ECEG 497 **Wireless System Design** **Spring 2025**

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 either immediately or soon after the exam.
4. If you begin the exam after the start time, you must complete it in the remaining allotted time. However, you may not take the exam if you arrive after the first student has completed it and left the room. The latter case is equivalent to missing the exam.
5. **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 exam will begin at 7:00 pm on Thursday, April 17 in Breakiron 264 (our usual classroom). You will have until 9:00 pm to complete 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.

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: $\text{NF} = 10\log(F)$
- 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.
  - $P_N = GkT_{eq}B$, $F = 1 + \dfrac{T_{eq}}{T_0}$, and $T_{eq} = (F-1)T_0$

    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
  - $T_A = b\left(\frac{f}{1\,\text{MHz}}\right)^a$ [unit = K],

    where *a* and *b* are experimentally determined values determined by type of environment (e.g., "city," "residential," "rural," "quiet rural"); *f* is in MHz; this is a *very* rough estimate of the noise environment and is based on data from many decades ago; actual noise could be an order of magnitude or more higher or lower than this estimate.

Nonlinear behavior of amplifiers and systems (intermodulation distortion, or IMD)

- representation of output signal as Taylor series (Maclaurin series, technically)

  $v_{out}(t) = a_1 v_{in} + a_2 v_{in}^2 + a_3 v_{in}^3 + \cdots$, where a_1, a_2, a_3, … are constants

  Generally, $|a_1| > |a_2| > |a_3| > \cdots$
- if DC is included,

  $v_{out}(t) = a_0 + a_1 v_{in} + a_2 v_{in}^2 + a_3 v_{in}^3 + \cdots$

  but DC products are easily removed using a DC blocking capacitor
- 1st-order products are linear outputs
- 2nd-order, 3rd-order, etc. are intermodulation products
- dB levels of 2nd-order products increase *two* times as fast as those of 1st-order products as input power (in dBm) increases ($P_{o2} \sim P_{in}^2$)
- dB levels of 3rd-order products increase *three* times as fast as those of 1st-order products as input power (in dBm) increases ($P_{o3} \sim P_{in}^3$)
- third-order intercept point (TOI or IP3 or P_3), referred to input or output (assume output if not specified)
- 1 dB or 3 dB compression point (or compression level)
- IMD products are usually troublesome only when they emerge from noise floor
- 3rd-order products are of most concern because the signals that cause them can pass through front-end filter of receiver or amplifier; their frequencies are close to the frequencies of the signals that caused them

Minimum discernable (or detectable) signal (MDS)

- defined as the "signal power applied to the input [that] results in a specified SNR at the output, assuming perfect impedance matching at [the] input and output, and assuming the bandwidth of the two-port is at least as large as the bandwidth of the signal." (Ellingson, *Radio Systems Engineering*, 2016)
- min. acceptable SNR is often specified as 0 dB but could be any value, depending on modulation, signal integrity requirements, etc.
- multiple definitions of MDS, but the two most widely used are (assuming SNR = 0 dB)

  $$\text{MDS} = kT_{eq}B = kT_0(F-1)B \qquad \text{(assumes noise-free input)}$$

  $$\text{MDS} = kT_0B + kT_{eq}B = kT_0FB \qquad \text{(assumes standard input noise),}$$

  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)
- if reference SNR is not 0 dB, then expressions for MDS above must be multiplied by SNR expressed in factor (not dB) form; alternatively, SNR in dB is added to MDS in dBm

- related to noise figure by (using definition with standard input noise):
  $$\text{MDS}[\text{dBm}] = 10\log\left(\frac{kT_0}{0.001}\right) + 10\log(B) + \text{NF} + \text{SNR}[\text{dB}]$$
- $10\log\left(\frac{kT_0}{0.001}\right) = -174\ \text{dBm}$

Dynamic range of amplifiers and receiver systems

- blocking dynamic range: $\text{BDR}[\text{dB}] = P_{in,1\,\text{dB}} - \text{MDS}[\text{dBm}]$, where $P_{in,1\text{ dB}}$ is the input power level at the 1 dB output compression point
- "two-tone" third-order, or spurious-free, dynamic range:
  $\text{SFDR} = \frac{2}{3}\left(\text{IP3}_{in} - \text{MDS}\right)$, where IP3$_{in}$ is the third-order input intercept point;
  all quantities are in dBm or dB
- remember that MDS is defined relative to an appropriate SNR (usually, but not always, SNR = 0 dB)

<u>Relevant course material:</u>

Homework: #6 and #7
Mini-Projects: [none]
Reading: Assignments from Mar. 24 through Apr. 11, including the supplemental readings "Signal-to-Noise Ratio and Noise Figure"

This exam will focus primarily on the course outcomes list below and related topics.

5. Calculate system noise figure given the gain and noise figures of individual system stages.
6. Understand the relationship between minimum detectable signal (MDS), third-order intercept (TOI or IP3), and spurious-free dynamic range (SFDR) of an amplifier or receiver system.

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.