ECEG 497 Wireless System Design Spring 2023

Policies and Review Topics for Exam #3

The following policies will be in effect for the exam. They will be included in a list of instructions and policies on the first page of the exam:

1. You will be allowed to use a non-wireless enabled calculator, such as a TI-89.
2. You will be allowed to use three 8.5 × 11-inch two-sided handwritten help sheets. No photocopied material or copied and pasted text or images are allowed. If there is a table or image from the textbook or some other source that you feel would be helpful during the exam, please notify me.
3. All help sheets will be collected at the end of the exam but will be returned to you later.
4. **You may not leave the exam room without prior permission except in an emergency or for an urgent medical condition. Please use the restroom before the exam.**

The following is a list of topics that could appear in one form or another on the exam. Not all of these topics will be covered, and it is possible that an exam problem could cover a detail not specifically listed here. However, this list has been made as comprehensive as possible. You should also be familiar with the topics on the review sheets for the previous exams.

Although significant effort has been made to ensure that there are no errors in this review sheet, some might nevertheless appear. The textbook and the supplemental readings are the final authority in all factual matters, unless errors have been specifically identified there. You are ultimately responsible for obtaining accurate information when preparing for your exam.

Parts and concepts of a basic wireless system
- baseband signals, transmitters and receivers
- the use of radio/wireless is a kind of frequency division multiplexing
- frequency downconversion and upconversion
- transmission lines and antenna(s)

Fundamental receiver architectures
- tuned radio frequency (TRF)
    - no mixing
    - highly selective front-end filter, then amplification, then conversion to baseband if the latter step can be accomplished without a mixer
    - rare in most modern radios, but common in RFID and keyless entry systems
- superheterodyne
    - dominant modern architecture
    - major advantage is that IF filter and amplifiers are optimized for a single narrow frequency range
    - single conversion: one frequency translation to IF, then conversion to baseband; the latter might make use of another frequency translation or a special circuit called a product detector
    - double conversion: first frequency translation to first IF, then second frequency translation to second IF, then conversion to baseband
    - triple conversion: like double conversion but with three IFs
    - quadruple (and up) conversion: not common

- direct conversion or homodyne
    - becoming more common, especially in software defined radios (SDRs)
    - frequency translation directly from RF to baseband
    - typically requires quadrature mixing (also called quadrature downconversion); i.e., LO with 0° and ±90° phase shifts feed two different mixers; input (RF) signal applied to both mixers
- hybrid of superheterodyne and quadrature mixing; widely used in cell phones

Mixers

- primary purpose is to provide frequency translation (frequency shifting)
- two inputs: RF signal and LO signal; output: IF (intermediate-frequency) signal
- second-order outputs are signals at sum and difference frequencies of RF and LO
  $f_{\mathrm{IF}} = f_{\mathrm{RF}} + f_{\mathrm{LO}}$ (sum product) or $f_{\mathrm{IF}} = \left| f_{\mathrm{RF}} - f_{\mathrm{LO}} \right|$ (difference product)
- IF and LO range selection
  $f_{\mathrm{LO}} = f_{\mathrm{IF}} - f_{\mathrm{RF}}$ (IF is sum product) or $f_{\mathrm{LO}} = f_{\mathrm{RF}} \pm f_{\mathrm{IF}}$ (IF is difference product)
- tuning of most superheterodyne and direct conversion radios is accomplished primarily by adjusting the first LO frequency (or the only LO frequency in the case of a single-conversion superheterodyne)
- high-side injection: $f_{\mathrm{LO}} > f_{\mathrm{RF}}$
- low-side injection: $f_{\mathrm{LO}} < f_{\mathrm{RF}}$
- possibility of spectral inversion (spectral flipping)
- mixing via signal multiplication: $v_{out}(t) = a_1 \cos(\omega_1 t) \times a_2 \cos(\omega_2 t)$
- mixing via signal “chopping,” equiv. to multiplication by a square wave
- diode ring mixer (double-balanced; provides isolation of input/output ports from LO)
- Gilbert cell mixer (“double diff amp”); based on differential amplifier circuit; can be made from BJTs or MOSFETs, but the latter is becoming common because MOSFET-based integrated circuits are cheap to produce; can be used in analog multiplier mode or “chopping” mode
- image frequencies and image bands
- image rejection mixers
    - phase shifters must be highly accurate
    - gain or attenuation through both signal paths must be equalized
    - allows for a practical homodyne (direct conversion) receiver, where the spectrum of the image signal is right next to the spectrum of the desired signal
- need for good front-end filtering if image signals are an issue
- $\cos(-x) = \cos(x)$; relevant when argument of cosine includes a negative frequency difference, which is nonphysical

Decibel and decibel-based units

- definition; advantage over using power ratios
- application to power gain vs. voltage gain
- overall gain/loss of a system in dB is equal to sum of gains/losses in dB of each stage
- mathematical identities involving logarithms
- dBm, dBW units
- use of dBm (or dBW) vs. dB – absolute vs. relative quantities

Noise in receiver systems

- sources of noise
    - radiated noise (picked up by antenna or receiver circuitry)
    - conducted noise (picked up by power and/or other cables)
    - internally-generated noise (thermal, shot, and flicker)

- usually only internally-generated noise can be controlled (somewhat) by designer
- signal-to-noise ratio (SNR)
  - output SNR is less than (worse than) input SNR
  - input SNR: $SNR_i = \dfrac{P_{Si}}{P_{Ni}}$,

    where P_{Si} = input signal power, P_{Ni} = input noise power
  - output SNR: $SNR_o = \dfrac{P_{So}}{P_{No}} = \dfrac{GP_{Si}}{GP_{Ni} + P_N} = \dfrac{P_{Si}}{P_{Ni} + P_N / G} < SNR_i$,

    where P_{So} = output signal power, P_{No} = output noise power, P_N = internally-generated noise power, and G = power gain of the stage (in factor, not dB, form)
- standard noise factor F
  - standard input noise power: $P_{Ni} = kT_0B$,

    where k = Boltzmann's constant (1.38×10^{-23} J/K), T_0 = standard temperature (290 K), and B = bandwidth of stage or system (narrowest in the system)
  - $F = 1 + \dfrac{P_N}{GkT_0B}$ or $P_N = (F-1)GkT_0B$
  - noise factor is always > 1
- standard noise figure (NF) in dB: $\mathrm{NF} = 10\log(F)$
- overall standard noise factor
  - $F_{tot} = F_1 + \dfrac{F_2 - 1}{G_1} + \dfrac{F_3 - 1}{G_1G_2} + \ldots + \dfrac{F_N - 1}{G_1G_2 \cdots G_{N-1}}$
  - each noise factor in the equation is a standard noise factor
  - the first few stages in a receiver are the most critical determiners of the overall system noise factor or figure
  - for passive (no transistors or diodes), lossy, impedance-matched stages: $G = 1/L$ and $F = L$ (where G and L are the gain and loss factors, not in dB; $L > 1$ as used here)
  - if a lossy stage is added to the input of a receiver, the noise figure (in dB) increases by the loss in dB
- equivalent noise temperature (T_{eq})
  - characterizes the internally generated noise as an equivalent *input* noise power (generated by a passive device at temperature T_{eq} connected to the input of the receiver or system) that leads to the same output noise power
  - especially useful for selecting an overall noise figure for a receiver. It is not productive to expend the effort (and money) to minimize internally generated noise if a large amount of noise is arriving via the antenna.
  - $P_N = GkT_{eq}B$, $F = 1 + \dfrac{T_{eq}}{T_o}$, and $T_{eq} = (F-1)T_o$

    where P_N = internally-generated noise power
- antenna temperature (T_A)
  - definition: "physical temperature of a resistor that delivers a power spectral density to a matched load equal to that delivered by a specified antenna to a conjugate-matched load." [Ellingson, *Radio Systems Engineering*, 2016]
  - kT_A = power spectral density (in W/Hz) due to external noise picked up by an antenna

- Highly directional antennas can avoid many strong noise sources like the sun or industrial sites by steering away from them. They also pick up less of the ambient noise from the ground and atmosphere. Thus, T_A is relatively low for high-gain antennas.
- T_A can be low for nondirectional antennas, even during daytime, if the surrounding noise level is relatively low. Although the sun is noisy, a nondirectional antenna does not have much gain in the sun's direction.
- usual goal for a receiver system is to make $T_{eq} < T_A$, where T_{eq} is the equivalent noise temperature of the receiver; this guarantees that internally generated noise is not the determining factor in the ability to detect signals
- $T_A = b\left(\dfrac{f}{1\,\text{MHz}}\right)^a$ [unit = K],

  where *a* and *b* are experimentally determined parametric values determined by type of environment (e.g., "city," "residential," "rural," "quiet rural"); *f* is in MHz

Relevant course material:

Homework: #6, #7, and #8
Mini-Projects: [none]
Reading: Assignments from Mar. 1 through Apr. 5, including the supplemental readings
"Mixer Circuits and Image Frequencies"
"Why Do Engineers Use the Decibel Unit?"
"Analog Multipliers Employing the Bipolar Transistor" (skim only)
"Signal-to-Noise Ratio and Noise Figure"

This exam will focus primarily on course outcomes #3 (given below) and related topics.

2. Recognize and analyze basic receiver and transmitter system architectures.
3. Predict the frequency translation properties and image response of a frequency mixer circuit.
5. Calculate system noise figure given the gain and noise figures of individual system stages.

The course outcomes are listed on the Course Policies and Information sheet, which was distributed at the beginning of the semester and is available on the Syllabus and Policies page at the course web site. The outcomes are also listed on the Course Description page. Note, however, that some topics not directly related to the course outcomes could be covered on the exam as well.