ELG4179: Wireless Communication Fundamentals

Instructor: Dr. Sergey Loyka (CBY A608)

Course web page: http://www.site.uottawa.ca/~sloyka/ (most of the course material, including lecture slides, assignments, marks) will be posted there).

Office hours: Thursday, 5-6pm. Outside office hours - by appointment only. No appointments on Fridays. No exceptions! You are encouraged to ask questions immediately after lectures (but not before). No questions by email (will not be answered).

Teaching assistant(s): TBD

Lectures: Monday 13:00-14:20, Wednesday 11:30-12:50, FSS 1006.


Labs: begin on Sep. 18, Tue. 19:00-21:50, CBY B02.

Assignments: about 6.

Midterm exam: Mon. Oct. 29, 13:00-14:20, FSS 1006. Includes everything covered in the class before the midterm; closed book; 1 letter-sized page of reference material is allowed. Marked exam papers will be returned within 1-2 weeks.
Marking scheme:

- Assignments + quizzes: 10%
- Labs: 10%
- Midterm Examination: 20%
- Final Examination: 60%

Lots of bonus points to everybody who takes active part in the course!

Final: Includes everything covered in the class, not just after midterm; closed book; 2 letter-sized pages of reference material is allowed. It is for evaluation purposes only and will not be returned to the students. Marks are final and will not be negotiated.

Notes:

- All the course components (lectures, tutorials, labs, assignments) are mandatory. Miss at your own risk.
- Marking scheme is final and will not be changed.
- Marks are determined by academic performance only (not by bargaining abilities).
- Marks will not be negotiated.
- All questions are to be answered during the semester (no guarantee afterwards).

Absence: valid if medical certificate (from the University medical authority.)
Pre-requisites:

ELG3175. Basic knowledge of communication systems
ELG3126. Probability theory.

ELG4176 is highly desirable.

Plagiarism: copying solutions to assignments, quizzes, exams and lab reports from anywhere is a serious academic fraud that carries a significant penalty. Plagiarism is absolutely not acceptable.

While working in groups on assignments is not a plagiarism, submitting identical or nearly identical solutions is and will be severely penalized. Every student is expected to submit his own individual solutions.

If two (or more) identical or almost identical sets of solutions are found, each student involved receives 0 (zero) for that particular assignment. If this happens twice, the students involved receive 0 (zero) for the entire assignment component of the course in the marking scheme and the case will be send to the Dean’s office for further investigation.

From the past experience, the students who copy assignments/labs, do poorly in exams.
Required textbook:

Additional texts:

The following 3 books are mostly undergraduate communications textbooks:

The following 3 books are mostly graduate-level textbooks:
The following 3 books deal with simulation issues:


Math handbooks (to refresh your math skills):


If you need some physics:

**Purpose of the course:** to introduce basic principles and techniques of modern wireless communication systems.

**Contents (tentative):**

- Link budget analysis and wireless (radio) propagation channel. Impact of antennas.
- Large-scale fading (shadowing), lognormal distribution. Small-scale (multipath) fading, Rayleigh/Rice distributions. Outage probability.
- Doppler effect & spread, coherence time. Delay spread and coherence bandwidth, power delay profile.
- Diversity techniques. Combining methods. Performance improvement.
- Interference cancellation/management. Smart antennas and MIMO systems.
- Multi-user systems and multiple access methods. Orthogonal (FDMA, TDMA, CDMA, SDMA) and random (ALOHA, CSMA).
- The cellular concept. Frequency re-use and spectral efficiency. System design fundamentals.
How to Study: Learning Efficiency Pyramid

“Tell me and I’ll forget; show me and I may remember; involve me and I’ll understand.” – old Chinese proverb.

Another version: “I hear, I forget; I see, I remember; I do, I understand”.

How to Study

“Education is the accumulation of understanding, not just an accumulation of facts” [D. Pozar]

- Learning efficiency pyramid is a good guideline
- **Reading** is necessary, but taken alone is not efficient
- **Solving problems** (“practice by doing”)  
  - is much more efficient  
  - examples, assignments, end-of-chapter problems  
  - “Remember that very little is gained by reading the solution to a problem before seriously attempting to solve it.” W. Briggs, Ants, Bikes and Clocks: Problem Solving for Undergraduates, 2005.

- **Group discussions**  
  - help provided you contribute something

- **Systematic study** during the semester  
  - is a key to a success.  
  - do not leave everything to the last day/night before exams!  
  - 1 class hour = 1 hour of individual studies

- **Lectures**  
  - should be supplemented by the items above  
  - take notes in the class!
Block Diagram of a Communication System

- Source – a source of information (e.g. voice, data file, YouTube video)
- Tx – a transmitter
- Channel – a path (link) from the Tx to the Rx (e.g. cable, wireless medium, etc.)
- Rx – a receiver
- Destination – a place where the information has to be delivered
Transmitter (Tx)

- Source coder – encodes the message to remove redundancy
- Channel coder – encodes the input to protect against errors introduced by the channel
- Local oscillator (LO) – generates the carrier
- Modulator – modulates the carrier using the encoded message
- Power amplifier (PA) – amplifies the modulated signal to required power level
- Antenna (A) – radiates the modulated signal as an electromagnetic wave
**Receiver (Rx)**

- Source decoder – decodes the source-encoded message
- Channel decoder – decodes the channel code
- Local oscillator (LO) – generates the carrier
- Mixer – down-converts the RF signal to IF frequencies
- IF amplifier (IFA): amplifies the IF signal significantly (up to $10^6$) and rejects adjacent channel signals and interference (frequency selectivity). Its bandwidth is the same as the signal bandwidth.
- Demodulator: demodulates the modulated signal
- Low-noise amplifier (LNA): amplifies a weak RF signal coming out of the antenna. Rejects the image frequency. Bandwidth: much wider than the signal bandwidth.
- Antenna (A) – receives an incoming electromagnetic wave carrying the message
Introduction To Wireless


There are few essential principles that make mobile/wireless communications special.

Differences between: “mobile” and “fixed wireless/radio”; “wireless” and “wired” etc.

Examples

• WiFi (wireless Internet access, WLAN)
• Cell/cordless phones
• Remote control
• Bluetooth
• Radio/TV broadcast (incl. satellite)
• Navigation (GPS, radar)

Historical Perspective

• 1844: invention of telegraph by Morse
• 1876: invention of telephone by Bell
• 1895/96: invention of radio by Popov/Marconi
• early 1900s: 1st use of radio
• 1900: 1st transatlantic transmission by Marconi
• 1933: invention of FM by Amstrong
• 1936: 1st TV broadcast by BBC
• 1947: transistor is invented in Bell lab
• 1948: Shannon discovers information theory
• 1957: Sputnik is launched by USSR
• 1973: 1st cell phone call (by Martin Cooper of Motorola to his rival at AT&T; the phone weighted 1kg and cost approximately $4000)
• 1981: IBM PC is introduced.
• 1990s: launch of Internet.
• 2000s: launch of WiFi
• 2007: launch of iPhone
• 2010: launch of iPad
Cellular Systems (cell phones)

Martin Cooper of Motorola made the first publicized handheld mobile phone call on a prototype DynaTAC model on April 4, 1973. This is a reenactment in 2007. (https://en.wikipedia.org/wiki/Mobile_phone)
Cell Phones

1st com. cell phone, 1984

Cell phone evolution...

...and today
Cellular System Standards


  ⇒ Narrowband, low-quality, voice, no additional services.

- **2nd generation (2G):** Various systems

  - Europe: GSM (TDMA, low-rate data services (up to 9.6 kb/s), deployed in 1992), uses GMSK; 800-900MHz, $\Delta f = 200\text{KHz}$, 8 users/channel.

  - North America: IS-54/136 and IS-95 (TDMA and CDMA), DQPSK for IS-54/136 (IS-54/136: 800/1800/1900 MHz, DQPSK, $\Delta f = 30\text{KHz}$, 4 users/channel), and PN-CDMA for IS-95, adopted and deployed in 1990-1992 ($\Delta f = 1.25\text{MHz}$, 64 users, 800/900MHz, 1900/1900MHz BPSK)

  - Japan: PDC (Personal Digital Cellular) similar to IS-54/136. Important—MS antenna diversity is possible.

All of them support up to **9.6kb/s** data.
- **2.5G system**: improvement of 2G system to allow for better data services (faster, email, internet). 2G systems were developed before internet - do not fit in well.
  - IS-95B for 2.5G CDMA: medium data rate, up to 115.2kb/s (in practice, up to 64kb/s)
3G systems:
- Evolution of 2G, with enhanced data services: Internet access, voice over IP (VoIP), higher link capacity.
- Two major standards: UMTS and CDMA2000.
- Downlink rate: 0.3-2 Mb/s; uplink: 200kb/s

4G systems:
- Data rates: 10 x 3G (peak at 50-100 Mb/s, less in practice, e.g. average 5-10 Mb/s)
- Fully-integrated Internet/data services
4G systems:
Optimized for high-speed data service (Internet), VoIP.
Two major standards: LTE (Long Term Evolution) and WiMax (Worldwide Interoperability for Microwave Access).

LTE Standard
Modulation: OFDM + QPSK/16QAM/64QAM, up to 20MHz bandwidth.
Rates: see below.

<table>
<thead>
<tr>
<th>Antenna configuration</th>
<th>FDD downlink peak data rates (64QAM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SISO</td>
</tr>
<tr>
<td>Peak data rate Mbps</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modulation depth</th>
<th>FDD uplink peak data rates (single antenna)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QPSK</td>
</tr>
<tr>
<td>Peak data rate Mbps</td>
<td>50</td>
</tr>
</tbody>
</table>


Note: MIMO = multiple-input multiple-output, or multi-antenna system.
SISO = single-input single-output, or single-antenna system.
5G Systems (under development)

- 5G: the latest wireless system standard (cellular), still under development\(^1\)
  - Significant improvement over 4G (current)
    - significantly higher data rates (peak: 10 Gb/s, cell edge 100 Mb/s, almost everywhere 10Mb/s)
    - better QoS (latency < 1ms, high reliability)
    - more services
  - Several key new technologies:
    - Millimeter waves
    - Hybrid networks, small cells, aggressive frequency re-use
    - Massive MIMO (multi-antenna)\(^2\)

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Wireless Local Area Networks (WLANs) – WiFi
IEEE 802.11.a(b,g,n); 2.4/5 GHz

Popular WiFi Equipment

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002
Popular WiFi (WLAN) Equipment
- **BLUETOOTH/IEEE 802.15**: ad-hoc networking within 10 meter range, 2.4GHz, up to 1Mb/s
- **IMT-2000**: family of standard approved by ITU.

Personal Area Network – Bluetooth Standard

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002
TABLE 8-17 WIFI STANDARDS

<table>
<thead>
<tr>
<th>Item</th>
<th>802.11a</th>
<th>802.11b</th>
<th>802.11g</th>
<th>802.11n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>5.0 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Max data rate</td>
<td>54 Mb/s</td>
<td>11 Mb/s</td>
<td>54 Mb/s</td>
<td>120 MB/s</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>DSSS</td>
<td>OFDM</td>
<td>DSSS &amp; OFDM</td>
</tr>
<tr>
<td>Bandwidth (typical)</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Diversity</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>MIMO</td>
</tr>
<tr>
<td>Range (max)</td>
<td>500 ft</td>
<td>500 ft</td>
<td>500 ft</td>
<td>1,500 ft</td>
</tr>
<tr>
<td>Compatible with</td>
<td>802.11a</td>
<td>802.11b</td>
<td>802.11b, 802.11g</td>
<td></td>
</tr>
</tbody>
</table>

DSSS = Direct-sequence spread spectrum
MIMO = Multiple input and multiple output

TABLE 8-18 WIMAX STANDARDS

<table>
<thead>
<tr>
<th>Item</th>
<th>Licensed Service</th>
<th>Unlicensed Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>2.5 GHz</td>
<td>5.5 GHz</td>
</tr>
<tr>
<td>Frequencies</td>
<td>2.5 to 2.69 MHz*</td>
<td>5.25 to 5.58 GHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>20 to 40 MHz</td>
<td>20 to 40 MHz</td>
</tr>
<tr>
<td>Purchase spectral space</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Power output</td>
<td>up to about 20 W</td>
<td>4 W EIRP</td>
</tr>
<tr>
<td>Range</td>
<td>30 miles</td>
<td>10 miles</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>OFDM</td>
</tr>
<tr>
<td>Dual channels via</td>
<td>FDD</td>
<td>TDD</td>
</tr>
<tr>
<td>Data rate (maximum)</td>
<td>108 Mb/s</td>
<td>108 Mb/s</td>
</tr>
<tr>
<td>Advantages</td>
<td>Less interference, Better NLOS reception</td>
<td>Fast rollout, Lower cost</td>
</tr>
</tbody>
</table>

*Additional WiMAX frequency bands are likely to be designated by the FCC.
FDD = Frequency-division duplexing (i.e., two frequency channels required—one for uplink and one for downlink)
TDD = Time-division duplexing (i.e., one frequency channel required, but two time slots required—one for uplink and one for downlink)
NLOS = Non Line-Of-Sight

**IEEE 802.11n Wi-Fi (WLAN) standard**

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Type</th>
<th>Coding Rate</th>
<th>Spatial Streams</th>
<th>Data Rate (Mbps) with 20 MHz CH</th>
<th>Data Rate (Mbps) with 40 MHz CH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>800 ns</td>
<td>400 ns (SGI)</td>
</tr>
<tr>
<td>0</td>
<td>BPSK</td>
<td>1 / 2</td>
<td>1</td>
<td>6.50</td>
<td>7.20</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1 / 2</td>
<td>1</td>
<td>13.00</td>
<td>14.40</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>3 / 4</td>
<td>1</td>
<td>19.50</td>
<td>21.70</td>
</tr>
<tr>
<td>3</td>
<td>16-QAM</td>
<td>1 / 2</td>
<td>1</td>
<td>26.00</td>
<td>28.90</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>3 / 4</td>
<td>1</td>
<td>39.00</td>
<td>43.30</td>
</tr>
<tr>
<td>5</td>
<td>64-QAM</td>
<td>2 / 3</td>
<td>1</td>
<td>52.00</td>
<td>57.80</td>
</tr>
<tr>
<td>6</td>
<td>64-QAM</td>
<td>3 / 4</td>
<td>1</td>
<td>58.50</td>
<td>65.00</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>5 / 6</td>
<td>1</td>
<td>65.00</td>
<td>72.20</td>
</tr>
<tr>
<td>8</td>
<td>BPSK</td>
<td>1 / 2</td>
<td>2</td>
<td>13.00</td>
<td>14.40</td>
</tr>
<tr>
<td>9</td>
<td>QPSK</td>
<td>1 / 2</td>
<td>2</td>
<td>26.00</td>
<td>28.90</td>
</tr>
<tr>
<td>10</td>
<td>QPSK</td>
<td>3 / 4</td>
<td>2</td>
<td>39.00</td>
<td>43.30</td>
</tr>
<tr>
<td>11</td>
<td>16-QAM</td>
<td>1 / 2</td>
<td>2</td>
<td>52.00</td>
<td>57.80</td>
</tr>
<tr>
<td>12</td>
<td>16-QAM</td>
<td>3 / 4</td>
<td>2</td>
<td>78.00</td>
<td>86.70</td>
</tr>
<tr>
<td>13</td>
<td>64-QAM</td>
<td>2 / 3</td>
<td>2</td>
<td>104.00</td>
<td>115.60</td>
</tr>
<tr>
<td>14</td>
<td>64-QAM</td>
<td>3 / 4</td>
<td>2</td>
<td>117.00</td>
<td>130.00</td>
</tr>
<tr>
<td>15</td>
<td>64-QAM</td>
<td>5 / 6</td>
<td>2</td>
<td>130.00</td>
<td>144.40</td>
</tr>
<tr>
<td>16</td>
<td>BPSK</td>
<td>1 / 2</td>
<td>3</td>
<td>19.50</td>
<td>21.70</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>31</td>
<td>64-QAM</td>
<td>5 / 6</td>
<td>4</td>
<td>260.00</td>
<td>288.90</td>
</tr>
</tbody>
</table>

802.11n Primer, Whitepaper, AirMagnet, August 05, 2008.
(n+1)G systems:

3G system rate = 10*(2G rate)
4G rate = 10*(3G rate).
Compatible with Internet (IP, Mobile IP, QoS).

A View of the Wireless World

**Figure 1** A view of the wireless world; seven technical directions aiming at the proper application provisioning, cost-efficient resource provisioning, and at the augmentation of the wireless world's intelligence. GSM: global system for mobile communications. GPRS: general packet radio service. EDGE: enhanced data rates for GSM evolution. UMTS: universal mobile telecommunications system. HSPA: high-speed packet access.

**Wireless Networks of 21st Century**

![Diagram showing various wireless networks including Office Wireless Network (OWN), Urban Wireless Network (UWN), Body Wireless Network (BWN), Home Wireless Network (HWN), and other related items like lights, entertainment, refreshment, and utilities.]

**FIGURE 2.2** Some of the wireless networks of the 21st century.

**Cellular system**

Major system components:

1) Mobile station (MS), or subscriber unit (SU), or mobile unit (MU) → e.g. a cell phone.

2) Base station (BS) (cellular operator equipment, with an antenna typically installed on a rooftop).

3) Mobile switching center (MSC) or mobile telephone switching office (MTSO) (controls multiple base stations).

*Figure 1.5* A cellular system. The towers represent base stations which provide radio access between mobile users and the mobile switching center (MSC).

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002
Basic terminology

- **Cell**: an area covered by a single base station.
- **Control channel**: channel used for call request, initiation, setup etc.…
- **Forward channel/link (downlink)**: a link from BS to MS.
- **Reverse channel/link (uplink)**: a link from MS to BS.
- **Simplex system**: one-way communication system.
- **Half-duplex system**: two-way communication, but not at the same time.
- **Full-duplex system**: two-way communication at the same time.
- **Mobile station (unit)**: is carried by a user.
- **Base station**: installed at the cell center, collects calls from all MSs in the cell.
- **Mobile switching center**: all BSs in a given region are connected to it. It coordinates all the BSs (hand-off) and directs calls to PSTN.
- **Hand-off**: transferring a MS from one BS to another.
- **Roamer(ing)**: MS operates in a service area other than from where it was subscribed.
- **Transceiver**: transmitter (Tx) + receiver (Rx)
- **FDD/TDD**: frequency/time division duplex
Summary

• Examples of wireless communication systems
• Historical background
• 1G, 2G, 2.5G, 3G, 4G and 5G systems.
• Different standards. Examples.
• Cellular systems. Basic terminology.

Reading/References

• Rappaport, Ch. 1-3.
• Your ELG3175/ELG4176 textbook
• Other books (see the reference list).

Note: Do not forget to do end-of-chapter problems. Remember the learning efficiency pyramid!