followed by the slave, followed by a series of alternating packets send by the slave and master
  - During a connection event, the master and slave stay on the same frequency
  - The assumption is that if the master packet was successfully transmitted, the interference is low enough to enable a good channel for the slave response

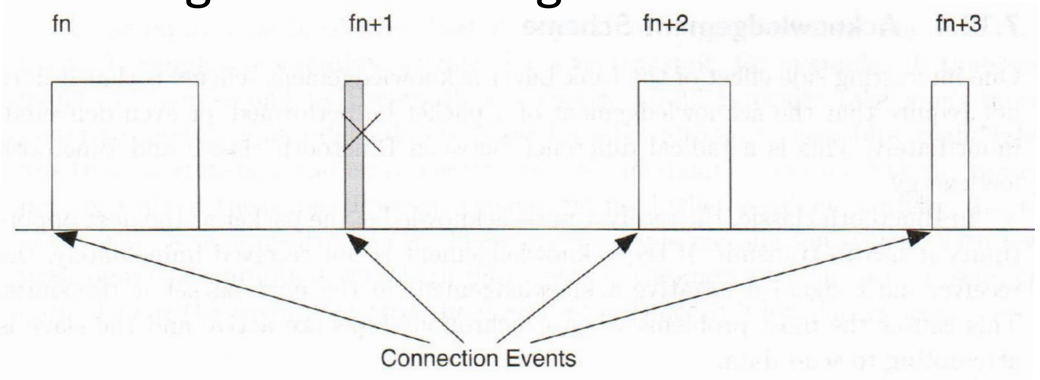


Figure 7–32 Single-channel connection events

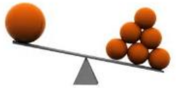
CSR: Bluetooth 4.0 Low Energy
http://chapters.comsoc.org/vancouver/BTLER3.pdf
Bluetooth Low Energy: The Developer's Handbook By Robin Heydon

BLE: Single Channel Connection Events

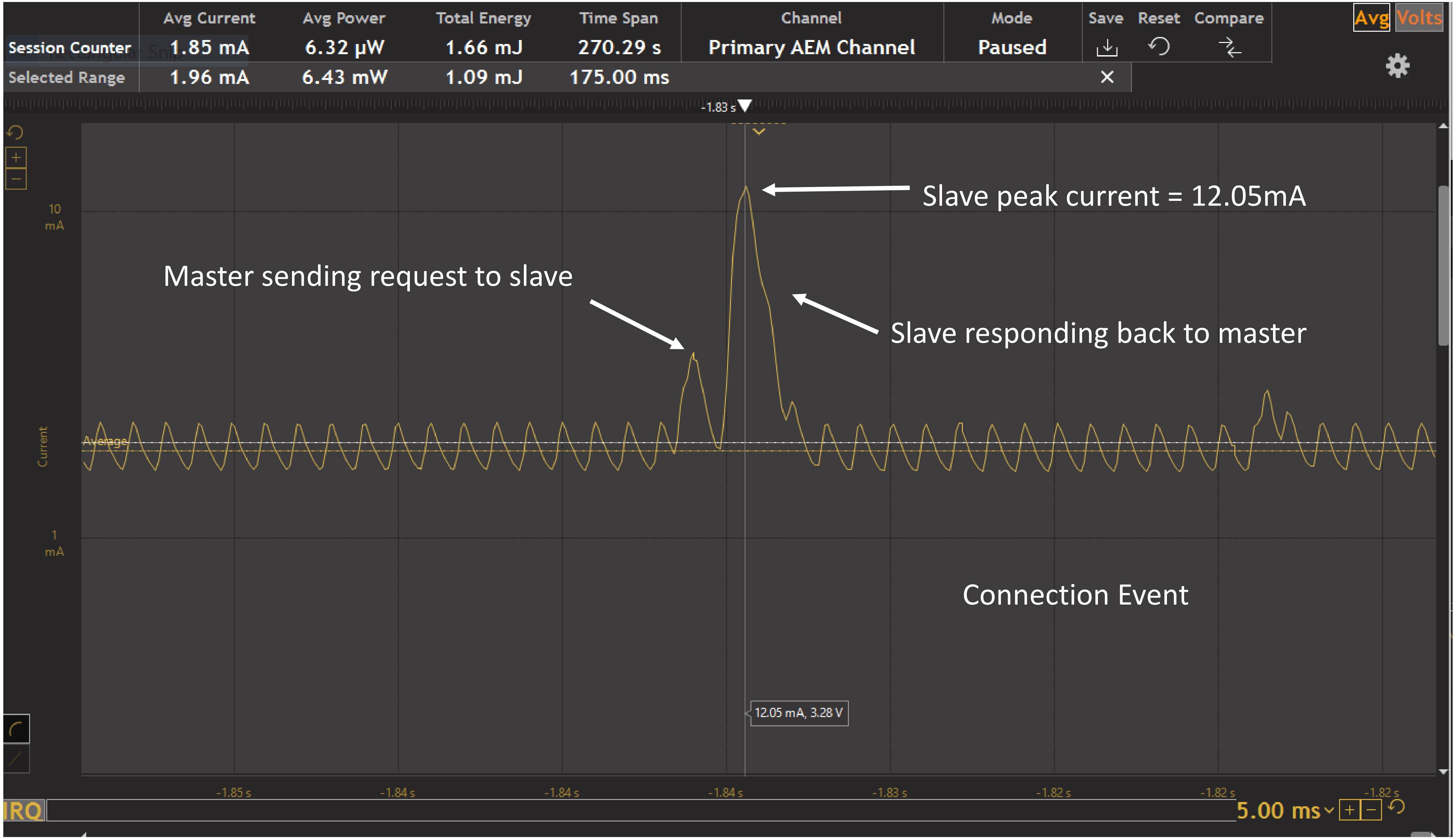
- If the assumption to use Single Channel Connection Events is that the channel is clear for the slave if open for the master, why not use this frequency channel all the time?
  - The master cannot signal this change to all the slaves
  - Consumes a lot of power to resynchronize the single frequency once the channel begins to begins to fail
  - With interference having a “bursty” nature, such as a WiFi packet occurring, staying on one channel continually begins to fail
  - The one-channel model also reduces the number of co-located networks because each will naturally drift to a clean frequency, and once filled, no more co-located networks would be able to be established without interfering on an existing network
- Frequency-hopping algorithm distributes network traffic in both time and frequency allowing for many more simultaneous networks to be active

BLE: Subrating Connection Events

- Low latency
  - Low latency means frequent contact between the slave and the master
  - Frequent contact means high use of the radio
  - High use of radio results in higher energy use and lower battery life
- Low power/energy
  - Low power means the slave is listening to the master infrequently
  - If the master is continually polling the slave and the slave has to listen to each of the polling connection events, it would not be low power
- How to balance between low latency and low power/energy?



  - Allow the slave to ignore most connection events from the master



Avg Current
Avg Power
Total Energy
Time Span
Channel
Mode
Save
Reset
Compare
Avg
Volts
Session Counter
1.85 mA
6.32 µW
1.66 mJ
270.29 s
Primary AEM Channel
Paused
Selected Range
1.96 mA
6.43 mW
1.09 mJ
175.00 ms
-1.83 s
Slave peak current = 12.05mA
Master sending request to slave
Slave responding back to master
10 mA
1 mA
Current
Average
Connection Event
12.05 mA, 3.28 V
-1.85 s
-1.84 s
-1.84 s
-1.84 s
-1.83 s
-1.82 s
-1.82 s
-1.82 s
IRQ
5.00 ms

BLE: Subrating Connection Events

- The feature of allowing the slave to ignore X number of connection events is called slave latency.
- The more connection events that a slave can miss, the lower power the slave can be.
- The limit to slave latency is that it cannot be longer than the supervision timeout of the connection.

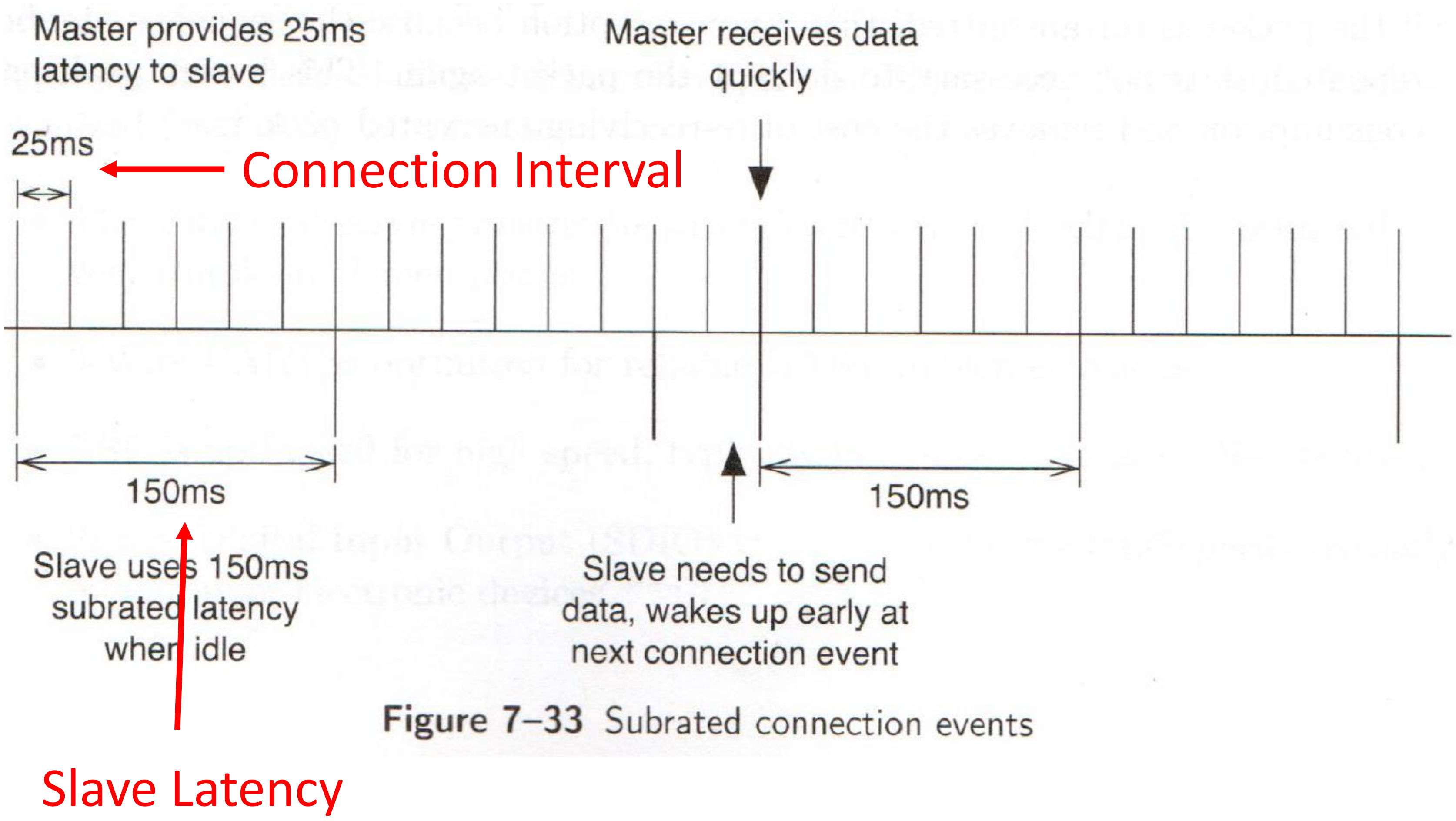


Figure 7–33 Subrated connection events

BLE: Subrating Connection Events

- It is not recommended to have a slave latency that gives fewer than 6 opportunities for the slave to resynchronize before the supervision timeout
- For example, if the supervision timeout is 600mS and the connection interval is 25mS, the slave latency should not be longer than 450mS
- Resulting in the slave to transmit data in an average of 25mS, connection interval, but only needing to connect 1 out of 24 connection events

Optimizing to the slave or less resource rich device

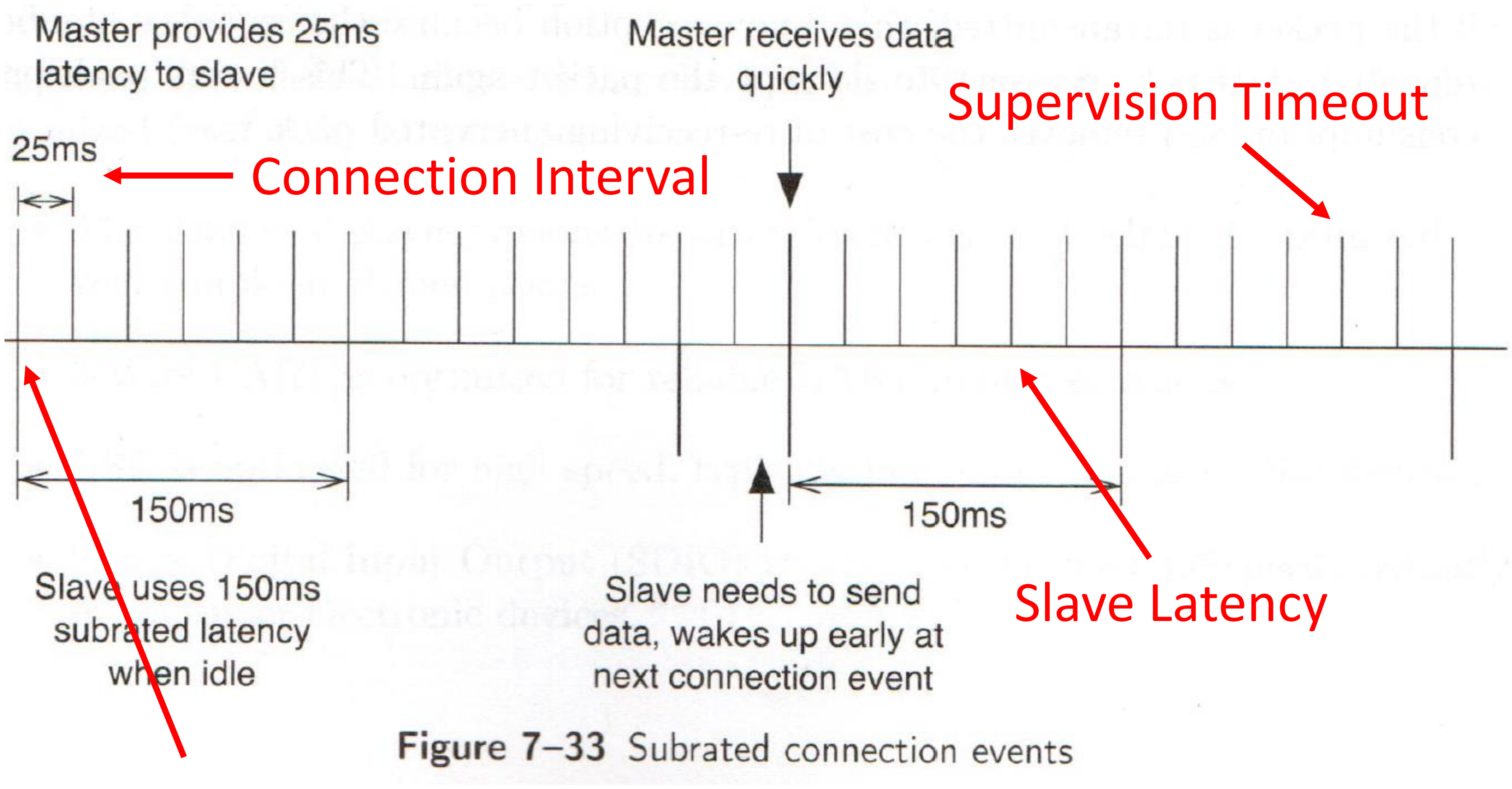
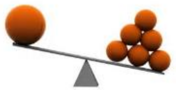


Figure 7–33 Subrated connection events

End of last master-slave connection event

BLE: Offline Encryption

- Encrypting data requires a significant amount of computational time and energy
  - Compute cipher blocks for the payload
  - Message authentication codes
  - Compute the authentication code itself
- For a maximum BLE packet, this would require seven iterations through the AES-128 encryption block consuming a large amount of energy
  - If the encryption had to occur real-time while the radio was on, the peak current would be significantly higher (higher I, less efficient. $P=I^2R$)



  - Resulting in higher peak currents from the button-cell battery and reducing the battery life

BLE: Offline Encryption

- Bluetooth Low Energy enables the encryption of the data and authentication code to be computed in the background
  - Before a packet is transmitted, the encryption of the data can be performed when the radio is still off
  - The encryption of the data does not depend on the sequence of the data, so it can be encrypted at anytime
    - The data can be retransmitted any number of times, and the encryption and the authentication code will not have to change
  - When receiving encrypted data, the CRC value is computed real time and is the only value that determines whether the data was received correctly.
    - The encrypted data can then remain in the Link Layer until the radio activity has stopped to decrypt the data

BLE: Peripherals

- For peripherals to operate extended time and possibly years on a button-cell battery, the states that the peripheral enters must be optimized
- This includes determining the optimal:
  - Advertising Interval
  - Connection Interval
  - Slave Latency
  - Access to attributes
  - Deciding to stay connected or to disconnect/reconnect

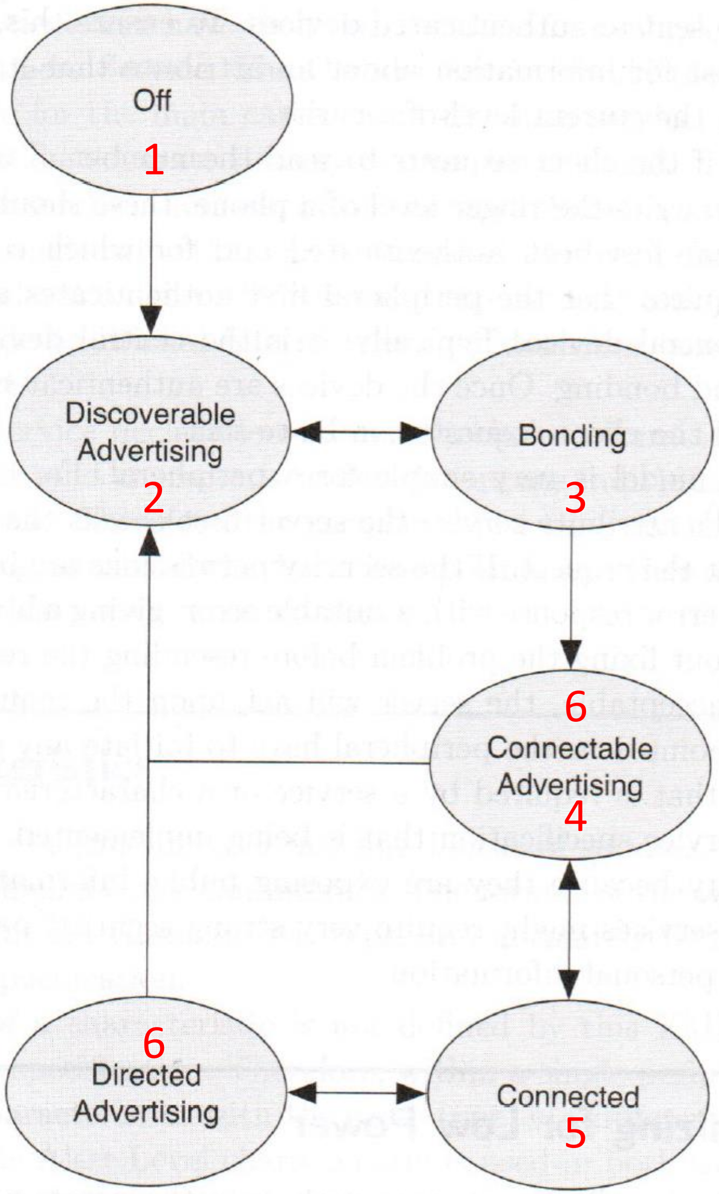


Figure 14–1 The typical states of a peripheral device