Optical and Transport Networks

Prof. Stefano Bregni **II Exam 2023-24 – 2 February 2024**

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

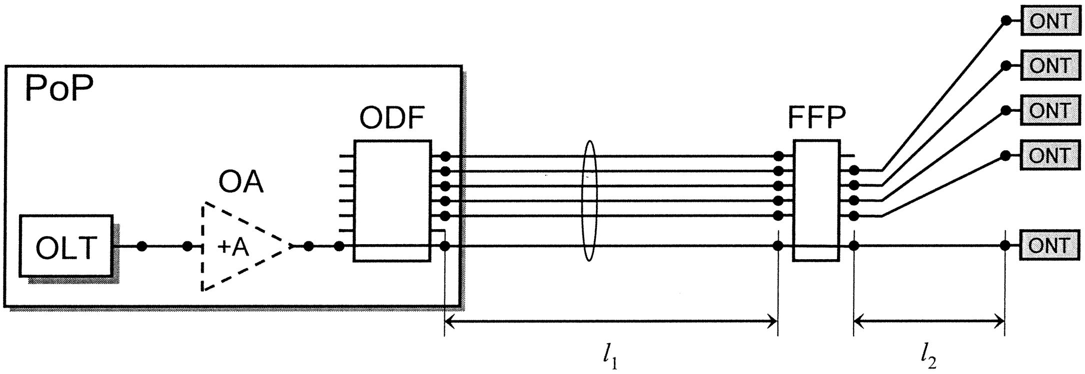
(Solve on this sheet in the space provided) (6 points)

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 $\alpha = 0.4$ dB/km;
- $l_1 = 15$ km, 500 m $\leq l_2 \leq 5$ 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 $P_{TX} = 2$ mW.

c) If the OLT transmission power is $P_{TX} = 2$ mW 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) max DPL $= \Delta l \alpha = (4.5 \text{ Km}) \cdot (0{,}4 \text{ dB/Km}) = 1{,}8$ dB

b) $P_{TX} = +3$ dBm . $P_{RX} = P_{TX} - 6\alpha_c - (l_1 + l_{2max})\alpha = -8$ dBm $= 0.16$ mW

c) $P_{TX} - 6\alpha_c - L\alpha > -27$ dBm $\rightarrow L > 67.5$ Km

d) $\Delta L = 4.5$ Km $\rightarrow$ TAE $\leq 22.5\,\mu s$

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Problem 2

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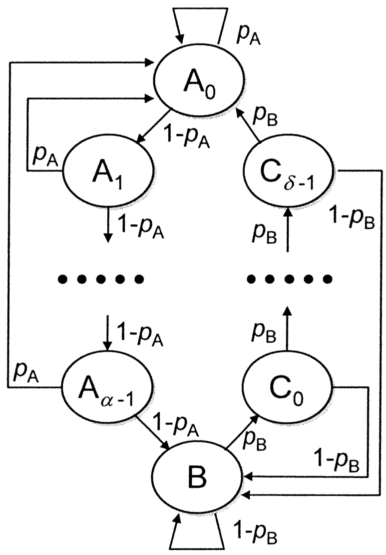
Consider the frame alignment algorithm represented by the diagram below (A_0 state: system aligned in service; B state: alignment lost). The frame aligner operates on a test PDH E4 framed signal at input (nominal frequency $f_0 = 139.264$ Mbit/s, frame length $L_m = 2928$ bit), with random content everywhere in all frames except the alignment word (12 bits during both hunting and maintenance). The test signal is affected by random transmission errors, uncorrelated and with rate ε. The values of the frame alignment parameters are $\alpha = 3$, $\delta = 2$.

a) Let the system be aligned and in service (A_0 state). What are the limit values of α and δ, in order to have the probability of *forced loss of alignment* less than 10^{-12}, if the line bit error rate is $\varepsilon = 10^{-9}$?



$P_A = (1-\varepsilon)^{12} \cong 1 - 12\varepsilon$

$P_{FL} = (1-P_A)^{\alpha} < 10^{-12}$

$(12\varepsilon)^{\alpha} < 10^{-12}$ $\quad \alpha \operatorname{Log}_{10}(12\varepsilon) < -12$

$\Rightarrow \alpha > 1{,}5 \Rightarrow \alpha \geq 2$

b) Let the system be out of alignment (B state). What are the limit values of α and δ, in order to have the probability of *fake alignment* less than 10^{-12}?

$P_B = \dfrac{1}{2^{12}} = 2.4414 \cdot 10^{-4}$

$P_{FA} = P_B^{\delta+1}$

$P_B^{\delta+1} < 10^{-12}$

$(\delta+1)\operatorname{Log}_{10} P_B < -12$

$\Rightarrow \delta > 2{,}3 \Rightarrow \delta \geq 3$

Problem 3

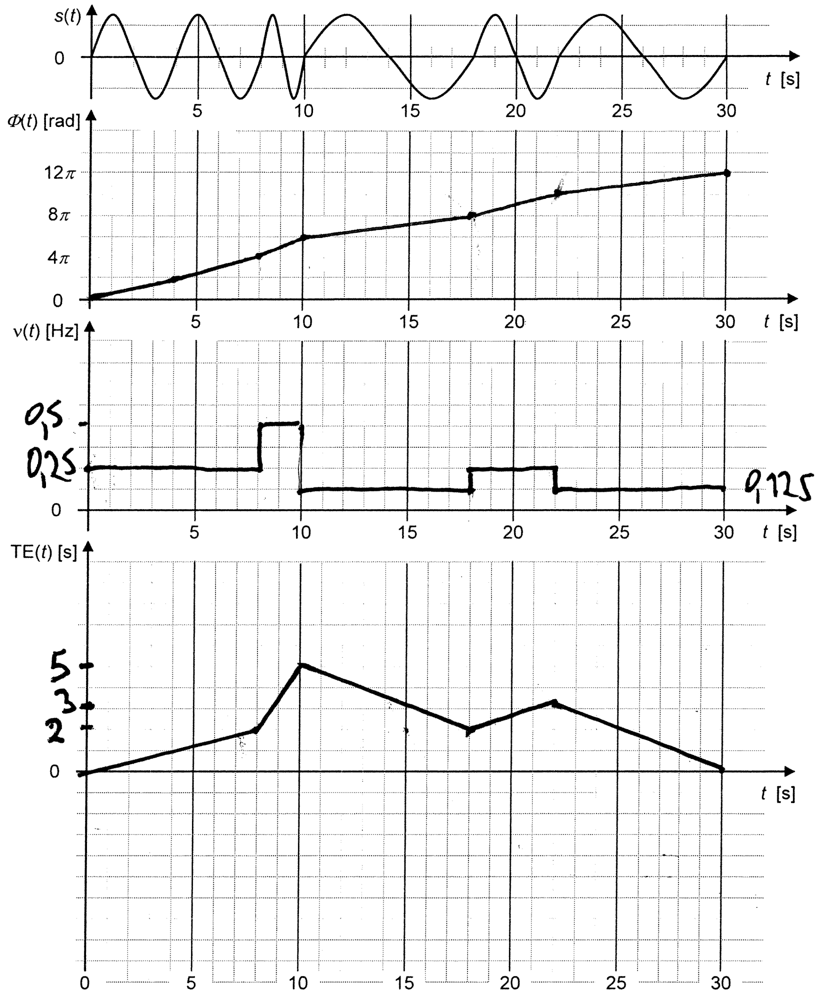
(Solve on this sheet in the space provided) (8 points)

a) Let $s(t)$ be a pseudo-sinusoidal timing signal as plotted in figure.

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

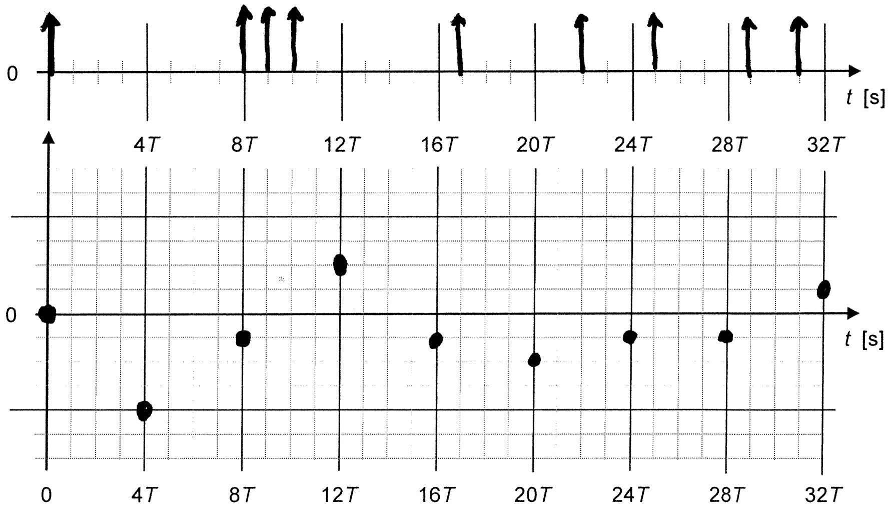
Where possible, plot on the graphs at right:
- the *Total Phase* $\Phi(t)$;
- the *instantaneous frequency* $\nu(t)$;
- the *Time Error* TE(t) with respect to an ideal reference timing signal with frequency $\nu_0 = 0.2$ Hz, starting from TE(0)=0, with the convention that positive TE denotes time advance.

$$\overline{\nu(t)} = \frac{6 \text{ cycles}}{30 \text{ s}} = 0{,}2 \text{ Hz}$$



b) A source transmits packets to a destination with constant rate every $4T$. Packets are supposed short enough to have duration negligible compared to T. Nine packets numbered $k = 0, 1, \ldots, 8$ are transported over the network and arrive to their destination with the sequence of inter-arrival times $\{y_k\} = (8T, T, T, 7T, 5T, 3T, 4T, 2T)$, where y_k is the inter-arrival time between packet k and the next one.

Plot on the graph the PDV values $e[k]$, measured in T units, at the instants $t_k = k(4T)$ of ideal arrival of packets, besides the latency of packet 0, starting from the initial point $e[0] = 0$, with the convention that positive PDV denotes time advance.



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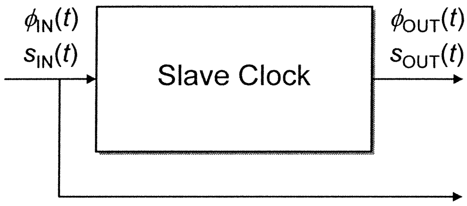
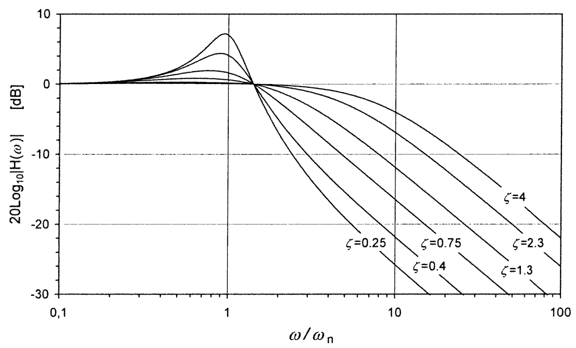
Problem 4

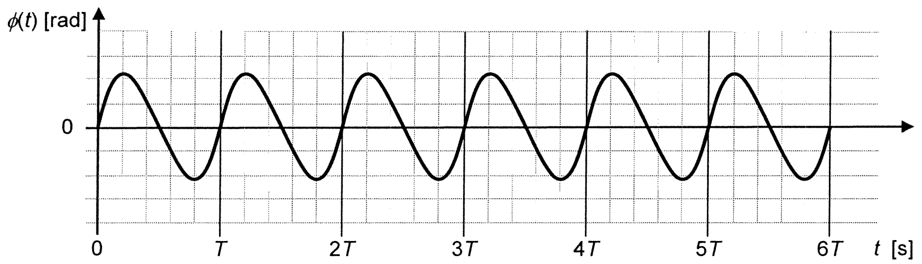
(Solve on this sheet in the space provided) (16 points)

1) Consider a Slave Clock based on a *second-order PLL* system, as shown in the figure below at left. Let us denote as $s_{IN}(t)$ and $s_{OUT}(t)$ its input and output timing signals, respectively, and as $\phi_{IN}(t)$ and $\phi_{OUT}(t)$ their respective *phase errors* vs. the Total Phase $\Phi(t)$ of the ideal timing signal $s(t) = A \sin 2\pi\nu_0 t$ considered as common reference in this model, having frequency ν_0. Therefore: $s_{IN}(t) = A \sin(\, 2\pi\nu_0 t + \phi_{IN}(t)\,)$ and $s_{OUT}(t) = A \sin(\, 2\pi\nu_0 t + \phi_{OUT}(t)\,)$. The closed-loop transfer function of the PLL is the standard $H(s)$ plotted below at right ($\omega_n = 4\pi$ s^{-1}, $\zeta = 4$). *(4 points)*

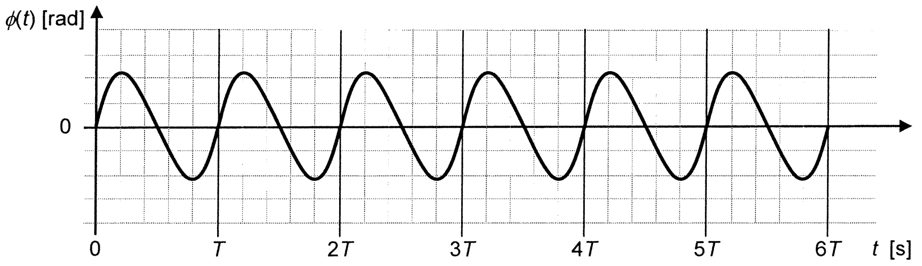




The input timing signal $s_{IN}(t)$ exhibits a phase error $\phi_{IN}(t)$ vs. the Total Phase of the ideal timing signal $s(t)$ as shown in the graphs below (sinusoidal). Plot on the same graphs the output phase $\phi_{OUT}(t)$ ignoring the initial phase alignment between input and output. Explain and express your considerations.



$T = 500$ ms



$T = 5$ ms

2) Consider a 100GbE signal transmitted over an optical fibre with refractive index $n = 1.6$ and length $L = 50$ 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 10°C diurnal excursion of fibre temperature. *(2 points)*

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

$$\Delta L = +l\left(\frac{1}{l}\frac{\partial l}{\partial \theta}\right)\Delta\theta = (50\,\text{km})\cdot(0.8\cdot 10^{-6}/\text{K})\cdot(10\,\text{K}) =$$

$$= 0.4\ \text{m}$$

$$\Rightarrow \Delta\tau = 2{,}13\ \text{ns} = 213\ \text{UI}$$

3) If the length of the frame alignment word is doubled, the alignment algorithm performance is improved during the hunting phase, or the maintenance phase, or both? Explain. *(2 points)*

4) Why a VC-4 can be used, but is not well suitable, to transport a 100M-Ethernet signal? What structure of VCs would you use, instead? How to identify the optimal structure? *(2 points)*

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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)*

6) Describe the different fields of applications of NTP vs. PTP for accurate time synchronization. What protocol achieves best accuracy? In any condition, or depending on the environment where it is applied? *(3 points)*