University of Southern California
EE544: RF Wireless Systems and Hardware

Department: Electrical & Computer Engineering
Course Number: EE544
Course Title: RF Wireless Systems and Hardware
Credit Units: 3
Semester: Spring 2020

Course Description:

RF systems are central to the wireless revolution that is changing our world. EE544 is a first-year graduate course that is at the subsystem and component level and covers a lot of territory. It deals with the design and analysis of practical **CMOS-RF circuit-level** implementations of functional blocks of RF communications systems. These include Low-Noise Amplifiers, Power Amplifiers, Mixers, Filters, Low-Phase Noise Oscillators, Modulators (Analog and Digital) and Demodulators, PLL-based & Digital Frequency Synthesizers and Digital Baseband Back-ends. Modeling will be conducted using both passive and active circuits. The course is heavy on the use of **CMOS-based technologies** in building these blocks. Essential to this course as well is of course the characterization of Noise and Distortion measures, their mitigation techniques and the overall performance analysis of the transceiver. Different Transceivers architectures (Super-Heterodyne and Direct Conversion) will be considered. **Simulation of Discrete RF circuits** will be assigned using Simulation tools such as Cadence, SpectreRF and HSPICE. **Matlab simulation** of the performance of several modulation techniques will also be assigned. A weekly discussion session is also conducted with emphasis on RF systems testing, measurements and simulations. Overview of 5G cellular system and 6G Wi-Fi will also be presented. This course is an "**ambitious, very challenging, heavily practical** course" unlike other courses that you might have taken in Communications and/or Signal Processing division here at USC or elsewhere. This course is a PREREQUISTE to your career in the fascinating world of RF Communications and Circuit Design.

Prerequisite by Topic:

Students taking this course are expected to have taken the following courses.

- EE348: Electronics (Most important is the CMOS, Preferably EE479 or EE448)
- EE301: Linear Systems and Signals (Fourier Series & Transform, Sampling, etc..
- EE364: Probability and Statistics (Probability Distributions, Noise, PSD, etc…)
- EE467/EE475: Communications Systems (Am/FM/Digital)
- Familiarity with MATLAB/SPICE is expected

Textbooks & References

- RF Microelectronics, 2nd edition, B. Razavi, Pearson 2012
- Microwave and RF Design, 2nd edition, M. Steer, Scitech 2013
- The Design of CMOS RF Integrated Circuits, 2nd edition, Thomas Lee
- Pdfs of all of the above texts will be posted.

Course Objectives: Upon completion of EE544, students should be able to

1. Understand the underlying system concepts that utilize RF components.
2. Identify various components used in RF Transceivers, including Mixers, Oscillators (fixed and tunable), Synthesizers, Amplifiers, Filters, Modulators, Demodulators, Duplexers, etc..
3. Understand the concepts of power, gain, phase, stability, noise, bias networks and impedance matching networks as applied to the design of RF amplifiers
4. Design, using CMOS LNA and power amplifiers, mixers, oscillators, etc… both narrowband and broadband.
5. Understand the techniques and tools used in designing RF receivers including heterodyne, low IF, Zero IF receivers and SDR
6. Understand and characterize noise sources in RF systems such as thermal noise, phase noise and other channel impairments and how do they affect the performance of RF systems.
7. Understand the nonlinear effects in RF components such as the 1-dB compression; Inter-modulation products, third-order intercepts; etc..
8. Determine the dynamic range of cascaded systems from module specifications
9. Identify design issues and trade-offs involving linearity, noise, power dissipation, and dynamic range in RF transceiver architectures.
10. Perform Link Budget analysis for Terrestrial and Satellite RF Systems
11. Conduct simulation of functional blocks using simulation tools such as cadence, ADS, HSPICE, SpectreRF and Matlab.

Topics Covered/Course Outline (Tentative)

1. **Introduction and Review**

- Introduction to RF concepts and applications
- The RF electromagnetic spectrum. Wavelength and Frequency
- Review of basic passive components
- Review of analysis of simple passive circuits in phasor domain
- RF electronics concepts. RF versus DC and low frequency signals
- Multiple Access Techniques including FDMA. TDMA and CDMA
- RF transceiver components. Modulation schemes.
- Transceiver Architectures: Super Heterodyne, Homodyne, Low-IF, SDR, etc…

2. **Transceiver Architectures**

- Super Heterodyne Architecture, Configuration, Frequency Planning, Technical Challenges and Design Considerations
- Direct Conversion Architecture, Configuration, Technical Challenges and Design Considerations
- Low IF-Architecture, Configuration, Technical Challenges and Design Considerations
- Band-Pass Sampling Architecture
- Software-Defined Radios (SDR)

3. **Modulation Techniques**

- Review of Analog Modulation Techniques including AM, FM, SSB, etc...
- Digital Modulation Techniques including MPSK, MFSK, QAM & OFDM
- Performance measures and design trade-offs.
- Power efficiency vs. Bandwidth efficiency
- Practical modulation techniques such as GMSK, $\pi/4$ QPSK, OFDM, etc…

4. **Receiver System: Analysis and Design**

- Receiver Sensitivity. Thermal noise voltage. Autocorrelation function. Power spectral density. Noise bandwidth.
- Noise sources: shot, flicker, burst, etc...
- Noise models for electronic devices. Equivalent input noise generators.
- Signal-to-noise ratio (SNR). Minimum Detectable Signal (MDS). Noise figure. Noise Temperature. Available gain (G) and Noise Figure for cascaded stages.
- Adjacent Channel Selectivity and Blocking Characteristics

- Receiver Dynamic Range
- Low and high frequency distortion analysis using series expansion.
- Non-linearity effects on RF system performance. Second and third order IM components. 1-dB Compression. Third-order Intercept.

5. Transmitter System: Analysis and Design

- Transmission Power and Spectrum.
- Modulation accuracy, EVM, ISI and Phase Noise
- Carrier Leakage
- AGC and Power management
- Adjacent Channel Power Ratio (ACPR)
- Impedance matching networks. Design of matching circuits using lumped elements. Transmission Lines as impedance matching

6. Antennas and the RF Link

- Overview of Antennas, Types
- Effective Isotropic Radiated Power, Antenna Aperture Size
- RF Link Budget, Multipath and path Losses, Rayleigh Fading
- RF Interferences.

7. RF Amplifier design (Both Power and LNA)

- Classes of power amplifiers
- Review of linear and switching power amplifier design techniques
- Gain match and power match, matching circuits for power amplifiers
- Conventional high-efficiency amplifiers.
- Tunable narrowband and broadband amplifiers.
- Multistage amplifiers.
- Front-end low noise amplifier design.
- Nonlinear effects in RF power amplifiers.
- Gain-Bandwidth enhancement techniques and linearization techniques.

8. Frequency Converters: Mixers

- Design of active & passive mixers. Switching type mixers. Multiple diodes mixer.
- Conversion to an IF range. Zero-IF conversion
- Double converters
- Conversion loss, nonlinear effects
- Characterization of mixer gain, intercept point, noise figure, image rejection, isolation. Measuring gain compression and inter-modulation distortion.

9. Oscillator Circuits

- Relaxation Oscillator circuits. Tuned Oscillators
- Hybrid Pi model for CMOS, loop gain analysis; negative resistance analysis
- Design stable DC bias circuits for oscillators
- Crystal Oscillators
- Phase Noise in Oscillators

10. Phase Lock Loops

- Voltage controlled Oscillator. Phase Comparator. Loop Filter
- Loop linear and non-linear operation. Acquisition and hold-in ranges. Closed loop response. Effect of noise on the operation of PLL in RF systems
- Frequency Synthesizers. Single and multiple crystal synthesizers.
- Indirect synthesizers using PLLs
- Digital Direct Synthesizers (DDS)

11. Back-end (Time Permitting)

- ADC and DAC Circuits (EE536b)