THE UNIVERSITY OF ADELAIDE AUSTRALIA

EXAMINATION FOR THE DEGREE OF B.E. and M.E.

Semester 2 2009

101908 OPTICAL COMMUNICATION ENGINEERING (Elec Eng 4041)
105302 SPECIAL STUDIES IN MARINE ENGINEERING (Elec Eng 7072)

Official Reading Time: 10 mins
Writing Time: 180 mins
Total Duration: 190 mins

Instructions:

- This is a closed book examination.
- Attempt **ALL** SIX questions.
- All questions carry equal marks; part marks are given in brackets where appropriate.
- Begin each answer on a new page.
- Examination materials must not be removed from the examination room.
- **ANSWERS TO QUESTIONS SHOULD BE EXPRESSED CLEARLY AND WRITTEN LEGIBLY. THESE ASPECTS OF PRESENTATION WILL BE TAKEN INTO ACCOUNT IN ASSESSMENT. IN PATRICULAR, YOU ARE ASKED TO CLEARLY HIGHLIGHT YOUR ANSWERS WITH A DOUBLE UNDERLINE, OTHERWISE MARKS MAY BE DEDUCTED.**

Materials:

- One Book
- The use of calculators is permitted, this equipment to be supplied by the candidate. No pre-recorded material nor calculator instruction book is permitted, and calculators with remote communication links will be barred from the examination room.
- Formulae sheets (3 pages) are attached at the end of the paper.

DO NOT COMMENCE WRITING UNTIL INSTRUCTED TO DO SO.

Question 1 begins on page 2

Question 1:

Consider a heterodyne receiver for a digital optical fibre communications system.

(a) Briefly explain how a heterodyne receiver detects phase, given that photodetectors can only detect amplitude or optical power.

(2 marks)

(b) What type of modulation scheme can a heterodyne system permit that is not otherwise achievable with direct detection using a standard receiver?

(1 mark)

(c) State the key advantage of phase detection over amplitude detection.

(1 mark)

(d) Heterodyne receivers offer increased sensitivity. Briefly state why.

(1 mark)

(e) Using a heterodyne receiver, compute the local-oscillator (LO) power required to make the SNR 1 dB *less* that the quantum limit. You may assume the IF bandwidth is 500 MHz and the received optic power is constant at 5 nW when a binary "1" is received. The dark current of the photodetector is I_D = 2 nA, and its responsivity is ρ = 0.5 A/W. Assume the temperature is 27ºC and a load resistance of 100 Ω.

(11 marks)

(f) If this were *not* a heterodyne system, then the receiver's bandwidth could be as small as 250 MHz. For this case determine the signal power required to achieve a SNR equal to that in part (e). (4 marks)

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.

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Question 2:

(a) A compact disc (CD) has several levels of error detection and correction. Provide a very brief description of the following, and explain their purpose:

(i) Eight to Fourteen Modulation (EFM)
(2 marks)

(ii) Reed-Solomon Code
(2 marks)

(iii) Interleaving
(2 marks)

(b) A DVD is a storage technology that provides sufficient data capacity and data rate to store high quality standard-definition video. Given that a conventional audio compact disc (CD) can store up to 73 minutes of audio, derive the approximate number of hours of standard definition TV (SDTV) video that a DVD can store using all its available layers.
(5 marks)

(c) Assume that one day we will have 10 billion homes on planet earth, each home having one phone on average. If these phones were to transmit simultaneously over one 4 MHz line, using frequency division multiplexing (FDM), what is the bandwidth required? Could a single optical beam, with a spectral wavelength λ = 1 μm, carry this multiplexed signal? (3 marks)

(d) Still using the same case of 10 billion phones and same spectral frequency, now assume digital modulation, with time division multiplexing (TDM) and a data rate of 64 kbps for each voice message. Demonstrate whether the single optical beam can carry this frequency or not.
(2 marks)

(e) A fibre telephone cable contains 144 fibres, at the T3 standard, implying each fibre is capable of carrying 672 voice messages. A conducting telephone cable contains 900 copper twisted pairs, and each pair can carry 24 messages. Compare the capacities of the fibre and conducting cables. How many of the conducting cables are required to equal the capacity of the fibre cable? Repeat the calculation if each fibre operates at the DS-4 standard (Note: DS-4 allows up to 4032 voice messages per fibre).
(4 marks)

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.

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Question 3:

A video signal having a bandwidth of 4.8 MHz is transmitted over a 10-km path. We want to design a system so that the SNR at the receiver is 48 dB. Analog modulation is used. Spectral wavelength used is $\lambda_0 = 1.3$ μm.

The receiver is an InGaAs PIN photodiode.
Responsivity; $\rho = 0.6$ A/W
Dark Current; $I_d = 5$ nA
Junction capacitance; $C_d = 5$ pF
Noise figure; $F = 2$ at 300 K
Assume 100% modulation ($m = 1$).

(a) Calculate the load resistor R_L for the receiver. Comment on why you would not use this value in practice. (2 marks)

(b) Assume the system is thermal noise limited and hence calculate the power needed at the photodiode receiver to achieve the specified SNR, using the value of R_L calculated in (a).
(6 marks)

(c) The available power from a laser diode source is $P_{ave} = 10$ mW. What is the available power budget left over for losses? (3 marks)

(d) Calculate the signal current. Assuming 4 V reverse bias on the photodiode, demonstrate if saturation and dark current will be negligible or not.
(4 marks)

(e) Calculate the thermal noise and shot noise powers, hence demonstrate if the assumption in (b) was justified or not. (5 marks)

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.

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Question 4:

Consider a single mode fibre operating at 1550 nm. The specification is to transmit 400 Mbps NRZ data over the 100 km fibre link with a bit error rate (BER) of 10^{-9} or better.

(a) Given that $\tau = 1/R_{NRZ}$ and allowing for the system rise time to be 70% of τ, compute the system rise time t_S.

(1 mark)

(b) Given a material dispersion of M = -20 ps/(nm x km) and a waveguide dispersion of M_g = 4.5 ps/(nm x km), compute the fibre rise time, t_F. The spectral linewidth is given as 0.15 nm.

(1 mark)

(c) If the rise time of the light source is $t_{LS} = 1\,\text{ns}$, find an upper limit on the photodetector rise time t_{PD}.

(4 marks)

(d) Assume a basic BJT amplifier circuit at the receiver. If the photodetector has a transit time limited rise time of $t_{TR} = 0.5\,\text{ns}$ and a junction capacitance of $C_d = 1\,\text{pF}$, calculate an upper limit on the load resistor.

(2 marks)

(e) Given that the fibre loss is 0.25 dB/km, the coupling efficiency to the fibre is 3 dB, there are two connectors with 1 dB loss each, there are 50 splices with 0.1 dB loss each and that the source power is 5 dBm, find the power at the receiver.

(2 marks)

(f) Calculate the optical power needed to achieve the specified BER assuming a quantum limited system. Comment on the result. You may assume dark current is negligible and therefore the expression for probability of an error $P_e = e^{-n_s}$ holds. The quantum efficiency of the detector is η = 0.7.

(4 marks)

(g) Now calculate the optical power needed to achieve the specified BER assuming a thermal limited system. Comment on the result. You may assume a detector responsivity of ρ = 1 A/W and a noise figure of F = 2. Room temperature conditions hold, thus let T = 300 K.

(6 marks)

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.

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Question 5:

(a) The power incident on a detector of light is 100 nW.

(i) Determine the number of photons per second incident on the detector if the wavelength is 800 nm (1.5 mark)

(ii) If we carried out the above calculation for a longer wavelength, briefly state if the number of photons per second goes up or down, and why? (1 mark)

(b) A T3 system running at 45 Mbps has a BER of 10^{-9}, compute the number of errors per minute. (0.5 mark)

(c) To operate properly, a particular fibre optic receiver requires -34 dBm of power. The system losses are 31 dB in total, from the light source to the receiver. Compute the power in mW that the light source needs to emit to meet the requirement. (2 marks)

(d) A cable contains 144 single-mode fibres, each operating at 2.3 Gb/s. How many digitised 64 kbps voice messages can be transmitted along this cable? (1 mark)

(e) What is the difference (in Watts) between -65 dBm and 65 dBm? (1 mark)

(f) A fibre system operates with a carrier wavelength of 1.55 μm. Suppose that the system can handle digital information at a rate equal to one-hundredth of one percent of the optical frequency. How many 20 Mbps HDTV compressed video channels can be multiplexed onto this fibre system? (2 marks)

(g) Prove that the power change γ in dB/km and the attenuation coefficient α are related by $\gamma = -8.685\alpha$, where α is given in the units of km^{-1}. (3 marks)

(h) Derive the dynamic range of a conventional compact disc (CD) in dB. (2 marks)

(i) A long fibre, of arbitrary length, has 10 optical amplifiers equally spaced along its length. The amplifiers are used to compensate loss due to fibre attenuation. You may assume that the amplifier gain exactly equals the loss due to fibre attenuation. Each amplifier has a 3 dB noise figure, the SNR at the transmitter is 10^8, and there is a 30 dB transmission loss between amplifiers along the fibre. Compute the SNR at the output of the fibre. (3 marks)

(j) A 1-Mb/s NRZ pulse train is transmitted along a shot-noise limited system at λ = 0.82 μm. The receiver has negligible dark current and an ideal quantum efficiency of unity. How many photons per bit must be incident on the photodetector if the desired BER is 10^{-4}? Compute the optic power incident upon the detector. (3 marks)

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.

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Question 6:

(a) Prove Johnson's thermal noise formula $\langle e_n^2 \rangle = 4kTR\Delta f$, where the symbols have all their usual meanings, by taking the following steps:

(i) Consider a resistor in parallel with a capacitor. Draw the equivalent circuit assuming the noisy resistor can be modelled by a single source in series with a lumped ideal resistor. Label the source $\langle e_n^2 \rangle$. Label the mean square noise across the capacitor Label the source $\langle v_n^2 \rangle$. Label the mean square noise current through the loop $\langle i_n^2 \rangle$. The angle brackets represent temporal averages.

(1 mark)

(ii) Apply Kirchhoff's voltage law (KVL) around the loop, and write down the equation in terms of time limited variables $e_n(t,\tau)$, $v_n(t,\tau)$ and $i_n(t,\tau)$, assuming that we sample these random signals for a finite time window of duration τ. Here we assume the window is sufficiently long and that stationarity holds. Briefly explain what stationarity means.

(2 marks)

(iii) Assuming this equation is free of delta functions, now write down the same equation in terms of window-limited Fourier transformed variables, $V_n(\omega,\tau)$ and $I_n(\omega,\tau)$.

(1 mark)

(iv) By substituting in the relation $I_n(\omega,\tau) = j\omega C V_n(\omega,\tau)$ and then applying Plancherel's theorem (i.e. the energy theorem), prove that,

$$\langle e_n^2 \rangle = \lim_{\tau\to\infty} \frac{1}{2\pi} \int_0^{+\infty} 2 \frac{|E_n(\omega,\tau)|^2}{\tau} d\omega . \qquad \text{(6 marks)}$$

(v) Explain why we cannot take the limit inside the integral without first taking ensemble averages. Now, by assuming the system is ergodic, i.e. $\lim_{\tau\to\infty} \langle e_n^2 \rangle_\tau = \overline{e_n^2}$, where the overbar indicates ensemble averaging, show that,

$$\langle e_n^2 \rangle = \frac{1}{2\pi} \int_0^{+\infty} S(\omega) d\omega$$

where $S(\omega)$ is the one-sided power spectral density (PSD).

(3 marks)

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(vi) Explain why for thermal noise, we can simply rewrite this expression as $\langle e_n^2 \rangle = \frac{1}{2\pi} S_0 \Delta\omega$, where S_0 is a constant PSD.

(1 mark)

(vii) By identical arguments to part (v), we can write down a similar expression for the mean square noise voltage across the capacitor as

$$\langle v_n^2 \rangle = \frac{1}{2\pi} \int_0^{+\infty} \lim_{\tau \to \infty} \frac{2\overline{V_n^2}}{\tau} \, d\omega .$$

Now, substitute this into $|V_n|^2 = \frac{|E_n|^2}{1 + (\omega RC)^2}$, and then show that

$$\langle v_n^2 \rangle = \frac{1}{2\pi} S_0 \frac{\pi}{2RC} .$$

(2 marks)

(viii) From the equipartition theorem you may assume that $\frac{1}{2} C \langle v_n^2 \rangle = \frac{1}{2} kT$. Use this relation to now finally arrive at the thermal noise formula.

(2 marks)

(b) A laser diode has a RIN of -135 dB/Hz. A receiver bandwidth of 1 GHz and a received average power of 20 μW.

(i) Compute the laser noise power at the receiver.

(1 mark)

(ii) Compute the average laser noise current if the detector has a responsivity of 0.3 A/W.

(1 mark)

END OF EXAMINATION QUESTIONS

You are reminded to clearly highlight your answers with a double underline, otherwise marks may be deducted.