ANX-PR/CL/001-01

LEARNING GUIDE

SUBJECT

93001069 - From Array Processing To Mimo Communications

DEGREE PROGRAMME

09AQ - Master Universitario en Ingenieria de Telecomunicacion

ACADEMIC YEAR & SEMESTER

2020/21 - Semester 2

Index

Learning guide

1. Description

1.1. Subject details

Name of the subject	93001069 - From Array Processing To Mimo Communications
No of credits	6 ECTS
Type	Optional
Academic year ot the programme	Second year
Semester of tuition	Semester 4
Tuition period	February-June
Tuition languages	English
Degree programme	09AQ - Master Universitario en Ingenieria de Telecomunicacion
Centre	09 - Escuela Tecnica Superior de Ingenieros de Telecomunicacion
Academic year	2020-21

2. Faculty

2.1. Faculty members with subject teaching role

Name and surname	Office/Room	Email	Tutoring hours *
Miguel Alejandro Salas Natera	C-411	miguel.salas@upm.es	Sin horario. Appointment arranged by email
Santiago Zazo Bello	C-326	santiago.zazo@upm.es	Sin horario. Appointment arranged by email

Ramon Martinez Rodriguez-Osorio (Subject coordinator)	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

- Analisis De SeÑal Para Comunicaciones

3.2. Other recommended learning outcomes

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

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

- It is recommended to know Matlab programming

4. Skills and learning outcomes *

4.1. Skills to be learned

CE1 - Capacidad para aplicar métodos de la teoría de la información, la modulación adaptativa y codificación de canal, así como técnicas avanzadas de procesado digital de señal a los sistemas de comunicaciones y audiovisuales.

CE2 - Capacidad para desarrollar sistemas de radiocomunicaciones: diseño de antenas, equipos y subsistemas, modelado de canales, cálculo de enlaces y planificación.

CG2 - Que los estudiantes sepan aplicar los conocimientos adquiridos y su capacidad de resolución de problemas en entornos nuevos o poco conocidos dentro de contextos más amplios (o multidisciplinares) relacionados con su área de estudio.

CG4 - Que los estudiantes sepan comunicar sus conclusiones ?y los conocimientos y razones últimas que las sustentan? a públicos especializados y no especializados de un modo claro y sin ambigüedades.

CG5 - Que los estudiantes posean las habilidades de aprendizaje que les permitan continuar estudiando de un modo que habrá de ser en gran medida autodirigido o autónomo.

CT1 - Capacidad para comprender los contenidos de clases magistrales, conferencias y seminarios en lengua inglesa.

CT2 - Capacidad para dinamizar y liderar equipos de trabajo multidisciplinares.

CT3 - Capacidad para adoptar soluciones creativas que satisfagan adecuadamente las diferentes necesidades planteadas.

CT4 - Capacidad para trabajar de forma efectiva como individuo, organizando y planificando su propio trabajo, de forma independiente o como miembro de un equipo.

CT5 - 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

RA10 - Saber realizar una presentación de carácter técnico, ante una audiencia de pares, que describa el trabajo realizado y sus resultados, de forma clara y bien estructurada, en el tiempo establecido, y usando un lenguaje preciso

RA117 - Conocer los aspectos básicos de los sistemas y servicios de radiocomunicaciones, su marco regulatorio y estándares técnicos de referencia.

RA136 - Manejar con soltura las bases del modelado matemático de señales aleatorias.

RA211 - Conocer los algoritmos matemáticos de los sistemas adaptativos de antena

RA119 - Conocimiento de técnicas avanzadas utilizadas en las Tecnologías de Acceso Radio

RA208 - Conocer las bases de diseño de los sistemas de multiples antenas (MIMO)

* 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 for by the system to work properly. Finally, a set of case study presented by students to explain the use of multiple antenna techniques to particular scenarios.

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 (4h)
    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 (12h)
    2.1. Antenna array processing
        2.1.1. Signal model
        2.1.2. Adaptive antennas. Time reference. Wiener, LMS and RLS solutions
        2.1.3. Adaptive antennas. Spatial reference. Capon and GSLC methods
    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 (12+8+8h)
    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. apacity 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 technologies (12h)

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

6. Schedule

6.1. Subject schedule*

Week	Face-to-face classroom activities	Face-to-face 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: 01:00 Lecture **Antenna array processing** Duration: 01:00 Problem-solving class **Direction of Arrival techniques** Duration: 02:00 Lecture			
4	**Direction of Arrival techniques** Duration: 02:00 Lecture	**Adaptive beamforming and DOA models** Duration: 02:00 Laboratory assignments		**Adaptive antenna codes** Individual work Continuous assessment Not Presential Duration: 00:00
5	**Single user MIMO** Duration: 02:00 Lecture **Single user MIMO** Duration: 02:00 Lecture			
6	**Single user MIMO** Duration: 02:00 Lecture	**SU MIMO** Duration: 02:00 Laboratory assignments		
7	**Single user MIMO** Duration: 02:00 Lecture **Single user MIMO** Duration: 02:00 Problem-solving class			**Single user mimo lab manual** Individual work Continuous assessment Not Presential Duration: 00:00

8	**Multi-User MIMO** Duration: 02:00 Lecture **Multi-User MIMO** Duration: 02:00 Lecture			
9	**Multi-User MIMO** Duration: 02:00 Lecture **Multi-User MIMO** Duration: 02:00 Problem-solving class			
10	**Massive MIMO** Duration: 04:00 Lecture			
11	**Massive MIMO** Duration: 02:00 Lecture **Massive MIMO** Duration: 02:00 Problem-solving class			**MU MIMO and Massive MIMO codes** Individual work Continuous assessment Not Presential Duration: 00:00
12	**Multiple antenna technologies** Duration: 03:00 Lecture **Multiple antenna technologies** Duration: 01:00 Problem-solving class			
13	**Multiple antenna technologies** Duration: 02:00 Lecture	**Calibration lab** Duration: 02:00 Laboratory assignments		**Calibration lab manual** Individual work Continuous assessment Presential Duration: 00:00
14	**Multiple antenna technologies** Duration: 02:00 Problem-solving class	**Case study presentation** Duration: 02:00 Additional activities		**Case study oral presentation.** Group presentation Continuous assessment and final examination Presential Duration: 02:00
15				
16				
17				**Final exam** 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 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. Continuous assessment

Week	Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills
4	Adaptive antenna codes	Individual work	No Presential	00:00	12.5%	3 / 10	CE1 CG2 CG5 CT1 CT5
7	Single user mimo lab manual	Individual work	No Presential	00:00	12.5%	3 / 10	CE1 CG2 CG5 CT1 CT5
11	MU MIMO and Massive MIMO codes	Individual work	No Presential	00:00	12.5%	3 / 10	CE1 CG2 CG5 CT1 CT5
13	Calibration lab manual	Individual work	Face-to-face	00:00	12.5%	3 / 10	CT1 CT5 CG2 CG5 CE1
14	Case study oral presentation.	Group presentation	Face-to-face	02:00	20%	3 / 10	CG4 CT2 CG2 CE2
17	Exam	Written test	Face-to-face	02:00	30%	3 / 10	CT3 CT1 CE1 CE2

7.1.2. Final examination

Week	Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills

14	Case study oral presentation.	Group presentation	Face-to-face	02:00	20%	3 / 10	CG4 CT2 CG2 CE2
17	Final exam	Written test	Face-to-face	02:00	50%	3 / 10	CT1 CE1 CE2 CG4 CT3
17	Submission of labs and exercises	Individual work	Face-to-face	00:00	30%	3 / 10	CT1 CT5 CG2 CG5 CE1

7.1.3. Referred (re-sit) examination

Description	Modality	Type	Duration	Weight	Minimum grade	Evaluated skills
Final exam	Individual presentation	Face-to-face	02:00	50%	3 / 10	CG4 CT3 CT1 CE1 CE2
Submission of labs and exercises	Individual work	Face-to-face	00:00	30%	3 / 10	CT1 CT5 CG2 CG5 CE1
Case study oral presentation.	Individual presentation	Face-to-face	00:30	20%	3 / 10	CT2 CG2 CE2 CG4

7.2. Assessment criteria

Students will be qualified through continuous evaluation by default. According to the Normativa de Evaluación del Aprendizaje de la Universidad Politécnica de Madrid, students willing to renounce to continuous evaluation must complete the Moodle task entitled "Renounce to continuous evaluation" before week four (exact date will be announced at the beginning of the course).

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.

Extraordinary examination will be carried out exclusively by the final assessment method.

Evaluation items and qualification criteria

The continuous evaluation is composed of the following items:

1. Indivdual 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 studnets 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.

Continuous evaluation

The qualification mark in continuous evaluation will be calculated as: 0.5*(Individual and lab exercises) + 0.2*(Case

study) + 0.3*(Exam)

Final ordinary evaluation

The qualification mark in the final evaluation will be calculated as: 0.3*(Individual and lab exercises) + 0.2*(Case study) + 0.5*(Exam)

The exam could include an oral part if required by the lecturers.

Final extraordinary exam

The qualification mark in the final evaluation will be calculated as: 0.3*(Individual and lab exercises) + 0.2*(Case study) + 0.5*(Exam)

The exam could include an oral part if required by the lecturers.

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

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. 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.