ECEG 497/697 **Wireless System Design** **Spring 2025**

Policies and Review Topics for Exam #2

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 two 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.**

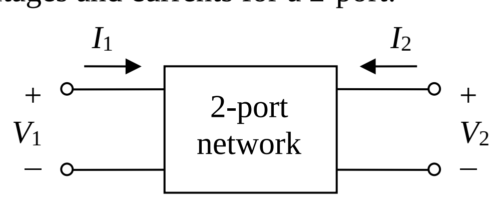
The exam will begin at 7:00 pm on Thursday, March 27 in Breakiron 264 (our usual classroom). You will have until 9:00 pm to complete the exam.

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 sheet for the previous exam.

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 authorities in all factual matters, unless errors have been specifically identified there. You are ultimately responsible for obtaining accurate information when preparing for your exam.

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; can also represent power relationships
- definitions of port voltages and currents for a 2-port:



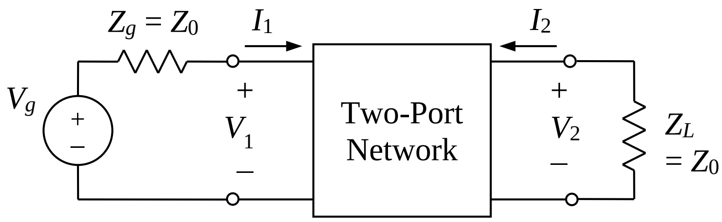
- Z (or impedance or open-circuit) parameters:
  - system of equations (2-port): $\begin{aligned} V_1 &= Z_{11} I_1 + Z_{12} I_2 \\ V_2 &= Z_{21} I_1 + Z_{22} I_2 \end{aligned}$
  - calculation of coefficients: $Z_{ij} = \left. \dfrac{V_i}{I_j} \right|_{I_{\bar{j}}=0}$, where $I_{\bar{j}} = 0$ indicates that all port currents except the *j*th are set to zero (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; often not safe in a real-world setting, and true opens are difficult to achieve because of stray impedance
- Y (or admittance or short-circuit) parameters:
  - system of equations (2-port): $\begin{aligned} I_1 &= Y_{11} V_1 + Y_{12} V_2 \\ I_2 &= Y_{21} V_1 + Y_{22} V_2 \end{aligned}$
  - calculation of coefficients: $Y_{ij} = \left. \dfrac{I_i}{V_j} \right|_{V_{\bar{j}}=0}$, where $V_{\bar{j}} = 0$ indicates that all port voltages but the *j*th are set to zero (subscript *j* with bar over it means "not")
  - measurements and/or calculations of Y parameters require *short*-circuit port terminations; often not safe in a real-world setting, and true shorts are difficult to achieve because of stray impedance
- S (scattering) parameters:
  - general system of equations (2-port): $\begin{aligned} V_{1R} &= S_{11} V_{1I} + S_{12} V_{2I} \\ V_{2R} &= S_{21} V_{1I} + S_{22} V_{2I} \end{aligned}$,

    alternate definition used in general literature: $\begin{aligned} b_1 &= S_{11} a_1 + S_{12} a_2 \\ b_2 &= S_{21} a_1 + S_{22} a_2 \end{aligned}$

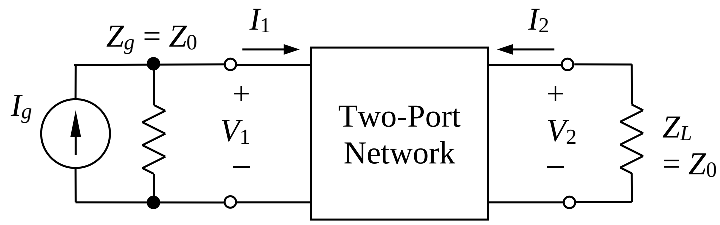
    where $a_i = \dfrac{V_{iI}}{\sqrt{Z_{0i}}}$ (normalized incident or incoming voltage wave),

    and $b_i = \dfrac{V_{iR}}{\sqrt{Z_{0i}}}$ (normalized "scattered," "reflected," or outgoing voltage wave)
  - If all port impedances are the same, then $S_{ij} = \left. \dfrac{V_{iR}}{V_{jI}} \right|_{V_{\bar{j}I}=0}$ (frequently true)
  - general calculation of coefficients: $S_{ij} = \left. \dfrac{b_i}{a_j} \right|_{a_{\bar{j}}=0}$, where $a_{\bar{j}} = 0$ indicates that all incident voltages but the *j*th are set to zero
  - measurements and/or calculations of S parameters require port terminations that are *matched* to the reference impedance; usually much easier to accomplish in a real-world setting than using shorts or opens as terminations
  - forward and reflected voltage waves are easier to measure than terminal voltages and currents at high frequencies; terminal voltages and currents are impossible to measure accurately in the microwave & millimeter-wave ranges and higher

- system configurations used to determine S-parameters using (a) Thévenin equivalent and (b) Norton equivalent representation of the signal source:



(a)



(b)

- definitions more useful for circuit analysis:

$$S_{11} = \left.\frac{2V_1}{V_g} - 1\right|_{Z_{L2}=Z_0} = \Gamma_1\big|_{Z_{L2}=Z_0} \qquad S_{12} = \left.\frac{2V_1}{V_g}\right|_{Z_{L1}=Z_0}$$

$$S_{21} = \left.\frac{2V_2}{V_g}\right|_{Z_{L2}=Z_0} \qquad S_{22} = \left.\frac{2V_2}{V_g} - 1\right|_{Z_{L1}=Z_0} = \Gamma_2\big|_{Z_{L1}=Z_0}$$

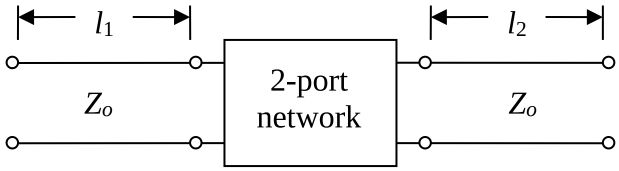
  where V_1 and V_2 are the total (actual) voltages at ports 1 and 2, respectively, V_g is the Thévenin equivalent generator voltage; and Γ_1 and Γ_2 are the reflection coefficients seen by sources connected to ports 1 and 2, respectively.
- alternate definitions using port currents:

$$S_{11} = 1 - \left.\frac{2I_1Z_0}{V_g}\right|_{Z_{L2}=Z_0} \qquad S_{12} = -\left.\frac{2I_1Z_0}{V_g}\right|_{Z_{L1}=Z_0}$$

$$S_{21} = -\left.\frac{2I_2Z_0}{V_g}\right|_{Z_{L2}=Z_0} \qquad S_{22} = 1 - \left.\frac{2I_2Z_0}{V_g}\right|_{Z_{L1}=Z_0}$$

  where I_1 and I_2 are the total (actual) currents at ports 1 and 2, respectively, and I_g is the Norton equivalent generator current.
- measurements and/or calculations of S parameters require *impedance-matched* port terminations
- interpretation of S parameters
  - on-diagonal parameters are the voltage reflection coefficients if other ports are match-loaded
  - off-diagonal parameters are gains/attenuations for matched conditions
  - S parameters are *voltage* ratios, not *power* ratios; magnitudes are often expressed in dB

- de-embedding (modification of S-parameters due to addition of lossless line lengths):



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

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

makes possible the practical use of vector network analyzers

- relationships between matrix representations
  - $[Z] = [Y]^{-1}$
  - $[S] = ([Y_0]+[Y])^{-1}([Y_0]-[Y])$, only if reference admittances for all ports are the same, where $[Y_0]$ is a diagonal matrix w/reference admittances
  - $[S] = ([Z]+[Z_0])^{-1}([Z]-[Z_0])$, only if reference impedances for all ports are the same, where $[Z_0]$ is a diagonal matrix w/reference impedances
  - $[Z] = Z_0([I]+[S])([I]-[S])^{-1}$
- if reciprocity applies (not always the case): $Z_{ij} = Z_{ji}$, $Y_{ij} = Y_{ji}$, and $S_{ij} = S_{ji}$

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 that always operate at a single frequency
- superheterodyne
  - dominant modern architecture
  - major advantage is that IF filter and IF 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 (10 log vs. 20 log)
- 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
- differences in power levels expressed in dBm or dBW should be expressed in dB (e.g., 20 dBm – 5 dBm = 15 dB, not 15 dBm)

Relevant course material:

Homework: #3, #4, and #5
Mini-Projects: [none]
Reading: Assignments from Feb. 17 through Mar. 21, including the supplemental readings
“Matrix Representations of Networks: Z, Y, and S-Parameters”
“Mixer Circuits and Image Frequencies”
“Analog Multipliers Employing the Bipolar Transistor” (skim only)
“Why Do Engineers Use the Decibel Unit?”

This exam will focus primarily on course outcome(s) listed below and related topics (like filters):

2. Recognize and analyze basic receiver and transmitter system architectures.
3. Predict the frequency translation properties and image response of a frequency mixer circuit.
4. Calculate the S parameters of a linear two-port network given its circuit diagram.

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.