EE 451: Communications Systems

Detailed Lesson-by-Lesson Schedule - Spring 2026

Class Meeting Times: Tuesday & Thursday, 2:30 PM - 3:45 PM, Loyola Science Center Room 142 **Textbook:** An Introduction to Analog and Digital Communications (2nd Ed.), Haykin & Moher

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Reading Quiz Schedule

10 reading quizzes administered through Brightspace (10 questions randomly selected from 50-question banks):

Lesson	Date	Topic	Reading
2	Thu, Jan 29	Fourier Transform and Signals	Chapter 2.1
3	Tue, Feb 3	Filtering and Distortion, Bandpass Signals, Hilbert Transform	Chapter 2.2-2.5
5	Tue, Feb 10	Amplitude Modulation Techniques	Chapter 3.1-3.3
7	Tue, Feb 17	SSB, VSB, and Receiver Architectures	Chapter 3.6-3.8
11	Tue, Mar 3	FM/PM Theory and Modulation	Chapter 4.1-4.5
13	Tue, Mar 10	FM Generation and Demodulation	Chapter 4.6-4.8
17	Tue, Mar 31	Pulse Modulation and Digital Transmission	Chapter 6
23	Tue, Apr 21	Probability and Random Variables	Chapter 8.1-8.4
25	Tue, Apr 28	Noise in Communication Systems	Chapter 9
27	Tue, May 5	Digital Performance and BER	Chapter 10

Total Points: 100 (10 quizzes $\times$ 10 points each)

Homework Schedule

Assignment	Assigned	Due	Topics
Homework 1	Thu, Jan 29	Thu, Feb 5	Complex numbers, phasors, signals
Homework 2	Thu, Feb 12	Thu, Feb 19	AM and ASK
Homework 3	Thu, Mar 5	Thu, Mar 12	FM, PM, FSK, BPSK
Homework 4	Thu, Apr 9	Thu, Apr 16	M-ary modulation, QAM, EVM
Homework 5	Thu, Apr 30	Thu, May 7	Probability, noise, SNR
Homework 6	Thu, May 7	Thu, May 14	BER, link budgets, modern systems

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Exam Schedule

Exam	Date	Coverage
Exam 1	Tue, Feb 24	Chapters 2-3, 7.1-7.2 (Fourier Analysis & AM)
Exam 2	Tue, Apr 14	Chapters 4-7 (Modulation & Digital Systems)
Final Exam	Week of May 18	Comprehensive (emphasis on Chapters 8-11)

Lab Schedule

Python/Jupyter Labs

Lab	Week	Date	Topic
Python Lab 1	2	Tue, Feb 3	Fourier Analysis and Spectral Visualization
Python Lab 2	3	Thu, Feb 12	AM/ASK Modulation and Envelope Detection
Python Lab 3	10	Tue, Apr 7	CDMA & Spread Spectrum Simulation
Python Lab 4	10	Thu, Apr 9	QPSK/QAM Simulation with EVM Analysis
Python Lab 5	14	Thu, May 7	BER Performance Simulation

GNU Radio Labs

Lab	Week	Date	Topic
GNU Radio Lab 1	9	Thu, Apr 2	FM Broadcast Reception & WiFi Spectrum Analysis
GNU Radio Lab 2	13	Thu, Apr 30	Noise Analysis and SNR Measurement

Baba Yaga's Hut Phasor Labs

Session	Week	Date	Topic
Part 1	7	Thu, Mar 12	AM Phasor Analysis with I/Q Demodulation
Part 2	8	Thu, Mar 26	DSB-SC, FM, and PM Phasor Analysis

W3USR Amateur Radio Station Activities

Activity	Week	Date	Topic
W3USR Activity 1	4	Thu, Feb 19	HF Station Tour and SSB/AM Reception
W3USR Activity 2	10	Thu, Apr 9	Digital Modes (FT8, APRS, PSK31)
W3USR Activity 3	15	Tue, May 12	Satellite Communications and Tracking

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Phase 1: Foundation (Weeks 1-2)

Week 1

Lesson 1 - Tuesday, January 27 Course Introduction & Complex Signal Review - Course overview, syllabus, grading policy, amateur radio extra credit opportunities - Introduction to W3USR amateur radio station capabilities - Cross-disciplinary applications: radar, sonar, audio processing, biomedical - Complex numbers and Euler's formula review - Sinusoids: amplitude, frequency, phase - I/Q (In-phase/Quadrature) representation - industry-critical terminology - Reading: Chapter 1, Chapter 2.1

Lab/Activity: Python/Jupyter setup and environment check - Install course software (Python, Jupyter, GNU Radio) - Introduction to NumPy and Matplotlib for signal visualization

Lesson 2 - Thursday, January 29 Signal Analysis Fundamentals - Convolution, unit step and impulse functions - Energy and power signals - Phasor representation of sinusoids - Introduction to analytic signals - Reading: Chapter 2.1

READING QUIZ 1 (10 points) - Topic: Fourier Transform and Signals - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Note: Correlation, a related operation to convolution, will be introduced in Lesson 4 after we study Fourier transforms. Correlation is essential for matched filtering and signal detection in communication systems.

Homework 1 Assigned: Complex numbers, phasors, basic signal operations

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Week 2

Lesson 3 - Tuesday, February 3 Fourier Analysis Essentials - Fourier series and Fourier transforms - Properties of Fourier transforms - Time-frequency duality - Bandwidth concepts - Reading: Chapter 2.2-2.5

READING QUIZ 2 (10 points) - Topic: Filtering and Distortion, Bandpass Signals, Hilbert Transform - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lab: Python Lab 1 - Fourier Analysis - Generate and plot sinusoids - Compute and visualize Fourier transforms - Explore time-frequency duality - Bandwidth calculations

Lesson 4 - Thursday, February 5 Fourier Analysis Applications - Spectral analysis of common signals - Parseval's theorem and energy spectral density - Introduction to correlation - Reading: Chapter 2.2-2.5

Homework 1 Due

Phase 2: Modulation Techniques - Integrated Analog & Digital (Weeks 3-8)

Week 3

Lesson 5 - Tuesday, February 10 Amplitude Modulation Theory - Need for modulation - DSB-SC (Double Sideband Suppressed Carrier) theory - Full carrier AM - Envelope detection - Modulation index and overmodulation - Reading: Chapter 3.1-3.3

READING QUIZ 3 (10 points) - Topic: Amplitude Modulation Techniques - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 6 - Thursday, February 12 Binary Amplitude Shift Keying (ASK) - On-Off Keying (OOK) - Binary ASK as discrete version of AM - Spectral characteristics of ASK - Comparison of analog AM and digital ASK - Reading: Chapter 7.1-7.2

Lab: Python Lab 2 - AM/ASK Modulation - Simulate AM signals with varying modulation depths - Implement envelope detection - Generate and analyze ASK signals - Compare AM and ASK spectra

Homework 2 Assigned: AM and ASK problems

Week 4

Lesson 7 - Tuesday, February 17 AM Systems & SSB - Single Sideband (SSB) modulation - Hilbert transform - SSB generation (filter method, phasing method) - Vestigial Sideband (VSB) - brief overview - Reading: Chapter 3.6-3.8

READING QUIZ 4 (10 points) - Topic: SSB, VSB, and Receiver Architectures - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 8 - Thursday, February 19 Receiver Architectures - Superheterodyne receiver design - Mixer theory and image frequencies - Direct conversion receivers (produce I/Q baseband) - Direct sampling receivers (modern high-speed ADC approach) - Comparison: superheterodyne vs direct conversion vs direct sampling - Automatic Gain Control (AGC) - Reading: Chapter 3.6-3.8

Lab Activity: W3USR Station Tour & HF Listening - Tour of W3USR amateur radio station - Listen to SSB voice communications on HF bands (20m, 40m) - Identify AM broadcast signals on 80m band - Demonstrate different receiver modes (AM, SSB, CW)

Homework 2 Due

Week 5

Lesson 9 - Tuesday, February 24 EXAM 1: Fourier Analysis & Amplitude Modulation - Coverage: Chapters 2-3, 7.1-7.2 - Format: Closed book, equation sheet provided

Lesson 10 - Thursday, February 26 Exam Review & Angle Modulation Introduction - Exam 1 review and discussion - Introduction to frequency and phase modulation - Narrowband vs. wideband FM - Reading: Chapter 4.1-4.2

Week 6

Lesson 11 - Tuesday, March 3 FM/PM Theory & Binary FSK - FM/PM mathematical representation - Frequency deviation and modulation index - Narrowband FM approximation - Wideband FM characteristics - Reading: Chapter 4.1-4.5

READING QUIZ 5 (10 points) - Topic: FM/PM Theory and Modulation - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 12 - Thursday, March 5 Binary FSK & MSK - Binary Frequency Shift Keying (FSK) - Continuous Phase FSK (CPFSK) - Minimum Shift Keying (MSK) - FSK as digital counterpart to FM - Comparison of FSK bandwidth to FM (Carson's rule application) - Reading: Chapter 7.3-7.4

Homework 3 Assigned: FM, PM, FSK, BPSK problems

Week 7

Lesson 13 - Tuesday, March 10 FM Generation & Demodulation - Direct FM generation (VCO) - Indirect FM generation (Armstrong method) - Frequency discriminators - PLL-based FM demodulation (operates on IQ baseband) - Reading: Chapter 4.6-4.8

READING QUIZ 6 (10 points) - Topic: FM Generation and Demodulation - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 14 - Thursday, March 12 Binary PSK & Carson's Rule - Binary Phase Shift Keying (BPSK) fundamentals - BPSK as phase modulation of IQ carrier - Coherent detection of BPSK (requires IQ demodulation) - Carson's rule for FM bandwidth - Pre-emphasis and de-emphasis in FM - Reading: Chapter 4.6-4.8, Chapter 7.2

Lab Activity: "Baba Yaga's Hut" - Phasor Analysis Lab (Part 1 of 2) - Build I/Q demodulator using function generators and oscilloscopes - Examine AM signals in time, frequency, and phasor domains simultaneously - Vary modulation depth and observe effects in all three representations - Couple to AM radio for audio demodulation - Students work in pairs on the one shared setup - Reference: w8edu_cwru/the-hut-on-phasors-legs.pdf

Homework 3 Due

SPRING BREAK: March 14-22 (No Classes)

Week 8

Lesson 15 - Tuesday, March 24 Pulse Modulation & Sampling Theorem - Sampling theorem and Nyquist rate - **Real sampling:** 2× bandwidth (traditional approach) - **IQ (complex) sampling:** 1× bandwidth (what SDRs like RTL-SDR use) - Why the difference: IQ sampling separates positive and negative frequencies - Aliasing and anti-aliasing filters - Pulse Amplitude Modulation (PAM) - Natural and flat-top sampling - Reading: Chapter 5

Lesson 16 - Thursday, March 26 PCM & Delta Modulation - Quantization and quantization noise - Pulse Code Modulation (PCM) - Companding (-law and A-law) - Delta modulation and adaptive delta modulation - Line codes (NRZ, RZ, Manchester, etc.) - Reading: Chapter 5

Lab: "Baba Yaga's Hut" - Phasor Analysis Lab (Part 2 of 2) - Examine DSB-SC (suppressed carrier) signals - Explore FM and PM in phasor representation - Vary carrier phase and observe rotation in phasor domain - Complete lab worksheets and analysis - Students work in pairs on the one shared setup

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Phase 3: Advanced Digital Communications (Weeks 9-11)

Week 9

Lesson 17 - Tuesday, March 31 Baseband Digital Transmission & Synchronization - Intersymbol Interference (ISI) concepts - Eye diagrams (separate I and Q channel displays) - Nyquist

criterion for zero ISI - Raised cosine filtering - Multipath propagation in WiFi and cellular systems - Carrier and symbol timing synchronization concepts - Phase-locked loops (PLL) and Costas loops for IQ carrier recovery - Why synchronization is critical in practice - Reading: Chapter 6

READING QUIZ 7 (10 points) - Topic: Pulse Modulation and Digital Transmission - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 18 - Thursday, April 2 ISI Mitigation, OFDM & Spread Spectrum Introduction - Causes of ISI in practical channels - Equalization concepts: why equalizers are needed - Introduction to OFDM as modern solution to frequency-selective fading - OFDM basics: subcarriers, cyclic prefix, guard intervals - Why WiFi and LTE use OFDM instead of complex equalizers - Introduction to spread spectrum concepts - Direct Sequence Spread Spectrum (DSSS) fundamentals - Frequency Hopping Spread Spectrum (FHSS) overview - Reading: Chapter 6

Lab: GNU Radio Lab 1 - RTL-SDR FM Reception & WiFi Spectrum Analysis

Part 1: FM Broadcast Reception (30 min) - Introduction to GNU Radio Companion - Connect and configure RTL-SDR (outputs IQ samples) - Build FM broadcast receiver flowgraph: - RTL-SDR source block - Frequency xlating filter to select station - **Limiter block** (remove amplitude variations - Armstrong's contribution!) - WBFM Receive block for demodulation (mono FM, not full stereo/RDS) - Audio sink for output - Visualize waterfall and spectrum displays - Listen to demodulated audio

Part 2: Understanding FM Demodulation (15 min) - Examine WBFM block internals (discriminator + de-emphasis) - Discuss pre-emphasis/de-emphasis (75 s time constant in US) - Why limiter is critical: removes amplitude noise before FM demod - Note: This is mono FM - stereo requires additional 19 kHz pilot tone processing

Part 3: WiFi Spectrum Analysis (15 min) - Retune RTL-SDR to 2.4 GHz WiFi band - Capture WiFi signals - Identify 802.11g/n preambles and OFDM spectrum shape - Compare OFDM spectrum (flat-topped, rectangular) to single-carrier FM (narrow, peaked)

EASTER BREAK: April 3-6 (No Classes)

Week 10

Lesson 19 - Tuesday, April 7 Spread Spectrum & CDMA - DSSS processing gain and bandwidth expansion - PN sequences and autocorrelation properties - CDMA (Code Division Multiple Access) fundamentals - Walsh codes and orthogonality - IQ spreading: separate codes for I and Q channels - Applications: 3G cellular (CDMA2000, WCDMA), GPS - WiFi 802.11b DSSS - Jamming resistance and security benefits - Reading: Supplemental materials

Lab: Python Lab 3 - CDMA & Spread Spectrum Simulation - Generate and analyze PN sequences - Simulate DSSS spreading and despreading - Demonstrate processing gain against interference - Multi-user CDMA with Walsh codes - Compare CDMA to TDMA/FDMA

Lesson 20 - Thursday, April 9 M-ary PSK, QAM & LTE/5G Modulation - Extension from binary to M-ary signaling - QPSK (Quadrature Phase Shift Keying) - encoding 2 bits using IQ - Offset QPSK (OQPSK) - M-ary PSK constellations in IQ plane - QAM (Quadrature Amplitude Modulation) - independent I and Q amplitude control - Spectral efficiency vs. power efficiency tradeoff - LTE and 5G modulation schemes: QPSK, 16-QAM, 64-QAM, 256-QAM - Adaptive modulation based on channel quality - Reading: Chapter 7.5-7.7

Lab: Python Lab 4 - QPSK/QAM Simulation & EVM Analysis - Generate QPSK constellation - Simulate QPSK modulation and demodulation - Examine eye diagrams for I and Q channels - Add AWGN and observe constellation spreading - Calculate and visualize Error Vector Magnitude (EVM) - Increase noise/distortion and watch EVM degrade - Observe how degraded constellations lead to demodulation failures - Optional: Analyze 64-QAM constellations from captured WiFi/LTE signals

Additional Topics: - WiFi modulation: 802.11n/ac/ax (up to 1024-QAM in WiFi 6) - Spectral efficiency comparison: WiFi vs. cellular - Multiple access: OFDMA in WiFi 6 and LTE - Error Vector Magnitude (EVM) fundamentals - EVM as measure of modulation quality (magnitude + phase error) - WiFi and 5G specifications using EVM requirements

FT8: A Modern Weak-Signal Mode - FT8 as practical example of 8-FSK modulation - Technical parameters: 50 Hz bandwidth, 15-second transmit cycles - Weak-signal performance: operates reliably at -20 dB SNR - Time synchronization requirements (GPS/NTP) - Costas arrays for tone sequence generation - Why Costas arrays: optimal autocorrelation allows multiple overlapping signals - Forward error correction using LDPC codes (preview of Week 14) - Why FT8 revolutionized HF amateur radio communications

Lab Activity: W3USR Digital Modes Demonstration - Observe FT8 operation on HF (20m, 40m bands) - Watch waterfall display showing 8-FSK tones - Observe automatic decoding and time synchronization - Listen to APRS on 2m (144.390 MHz) - Demonstrate PSK31 and RTTY if time permits - Show computer integration for digital mode decoding

Homework 4 Assigned: M-ary modulation, QAM, EVM, WiFi/cellular spectral efficiency problems

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Week 11

Lesson 21 - Tuesday, April 14 EXAM 2: Modulation & Digital Systems - Coverage: Chapters 4-7 - Format: Closed book, equation sheet provided

Lesson 22 - Thursday, April 16 Exam Review & Introduction to Probability - Exam 2 review and discussion - Motivation for probability in communications - Random experiments and sample spaces - Probability axioms - Reading: Chapter 8.1

Homework 4 Due

Phase 4: Noise, Probability & System Performance (Weeks 12-15)

Week 12

Lesson 23 - Tuesday, April 21 Probability Fundamentals & Channel Capacity - Conditional probability - Bayes' theorem - Independent events - Shannon's theorem and channel capacity - Relationship between SNR, bandwidth, and capacity - Fundamental limits of communication systems - Reading: Chapter 8.1-8.2

READING QUIZ 8 (10 points) - Topic: Probability and Random Variables - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 24 - Thursday, April 23 Random Variables & Gaussian Distribution - Discrete and continuous random variables - Probability Mass Functions (PMF) - Probability Density Functions (PDF) - Cumulative Distribution Functions (CDF) - Expected value and variance - Gaussian (Normal) distribution - Q-function and error function - Reading: Chapter 8.3-8.4

Week 13

Lesson 25 - Tuesday, April 28 Noise Fundamentals - Thermal noise fundamentals - Noise power spectral density - Additive White Gaussian Noise (AWGN) - Noise figure and noise temperature - Reading: Chapter 9

READING QUIZ 9 (10 points) - Topic: Noise in Communication Systems - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 26 - Thursday, April 30 Noise in Analog Systems - SNR calculations for AM systems - Noise performance of DSB-SC and SSB - FM noise performance and threshold effect - FM improvement over AM - Reading: Chapter 11.1-11.3

Lab: GNU Radio Lab 2 - Noise and SNR Analysis - Add AWGN to AM and FM signals - Measure SNR using spectrum analyzer blocks - Compare noise performance of AM vs. FM - Observe FM threshold effect

Homework 5 Assigned: Probability, noise, and SNR calculations

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Week 14

Lesson 27 - Tuesday, May 5 Digital Performance Analysis - Bit Error Rate (BER) fundamentals - Matched filtering - Signal space and correlation receivers - Decision regions - Reading: Chapter 10

READING QUIZ 10 (10 points) - Topic: Digital Performance and BER - 10 questions randomly selected from 50-question bank - Administered via Brightspace at beginning of class

Lesson 28 - Thursday, May 7 BER, EVM & Channel Coding - BER for BPSK - BER for FSK (coherent and non-coherent) - BER for QAM - Performance comparison of modulation schemes - EVM vs. BER: complementary metrics - Why modern systems (WiFi/5G) specify EVM

limits - Channel coding fundamentals: block codes, convolutional codes - Modern codes: LDPC (WiFi), Turbo (LTE), Polar (5G) - Why channel coding is essential in modern systems - Reading: Chapter 10

Lab: Python Lab 5 - BER Performance Simulation - Simulate BPSK, QPSK, and QAM in AWGN - Generate BER vs. SNR curves - Compare theoretical and simulated performance - Explore effect of matched filtering

Homework 5 Due / Homework 6 Assigned: BER calculations, link budgets, WiFi/cellular system analysis

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Week 15

Lesson 29 - Tuesday, May 12 Link Budgets, WiFi, Cellular & SDR Concepts - Link budget calculations (Friis equation) - Path loss at different frequencies: WiFi (2.4/5 GHz) vs. cellular (900 MHz) vs. 5G mmWave (28 GHz) - Antenna gains, system noise temperature - Margin analysis for WiFi and cellular systems - Software-Defined Radio (SDR) architecture - Modern communication systems overview: - WiFi standards evolution (802.11a/g/n/ac/ax/be) - LTE and 5G NR architecture basics - MIMO and beamforming in WiFi 6 and 5G - Frequency bands and channel bandwidths - Reading: Chapter 11.4-11.7

Lab Activity: W3USR Satellite Communications - Predict satellite pass using tracking software - Configure azimuth/elevation rotator for satellite tracking - Demonstrate FM voice satellite contact (if satellite available) - Or: demonstrate digital satellite telemetry reception

Lesson 30 - Thursday, May 14 HAMVENTION - NO CLASS - Instructor attending Hamvention (Dayton Hamvention, the world's largest amateur radio convention) - **Self-study assignment:** Review comprehensive course material - Watch recorded lecture on modern wireless systems (WiFi 6, 5G NR, SDR concepts) - Optional: Explore GNU Radio tutorials or advanced modulation projects - Prepare questions for final exam review session

Homework 6 Due (submit electronically)

Final Exam Period

Final Exam - Thursday, May 21, 12:45–2:45 PM

Comprehensive Final Exam - Coverage: All course material (Chapters 1-11) - Emphasis on noise, probability, and system performance (Chapters 8-11) - Format: Closed book, equation sheet provided

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Last updated: January 2026