Optical and Transport Networks

Prof. Stefano Bregni **III Exam 2022-23 – 9 June 2023**

Last and first name: *(capital letters)*
(signature)

Matriculation number:

NB: In any exercise, any answer not justified adequately, even with few words, will not be considered.

Problem 1

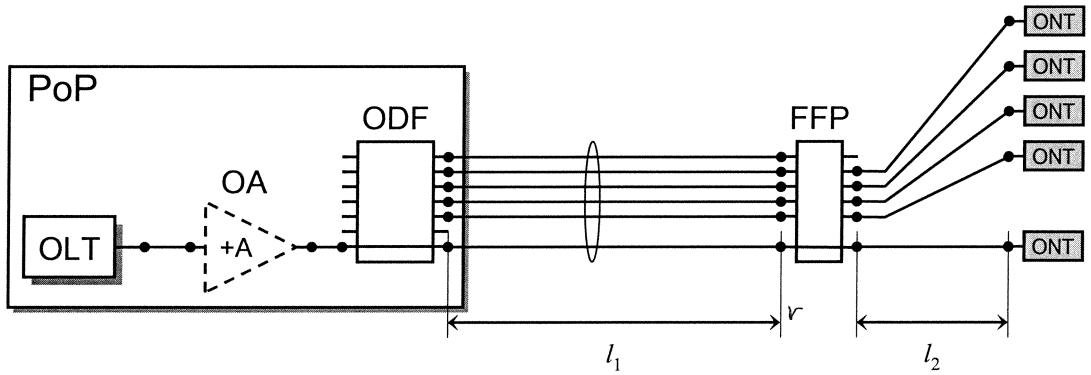
(Solve on this sheet in the space provided) (6 points)

Consider a Point-to-Point (P2P) network reaching 2000 users at variable distances from the Ethernet Optical Line Termination (OLT) according to the scheme in figure.

The line from the OLT is cross-connected via an Optical Distribution Frame (ODF) to the user lines. An Optical Amplifier (OA), if needed, may be added before the ODF at the Point-of-Presence (PoP). After a first feeder fibre segment with length l_1, another ODF (Fibre Flexibility Point, FFP) cross-connects to the users. The fibre segments between the FFP and the users have variable length in the range specified below. The length of other segments of fibres connecting network elements is negligible.

Assume the following data for the P2P network elements:

- fibre with attenuation $\alpha = 0.25$ dB/km;
- $l_1 = 2$ km, 500 m $\le l_2 \le 5$ km;
- OLT transmission power P_{TX};
- splitter insertion loss $\alpha_s = 1$ dB;
- power loss by each couple of optical connectors $\alpha_c = 0.5$ dB (connections marked with dots in figure);
- sensitivity of ONT receivers $P_{RX} > -33$ dBm, with at least 6 dB of safety margin to be guaranteed;
- optional OA gain $+A$ [dB] (excluding the additional attenuation $2\alpha_c$ introduced by its two couples of connectors);



a) Evaluate the maximum *Differential Path Loss* [dB] between ONTs.

b) Evaluate the power P_{RX} [W] received by the farthest ONT without OA if $P_{TX} = 500$ μW.

c) If the OLT transmission power is $P_{TX} = -1$ dBm and there is no OA, what is the maximum total distance $L = l_1 + l_2$ between the PoP and the users that can be covered?

d) The same P2P network is used to connect base stations of a cellular network. What is the maximum Time Alignement Error (TAE) between any couple of terminals (ONT) synchronized by the received signals, assuming all signals are synchronous on transmission? Explain your calculation. Do you expect that the TAE between ONTs is constant or may vary over time? Why?

a) $\Delta PL = \Delta l \alpha = (4.5\ \text{Km}) \cdot (0{,}25\ \text{dB/Km}) = 1{,}125\ \text{dB}$

b) $P_{TX} = -3.01\ \text{dBm}$ $P_{RX} = P_{TX} - 6\alpha_c - (l_1 + l_{2max})\alpha = -7{,}76\ \text{dBm} \simeq 167{,}5\ \mu\text{W}$

c) $P_{TX} - 6\alpha_c - L\alpha > -27\ \text{dBm} \rightarrow L > 92\ \text{Km}$

d) $\Delta L = 4{,}5\ \text{Km} \rightarrow \text{TAE} \le 22{,}5\ \mu\text{s}$

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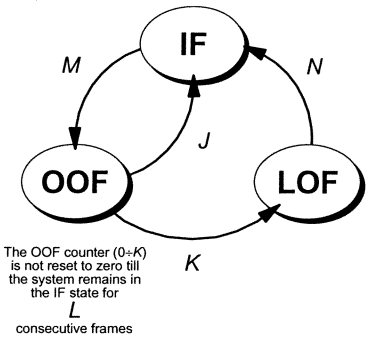
Problem 2

(Solve on this sheet in the space provided) (6 points)

Consider the standard SDH frame alignment algorithm, represented by the diagram below. The frame aligner operates on a test STM-1 framed signal at input (nominal frequency $f_0 = 155.520$ Mbit/s, frame length $L_m = 19440$ bit), with random content everywhere in all frames except the alignment word, which consists of X bits during hunting and 4 bits during maintenance. The test signal is affected by random transmission errors on the line, uncorrelated and with rate ε.

a) Let P_1 be the probability that the system, being aligned and in service (IF state), moves from Out-Of-Frame (OOF) to Loss-of-Frame (LOF) within 3 ms due to random transmission errors. What is the limit value of ε, in order to have $P_1 < 10^{-30}$?



$$P_1 = \left[1-(1-\varepsilon)^4\right]^{24} \cong (4\varepsilon)^{24} < 10^{-30}$$

$$\Rightarrow \varepsilon < 1.4 \cdot 10^{-2}$$

b) Let P_2 be the probability that the system, being in state Out-Of-Frame (OOF), regains alignment (IF state) within J frame periods, due to simulation of the alignment word by the random payload. What is the minimum value of J, in order to have $P_2 < 10^{-5}$?

$$P_2 = \left(\frac{1}{24}\right)^J < 10^{-5} \quad \Rightarrow \quad J \geq 4$$

c) Define and explain the concepts of *forced loss of alignment* vs. *real loss of alignment*.

d) Give a good reason to have N small and another to have N large.

Problem 3

(Solve on this sheet in the space provided) (6 points)

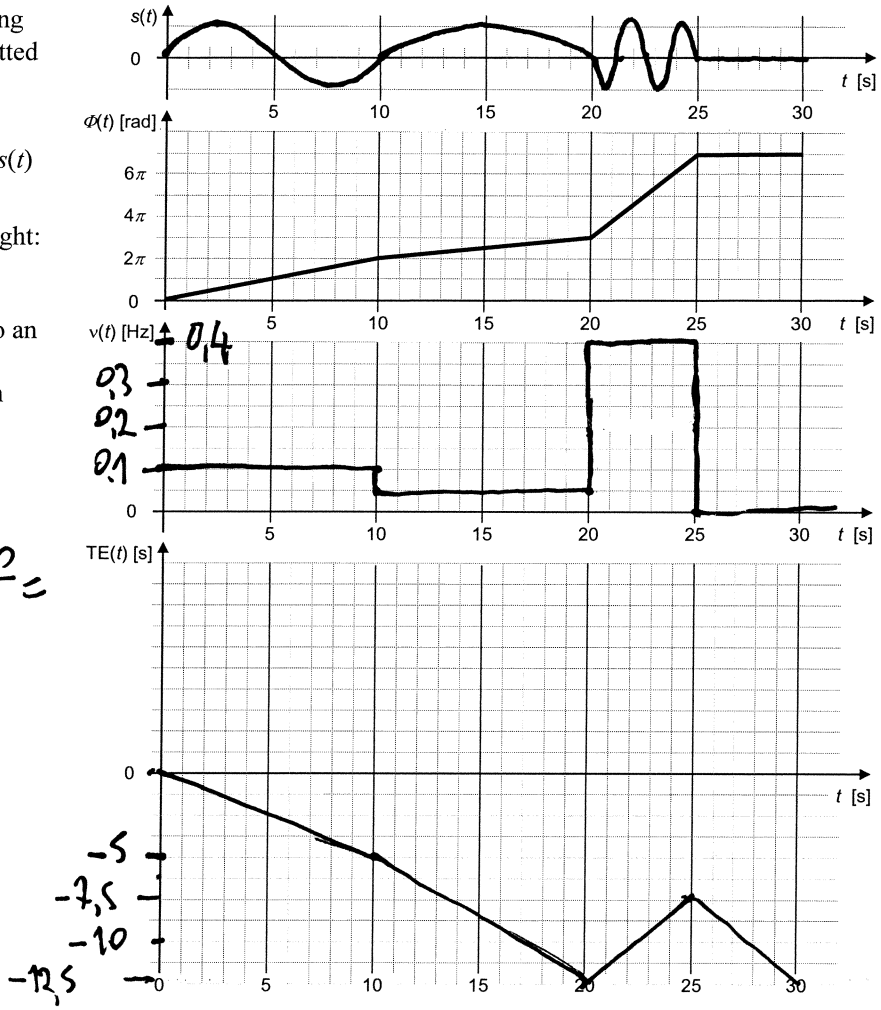
a) Let $s(t)$ be a pseudo-sinusoidal timing signal with *Total Phase* $\Phi(t)$ as plotted in figure.

- Calculate the average frequency of $s(t)$ over the interval $0 \le t \le 30$ s.

Where possible, plot on the graphs at right:
- the timing signal $s(t)$;
- the *instantaneous frequency* $\nu(t)$;
- the *Time Error* TE(t) with respect to an ideal reference timing signal with frequency $\nu_0 = 0.2$ Hz, starting from TE(0)=0, with the convention that positive TE denotes time advance.

$\overline{\nu(t)}\Big|_{0\le t\le 30} = \frac{3{,}5\ \text{cycles}}{30\ \text{s}} =$

$= 0{,}117\ \text{Hz}$



- b) Define the *Time Interval Error* of a clock generating the time $T(t)$ with respect to the ideal time t.

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Problem 4

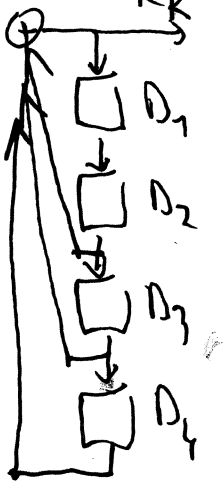
(Solve on this sheet in the space provided) (6 points)

a) Draw the scheme of a *self-synchronizing scrambler* with characteristic polynomial $P(x) = x^4 + x^3 + x^2 + 1$, fed with all "0"s and utilized as PRBS generator. Denote the bit sequence at the input as $\{I_k\} = \{0, 0, \ldots\}$ and the sequence at the output as $\{R_k\}$.

b) Initialize the delay cells D_i ($i = 1, 2, 3, 4$) as $\{0, 1, 1, 1\}$ at the initial step $k = 0$. Calculate the PRBS sequence $\{R_k\}$ generated at the output, highlighting its periodicity. What is its period P?

c) Verify whether $P(x)$ is reducible or irreducible. What is the maximum period that we could expect from this scrambler, considering the grade of its characteristic polynomial? More specifically, would you be able to state what are the possible values of its period?

a)



b)

k	I_k	D_{1k}	D_{2k}	D_{3k}	D_{4k}	R_k
0	0	0	1	1	1	1
1	0	1	0	1	1	0
2	0	0	1	0	1	0
3	0	0	0	1	0	1
4	0	1	0	0	1	1
5	0	1	1	0	0	1
6	0	1	1	1	0	0
7	0	0	1	1	1	1

$\Pi = 7$

c) $P(x) = x^4 + x^3 + x^2 + 1$

divisibile per $(x+1)$

$\Rightarrow P(x) = (x+1)(x^3 + x + 1)$

$x^4 + x^3 + x^2 + 1 \;|\; x+1$

$x^4 + x^3$ $\quad\quad x^3 + x + 1$

$x^2 + 1$

$x^2 + x$

$x + 1$

$x + 1$

//

$\Pi \leq 2^4 - 1 = 15$

If $P(x)$ irreducible:

$\Pi \in \{1, 3, 5, 15\}$

Problem 5

(Answer on this sheet in the space provided) (12 points)
NB: In any exercise, any answer not justified adequately, even with few words, will not be considered.

1) Consider a 10GbE signal transmitted over an optical fibre with refractive index $n = 1.6$ and length $L = 150$ km. Knowing that the coefficient of fractional variation of length vs. temperature of the fibre is $\frac{1}{l}\frac{\partial l}{\partial \theta} = +0.8 \cdot 10^{-6}$/K, calculate the peak-to-peak amplitude (expressed in [UI]) of the wander caused by fibre length variation induced by 15°C diurnal excursion of fibre temperature. *(2 points)*

$\tau = \frac{1}{v} = L\frac{n}{c} \rightarrow \Delta\tau = \Delta L \frac{n}{c}$

$\Delta L = +l\left(\frac{1}{l}\frac{\partial l}{\partial \theta}\right)\Delta\theta = (150\,\text{Km})(0{,}8 \cdot 10^{-6}/\text{K}) \cdot (15\,\text{K}) =$

$= 1{,}8\,\text{m}$

$\Delta\tau = 9.6\,\text{ns} = 9.6\,\text{UI}$

2) Define the *packet jitter* of a sequence of packets transmitted with constant rate $R = 1/T$ over a network. *(2 points)*

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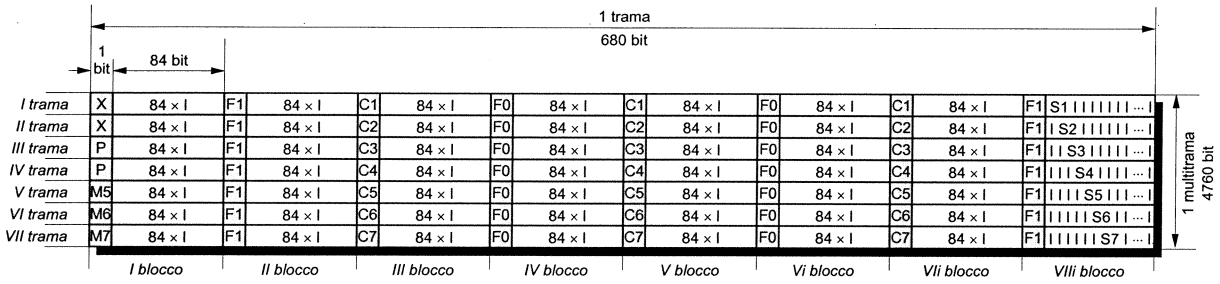
3) The figure below depicts the frame/multiframe structure of the North-American PDH signal DS3 (having nominal frequency $f_0 = 44.736$ Mbit/s), which multiplexes 7 tributaries DS2 ($f_0 = 6.312$ Mbit/s). Calculate the nominal justification ratio (defined as fraction of justification opportunity bits occupied by dummy bits). *(2 points)*



parola di allineamento di multitrama: M5, M6, M7 = 0, 1, 0
parola di allineamento di trama: F1, F0, F0, F1 = 1, 0, 0, 1
X = bit di servizio
P= bit di parità calcolato sulla multitrama precedente
I = bit di tributario
C1, C2, C3, C4, C5, C6, C7 = bit di controllo di giustificazione del tributario 1, 2, 3, 4, 5, 6, 7
S1, S2, S3, S4, S5, S6, S7 = bit opportunità di giustificazione del tributario 1, 2, 3, 4, 5, 6, 7

Translation notes:
multitrama = multiframe; trama = frame; blocco = block; parola di allineamento = alignment word; tributario = tributary; bit di opportunità di giustificazione = justification opportunity bit

$$\frac{672 - \rho}{4760} \cdot 44{,}736 \text{ Mb/s} = 6{,}312 \text{ Mb/s}$$

$$\Rightarrow \rho = 939{,}056$$

4) Describe the principle of *Bit Interleaved Parity* codes BIP(n,m). What is the purpose of interleaving? What is a reasonable criterion to determine the interleaving depth n? *(3 points)*

5) Define the efficiency η of bit error rate estimation by a BIP code. Explain why it is a decreasing function of the line bit error rate ε, from $\eta \to 1$ (for $\varepsilon \to 0$) to $\eta \to 0$. Why consecutive errors may affect negatively the efficiency of bit error rate estimation? *(3 points)*