ECE 792-058: Signal Processing and Machine Learning for Advanced MIMO Systems

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Class Hours: M/W 11:45am-1pm
Office hours: online via zoom or in person
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Class Room: EB2 1227

Course Description

Antenna arrays are a key technology in applications of wireless communication and radar. They are used to provide higher spectral efficiency, higher data rates, more reliable communication, better imagining, and high quality Doppler-range estimates. This course provides the foundations for developing signal processing and machine learning algorithms for communication and radar systems incorporating multiple antennas. It starts with an overview of the fundamentals of array signal processing, the multiple-input multiple-output (MIMO) channel, and algorithms for tasks like channel estimation and direction-of-arrival estimation. It continues with an introduction to MIMO communication including spatial multiplexing, precoding, hybrid precoding, and sparse channel estimation. Fundamentals for MIMO radar are also provided, such as range, doppler, and angle estimation. During the course, considerations are made for operating at lower frequencies, millimeter wave, and sub-THz frequencies. Model-based signal processing and data-based machine learning are introduced to solve these problems. Applications to 5G cellular networks and beyond, as well as to joint radar and communication systems are discussed.

Material

- Course Slides available on Moodle
- Homeworks and solutions after due date available in Moodle
- Reading material from a variety of sources including tutorial presentations, specific book chapters, and papers in the research literature. This will be specified in every lecture as needed.

Prerequisites

- Knowledge of digital signal processing obtained from ECE 513 or equivalent
- Knowledge of probability and stochastic processes from ECE 514 or equivalent
- Basic concepts of wireless communication at the undergraduate level: signal models, modulation, equalization, etc.
- Ability to program in MATLAB or equivalent skills in Python

Course Objectives

Successful students:

1. Understand the concept of multiple antenna communication and how digital signal processing algorithms are key for the design of MIMO systems
2. Know basic signal processing techniques for MIMO communication at sub-6 GHz bands: precoding, channel estimation. and synchronization.
3. Understand the idea of multiuser MIMO communication versus single user MIMO communication.
4. Understand the differences in terms of propagation and channel models between sub-6GHz and mmWave bands.
5. Know algorithms to estimate the channel in MIMO systems with large arrays.
6. Know algorithms for beam training and precoder/combiner design in MIMO systems with large arrays
7. Have the ability to implement and evaluate a basic MIMO communication system operating either at mmWave or sub-6GH bands.
8. Know the role of MIMO communication and OFDM in some of the current standards for WiFi or cellular.
9. Understand the basic principles of radar systems in general and MIMO systems in particular.
10. Know the difference between phased-array radar and MIMO radar and the different adaptive space-time techniques used at the radar receiver.
11. Have a basic understanding of MIMO joint sensing and communication systems.

Course structure

The course consists of two 75-minute lectures per week. The lectures will include slides and examples. There will be biweekly homework assignments with analytical and MATLAB problems (also possible to solve them in Python). The course will include a term project of three possible types:

- Research: attempt to tackle a new research problem
- Survey: good survey of a research area
- Implementation (working demo required, 1 page report)

If you choose a research project, it can be aligned with your current research (you are advised to discuss the project with your advisor to select a mutually interesting topic).

Course Overview

- Introduction
  - Introduction to the course
  - Overview of MIMO communication
- Fundamentals of antenna arrays
- MIMO communication at sub-6GHz bands
  - Receiver diversity, transmit diversity
  - MIMO transceiver techniques
    - Precoding
    - Channel estimation and equalization
    - Synchronization
  - MIMO-OFDM
  - Multiuser MIMO
- MIMO communication with large arrays (mmWave and massive MIMO): MIMO architectures, beam training, precoder/combiner design, and channel estimation
  - Model-based approaches
  - Data-driven approaches
- Sensing in MIMO systems
  - Overview of radar with multiple antennas and joint sensing and communication
  - Fundamentals of radar signal processing
  - Space-time adaptive processing in phased-array radars
  - MIMO radar with collocated antennas
    - Virtual arrays

    - Space-time adaptive processing in MIMO radars
    - Waveform design
    - Detection in MIMO radar
  - MIMO radar with widely separated antennas
  - Introduction to joint sensing and MIMO communication

Grading

The course will be graded on the basis of Homework (40%), Final Project (20%), Midterm 1 (20%), and Final (20%).

Please check the course website for homework turn-in format, dates and requirements. Solutions for homework problems will be given after due dates. You can expect to receive feedback on your homework by email, including your grade and comments. You can review your graded homework in person by sending an email to the instructor requesting to set up the corresponding meeting. Discussion of homework questions is encouraged but please submit your own independent homework solutions. If you think the discussion with other students have had a relevant part in your solution, you must indicate names of collaborating students on homework. Direct copying from another student is cheating. Late homework will not be given any credit, except in legitimate cases approved by the instructor and prearranged at least seven days in advance or under extraordinary circumstances.

Midterm will be held during the regular class time. It will require the use of a Windows or Mac laptop. Two paged of handwritten notes and equations are allowed in the exams. Calculators may be used. Test dates in this syllabus are preliminary. Please, check the course websites for the final dates.

The final project will be due at the end of the semester. Please, check the course websites for the final date. More information for turn-in format will be available in the course website.

Regrade Policy - All requests for regrades must be made through email. No verbal complaints will be considered. Before submitting any request for partial credit, please keep in mind that the first objective of grading is to be consistent. It may seem unfair that you did not get as much partial credit as you think you deserve. Keep in mind, however, that this may have been consistently applied to all students thus no more partial credit can be given. Mistakes can be made in the grading process, which will be corrected, but it is unlikely that more partial credit will be given. Be aware that the result of a regrade can actually be a lower score as the entire problem will be regraded.

About your instructor

Nuria González-Prelcic is currently an Associate Professor in the Electrical and Computer Engineering Department at North Carolina State University. Her main research interests include signal processing theory and signal processing and machine learning for wireless communications: filter banks, compressive sampling and estimation, multicarrier modulation, massive MIMO, MIMO processing for millimeter-wave communication and sensing, including vehicle-to-everything (V2X), air-to-everything (A2X) and satellite MIMO communication. She has published more than 120 papers in the last few years in the topic of signal processing for millimeter-wave

MIMO communications. She has just received the 2020 IEEE Signal Processing Society Donald G. Fink Overview Paper Award for the paper " "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems", published in 2016. She is and Editor for the IEEE Transactions on Wireless Communications and IEEE Transactions on Communications. She is a member of the IEEE Sensor Array and Multichannel Signal Processing Technical Committee. She was the founder director of the Atlantic Research Center for Information and Communication Technologies (atlanTTic) at the University of Vigo, Spain, from July 2008 to January 2017, where she also was an Associate Professor.

Letter Grades

This Course uses Standard NCSU Letter Grading:

97	$\leq$	A+	$\leq$	100
93	$\leq$	A	$<$	97
90	$\leq$	A-	$<$	93
87	$\leq$	B+	$<$	90
83	$\leq$	B	$<$	87
80	$\leq$	B-	$<$	83
77	$\leq$	C+	$<$	80
73	$\leq$	C	$<$	77
70	$\leq$	C-	$<$	73
67	$\leq$	D+	$<$	70
63	$\leq$	D	$<$	67
60	$\leq$	D-	$<$	63
0	$\leq$	F	$<$	60

Requirements for Credit-Only (S/U) Grading

In order to receive a grade of S, students are required to take all exams, complete all assignments and project, and earn a grade of C- or better. Conversion from letter grading to credit only (S/U) grading is subject to university deadlines. Refer to the Registration and Records calendar for deadlines related to grading. For more details refer to http://policies.ncsu.edu/regulation/reg-02-20-15.

Requirements for Auditors (AU)

Information about and requirements for auditing a course can be found at:
http://policies.ncsu.edu/regulation/reg-02-20-04.

Policies on Incomplete Grades

If an extended deadline is not authorized by the instructor or department, an unfinished incomplete grade will automatically change to an F after either (a) the end of the next regular

semester in which the student is enrolled (not including summer sessions), or (b) the end of 12 months if the student is not enrolled, whichever is shorter. Incompletes that change to F will count as an attempted course on transcripts. The burden of fulfilling an incomplete grade is the responsibility of the student. The university policy on incomplete grades is located at http://policies.ncsu.edu/regulation/reg-02-50-3. Late Assignments

There will be no make-up homework assignments or exams. Grades for a missing item with **valid excuses and documentation** will be estimated using the grades of other available items in the same category.

Attendance Policy

For complete attendance and excused absence policies, please see
http://policies.ncsu.edu/regulation/reg-02-20-03

Academic Integrity

0.1 Academic Integrity

Students are required to comply with the university policy on academic integrity found in the Code of Student Conduct found at http://policies.ncsu.edu/policy/pol-11-35-01 Students are required to comply with the university policy on academic integrity found in the Code of Student Conduct found at http://policies.ncsu.edu/policy/pol-11-35-01 Violations of academic integrity will be handled in accordance with the Student Discipline Procedures (NCSU REG 11.35.02).

0.2 Honor Pledge

Your signature on any test or assignment indicates "I have neither given nor received unauthorized aid on this test or assignment."

Digital Course Components

Students may be required to disclose personally identifiable information to other students in the course, via digital tools, such as email or web-postings, where relevant to the course. Examples include online discussions of class topics, and posting of student coursework. All students are expected to respect the privacy of each other by not sharing or using such information outside the course. **Digital Course Components:** Moodle for course materials, Q&A, and discussion; email for homework submission and feedback.

Accommodations for Disabilities

Reasonable accommodations will be made for students with verifiable disabilities. In order to take advantage of available accommodations, students must register with the Disability Resource Office at Holmes Hall, Suite 304, Campus Box 7509, 919-515-7653. For more information on NC

State?s policy on working with students with disabilities, please see the Academic Accommodations for Students with Disabilities Regulation (REG02.20.01) (https://policies.ncsu.edu/regulation/reg-02-20-01/).

Non-Discrimination Policy

NC State provides equal opportunity and affirmative action efforts, and prohibits all forms of unlawful discrimination, harassment, and retaliation ("Prohibited Conduct") that are based upon a person's race, color, religion, sex (including pregnancy), national origin, age (40 or older), disability, gender identity, genetic information, sexual orientation, or veteran status (individually and collectively, "Protected Status"). Additional information as to each Protected Status is included in NCSU REG 04.25.02 (Discrimination, Harassment and Retaliation Complaint Procedure). NC State's policies and regulations covering discrimination, harassment, and retaliation may be accessed at http://policies.ncsu.edu/policy/pol-04-25-05 or https://oied.ncsu.edu/divweb/. Any person who feels that he or she has been the subject of prohibited discrimination, harassment, or retaliation should contact the Office for Equal Opportunity (OEO) at 919-515-3148.