An Overview of Wireless Communications

Vincent Poor
(poor@ee)

OUTLINE

• What is Wireless?
• Analog & Digital Information Sources
• Digital Modulation & Demodulation
• Physical Properties of Wireless Channels
• Multiple-Access Techniques
• Radio Protocols
• Emerging Technologies

WHAT IS WIRELESS?

Communication Networks (Briefly)

• Plain Old Telephone Service (POTS)
  - Telephones are connected to a branch exchange by pairs of copper wires.
  - Exchanges are networked through central offices over digital lines (e.g., optical fibers) to connect calls between phones.
• Computer Networks (the Internet and all that)
  - Computers & peripherals are connected (via Ethernet) to other devices in a local area network (LAN).
  - LAN’s are networked by routers over high-speed lines to other networks; e.g., the Internet.
• Broadcast Networks
  - Sender transmits same content to all possible recipients.
  - E.g., broadcast TV, AM radio, FM radio, cable TV.

What is Wireless? Tetherless.

• Wireless means communication by radio.
• Usually, this means the last link between an end device (telephone, computer, etc.) and an access point to a network.
• Wireless often still involves a significant wireline infrastructure (the “backbone”).
• Wireless affords mobility, portability, and ease of connectivity.

Wireless Applications

• Mobile telephony/data/multimedia (“3G”)
• Telematics
• Nomadic computing
• Wireless LANs (IEEE 802.11/“WiFi”; HiperLAN)
• Bluetooth (pico-nets; PANs- personal area nets)
• Wireless local loop
Wireless Challenges

- High data rate (multimedia traffic)/greater capacity
- Networking (seamless connectivity)
- Resource allocation (quality of service - QoS)
- Manifold physical impairments (more later)
- Mobility (rapidly changing physical channel)
- Portability (battery life)
- Privacy/security (encryption)

IEEE 802.11 Wireless LANs

- Operation with infrared, or (more typically) in the lightly regulated, license-free ISM bands.
- 802.11: 1-2 Mbps, spread spectrum in the 2.4 GHz band (c. 1997)
- 802.11b: 5.5-11 Mbps, spread-spectrum in the 2.4 GHz band (c. 1999)
- 802.11a: 6-54 Mbps, orthogonal frequency-division multiplexing (OFDM) in the 5 GHz band (c. 2001)
- 802.11g: 22 Mbps, spread-spectrum (plus better coding) in the 2.4 GHz band; (approved 11/15/01)

Cellular Telephony

- Operation in regulated spectrum around 800-900 MHz (“cellular”), and 1.8-1.9 GHz (“PCS”).
- 1G: Analog voice - frequency-division multiple access (FDMA); AMPS, NMT, etc. (80’s)
- 2G: Digital voice - time-div. MA (TDMA), code-div. MA (CDMA); GSM, USDC, IS-95 (90’s)
- 2.5G: Dig. voice & low-rate data - TDMA/CDMA; EDGE, HDR, GPRS, etc. (late 90’s, early 00’s)
- 3G: Dig. voice & higher-rate data - mostly wide-band CDMA; WCDMA, cdma2000 (now & soon)

Bandwidth Requirements (Kbps)

<table>
<thead>
<tr>
<th>Activity</th>
<th>GSM</th>
<th>2G</th>
<th>2.5G</th>
<th>3G</th>
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<td>Compressed audio clips</td>
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<td>Compressed video clips</td>
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<td>LAN applications</td>
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<td>500-10,000</td>
<td>Wireless LAN</td>
</tr>
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</table>

Source: Stagg Newman (McKinsey)

Communication Links

- Communication networks are composed of links between devices.
- The devices can be telephones, computers, peripherals, pagers, PDA’s, switches, televisions, satellites, &c. The links are physical media, such as
  - copper wires (e.g., POTS, LAN’s)
  - coaxial cables (e.g., CATV, Ethernet)
  - optical fibers (e.g., submarine cables)
  - free space (the “ether” for wireless)
- Information moves over communication links in the form of signals.
Abstract Communication Model

For the time being, we can ignore the physical aspects of communication links and signals and consider a more abstract model for this process:

Information Source ----> Modulator ----> Channel ----> Demodulator ----> Information Destination

Information Sources

• The information source produces the contents of the message to be transmitted over the link (a “content provider”).
• Physically, this is voice, data, text, images, video, etc.
• Info. sources fall into two basic categories:
  - Analog
  - Digital

Analog Sources

Analog: Information takes the form of a continuous function of time.

Examples: voice, music, photographs, video, etc.

Digital Sources

Digital: Information takes the form of a sequence (or file) of discrete values - often 0’s and 1’s.

...0001101011011100010011...

Examples: text, financial transactions, digitized music (e.g. CD, mp3), digitized video (eg. HDTV, satellite TV, MPEG, DVD), digitized images (e.g., JPEG, gif), HTML files, etc.

Digitization of Analog Sources

• Note: Some digital sources are obtained by digitizing inherently analog sources.
• This involves analog-to-digital (A/D) conversion.
• Transmission of information digitally is advantageous because it facilitates:
  - **Coding** to guard against channel-induced errors
  - **Compression** to minimize the resources needed to transmit it
  - **Encryption** to protect the source from being intercepted

A/D Conversion

A/D conversion involves three steps:

• **Sampling** (time digitization)
• **Quantization** (amplitude digitization)
• **Compression** (removal of redundancy)
Sampling

An analog source is converted to a sequence of numbers:

The Nyquist Rate

If the source spectrum has maximum frequency $f_{\text{max}}$, i.e.

Then a sampling rate of $2f_{\text{max}}$ is sufficient to capture the information in the source

Equivalently, the interval between samples should be at most $\frac{1}{2f_{\text{max}}}$

Quantization

- The samples from an analog source can take on a continuum of values.
- To complete the digitization process, the values must be converted to discrete values.
- For example, we could round off to the nearest whole number, to other decimal places, or to other resolutions.
- Note that quantized output must be truncated at a maximum level.
- If $L$ is the total number of possible output levels per sample, then the number of bits needed to represent each sample is $\log_2 L$ bits/sample.

Quantizer Illustration

Pulse-Code Modulation (PCM)

- A signal that has been sampled and quantized is called a PCM signal.
- If samples of an analog source are taken at $S$ samples-per-second and quantized to $L$ levels, then the bit-rate, in bits-per-second, of the digital source is

$$S \times \log_2 L$$

PCM Example - Toll Quality Voice

- Voice is sent over telephone switching systems as PCM:
  - Sampling rate - 8,000 samples/second
  - $L = 256$ (i.e., 8 bits/sample)
  - Rate = 64,000 bps
PCM Example - CD Quality Audio

- **Audio** is collected for CD storage as PCM:
  - sampling rate - 44,100 samples/second
  - $L = 65,536$ (i.e., 16 bits/sample)
  - Rate = 705,600 bps
  - Stereo (2 channels) then gives approximately 1.4Mbps

PCM Example - Images/Video

- A lower resolution **image** might have 72 samples (called pixels in this case) per linear inch, or 5,184 pixels per square inch.
  - These are typically quantized at 8 bits/sample/color, or 24 bits/sample total.
  - So, with these conditions a 5"x7" color image contains about 4.4Mbits of data.
- The **video** part of HDTV has a PCM rate of about 1Gbps

Compression

- For transmission of these sources over limited bandwidth channels (e.g., wireless) these PCM rates are much too high.
- **Compression** is used to reduce the required bit rate. Two general types:
  - **Lossless**: Removes redundancy from data, but is completely reversible (e.g., compression of data files via gzip, etc.)
  - **Lossy**: Compresses the source further, but introduces some distortion
- Most practical compression schemes for voice, audio, images & video involve **lossy** compression to a tolerable (i.e. imperceptible) level of distortion, followed by **lossless** compression to remove residual redundancy.

Compression - Examples

- **DIFFERENTIAL PCM (DPCM)**: Differences in successive samples are quantized (rather than the samples themselves). This allows for comparable quality with fewer quantization levels.
  - Sometimes used in coding voice - e.g., in cordless phones - where it can reduce the rate to 32kbps; i.e. 2-to-1 compression.
- **LINEAR – PREDICTIVE CODING (LPC)**: Similar to DPCM, but using differences between each sample and a prediction of that sample formed from many past samples.
  - Many variations are used in coding voice - e.g., in digital cellular, this can achieve 8,000 - 16,000 bps with reasonable quality; i.e., 8-to-1 or 4-to-1 compression.

Compression - More Examples

- **MP3**: “Sub-band Coding” - Quantizes different frequency bands with different numbers of quantization levels.
  - Used in compressing audio - can reduce stereo CD rate down to about 128,000 bps, for a compression rate of about 10-to-1.
- **JPEG** (Image Compression Standard): Compress 8x8 blocks of pixels using lossy **transform coding** followed by lossless compression.
  - Compression ratios depend on the type of picture and the desired quality, but can typically be around 24-to-1, which yields 1 bit per pixel in the compressed file.

Compression - A Final Example

- **MPEG**: (Video Compression): is a bit like JPEG combined with motion estimation and something like differential coding. There are several versions.
  - The version used in HDTV compresses HDTV video signal down to 20 Mbps - i.e., 50-to-1.
  - Lower-quality video can be transmitted at 100’s of kbps, and low-bit-rate video (e.g., streaming video) even lower. (For wireless transmission, these lower rates are essential.)
DIGITAL MODULATION & DEMODULATION

Recall the Model

Modulator/Demodulator
- The information source is usually not in a form that can be sent directly through the channel.
- The modulator converts the information source into a signal that can be sent through the channel; i.e., it couples the source to the channel.
- At the other end of the channel, the demodulator reconverts the signal received through the channel into its original form.
- For two-way (i.e., duplex) communication, both ends of the link have a modulator and a demodulator, a combination known as a modem.
- By symmetry, we can consider only a one-way link for now.

Carrier Signals
- The channel has certain types of signals that are easily transmitted - known as carriers.
- Basically, the modulator works by putting the information source onto a carrier.
- For physical channels, sinusoidal signals are the most suitable carriers.
- Basic modulation systems work by varying the amplitude, frequency or phase of a sinusoidal carrier in concert with the information source.

Signaling Rate
- Consider a sequence of binary digits from a digital source: 
  ....... 0110011010101011101......
- We want to transmit this source over the channel at a rate of B bits per second (bps).
- To do this, we should send one binary symbol every $T = \frac{1}{B}$ seconds (the symbol interval).

Basic Binary Modulation
- When its turn comes up, a given bit is sent by choosing one of two possible distinct signals, $s_0(t)$ or $s_1(t)$, to transmit during its bit interval.
- If the given bit is 0, we send $s_0(t)$, and if the bit is 1, we send $s_1(t)$.
- This process is repeated every T seconds, sending $s_0(t)$ or $s_1(t)$ depending on the bit value to be sent at that time.
- Different choices of $s_0(t)$ or $s_1(t)$ give different types of digital modulators.
Forms of Binary Modulation

On-Off Keying, Frequency-Shift Keying & Phase-Shift Keying:

\[
\begin{align*}
\text{OOK: } s_0(t) &= 0, \quad 0 \leq t < T \\
&= A \sin(2\pi f_c t), \quad 0 \leq t < T \\
\text{FSK: } s_0(t) &= A \sin(2\pi (f_c - \Delta) t), \quad 0 \leq t < T \\
&= A \sin(2\pi (f_c + \Delta) t), \quad 0 \leq t < T \\
\text{PSK: } s_0(t) &= A \sin(2\pi (t + \pi) t), \quad 0 \leq t < T \\
&= A \sin(2\pi t), \quad 0 \leq t < T \\
\end{align*}
\]

- \( f_c \) is the carrier frequency.

Bandwidths of Digitally Modulated Signals

- Modulation of the carrier broadens its spectral line in the frequency domain.
- OOK and PSK occupy approximately the frequency range \((f_c - B, f_c + B)\), for a total approximate bandwidth of \(2B\) (i.e., twice the bit rate).
- FSK is like two OOK signals at carriers \( f_c - \Delta \) and \( f_c + \Delta \), which gives an approximate bandwidth of \(2(\Delta + B)\).

M-ary Digital Modulation

- In the previous examples, the information source is binary: it takes two values ("0" or "1").
- These modulations can be generalized to digital sources with a greater number of possible values, say \(M\) values.
- By choosing \(M\) different amplitudes, \(M\) different phases, or \(M\) different frequencies, the source can also be modulated onto a carrier.

Example - QPSK

- Quadrature Phase Shift Keying (QPSK) sends two simultaneous independent BPSK signals, one on the carrier

\[
A \sin(2\pi f_c t)
\]

and the other on the "quadrature" carrier

\[
A \cos(2\pi f_c t)
\]

- This is 4-ary PSK, with phases \(\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}\)
- QPSK occupies the same bandwidth as binary PSK (BPSK), but allows twice the data rate.

Spectral Efficiency

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Spectral Efficiency</th>
</tr>
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<tr>
<td>OOK</td>
<td>1/2</td>
</tr>
<tr>
<td>BPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
</tr>
<tr>
<td>FSK</td>
<td>3/4</td>
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</tbody>
</table>

- M-ary signaling allows greater spectral efficiencies.

Constellations of M-ary PSK

- Recall that QPSK is 4-ary PSK, with phases \(\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}\)
- We can represent this as a signaling constellation:

- It's common to decompose modulated carriers into in-phase (I) and quadrature (Q) parts, and to represent the result as a complex scalar \(I + jQ\).
- This is called complex basebanding.
Quadrature Amplitude Modulation (QAM)

• QPSK can also be thought of as the modulation of the amplitudes of two quadrature carriers, using the two amplitude values +1 and -1 on each carrier.
• This can be generalized to allow more than two amplitude values on each of the quadrature carriers, a technique known as QAM, e.g.

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<tr>
<td>Q</td>
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</table>

Noncoherent Demodulation

• OOK can be demodulated simply by detecting the amount of energy in the signaling band \((\Delta f-\Delta,\Delta f+\Delta)\), and comparing with a threshold.
• FSK is like two OOK signals at carriers \(f_c-\Delta\) and \(f_c+\Delta\). This can thus be modulated by detecting the amount of energy in each of the bands \((f_c-\Delta, f_c-\Delta+\Delta)\) and \((f_c+\Delta, f_c+\Delta+\Delta)\), and comparing the two values.
• PSK cannot be detected without making use of the carrier phase. This is called coherent demodulation.

Coherent Demodulation

• The PSK signaling waveforms are given by

\[
\begin{align*}
s(t) &= A \sin(\omega t + \phi(t)) \quad 0 \leq t \leq T \\
\hat{s}(t) &= A \sin(\omega t) \quad 0 \leq t \leq T
\end{align*}
\]

• Multiplying by the carrier gives

\[
\begin{align*}
s(t) \sin(\omega t) &= \frac{A^2}{2} \cos(\Phi(t)) \quad 0 \leq t \leq T \\
\hat{s}(t) \sin(\omega t) &= \frac{A^2}{2} \cos(\Phi(t)) \quad 0 \leq t \leq T
\end{align*}
\]

• The double-frequency terms can be eliminated by low-pass filtering.

Differential PSK (DPSK)

• FSK is simplest to demodulate, but PSK performs better (as we’ll see next time).
• Differential PSK transmits bits by shifting the phase only to indicate a change in bit polarity (i.e., a shift from 1 to 0 or 0 to 1).
• This simplifies demod of PSK by eliminating the need for estimating the carrier phase. Combines ease of demodulation, with good performance.
• Also can do DQPSK (used in commercial CDMA).

Radio Spectrum Basics

• As we have noted, sinusoidal signals are suitable carriers for transmitting information by wireless.
• Physically, these carriers are electromagnetic waves that oscillate at the carrier frequency as they propagate from the transmit antenna to the receive antenna.
• It is convenient for technological and regulatory reasons to view and classify the electromagnetic environment in terms of carrier frequency.
• This taxonomy is referred to as the radio spectrum, or more generally the electromagnetic spectrum.

What Limits Transmission?

• The rate at which symbols can be transmitted is limited by the bandwidth of the channel.
• The rate at which errors are introduced into the bit stream [i.e. the bit error rate (BER)] depends on the noise level in the channel.
• More later.
Frequency Band Designations

<table>
<thead>
<tr>
<th>RADIO</th>
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<th>UV</th>
<th>X-RAYS</th>
<th>GAMMA RAYS</th>
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<tr>
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<td></td>
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<tr>
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<td>MF</td>
<td>HF</td>
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<td>30M</td>
<td>300M</td>
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</table>

- VLF: Very Low Frequency
- LF: Low Frequency
- MF: Medium Frequency
- HF: High Frequency
- VHF: Very High Frequency
- UHF: Ultra High Frequency
- SHF: Super High Frequency
- EHF: Extremely High Frequency

Note: these designations were set by an international conference in 1959.

Some US Frequency Allocations

- **Submarine Communications**: 30 kHz
- **Navigation (Loran C)**: 100 kHz
- **AM Radio**: 540 – 1,600 kHz (medium wave)
- **Tactical Comm/Radio Amateur**: 3 – 30 MHz (short wave)
- **Cellular**: 824 – 894 MHz (UHF) [not contiguous]
- **PCS**: 1.85 – 1.99 GHz (UHF) [not contiguous]
- **Satellite Comm**: SHF
- **Wireless LANs**: the upper ISM bands and IR (not regulated).

ISM Bands

- **ISM** = Industry, Science & Medicine
- Few restrictions except transmit power of 1 watt or less.
- **ISM Bands**:
  - 902 – 928 MHz
  - 2.4 – 2.4835 GHz
  - 5.725 – 5.850 GHz
- **E.g., IEEE 802.11 Wireless LANs**:
  - 2.4 – 2.4835 GHz (1 - 2, 11 Mbps service)
  - 5.725 – 5.850 GHz (6 - 54 Mbps service)

Recall the Model

Now we’ll focus attention on the channel.

PHYSICAL PROPERTIES OF WIRELESS CHANNELS

- **Information Source** → **Modulator** → **Channel**
- **Information Destination** ← **Demodulator**

Question: If higher-order (M-ary) signaling allows for increased spectral efficiency, what limits the rate of data transmission over a wireless link?

Answer: Impairments imposed by the physical properties of the channel; e.g.,
- noise (receiver & background)
- path loss (spatial diffusion & shadowing)
- multipath (fading & dispersion)
- interference (multiple-access & co-channel)
- dynamism (mobility, random-access & bursty traffic)
- and, ultimately, limited transmitter power

General Comments
Noise

- Noise is present in all communication systems.
  - Two basic types:
    - Background noise, generated in the channel (e.g., background light in IR systems, etc.)
    - Receiver noise, generated in the receiver electronics (“thermal noise”)
  - Noise is sufficiently complex to be usefully modeled only via probabilistic methods.
  - A useful noise model is “white” noise, which is noise whose spectrum is constant for all frequencies, and whose amplitude distribution is Gaussian.

White Noise

- The spectrum of a random process specifies how the process’ energy is distributed as a function of frequency.
- The integral under the spectrum over any given band of frequencies equals the amount of energy in that band.

Signal-to-Noise Ratio (SNR)

- A key parameter of the noise is the spectral height or noise level, often designated as N_o/2.
- A key parameter of the signal is the received energy per bit, usually designated by E_b.
- The ratio E_b/N_o (“enob”) is a measure of signal-to-noise ratio (SNR), and is a key parameter in determining the quality of a communications link.

Bit Error Rate (BER)

- The performance of a digital link can be measured in part by the bit-rate; but performance depends also on the quality of transmission, as measured by the bit-error rate (BER).
- The BER (also known as the “probability of bit error”) is, as its name implies, the rate at which errors are introduced into the transmitted data stream by the channel.
- E_b/N_o determines the rate of bit errors caused by white noise.
- This varies with modulation type.

BERs for Binary Modulation

Note: the horizontal axis is marked-off in decibels (dB), which are units computed as 10 log_{10}(E_b/N_o).

BERs of Higher-Order Modulation

- Recall QPSK which sends two simultaneous independent BPSK signals, one on each of two carriers in quadrature.
  - QPSK occupies the same bandwidth as binary PSK (BPSK), but allows twice the data rate. It also has the same BER as BPSK.
- What about other M-ary modulations?
Error Rates of M-ary Modulation

- In white noise, the symbol error rates (SERs) of QAM and M-PSK modulations depends primarily on the distance between the two closest constellation points, relative to the noise level.
- Alternatively, the BER depends on how bits are coded into symbols; typically they are coded so that minimum-distance symbols differ by only one bit, in which case BER = SER/M.
- The SNR depends on the average distance of the constellation points from the origin (again, relative to the noise level). So, for fixed SNR, the SER (and BER) increases with increasing M.
- For wireless applications, high-order QAM or M-PSK are not frequently used (an exception is in video transmission) because of the low SNR’s on such channels.

Large Scale Propagation Effects

- $E_b$ is affected by the distance, $d$, between the transmitter and receiver:
  - for free-space propagation, the energy falls off inversely with $d^2$.
  - for propagation near the Earth’s surface, the energy falls off inversely with $d^r$ with $r$ approximately in the range 3 - 4.
- $E_b$ is also affected by shadow fading and multipath fading.
- Shadow fading refers to attenuation of $E_b$ caused by intervening obstructions; this effect is typically modeled as a random (log-normally distributed) scale-factor multiplying $E_b$.

Propagation Effects

- Noise affects all communication systems.
- For wireless systems, propagation effects also play a significant role in link performance.
- Two basic types of effects:
  - Large-scale effects (spatial diffusion & shadow fading)
  - Small-scale effects (multipath fading)

Multipath

- Multiple copies of the transmitted signal arrive at the receiver due to reflections (off buildings, walls, etc.).
- The destructive and constructive interference of the different paths causes fading; i.e., fluctuations in $E_b$:
  - Superposition of widely separated paths causes frequency-selective fading; modeled via a channel impulse response.
  - Superposition of many closely separated paths causes flat fading; modeled as independent Gaussian random variables in I and Q channels (so-called Rayleigh fading).
- Mobility adds dynamism to the fading:
  - slow fading is steady over many symbol intervals
  - fast fading changes very rapidly (bad!)

Frequency-Selective Fading

- The use of wideband signals (e.g., spread spectrum), allows different paths to be resolved and added constructively. (The technique for this is called a RAKE receiver.)
- With narrowband signals, frequency-selective fading is an impairment; i.e., it negatively affects performance.
Multipath: Dispersion

- The delay spread is the time difference between the first and the last path to arrive at the receiver.
- If the delay spread is significant relative to the symbol interval, then multiple symbols can overlap at the receiver.
- This phenomenon is called dispersion, and it causes inter-symbol interference (ISI).
- ISI is not a significant impairment in current cellular systems, but will be a factor in emerging high-rate systems (e.g., 3G).
- ISI can be corrected by an equalizer.

Interference

- Communications through an open medium (e.g., a radio channel) are susceptible to many other kinds of interference:
  - Multiple-access Interference (MAI): interference caused by other signals in the same network (e.g., the same cell in a cellular network)
  - Co-channel Interference (CCI): interference from other communication networks operating in the same band (e.g., adjacent-cell interference in a cellular system, unregulated communication signals, spurious transmissions, emissions from electrical equipment).

Dynamism

- Many impairments are exacerbated by the dynamism of wireless channels:
  - mobility
  - entry/exit of users from channels
  - bursty data sources
- Dynamism can be addressed by using adaptive receiver techniques that adapt to the signaling environment.

Further Issues

- Power Limitations:
  - Many of the impairments can be overcome more easily by transmitting at higher power levels.
  - This is not practical in portable (battery operated) devices, where power is at a premium.
- Error-Control Coding:
  - High link BER can be overcome using error-control coding (ECC).
  - This involves the transmission of additional bits to use in error control; thus, it uses extra resources.
  - The ratio of the number of data bits to the number of transmitted bits, is called the rate of the code.
  - Most digital wireless systems use some form of ECC.

 Basics

- Now, we will address the question of how available bandwidth can be allocated to multiple users of a service.
- There are three basic “dimensions” that can be allocated to provide multiple access:
  - space
  - time
  - frequency
- Techniques for doing this are called multiple-access techniques.
- Here, we’ll focus on time and frequency based multiple-access techniques.
**Time and Frequency Allocation**

- Spatial allocations are largely fixed by significant infrastructure deployment decisions.
- Time and frequency can be allocated more flexibly.
- There are three basic allocation schemes for these resources:
  - Frequency-division multiple access (FDMA)
  - Time-division multiple access (TDMA)
  - Code-division multiple access (CDMA)

**FDMA Example - AMPS**

*Advanced Mobile Phone Service (AMPS) - U.S. Analog Cellular*

- 50 MHz of total bandwidth is available
  - 869 - 894 MHz for the “forward” (base to mobile) link
  - 824 - 849 MHz for the “reverse” (mobile to base) link
- These are divided into 30kHz-wide (FM voice) channels.
- Only a subset of the channels are used in any given cell (this avoids inter-cell interference).

**TDMA - Examples**

*U.S. Digital Cellular (USDC) (also called IS-54/IS-136)*

- 30kHz AMPS channels are subdivided using TDMA
- 8 subchannels (for 4 kbps digital voices)
- DQPSK modulation is used
- Time intervals are about 1/4 millisecond (10^{-3} second)
- Time slots are about 24 ms
- Can also give 2 slots/user for 8 kbps voice
- Also called Digital AMP (D-AMPS)
- Also, *Global System for Mobile (GSM) - European digital cellular.*

**FDMA**

- In FDMA, the available radio spectrum is divided into *channels* of fixed bandwidth, which are then assigned to different users.
- While a user is assigned a given channel, no one else is allowed to transmit in that channel.

**TDMA**

- In TDMA, time is divided into *intervals* of regular length, and then each interval is subdivided into *slots.*
- Each user is assigned a *slot number,* and can transmit over the entire bandwidth during its slot within each interval.

**CDMA**

- In FDMA, users are divided into *distinct frequency channels,* which they can *exclusively* use while connected to the network.
- In TDMA, users are divided into *distinct time slots,* again for their *exclusive* use while connected.
- In CDMA, all users are allowed *all the available bandwidth all of the time* while connected.
- The manner in which these resources are used is controlled by a *code or pattern,* unique to each user.
**CDMA - Cont’d**

- The receiver knows the pattern of time/frequency use of the various users, and can separate them accordingly.
- Two basic types of CDMA:
  - frequency hopping
  - direct sequence

**Frequency Hopping**

- In frequency hopping an ordinary source (say voice) is modulated into a carrier as usual.
- But, instead of having a single carrier frequency, the carrier frequency is “hopped”, seemingly at random, throughout the entire range of available frequencies.
- The hopping pattern is not really random but is merely very complex so as to appear random (this is called pseudorandom pattern)
- The receiver knows the hopping pattern, and can demodulate simply by hopping the demodulator’s frequency accordingly.

**Spread Spectrum**

- Because the transmitted signal with frequency hopping occupies a bandwidth much than that of the source, this is an example of spread spectrum modulation.
- Spread spectrum was originally developed for military communications because of two advantages:
  - it’s hard to jam
  - it’s hard to intercept
- It also has the advantage that it’s less susceptible to some physical channel impairments (e.g., frequency-selective fading) than is narrowband signaling.

**Frequency Hopping CDMA (FH/CDMA)**

- Frequency hopping can be used as a multiple access technique by assigning each user a distinct hopping pattern.
- Although sometimes two users may hop to the same frequency, this can be fixed through error-control coding.
- An advantage is that FH users can randomly access the channel without need for a reserved channel or time slot.
- FH/CDMA is used very commonly in tactical communications, and in some wireless LAN’s. Also GSM uses some elements of FH to reduce inter-cell interference.

**FH/CDMA - Example**

- Wireless LAN’s (IEEE 802.11 standard)
  - frequency band 2.4-2.4835 GHz (ISM Band)
  - source: data at 1 - 2 Mbps
  - modulation: FSK
  - the carrier hops 2.5 times per second through 79, 1-MHz sub-bands.

**Direct Sequence Spread Spectrum**

Suppose we multiply a baseband data signal by another binary baseband signal, with a much higher symbol rate.

![Diagram](image)

The resulting signal

\[ p(t) = c(t) m(t) \]

is also a high-rate baseband signal, which much higher bandwidth than the original baseband data signal.
Now suppose \( p(t) = c(t)m(t) \) is modulated onto a carrier and then demodulated at a receiver.

- If the receiver knows the higher-rate signal \( c(t) \), then it can form \( c(t)p(t) = c^2(t)m(t) - m(t) \) (since \( c(t) = +1 \) or \(-1\) and so \( c^2(t) = 1 \)).
- This process (called **despreading**) recovers the baseband data signal.

This process (called **despreading**) recovers the baseband data signal.

The transmitted bandwidth is \( 2/T_c \), which is much larger than the \( 2/T \) bandwidth required by OOK or PSK, and so this is another form of spread spectrum.

- It's called **direct sequence** because the "sequence" \( c(t) \) is modulated directly onto the baseband data signal (instead of via the carrier, as in FH).

- The symbols are called **chips** (to distinguish them from the bits of the actual data source.)
- The signal \( c(t) \) is called the **pseudo-noise (PN) signal**; it is usually chosen to be periodic and to have other structure to make it easy to generate.

The **spreading ratio** is a key parameter in spread-spectrum systems; it refers to the factor by which the bandwidth of the source signal is spread.

- For DSSS, spreading ratio = \( T/T_c \) = the no. of chips per bit.
- \( 1/T_c \) is called the **chip rate**.

- Like frequency hopping, direct-sequence can be used as a multiple-access technique.
- Different users are assigned different spreading codes.
- The receiver can pick out a given user by despreading with its code.
- Like a "cocktail party" effect.
**DS/CDMA - Cont’d**

- DS/CDMA has a number of advantages:
  - robustness to physical impairments of mobile radio channels (frequency-selective fading).
  - allows greater privacy / security
  - allows greater flexibility in assignment of users (“graceful degradation”)
  - in cellular systems allows reuse of frequencies in adjacent cells (greater capacity)
  - can take advantage of bursty traffic and amplitude fading of interferers.
  - can be overlaid on existing services (good for use in ISM bands).

**DS/CDMA - Examples**

- US CDMA Cellular (IS-95):
  - frequency band same as AMPS
  - source: digital voice at 9.6 kbps
  - modulation DQPSK (downlink)
  - spreading gain 128 chips/bit
  - chip rate is 1.2288 Mchips/second (Mcps)

- 3rd Generation (3G) Cellular: Wideband CDMA (W-CDMA)
  - source: digital voice or multimedia (rates range from 9.6kbps to 2Mbps)
  - variable spreading gain
  - chip rates up to 5Mcps

- Wireless LANs (IEEE 802.11b, 802.11g)

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**xDMA Summary**

**PACKET RADIO**

**Fixed Channel Assignment**

- FDMA, TDMA and CDMA are called *fixed-assignment* channel-access methods because each user is given a share of the channel resources (e.g., a frequency band, a time-slot, or a code) through which to transmit.

- These methods make relatively efficient use of radio resources when there is a steady flow of information from the source — e.g., voice, a data file, a fax.

- However, for sources generating short messages at random times, this is inefficient; and *random-access methods* — also called *packet radio* — are of interest.

**Data Packets**

- In random-access systems, a data sequence from a digital source is broken down into smaller pieces which are organized into *data packets*.

- A data packet is a series of digital symbols with a structure something like the following:

  | TAIL | ERROR CONTROL | DATA PAYLOAD | ID | HEADER |

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COS598u: Pervasive Information Systems
Random Access Protocols

- Packets are transmitted to a destination through a shared radio network without explicit channel assignment. [They can also be switched through a backbone network.]
- When they all arrive safely at the destination, the payloads are reassembled into the original data sequence from the information source.
- Since the channel is shared, protocols must be observed to assure the fair and orderly transfer of data.
- We’ll talk about two basic protocols:
  - ALOHA
  - Carrier-sense Multiple Access (CSMA)

Packet Radio Basics

- Subscribers attempt to access a single radio channel by transmitting packets to a common receiver — say, a base station — in a minimally coordinated fashion.
- If the packet is correctly received (as assessed by the CRC), an ACK (acknowledgement) identifying the received packet is broadcast back to the subscribers.
- If the receiver detects a collision of two packets or otherwise erroneous reception, it broadcasts a NACK (negative acknowledgement). The transmitter then must re-send the packet.

Contention Protocols

- Protocols establish the manner in which packets can be sent originally, and how they should be re-sent if a NACK is received.
- Such schemes are called contention techniques.
- They key parameters are
  - Throughput: the average number of packets successfully transmitted per unit time
  - Delay: the average delay experienced by a typical packet

ALOHA

- ALOHA: developed at the Univ. of Hawaii for bursty low-data-rate transmission over satellite systems.
- Pure ALOHA:
  - a user transmits as soon as a packet is ready to go
  - if a collision occurs (NACK received) the transmitter waits a random period of time and then retransmits
  - simple, but low throughput
- Other forms improve throughput, but reduce flexibility.
  - slotted ALOHA: transmission can occur only at the beginning of specific time slots (doubles throughput).
  - reservation ALOHA: a transmitter with a long file can reserve slots.

ALOHA Example

Ericsson MOBITEX System:

- low data rate data-only cellular system:
  - dispatch, PDA’s (e.g., PalmVII), etc.
- radio protocol:
  - reservation slotted-ALOHA

Carrier-Sense Multiple Access (CSMA)

- The transmitter "listens" to see if the channel is idle (i.e., no carrier is detected).
- If the channel is idle, the user transmits according to a fixed protocol.
- Collision still occur because of simultaneous transmission, and also because of transmission delay.
**CSMA Varieties**

- **Types:**
  - **1-persistent CSMA:** packet is transmitted as soon as the channel is idle.
  - **non-persistent CSMA:** NACK'ed packets are retransmitted only after a random amount of time.
  - **CSMA with collision detection (CSMA/CD):** The transmitter listens while transmitting to see if anyone else is also transmitting — ("listen while talk"). If so, transmission is aborted immediately.

**CSMA - Examples**

- **Ethernet**
  - uses CSMA/CD

- **Wireless LANs (IEEE 802.11)**
  - uses CSMA/CA ("collision avoidance")

- **Cellular Digital Packet Data (CDPD)**
  - packet service over idle AMPS channels
  - uses a form of CSMA/CD called "digital sense multiple access" (DSMA)

**Other Issues in Networking**

- Network management is organized in layers of responsibility.
- The **physical layer** refers to the transmission of data through the physical medium (i.e., by mod/demod).
- The next layer up is the **data-link layer**, which is responsible for:
  - establishing and maintaining connections
  - error control
  - media-access control (MAC)
- Random-access schemes are MAC protocols.

**Other Issues - Cont’d**

- **MAN's and WAN's** have **higher-order layers** to handle routing through the network, end-to-end verification, applications, etc.
- **Examples of higher-level protocols are:**
  - Internet Protocol (IP)
  - Transmission Control Protocol (TCP)
  - Wireless Application Protocol (WAP)

**Emerging Technologies**

**Orthogonal Frequency Division Multiplexing (OFDM)**

- **Main Issue:** Frequency-selective channels cause inter-symbol interference (ISI) in broadband data transmission. The mitigation of this ISI requires high receiver complexity.
  - OFDM transmits many narrowband data signals on closely-spaced carriers. This exploits **frequency diversity**.
  - OFDM allows a very simple receiver for broadband data.
  - IEEE 802.11a uses OFDM for 6-54 Mbps wireless LANs.
  - Also good for home entertainment systems.
  - Main drawback - Doppler effects limit mobility.
Ultra Wideband (UWB)

**Main Issue:** Radio spectrum is scarce and precious. UWB allows overlay of new services on existing ones.

- UWB transmits data on extremely short pulses.
- The energy in these pulses is thereby spread over a very wide radio bandwidth, and is thus very low in any particular band.
- Cross-interference with other communications signals is minimal.
- Receiver complexity is low.
- Main drawback - lack of FCC approval.

Multiuser Detection (MUD)

**Main Issue:** Spread-spectrum technologies (CDMA, WiFi, Bluetooth, etc.) allow multiple users to share a common channel. This causes interference, which limits capacity.

- MUD increases the capacity of such channels by mitigating interference through intelligent time-domain signal processing.
- The basic idea is to exploit (rather than ignore) cross-correlations among different users’ signals.
- Capacity gains of several × can be obtained.
- 3G standards permit MUD.
- Main drawback - complexity (chip real estate; power).

Smart Antennas

**Main Issue:** Antennas spaced sufficiently far apart experience independent fading and noise. This allows exploitation of spatial diversity.

- By properly combining the outputs of multiple receiver antennas, beams can be formed to isolate transmitters.
- Transmitter beamforming is also possible.
- Beamforming can be done electronically to “track” mobile transmitters/receivers (some difficulties with this).
- Spatial processing can be combined with temporal processes (e.g., MUD) - “space-time processing”
- Main drawback - complexity (RF hardware; processing)

Space-Time Coding

**Main Issue:** Different paths between transmitter and receiver exhibit independent fading. This allows exploitation of angle diversity.

- Space-time coding transmits different, but related, data streams over each element of an array of antennas.
- The receiver can have one or more antennas; and it does not necessarily need to know the channel characteristics.
- Capacity gains of many × can theoretically be obtained.
- 3G standards permit space-time coding.
- Main drawback - complexity (RF hardware; processing).

Info-Station “Free Bits”

**Main Issue:** The objective of cellular is “anytime, anywhere” service. This is a very expensive solution for high-data-rate apps, perhaps unnecessarily so.

- Info-stations provide very high data-rate service, but only at selected locations (lamp posts, stop lights, doorways, etc.).
- The philosophy is “many time, many where”, more in line with the best effort philosophy of wireline Internet.
- This lowers the cost of high data-rate considerably, since only the best channels need to be provisioned.
- Main drawback - it’s still a research problem.

Info-Stations: System of “Sweet Spots”

- Small, separated “cells”
- Low power (~100 mw)
- Brief connections (~1 sec)
- Very high bit rate (~1 G bps)
- Simple infrastructure (LAN on a pole, IP access)
- Unlimited capacity for a flat rate

*Courtesy of Roy Yates (WINLAB)*
THE END