Wireless Protocols for IoT Part I: Bluetooth and Bluetooth Smart

Raj Jain
Professor of CSE
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

Audio/Video recordings of this class lecture are available online at:
http://www.cse.wustl.edu/~jain/cse574-24/

Student Questions

Next Q on 11-5

Overview

1. Bluetooth: Frame Format, Energy Management
2. Bluetooth Protocol Stack, Application Profiles
3. Bluetooth LE: Protocol Stack, PHY, MAC
4. Bluetooth and Wi-Fi Coexistence

Note: This is one in a series of lectures on WPANs. ZigBee and other networks are discussed in subsequent lectures.

Student Questions

Bluetooth

- Started with Ericsson's Bluetooth Project in 1994 for radio-communication between cell phones over short distances
- Named after Danish king Herald Blatand (AD 940-981) who was fond of blueberries
- Intel, IBM, Nokia, Toshiba, and Ericsson formed Bluetooth SIG in May 1998
- Version 1.0A of the specification came out in late 1999.
- IEEE 802.15.1, approved in early 2002, is based on Bluetooth Later versions were handled by Bluetooth SIG directly
- Key Features:
  - Lower Power: 10 mA on standby, 50 mA while transmitting
  - Cheap: $5 per device
  - Small: 9 mm^2 single chips

Student Questions

- Is Bluetooth transmission secure?

Yes. But in most wireless technologies (both Wi-Fi and Bluetooth), the initial connections require clear broadcasts. That gives away your privacy.
See Slide 11-31 on Beacons used by businesses to determine who you are.

Bluetooth Versions

- **Bluetooth 1.1**: IEEE 802.15.1-2002
- **Bluetooth 1.2**: IEEE 802.15.1-2005. Completed Nov 2003. Extended SCO, Higher variable rate retransmission for SCO + **Adaptive frequency hopping** (avoid frequencies with interference).
- **Bluetooth 2.0** + **Enhanced Data Rate (EDR)** (Nov 2004): 3 Mbps using DPSK. For video applications. Reduced power due to reduced duty cycle
- **Bluetooth 2.1** + EDR (July 2007): Secure Simple Pairing to speed up pairing
- **Bluetooth 3.0**+ **High Speed (HS)** (April 2009): 24 Mbps using Wi-Fi PHY + Bluetooth PHY for lower rates
- **Bluetooth 4.0** (June 2010): Low energy. Smaller devices require longer battery life (several years). New incompatible PHY. **Bluetooth Smart or BLE**
- **Bluetooth 4.1**: 4.0 + Core Specification Amendments (CSA) 1, 2, 3, 4
- **Bluetooth 4.2** (Dec 2014): Larger frames, security/privacy, IPv6 profile

Ref: ITL, "Security of Bluetooth Systems and Devices," http://csrc.nist.gov/publications/nistbul/august-2012_itl-bulletin.pdf

Student Questions

- Can you explain what SCO is?

Yes, later in Slide 11-16.

- You listed Bluetooth1.1-4.2, so do we need to be familiar with all these and their features?

Yes, key features.

Bluetooth 5

- June/December 2016
- Enhanced Bluetooth low energy
- Supports many more devices at low energy, e.g., headphones,
- Dual-audio: two headphones playing two streams
- 2X Data rate using a new modulation ⇒ 2 Mbps

Or 4X range 800 ft using a special coding (Good for beacons)

Long-Range mode allows 1.6 km at 125 kbps

- 8X broadcast capacity by changing the advertising procedure. 255B instead of 31B with v4.2
- aptX compression allows CD quality audio over 1 Mbps. Bluetooth 5.0 allows better quality using 2 Mbps.
- +20 dBm transmit power in LE mode ⇒ Good for bursts
- Both ends must be Bluetooth 5 to benefit. Backward compatible with older devices using older modes

Ref: Madhur Bhargava, " IoT Projects with Bluetooth Low Energy," Packt Publishing, August 2017, 278 pp., ISBN:978-1-78839-683-7 (Safari Book).

Student Questions

- Why is version 5 at 2 Mbps when version 3.0 on the previous slide said 24 Mbps?

This is "Low energy."

- What new modulation is being used?

Gaussian Frequency Shift Keying (GFSK) vs. older Differential Quadrature Phase-Shift Keying (DQPSK).

- Can one device with Bluetooth 4 and another device with BLE communicate?

Yes. It is a matter of implementation. New features will not be there in older devices, but newer ones will use older protocols when needed.

- Do two devices have to use the same Bluetooth protocol for communication, regardless of what version?

Yes. The version is negotiated first.

- What is the most common use of Bluetooth?

Headsets

Bluetooth 5

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Student Questions

- Since the data rate of BT 5 are even worse than 802.11n, and in daily cases, their ranges are quite similar, why was it not replaced?

11n is not compatible with other BTs while BT5 is.

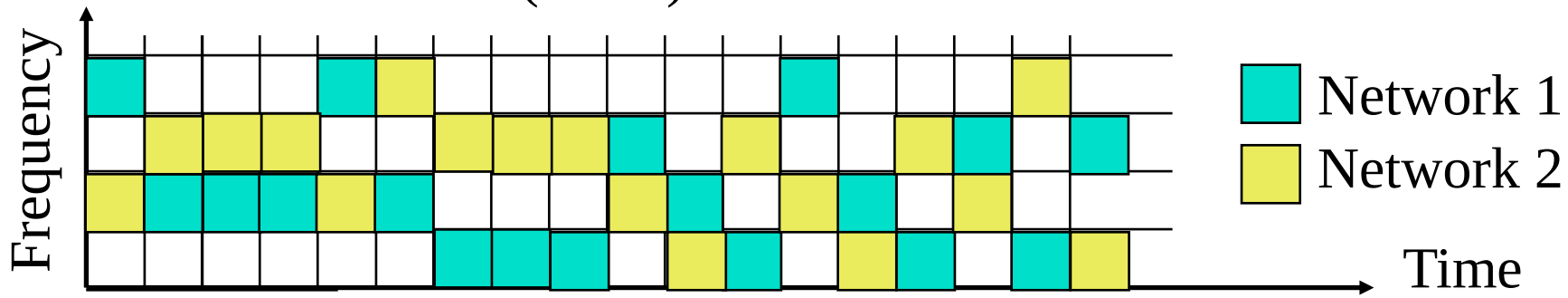
- Does '255B' mean 255 bytes? I understand that the figure 255 comes from (2^8), but how does the figure 31 come about?

Yes, B=Bytes, b=bits.
$255=2^8-1$, $31=2^5-1$
Possibly, the limits were set to control overhead.These are limits on broadcast packets. 512B for normal data packets. Of these 4 bytes are used for some overhead. The payload is only 251 and 27B only.

Next Q on 11-6

Bluetooth: Details

- **Frequency Range:** 2402 - 2480 MHz
  (total 79 MHz band) 23 MHz in some countries, e.g., Spain
- **Data Rate:** 1 Mbps using 1 MHz (Nominal) 720 kbps (User)
- **Radio Frequency hopping:** 1600 times/s ⇒ 625 us/hop
- **Security:** Challenge/Response Authentication. 128b Encryption
- **TX Output Power:**
  - Class 1: 20 dBm Max. (0.1W) – 100m
  - Class 2: 4 dBm (2.5 mW)
  - **Class 3**: 0 dBm (1mW) – 10m



Ref: http://www.bluetooth.com/, http://www.bluetooth.org/, http://grouper.ieee.org/groups/802/15/index.html
http://www.cse.wustl.edu/~jain/cse574-24/

Student Questions

- Given that frequency hopping doesn't sense the spectrum, is there a lot of interference?

Not really. With 79 channels, the probability of colliding is 1/79^2 or ≈10^{-4}.

- At each time slot, we use only 1 MHz of the whole available 79 MHz, but we may change the frequency at each time slot. Correct?

Yes.

- How can the receiver know which 1 mHz channel to switch to for reception given constant frequency hopping?

Using pseudorandom number generation. If you start with the same seed, you get the same sequence.

- How did we calculate 625us/hop?

1/1600 = 625

❖Can you explain what the TX Output Power classes mean?

More powerful devices can reach farther and have different applications

Next Q on 11-10

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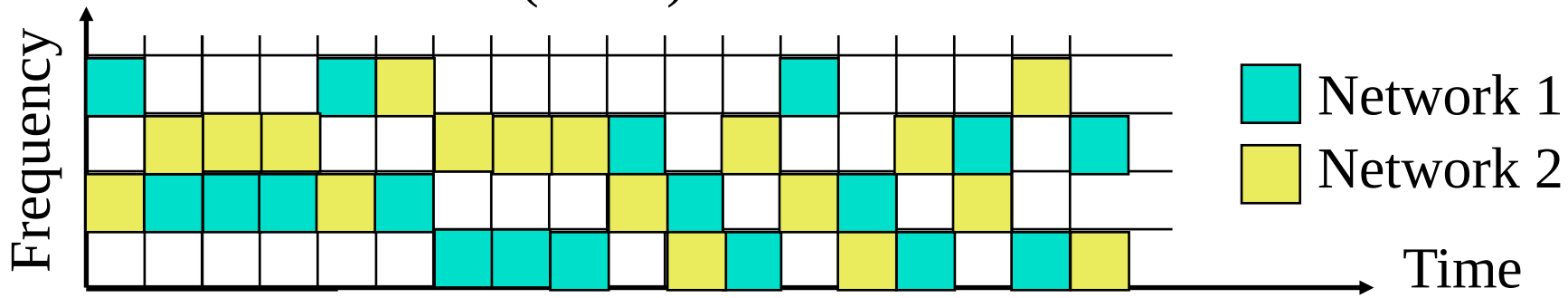

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Student Questions

- Because Bluetooth is frequency hopping in the same band as Wi-Fi, is it possible if all Wi-Fi channels are in use that Bluetooth could never transmit? Does it handle this in any way?

It happens rarely and your Bluetooth connection is dropped but probably made again. There are several methods in the standard to avoid this. For example, a single device will not use the same band for both at the same time.

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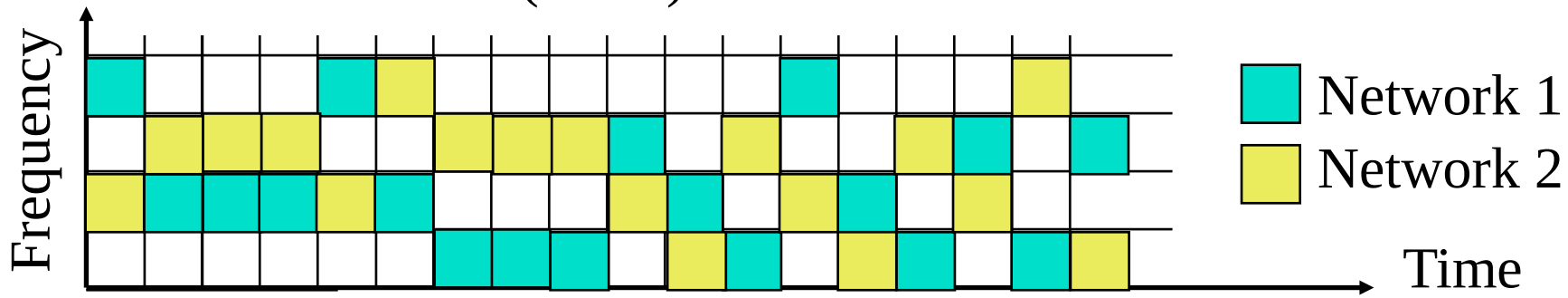

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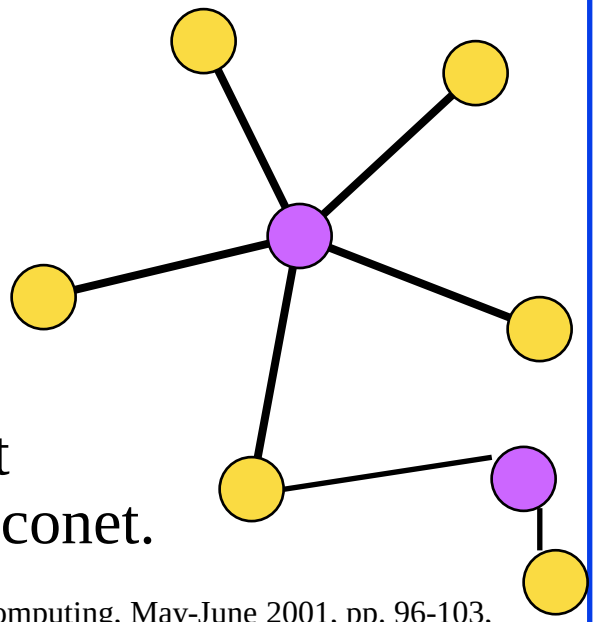
Student Questions

Piconet

- Piconet is formed by a master and many slaves
  - Up to 7 active slaves.
    Slaves can only transmit when requested by the master
  - Up to 255 Parked slaves (See Slide 11-11)
- Master polls active slaves for transmission
- Each station gets an 8-bit parked address
  $\Rightarrow$ 255 parked slaves/piconet
- The parked station can join in 2us.
- Other stations can join in more time.
- **Scatter net**: A device can participate in multiple Pico nets $\Rightarrow$ Timeshare and must synchronize to the master of the current piconet.



Ref: P. Bhagwat, "Bluetooth Technology for short range wireless Apps," IEEE Internet Computing, May-June 2001, pp. 96-103, bluetooth.pdf (Must read)

Student Questions

- Is a Piconet specific to bluetooth, or do other protocols use similar networks?

This is quite common amont IoT protocols. We will see similar (bigger networks) in ZigBee. The names are different.
In Wi-Fi we call these Service Set and need a dedicated Access Point.

- In scatter net, does the device need to synchronize with two masters or just one?

Synchronize to the master it is talking to at the moment, like working two jobs.

- Could two devices make up a piconet?
- *Yes. That's the most common case.* Can a node simultaneously be both master and slave in a piconet? If not, should it form by making two channels or something?

Masters can easily speak to the slaves. There is no need to be a slave. However, in a scatter net, you may be a slave in one and a master in another.

- Can you explain point 4?

Parked stations have 8-bit addresses, and their info is already with the master.

- Point 1, part two, do you mean inactive instead of parked?

Parked do not have 3-bit addresses.
Actives have 3-bit addresses. They include those transmitting, sniffing, or on hold. I meant parked.

Piconet

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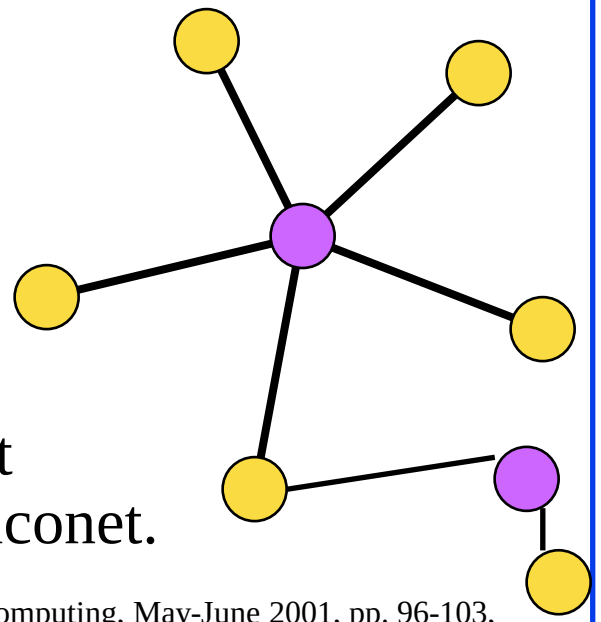

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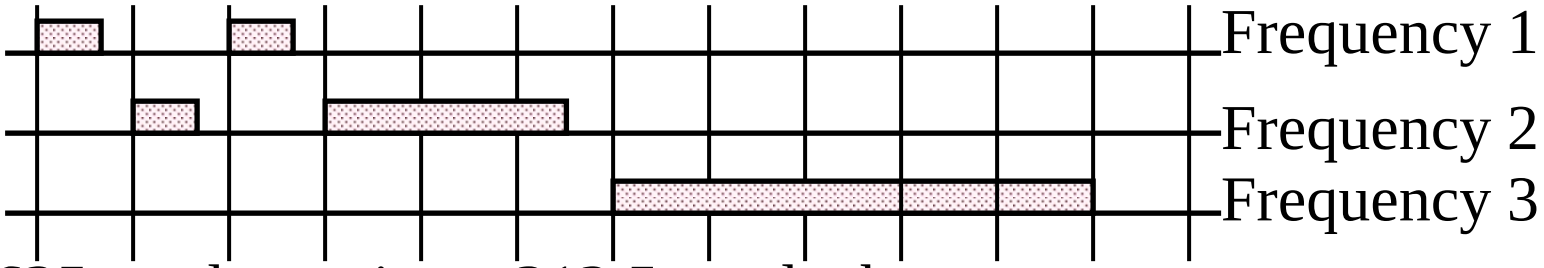
Student Questions

- How does a Scatter net differ from a Piconet, and how does it allow devices to participate in multiple Piconets?

Timeshare and synchronize with both masters. Like a person with two jobs.

Frequency Hopping Sequences



- 625 μs slots using a 312.5 μs clock
- Time-division duplex (TDD)
  ⇒ Downstream and upstream alternate
- Master starts in even-numbered slots only.
- Slaves start in odd-numbered slots only
- Slaves can transmit in one slot right after receiving a frame from the master
- Frames = 1 slot, 3 slot, or 5 slots long
- The frequency hop is skipped during a frame.

Student Questions

- "How is the frequency hop coordinated?

Frequency hopping uses a pseudo-random number generated. Two nodes that use the same parameters and seed will generate the same sequence of numbers. The nodes interchange the parameters and seed on connection initialization.

- What happens in the event of a frequency collision with another bluetooth transmission?

The collision is limited to one frequency hop or less. Then they go on different ways.

- Does it mean that slaves start their transmission in odd-numbered slots and continue for 1, three, or five consecutive slots?

Yes.

- In the picture, which one is the master node?

The figure shows three frequencies, not stations. It is all one station. It could be master or slave, depending on whether the first slot is even or odd-numbered.

- Are the masters and slaves the frequencies themselves? So would the master be Frequency 2 in the example image?

No. The figure shows only frequency hopping by one station.

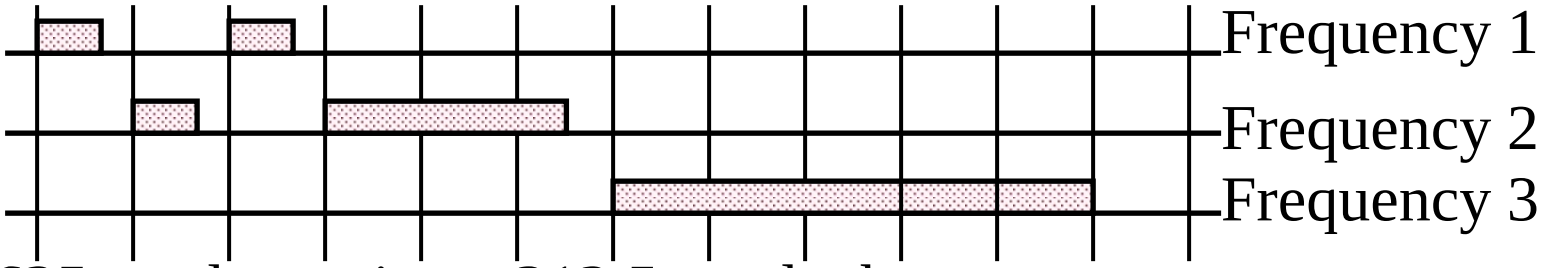
- Does this mean that the master always transmit in even numbers only?

No. They start in even numbered slots. They may continue for 1, 3 or 5 slots.

- Is BLE still following this even/odd-slot scheme for master/slaves? It seems inefficient.

Yes.

Frequency Hopping Sequences



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Student Questions

- Will the seed of the hopping sequence generator first be sent to the slaves?

It is told at connection setup.

- Can the frame length be non-integer like what it is in the picture? If so, is that OK if it is close to an even-number length?

The frames can be fractional in length. But slots are aligned, and the transmissions start at slot boundaries only, regardless of the previous transmission.

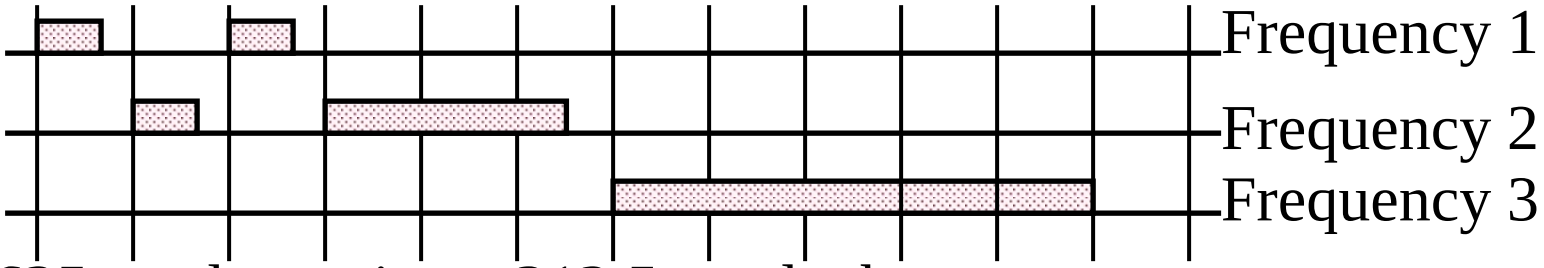
- ❖ Can a frame size be larger than 5 slots?

Frames larger than 5 slots are sent in multiple frames.

- Why does the Master device start in even-numbered slots while the Slave device starts in odd-numbered slots in Bluetooth communication?

This was done to keep the logic simple. It works as long as all frames are odd-sized.

Frequency Hopping Sequences



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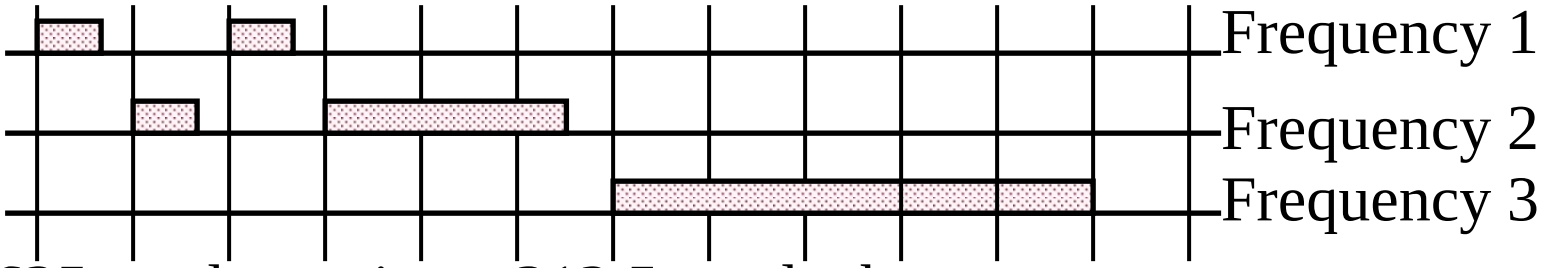
Student Questions

- Regarding Bluetooth's frequency hopping: I understand that collisions are rare/limited to one frequency hop, but is there a level of congestion at which collisions make Bluetooth devices unusable? Or is the ceiling so high it's not a practical concern?

It is a concern. There is no prespecified ceiling. However, if a packet is lost more than 4 times, TCP disconnects and your Bluetooth connection disconnects and my try to reconnect immediately. There are a few other solutions that will be discussed later in this module.

Frequency Hopping Sequences



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Student Questions

- Do the slaves/masters only start in odd/even numbered slots, or do they stay there? Can a master hop into an odd-numbered slot and vice-versa for a slave?

No. The standard requires both slaves and masters to follow the odd/even rule.

Bluetooth Frame Format

Access Code	Baseband/Link Control Header	Data Payload
72b	54b	0-2744b

- Frames can be up to five slots long. Five slots =3125 us.
- Access codes:
  - Channel access code identifies the piconet
  - Device access code for paging requests and response
  - Inquiry access code to discover units
- Header: member address (3b), type code (4b), flow control, ack/nack (1b), sequence number, and header error check (8b) 18b. Header is encoded using 1/3 rate FEC resulting in 54b
- Synchronous traffic has periodic reserved slots.
- Other slots can be allocated for asynchronous traffic

Student Questions

- Do units mean other Bluetooth devices?

Yes.

- In this slide, you said if we have a 3-slot frame, we can multiply by 3/5 and get about 1200. Why do we not use 3125 * 3/5 = 1875?

Yes. Your calculation is correct.

- What layer is this?

MAC

- 3125 bit or Microsecond?

Microseconds

- Point 3, can you break down the 54b?

(3+4+1+1+1+8)×3=18×3=54

- Is the Bluetooth frame format the same for every generation of Bluetooth?

Yes, but EDR adds a few extra fields in the data.

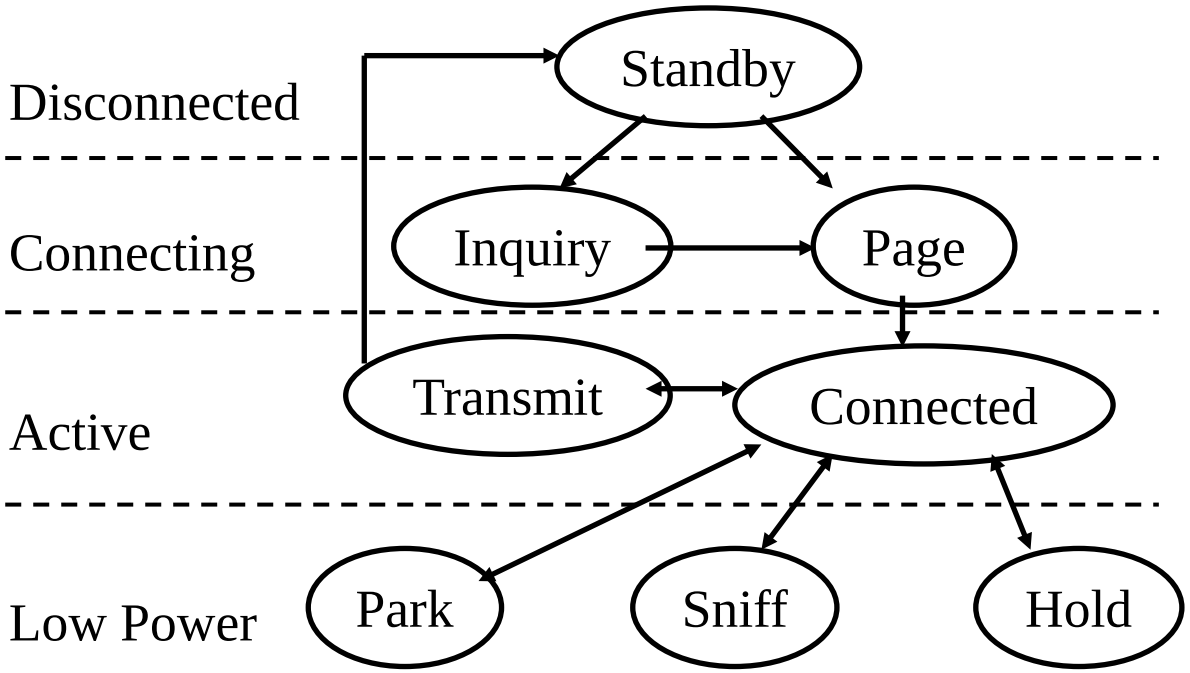
- Can you explain why five slots=3125 bits?

3125 us. Each slot is 625 us.

- Could you go over how the slots and frames work? How can the header have 126 bits, the payload is 0-2745 bits, but five slots have a max of 3125 bits. I'm just having a hard time figuring out the math of it.

3125 bits has been corrected to 3125 us. 2745 bits has been corrected to 2744 bits. The maximum frame is 2870 bits. There can be some gaps after the frames.

Bluetooth Operational States



- **Standby**: Initial state
- **Inquiry**: Master sends an inquiry frame. Slaves scan for inquiries and respond with their address and clock after a random delay (CSMA/CA)

Student Questions

- Is there a handshake involved between the page state and the connected state? what information does the master and slave exchange?

Several messages are exchanged including the type of service.

- While on Hold, could that be when a device connects to another master to communicate with it?

Yes. It could.

- Can a device be connected to more than one master at a time?

No. But in scatter nets, it timeshares between two masters.

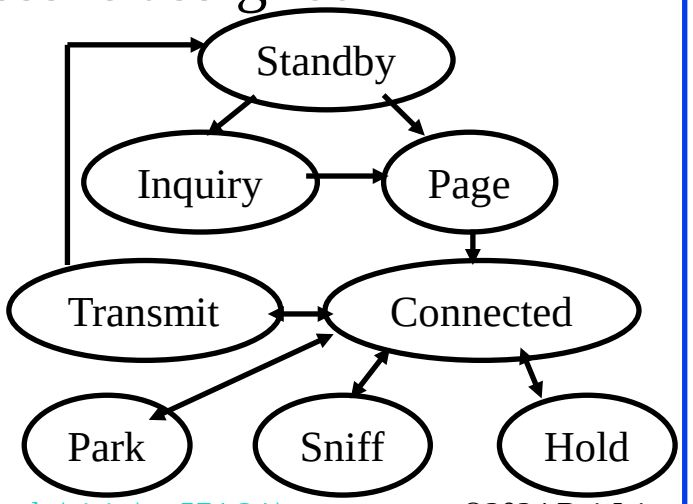
- Are we expected to to know the flow of the operational states? Or just understand what occurs in each state?

Yes, you need to understand the flow.

Next Q on 11-22

Bluetooth Operational States (Cont)

- **Page**: Master in page state invites devices to join the piconet. Page message is sent in 3 consecutive slots (3 frequencies). Slave enters the page response state and sends the page response, including its device access code.
- Master informs slave about its clock and address so that slave can participate in the piconet. Slave computes the clock offset.
- **Connected**: A short 3-bit logical address is assigned
- **Transmit**:



Student Questions

- What is the clock offset?

Offset=How far is your tick from the master's tick?

- In the video, the standby state transitions to the inquiry state and then to the page state. However, the figure shows that the standby state can transition directly to the page state. Is this correct?

Yes, if a page response is heard, a station can transition to page state even w/o inquiry.

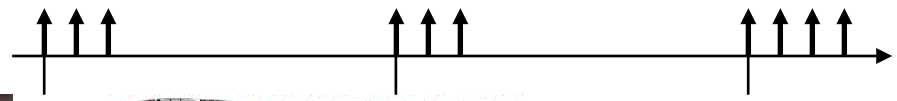
- You mentioned "Slave computes the clock offset", can you explain in detail how?

Clock offset = Difference in the clocks. The value of the clock helps determine the random seed.

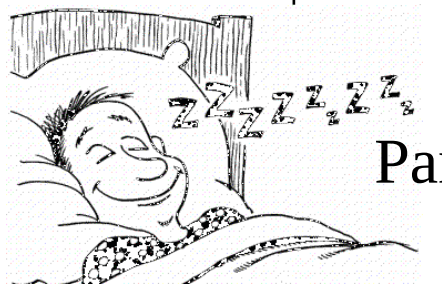
Energy Management in Bluetooth

Three inactive states:

1. **Hold**: No Asynchronous Connection List (ACL). Synchronous Connection Oriented (SCO) continues.
   A node can do something else: scan, page, inquire
2. **Sniff**: Low-power mode. Slave listens after fixed sniff intervals.
3. **Park**: Very Low-power mode. It gives up its 3-bit active member address and gets an 8-bit parked member address. Wake up periodically and listen to beacons. Master broadcasts a train of beacons periodically



Sniff



Park

Student Questions

- ❑ Do applications control what state the Bluetooth device is in? Does the application profile specify this?

Yes, applications follow the needs of the user.

- ❑ How could the nodes know they should turn to sniff or park state? Can a node in the sniff state turn to the park state?

Yes, that's what they do. Like sleep and hibernate states in computers.

- ❑ What do you mean by "slaves listen after fixed sniff intervals"?

They set an alarm and go to sleep.

- ❑ Is the only difference between sniff and park that they do not give up their address in a sniff?

The sleep intervals are different.

- ❑ Is the difference between park and standby (disconnected) only the 8-bit parked member address?

Standby=Disconnected

Energy Management in Bluetooth

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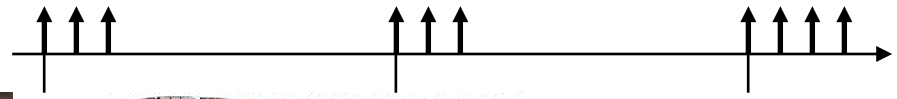
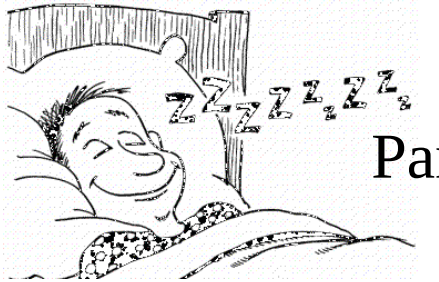


Sniff



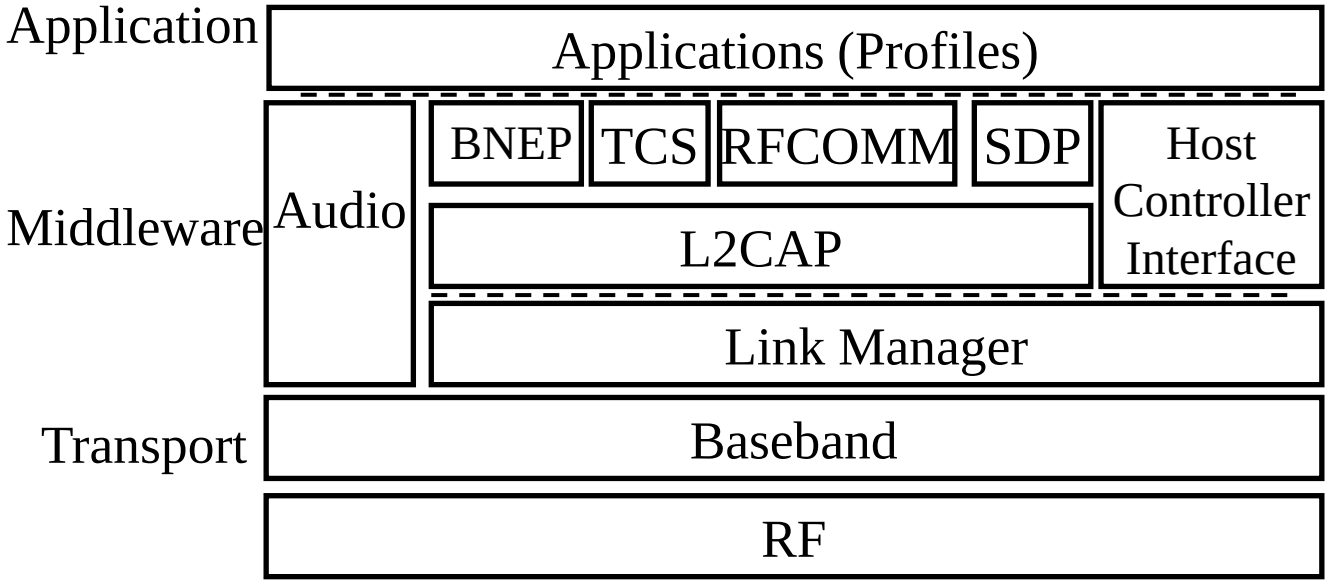
Park

Student Questions

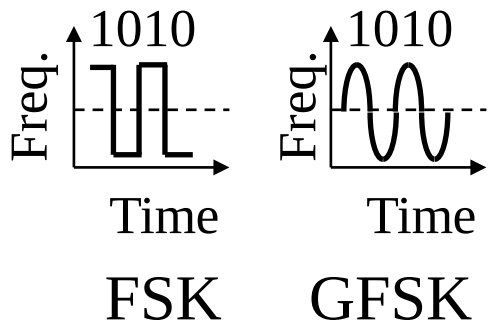
- In Park, the device gives up it's 3-bit logical address. Can we interpret this as meaning that we are limited in the number of ACTIVE Bluetooth devices we can use, but can connect to more than that?

Yes.

Bluetooth Protocol Stack



- **RF**: Frequency hopping Gaussian Frequency Shift Keying (GFSK) modulation
- **Baseband**: Frequency hop selection, connection, MAC



Student Questions

- Why does Audio Middleware not need a Link Manager?

Audio was given a fast path since it is the most latency sensitive application and was the primary application in the beginning.

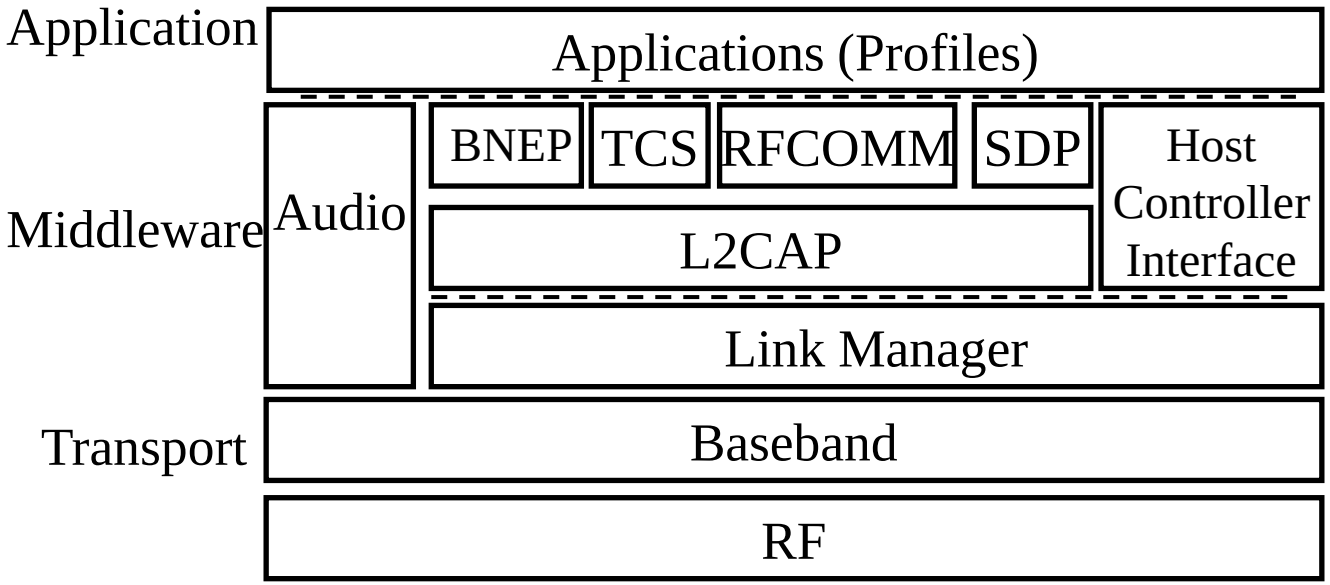
- How is the security of Bluetooth compared to Wi-Fi?

Wi-Fi security is more mature. Bluetooth is catching up. See "Beacons" at end of this lecture about violation of privacy.

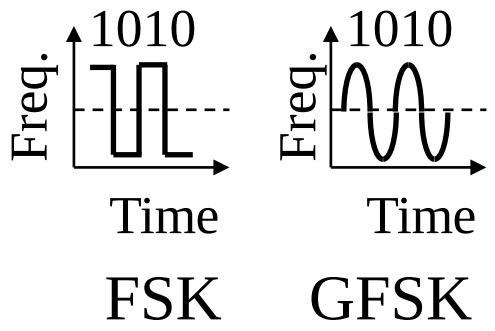
- Based on the diagram, GFSK seems to make less sense than normal FSK? Why use it?

Frequency shift is not visible from the diagram. GFSK is claimed to have lower power utilization.

Bluetooth Protocol Stack



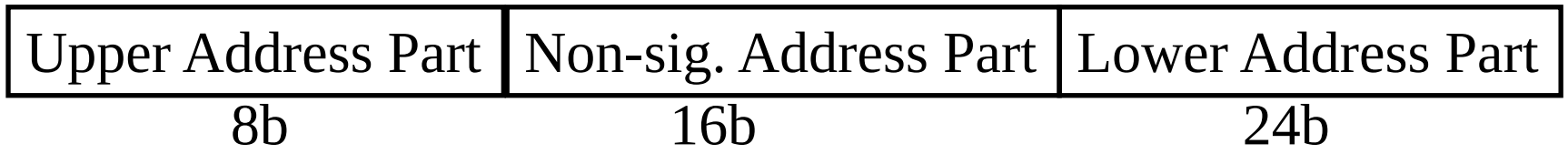
- **RF**: Frequency hopping Gaussian Frequency Shift Keying (GFSK) modulation
- **Baseband**: Frequency hop selection, connection, MAC



Student Questions

Baseband Layer

- Each device has a 48-bit IEEE MAC address
- three parts:
  - Lower address part (LAP) – 24 bits
  - Upper address part (UAP) – 8 bits
  - Non-significant address part (NAP) - 16 bits
- UAP+NAP = Organizationally Unique Identifier (OUI) from IEEE
- LAP is used in identifying the piconet and other operations
- Clock runs at 3200 cycles/sec or 312.5 μs (twice the hop rate)



Student Questions

- What part of the addresses is pre assigned and what is not?

All 48-bits are assigned to a device. In IEEE 802 addresses, the first 24 bits indicate the manufacturer.

- What is the implication or the effect of the 5th point?

Slot is two clock cycles long.

- How do we make all devices have a unique MAC Address? How about non-IEEE devices?

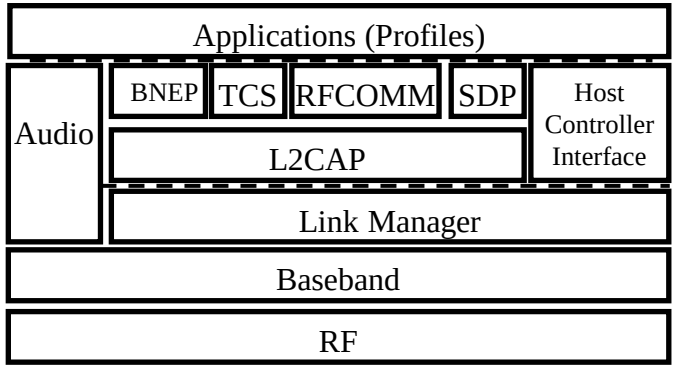
There are no Non-IEEE Bluetooth devices. IEEE does allow global and local addresses.

- What do UAP and NAP identify?

NAP is used for some functions.

Bluetooth Protocol Stack (Cont)

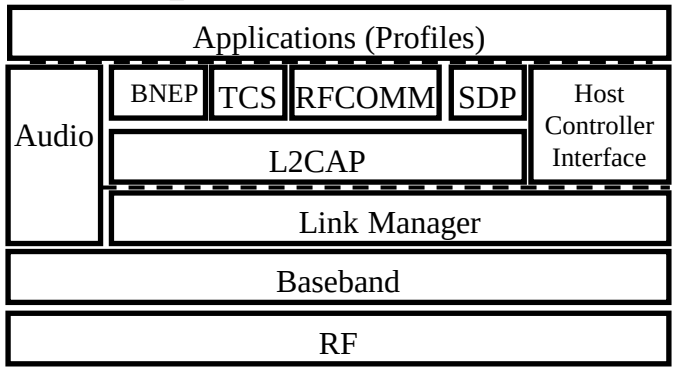
- **Link Manager:** Negotiate parameters, Set up connections
- **Logical Link Control and Adaptation Protocol (L2CAP)**:
  - Protocol multiplexing
  - Segmentation and reassembly
  - Controls peak bandwidth, latency, and delay variation
- Host **Controller Interface**: Chip-independent interface to Bluetooth chip. Allows the same software to run on all chips.
- **RFCOMM Layer**: Presents a virtual serial port
  - Sets up a connection to another RFCOMM
- **Service Discovery Protocol (SDP):** Devices can discover the services offered and their parameters



Student Questions

Bluetooth Protocol Stack (Cont)

- **Bluetooth Network Encapsulation Protocol (BNEP):** To transport Ethernet/IP frames over Bluetooth
- **IrDA Interoperability protocols**: Allow existing IrDA applications to work w/o changes. IrDA object Exchange (IrOBEX) and Infrared Mobile Communication (IrMC) for synchronization
- **Audio** is carried over 64 kbps over SCO links over baseband
- **Telephony control specification binary (TCS-BIN)**: Call control including group management (multiple extensions, call forwarding, and group calls)
- **Application Profiles**: Set of algorithms, options, and parameters.



Student Questions

- What are the SCO links over the baseband?

Synchronous Connection Oriented (SCO) operation is used for voice/video. Fixed slot positions are reserved in both directions. Provides a circuit-switched link-like service. Asynchronous operations are used for data and control.

- In the video, it is mentioned that phone calls and music are two separate applications. So, why is there an audio component in the middleware?

They need different profiles but both use the audio component.

End of Part 1

Application Profile Examples

- Headset Profile
- Global Navigation Satellite System Profile
- Hands-Free Profile
- Phone Book Access Profile
- SIM Access Profile
- Synchronization Profile
- Video Distribution Profile
- Blood Pressure Profile
- Cycling Power Profile
- Find Me Profile
- Heart Rate Profile
- Basic Printing Profile
- Dial-Up Networking Profile
- File Transfer Profile

Ref: Bluetooth SIG, "Adopted Bluetooth Profiles, Services, Protocols and Transports," https://www.bluetooth.org/en-us/specification/adopted-specifications

Student Questions

- With profiles, can you only make applications based on the predefined profiles, or can you make new profiles as needed?

Any changes in profiles need to be approved by Bluetooth SIG, otherwise, different manufacturers devices will not interoperate. New profiles are being added by the SIG regularly.

- At the most basic definition, is an application profile just a saved configuration of options?

Yes, standard options and parameters for each application.

Bluetooth Smart

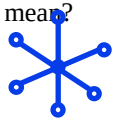
- **Low Energy**: 1% to 50% of Bluetooth classic
- **For short broadcast**: Your body temperature, Heart rate, Wearables, **sensors**, automotive, industrial.
  Not for voice/video, file transfers, …
- **Small messages**: 1Mbps data rate but throughput not critical.
- **Battery life**: In years from coin cells
- **Simple**: Star topology. No scatter nets, mesh, …
- **Lower cost** than Bluetooth Classic
- New protocol design based on Nokia's **WiBree** technology.
  It shares the same 2.4GHz radio as Bluetooth
  ⇒ Dual-mode chips
- All new smartphones (iPhone, Android, …) have dual-mode chips

Student Questions

- Why did Bluetooth use 2.4GHz frequency? Isn't this band already crowded by Wi-Fi?

When Bluetooth started there was not much choice. Also others would have been more expensive.

- What does star topology mean?



- Is Bluetooth smart the rebranded version of WiBree?

Yes.

- Bluetooth Smart uses 1-50% of the energy Bluetooth Classic uses. That seems like quite a wide range. Why is that?

Depends on the frequency of interrupts the savings is more or less. If you do high-frequency sensing, the energy savings may be less.

Bluetooth Smart

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Student Questions

- In my views, they are quite easy to interfare with each other when using 2.4G Wi-Fi and BT at the same time, it that right?

As discussed yesterday, hopping minimizes interference. Also, BT and Wi-Fi on the same device do not interfere.

- If Bluetooth smart is the same frequency and same data rate as Bluetooth classic, how is it 1% of the power?

There is much more sleep if there are no interruptions—also, a different design.

Bluetooth Smart

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- All new smartphones (iPhone, Android, …) have dual-mode chips

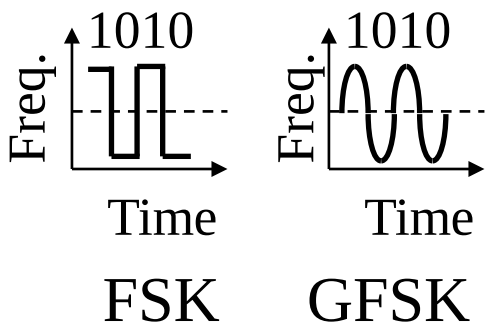
Student Questions

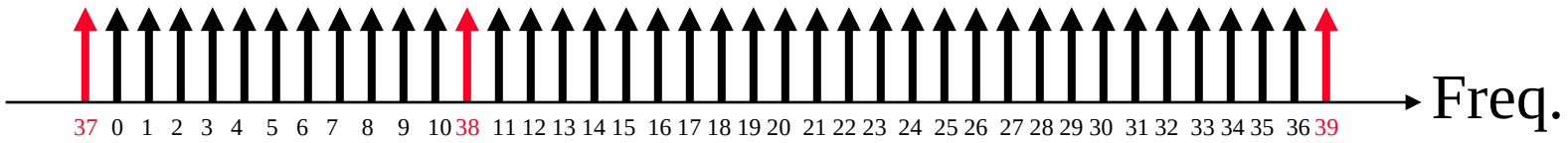
- Why does it say that the throughput of Bluetooth is not crucial? Is the reason that the messages from the device implementing Bluetooth Smart are too short?

Yes, they are not high-throughput applications.

Bluetooth Smart PHY

- 2.4 GHz. 150 m open field
- Star topology
- 1 Mbps Gaussian Frequency Shift Keying
  Better range than Bluetooth Classic
- Adaptive Frequency Hopping. 40 Channels with 2 MHz spacing.
- 3 channels reserved for advertising and 37 channels for data
- Advertising channels specially selected to avoid interference with Wi-Fi channels





Ref: J. Decuir, "Bluetooth 4.0: Low Energy," 2010,
https://californiaconsultants.org/wp-content/uploads/2014/05/CNSV-1205-Decuir.pdf

Student Questions

- Can you clarify what advertising is vs Data?

Explained in the next slide.

- Could you explain what adaptive frequency hopping is? What makes it "adaptive," and how is that different than how Bluetooth Classic frequency hops?

The device exchanges a "Slot Availability Mask (SAM)" listing channels with low interference, and then both hop on this subset. Useful when a node is already using a set of channels for Wi-Fi.

- Till which Bluetooth version that 79 channels instead of 40 are used for hopping.

V4

- Most phones can only use Bluetooth at a short distance; does it set a limit, or it because the field is not open enough?

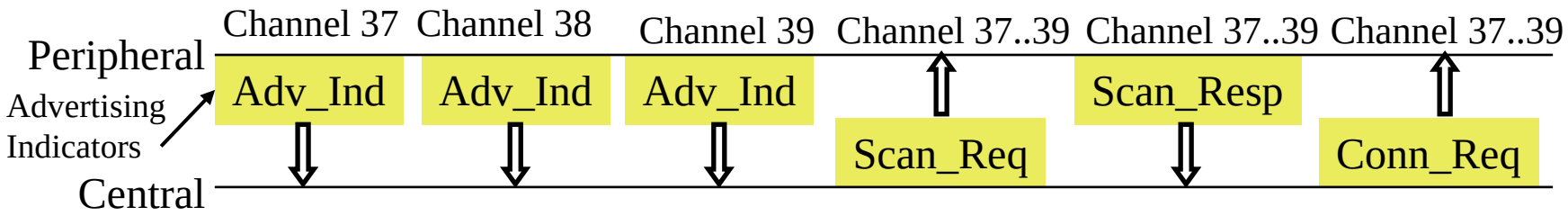
There is a power limit, no distance limit. Open fields help.

- Why are the channel numbers not in order, with 37 appearing to the left of 0?

Yes, the advertising channels are sequenced from 37-39.

Bluetooth Smart MAC

- Two Device Types: "**Peripherals**" are simpler than "**central.**"
- Two PDU Types: Advertising, Data
- **Non-Connectable Advertising**: Broadcast data in clear
- **Discoverable Advertising**: Central may request more information. Peripheral can send data without connection
- **General Advertising**: Broadcast presence wanting to connect. Central may request a short connection.
- **Directed Advertising**: Transmit signed data to a previously connected master



Ref: J. Decuir, "Bluetooth 4.0: Low Energy," 2010, https://californiaconsultants.org/wp-content/uploads/2014/05/CNSV-1205-Decuir.pdf

Student Questions

- I see the Con_Req across multiple channels- how does the Peripheral/Central ensure only one connection is made?

One channel is sufficient. However, if there are many nodes, it may become overloaded.

- If these advertising messages are broadcast on all three advertising channels how do we prevent collisions between two devices, or is the probability of collisions low enough to ignore?

Advertisements are done only one channel at a time. Not simultaneously on all 3 channels.

- For discoverable advertising, is the data still broadcast, or is it just sent to the requesting central device?

Requesting central device

- What's "Adv_Ind"?

Advertising Indicators (broadcasts)

- Do peripherals mean slaves?

Yes

- Does the master always broadcast the same information at three advertising channels?

One of the three

Bluetooth Smart MAC

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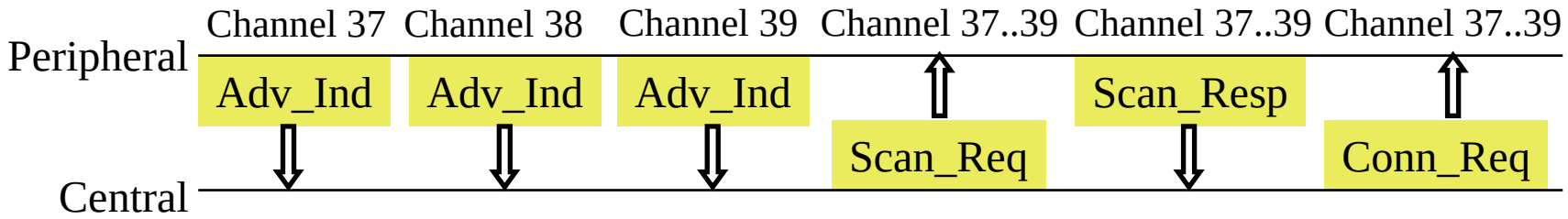

Ref: J. Decuir, "Bluetooth 4.0: Low Energy," 2010, https://californiaconsultants.org/wp-content/uploads/2014/05/CNSV-1205-Decuir.pdf

Student Questions

- What are central and peripheral devices? Are they related to the master and slave?

Yes.

- When is discoverable advertising being used (after or before connection), and for what purpose?

To identify each other and for capability negotiation during connection.

- Is it correct that signed data is accessible by anyone as long as they have the public key?

The signature can be verified by anyone using Public Key. But the data can still be encrypted before or after the signature.

- Can you explain one more time why Bluetooth smart requires dual-mode chips?

Two designs: Original Bluetooth and Nokia WiBree.

Bluetooth Smart MAC

- Two Device Types: "**Peripherals**" are simpler than "**central.**"
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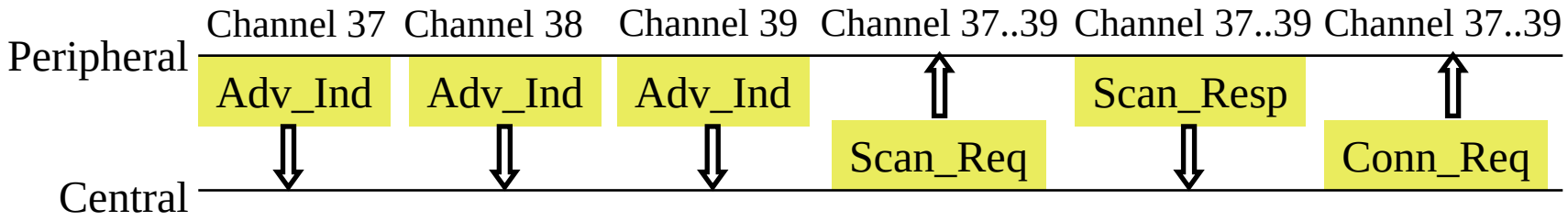


Ref: J. Decuir, "Bluetooth 4.0: Low Energy," 2010, https://californiaconsultants.org/wp-content/uploads/2014/05/CNSV-1205-Decuir.pdf

Student Questions

- What role does the central device play in Discoverable Advertising compared to Non-connectable advertising

Non-Connectable: "The temperature is 73F.

Discoverable: "I am a thermostat"

General: "Which headsets are here?"

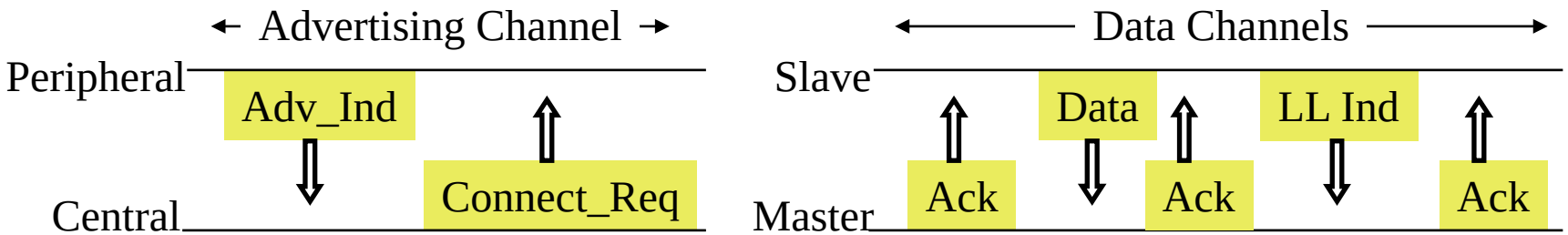
Directed: data/media

- PDU here indicates the PhDU, right?

No, MPDU.

Bluetooth Smart MAC (Cont)

- After connecting, the master tells the slave about the hopping sequence and wake-up cycle
- All subsequent data transfers in 37 data channels
- Both devices can sleep between transactions
- Data can be encrypted.
- ~3 μs per transaction, 15 μW Power = 10 μA using 1.5V
  ⇒ 30μAs/transaction
  ⇒ 21.6 M transactions using 180 μAh battery
  ⇒ 41.1 years with one transaction/minute



Student Questions

- The slides say ms, mW, and mA, but in the video, you say uW, uA. Which ones are correct?

PowerPoint bug. It changes the font to the installed font if the symbol font is unavailable. Symbol μ = Times New Roman m

- In point 4, which 'm' is micro and which is milli? In the video you were not sure about units.

All m's are micro.

- What's "LL Ind"?

Logical Link Termination Indicator

- Could you explain the graph located in the bottom right corner?

This shows a sequence of data/Ack pairs followed by a disconnect (LL Ind).

Bluetooth Smart MAC (Cont)

- After connecting, the master tells the slave about the hopping sequence and wake-up cycle
- All subsequent data transfers in 37 data channels
- Both devices can sleep between transactions
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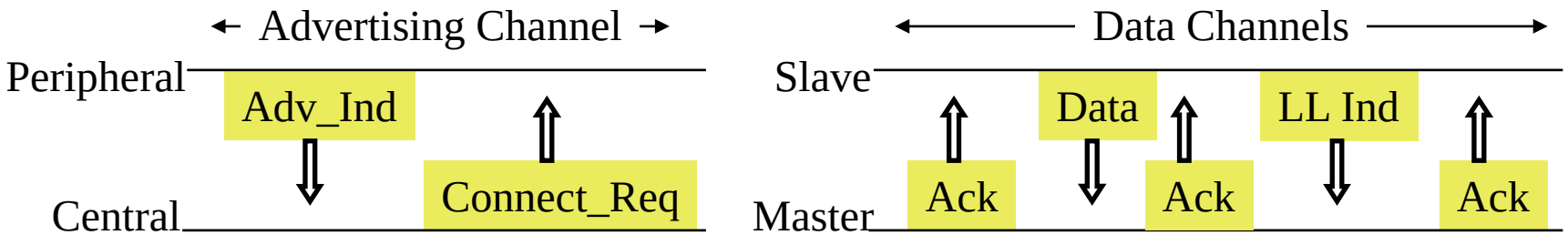
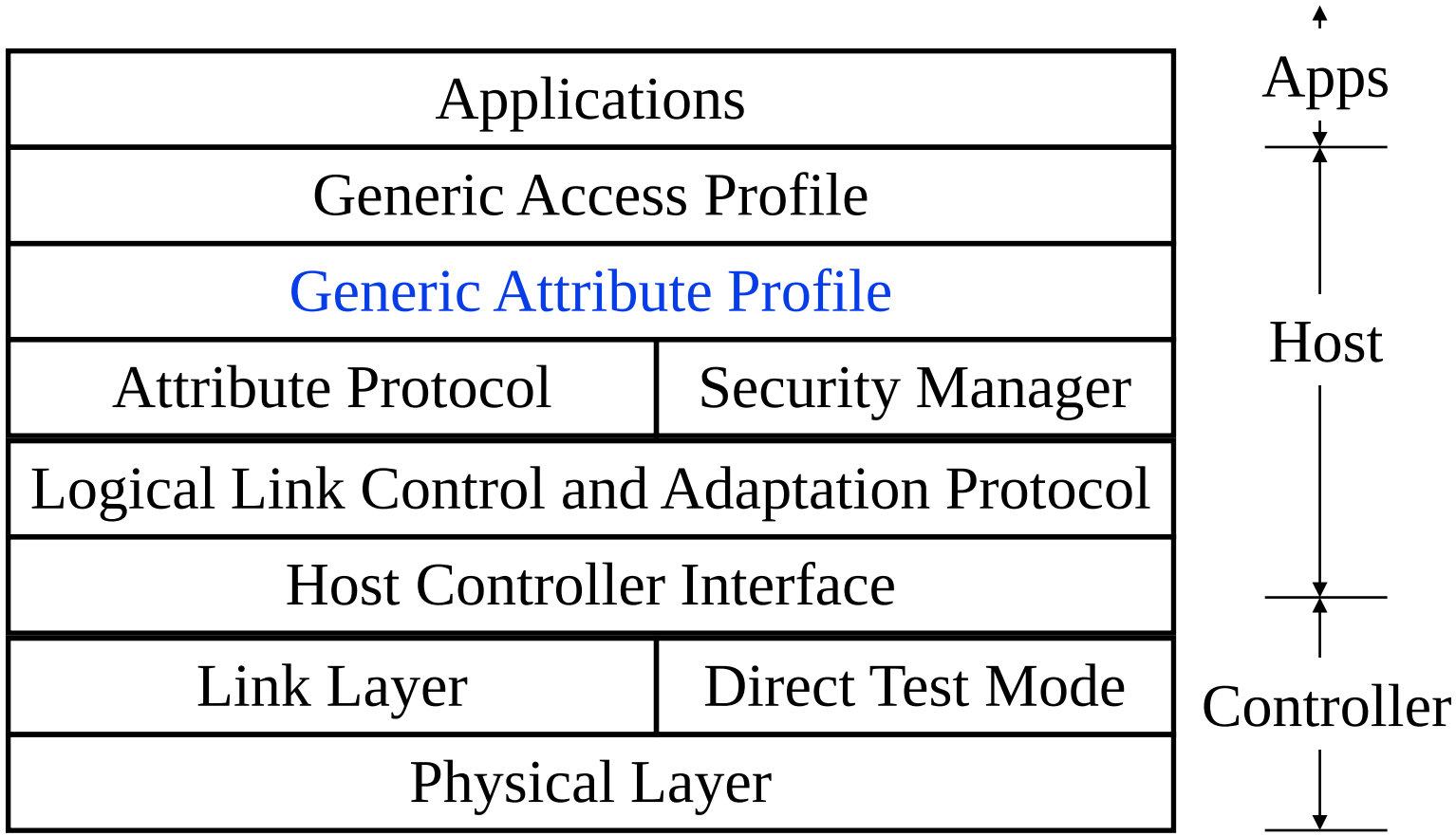


Student Questions

- What does "both devices can sleep between transactions" mean?

Peripheral and Central can both sleep.

Bluetooth Smart Protocol Stack



Ref: J. Decuir, "Bluetooth 4.0: Low Energy," 2010, https://californiaconsultants.org/wp-content/uploads/2014/05/CNSV-1205-Decuir.pdf

Student Questions

- ❑ Is the Serial interface not exposed for the Bluetooth smart protocol stack?

The serial wireless interface is called an antenna connector.

- ❑ Is Generic Access Profile the whole standby --> inquiry --> page --> connect procedure?

Profiles are databases, not protocols.

❖What is the relationship between Application Profile, Generic Access Profile and Generic Attribute Profile?

Applications: headset, phone, …
Access Profile: Workload characteristics, e.g., Small 20B packets
Attribute Profile: Protocol/Security parameters used, e.g., power level

End of Q

Generic Attribute (GATT) Profile

- Defines data formats and interfaces with the Attribute Protocol
- Type-Length-Value (TLV) encoding is used
- Each attribute has a 16-bit Universally Unique ID (UUID) standardized by Bluetooth SIG
- 128-bit UUID if assigned by a manufacturer
- Allows any client to find a server, read/write data
  Allows servers to talk to generic gateways
- Allows security up to AES-128
- Each attribute is encoded in XML
- Makes profile (application) development easier

Student Questions

- UIDs that SIG created cannot be changed, but those created by a manufacturer could be changed in the future. For instance, we might have multiple 128-bit UIDs that refer to the same attribute.

This can occur since manufacturers' UIDs are independently set. However, manufacturers publish their UIDs to avoid this.

- Can you explain what "Each to encode in XML" means again

Each attribute is encoded in XML.

Bluetooth Gateway Devices

- A gateway device helps connect a Bluetooth device to the Internet. Smartphones, Tablets, PC, …
- A generic app can forward the data to the URL sent by the device

Student Questions

- It seems that many Bluetooth devices have the problem that the gateway devices restrict their functions. The same connection requires double-checking on the phone; the remote access requires the app to be in the front end, which is annoying. Is that common, or are there any solutions?

This is up to the application/OS interface designers and implementers. This may be done to avoid accidental connections. Not a part of the standards.

Bluetooth Smart Applications

- Proximity: In the car, In room 303, In the mall
- Locator: Keys, watches, Animals
- Health devices: Heart rate monitor, physical activities monitors, thermometer
- Sensors: Temperature, Battery Status, tire pressure
- Remote control: Open/close locks, turn on lights

Student Questions

Ref: E. Vlugt, "Bluetooth Low Energy, Beacons and Retail," Verifone White paper, 2013, 12 pp., https://www.slideshare.net/verifone/bluetooth-low-energy-beacons-and-retail-final

Beacons

- Advertising based on proximity
- Peripherals (your phone) broadcast their presence if Bluetooth is turned on
- Primary aim of these broadcasts is to allow device discovery and indoor navigation
- Advertising frames consist of a header and max 27B of payload with multiple TLV-encoded data items
  - May include signal strength ⇒ Distance
- iOS7 iPhones can send/receive iBeacons
- Can be used for customized advertising, indoor location, geofencing
- PayPal uses this to identify you.
  You can pay using a PIN and your phone.

- Google is promoting Eddystone beacons, which require only a browser (not another app) to discover proximity using beacons

Student Questions

- Is this similar to how NFC works?

NFC does not advertise. It is more like a storage than networking. You can read the card numbers within 2 cm.

- How can locations be calculated using bluetooth? Is it similar to cell tower triangulation?

Yes. Recently they have added "Angle of Arrival" too.

- Are there any rules about privacy? Can stores collect data on me as I walk around? These days on websites, you have to accept data collection via cookies.

European Privacy Global Data Privacy (GDPR) Law requires permission on websites and allows deletion on request. No US law. But on the Internet, the provider does not know whether you are in Europe or not. No laws on advertising.

- How is geofencing implemented using just the iBeacons?

i is for Apple iPhone/iPad/i…

- Is iBeacon different from the general Bluetooth beacons?

May have been customized but standards compliant.

- How far do the Beacon broadcasts reach?

There is no distance limit. Only Power limit, generally up to 30 m in open spaces.

Beacons

- Advertising based on proximity
- Peripherals (your phone) broadcast their presence if Bluetooth is turned on
- Primary aim of these broadcasts is to allow device discovery and indoor navigation
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- Google is promoting Eddystone beacons, which require only a browser (not another app) to discover proximity using beacons

Student Questions

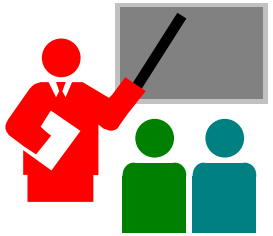
- Is Apple's air tag like a Beacon?

Yes, it may use Beacons.

- When do we need a stronger Beacon?

Your question is not clear to me.

Summary



1. Bluetooth basic rate uses frequency hopping over 79 1-MHz channels with 1, 3, and 5 slots frames.
2. Three inactive states: hold, sniff, park. It has a fixed set of applications called "Profiles."
3. Bluetooth and Wi-Fi co-exist by time-sharing or adaptive frequency notching
4. Bluetooth Smart is designed for short broadcasts by sensors. 40 2-MHz channels with 3 channels reserved for advertising. One or two message exchanges
5. Generic attribute profile allows new applications using UUID for data types

Student Questions

- ❑ Do BLE and Bluetooth 5 use 1/3/5-slot frames transmitted in even or odd-numbered time slots?

YES

- ❑ Assume a device has a 2-slot frame. Can the frame be continuously transmitted without frequency hopping?

Yes, in 3-slots.

- ❑ When Bluetooth is turned on, can any information be retrieved from the device?

Generally, no information other than name and MAC address is broadcast. But hackers have found ways to sneak in connections.

Homework 11

- Submit an answer to the following problem: Assume that 256 bits could be transmitted in one slot in Bluetooth. How many slots are needed if the payload size is (a) 512 bits, (b) 728 bits, and (c) 1024 bits? Assume that the non-payload portions do not change.

Student Questions

- Is the non-payload portion always a fixed length or is it a fixed percentage of the total message length?

Fixed length.

- What are the answers here? Not yet graded on Canvas.

We will go over the answers at the end of this session.

Reading List: Bluetooth

- Madhur Bhargava, " IoT Projects with Bluetooth Low Energy," Packt Publishing, August 2017, 278 pp., ISBN:978-1-78839-683-7 (Safari Book).
- Kevin Townsend, Carles Cufí, Akiba, Robert Davidson, "Getting Started with Bluetooth Low Energy," O'Reilly Media, Inc., May 2014, 180 pp., ISBN:978-1-4919-4951-1 (Safari Book), Chapter 2.
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Student Questions

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Student Questions

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- K.V.S.S.S.S. Sairam, N. Gunasekaran, and S.R. Redd, "Bluetooth in wireless communication" Volume 40, Issue 6, Page(s):90 - 96, IEEE Communications Magazine, June 2002, http://ieeexplore.ieee.org/iel5/35/21727/01007414.pdf?tp=&arnumber=1007414&isnumber=21727
- B. Chatschik, "An overview of the Bluetooth wireless technology", Volume 39, Issue 12, Page(s):86 - 94, IEEE Communications Magazine, 2001, http://ieeexplore.ieee.org/iel5/35/20896/00968817.pdf?tp=&arnumber=968817&isnumber=20896

Student Questions

References (Cont)

- Martin Wooley, "Bluetooth Core Specification Version 5.1 Feature Overview," Bluetooth SIG, December 2020, https://www.bluetooth.com/wp-content/uploads/Files/Specification/1901_Feature_Overview_Brief_FINAL.pdf
- Martin Wooley, "Bluetooth Core Specification Version 5.2 Feature Overview," Bluetooth SIG, December 2020, https://www.bluetooth.com/wp-content/uploads/2020/01/Bluetooth_5.2_Feature_Overview.pdf
- Martin Wooley, "Bluetooth Core Specification Version 5.3 Feature Enhancements," Bluetooth SIG, June 2021, https://www.bluetooth.com/wp-content/uploads/2021/01/Bluetooth_5.3_Feature_Enhancements_Update.pdf

Student Questions

Acronyms

- ACL Asynchronous Connection List
- AD Advertisement
- AES-128 Advanced Encryption Standard w 128-bit keys
- BIN Binary
- BLE Bluetooth Low Energy
- BNEP Bluetooth Network Encapsulation Protocol
- CAP Connection Access Profile
- CSA Core Specification Amendment
- dBm Deci-bel milli-watt
- DPSK Differential Phase Shift Keying
- EDR Enhanced Data Rate,
- FEC Forward Error Correction
- FSK Frequency Shift Keying
- GATT Generic Attribute
- GFSK Gaussian Frequency Shift Keying
- GHz Giga Hertz
- HS High Speed,

Student Questions

Acronyms (Cont)

- IBM International Business Machines
- ID Identifier
- IEEE Institution of Electrical and Electronics Engineers
- iOS Apple's iDevices Operating System
- Ind Indicator
- IoT Internet of Things
- IP Internet Protocol
- IPv6 Internet Protocol version 6
- IrDA Infrared Data Association
- IrMC Infrared Mobile Communications
- IrOBEX Infrared Object Exchange
- LAN Local Area Network
- LAP Lower address part
- LE Low Energy
- LL Logical Link
- MAC Media Access Control
- MAN Metropolitan Area Network

Student Questions

Acronyms (Cont)

- MHz Mega Hertz
- mW milli Watt
- NAP Non-significant address part
- OUI Organizationally Unique Identifier
- PAL Protocol Adaptation Layer
- PC Personal Computer
- PDU Protocol Data Unity
- PHY Physical Layer
- PIN Personal Identification Number
- RF Radio Frequency
- RFCOMM Radio Frequency Communication
- RFID Radio Frequency Identifier
- SCO Synchronous Connection Oriented
- SDP Service Discovery Protocol
- SG Study Group
- SIG Special Interest Group

Student Questions

Acronyms (Cont)

SIM	Subscriber Identity Module
TCS	Telephony Control Specification
TDD	Time-division duplex
TLV	Type-Length-Value
TV	Television
TX	Transmit
UAP	Upper address part
UCD	Unicast Connectionless Data
URL	Uniform Resource Locator
UUID	Universally Unique Identifier
μW	Micro-Watt
WAN	Wide Area Network
WBS	Wide Band Speed
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WPAN	Wireless Personal Area Networks

Student Questions

Acronyms (Cont)

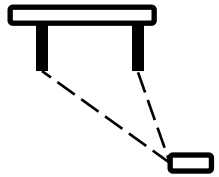
- WRAN Wireless Regional Area Network
- XML Extensible Markup Language

Student Questions

Bluetooth 5.1

- Bluetooth 5.1 in January 2019 (2 years after 5.0)

1. **Direction Finding:** Angle of Arrival (AoA) and Angle of Departure (AoD) for locating devices and indoor positioning. One of the two devices should have multiple antennas.



2. **Attribute caching:** Faster connections
3. **Randomized Advertising Channel Selection:** Removed strict sequencing between 37, 38, 39
   ⇒ Avoids collisions

4. **Periodic Advertising Sync Transfer**: Allows one device (smartphone) to pass on info on another device (TV) to a low-energy companion (smartwatch)
   ⇒ Lower energy consumption on the companion

Ref: Martin Wooley, "Bluetooth Core Specification Version 5.1 Feature Overview," Bluetooth SIG, December 2020, https://www.bluetooth.com/wp-content/uploads/Files/Specification/1901_Feature_Overview_Brief_FINAL.pdf

Student Questions

Bluetooth 5.2

- Bluetooth 5.2 in December 2019

1. **Enhanced Attribute Protocol (EATT):**
   Allows multiple applications to operate simultaneously by interleaving transactions.
2. **Low-Energy Power Control**: Allows monitoring quality and requesting power level changes ⇒ Saves battery
3. **Low-Energy Isochronous Channels**:
   Time-synchronized unicast or broadcast
   ⇒ Allows audio to multiple devices
4. **Low-Energy Audio**: Uses LE Isochronous channels with special features for hearing aids. Can customize for different locations: theatres, conferences, lecture halls, airports, …

Ref: Martin Wooley, "Bluetooth Core Specification Version 5.2 Feature Overview," Bluetooth SIG, December 2020, https://www.bluetooth.com/wp-content/uploads/2020/01/Bluetooth_5.2_Feature_Overview.pdf

Student Questions

- As SIG announced Bluetooth 6 recently, how long will it take to market?

They are expected next year. See Slide 11-42.

Bluetooth 5.3

- Bluetooth 5.3 in July 2021. Many products are on the market.

1. **Periodic Advertisement**: Do not interrupt the host application if the data is the same as before, e.g., temperature from thermostats
2. **Encryption Key Size Control**: Devices can specify the minimum key length requirement to the controller
3. **Connection Subrating**: Allows quickly changing parameters after periodic wakeup
4. **Channel Classification Enhancement**: Devices also can send Slot Availability Mask (SAM) to the controller.

Student Questions

Ref: Martin Wooley, "Bluetooth Core Specification Version 5.3 Feature Enhancements," Bluetooth SIG, June 2021, https://www.bluetooth.com/wp-content/uploads/2021/01/Bluetooth_5.3_Feature_Enhancements_Update.pdf

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Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-24/j_11ble.htm

Student Questions

Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

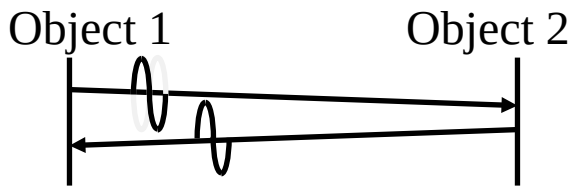
CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

Student Questions

Bluetooth 6.0

- **Channel Sounding**: Finding the distance between two Bluetooth objects accurately by measuring the round trip time or phase difference between sent and received signals.



- **Decision-Based Advertising Filtering**: Summary on the advertising channel is used to decide if a detailed report should be found on the data channels.
- **Monitoring Advertisers**: A Bluetooth controller may filter out unwanted advertisements if instructed by the host application.
- **Isochronous Adaptation Layer (ISOAL):** Improves audio.
- **Negotiable Inter-Frame Spacing:** Was fixed at 150µs before.

Ref: M. Woolley, "Bluetooth Core Specification version 6.0: Feature Overview," Bluetooth SIG, August 2024, https://www.bluetooth.com/core-specification-6-feature-overview/

Student Questions