Wireless Networks and Protocols

MAP-TELE

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  » Universidade de Aveiro
Syllabus

- **Introduction to Wireless Networks and Protocols**
  - What are Wireless networks
  - History of wireless networks
  - Standards and market issues
  - Evolution and trends on wireless networking

- **Fundamentals of wireless communications**
  - Transmission
  - Wireless data links and medium access control
  - Networking
  - Mobility concepts and management
Syllabus

- Telecommunications systems
  - GSM and GPRS
  - UMTS
  - TETRA
  - Broadcast and satellite: DVB, DMB

- IEEE wireless data networks
  - WLAN: 802.11
  - WMAN: 802.16
  - WPAN: 802.15

- Convergence and interoperability of wireless systems
  - 4G wireless networks
  - 3GPP and Mobile IPv6 approaches
  - Integration of ad-hoc networks
Syllabus

- **Quality of service**
  - Characterization and models
  - Case studies: 3GPP-QoS, IEEE-QoS, IP-QoS

- **Support for services and applications**
  - Web services components: XML and SOAP, UDDI and WSDL
  - Services and applications platforms
Bibliography

- Slides
- Recommended papers
- Chapters from multiple books
  - Mobile IP Technology and Applications, Stefan Raab and Madhavi W. Chandra, Cisco Press, 2005
  - GSM cellular radio telephony, Joachim Tisal, John Wiley & Sons, 1997
  - Wireless Communications and Networks, William Stallings, Prentice Hall, 2002
Grades

- Final Exam - 50%
- Review of papers - 20%
- Small project - 30%
WNP – Wireless Networks

- About wireless communications systems
- Addressed from a network and system perspectives

Common wireless communications systems
**Wired versus Wireless networks**

- **Wireless Networks** characterised by
  - wireless links
  - mobility of nodes
  - dynamic network topologies

![Diagram of Wired and Wireless Networks]

- **Terminal Mobility**

![Dynamic network topology diagram]
Wireless Link

- Low powers received $\Rightarrow$ low SNR
  $\Rightarrow$ large % of bits possibly received in error

- SNR varies with time and positions
  $\Rightarrow$ variable capacity (bit/s) or variable error ratio (BER)

- Broadcast nature
  » Information easily accessible by third parties $\Rightarrow$ security mechanisms
How to obtain low Bit Error Ratio in a Wireless Link?
Mobility

- Mobility: characteristic of portable terminals and moving objects

- Problems introduced by the mobile terminal
  - determine its new location
  - Find radio resources in new location
  - determine the new path for data delivery
The terminal is receiving packets and, after moving to a new location, the terminal is expected to continue receiving packets.

What procedure would you implement to manage the terminal mobility?
Dynamic Network Topology

- Nodes move
- Capacity of a link (bit/s) varies along the time
- Communication of a node interferes with a neighbor node
- Shortest path between two nodes varies along the time
- Capacity of the network becomes hard to characterize
History – Past and Radio

♦ Past
  » Fire signals used to communicate the fall of Troy to Athens
  » 2nd century B.C., sets of torches to transmit characters
  » 1793, 3 part semaphores on top hills and towers
  » 1837, electric telegraph

♦ Radio transmission
  » 1895, first radio transmission
  » 1906, amplitude-modulated (AM) radio
  » 1920, broadcast of radio news program
  » 1928, TV broadcast trials
  » 1933, frequency-modulated (FM) radio
  » 1946, Swedish police had the first radio phones installed in cars
  » 1950, mobile phone with direct dialling
History – Cell, 1st Generation

♦ Cellular topology
  » 1950’s, cellular network concept
     power of transmitted signal falls with square of distance
     2 users can operate on same frequency at separate locations
  » 1971, Finland, ARP, first public commercial cellular, mobile network

♦ 1st Generation ➔ Analogue, Frequency Division Multiplexing
  » 1982, NMT network covering Finland/Sweden/Norway/Denmark
  » 1983, AMPS in America
  » 1985, TACS, Total Access Communications Service, in Europe
History – Packet Radio

- 1971, ALOHANET packet radio
  » computers communicate with central HUB
- 1980's ad-hoc, self-configurable packet networks
- 1985, Wireless LANs authorized to use ISM bands
- 1997, first WLAN standard
History – 2\textsuperscript{nd} and 3\textsuperscript{rd} Generation

- 2nd Generation
  - digital transmission and signalling; ISDN based
  - 1982, specification GSM is started
  - Early 1990’s
    - Europe: GSM
    - USA: D-AMPS, cdmaOne
    - Japan: Personal Digital Cellular (PDC)

- 3G systems
  - aimed at multimedia communication
  - 2001, Japan, first implementation of 3G systems
**Type of Networks**

- **WPAN - Wireless Personal Area Networks**
  - short distances among a private group of devices

- **WLAN - Wireless Local Area Networks**
  - areas such as a home, office or group of buildings

- **WMAN - Wireless Metropolitan Area Networks**
  - from several blocks of buildings to entire cities

- **PLMN - Public Land Mobile Networks**
  - regions and countries

- **Broadcast**
  - single direction, audio and video
Technologies Comparison

• U=bit/s/Hz/km²
  – PLMN ➔ 10 to 40 U (based on UMTS)
  – WMAN ➔ 25 to 50 U
  – WLAN ➔ 100 to 500 U
Evolution of Technologies

<table>
<thead>
<tr>
<th>Rate (bit/s)</th>
<th>Mobility (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b WLAN</td>
<td>2G Cellular</td>
</tr>
<tr>
<td>802.11n</td>
<td>3G</td>
</tr>
<tr>
<td>4G</td>
<td>Wimax/3G</td>
</tr>
</tbody>
</table>

- **2G Cellular**: 802.11b WLAN, 2G
- **3G**: 802.11n, 3G
- **4G**: Wimax/3G
Standard Organizations - IEEE

- IEEE - Institute of Electrical and Electronics Engineers
  
  802 Standards for Local / Metropolitan Area Network, wired and wireless
  
  » Wireless LANs (802.11)
  » Wireless Personal Area Networks (802.15),
  » Broadband Wireless Metropolitan Area Networks (802.16)
  » Mobile Broadband Wireless Access (802.20)
  » Media Independent Handoff Working Group (802.21)

http://standards.ieee.org/getieee802/index.html

- Layers 1 and 2 of the OSI communications model
- Below the IP communications layer
Standards – 3GPP

- Scope of 3GPP
  - Specifications for the 3rd Generation mobile system
  - Maintain GSM, GPRS and EDGE
  - Specifications developed by Technical Specification Groups (TSG)

http://www.3gpp.org
Standards - IETF

- Defines standards for the Internet, including
  - TCP/IP
  - key services
  - routing protocols
  - deployment of IP over technologies
Standards - Other

- ITU - Worldwide
- ETSI - Europe
- 3GPP2 – American 3GPP
Homework

1. Review slides
2. Read from Schiller
   » Chap. 1
3. Read from Goldsmith
   » Chap. 1
- How does an EM wave propagate in a wireless channel?
- What is an antenna and an antenna gain?
- What is shadowing, reflection, refraction, scattering, and diffraction?
- What is path loss? How to model it?
- What is the simple path loss model?
- How to model shadowing?
- What is multipath? How does it affect the power received? How does it affect narrowband and wideband communications?
- What is the maximum theoretical capacity of a wireless channel?
Electromagnetic Wave

\[ \lambda = \frac{c}{f} \]

\[ c = 3 \times 10^8 \text{ m/s}, \text{ speed of light} \]

\[ f_c = 3 \text{ GHz} \Rightarrow \lambda = 10 \text{ cm} \]
\[ f_c = 1 \text{ GHz} \Rightarrow \lambda = 30 \text{ cm} \]
\[ f_c = 300 \text{ MHz} \Rightarrow \lambda = 1 \text{ m} \]
Frequencies for Radio Transmission

Frequency bands as defined by the ITU-R **Radio Regulations**

\[ \text{band}_i \in [0.3 \times 10^3 \text{ Hz}, 3 \times 10^3 \text{ Hz}]. \]

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Symbol</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>VLF</td>
<td>3-30 kHz</td>
</tr>
<tr>
<td>5</td>
<td>LF</td>
<td>30-300 kHz</td>
</tr>
<tr>
<td>6</td>
<td>MF</td>
<td>3000-3000 kHz</td>
</tr>
<tr>
<td>7</td>
<td>HF</td>
<td>3-30 MHz</td>
</tr>
<tr>
<td>8</td>
<td>VHF</td>
<td>30-300 MHz</td>
</tr>
<tr>
<td>9</td>
<td>UHF</td>
<td>300-3000 MHz</td>
</tr>
<tr>
<td>10</td>
<td>SHF</td>
<td>3-30 GHz</td>
</tr>
<tr>
<td>11</td>
<td>EHF</td>
<td>30-300 GHz</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>300-3000 GHz</td>
</tr>
</tbody>
</table>

\[ f_c = 3 \text{ GHz} \quad \Rightarrow \lambda = 10 \text{ cm} \]
\[ f_c = 1 \text{ GHz} \quad \Rightarrow \lambda = 30 \text{ cm} \]
\[ f_c = 300 \text{ MHz} \quad \Rightarrow \lambda = 1 \text{ m} \]
Wireless Systems in Europe

- In Portugal
  ANACOM attributes the frequencies
  http://www.anacom.pt

- FWA
  Fixed Wireless Access

- ISM
  Industrial, Scientific and Medical

<table>
<thead>
<tr>
<th>Wireless Systems in Europe</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast TV</td>
<td>47-68 MHz</td>
</tr>
<tr>
<td></td>
<td>174-216 MHz</td>
</tr>
<tr>
<td></td>
<td>470-582 MHz</td>
</tr>
<tr>
<td></td>
<td>582-862 MHz</td>
</tr>
<tr>
<td>2G PLMN (GSM)</td>
<td>890-914 MHz</td>
</tr>
<tr>
<td></td>
<td>935-959 MHz</td>
</tr>
<tr>
<td></td>
<td>1710-1785 MHz</td>
</tr>
<tr>
<td></td>
<td>1805-1880 MHz</td>
</tr>
<tr>
<td>3G PLMN (UMTS)</td>
<td>1900-1980 MHz</td>
</tr>
<tr>
<td></td>
<td>2010-2025 MHz</td>
</tr>
<tr>
<td></td>
<td>2110-2170 MHz</td>
</tr>
<tr>
<td>FWA</td>
<td>3400-3600 MHz</td>
</tr>
<tr>
<td></td>
<td>3600-4200 MHz</td>
</tr>
<tr>
<td></td>
<td>24.5-26.5 GHz</td>
</tr>
<tr>
<td></td>
<td>27.5-29.5 GHz</td>
</tr>
<tr>
<td>ISM</td>
<td>13553-13567 kHz</td>
</tr>
<tr>
<td></td>
<td>26957-27283 kHz</td>
</tr>
<tr>
<td></td>
<td>40.66-40.70 MHz</td>
</tr>
<tr>
<td></td>
<td>2400-2500 MHz</td>
</tr>
<tr>
<td></td>
<td>5725-5875 MHz</td>
</tr>
<tr>
<td></td>
<td>24-24.25 GHz</td>
</tr>
</tbody>
</table>
How does the power of a received signal depend on the distance and wavelength ($\lambda$)?
Antenna – The Isotropic Radiator

- **Antenna**
  couples wires to space, for electromagnetic (EM) wave transmission or reception

- **Radiation pattern**
  pattern of EM radiation around an antenna

- **Isotropic radiator**
  » equal radiation in 3 directions ($x$, $y$, $z$)
  » theoretical reference antenna
Antennas - Simple Dipoles

- Real antennas are not isotropic radiators
- Simple antenna dipoles
  - Length $\lambda/2$ ➔ Hertzian dipole
  - Length $\lambda/4$ on car roofs
- Shape of antenna proportional to $\lambda$
- Radiation pattern of a simple Hertzian dipole
Antenna Gain, EIRP

- **Antenna Gain**
  - maximum power in direction of the main lobe ($P_{\text{main_lobe}}$), compared to power of an isotropic radiator ($P_t$) transmitting the same average power
  - **balloon**

\[
G = \frac{P_{\text{main_lobe}}}{P_t} = \frac{4\pi A_e}{\lambda^2}
\]

$A_e$ – Antenna aperture
depends on physical antenna characteristics

- **Effective Isotropic Radiate Power (EIRP)**
  - $EIRP = P_t G_t$
  - Maximum radiated power in the direction of maximum antenna gain
Received Power at Distance $d$ - $P_r(d)$

- Power flow density $P_d \text{ (W/m}^2\text{)}$

$$P_d = \frac{EIRP}{4\pi d^2} = \frac{P_t G_t}{4\pi d^2} \text{ (W/m}^2\text{)}$$

- Received Power at distance $d$, $P_r(d)$

$$P_r(d) = P_d A_e = \frac{P_t G_t}{4\pi d^2} \frac{G_r \lambda^2}{4\pi} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \text{ Watt}$$
Transmit and Receive Signal Models

- Transmitted signal modeled as
  \[ s(t) = \Re \left\{ u(t)e^{j2\pi f_c t} \right\} \]
  \[ = \Re \left\{ u(t) \right\} \cos(2\pi f_c t) - \Im \left\{ u(t) \right\} \sin(2\pi f_c t) \]
  \[ = s_I(t) \cos(2\pi f_c t) - s_Q(t) \sin(2\pi f_c t) \]

- The received signal
  \[ r(t) = \Re \left\{ v(t)e^{j2\pi f_c t} \right\}, \]

- if \( s(t) \) is transmitted through a time-invariant channel \( c \) then
  \[ v(t) = u(t) * c(t), \quad V(f) = H_l(f)U(f). \]

where
- \( c(t)=h_l(t) \) is the equivalent lowpass impulse response of the channel
- \( H_l(f) \) is the equivalent lowpass frequency response of the channel
Doppler Shift

- The received signal may have a Doppler shift of

\[ \Delta d = v \Delta t \cos \theta \]

\[ \Delta \phi = 2\pi \frac{\Delta d}{\lambda} = 2\pi \frac{v \Delta t \cos \theta}{\lambda} \]

- Doppler frequency, \( f_D \)

\[ f_D = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{v \cos \theta}{\lambda} \]
Suppose you are moving towards the transmitter.

Will the perceived frequency of the carrier increase or decrease?
$W, \text{ dBW, dBm, dB, Gain}$

$P_{r_{W}}, \left( \text{Power} = \frac{\text{Energy}}{\text{Time}} \right), \quad 1W = \frac{1J}{1s}$

$P_{r_{dBW}} = 10. \log \left( \frac{P_{r_{W}}}{1W} \right) = 10. \log P_{r_{W}}$

$P_{r_{dBm}} = 10. \log \left( \frac{P_{r_{W}}}{1mW} \right)$

$Gain_{dB} = 10. \log \left( \frac{P_{r_{W}}}{P_{s_{W}}} \right) = 10. \log P_{r_{W}} - 10. \log P_{s_{W}} = P_{r_{dBW}} - P_{s_{dBW}} = P_{r_{dBm}} - P_{s_{dBm}}$

$\text{Loss}_{dB} = \text{Atenuation}_{dB} = P_{s_{dBW}} - P_{r_{dBW}} = P_{s_{dBm}} - P_{r_{dBm}}$
Signal Propagation – Key Concepts

- Propagation often modeled as rays (light)
- Line-of-Sight (LOS) – direct ray receiver gets from transmitter
- Relevant concepts
  - Shadowing, Reflection ➔ caused by objects much larger than the wavelength
  - Refraction ➔ caused by different media densities
  - Scattering ➔ caused by surfaces in the order of wavelengths
  - Diffraction ➔ similar to scattering; deflection at the edges
Real World Examples
Signal Propagation and Wireless Channels

Received Power can be modelled by 3 factors

- **Path loss**
  - Dissipation of radiated power; depends on the sender-receiver distance

- **Shadowing**
  - caused by the obstacles between the transmitter and the receiver
  - attenuates the signal

- **Multipath**
  - constructive and destructive addition of multiple signal components

\[ \frac{P_r}{P_t} = \frac{d}{vt} \]
Path Loss Models

- Free space path loss model
  Too simple

- Ray tracing models
  Demand site-specific information

- Empirical models
  Do not generalize to other environments

- Simplified model
  Good for high-level analysis
Path Loss - Free Space (LOS) Model

- Path loss (PL) for unobstructed LOS path
  - Power falls off
    - Proportional to $1/d^2$
    - Proportional to $\lambda^2$ (inversely proportional to $f^2$)

$$P_{r}/P_s = \left(\frac{\lambda \sqrt{G_l}}{4\pi d}\right)^2$$

$$G_l = \sqrt{G_s G_r}$$

$$PG_{dB} = 10 \log(P_r/P_s)$$

$$PG_{dB} = 20 \log\left(\frac{\lambda \sqrt{G_l}}{4\pi}\right) - 20 \log(d)$$

$d=vt$
**Path Loss – Two-Ray Model**

- One LOS ray + one ray reflected by ground
- Ground ray cancels LOS path above critical distance $d_c = 4h_t h_r / \lambda$
- Power falls off
  - Proportional to $d^2$ ($h_t < d < d_c$)
  - Proportional to $d^4$ ($d > d_c$)

\[ P_r \text{ dBm} = P_t \text{ dBm} + 10 \log_{10}(G_t) + 20 \log_{10}(h_t h_r) - 40 \log_{10}(d) \]
Path – Loss Empirical Models

- Okumura model
  - Empirically based (site/freq specific); 150-1500 MHz, Tokyo
  - Empirical plots

- Hata model
  - Analytical approximation to Okumura model

- Cost 231 Model
  - Extension Hata model to higher frequency (1.5 GHz < $f_c$ < 2 GHz)

- Walfish/Bertoni
  - Extends Cost 231 to include diffraction from rooftops
Path Loss – Indoor Factors

- Walls, floors, layout of rooms, location and type of objects
  - Impact on the path loss
  - The losses introduced **must be added** to the free space losses

<table>
<thead>
<tr>
<th>Partition</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hollow brick</td>
<td>8</td>
</tr>
<tr>
<td>concrete wall</td>
<td>13</td>
</tr>
<tr>
<td>aluminum siding</td>
<td>20</td>
</tr>
<tr>
<td>window</td>
<td>6</td>
</tr>
<tr>
<td>floor</td>
<td>10</td>
</tr>
</tbody>
</table>
Path Loss - Simplified Model

- Used when path loss is dominated by reflections
  \[ P_r = P_s K \left( \frac{d_0}{d} \right)^\gamma, \quad 2 \leq \gamma \leq 8 \]
  \[ P_{r_{dBm}} = P_{s_{dBm}} + K_{dB} - 10 \gamma \log \left[ \frac{d}{d_0} \right] \]
  \[ d_0 \approx 10\lambda \]

- K
  » determined by measurement at \( d = d_0 \Rightarrow K_{dB} = P_{r_{dBm}} - P_{s_{dBm}} \)
  » or, \( K_{dB} = 10 \log \left[ \frac{\lambda}{4\pi d_0} \right]^2 \)

- Path loss exponent \( \gamma \) is determined empirically

<table>
<thead>
<tr>
<th>Environment</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban macrocells</td>
<td>3.7 - 6.5</td>
</tr>
<tr>
<td>Urban microcells</td>
<td>2.7 - 3.5</td>
</tr>
<tr>
<td>Office building</td>
<td>1.6 - 3.5</td>
</tr>
<tr>
<td>Store</td>
<td>1.8 - 2.2</td>
</tr>
<tr>
<td>Factory</td>
<td>1.6 - 3.3</td>
</tr>
<tr>
<td>Home</td>
<td>3</td>
</tr>
</tbody>
</table>
Shadowing

- Models attenuation introduced by obstructions
- Random due to random number and type of obstructions \( \psi \)

\[
\left( \frac{P_r}{P_s} \right)_{dB} = 10 \log K - 10\gamma \log \frac{d}{d_0} - \psi_{dB}
\]

where \( \psi_{dB} \) is a Gaussian distributed random variable characterized by \( \mu_{\psi_{dB}} = 0 \) and \( \sigma_{\psi_{dB}} \)
Combined Path Loss and Shadowing

\[
\frac{P_r}{P_s} (dB) = 10 \log_{10} K - 10 \gamma \log_{10} \left( \frac{d}{d_0} \right) - \psi_{dB},
\]

\[\psi_{dB} \sim N(0, \sigma_{\psi}^2)\]
Outage Probability and Cell Coverage Area

- Path loss model $\rightarrow$ circular cells

- Path loss + shadowing $\rightarrow$ amoeba cells
  tradeoff between coverage and interference

- Outage probability
  Probability received power below given minimum

- Cell coverage area $\rightarrow$ % of cell locations at desired power
  » Increases as shadowing variance ($\sigma_\psi$) decreases
  » Large % indicates interference to other cells
Statistical Multipath Model

- Multipath $\rightarrow$ multiple rays
  - multiple delays from transmitter to receiver $\rightarrow \tau_i$
  - time delay spread $T_m = \max_n |\tau_n - \tau_0|$

- Multipath channel has a time-varying gain
  - caused by the transmitter / receiver movements
  - location of reflectors which originate the multipaths
Multipath – Narrowband Channel

- In a narrowband channel
  
  low \( B \) $\rightarrow$ low symbol rate (symbol/s) $\rightarrow$ large time/symbol (1/B)  
  
  $\Rightarrow$ multipath components arrive in the time period of their symbol

  \[
  T_m = \max_n |\tau_n - \tau_0| \quad T_m << B^{-1}
  \]

- Assume also \( u(t - \tau_i) \approx u(t) \)

- No spreading in time (no distortion)
Multipath – Narrowband Channel

- Under Uniform Angle of arrival in $[0, 2\pi]$:
  » Autocorrelation is zero for $d=0.4\lambda$
Multipath - Narrowband Channel – Rayleigh Fading

- If there is no Line-of-Sight (LOS) component
  - Power received may be modeled by
  - an exponential probability density function

\[ p_{Z^2}(x) = \frac{1}{P_r} e^{-x/P_r} \]

- P_r – average received power (path loss + shadowing)

- If there is LOS ➔ Power received given by a Ricean distribution
Suppose you are the receiver. What information does this exponential distribution provide to you?

\[ p_{Z^2}(x) = \frac{1}{P_r} e^{-x/P_r} \]
Multipath – Wideband Channel

- Multipath components
  » may arrive at the receiver within the time period of the next symbol
  » causing Inter-Symbol Interference (ISI).

- Techniques used to mitigate ISI
  » multicarrier modulation
  » spread spectrum

\[ T_m = \max_n |\tau_n - \tau_0|, \quad T_m \gg B^{-1} \]
Multipath + Shadowing + Path Loss
Capacity of an Wireless Channel

- Assuming Additive White Gaussian Noise (AWGN)
  - Given by Shannon’s law
    \[ C = B \log_2(1 + \gamma) \text{ (bit/s)} \]
    \[ \gamma = \frac{P_r}{N_0B} \]
    \(N_0\) – Noise power spectral density

- Capacity in a fading channel (shadowing + multipath)
  - usually smaller than the capacity of an AWGN channel
Homework

1. Review slides
   » use them to guide you through the recommended books

2. Read from Goldsmith
   » Chap. 2, Chap. 3 (sections 3.1, 3.2, 3.3), Chap. 4 (section 4.1)

3. Read from Schiller
   » Chap. 2 (sections 2.1, 2.2, 2.3, 2.4)

4. Rappaport also provides an excellent description of these topics
   » See Chap. 3 and Chap. 4
- How to transmit bits in a carrier? What are the modulations commonly used in wireless networks?
- How does the BER depend on the modulation and SNR?
- What is a code? What are its benefits for wireless communications? Why is interleaving combined with codes?
- What is multicarrier modulation? What is OFDM? Why is it so important? How to implement it with DFTs?
- What is spread spectrum? How does the RAKE receive work?
- What is Software Defined Radio?
- What are the main purposes of Cognitive Radio?
Digital Modulation/Demodulation

- **Modulation**: maps information bits into an analogue signal (carrier)
- **Demodulation**: determines the bit sequence based on received signal

Two categories of digital modulation

- **Amplitude modulation -** $\alpha(t)$, **Phase modulation -** $\theta(t)$
- Frequency modulation - $f(t)$

- Modulated signal $s(t)$
  \[ s(t) = \Re\{u(t)e^{j(2\pi f_c t)}\} \]

- Amplitude modulation:
  \[
  s(t) = \alpha(t) \cos[2\pi(f_c + f(t))t + \theta(t) + \phi_0] = \alpha(t) \cos(2\pi f_c t + \phi(t) + \phi_0)
  \]

- Phase modulation:
  \[
  s(t) = \alpha(t) \cos \phi(t) \cos(2\pi f_c t) - \alpha(t) \sin \phi(t) \sin(2\pi f_c t)
  \]

- Signal transmitted over time symbol $i \rightarrow s_i(t)$
Amplitude and Phase Modulation

- $K = \log_2 M$ bits sent over a time symbol interval
- Amplitude/phase modulation can be:
  - Pulse Amplitude Modulation (MPAM)
    - information coded in amplitude
    $$MPAM - s_i(t) = Re\left\{ A_i \ g(t)e^{j2\pi f_ct}\right\}$$
  - Phase Shift Keying (MPSK)
    - information coded in phase
    $$MPSK - s_i(t) = Re\left\{ A \ g(t)e^{j\theta_i}e^{j2\pi f_ct}\right\}$$
  - Quadrature Amplitude Modulation (MQAM)
    - information coded both in amplitude and phase
    $$MQAM - s_i(t) = Re\left\{ A_i \ e^{j\theta_i}g(t)e^{j2\pi f_ct}\right\}$$
Amplitude/Phase Modulator/Demodulator

Communication System Model (no path loss)
**Differential Modulation**

- Bits associated to a symbol depend on the bits transmitted over a previous symbol

- **Differential BPSK (DPSK)**
  - 0 → no change phase
  - 1 → change phase by $\pi$

- **Differential 4PSK (DQPSK)**
  - 00 → change phase by 0
  - 01 → change phase by $\pi/2$
  - 10 → change phase by $-\pi/2$
  - 11 → change phase by $\pi$
Estimating BER – Nearest Neighbor Approximation

$P_s$ – probability of a symbol being received in error

$$P_s = \sum_{i=1}^{M} p(r \notin Z_i|m_i \text{ sent}) p(m_i \text{ sent})$$

$P_s \approx M_{d_{\text{min}}} Q\left(\frac{d_{\text{min}}}{\sqrt{2N_0}}\right)$

$d_{\text{min}}$ – minimum distance between constellation points

$M_{d_{\text{min}}}$ – number of constellation points at distance $d_{\text{min}}$

$$Q(z) = \frac{1}{2} \text{erfc}\left(\frac{z}{\sqrt{2}}\right) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2},$$

Example

$s_1 = (A, 0), s_2 = (0, A), s_3 = (-A, 0)$ and $s_4 = (0, -A)$

Assume $A/\sqrt{N_0} = 4$.

$d_{\text{min}} = d_{12} = d_{23} = d_{34} = d_{14} = \sqrt{A^2 + A^2} = \sqrt{2}A^2$.

$M_{d_{\text{min}}} = 2$

$P_s \approx 2Q(4) = 3.1671 \times 10^{-5}$.

$P_b = BER \approx \frac{P_s}{\log_2 M}$

A symbol error associated with an adjacent decision region corresponds to only one bit error.
How does $P_s$ depend on the SNR?

\[ P_s \approx M_{d_{\text{min}}} Q \left( \frac{d_{\text{min}}}{\sqrt{2N_0}} \right) \]
Digital Modulation – BER and SNR

$$SNR = \frac{P_r}{N_0 B} = \frac{E_s}{N_0 B T_s} = \frac{E_b}{N_0 B T_b}, \quad T_s \approx \frac{1}{B},$$

$$\gamma_s = \frac{E_s}{N_0}, \quad \gamma_b = \frac{E_b}{N_0}$$

<table>
<thead>
<tr>
<th>Modulation</th>
<th>$P_b(\gamma_b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFSK</td>
<td>$P_b = Q(\sqrt{\gamma_b})$</td>
</tr>
<tr>
<td>BPSK</td>
<td>$P_b = Q(\sqrt{2\gamma_b})$</td>
</tr>
<tr>
<td>QPSK, 4QAM</td>
<td>$P_b \approx 2 \frac{Q(\sqrt{\gamma_b})}{\sqrt{M}}$</td>
</tr>
<tr>
<td></td>
<td>$P_b \approx \frac{2}{\log_2 M} \frac{Q(\sqrt{2\gamma_b})}{\log_2 M}$</td>
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<tr>
<td></td>
<td>$P_b \approx \frac{4}{\log_2 M} \frac{Q(\sqrt{3\gamma_b})}{\log_2 M}$</td>
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</tbody>
</table>

Average $P_b$ for BPSK in Rayleigh Fading and AWGN

Average $P_b$ for MQAM in Rayleigh Fading and AWGN
Coding

- Coding enables bit errors to be either detected or corrected by receiver

- Coding gain, $C_g$  
  the amount of SNR that can be reduced for a given $P_b$

- Coding rate, $k/n$  
  » Code generates $n$ coded bits for every $k$ uncoded bits  
  » If channel+modulation enable the transmission of $R$ bit/s  
  » Information rate = $R * k/n$ bit/s
C**oding in Wireless Channels**

- Codes designed for AWGN channels
  - do not work well on fading channels
  - cannot correct the long error bursts that may occur in fading

- Codes for fading channels are usually
  - based on an AWGN channel code
  - combined with interleaving
  - objective → spread error bursts over multiple codewords
**Multicarrier Modulation**

- Divides a bitstream into $N$ low rate substreams
- Sends substreams simultaneously over narrowband subchannels
- **Subchannel**
  - has bandwidth $B_N = B/N$
  - provides a data rate $R_N \approx R/N$
  - For $N$ large, $B_N = B/N \ll 1/T_m$
    - flat fading (narrowband like effects) on each sub-channel, no ISI

![Diagram of Multicarrier Modulation](image)

$R$ bit/s

**Serial To Parallel Converter**

$R/N$ bit/s

QAM Modulator

$X \cos(2\pi f_0 t)$

QAM Modulator

$X \cos(2\pi f_N t)$

$\sum$

$T_m = \max_n |\tau_n - \tau_0|$
Overlapping Substreams

- Separate subchannels could be used, but
  - required passband bandwidth is $N \times B_N = B$

- OFDM uses overlaps substreams
  - Substream separation is $B/N$
  - Total required bandwidth is $B/2$, for $T_N = 1/B_N$
Most of the recent wireless communications technologies are adopting OFDM (e.g. WLAN, WIMAX, LTE).

Why?
OFDM uses Discrete Fourier Transforms

- Discrete Fourier transforms given by

\[ DFT\{x[n]\} = X[i] \triangleq \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n]e^{-j \frac{2\pi n i}{N}}, \quad 0 \leq i \leq N - 1 \]

\[ IDFT\{X[i]\} = x[n] \triangleq \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i]e^{j \frac{2\pi n i}{N}}, \quad 0 \leq n \leq N - 1 \]

- Circular convolution

\[ DFT\{y[n]\} = x[n] \otimes h[n] = X[i]H[i], \quad 0 \leq i \leq N - 1. \]

\[ x[n] \otimes h[n] = \hat{x}[n] * h[n] = y[n] \]
FFT Implementation of OFDM - TX

- Use IFFT at TX to modulate symbols on each subcarrier
- Cyclic prefix makes circular channel convolution → no interference between FFT blocks in RX processing

\[ x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j2\pi ni/N}, \quad 0 \leq n \leq N - 1. \]
 FFT Implementation of OFDM - RX

Reverse structure at RX

\[ x(t) = \cos(2\pi f_c t) \]

Diagram:
- Input \( x(t) \) to LPF
- LPF to A/D converter
- Remove cyclic prefix and Serial to Parallel Convert
- Input to FFT
- FFT output \( Y[0] \) and \( Y[N-1] \)
- Parallel To Serial Convert
- Output to QAM demodulator
- QAM demodulator to D/A converter
- D/A to TX

\( R \) bit/s for TX and RX

\[ x(t) = \cos(2\pi f_c t) \]
Spread Spectrum

- Spread spectrum techniques
  - hide the information signal below the noise floor
  - mitigate inter-symbol interferences
  - combine multipath components

- The spread spectrum techniques
  - multiply the information signal by a spreading code
Spread Spectrum – Direct Sequence

Information signal \((R_b \text{ bit/s})\)

Spread signal \((R_c = N R_b \text{ chip/s})\)

Pseudo-random sequence \((R_c = N R_b \text{ chip/s})\)

De-modulator

Information signal
Direct Sequence Spread Spectrum – Immunity to Interferences

- Original signal: $P_f$
- Spread signal: $P_f$
- Interferences: $P_f$
- Received signal: $P_{\text{received}}$
- Signal after de-spreading: $P_{\text{received}}$

- Signal
- Wideband interference
- Narrowband interference
Software Defined Radio

- Software Defined Radio aims at implementing the radio functions in software.
- Digital Signal Processors being integrated with microcontroller for better integration of radio and communications functions.
Cognitive Radio

- Cognitive radio
  - fills unused bands
  - avoids interferences
  - increases spectral efficiency

- Paves the way to
  - dynamic spectrum licensing
  - secondary markets in spectrum usage
Homework

1. Review slides

1. Detailed information about these topics can found at the Goldsmith’s book
   » Chap. 5 (sections 5.1, 5.2, 5.3, 5.5)
   » Chap. 6 (sections 6.1, 6.3)
   » Chap. 7 (sections 7.1, 7.2)
   » Chap. 8 (section 8.1)
   » Chap. 9 (section 9.1)
   » Chap. 12 (sections 12.1, 12.2, 12.4)
   » Chap. 13 (sections 13.1, 13.2, 13.3)