ANX-PR/CL/001-01

LEARNING GUIDE

SUBJECT

93000926 - From Array Processing To Mimo Communications

DEGREE PROGRAMME

09AT - Master Universitario En Teoria De La Señal Y Comunicaciones

ACADEMIC YEAR & SEMESTER

2023/24 - Semester 2

Index

Learning guide

1. Description

1.1. Subject details

Name of the subject	93000926 - From Array Processing To Mimo Communications
No of credits	6 ECTS
Type	Optional
Academic year ot the programme	First year
Semester of tuition	Semester 2
Tuition period	February-June
Tuition languages	English
Degree programme	09AT - Master Universitario en Teoria de la Señal y Comunicaciones
Centre	09 - Escuela Tecnica Superior De Ingenieros De Telecomunicacion
Academic year	2023-24

2. Faculty

2.1. Faculty members with subject teaching role

Name and surname	Office/Room	Email	Tutoring hours *
Miguel Alejandro Salas Natera (Subject coordinator)	C-411	miguel.salas@upm.es	Sin horario. Appointment arranged by email
Ramon Martinez Rodriguez-Osorio	C-411	ramon.martinez@upm.es	Sin horario. Appointment arranged by email

* The tutoring schedule is indicative and subject to possible changes. Please check tutoring times with the faculty member in charge.

3. Prior knowledge recommended to take the subject

3.1. Recommended (passed) subjects

- Temas Avanzados En Tecnología De Antenas

- Tecnologías De Radiofrecuencia

3.2. Other recommended learning outcomes

- It is recommended to have a strong knowledge in basic concept about antennas, radiated fields, electromagnetic waves and basic antenna parameters

- Knowledge of matrix theory, digital transmission concepts and signal processing

- It is recommended to know Matlab programming

4. Skills and learning outcomes *

4.1. Skills to be learned

CE01 - Analizar y aplicar técnicas para el diseño y desarrollo avanzado de equipos y sistemas, basándose en la teoría de la señal y las comunicaciones, en un entorno internacional

CE03 - Valorar y contrastar la utilización de las diferentes técnicas disponibles para la resolución de problemas reales dentro del área de teoría de la señal y comunicaciones.

CT01 - Capacidad para comprender los contenidos de clases magistrales, conferencias y seminarios en lengua inglesa

CT03 - Capacidad para adoptar soluciones creativas que satisfagan adecuadamente las diferentes necesidades planteadas

CT04 - Capacidad para trabajar de forma efectiva como individuo, organizando y planificando su propio trabajo, de forma independiente o como miembro de un equipo

CT05 - Capacidad para gestionar la información, identificando las fuentes necesarias, los principales tipos de documentos técnicos y científicos, de una manera adecuada y eficiente

4.2. Learning outcomes

RA31 - To carry out novel designs and applications in the field of MIMO antennas and systems

RA29 - Knowing the mathematical algorithms of adaptive antenna systems

RA47 - Knowing and evaluating MIMO systems

RA53 - To carry out antenna and system technologies analysis based on the algorithms of adaptive antennas

* The Learning Guides should reflect the Skills and Learning Outcomes in the same way as indicated in the Degree Verification Memory. For this reason, they have not been translated into English and appear in Spanish.

5. Brief description of the subject and syllabus

5.1. Brief description of the subject

This course covers the two main multipe antenna techniques: antenna array processing and MIMO systems. Both topics are covered from a formal perspective, starting with signal models as the basics to develop the diversity techniques. The course covers not only mathematical and signal processing aspects, but also the impact of selecting a particular implementation or antenna array, how multiple antenna techniques are introduced in current communication standards, and how the wireless channel affects system performance. Thus, students finish the course with an integrated vision on multiple antenna diversity techniques, system level impact and implementation issues.

The course starts with an introduction that includes the mathematical foundations of multiple antenna techniques (information theory, matrix theory and estimation).

Next unit deals with the first group of multiple antenna systems, i.e antenna array processing techniques and

direction of arrival methods. The first part covers time and spatial reference approaches, and explains different adaptive algorithms and beamforming approaches. The direction of arrival sessions cover conventional or search methods based on exploiting the power angular spectrum, and subspace based methods.

The third unit covers MIMO systems, starting with Single User MIMO channel models, capacity, architectures (diversity techniques, space-time coding and spatial multiplexing) and receivers. It continues with Multiple User MIMO (MU MIMO), that includes signal and channel models, suboptimum approaches and optimum beamformers and power allocation in uplink and downlink scenarios.

The last unit covers multiple antenna technologies, beginning with and explanation of the impairments that are found in the implementation of a multiple antenna system (mutual coupling, phase noise, imbalances in RF). The unit continues with a description of MIMO system architectures from RF front-ends and antenna to signal processing hardware, and the calibration issues required by the system to work properly. Finally, a set of case studies presented by students to explain the use of multiple antenna techniques to particular scenarios will be proposed.

Course contents are presented under the theoretical point of view and complemented with the practical simulation or exercises along the course.

5.2. Syllabus

1. Introduction to multiple antenna systems
   1.1. Course presentation
   1.2. Introduction to multiple antenna systems
      1.2.1. Multiple antennas: system aspects
      1.2.2. Mathematical foundations
2. Antenna array processing and Direction of Arrival techniques
   2.1. Antenna array processing
      2.1.1. Signal model
      2.1.2. Adaptive algorithms criteria. MMSE; MV; MCOx
      2.1.3. Adaptive antennas. Time reference.
      2.1.4. Adaptive antennas. Spatial reference.
   2.2. Direction of arrival techniques
      2.2.1. Signal model
      2.2.2. Conventional methods
      2.2.3. Subspace based methods
3. MIMO systems
   3.1. Signal and channel modelling in SU MIMO systems
      3.1.1. Propagation models in multiantenna scenarios
      3.1.2. MIMO signal and space-time channel model
   3.2. SU MIMO channel capacity
      3.2.1. Capacity of SIMO, MIMO, SIMO and MIMO systems: channel unknown at transmitter
      3.2.2. Capacity of SIMO, MIMO, SIMO and MIMO systems: channel known at transmitter. Waterfilling
   3.3. Single User MIMO architectures (SU MIMO)
      3.3.1. Diversity techniques
      3.3.2. Space-Time coding techniques
      3.3.3. Spatial Multiplexing
      3.3.4. MIMO receivers. Spatial matched filters, ZF and MMSE receivers. SIC receivers

3.4. Multiuser MIMO (MU MIMO)

3.4.1. Signal and channel model in MU MIMO

3.4.2. Suboptimum approaches

3.4.3. Optimum beamformer and power allocation in uplink

3.4.4. Optimum beamformer and power allocation in downlink

3.5. Massive MIMO

3.5.1. Introduction. Fundamentals and limitations

3.5.2. Signal and channel model in single cell and multiple cell scenarios

3.5.3. Optimum decoder and precoder in Massive MIMO arrays

4. Multiple antenna and antenna array technologies

4.1. Implementation of multiple antenna systems

4.1.1. Modelling of multiple antenna architectures. Impairments in analog and digital domains

4.1.2. Calibration

4.1.3. Technologies in antennas, analog and digital domains

4.2. Case studies for MIMO, mMIMO, and Satellite communications as well the use of technologies like the RIS, RFSoC, etc.

6. Schedule

6.1. Subject schedule*

Week	Classroom activities	Laboratory activities	Distant / On-line	Assessment activities
1	**Introduction to the course** Duration: 02:00 Lecture **Mathematical foundations** Duration: 02:00 Lecture			
2	**Antenna array processing** Duration: 02:00 Lecture **Antenna array processing** Duration: 02:00 Lecture			
3	**Antenna array processing** Duration: 02:00 Lecture **Antenna array processing** Duration: 02:00 Problem-solving class			
4	**Direction of Arrival techniques** Duration: 02:00 Lecture **Direction of Arrival techniques** Duration: 02:00 Lecture			
5	**Case study pregress meeting presentation** Duration: 02:00 Additional activities	**Adaptive beamforming and DOA models** Duration: 02:00 Laboratory assignments		**Adaptive antenna codes** Individual work Continuous assessment Presential Duration: 00:00
6	**Single user MIMO** Duration: 02:00 Lecture **Single user MIMO** Duration: 02:00 Lecture			
7	**Single user MIMO** Duration: 02:00 Lecture **Single user MIMO** Duration: 02:00 Lecture			

8	**Single user MIMO** Duration: 02:00 Problem-solving class	**SU MIMO** Duration: 02:00 Laboratory assignments		**Single user mimo lab manual** Individual work Continuous assessment Presential Duration: 00:00
9	**Multi-User MIMO** Duration: 02:00 Lecture **Multi-User MIMO** Duration: 02:00 Lecture			
10	**massive MIMO** Duration: 02:00 Lecture **massive MIMO** Duration: 02:00 Lecture			
11	**Multiple antenna technologies** Duration: 01:30 Lecture **Multiple antenna technologies** Duration: 02:00 Lecture	**Description and discussion of use cases to be used in next PR session** Duration: 00:30		
12	**Multiple antenna technologies** Duration: 00:30 Problem-solving class **Multiple antenna technologies** Duration: 02:00 Problem-solving class	**Architecture, Adaptive beamforming and DOA analysis** Duration: 01:30 Laboratory assignments		**Revision of use cases with educational array processing software** Individual work Continuous assessment Not Presential Duration: 00:00
13	**Multiple antenna technologies** Duration: 02:00 Lecture **Multiple antenna technologies** Duration: 02:00 Lecture			
14	**Case study oral presentation** Duration: 02:00 Additional activities **Case study oral presentation** Duration: 02:00 Additional activities			**Case study oral presentation.** Individual work Continuous assessment and final examination Presential Duration: 02:00
15				
16				
17				**Global examination** Written test Final examination Presential Duration: 02:00 **Exam** Written test Continuous assessment Presential Duration: 02:00

				Submission of labs and exercises Individual work Final examination Not Presential Duration: 00:00

Depending on the programme study plan, total values will be calculated according to the ECTS credit unit as 26/27 hours of student face-to-face contact and independent study time.

* The schedule is based on an a priori planning of the subject; it might be modified during the academic year, especially considering the COVID19 evolution.

7. Activities and assessment criteria

7.1. Assessment activities

7.1.1. Assessment

Week	Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills
5	Adaptive antenna codes	Individual work	Face-to-face	00:00	16.66%	3 / 10	CT01 CE01 CE03 CT05
8	Single user mimo lab manual	Individual work	Face-to-face	00:00	16.66%	3 / 10	CT01 CE01 CE03 CT05
12	Revision of use cases with educational array processing software	Individual work	No Presential	00:00	16.66%	3 / 10	CE03 CT05 CT01 CE01
14	Case study oral presentation.	Individual work	Face-to-face	02:00	20%	3 / 10	CT04 CE03 CT05
17	Exam	Written test	Face-to-face	02:00	30%	3 / 10	CT01 CT03 CE01 CE03

7.1.2. Global examination

Week	Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills
14	Case study oral presentation.	Individual work	Face-to-face	02:00	20%	3 / 10	CT04 CE03 CT05
17	Global examination	Written test	Face-to-face	02:00	50%	3 / 10	CT01 CT03 CE01 CE03
17	Submission of labs and exercises	Individual work	No Presential	00:00	30%	3 / 10	CT01 CT03 CT05

7.1.3. Referred (re-sit) examination

Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills
Global examination	Individual presentation	Face-to-face	02:00	50%	3 / 10	CT03 CE01 CE03 CT01
Submission of labs and exercises	Individual work	Face-to-face	00:00	30%	3 / 10	CT01 CT03 CE01 CT05
Case study oral presentation.	Individual presentation	Face-to-face	00:30	20%	3 / 10	CT04 CE03 CT05

7.2. Assessment criteria

Evaluation will assess if students have acquired all the competences of the subject. Thus, evaluation through final assessment will be carried out considering all the evaluation techniques used in continuous evaluation (EX, ET, TG, etc.), and will be celebrated in the exam period approved by Junta de Escuela for the current academic semester and year. Evaluation activities that assess learning outcomes that cannot be evaluated through a single exam can be carried out along the semester.

Progressive evaluation items and qualification criteria (ordinary call)

The distributed evaluation is composed of the following items:

1. Individual and laboratory exercises (50%). They shall be delivered along the course, in general by the end of the units. These activities can be carried out on-site or be proposed as homework. Attendance to on-site activites will be mandatory for all students. The qualification of this item will be obtained as the average of the marks obtained in each of the individual and laboratory exercises.
2. Case study (20%). Students shall prepare and provide a short oral presentation about the use of multiple antenna techniques applied to the proposed case study (e.g. discuss the use of antenna arraying for a radar system, or evaluate how multiple antenna techniques are introduced in 802.11ac). It will be done individually or in groups of two students, depending on the number of students enrolled in the course. This activity is mandatory for all students in the course.
3. Exam (30%). Written exam wih theoretical questions and short exercises. A minimum of 3 points out 10 is

required to pass the exam.

Evaluation by global test in the ordinary call

In this case, students have to carry out the distributed with the same items like the progressive evaluation.

Extraordinary call

The evaluation in the extraordinary call will be carried out through the global test with a value of 100%. For those students who have passed the deliveries of laboratory exercises and case study in the progressive evaluation will calculate the grade using the same criteria as the progressive assessment,

8. Teaching resources

8.1. Teaching resources for the subject

Name	Type	Notes
David Tse, Fundamentals of Wireless Communications.	Web resource	D. Tse and P. Viswanath, Fundamentals of Wireless Communications, Cambridge University Press, 2005 (http://www.eecs.berkeley.edu/~dtse/book.html).
Chandran. Advances in direction of arrival estimation	Bibliography	Advances in direction-of-arrival estimation. Sathish Chandran. Boston Artech House | cop. 2006
Compton. Adaptive antennas. Concepts and performance	Bibliography	Adaptive antennas : concepts and performance. R.T. Compton. Englewood Cliffs, New Jersey Prentice-Hall | 1988
Marzetta. Fundamentals of Massive MIMO	Bibliography	T. L. Marzetta, E. G. Larsson, H. Yang and H. Q. Ngo, "Fundamentals of Massive MIMO", Cambridge University Press, 2016.
Brown. Practical Guide to the MIMO Radio Channel.	Bibliography	T. Brown, E. De Carvalho and P. Kyritsi, "A Practical Guide to the MIMO Radio Channel", Wiley, 2012.
Paulraj. Introduction to ST Wireless Comms	Bibliography	A. Paulraj, R. Nabar and D. Gore, "Introduction to Space-Time Wireless Communications", Cambridge University Press, 2006.
Raviraj Adve. Lecture notes on Smart Antennas and MIMO systems	Web resource	https://www.comm.utoronto.ca/~rsadve
Educational Array Processing Techniques Simulation tool	Others	Software developed by APMC professors for the evaluation of different architecture, scenarios and array processing techniques.

9. Other information

9.1. Other information about the subject

APMC course is related to SDG 9 ("Industry, Innovation, Infrastructure") as contents deal with the design of new infrastructures to increase access to ICT and broadband services (This is included into the case studies). The communication technologies covered in the course provide a solution to the increasing demand of communication services that will generate new business opportunities and contribute to digital innovation and reach the digital transformation of the society.