EE4-18
EE9-AO6

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2017

MSc and EEE PART IV: MEng and ACGI

Corrected copy

RADIO FREQUENCY ELECTRONICS

Tuesday, 16 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : S. Lucyszyn

Second Marker(s) : A.S. Holmes

Special instructions for invigilators

This is a closed book examination.

Special instructions for students

All variable have their usual meaning.

The Questions

1.

a) At frequencies below 1 GHz:

i) Briefly explain the advantages and disadvantages of using lumped-element components within integrated circuits and state the general frequency behaviour of this solution.

[2]

ii) Briefly explain the advantages and disadvantages of using distributed-element components within integrated circuits and state the general frequency behaviour of this solution.

[2]

iii) What is the dominant noise contribution at the input to a receiver? State its origin and general frequency behaviour. What can be observed when an analogue AM receiver switches bands?

[2]

iv) What ubiquitous application is found just below 1 GHz? In general, for this application, where would you expect to find the lumped- and distributed-element solutions within a complete end-to-end system?

[2]

b) At frequencies above 1 GHz and below 300 GHz:

i) Do the passive and active technologies use photonic or electronic or thermal solutions for implementing integrated circuits? State the general frequency behaviour of the solution.

[2]

ii) What is the dominant noise contribution at the input to a receiver and state its origin and general frequency behaviour?

[2]

iii) What commercial application is found at 250 GHz? Briefly explain why this application is at this frequency and why system performance can degrade below and above this frequency.

[2]

c) At frequencies above 300 GHz and below 10 THz, briefly explain the disadvantages and a possible solution associated with:

i) Passive components.

[2]

ii) Active components.

[2]

iii) Atmospheric attenuation.

[2]

2. Consider an Earth-Space path link through a pristine and homogeneous atmosphere, as shown in Figure 2.1.

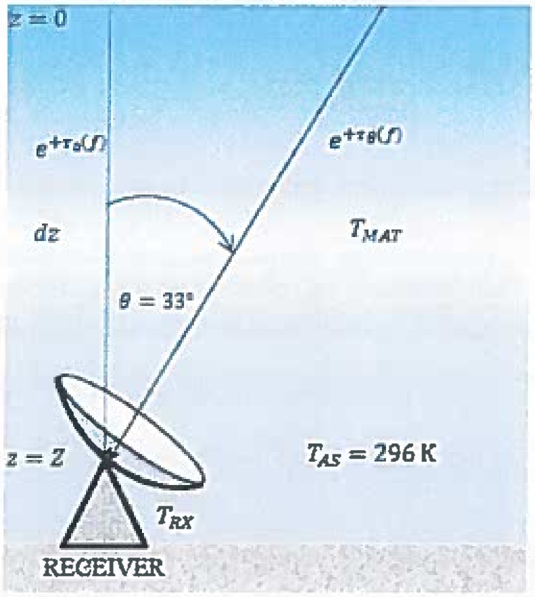

Figure 2.1. Ground-based receiver with 33° zenith angle.

a) Using the principle of conservation of energy, mathematically define transmittance, absorptance and reflectance for a non-opaque medium.

[2]

b) Define specific attenuation, in terms of atmospheric loss factor, opacity, extinction coefficient and path length.

[2]

c) Using the information given in Figure 2.1, derive from first principles the sky brightness temperature for all source contributions. Clearly state any simplifying assumptions.

[6]

d) From Figure 2.1 and the derivation in 2(c), draw the equivalent noise temperature model, clearly labelling all parameters.

[2]

e) Derive an expression for the carrier-to-noise power ratio at the input to a noisy receiver within a vacuum atmosphere $C_{\theta V}/N_{\theta V}$.

[2]

f) Derive an expression for the carrier-to-noise power ratio at the input to a noisy receiver considering both molecular absorption and emission within the Earth's atmosphere C_θ/N_θ.

[2]

g) Calculate the reduction of C/N in dB at the receiver when both molecular absorption and emission are included, given: $T_{MAT} = 0.95T_{AS}$, a 90% transmittance through the atmosphere and a receiver having a noise temperature of 100 K.

[4]

3. You are required to design an impedance matching network that can transform the system reference impedance $Zo = 50\,\Omega$ to resistance $R = 0.5\,\Omega$, at 1 GHz, using L-matching networks having N stages. Any non-ideal lumped element will have an unloaded Q-factor of $Q_u = 30$, and the overall network will have an insertion loss IL given by equation (3.1):

$$IL = \frac{1}{1+N\frac{Q_{Network}}{Q_u}} \tag{3.1}$$

a) For a lossless 2 lumped-element matching network:

i) Draw the equivalent circuit model for a complete network that can take advantage of any possible dual uses for its lumped elements and state what these additional topological advantages may be. [2]

ii) Write the expression for the network Q-factor. [1]

iii) Calculate the component values for each element. [2]

b) For a lossless 4 lumped-element matching network:

i) Draw the equivalent circuit model for the complete network. [2]

ii) Write the expression for the optimum network Q-factor. [2]

c) For a lossless 8 lumped-element matching network:

i) Draw the equivalent circuit model for the complete network. [1]

ii) Write the expression for the optimum network Q-factor. [1]

d) In terms of N-stages:

i) From 3(a)(ii), 3(b)(ii) and 3(c)(ii), write the general expression for the optimum lossless network Q-factor and its associated bandwidth. [2]

ii) For $N \in [1, 2, 3, 4, 5, 6]$, calculate the optimum Q-factor and the associated bandwidth for a lossless network. [2]

iii) What interesting behaviour can be seen as bandwidth changes with N and explain the analogy with free space when taken to its limit. [2]

iv) For $N \in [1, 2, 3, 4, 5, 6]$, calculate the insertion loss in dB if non-ideal lumped elements are used. [2]

v) What interesting behaviour can be seen as IL changes with N and explain the reason for this? [1]

4. A uniform transmission line of physical length T, having characteristic impedance Z_{TX} and propagation constant $\gamma = \alpha + j\beta$, is connected between two subsystems having port impedances equal to the system reference impedance Zo. A transmission line without reflections has a voltage-wave transmission coefficient of $e^{-\gamma T}$. An infinitely long transmission line has an input voltage-wave reflection coefficient ρ_1. Note the following mathematic identity:

$$\sum_{m=0}^{\infty} A^m = \frac{1}{1-A} \qquad (4.1)$$

a) Given $Z_{TX} \neq Zo$, with the aid of a sketch, derive from first principles the:

   i) Closed-form expression for the overall voltage-wave transmission coefficient in terms of ρ_1 and $e^{-\gamma T}$ only.

   [5]

   ii) Closed-form expression for the overall voltage-wave reflection coefficient in terms of ρ_1 and $e^{-\gamma T}$ only.

   [5]

b) Given a quarter-wavelength lossless transmission line, using the derivations from 4(a):

   i) Simplify the expression for overall voltage-wave transmission coefficient and calculate the overall insertion loss in dB, given $Z_{TX} = 291\ \Omega$ and $Zo = 50\ \Omega$.

   [3]

   ii) Simplify the expression for overall voltage-wave reflection coefficient and calculate the overall return loss in dB, given $Z_{TX} = 291\ \Omega$ and $Zo = 50\ \Omega$.

   [3]

   iii) Prove that the principle of conservation of energy is observed.

   [2]

c) With the aid of sketches, illustrate what happens to the frequency response of the overall system when the length of an impedance mismatched interconnecting transmission line increases and explain why.

   [2]

5. With a given filter order n, the element values for the Butterworth low pass prototype can be calculated using equation (5.1):

$$g_o = 1.0$$
$$g_i = 2\sin\left(\frac{(2i-1)\pi}{2n}\right) \quad for\ i = 1\ to\ n \qquad (5.1)$$
$$g_{n+1} = 1.0$$

a) Design a 5-pole LC Butterworth bandpass filter with a passband from 2.4 to 2.5 GHz and terminating impedance of 50 Ω. The first and last components should be series elements. Explain why there is a large variation in component values and suggest a way to avoid this.

[10]

b) Show mathematically, from first principles, how a shunt RLC tuned circuit can replace a series RLC tuned circuit by employing admittance (J)-inverters. How can the admittance inverters be implemented with lumped-element components.

[6]

c) Using a capacitive J-inverter:

i) What would be an appropriate value for J^2 and why? For the example in 5(a), calculate the appropriate modulus value for the capacitance in the admittance inverter.

[2]

ii) Explain what happens to the negative capacitances?

[1]

iii) For the example in 5(a), what action can be taken to avoid unwanted resonances at high frequencies caused by parasitics?

[1]

6. a) Derive, from first principles, the general radar range equation. Assume the following lossless system:

- The transmitter has an input power P_T feeding an antenna having a power gain G_T that is located at a range R_T from the target.
- The target has a radar cross section σ.
- The receiver has an input power P_R delivered by an antenna having a power gain G_R that is located at a range R_R from the target.

[5]

b) Two amateur radio enthusiasts, living 1 km apart, communicate at 432 MHz using the overhead moon as a passive satellite (i.e. a reflecting target). The distance to the moon from both enthusiasts is $R_M = 381{,}500$ km and the diameter of the moon is $D_M = 3{,}500$ km. Neglect the effects of the earth's atmosphere.

i) If identical lossless paraboloidal reflector antennas are used at both locations, calculate the power gain in dBi of the antennas if they have a diameter of 9 m. Note that for an ideal lossless paraboloidal reflector antenna its directivity D_o is given by:

$$D_o = 4\pi \frac{Aperture\ Area}{\lambda^2} \qquad (6.1)$$

[3]

ii) Comment on the resulting beam efficiency for this application, when considering the angle that the moon subtends as seen by an observer on the earth, if the -3 dB beam width θ is given by:

$$\theta = \sqrt{\frac{4\pi}{D_o}} \qquad (6.2)$$

[3]

iii) With $P_T = 20$ dBW, calculate the power at the receiver. As a first order approximation, assume that the moon's radar cross-section can be modelled as a perfectly reflecting flat circular disc.

[3]

iv) With an antenna temperature $T_A = 100$ K and a receiver noise temperature $T_{RX} = 75$ K, calculate the carrier-to-noise power ratio at a receiver having a final IF bandwidth of 7 kHz. Boltzmann's constant $k = 1.38 \times 10^{-23}$ W/Hz/K.

[3]

v) Calculate the minimum possible propagation delay time between the two ground stations if both antennas suffer from unwanted side lobes.

[3]