Please review the “Exam Policies” section of the Exams page at the course web site. Please note
the following two changes from policies used in the past:

1. You will be allowed to use two 8.5 × 11-inch two-sided handwritten help sheets. There are
no restrictions on the material you may place on the help sheets, except that 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
the instructor.
2. All help sheets will be collected at the end of the exam but will be returned to you later.

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 sheet for the previous exam.

Although great effort has been made to ensure that there are no errors in this review document,
some might nevertheless appear. The textbook is 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.

Receiver system design considerations
- front end design of a typical superheterodyne receiver
- homodyne (direct conversion) receiver
- advantages of frequency translation (heterodyning) as opposed to TRF (tuned radio
  frequency) architecture
  o allows optimization of narrow filter at a single, stationary IF instead of moving
    the pass-band of the filter
  o total receiver gain can be distributed among different frequency ranges (e.g., some
    at RF, some at one or more IFs; some at baseband), which aids stability
  o tuning accomplished by moving the frequency of a single oscillator. In general,
    filters’ pass-bands do not have to be tuned.

Mixers
- primary purpose is to provide frequency translation (frequency shifting)
- two inputs: RF signal and LO signal; output: IF signal
- second-order outputs are signals at sum and difference frequencies (of RF and LO)
  \[ f_{\text{IF}} = f_{\text{RF}} + f_{\text{LO}} \text{ (summing mixer)} \]  or
  \[ f_{\text{IF}} = |f_{\text{RF}} - f_{\text{LO}}| \text{ (differencing mixer)} \]
- IF and LO range selection
  \[ f_{\text{LO}} = f_{\text{IF}} - f_{\text{RF}} \text{ (summing mixer)} \]  or
  \[ f_{\text{IF}} = f_{\text{RF}} \pm f_{\text{IF}} \text{ (differencing mixer)} \]
- high-side injection: \[ f_{\text{LO}} > f_{\text{RF}} \]
- low-side injection: \[ f_{\text{LO}} < f_{\text{RF}} \]
- diode ring mixer (double-balanced; provides isolation of input/output ports)
- mixing via signal multiplication: \[ v_{\text{out}}(t) = a_1 \cos(\omega_1 t) \times a_2 \cos(\omega_2 t) \]
- image frequencies and image bands
- image rejection mixers
  - phase shifters must be highly accurate
  - 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
- \( \cos(-x) = \cos(x) \); relevant when argument of cosine includes a negative frequency difference, which is nonphysical

Filters
- simple one-pole low-pass filters:
  - fraction of available power delivered to load:
    \[
    \frac{P_L}{P_A} = \frac{4R_sR_L}{(R_g + R_L)^2} \left[ \frac{1}{1 + \left( \frac{\omega}{\omega_c} \right)^2} \right]
    \]
  - series inductor: \( \omega_c = \frac{R_g + R_L}{L} \)
  - parallel capacitor: \( \omega_c = \frac{1}{(R_g + R_L)C} \)
  - stop-band roll-off = -20 dB/decade (-6 dB/octave)
- simple one-pole high-pass filters:
  - fraction of available power delivered to load:
    \[
    \frac{P_L}{P_A} = \frac{4R_sR_L}{(R_g + R_L)^2} \left[ \frac{\left( \frac{\omega}{\omega_c} \right)^2}{1 + \left( \frac{\omega}{\omega_c} \right)^2} \right]
    \]
  - parallel inductor: \( \omega_c = \frac{R_g||R_L}{L} \)
  - series capacitor: \( \omega_c = \frac{1}{(R_g + R_L)C} \)
  - stop-band roll-off = +20 dB/decade (+6 dB/octave)
- simple band-pass filters
  - fraction of available power delivered to load:
    \[
    \frac{P_L}{P_A} = \frac{4R_sR_L}{(R_g + R_L)^2} \frac{1}{1 + \left( \frac{\omega}{\Delta \omega} \right)^2 \left( 1 - \frac{\omega^2}{\omega_c^2} \right)^2}
    \]
  - series RLC: \( \omega_o = \frac{1}{\sqrt{LC}} \), \( \Delta \omega = \frac{R_g + R_L}{L} \), \( Q_{net} = \frac{\omega_o}{\Delta \omega} = \frac{\omega_o L}{R_g + R_L} = \frac{X_L}{2R_{sys}} \)
  - parallel RLC: \( \omega_o = \frac{1}{\sqrt{LC}} \), \( \Delta \omega = \frac{1}{\left( R_g||R_L \right)C} \), \( Q_{net} = \frac{\omega_o}{\Delta \omega} = \left( R_g||R_L \right)\omega_o C = \frac{R_{sys}}{2|X_C|} \)
  - stop-band roll-off = ±20 dB/decade (±6 dB/octave)

Coupled-resonator filters
- goal: maximize stored energy relative to energy dissipated per cycle (i.e., maximize Q)
- provide larger Q (narrower bandwidth) for given resonator reactances than with simple band-pass filters that don’t use coupling capacitors
- parallel LC resonators with series coupling (usually by capacitors); a.k.a. top coupling
- series LC resonators with shunt coupling (usually by capacitors)
- difference between “network” Q (\( Q_{net} \)) and “series-parallel transformation” Q (\( Q_t \))
- coupling capacitors usually preferred over coupling inductors
Matrix representations of networks
- Equivalent circuit models at VHF, UHF, microwave frequencies are very complicated due to stray reactances, but they apply over wide frequency ranges.
- Matrix representations are simpler (only 4 values needed for 2-port device), but valid at only one frequency (lists of parameters are required for wideband applications).
- Typically represent voltage-voltage, voltage-current, and/or current-voltage relationships at the network’s terminals.
- Definitions of port voltages and currents for a 2-port:

\[
V_1 = Z_{11}I_1 + Z_{12}I_2 \\
V_2 = Z_{21}I_1 + Z_{22}I_2
\]

- \( Z \) (impedance) parameters:
  - System of equations (2-port):
    \[
    V_1 = Z_{11}I_1 + Z_{12}I_2 \\
    V_2 = Z_{21}I_1 + Z_{22}I_2
    \]
  - Calculation of coefficients: \( Z_{ij} = \frac{V_{ij}}{I_{ij}} \)
    (subscript is \( j \) with a bar over it, the Boolean symbol for “not”)
  - Measurements and/or calculations of \( Z \) parameters require open-circuit port terminations.

- \( Y \) (admittance) parameters:
  - System of equations (2-port):
    \[
    I_1 = Y_{11}V_1 + Y_{12}V_2 \\
    I_2 = Y_{21}V_1 + Y_{22}V_2
    \]
  - Calculation of coefficients: \( Y_{ij} = \frac{I_{ij}}{V_{ij}} \)
  - Measurements and/or calculations of \( Y \) parameters require short-circuit port terminations.

- \( S \) (scattering) parameters:
  - General system of equations (2-port):
    \[
    b_1 = S_{11}a_1 + S_{12}a_2 \\
    b_2 = S_{21}a_1 + S_{22}a_2
    \]
    where \( a_i = \frac{V_{id}}{\sqrt{Z_{oi}}} \) (normalized incident voltage),
    and \( b_i = \frac{V_{ir}}{\sqrt{Z_{oi}}} \) (normalized “scattered,” or “reflected” voltage)
    can also use:
    \[
    V_{1r} = S_{11}V_{1i} + S_{12}V_{2i} \\
    V_{2r} = S_{21}V_{1i} + S_{22}V_{2i}
    \]
  - Calculation of coefficients: \( S_{ij} = \frac{b_{ij}}{a_j} \)
    (where \( a_j = \) all inc. voltages but the \( j \)th)
  - If all port impedances are the same, then \( S_{ij} = \frac{V_{ir}}{V_{ir}} \) (frequently true)
definitions more useful for analysis:

\[ S_{11} = \Gamma_1 \bigg|_{Z_{l2}=Z_o} \quad S_{21} = \frac{2V_1}{V_g} \bigg|_{Z_{l2}=Z_o} \quad S_{12} = \frac{2V_1}{V_g} \bigg|_{Z_{l1}=Z_o} \quad S_{22} = \Gamma_2 \bigg|_{Z_{l1}=Z_o} , \]

where \( V_1 \) and \( V_2 \) are the total voltages at ports 1 and 2, respectively, \( V_g \) is the Thévenin equivalent generator voltage; and \( \Gamma_1 \) and \( \Gamma_2 \) are the reflection coefficients seen by sources connected to ports 1 and 2, respectively.

- care must be taken when finding \( V_i I \) and \( V_i R \)
- measurements and/or calculations of S parameters require impedance-matched port terminations
- de-embedding (modification of S parameters due to addition of lossless line lengths):

![Diagram of 2-port network with l1 and l2 as line lengths and Zo as characteristic impedance]

\[
S_{11}(l_1) = S_{11}(0)e^{-j2\beta l_1} \quad S_{12}(l_1, l_2) = S_{12}(0,0)e^{-j\beta (l_1 + l_2)} \\
S_{22}(l_2) = S_{22}(0)e^{-j2\beta l_2} \quad S_{21}(l_1, l_2) = S_{21}(0,0)e^{-j\beta (l_1 + l_2)}
\]

makes possible the practical use of vector network analyzers

- interpretation of S parameters
  - on-diagonal parameters are reflection coefficients if other ports are matched
  - off-diagonal parameters are gains/attenuations for matched conditions
  - S parameters are voltage ratios, not power ratios; magnitudes often expressed in dB

- relationships between matrix representations
  - \([Z] = [Y]^{-1}\)
  - \([S] = ([Y_o] + [Y])^{-1}([Y_o] - [Y])\), where \([Y_o]\) is a diagonal matrix w/port admittances
  - \([S] = ([Z] + [Z_o])^{-1}([Z] - [Z_o])\), only if all port impedances are the same, where \([Z_o]\) is a diagonal matrix w/port impedances

- reciprocity: \( Z_{ji} = Z_{ij} \), \( Y_{ji} = Y_{ij} \), and \( S_{ji} = S_{ij} \)

- input impedance of terminated lossless line:

\[
Z_{in}(-l) = Z_o \frac{Z_L + jZ_o \tan(\beta l)}{Z_o + jZ_L \tan(\beta l)} = Z_o \frac{1 + \Gamma_L e^{-j2\beta l}}{1 - \Gamma_L e^{-j2\beta l}}
\]

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: \( SNR_i = \frac{P_{Si}}{P_{Ni}} \)

where \( P_{Si} = \) input signal power, \( P_{Ni} = \) input noise power
output SNR: 
\[ \text{SNR}_o = \frac{P_{So}}{P_{No}} = \frac{GP_{Si}}{GP_{Ni} + P_N} = \frac{P_{Si}}{P_{Ni} + P_N / G} < \text{SNR}_i, \]
where \( P_{So} \) = output signal power, \( P_{No} \) = output noise power, \( P_N \) = internally-generated noise power, and \( G \) = gain of the stage (in factor, not dB, form)

- standard noise factor \( F \)
  - standard input noise power: 
    \[ P_{Ni} = kT_o B, \]
    where \( k \) = Boltzmann’s constant (1.38 × 10^{-23} J/K), \( T_o \) = standard room temperature (290 K), and \( B \) = bandwidth of stage or system (narrowest)
  - \( F = 1 + \frac{P_N}{GkT_o B} \) or 
    \[ P_N = (F - 1)GkT_o B \]
  - noise factor is always \( > 1 \)

- standard noise figure (NF): \( \text{NF} = 10 \log(F) \)

- overall standard noise factor
  - \( F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \ldots + \frac{F_N - 1}{G_1G_2 \cdots G_{N-1}} \)
  - 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 in ratio form)

Nonlinear behavior of amplifiers (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 \( a_1, a_2, a_3, \ldots \) are constants
  - 1st-order products are linear outputs
  - 2nd-order, 3rd-order, etc. are intermodulation products
  - dB levels of 2nd-order products increase \( \text{two} \) 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 \( \text{three} \) 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 P3), referred to input or output (assume output if not specified)
  - 1-dB or 3-dB compression point (or compression level)
  - IMD products usually troublesome only when they emerge from noise floor of amplifier
  - 3rd-order products are of most concern because the signals that cause them can pass through front-end filter of receiver or amplifier

Minimum detectable signal (MDS)
- defined as the input noise floor; given by \( \overline{P}_{No} \) (output noise referred to input) plus min. acceptable SNR (if expressed in dB)
- min. acceptable SNR is often specified as 0 dB but could be any value, depending on modulation, signal integrity requirements, etc.
- related to noise factor by \( \text{MDS(Watts)} = kT_o BF \times \text{SNR} \) (SNR in factor form)
- related to noise figure by:

\[
\text{MDS[dBm]} = 10 \log \left( \frac{kT_o}{0.001} \right) + 10 \log(B) + \text{NF} + \text{SNR[dB]}
\]

- \[10 \log \left( \frac{kT_o}{0.001} \right) = -174 \text{ dBm}\]

Dynamic range of amplifiers and receiver systems
- blocking dynamic range: \[\text{BDR}_{1_{\text{dB}}} = P_{i,n,1_{\text{dB}}} - \text{MDS[dBm]},\] where \(P_{i,n,1_{\text{dB}}}\) is the input power level at the 1-dB compression point; MDS is the minimum detectable input signal
- “two-tone” third-order, or spurious-free, dynamic range:

\[\text{SFDR} = \frac{2}{3} \left( \text{IP3}_{n} - \text{MDS} \right),\] where \(\text{IP3}_{n}\) is the third-order input intercept point;

all quantities are in dBm or dB
- MDS = \(kT_oBF\) (i.e., output noise referred to input) usually, but could be higher if min. acceptable output SNR greater than 0 dB is required

Relevant coursework, textbook sections, and supplemental material:

Homework: #3 through #5
Labs: #3 through #4
Textbook: Secs. 3.4, 6.2, 6.3, 6.5, 10.11, 10.13
  “Mixer Circuits and Image Frequencies”
  “Basic Filter, Part 1 – Low-Pass Filters”
  “Basic Filter, Part 2 – High-Pass Filters”
  “Basic Filter, Part 3 – Band-Pass Filters”
  “Basic Filter, Part 4 – Coupled-Resonator Filters”
excerpt “Noise in Microwave Circuits” from D. Pozar, *Microwave and Wireless Systems*
excerpt “Dynamic Range and Intermodulation Distortion” from D. Pozar, *Microwave and Wireless Systems*
Notes on Amplifier Nonlinearity and Intermodulation Distortion