ECE 463: Digital Communications Lab.

Lecture 13: IoT III
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Previous Lecture:

☑ Backscatter Communication
☑ RFIDs

This Lecture:

☑ Bluetooth
☑ DSSS & FHSS
☑ Wrap Up
IoT Technologies

Range

Data Rate

Mbps

Kbps

bps

10 cm 1 m 10 m 100 m 1 km 10 km

NFC

RFID

ZigBee

Bluetooth

WiFi

Cellular

LoRa

NB-IoT

LTE-M

neul

sigfox
Bluetooth

Wearables

Smart Devices

Tracking
Bluetooth

Bluetooth v4.0+: BLE
Bluetooth Low Energy
<table>
<thead>
<tr>
<th>Bluetooth</th>
<th>Bluetooth v4.0+: BLE</th>
<th>Bluetooth Low Energy</th>
</tr>
</thead>
</table>

**Bluetooth**
- Traditional wireless devices, streaming rich content, like video and audio

**Bluetooth Smart Ready**
- Devices that connect with both
  - The center of your wireless world

**Bluetooth Smart**
- Sensor devices, sending small bits of data, using very little energy

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<table>
<thead>
<tr>
<th>If your product bears this logo...</th>
<th>It's compatible with products bearing any of these logos...</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Bluetooth SMART READY" /></td>
<td><img src="image" alt="Bluetooth" /> <img src="image" alt="Bluetooth" /> <img src="image" alt="Bluetooth" /> <img src="image" alt="Bluetooth" /></td>
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# Bluetooth vs. Bluetooth Low Energy

<table>
<thead>
<tr>
<th></th>
<th>Classic Bluetooth</th>
<th>Bluetooth Low Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency:</strong></td>
<td>2400 MHz – 2483.5 MHz</td>
<td>2400 MHz – 2483.5 MHz</td>
</tr>
<tr>
<td><strong>Bands:</strong></td>
<td>79 channels (1 MHz sep.)</td>
<td>40 channels (2 MHz sep.)</td>
</tr>
<tr>
<td></td>
<td>32 for device discovery</td>
<td>3 for device discovery</td>
</tr>
<tr>
<td><strong>Connection Setup:</strong></td>
<td>100 ms</td>
<td>≈3ms</td>
</tr>
<tr>
<td><strong>Power:</strong></td>
<td>1</td>
<td>20 to 100x lower power</td>
</tr>
<tr>
<td><strong>Range:</strong></td>
<td>up to 150m</td>
<td>up to 50m</td>
</tr>
<tr>
<td><strong>Data Rate:</strong></td>
<td>2-3 Mbps</td>
<td>200 Kbps – 1Mbps</td>
</tr>
<tr>
<td><strong>Modulation:</strong></td>
<td>GFSK</td>
<td>GFSK</td>
</tr>
<tr>
<td><strong>FHSS:</strong></td>
<td>1600 hops/sec</td>
<td>Longer dwell time</td>
</tr>
<tr>
<td></td>
<td>625µsec (dwell time)</td>
<td>max (400 msec)</td>
</tr>
<tr>
<td></td>
<td>Pseudo Random Seq.</td>
<td></td>
</tr>
</tbody>
</table>
Bluetooth Low Energy Frequency Hopping

Frequency hopping: $f_{n+1} = (f_n + hop) \mod 37$
Bluetooth Low Energy Frequency Hopping

Frequency hopping: $f_{n+1} = (f_n + \text{hop}) \mod 37$
Bluetooth Low Energy Frequency Hopping

Frequency hopping: $f_{n+1} = (f_n + hop) \mod 37$

What about Interference from WiFi?
Use Adaptive Frequency Hopping!
Bluetooth Low Energy Frequency Hopping

Use Adaptive Frequency Hopping!

Avoid bad channels by remapping them to other channels.
Bluetooth Low Energy Frequency Hopping

Use Adaptive Frequency Hopping!

Avoid bad channels by remapping them to other channels.
Spread Spectrum Technology

DSSS: Direct Sequence Spread spectrum

- PN Sequence (Chip)
- Power

FHSS: Frequency Hopping Spread spectrum

- Frequency
- Time

CSS: Chirp Spread Spectrum

- Frequency
- Time

Applications:

| 3G, 802.11b, GPS, Military | Bluetooth, Military | LPWAN, Radar |
DSSS: Direct Sequence Spread Spectrum

- **Problem:** frequency dependent fading & interference can wipe out narrow band signals for duration of the interference
- **Solution:** spread the narrow band signal into a broad band signal using a special code
- XOR the signal with PN sequence (chipping sequence)
DSSS: Direct Sequence Spread Spectrum

At TX

Chipping Sequence

At RX

Chipping Sequence

user data

resulting signal

resulting signal

XOR

chipping sequence

chipping sequence

XOR

T_b

T_c

0 1

0 1

0 1
DSSS: Direct Sequence Spread Spectrum

At TX

Chipping Sequence

power

interference

frequency

At RX

Chipping Sequence

power

spread interference

frequency

resulting signal = user data

XOR

chipping sequence

resulting signal

XOR

chipping sequence

= user data
Code Division Multiple Access (CDMA)

- DSSS enables multiple users to transmit at the same time using CDMA

- unique “code” assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own “chipping” sequence (i.e., code) to encode data
  - allows multiple users to “coexist” and transmit simultaneously with minimal interference (if codes are “orthogonal”)

- **encoded signal** = (original data) X (chipping sequence)
- **decoding**: inner-product of encoded signal and chipping sequence
CDMA encode/decode

sender

data bits code

slot 1

\[ d_1 = -1 \]

\[ d_0 = 1 \]

slot 0

channel output \( Z_{i,m} = d_i \cdot c_m \)

receiver

received input code

slot 1

\[ d_1 = -1 \]

\[ d_0 = 1 \]

slot 0

channel output

\[ D_i = \sum_{m=1}^{M} Z_{i,m} \cdot c_m \]

\( M \)
**CDMA: two-sender interference**

**senders**

**Sender 1**
- Data bits: \(d_1 = -1\)
- Code: 1 1 1 1

**Sender 2**
- Data bits: \(d_2 = 1\), \(d_0 = -1\)
- Code: 1 1 1 1

**channel sums together transmissions by sender 1 and 2**

**receiver 1**

- Using the same code as sender 1, receiver recovers sender 1’s original data from summed channel data!
Code Division Multiple Access (CDMA)

• Ideally, need codes to have good:
  Auto-correlation properties: \( c_i(t) \cdot c_i(t) = 1 \)
  Cross-correlation properties: \( c_i(t) \cdot c_j(t) = 0 \) for \( j \neq i \)

\[
\left( \sum_i h_i d_i(t) c_i(t) \right) \cdot c_i(t) = h_i d_i(t)
\]

• Need orthogonal codes:
  For \( N \) users, length of code is exponential in \( N \rightarrow 2^{N-1} \)

• Example of good codes: Gold Codes, Walsh Codes
DSSS: Direct Sequence Spread Spectrum

DSSS enables decoding at very low SNR

• Transmit: $bit \times c(t)$

• Receiver: $h \times bit \times c(t) + n(t)$

• Decode:

\[
\sum_{t=1}^{M} h \times bit \times c(t) \times c(t) + n(t) \times c(t) = M \times h \times bit + \sum_{t=1}^{M} n(t) \times c(t) = M \times h \times bit + n'(t)
\]
DSSS: Direct Sequence Spread Spectrum

DSSS enables decoding at very low SNR

- Transmit: $bit \times c(t)$

- Receiver: $h \times bit \times c(t) + n(t)$

- Decode:
  \[
  \sum_{t=1}^{M} h \times bit \times c(t) \times c(t) + n(t) \times c(t)
  \]

  \[
  = M \times h \times bit + \sum_{t=1}^{M} n(t) \times c(t)
  \]

  \[
  = M \times h \times bit + n'(t)
  \]
DSSS: Direct Sequence Spread Spectrum

DSSS enables decoding at very low SNR

• Transmit: $bit \times c(t)$

• Receiver: $h \times bit \times c(t) + n(t)$

• Decode: $= M \times h \times bit + n'(t)$

$\text{SNR Before} = \frac{|h|^2}{\sigma^2}$

$\text{SNR After} = \frac{|Mh|^2}{M\sigma^2} = M \times \frac{|h|^2}{\sigma^2}$

SNR Increased By $M$ times
DSSS: Direct Sequence Spread Spectrum

DSSS enables decoding at very low SNR

• GPS uses DSSS with code length $M = 1023$

• GPS uses BPSK: Can be decode well at $SNR > 6 \text{ dB}$

• GPS signals can be decoded if received at SNR:

$$6 \text{ dB} - 10 \log_{10} M = -24 \text{ dB}$$

• GPS signals come from satellites $\rightarrow$ typically received below the noise floor.
DSSS: Direct Sequence Spread Spectrum

DSSS enables decoding at very low SNR

• GPS uses DSSS with code length $M = 1023$

GPS receivers sometimes use a single bit ADC to sample the signal and yet can still decode correctly. How come?

Quantization SNR: $6 \text{ dB} \times \text{Quantization bits}$

\[= 6 \text{ dB} \gg -23 \text{ dB}\]
Summary

**Single Carrier TX/RX:**
- Up/Down Conversion (Lec. 2)
- Pulse Shaping (Lec. 3)
- Modulation (Lec. 4, 5, 8) (DBPSK, BPSK, ASK, FSK, PSK, PAM, QAM,...)
- Frame Synchronization (Lec. 5)
- Channel Equalization (Lec. 6)
- Carrier Recovery & CFO (Lec. 7)
- AGCs (Lec. 8)
Summary

Multi-Carrier TX/RX:

- OFDM (Lec. 9, 10)
- OFDM Synchronization (Lec. 10)

**TX**

Bits → Modulation → Serial to Parallel → IFFT → Parallel to Serial → Re{} → DAC → LPF → Mixer → BPF → PA

**RX**

LNA → BPF → PLL → 90° → Mixer → LPF → ADC → I → + → Serial to Parallel → FFT → Parallel to Serial → Demodulation → Bits
Summary

IoT:

- LPWAN: LoRA (Lec. 11)
- Backscatter Communication: RFIDs, Miller code, full duplex (Lec. 12)
- Bluetooth (Lec. 13)
- Spread Spectrum: DSSS, FHSS, CSS (Lec. 11, 12, 13)
Quiz 2

• Covers Lectures & Lab : 8-13

• Closed Book! Bring nothing except:
  ➢ Pen or Pencil
  ➢ Calculator (No Phones)

• Types of Questions to Expect:
  ➢ 3 Problems (1 on modulation, 1 on OFDM, 1 on IoT)

• No Labs the week of the Quiz.