Adapting to the Wireless Channel

COS 598a: Wireless Networking and Sensing Systems

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What is modulation?

• To *modulate* means to **change**. Change what?
  – The **amplitude** and **phase** (*i.e.*, **angle**) of a **carrier signal**
  – For 802.11 WiFi local area networks, this carrier signal is usually at 2.4 GHz or 5 GHz

![Diagram of modulation](image)

• **Digital modulation**: Use only a finite set of choices (*i.e.*, **symbols**) for how to change the carrier and phase
  – Transmitter and receiver agree upon the symbols beforehand
From information bits to symbols...

- Simplest possible scheme
  - Pick two symbols (binary)
  - The information bit decides which symbol you transmit
  - So, this is called **binary phase shift keying**
    - **Sending rate:** 1 bit/symbol
...and back to bits!

Received BPSK constellation

- **Decision boundary**
- **Decision region**
- **Received symbols**

- Received symbols
- Decision boundary
- Decision region
- In phase (I) amplitude
- Quadrature (Q) amplitude

```
“1”

“0”
```

Graph showing the received BPSK constellation with decision boundaries and regions for symbols "1" and "0".
Sending twice as fast

Quadrature phase shift keying (QPSK)

Input bits="10"

Input bits="00"

Input bits="11"

Input bits="01"

Sending 2 bits/symbol
...and back to bits, twice as fast!

Received QPSK constellation
Change modulations, increase bitrate

Binary Phase-Shift Keying (BPSK)

Quadrature Phase-Shift Keying (QPSK)

16-Quadrature Amplitude Modulation (16-QAM)
The wireless channel

**Transmitted signal**

reception: \( r(t) = s(t) + n(t) \)

Input bit="0"

Input bit="1"

Transmitted signal

Q

I

Input bit="1"

Input bit="0"

-1

+1

Quadrature (Q) amplitude

In phase (I) amplitude
Signal to noise ratio (SNR)

• Measured in **decibels (dB):** $10 \times \log_{10}$ of a quantity

$$\text{SNR} = 20 \ \text{dB}$$

$$\text{SNR} = 8 \ \text{dB}$$

SNR (dB) = $10 \log_{10} \left( \frac{\text{signal power}}{\text{noise power}} \right)$

= $10 \log_{10} \left( \frac{1^2}{\sigma^2} \right)$  (assuming Gaussian noise)

= $-20 \log_{10} \sigma$
Modulation adaptation
Error control coding

Channel encoder

Modulation (BPSK, QPSK, ...)

n bits

k bits

Source bits

Channel decoder

Demodulation

n bits

k bits

Source bits

Code rate: $R = \frac{k}{n}$
### 802.11: adapt code rate, modulation

<table>
<thead>
<tr>
<th>Bit-rate</th>
<th>802.11 Standards</th>
<th>DSSS or OFDM</th>
<th>Modulation</th>
<th>Bits per Symbol</th>
<th>Coding Rate</th>
<th>Mega-Symbols per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>b</td>
<td>DSSS</td>
<td>BPSK</td>
<td>1</td>
<td>1/11</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>DSSS</td>
<td>QPSK</td>
<td>2</td>
<td>1/11</td>
<td>11</td>
</tr>
<tr>
<td>5.5</td>
<td>b</td>
<td>DSSS</td>
<td>CCK</td>
<td>1</td>
<td>4/8</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>b</td>
<td>DSSS</td>
<td>CCK</td>
<td>2</td>
<td>4/8</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>a/g</td>
<td>OFDM</td>
<td>BPSK</td>
<td>1</td>
<td>1/2</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>a/g</td>
<td>OFDM</td>
<td>BPSK</td>
<td>1</td>
<td>3/4</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>a/g</td>
<td>OFDM</td>
<td>QPSK</td>
<td>2</td>
<td>1/2</td>
<td>12</td>
</tr>
<tr>
<td>18</td>
<td>a/g</td>
<td>OFDM</td>
<td>QPSK</td>
<td>2</td>
<td>3/4</td>
<td>12</td>
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<tr>
<td>24</td>
<td>a/g</td>
<td>OFDM</td>
<td>QAM-16</td>
<td>4</td>
<td>1/2</td>
<td>12</td>
</tr>
<tr>
<td>36</td>
<td>a/g</td>
<td>OFDM</td>
<td>QAM-16</td>
<td>4</td>
<td>3/4</td>
<td>12</td>
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<tr>
<td>48</td>
<td>a/g</td>
<td>OFDM</td>
<td>QAM-64</td>
<td>6</td>
<td>2/3</td>
<td>12</td>
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<tr>
<td>54</td>
<td>a/g</td>
<td>OFDM</td>
<td>QAM-64</td>
<td>6</td>
<td>3/4</td>
<td>12</td>
</tr>
</tbody>
</table>
BER vs SNR

Figure 1-2: Theoretical bit error rate (BER) versus signal-to-noise ratio for several modulation schemes assuming AGWN. The y-axis is a log scale. Higher bit-rates require larger S/N to achieve the same bit-rate as lower bit-rates.
Link/PHY checks packet integrity

Throughput = delivery rate × bitrate = \((1 - BER)^n \times \text{bitrate}\)

Packet delivery rate = \((1 - BER)^n\)

- Change modulation
- Change coding rate

\(n = 1500 \times 8\) bits
Packetized throughput

Throughput = delivery rate × bitrate = (1 − BER)^n × bitrate

Why are the knees of the curves where they are?

n = 1500 × 8 bits
Delivery rate vs BER

Throughput = delivery rate × bitrate = \((1 - BER)^n \times \text{bitrate}\)

\(n = 1500 \times 8 \text{ bits}\)
**BER vs SNR**

- For each modulation: *What are the SNRs required for BER < 10^{-5}?*

  - BPSK: 7 dB; QPSK: 12 dB; 16-QAM: 20 dB; 64-QAM: 26 dB
Packetized throughput

Throughput = delivery rate × bitrate = \((1 - BER)^n \times \text{bitrate}\)

- BPSK (1 megabit/s)
- QPSK (2 megabit/s)
- QAM-16 (4 megabits/s)
- QAM-64 (6 megabits/s)

n = 1500 × 8 bits
Measuring time to send a packet

Assume unicast, RTS/CTS is disabled. Let’s go to the spec (802.11b DSSS values):

\[
\text{tx\_time}(\text{bitrate}, r, N) = \text{DIFS} + \text{backoff}(r) + (r + 1)\left(\text{SIFS} + \text{ACK} + \text{HEADER} + \frac{8 \cdot N}{\text{bitrate}}\right)
\]

- Similar to MACAW
  - Key difference: as long as medium is idle
SampleRate in operation

<table>
<thead>
<tr>
<th>Bit-rate</th>
<th>Tries</th>
<th>Packets Ack’ed</th>
<th>Succ. Fails</th>
<th>Total TX Time</th>
<th>Avg TX Time</th>
<th>Lossless TX Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>16</td>
<td>0</td>
<td>4</td>
<td>250404</td>
<td>∞</td>
<td>1873</td>
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<tr>
<td>5.5</td>
<td>100</td>
<td>100</td>
<td>0</td>
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<td>2976</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>12995</td>
</tr>
</tbody>
</table>

Steep

Gradual

![Graph showing packet distribution per bit-rate and sample rate in operation](image-url)
Evaluation methodology

Indoor testbed: 45 node a/b/g  
Outdoor testbed: 38 node b/g

• Select **random** links in testbed with non-zero throughput

• Test each link in **isolation** for 30 seconds
  – Sender transmits 1500-byte UDP unicast packets as fast as possible

• Run bit rate adaptation schemes: SampleRate, ARF, AARF, ONOE

• **Static best** comparison point: for each bitrate, fix bitrate, test throughput
Indoor 802.11a Performance

Evidence that ARF spends too much time trying higher bit rates
**Hop count and throughput**

![Graph showing hop count and throughput]

- **Minimum-hop-count routes** are significantly throughput-suboptimal.

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**Legend**
- **Max 4-hop throughput**
- **3-hop**
- **2-hop**

**Axes**
- **Y-axis**: Cumulative fraction of node pairs
- **X-axis**: Packets per second delivered

**Graph Details**
- The graph compares the throughput of different hop counts and routes.
- The red arrows highlight the throughput improvement of shorter hop-count routes.
- The graph shows that the throughput for 2-hop routes is higher than for 3-hop and 4-hop routes.