ECEG 497 Wireless System Design Spring 2023

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 and that is not included on the table and formula sheet that I will provide, 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 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 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.

Realistic models of resistors, inductors, and capacitors

- stray (parasitic) resistance, inductance, and capacitance
- component models
- behavior of components at high frequencies (above intended freq. range)
- self-resonances of inductors/capacitors
- inductors often have troublesome resistance even at low frequencies → low Q

Skin effect (increased resistance of wires at high frequencies)

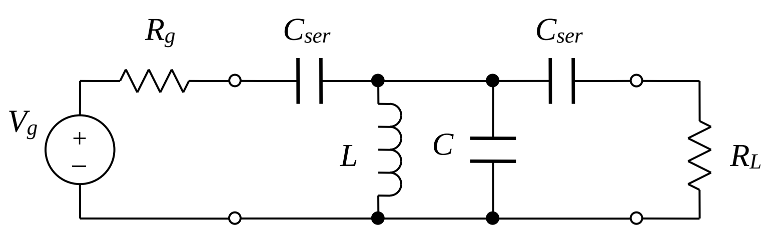
Filters

- concept of available power and its calculation
- simple one-pole low-pass filters:
    - fraction of available power (P_A) delivered to load (P_L), assuming real source and load impedances:
      $$\frac{P_L}{P_A} = \frac{4R_g R_L}{\left(R_g + R_L\right)^2}\left[\frac{1}{1+\left(\omega/\omega_c\right)^2}\right]$$
    - series inductor: $\omega_c = \dfrac{R_g + R_L}{L}$
    - parallel capacitor: $\omega_c = \dfrac{1}{\left(R_g \| R_L\right)C}$
    - stop-band roll-off = –20 dB/decade (–6 dB/octave)

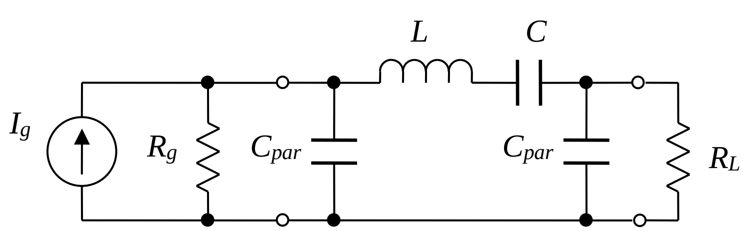
- simple one-pole high-pass filters:
  - fraction of available power delivered to load:
    $$\frac{P_L}{P_A} = \frac{4R_g R_L}{(R_g + R_L)^2}\left[\frac{(\omega/\omega_c)^2}{1+(\omega/\omega_c)^2}\right]$$
  - parallel inductor: $\omega_c = \frac{R_g \| R_L}{L}$
  - series capacitor: $\omega_c = \frac{1}{(R_g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

Coupled-resonator band-pass filters

- goal: maximize stored energy relative to energy dissipated per cycle (i.e., maximize Q) to achieve narrower passband with reasonable component values
- provide larger Q (narrower bandwidth) for given resonator reactances than with simple band-pass filters that do not use coupling components
- parallel LC resonators with series coupling (usually by capacitors); a.k.a. top coupling



- series LC resonators with shunt coupling (usually by capacitors)

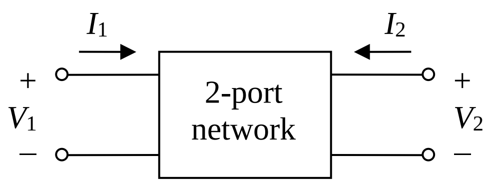


- difference between "network" Q (Q_{net}) and "series-parallel transformation" Q (Q_t)
- coupling capacitors usually preferred over coupling inductors; however, coupling inductors can help ensure good roll-off on both sides of passband.

- impedance-matching transformers can be used instead of coupling capacitors (or inductors) to increase/decrease apparent source/load resistances, but they are heavier, bulkier, and lossier than capacitors. Advantage of transformers: broadband impedance transformation

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:



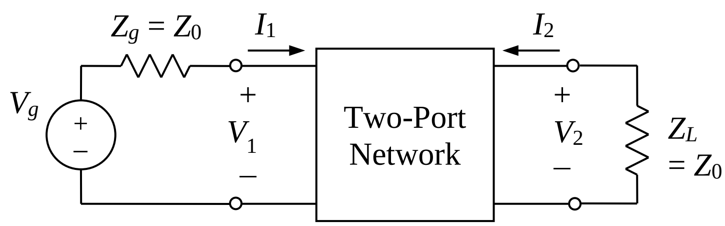
- Z (or impedance or open-circuit) parameters:
  - system of equations (2-port): $$V_1 = Z_{11}I_1 + Z_{12}I_2$$ $$V_2 = Z_{21}I_1 + Z_{22}I_2$$
  - calculation of coefficients: $Z_{ij} = \left.\frac{V_i}{I_j}\right|_{I_{\bar{j}}=0}$, where $I_{\bar{j}} = 0$ is for all port currents except the *j*th (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 to do in a real-world setting)
- Y (or admittance or short-circuit) 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: $Y_{ij} = \left.\frac{I_i}{V_j}\right|_{V_{\bar{j}}=0}$, where $V_{\bar{j}} = 0$ is for all port voltages but the *j*th
  - measurements and/or calculations of Y parameters require *short*-circuit port terminations (often not safe to do in a real-world setting)
- S (scattering) parameters:
  - general system of equations (2-port): $$V_{1R} = S_{11}V_{1I} + S_{12}V_{2I}$$ $$V_{2R} = S_{21}V_{1I} + S_{22}V_{2I},$$

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

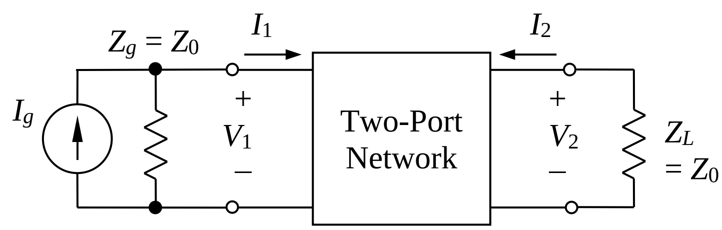
    where $a_i = \frac{V_{iI}}{\sqrt{Z_{0i}}}$ (normalized incident or incoming voltage wave),

    and $b_i = \frac{V_{iR}}{\sqrt{Z_{0i}}}$ (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 $a_{\bar{j}} = 0$ is for all incident voltages but the *j*th
- 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:

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

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

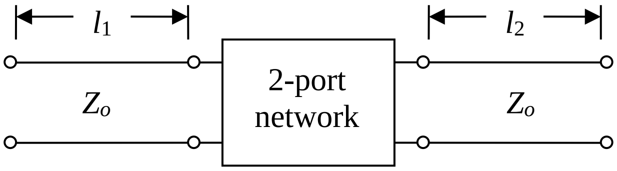
  where V_1 and V_2 are the total (actual) voltages at ports 1 and 2, respectively, V_g is the Thévenin equivalent generator voltage; and Γ_1 and Γ_2 are the reflection coefficients seen by sources connected to ports 1 and 2, respectively.
- alternate definitions using port currents:

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

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

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



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

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 are often expressed in dB
- relationships between matrix representations
    - $[Z] = [Y]^{-1}$
    - $[S] = ([Y_0] + [Y])^{-1}([Y_0] - [Y])$, where $[Y_0]$ is a diagonal matrix w/port admittances
    - $[S] = ([Z] + [Z_0])^{-1}([Z] - [Z_0])$, only if all port impedances are the same, where $[Z_0]$ is a diagonal matrix w/port 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 $S_{ij} = S_{ji}$

<u>Relevant course material:</u>

Homework: #3, #4, and #5
Mini-Projects: [none]
Reading: Assignments from Feb. 8 through Feb. 27, including the supplemental readings
"Basic Filters, Part 1: Low-Pass Filters"
"Basic Filters, Part 2: High-Pass Filters"
"Basic Filters, Part 3: Band-Pass Filters"
"Basic Filters, Part 4: Coupled-Resonator Filters"
"Matrix Representations of Networks"

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

4. Calculate the S-parameters of a given linear two-port network.

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.