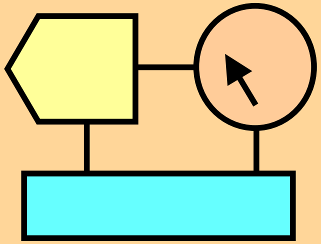
Applied Electronics

Ce – Exercises with Interconnections

- Delays and skew with RC model
- Transmission lines, reflections
- Cycle speed
  - Serial clock tolerance
  - Bypass capacitors



Ce: Exercises with Interconnections

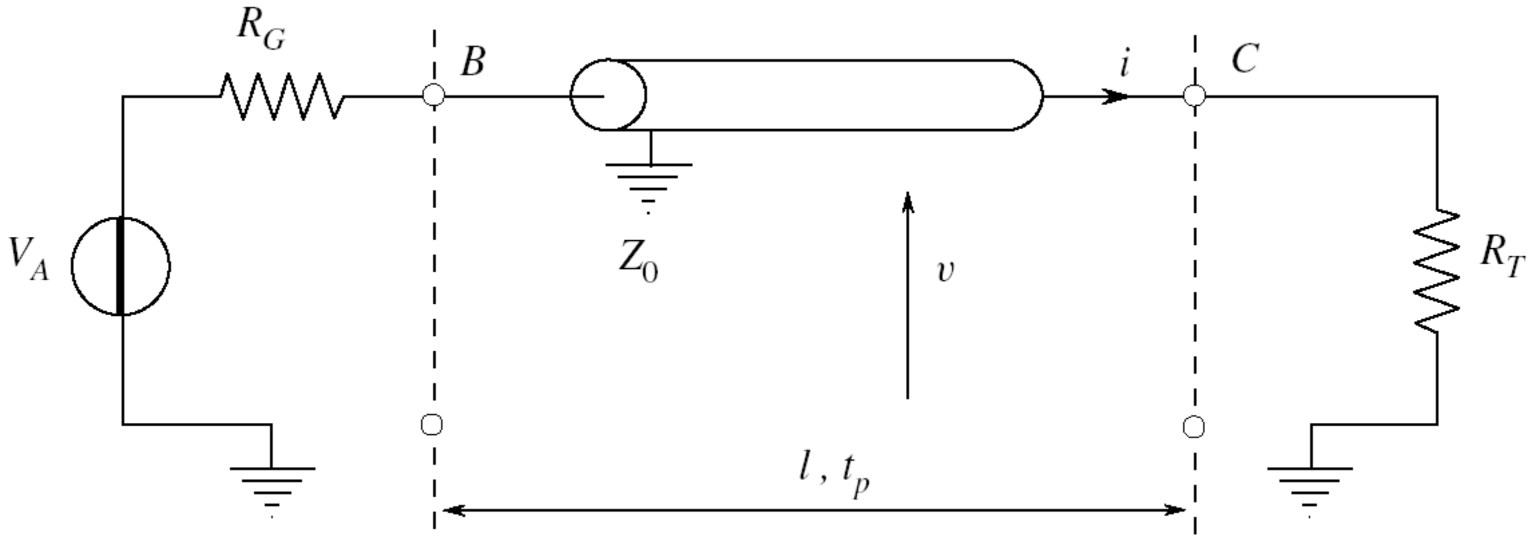
- Delays and skews with RC models
  - Ce1, Ce2
- Transmission line models
  - Ce3, Ce4
- Time Diagrams, IWS
  - Ce5, Ce6
- Examples of exam exercises
  - Ce7, Ce8

Exercise Ce4: Time Diagrams

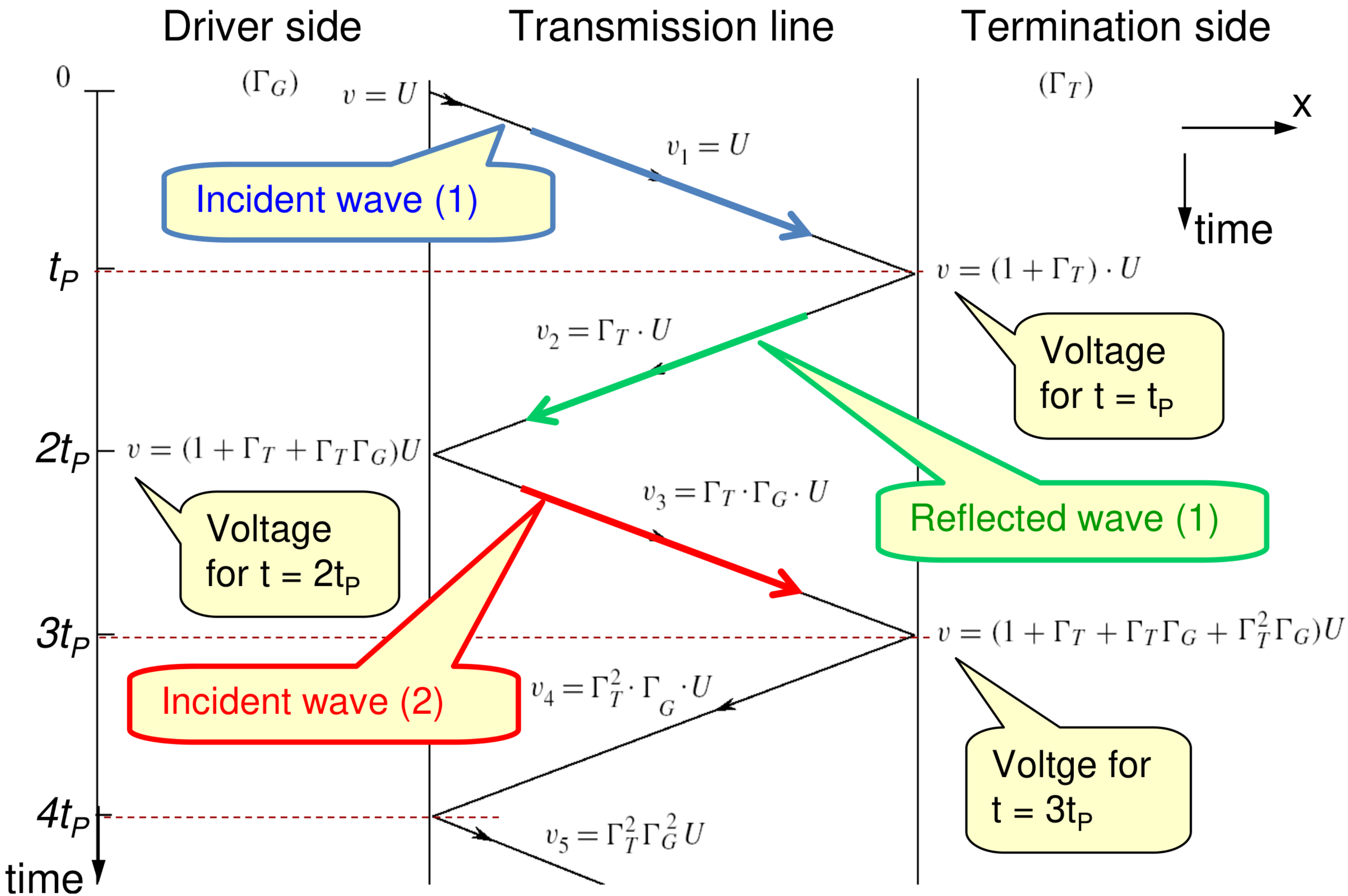
- Draw for $4\ t_{\mathrm{P}}$, using the lattice diagram technique, the time evolution of V_{B} and V_{C} for a V_{A} switch from $0\ \mathrm{V}$ to $5\ \mathrm{V}$.
Parameters:

$$R_{\mathrm{G}} = 50\ \Omega, \qquad R_{\mathrm{T}} = \infty, \qquad Z_{\infty} = 50\ \Omega,$$
$$P = 0{,}8\ \mathrm{c}, \qquad l = 20\ \mathrm{cm}$$

- Repeat the calculation with $R_{\mathrm{G}} = 270\ \Omega$ and $R_{\mathrm{G}} = 15\ \Omega$



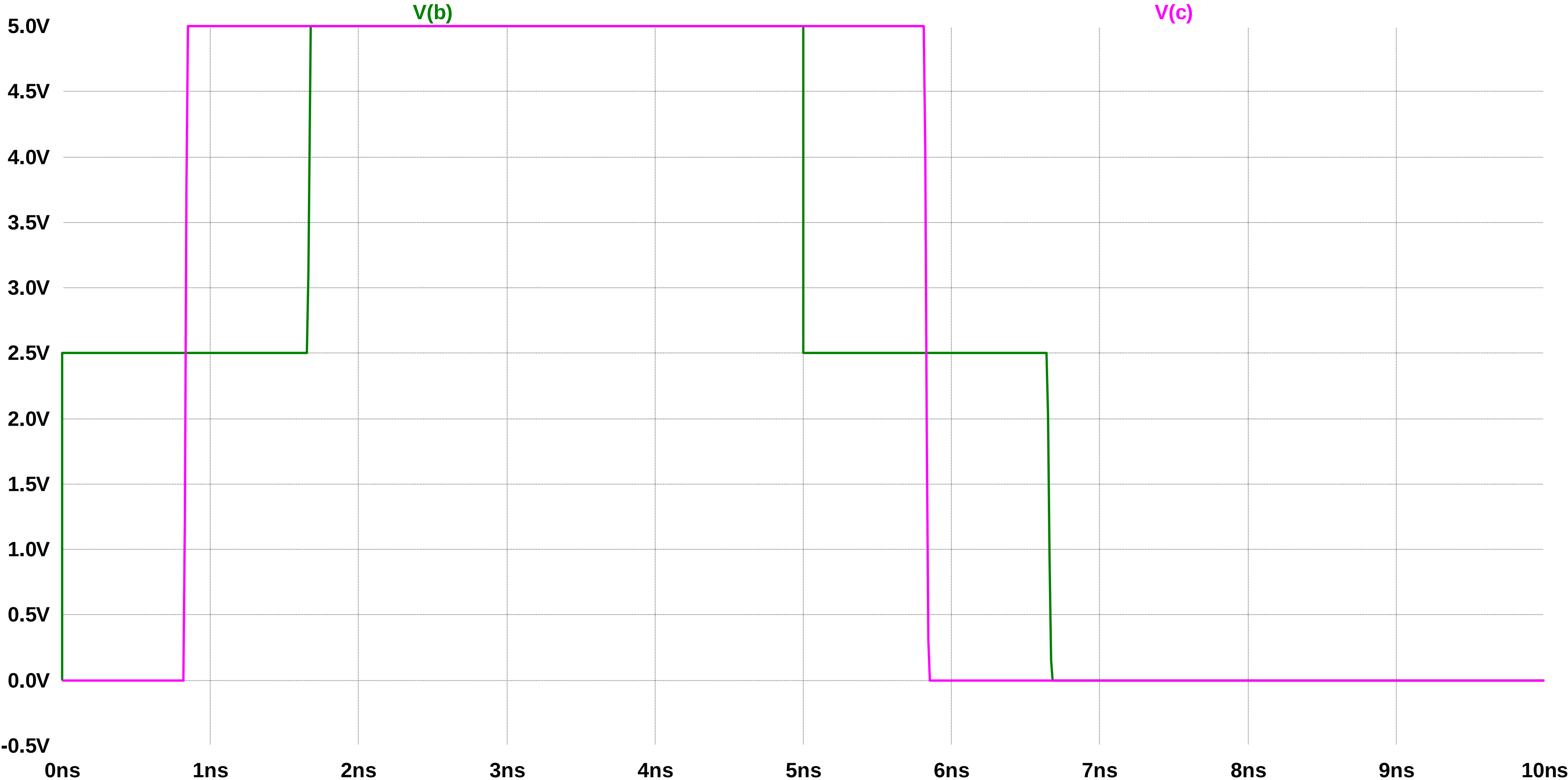
Exercise Ce4: Time Diagrams



Exercise Ce4: Time Diagrams $\boldsymbol{R_\mathrm{G} = 50\ \Omega}$

- $\Gamma_\mathrm{G} = \dfrac{R_\mathrm{G} - Z_\infty}{R_\mathrm{G} + Z_\infty} = \dfrac{50\ \Omega - 50\ \Omega}{50\ \Omega + 50\ \Omega} = 0, \qquad \Gamma_\mathrm{T} = \dfrac{\infty - 50\ \Omega}{\infty + 50\ \Omega} = 1$
- $t_\mathrm{P} = \dfrac{l}{P} = \dfrac{0.2\ \mathrm{m}}{0.8 \cdot 3{\cdot}10^8\ \mathrm{m/s}} = 0.83\ \mathrm{ns}$
- $V_\mathrm{B}(0) = \dfrac{Z_\infty}{R_\mathrm{G} + Z_\infty} V_\mathrm{A} = \dfrac{50\ \Omega}{50\ \Omega + 50\ \Omega} 5\ \mathrm{V} = 2.5\ \mathrm{V}$
- $V_\mathrm{C}(t_\mathrm{P}) = (1 + \Gamma_\mathrm{T}) V_\mathrm{B}(0) = (1 + 1) \cdot 2.5\ \mathrm{V} = 5\ \mathrm{V}$
- $V_\mathrm{B}(2\ t_\mathrm{P}) = (1 + \Gamma_\mathrm{T} + \Gamma_\mathrm{T}\Gamma_\mathrm{G}) V_\mathrm{B}(0) =$
  $(1 + 1 + 1 \cdot 0) \cdot 2.5\ \mathrm{V} = 5\ \mathrm{V}$
- $V_\mathrm{C}(3\ t_\mathrm{P}) = \left(1 + \Gamma_\mathrm{T} + \Gamma_\mathrm{T}\Gamma_\mathrm{G} + \Gamma_\mathrm{T}^2\Gamma_\mathrm{G}\right) V_\mathrm{B}(0) =$
  $(1 + 1 + 1 \cdot 0 + 1^2 \cdot 0) \cdot 2.5\ \mathrm{V} = 5\ \mathrm{V}$
- $V_\mathrm{B}(4\ t_\mathrm{P}) = \left(1 + \Gamma_\mathrm{T} + \Gamma_\mathrm{T}\Gamma_\mathrm{G} + \Gamma_\mathrm{T}^2\Gamma_\mathrm{G} + \Gamma_\mathrm{T}^2\Gamma_\mathrm{G}^2\right) V_\mathrm{B}(0) =$
  $(1 + 1 + 1 \cdot 0 + 1^2 \cdot 0 + 1^2 \cdot 0^2) \cdot 2.5\ \mathrm{V} = 5\ \mathrm{V}$

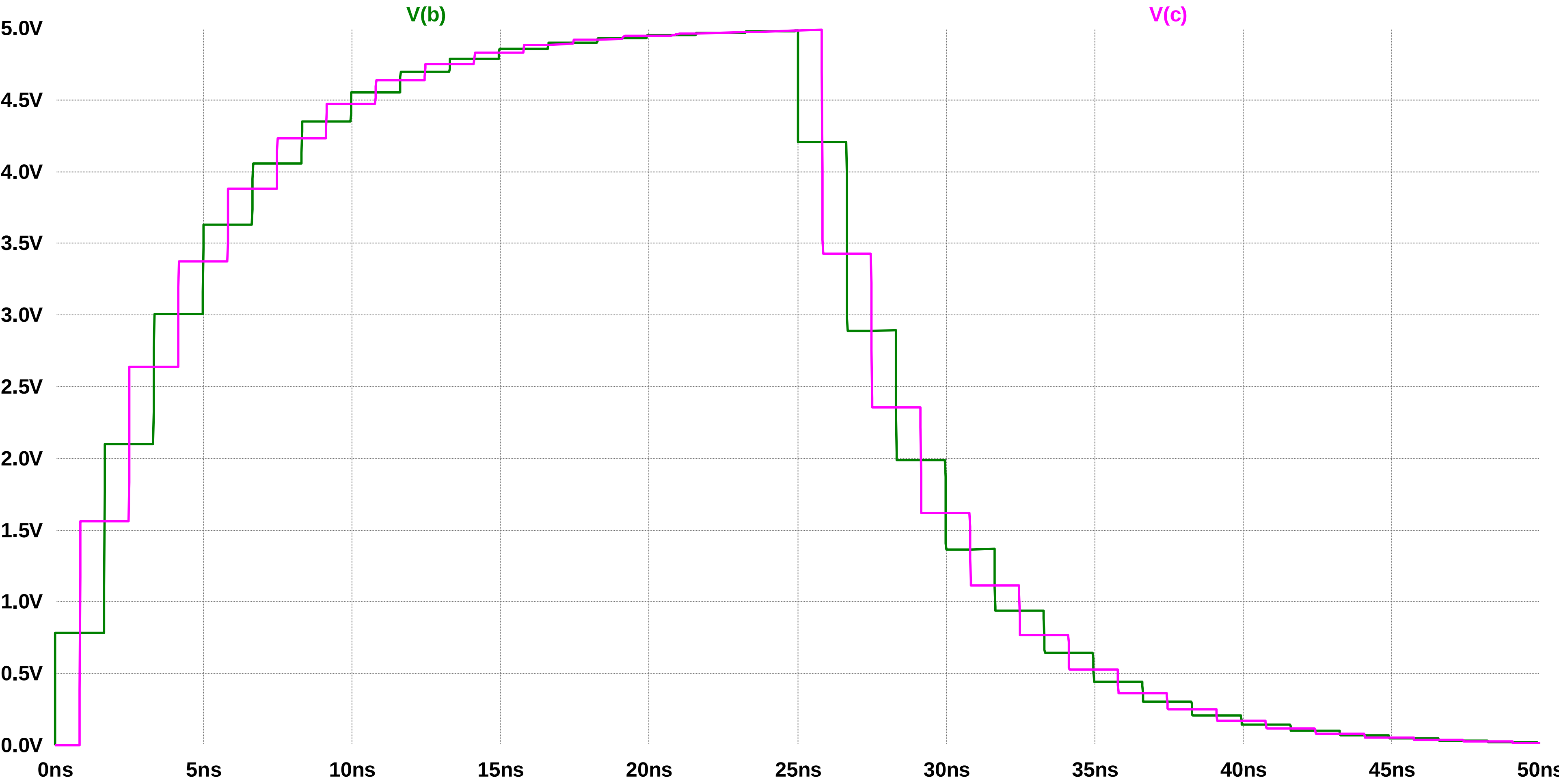
Exercise Ce4: Time Diagrams $R_G = 50\ \Omega$



Exercise Ce4: Time Diagrams $\boldsymbol{R_{\mathrm{G}} = 270\ \Omega}$

- $\Gamma_{\mathrm{G}} = \dfrac{R_{\mathrm{G}} - Z_\infty}{R_{\mathrm{G}} + Z_\infty} = \dfrac{270\ \Omega - 50\ \Omega}{270\ \Omega + 50\ \Omega} = 0.69, \qquad \Gamma_{\mathrm{T}} = \dfrac{\infty - 50\ \Omega}{\infty + 50\ \Omega} = 1$
- $t_{\mathrm{P}} = \dfrac{l}{P} = \dfrac{0.2\ \mathrm{m}}{0.8 \cdot 3{\cdot}10^8\ \mathrm{m/s}} = 0.83\ \mathrm{ns}$
- $V_{\mathrm{B}}(0) = \dfrac{Z_\infty}{R_{\mathrm{G}} + Z_\infty} V_{\mathrm{A}} = \dfrac{50\ \Omega}{270\ \Omega + 50\ \Omega} 5\ \mathrm{V} = 0.78\ \mathrm{V}$
- $V_{\mathrm{C}}(t_{\mathrm{P}}) = (1 + \Gamma_{\mathrm{T}}) V_{\mathrm{B}}(0) = (1 + 1) \cdot 0.78\ \mathrm{V} = 1.56\ \mathrm{V}$
- $V_{\mathrm{B}}(2\, t_{\mathrm{P}}) = (1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}}) V_{\mathrm{B}}(0) =$
  $(1 + 1 + 1 \cdot 0{,}69) \cdot 0.78\ \mathrm{V} = 2.10\ \mathrm{V}$
- $V_{\mathrm{C}}(3\, t_{\mathrm{P}}) = \left(1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}}\right) V_{\mathrm{B}}(0) =$
  $(1 + 1 + 1 \cdot 0.69 + 1^2 \cdot 0.69) \cdot 0.78\ \mathrm{V} = 2.64\ \mathrm{V}$
- $V_{\mathrm{B}}(4\, t_{\mathrm{P}}) = \left(1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}}^2\right) V_{\mathrm{B}}(0) =$
  $(1 + 1 + 1 \cdot 0.69 + 1^2 \cdot 0.69 + 1^2 \cdot 0.69^2) \cdot 0.78\ \mathrm{V} = 3.01\ \mathrm{V}$

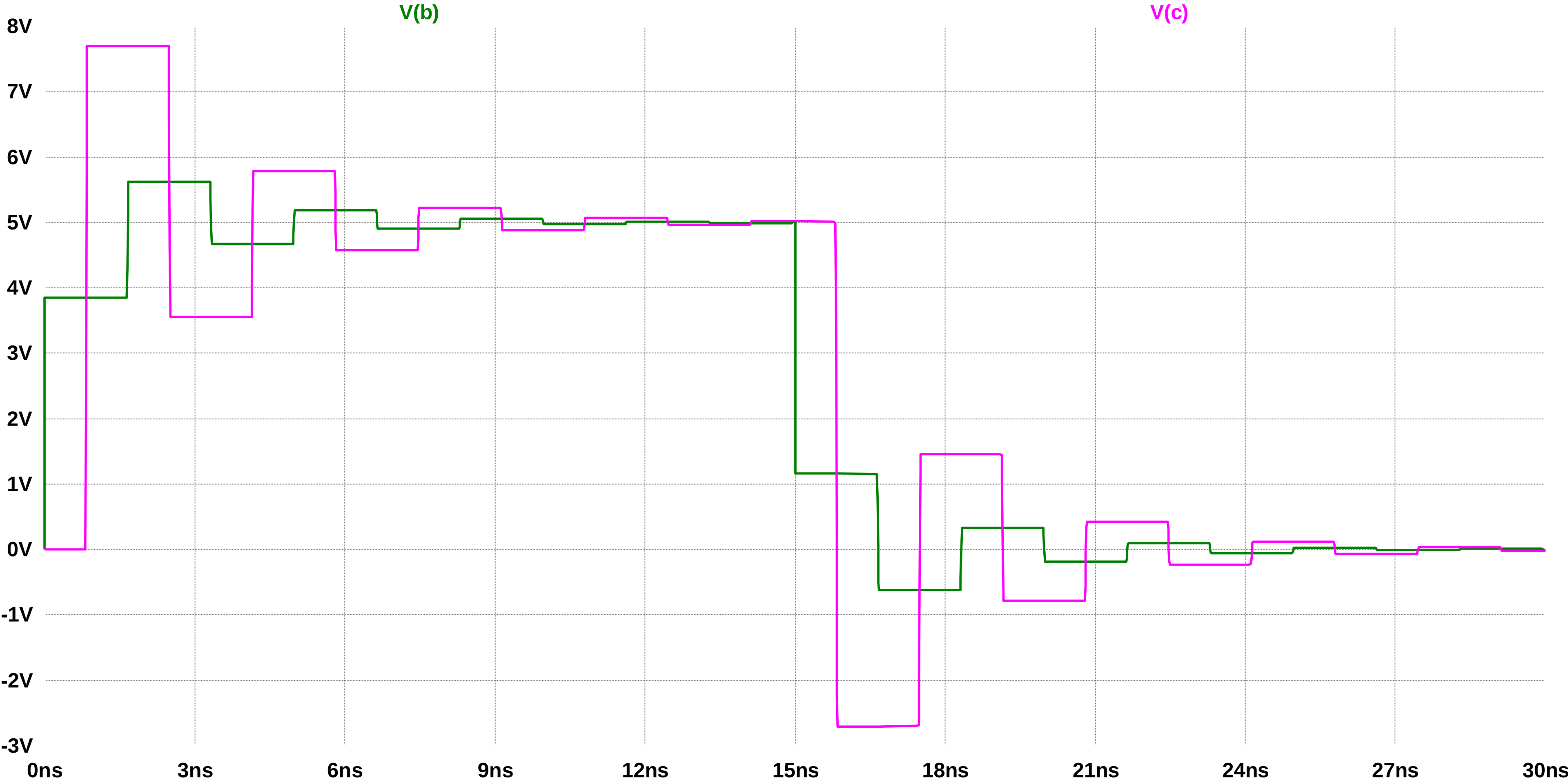
Exercise Ce4: Time Diagrams $\boldsymbol{R_G = 270\ \Omega}$



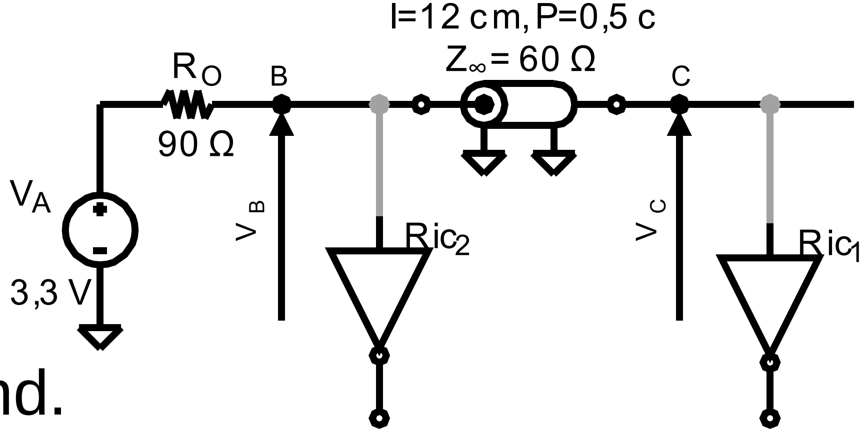
Exercise Ce4: Time Diagrams $\boldsymbol{R_{\mathrm{G}} = 15\ \Omega}$

- $\Gamma_{\mathrm{G}} = \dfrac{R_{\mathrm{G}} - Z_\infty}{R_{\mathrm{G}} + Z_\infty} = \dfrac{15\ \Omega - 50\ \Omega}{15\ \Omega + 50\ \Omega} = -0.54,\qquad \Gamma_{\mathrm{T}} = \dfrac{\infty - 50\ \Omega}{\infty + 50\ \Omega} = 1$
- $t_{\mathrm{P}} = \dfrac{l}{P} = \dfrac{0.2\ \mathrm{m}}{0.8 \cdot 3{\cdot}10^8\ \mathrm{m/s}} = 0.83\ \mathrm{ns}$
- $V_{\mathrm{B}}(0) = \dfrac{Z_\infty}{R_{\mathrm{G}} + Z_\infty} V_{\mathrm{A}} = \dfrac{50\ \Omega}{15\ \Omega + 50\ \Omega} 5\ \mathrm{V} = 3.85\ \mathrm{V}$
- $V_{\mathrm{C}}(t_{\mathrm{P}}) = (1 + \Gamma_{\mathrm{T}}) V_{\mathrm{B}}(0) = (1 + 1) \cdot 3.85\ \mathrm{V} = 7.70\ \mathrm{V}$
- $V_{\mathrm{B}}(2\ t_{\mathrm{P}}) = (1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}}) V_{\mathrm{B}}(0) =$
  $[1 + 1 + 1 \cdot (-0.54)] \cdot 3.85\ \mathrm{V} = 5.62\ \mathrm{V}$
- $V_{\mathrm{C}}(3\ t_{\mathrm{P}}) = \left(1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}}\right) V_{\mathrm{B}}(0) =$
  $[1 + 1 + 1 \cdot (-0.54) + 1^2 \cdot (-0.54)] \cdot 3.85\ \mathrm{V} = 3.54\ \mathrm{V}$
- $V_{\mathrm{B}}(4\ t_{\mathrm{P}}) = \left(1 + \Gamma_{\mathrm{T}} + \Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}} + \Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}}^2\right) V_{\mathrm{B}}(0) =$
  $[1 + 1 + 1 \cdot (-0.54) + 1^2 \cdot (-0.54) + 1^2 \cdot (-0.54)^2]$

Exercise Ce4: Time Diagrams $R_G = 15\ \Omega$

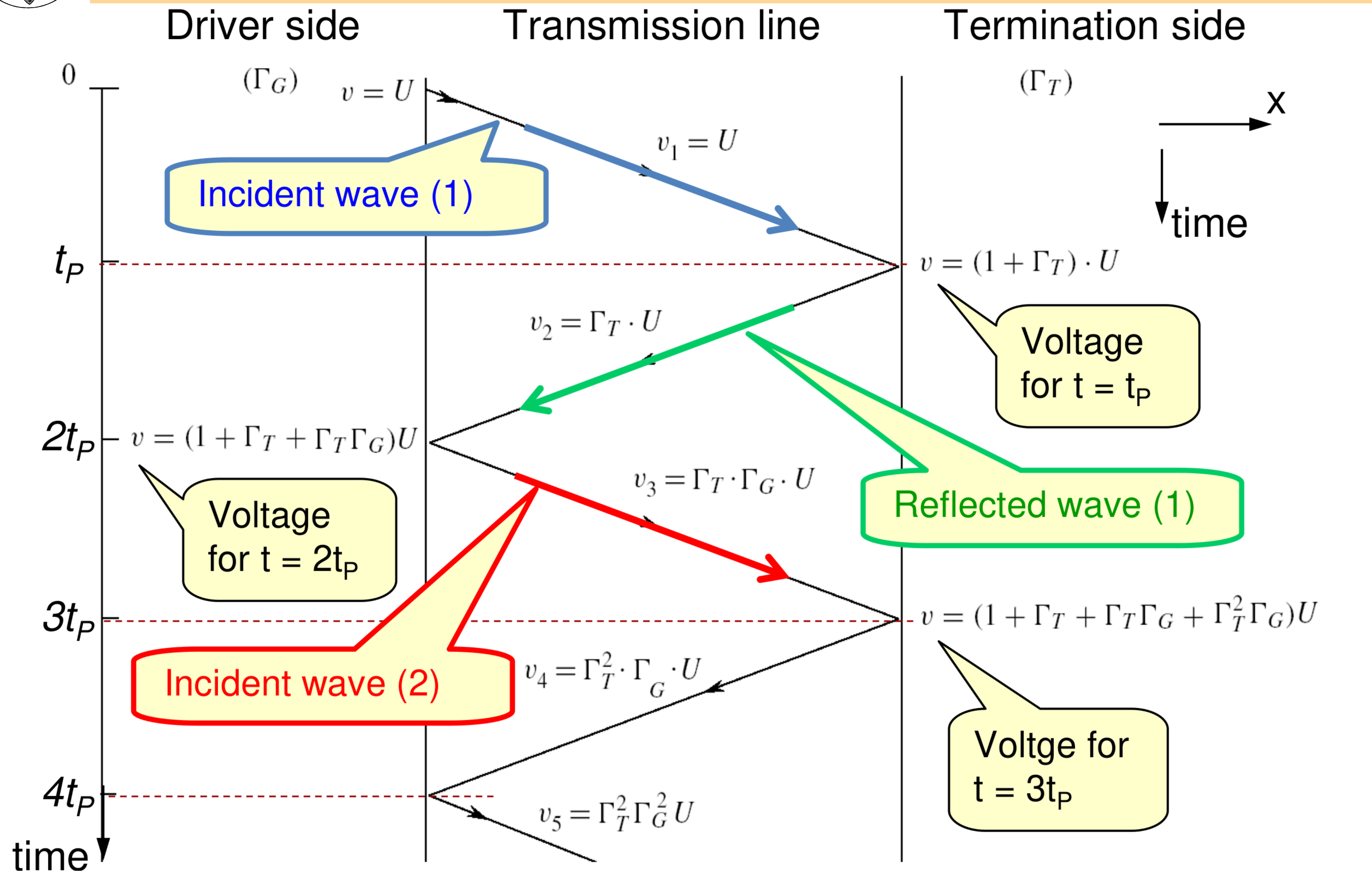


Exercise Ce7



- A driver powered at $3.3\ \mathrm{V}$ and with $R_{\mathrm{O}} = 90\ \Omega$ drives a connection with $Z_{\infty} = 60\ \Omega$, propagation speed $p = 0.5\ \mathrm{c}$, length $12\ \mathrm{cm}$, open at remote end. The receivers are CMOS with $V_{\mathrm{IL}} = 0.8\ \mathrm{V}$ and $V_{\mathrm{IH}} = 2\ \mathrm{V}$. For the transition L→H:
  a) Determine the amplitude of the first step and the propagation time
  b) Determine the minimum and maximum transmission times for receivers located on the driver side and termination side
  c) Qualitatively draw the waveform at the termination if the input capacitance of the receiver connected there is $10\ \mathrm{pF}$.

Exercise Ce7



Exercise Ce7: a)

- $V_{\mathrm{B}}(0) = \dfrac{Z_\infty}{R_{\mathrm{D}} + Z_\infty} V_{\mathrm{A}} = \dfrac{60\ \Omega}{90\ \Omega + 60\ \Omega} 3.3\ \mathrm{V} = 1.32\ \mathrm{V}$
- $t_{\mathrm{P}} = \dfrac{l}{p} = \dfrac{0.12\ \mathrm{m}}{0.5 \cdot 3{\cdot}10^8\ \mathrm{m/s}} = 0.8\ \mathrm{ns}$

Exercise Ce7: b)

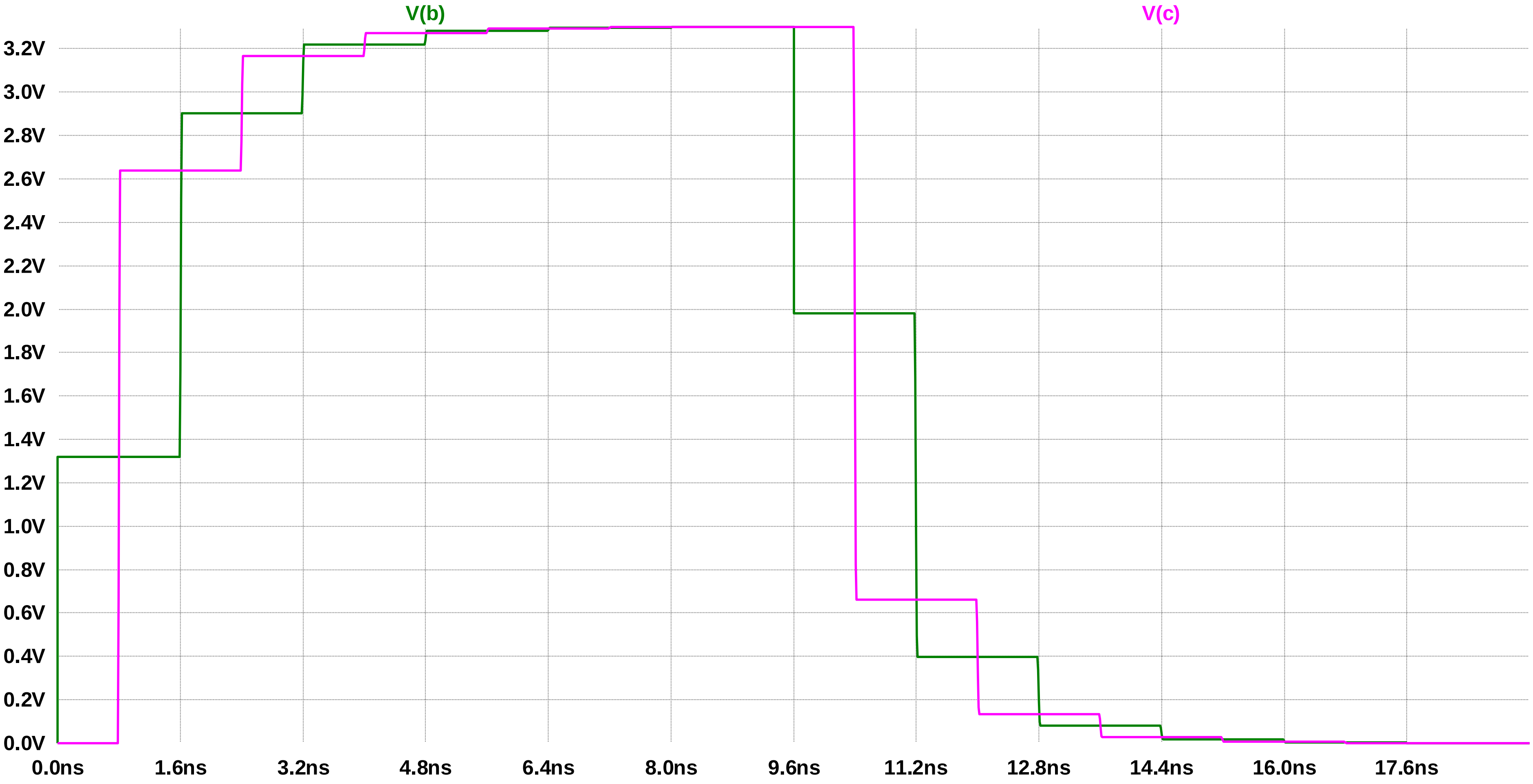
- $\Gamma_\mathrm{D} = \dfrac{R_\mathrm{O} - Z_\infty}{R_\mathrm{O} + Z_\infty} = \dfrac{90\ \Omega - 60\ \Omega}{90\ \Omega + 60\ \Omega} = 0{,}2, \quad \Gamma_\mathrm{T} = \dfrac{\infty - 60\ \Omega}{\infty + 60\ \Omega} = 1$

- $V_\mathrm{B}(0) = \dfrac{Z_\infty}{R_\mathrm{D} + Z_\infty} V_\mathrm{A} = \dfrac{60\ \Omega}{90\ \Omega + 60\ \Omega} 3.3\ \mathrm{V} = 1.32\ \mathrm{V}$
  - $V_\mathrm{B}(0) > V_\mathrm{IL} \Rightarrow \boldsymbol{t^\mathrm{B}_{\mathrm{TX}_\mathrm{min}} = 0\ \mathrm{s}}$; $V_B(0) < V_{IH}$
- $V_\mathrm{B}(2\ t_\mathrm{P}) = (1 + \Gamma_\mathrm{T} + \Gamma_\mathrm{T}\Gamma_\mathrm{G})V_\mathrm{B}(0) =$

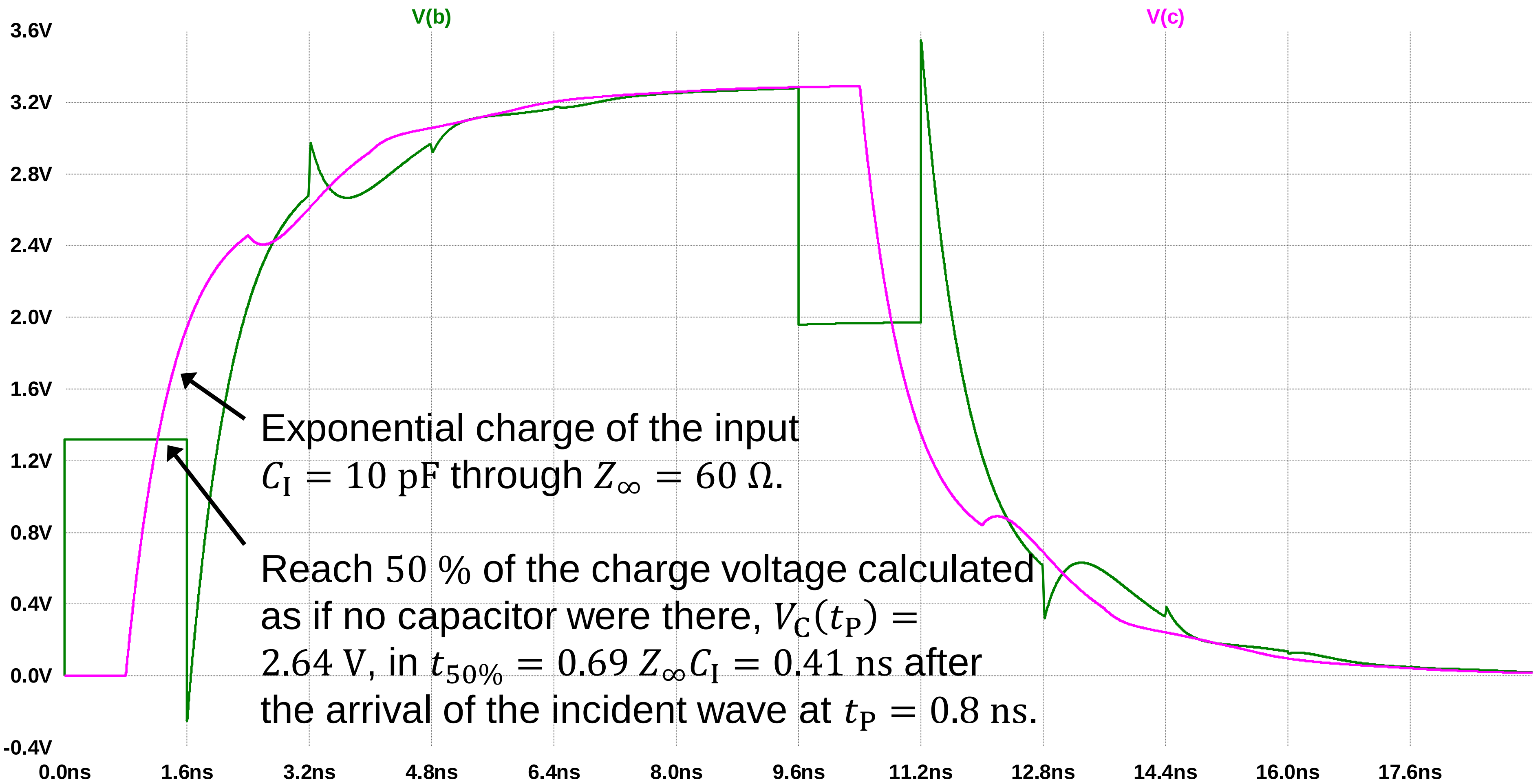
  $(1 + 1 + 1 \cdot 0.2) \cdot 1.32\ \mathrm{V} = 2.9\ \mathrm{V}$
  - $V_\mathrm{B}(2\ t_\mathrm{P}) > V_\mathrm{IH} \Rightarrow \boldsymbol{t^\mathrm{B}_{\mathrm{TX}_\mathrm{max}}} = 2\ t_\mathrm{P} = 2 \cdot 0.8\ \mathrm{ns} = \mathbf{1.6\ ns}$

- $V_\mathrm{C}(t_\mathrm{P}) = (1 + \Gamma_\mathrm{T})V_\mathrm{B}(0) = (1 + 1) \cdot 1.32\ \mathrm{V} = 2.64\ \mathrm{V}$
  - $V_\mathrm{C}(t_\mathrm{P}) > V_\mathrm{IL}$ and $V_\mathrm{C}(t_\mathrm{P}) > V_\mathrm{IH} \Rightarrow \boldsymbol{t^\mathrm{C}_{\mathrm{TX}_\mathrm{min}}} = \boldsymbol{t^\mathrm{C}_{\mathrm{TX}_\mathrm{max}}} = t_\mathrm{P} = \mathbf{0.8\ ns}$

Exercise Ce7: b)



Exercise Ce7: c)



Exponential charge of the input $C_\mathrm{I} = 10\ \mathrm{pF}$ through $Z_\infty = 60\ \Omega$.

Reach $50\ \%$ of the charge voltage calculated as if no capacitor were there, $V_\mathrm{C}(t_\mathrm{P}) = 2.64\ \mathrm{V}$, in $t_{50\%} = 0.69\ Z_\infty C_\mathrm{I} = 0.41\ \mathrm{ns}$ after the arrival of the incident wave at $t_\mathrm{P} = 0.8\ \mathrm{ns}$.

Exercise Ce8

- A backplane has $L_{\mathrm{U}} = 8\ \mathrm{nH/cm}$, $Z_{\infty} = 85\ \Omega$ without loads, length $l = 48\ \mathrm{cm}$, without terminations, with 24 equidistant connectors. The boards that can be inserted into the connectors have a capacitive load $C_{\mathrm{P}} = 35\ \mathrm{pF}$ each. The system can hold from 2 to 24 boards.
  CMOS driver/receiver parameters:
  $V_{\mathrm{AL}} = 3.3\ \mathrm{V}$; $R_{\mathrm{O}} = 95\ \Omega$; $V_{\mathrm{IH}} = 2\ \mathrm{V}$, $V_{\mathrm{IL}} = 1\ \mathrm{V}$.
  a) Calculate the propagation time t_{P} between the ends, with 2 and 24 boards.
  b) Determine the $t_{\mathrm{TX_{min}}}$ between two boards in extreme positions.
  c) Calculate $t_{\mathrm{TX_{max}}}$ with 24 boards inserted, driven at one end.
  d) Indicate driver max R_{OH} to operate in IWS for lines driven at one end, with 24 boards inserted.

Exercise Ce8: a)

- $Z_\infty = \sqrt{\frac{L_\mathrm{U}}{C_\mathrm{U}}}$, $C_\mathrm{U} = \frac{L_\mathrm{U}}{Z_\infty^2} = \frac{8 \cdot 10^{-9}\ \mathrm{nH/cm}}{85^2\ \Omega^2} = 1.11\ \mathrm{pF/cm}$
- $N = 2$ mounted boards (we assume distributed C_P)
  - $C_{\mathrm{U}_2} = \frac{C_\mathrm{U}\, l + N\, C_\mathrm{P}}{l} = C_\mathrm{U} + \frac{N\, C_\mathrm{P}}{l} = 1.11\ \mathrm{pF/cm} + \frac{2 \cdot 35\ \mathrm{pF}}{48\ \mathrm{cm}} = 2.57\ \mathrm{pF/cm}$
  - $P_2 = \frac{1}{\sqrt{L_\mathrm{U}\, C_\mathrm{U}}} = \frac{1}{\sqrt{8\ \mathrm{nH/cm} \cdot 2.57\ \mathrm{pF/cm}}} = 6.97 \cdot 10^9\ \mathrm{cm/s}$
  - $t_{\mathrm{P}_2} = \frac{l}{P} = \frac{48\ \mathrm{cm}}{6.97 \cdot 10^9\ \mathrm{cm/s}} = \mathbf{6.89\ ns}$
- $N = 24$ mounted boards (we assume distributed C_P)
  - $C_{U_{24}} = \frac{C_U\, l + N\, C_\mathrm{P}}{l} = C_\mathrm{U} + \frac{N\, C_\mathrm{P}}{l} = 1.11\ \mathrm{pF/cm} + \frac{24 \cdot 35\ \mathrm{pF}}{48\ \mathrm{cm}} = 18.61\ \mathrm{pF/cm}$
  - $P_{24} = \frac{1}{\sqrt{L_\mathrm{U}\, C_\mathrm{U}}} = \frac{1}{\sqrt{8\ \mathrm{nH/cm} \cdot 18.61\ \mathrm{pF/cm}}} = 2.59 \cdot 10^9\ \mathrm{cm/s}$
  - $t_{\mathrm{P}_{24}} = \frac{l}{P} = \frac{48\ \mathrm{cm}}{2.59 \cdot 10^9\ \mathrm{cm/s}} = 18.53\ \mathrm{ns}$

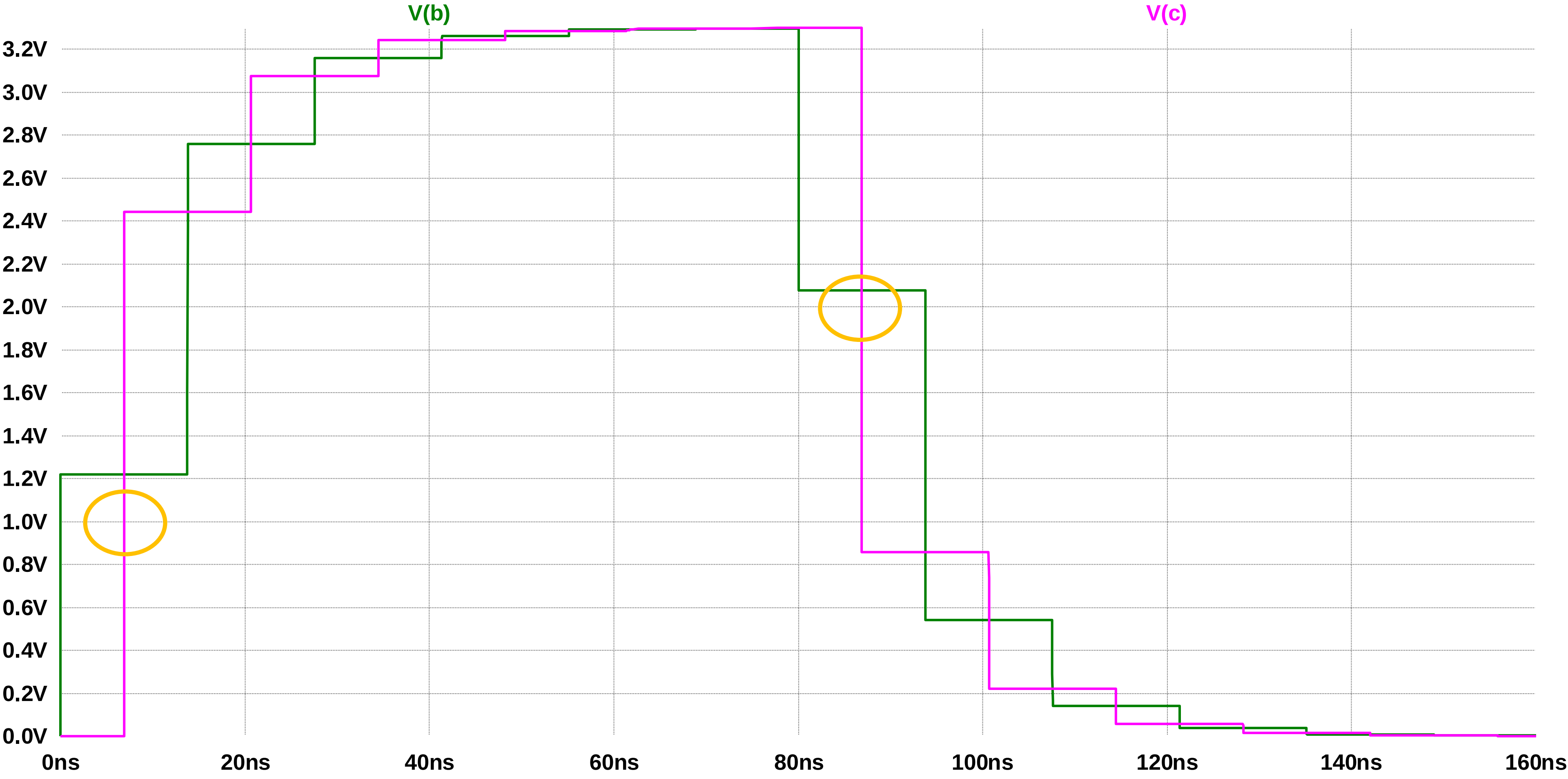
Exercise Ce8: b)

- Transmission time t_{TX} is a multiple of the propagation time, t_{P}
- From point a), t_{P} is minimum for $N = 2$ mounted boards
  - $t_{\mathrm{P}_2} = 6.89\ \mathrm{ns}$
  - $Z_{\infty_2} = \sqrt{\dfrac{L_{\mathrm{U}}}{C_{\mathrm{U}_2}}} = \sqrt{\dfrac{8\ \mathrm{nH/cm}}{2.57\ \mathrm{pF/cm}}} = 55.8\ \Omega$
  - $\Gamma_{\mathrm{G}_2} = \dfrac{R_{\mathrm{O}} - Z_{\infty_2}}{R_{\mathrm{O}} + Z_{\infty_2}} = \dfrac{95\ \Omega - 55.8\ \Omega}{95\ \Omega + 55.8\ \Omega} = 0.26$
  - $\Gamma_{\mathrm{T}} = 1$ (open termination)

Exercise Ce8: b)

- Two boards at ends B and C
  - Driver board at the end B
- $V_{\mathrm{B}_2}(0) = \dfrac{Z_{\infty_2}}{R_{\mathrm{G}} + Z_{\infty_2}} V_{\mathrm{AL}} = \dfrac{55.8\ \Omega}{95\ \Omega + 55.8\ \Omega} 3.3\ \mathrm{V} = 1.22\ \mathrm{V}$
- $t_{\mathrm{TX_{min}}}^{\mathrm{L\to H}}$ for transition L→H to match the minimum threshold, V_{IL}
  - $V_{B_2}(0) = 1.22\ \mathrm{V}$
  - $V_{\mathrm{C}_2}\left(\boldsymbol{t}_{\mathbf{P_2}}\right) = (1 + \Gamma_{\mathrm{T}}) V_{\mathrm{B}_2}(0) = (1 + 1) \cdot 1.22\ \mathrm{V} = 2.44\ \mathrm{V} > V_{\mathrm{IL}}$
- $t_{\mathrm{TX_{min}}}^{\mathrm{H\to L}}$ for transition H→L to match the maximum, V_{IH}
  - $V_{\mathrm{B}_2}(0) = V_{\mathrm{AL}} - \dfrac{Z_{\infty_2}}{R_{\mathrm{G}} + Z_{\infty_2}} V_{\mathrm{AL}} = 3.3\ \mathrm{V} - 1.22\ \mathrm{V} = 2.08\ \mathrm{V}$
  - $V_{\mathrm{C}_2}\left(\boldsymbol{t}_{\mathbf{P_2}}\right) = (1 + \Gamma_{\mathrm{T}})\left[-V_{\mathrm{B}_2}(0)\right] + V_{\mathrm{AL}} = 0.86\ \mathrm{V} < V_{\mathrm{IH}}$
- $t_{\mathrm{TX_{min}}} = t_{\mathrm{P}_2} = 6.89\ \mathrm{ns}$

Exercise Ce8: b)



Exercise Ce8: c)

- Transmission time t_{TX} is a multiple of the propagation time, t_{P}
- From the point a), t_{P} is maximum for $N = 24$ mounted boards
  - $t_{\mathrm{P}_{24}} = 18.53\ \mathrm{ns}$
  - $Z_{\infty_{24}} = \sqrt{\frac{L_{\mathrm{U}}}{C_{\mathrm{U}_{24}}}} = \sqrt{\frac{8\ \mathrm{nH/cm}}{18.61\ \mathrm{pF/cm}}} = 20.7\ \Omega$
  - $\Gamma_{\mathrm{G}_{24}} = \frac{R_{\mathrm{O}} - Z_{\infty_{24}}}{R_{\mathrm{O}} + Z_{\infty_{24}}} = \frac{95\ \Omega - 20.7\ \Omega}{95\ \Omega + 20.7\ \Omega} = 0.64$
  - $\Gamma_{\mathrm{T}} = 1$ (open termination)

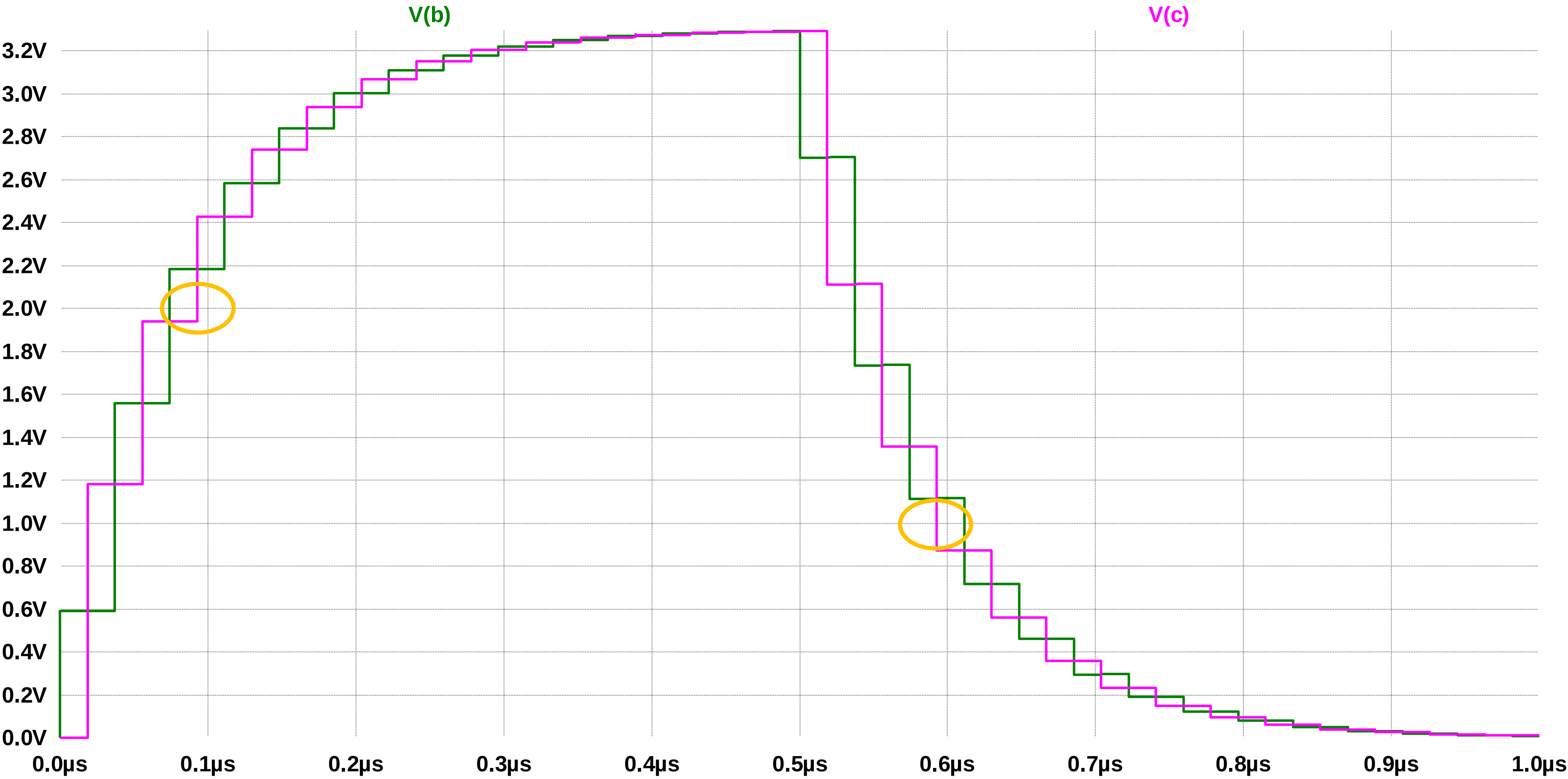
Exercise Ce8: c)

- Boards driven from the B end
- The most distant board is mounted at the C end
- $V_{\mathrm{B}_{24}}^{\mathrm{L}\to\mathrm{H}}(0)=\dfrac{Z_{\infty_{24}}}{R_{\mathrm{G}_{24}}+Z_{\infty_{24}}}V_{\mathrm{AL}}=\dfrac{20.7\ \Omega}{95\ \Omega+20.7\ \Omega}\cdot 3.3\ \mathrm{V}=0.59\ \mathrm{V}$

- $t_{\mathrm{TX}_{\max}}^{\mathrm{L}\to\mathrm{H}}$ for L→H transition
  - Comparison with the maximum threshold, $V_{\mathrm{TH}}=V_{\mathrm{IH}}$
  - $V_{\mathrm{C}_{24}}^{\mathrm{L}\to\mathrm{H}}(t_{\mathrm{P}})=(1+\Gamma_{\mathrm{T}})V_{\mathrm{B}_{24}}^{\mathrm{L}\to\mathrm{H}}(0)=(1+1)\cdot 0.59\ \mathrm{V}=1.18\ \mathrm{V}<V_{\mathrm{IH}}$
  - $V_{\mathrm{C}_{24}}^{\mathrm{L}\to\mathrm{H}}(3\ t_{\mathrm{P}})=\left(1+\Gamma_{\mathrm{T}}+\Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}_{24}}+\Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}_{24}}\right)V_{\mathrm{B}_{24}}^{\mathrm{L}\to\mathrm{H}}(0)=$
    $[1+1+1\cdot 0.64+1^2\cdot 0.64]\cdot 0.59\ \mathrm{V}=1.94\ \mathrm{V}<V_{\mathrm{IH}}$
  - $V_{\mathrm{C}_{24}}^{\mathrm{L}\to\mathrm{H}}(\mathbf{5}\ \boldsymbol{t}_{\mathbf{P}})=\left(1+\Gamma_{\mathrm{T}}+\Gamma_{\mathrm{T}}\Gamma_{\mathrm{G}_{24}}+\Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}_{24}}+\Gamma_{\mathrm{T}}^2\Gamma_{\mathrm{G}_{24}}^2+\Gamma_{\mathrm{T}}^3\Gamma_{\mathrm{G}_{24}}^2\right)V_{\mathrm{B}_{24}}^{\mathrm{L}\to\mathrm{H}}(0)=$
    $[1+1+1\cdot 0.64+1^2\cdot 0.64+1^2\cdot 0.64^2+1^3\cdot 0.64^2]\cdot 0.59\ \mathrm{V}=$
    $2.42\ V>V_{\mathrm{IH}}$

- $t_{\mathrm{TX_{max}}}^{\mathrm{H\to L}}$ for H→L transitions
  - Comparison with the minimum threshold, $V_{\mathrm{TH}} = V_{\mathrm{IL}}$
  - $V_{\mathrm{C_{24}}}^{\mathrm{H\to L}}(t_{\mathrm{P}}) = (1+\Gamma_{\mathrm{T}})\left[-V_{\mathrm{B_{24}}}^{\mathrm{L\to H}}(0)\right] + V_{\mathrm{AL}} =$
    $2\cdot(-0.59\ \mathrm{V}) + 3.3\ \mathrm{V} = 2.12\ \mathrm{V} > V_{\mathrm{IL}}$
  - $V_{\mathrm{C_{24}}}^{\mathrm{H\to L}}(3\ t_{\mathrm{P}}) = \left(1+\Gamma_{\mathrm{T}}+\Gamma_{\mathrm{T}}\Gamma_{\mathrm{G_{24}}}+\Gamma_{\mathrm{T}}^{2}\Gamma_{\mathrm{G_{24}}}\right)\left[-V_{\mathrm{B_{24}}}^{\mathrm{L\to H}}(0)\right] + V_{\mathrm{AL}} =$
    $[1+1+1\cdot 0.64+1^{2}\cdot 0.64]\cdot(-0.59\ \mathrm{V}) + 3.3\ \mathrm{V} = 1.36\ \mathrm{V} > V_{\mathrm{IL}}$
  - $V_{\mathrm{C_{24}}}^{\mathrm{H\to L}}(\mathbf{5}\ \boldsymbol{t_{\mathrm{P}}}) = \left(1+\Gamma_{\mathrm{T}}+\Gamma_{\mathrm{T}}\Gamma_{\mathrm{G_{24}}}+\Gamma_{\mathrm{T}}^{2}\Gamma_{\mathrm{G_{24}}}+\Gamma_{\mathrm{T}}^{2}\Gamma_{\mathrm{G_{24}}}^{2}+\Gamma_{\mathrm{T}}^{3}\Gamma_{\mathrm{G_{24}}}^{2}\right)\left[-V_{\mathrm{B_{24}}}^{\mathrm{L\to H}}(0)\right] + V_{\mathrm{AL}} =$
    $[1+1+1\cdot 0.64+1^{2}\cdot 0.64+1^{2}\cdot 0.64^{2}+1^{3}\cdot 0.64^{2}]\cdot(-0.59\ \mathrm{V}) + 3.3\ \mathrm{V}$
    $= 0.88\ V < V_{\mathrm{IL}}$
- $t_{\mathrm{TX_{max}}}^{\mathrm{H\to L}} = 5\ t_{\mathrm{P}} = 5\cdot 18.53\ \mathrm{ns} = 92.7\ \mathrm{ns}$

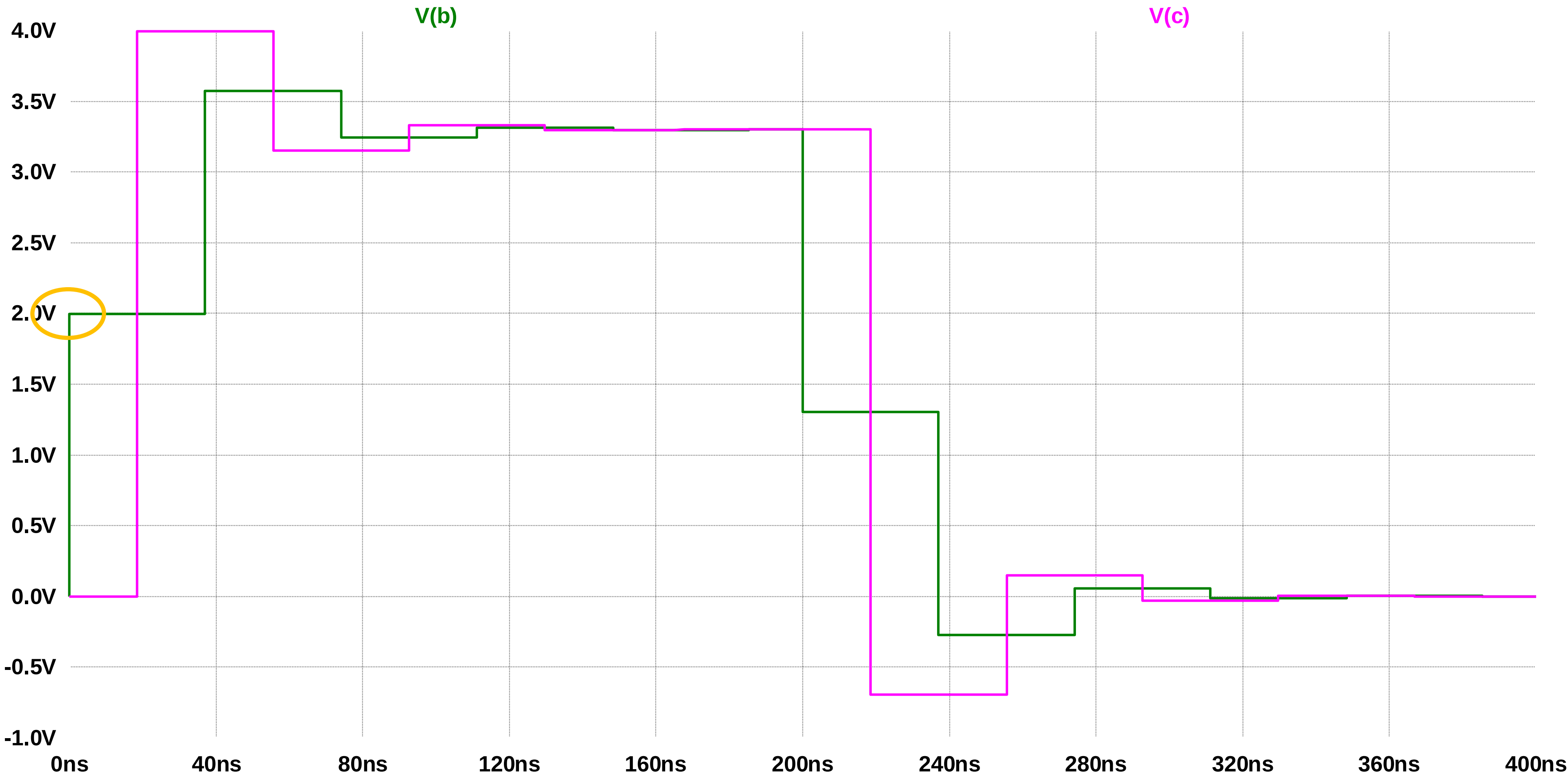
Exercise Ce8: c)



Exercise Ce8: d)

- With 24 boards mounted we know from c)
  - $Z_{\infty_{24}} = 20.7\ \Omega$
- It is required R_{OH}, which applies to the transition L→H
  - $V_{\mathrm{B}_{24}}^{\mathrm{L}\to\mathrm{H}}(0) = \frac{Z_{\infty_{24}}}{R_{\mathrm{OH}} + Z_{\infty_{24}}} V_{\mathrm{AL}} \geq V_{\mathrm{IH}}$ for IWS
  - $R_{\mathrm{OH}} \leq \mathrm{Z}_{\infty_{24}} \left(\frac{V_{\mathrm{AL}}}{V_{\mathrm{IH}}} - 1\right) = 20.7\ \Omega \cdot \left(\frac{3.3\ \mathrm{V}}{2\ \mathrm{V}} - 1\right)$ ➔ $R_{\mathrm{OH}} \leq 13.5\ \Omega$

Exercise Ce8: d)



Summary of exercises Ce

- Calculation of delays (transmission time, skew) with RC model.

- Calculation of delays (propagation time, transmission, skew) with line model.

- Behavior under different termination conditions.

- Overall timing and worst-case analysis for synchronous and asynchronous cycles, depending on:
  - Transmission system parameters (RC or lines)
  - Component parameters (driver, receiver)
  - Termination conditions