Optical and Transport Networks

Prof. Stefano Bregni **I Exam 2024-25 – 24 January 2025**

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

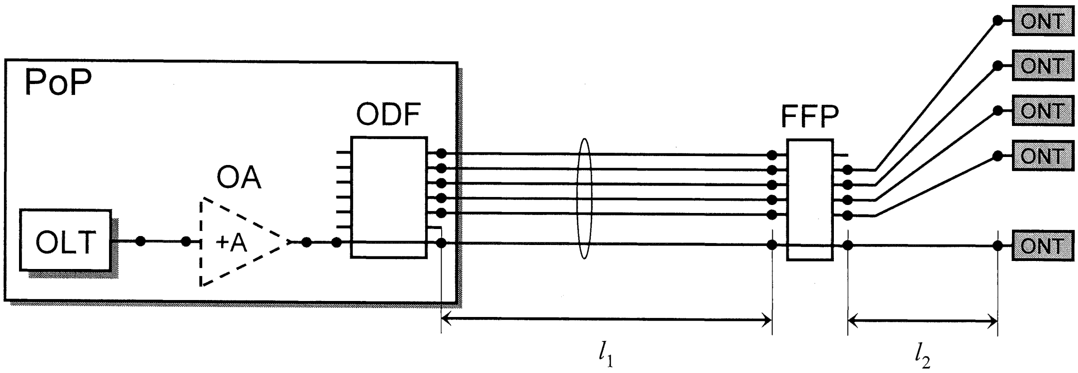
(Solve on this sheet in the space provided) (8 points)

Consider a Point-to-Point (P2P) network reaching 1500 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 $\alpha = 0.3$ dB/km and refractive index $n = 1.5$;
- $l_1 = 25$ 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) Consider the case a 10GbE signal is transmitted over the fibres. 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 20°C diurnal excursion of fibre temperature at the farthest ONT.

b) Evaluate the power P_{RX} [W] received by the farthest ONT without OA if $P_{TX} = 300$ μW.

c) If the OLT transmission power is $P_{TX} = 1$ 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 P2P network is used to connect base stations of a cellular network.

- What is the maximum *Time Alignment Error* (TAE) between any two ONTs synchronized by the received signals, assuming one way synchronization OLT→ONT and assuming that all fiber segments have the same temperature at any time of the day?
- Do you expect that the TAE between ONTs is constant or may vary over time? Why? How much? (Again, considering only the fibre length variation due to temperature variation)

a) $\tau = \frac{1}{v} = L\frac{n}{c} \longrightarrow \Delta\tau = \Delta L \frac{n}{c}$

$\Delta L = +\ell\left(\frac{1}{\ell}\frac{\partial \ell}{\partial \theta}\right)\Delta\theta = (30\,\text{km})\cdot(0.8\cdot 10^{-6}/K)\cdot(20\,K) =$

$= 0{,}480\,\text{m}$

$\Rightarrow \Delta\tau = 2{,}4\,\text{ns} = 24\,\text{UI}$

b) $P_{TX} = -5{,}23\,\text{dBm}$

$P_{RX} = P_{TX} - 6\alpha_c - (\ell_1 + \ell_{2max})\alpha = -17.23\,\text{dBm}$

$= \sim 18.9\,\mu W$

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

$P_{TX} = 0\,\text{dBm} \Rightarrow L < 80\,\text{Km}$

d) $0 \leq \Delta L \leq 4{,}5\,\text{Km} \Rightarrow 0 \leq TAE \leq 22.5\,\mu s$

$\Delta(\Delta L) \leq (4.5\,\text{Km})\cdot\left(0{,}8\,\frac{10^{-6}}{K}\right)\cdot 20\,K = 72\,\text{mm}$

$\Delta(TAE) \leq 0{,}36\,\text{ns}$

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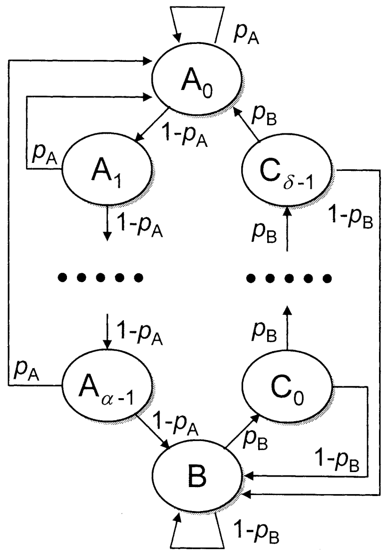
Problem 2

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

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 (10 bits during both hunting and maintenance). The test signal is affected by random transmission errors, uncorrelated and with rate ε.

a) The values of the frame alignment parameters are $\alpha = 5$, $\delta = 1$. Let the system be aligned and in service (A_0 state). What is the probability of *forced loss of alignment*, if the line bit error rate is $\varepsilon = 10^{-7}$?



$$P_A = (1-\varepsilon)^{10} \cong 1 - 10\varepsilon$$

$$P_{FL} = (1 - P_A)^5 = 10^{-30}$$

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^{-15}?

$$P_B = \frac{1}{2^{10}}$$

$$P_{FA} = P_B^{\delta+1} < 10^{-15} \quad \rightarrow \quad (\delta+1) \operatorname{Log}_{10} P_B < -15$$

$$\delta > 3{,}98 \Rightarrow \delta \geq 4$$

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Problem 3

(Solve on this sheet in the space provided) (7 points)

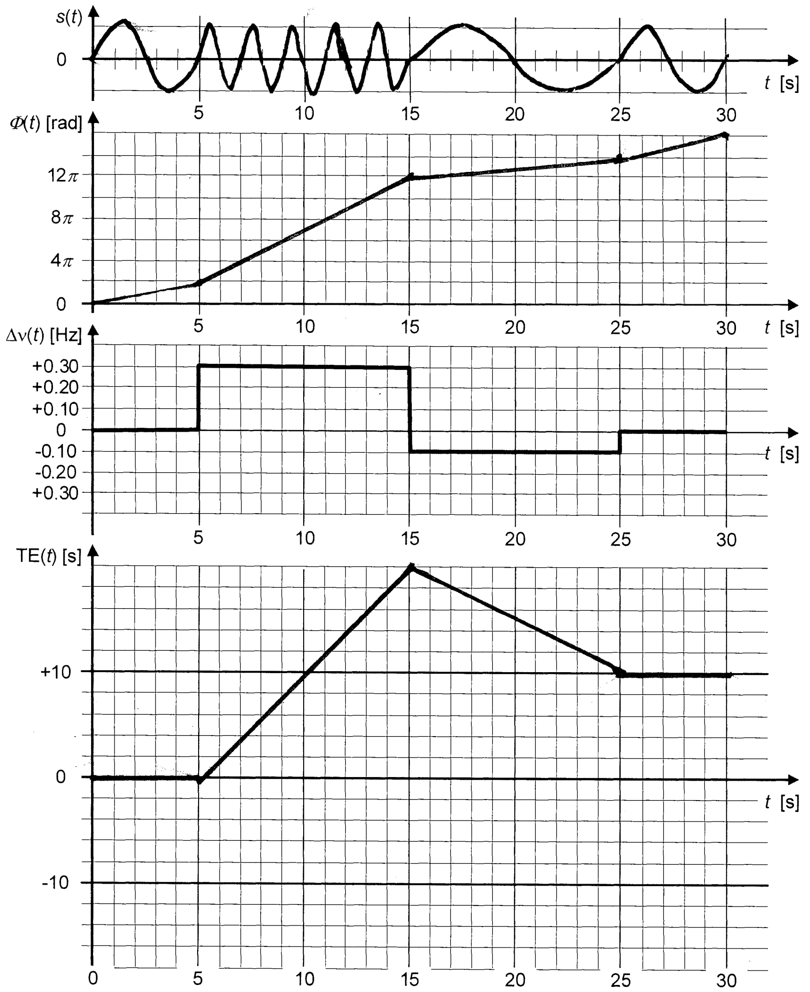
a) Let $s(t)$ be a pseudo-sinusoidal timing signal with nominal frequency $\nu_0 = 0.2$ Hz and *instantaneous frequency error* $\Delta\nu(t) = \nu(t) - \nu_0$ as plotted in figure.

Where possible, plot on the graphs at right:

- the timing signal $s(t)$;
- the *Total Phase* $\Phi(t)$ of $s(t)$ and of the ideal timing signal with frequency ν_0, both starting from $\Phi(0) = 0$;
- the *Time Error* TE(t) with respect to an ideal timing signal with frequency ν_0, starting from TE(0)=0, with the convention that positive TE denotes time advance.

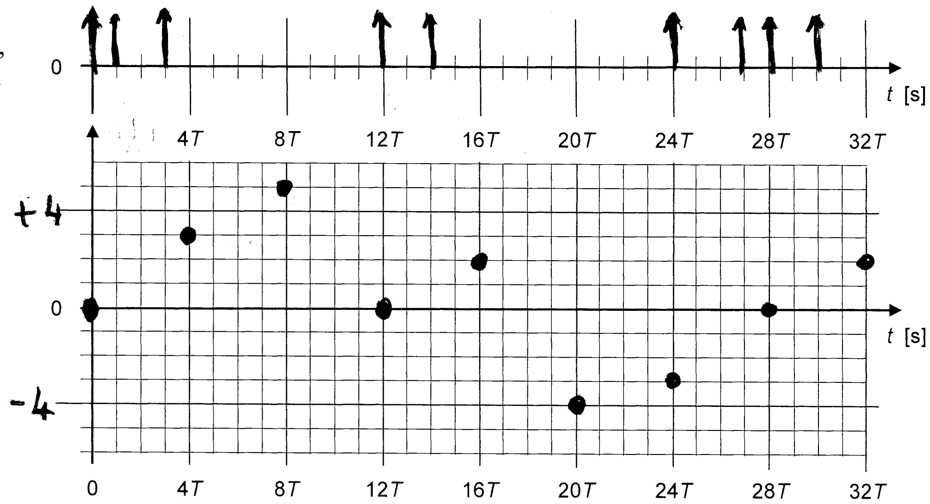
$$T(t) = \frac{\Phi(t)}{2\pi\nu_1}$$

$$T_0 = \frac{1}{\nu_0} = 5 \text{ s}$$



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 $\{y_k\} = (T, 2T, 9T, 2T, 10T, 3T, 1T, 2T)$, where y_k is the inter-arrival time between packet k and the next one.

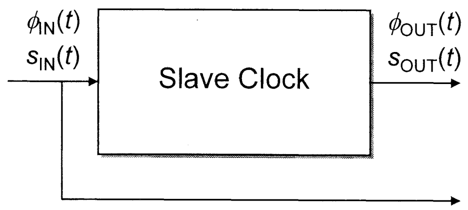
Plot on the graph the PDV values $e[k]$, measured in T units, at the instants $t_k = k(4T)$ of ideal arrival of packets, besides the latency of packet 0, starting from the initial point $e[0] = 0$, with the convention that positive PDV denotes time advance.

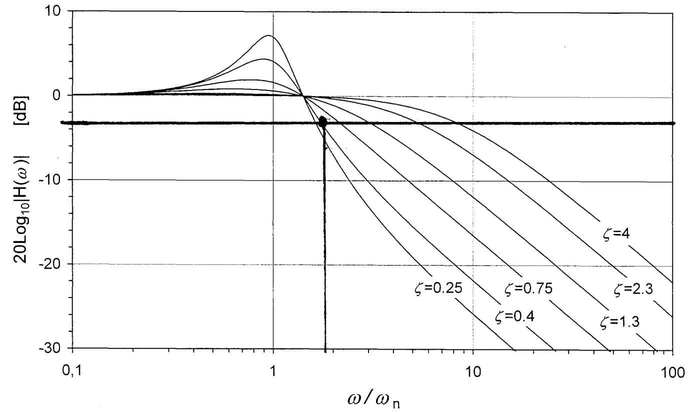


Problem 4

(Solve on this sheet in the space provided) (15 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 ($\omega_n = 1000\pi\ \mathrm{s}^{-1}$, $\zeta = 0.4$). *(4 points)*

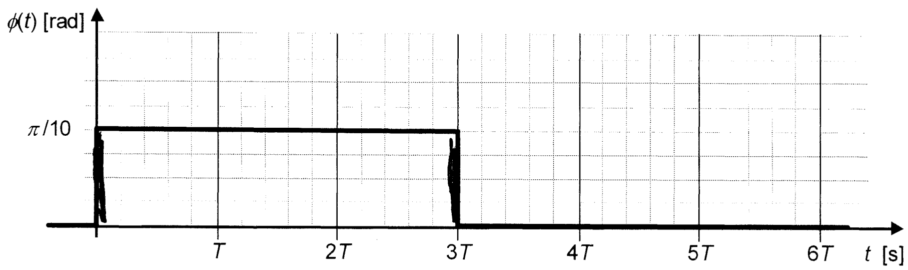




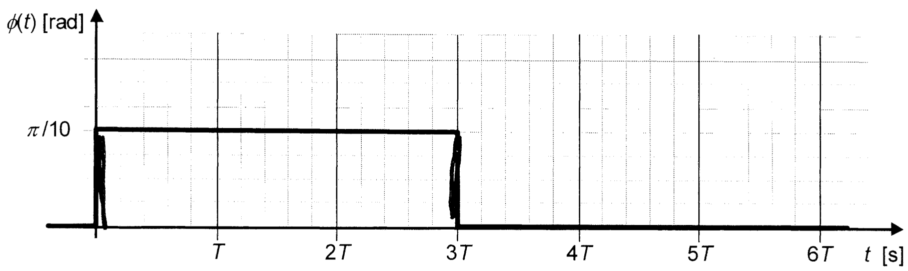
- What is the cutoff frequency (-3 dB point) [Hz] of the slave clock?

~ 1 kHz

- 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. Plot on the same graph the phase error $\phi_{OUT}(t)$-$\phi_{IN}(t)$. Explain your responses and express your considerations.



$T = 1$ s



$T = 1000$ s

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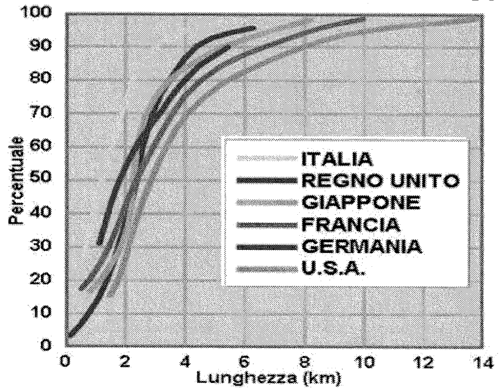
2) In the plot below, representing the cumulative distribution of the length of deployed twisted pairs in the local loop of various countries, the curve of Italy is the highest, while the curve of USA is the lowest. What is the impact of this situation for operators who plan to upgrade the transmission capacity of xDSL systems in those two countries? Is this statistics enough, in order to foresee if the upgrade will be more or less successful in those countries? *(2 points)*



3) Consider the case a 100GbE signal transmitted over an optical fibre of length L = 100 km. 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. The coefficient of variation of the refractive index vs. temperature of the fibre is $\partial n / \partial \theta = +5 \cdot 10^{-6}$/K. The diurnal wander caused by the former and the diurnal wander caused by the latter add up or compensate partially? That is, do the two wander contributions have the same or opposite sign? *(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)*

5) Why the ratio of the line bit error rate ε over the BIP(n,m) violation rate v is not always equal to $\varepsilon/v = 1$? Is it greater or smaller than 1? Does it increase or decrease with ε? Explain. *(2 points)*

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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)*