ELG5132: Smart Antennas

- **Prof:** Dr. Sergey Loyka (CBY A608)
- **Lectures:** Mon. 16:00 - 17:20 (CBY C206), Wed. 16:00-17:20 (CBY B012)
- **Office hours:** Thursday, 5-6pm. You are encouraged to ask questions during and after lectures (but not before). No questions by email (will not be answered).
- **Course web page:** [http://www.site.uottawa.ca/~sloyka/](http://www.site.uottawa.ca/~sloyka/)
- **Prerequisites:** ELG4176, or ELG4179, or ELG5133 ([SYSC 5606](#)), or equivalent. **Required background:** basic communication theory, signals & systems, probability, linear algebra/matrices. Antennas & propagation is a plus.
- **Assignments/Quizzes:** informal (bonus points)
- **Course mini-project:** topics will be provided.
- **Final exam:** 3h in December, date TBD, open book
• **Marking scheme:**
  - Term paper (mini-project) + presentation 50%
  - Final examination 50%
  - Lots of bonus points to everybody who takes active part in the course


• **Weekly schedule (approx.):**
  • **Week 1:** Introduction to wireless communications: generic system architecture and its main limitations. Propagation channel and interference effects. Motivation for using smart antennas.
  • **Week 2-3:** Propagation channel: basic radio wave propagation mechanisms and its system-level effects. Traditional (“scalar”) propagation channel characterization. Spatio-temporal (“vector”) channel characterization.
• **Week 4:** Introduction to antenna arrays and smart antennas. Interference cancellation. Types of smart antennas: switched-beam, adaptive, diversity combining and multiple-input multiple output (MIMO). Range and capacity improvement. Space-division multiple access (SDMA).

• **Week 5-6:** Beamforming algorithms (MVDR, MMSE, max. SNR, eigenvector, etc.). Optimal spatial filtering. Direction-of-arrival estimation (Capon, MUSIC). Adaptive least squares.

• **Week 7-10:** Introduction to the MIMO architecture: high-level description & basic principles. MIMO channel capacity. Matrix channel modeling and impact of correlation.

• **Week 11-12:** Receiver algorithms: ZF and MMSE V-BLAST, ML. Space-time coding: basic principles, Alamouti scheme, diversity and coding gains. Performance analysis. Topics of current research interest (multi-user systems/networks & interference, security, cognitive radio).

• **Note:** no electromagnetics in this course!
References: Books

Papers (selected only):


Papers (selected only):

Papers (selected only):


Useful Journals

• IEEE Transactions on Wireless Communications
• IEEE Transactions on Communications
• IEEE Transactions on Signal Processing
• IEEE Transactions on Antennas and Propagation
• IEEE Transactions on Information Theory
• IEEE Journal on Selected Areas in Communications (JSAC)
• IEEE Journal of Selected Topics in Signal Processing (JSTSP)
• IEEE Transactions on Vehicular Technology
• IEEE Signal Processing Magazine
How to Study: Learning Efficiency Pyramid

How to Study

• 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
• 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!
• Lectures
  – should be supplemented by the items above
Basic Wireless System Architecture and Its Main Limitations

Source -> source of information to be transmitted
Destination -> destination of transmitted information
Tx and Rx -> transmitter and receiver
$A_{nt}$ & $A_{nr}$ -> Tx and Rx antennas
PC – propagation channel

- Tx includes coding/modulation circuitry (or DSP), power amplifiers, frequency synthesizers etc.
- Rx includes LNA, down conversion, demodulation, decoding etc.
• **Examples**: WiFi, cellular phones, radio and TV broadcasting, GPS, cordless phones, radar, etc.

• **Main advantages**: flexible (service almost everywhere), low deployment cost (compare with cable systems).

• **Main disadvantages**: PC is very bad, limits performance significantly, almost all development in wireless com. during last 50 years were directed to combat PC.
Simplified Link Budget Analysis

\[ P_r = \frac{G_r G_t P_t}{L_p} \]

- \( P_t \) – Tx power
- \( P_r \) – received power
- \( L_p \) – propagation loss
- \( G_t \) and \( G_r \) – Tx and Rx antenna gains

In practice, some other factors are added (including safety margins),

**Practical limits for \( G_r \) and \( G_t \):** \( G_r, G_t \leq (40 \sim 60) \text{dB} \)

**Fixed microwave systems:** up to 40dB
**Mobile systems:** 2~3 dB (no smart antennas)
- $P_r$ is limited from below (i.e., noise etc.)

$$P_r \geq P_{\text{min}}$$

- to provide satisfactory performance. $P_{\text{min}}$ – Rx sensitivity
- For given $P_{\text{min}}$ and $L_p$ (depends on geometry, propagation scenario), can find $G_r, G_t, P_t$ (design trade-off)
- Example:

\[
P_{\text{min}} = 10^{-12} \text{W} (-90 \text{ dBm}); \quad L_p = 150 \text{ dB} (10^{15});
\]

\[
G_r = 10 \text{ dB}; \quad G_t = 10 \text{ dB};
\]

\[
P_t = \frac{P_{\text{min}} L_p}{G_t G_r} = \left( P_{\text{min}} + L_p - G_t - G_r \right)[\text{dB}] = 40 \text{ dBm} = 10 \text{W};
\]
Effect of Interference

- No interference -> SNR
  \[
  SNR = \gamma = \frac{P_{sig}}{P_{noise}}
  \]

- Interference -> SNIR
  \[
  SNIR = \gamma = \frac{P_{sig}}{P_{noise} + P_{int}}
  \]

- Satisfactory performance requires \( \gamma = (10...30)dB \)

- Minimum received power (no interf.):
  \[
  P_r \geq \gamma \cdot P_{noise}
  \]

- Minimum received power (interf.):
  \[
  P_r \geq \gamma \left( P_{noise} + P_{int} \right) > \gamma P_{noise}
  \]

- The effect of interference is to boost the required Rx power.
Free Space Propagation Loss

- LOS is not obstructed, no multipath etc.
  \[ L_p = \left( \frac{4\pi R}{\lambda} \right)^2 \]

- Example: \( f_0 = 10 GHz (\lambda_0 = 3 cm); R = 100 km; L_p \approx 10^{15} = 150 dB \)

- Multipath propagation, obstruction of LOS etc. can significantly increase \( L_p \).
- Its value is very large and must be compensated by other system components
- This is not the only problem with PC, multipath results in fading, which results in \( L_p \) variations (in time and space) up to 30~40 dB or more down (sometimes even more!), this must be compensated for as well.
However, while all the other system components (i.e., Tx, Rx, Ant, Anr) are well under control, PC is out of our control. Then there is nothing we can do about it (with small exceptions).

Hence, all the system design is directed to compensate the effect of PC.

Smart antennas can be effective tool in compensating for PC effects; much more efficient than other system components.
Fading Channel Example

SISO 1x1

MIMO 2x2

Signal level, dB vs. time
BER of AWGN and Fading Channels

FIGURE 5.1 Probability of error for coherent BPSK in the presence of Rayleigh fading and in the absence of fading.
BER of Fading Channels with CCI

**FIGURE 5.5** Error floor behavior in the presence of CCI fading for the case of MSK with a differential detector.
BER of Fading Channels with Diversity

![Graph showing BER performance with diversity](image-url)

**Figure 5.18** The average probability of error for the selection combiner for the case of coherent BPSK.
Motivation for Using Smart Antennas

- System performance is limited by PC and external interference (i.e., other users etc.). Need some tools to improve it
- Time-domain and frequency domain techniques (coding, modulation, filtering, etc.) have been extensively studied in past 50 years.
- These techniques are at their limits, improvement is very small (fraction of a dB).
- What is a smart antenna: multiple antenna elements (antenna array) + appropriate signal processing
- Spatial processing, implemented in the form of a smart antenna, is not much used (and not understood so well). Hence, the potential of this field is tremendous -> it is “the last frontier”.

Lecture 1: ELG5132: Smart Antennas @ S. Loyka
What can be done using smart (adaptive, intelligent) antennas:

- Increase in range (coverage), can be traded-off for battery life, decreased Tx power or Rx sensitivity (noise floor).
- Increase in capacity (both bit/s/Hz (spectrum efficiency) and users/sector).
- Increase in quality of service and to provide new services (position location).
- Smart antennas can also be used to reduce delay spread and to slow down channel variations.
- All this is accomplished by spatial signal processing—may be thought of as a spatial filtering.
- Spectrum efficiency can be trade-off for increased data rate.
- Capacity increase – SDMA (similar to FDMA and TDMA)
• Fundamentally, a new dimension is added to signal processing: 2-D -> 3-D!
Smart Antennas: Why?

(a) Switched Beam Systems can select one of several beams to enhance receive signals. Beam 2 is selected here for the desired signal.

(b) An adaptive antenna can adjust its antenna pattern to enhance the desired signal, null or reduce interference, and collect correlated multipath power.

WiFi MIMO (multi-antenna)

- “MU-MIMO – the latest innovation in WiFi”
- Commercially-available WiFi MIMO routers
  - Linksys, Belkin, Motorola etc.
Cellular MIMO

- “The last frontier”
- Commercially-available systems (LTE)
  - Ericsson, Motorola, etc.
- “Ericsson 5G delivers 5 Gbps speeds” (07.2014)
Massive MIMO for 5G*

- 5G: the latest wireless system standard (cellular), still under development
- Significant improvement over 4G (current)
- Several key new technologies:
  - Millimeter waves
  - Hybrid networks, small cells, aggressive frequency re-use
  - **Massive MIMO (multi-antenna)**

Implementation of Antenna Arrays

http://www.wa5vjb.com/

http://www.mifi-hotspots.com

www.cst.com