Applied Electronics

C3 – Interconnections with transmission lines

- Incident wave switching
- Reflected wave switching
- Delays and skew
- Terminations

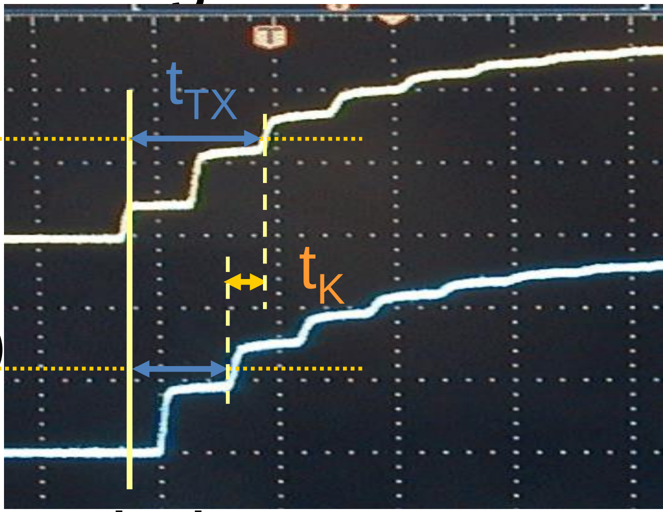
Lecture C3: Interconnections With Transmission Lines

- Incident Wave and Reflected Wave Switching
- Delays and skew
- Terminations

- References:
  - D. Del Corso: Interconnections for high-speed…: lectures 1, 2

Transmission time and skew

- Transmission time t_{TX} is the delay until the signal crosses receiver threshold (V_T). Depends on:
  - Interconnection parameters
  - Driver and Receiver parameters
  - Operating conditions (V_{DD}, temperature, …)
  - Receiver position on the line

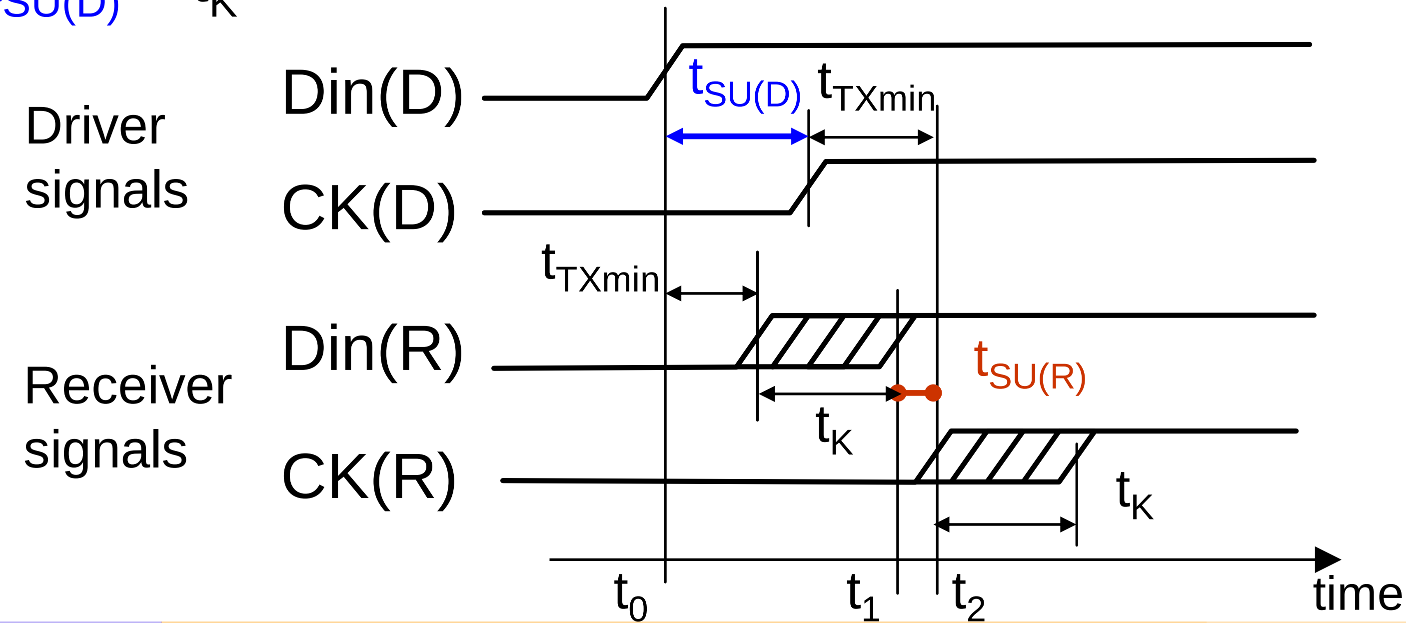


- Skew t_K (misalignment) comes from t_{TX} variations
- Objectives
  - Minimize delay and variations (low skew)
  - Avoid multiple crossings
  - Reduce power consumption

- Skew changes the temporal relationships between signals
  - Set-up time, t_{SU}, is reduced by t_K

$t_1 = t_0 + t_{TXmin} + t_K$ $\quad\quad$ $t_2 = t_0 + t_{SU(D)} + t_{TXmin}$

$t_{SU(R)} = t_2 - t_1 = t_{SU(D)} - t_K$



What are the causes of skew?

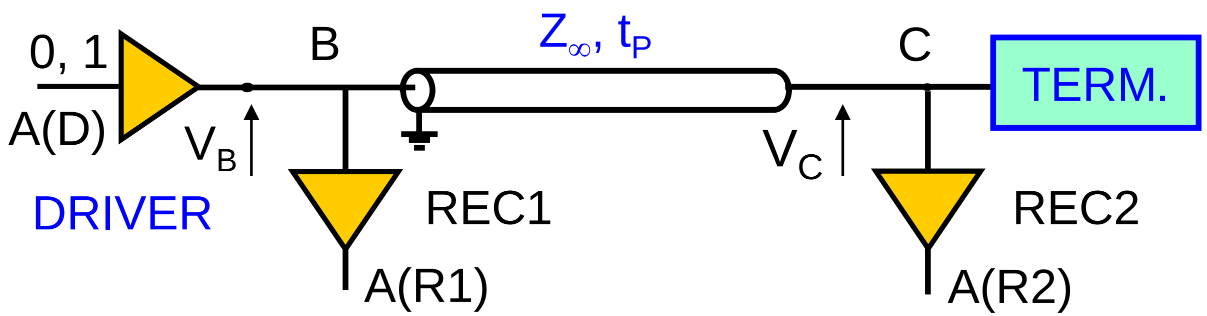
- Basic problem: timing misalignment due to skew, t_K, from variations in the transmission time: $t_K = t_{TXmax} - t_{TXmin}$
- Evaluate and check skew, t_K → signal integrity problem
  - Analysis of timing constraints of logic circuits → this course
  - Signal propagation mechanisms → electromagnetic fields
- Parameters that affect transmission t_{TX} and skew t_K times
  - TX and RX parameters
    - V_H, V_L, V_T, ...
  - Propagation
    - Reflections, terminations, discontinuities, crosstalk
  - Load, especially capacitive loads
  - Ground bounce and switching noise

Connection topologies

- Point-to-point connections
  - ♦ Driver at one end (left) → near side, near-end
  - ♦ Receiver at the other end (right) → remote side, far-end
  - ♦ Propagation conditions are well defined
- Bus connections
  - ♦ Multi-point communication structures
  - ♦ Driver at one end or at an intermediate point
  - ♦ Several receivers, in various positions
    - Variable load, discontinuity
    - Variable propagation parameters

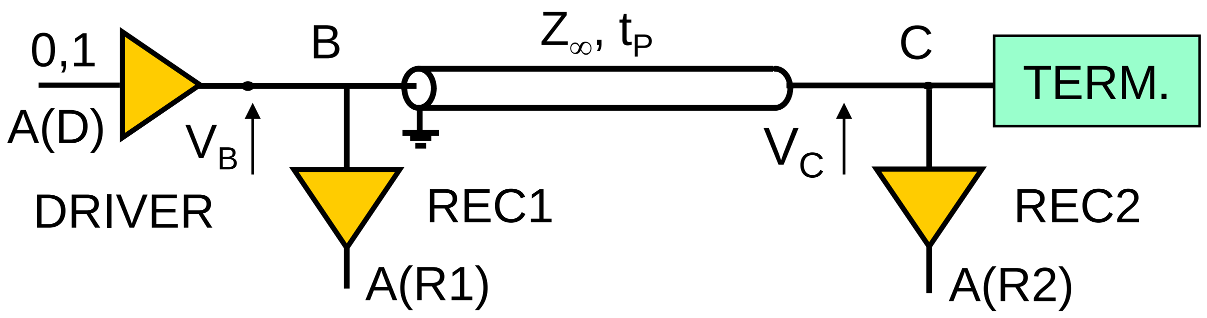
Reference structure

- Driver circuit at far left (near-end)
- Transmission line with parameters Z_∞, t_P
- A termination at far right (far-end)
- Receivers in any position
  - At the driver, at the termination (near/far end), intermediate, ...



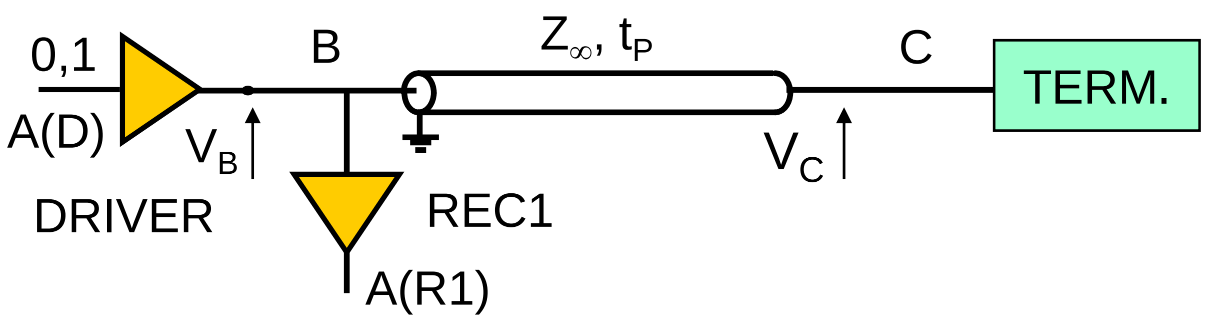
Skew overall (or global)

- The overall skew t_{KC} includes variations of t_{TX} due to
  - Parameter dispersion (V_T, C_P, ...)
  - Different receiver positions (near, far, intermediate)
- Typically, it is not relevant to the protocols (next lecture)
- Overall skew between all receivers
  - $t_{KC} = \max(t_{TXmaxi}) - \min(t_{TXminj})$



Local skew

- Local skew, t_K, includes variations of t_{TX} caused *only* by parameter dispersion (V_T, C_P, ...)
  - It is the skew between different ports of a single receiver (card)
- Local skew for receiver i:
  - $t_K = \max(t_{TXmaxi}) - \min(t_{TXmini})$



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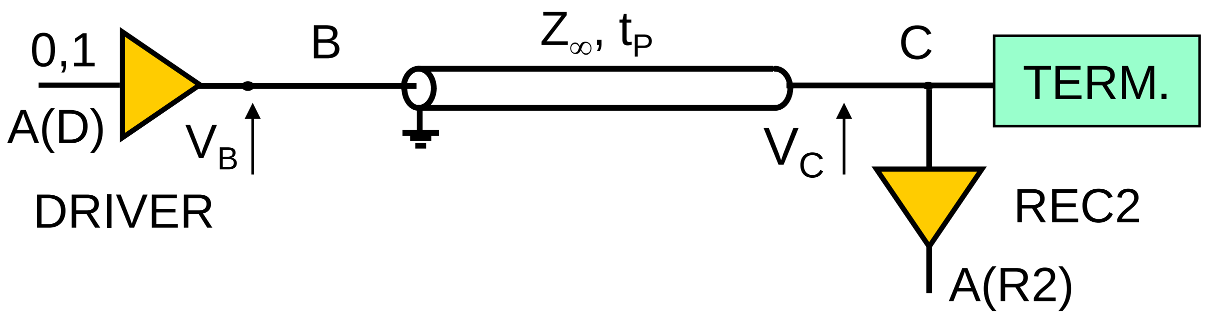
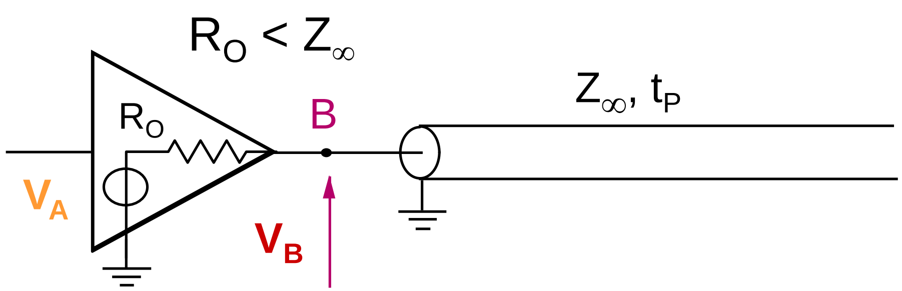


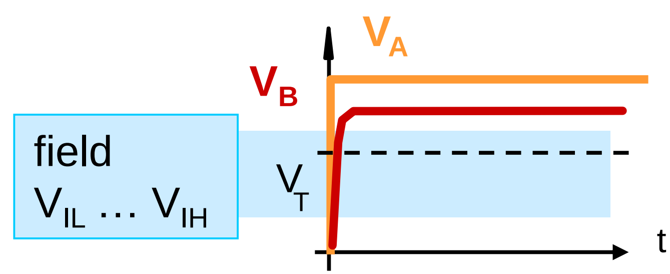
First voltage step

- Driver transition: first voltage step
  - Causes an incident wave that propagates along the line
- On transition, the driver is loaded with Z_∞
  - The amplitude of the first step depends on the ratio R_O / Z_∞
- The termination can reflect the signal
  - The signal on the line is the sum of the incident wave and the reflections
- Analysis for three cases
  - Low R_O / Z_∞: ($R_O < Z_\infty$) → fast buses
  - High R_O / Z_∞: ($R_O > Z_\infty$) → slow buses
  - Driver adapted: $R_O = Z_\infty$ → good compromise

High Current Driver: Low R_O / Z_∞ → IWS

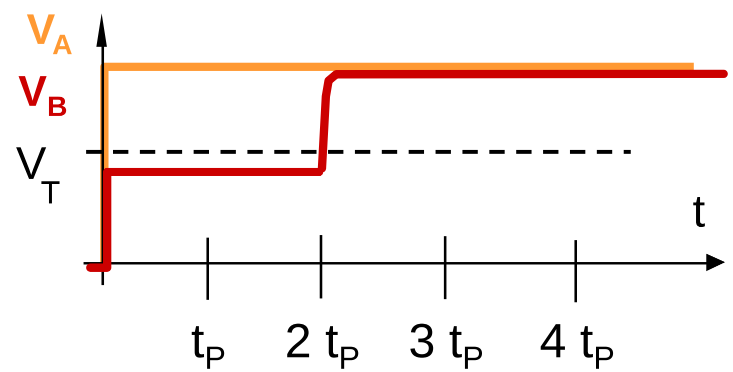
- Low R_O / Z_∞ → $R_O < Z_\infty$ → high first step
  - ♦ Receiver threshold is crossed by the first step
  - ♦ Incident Wave Switching (IWS), low t_{TX}, fast
    - Used in high-speed buses
  - ♦ $\Gamma_D < 0$ → negative reflection at the driver
    - Oscillations → possible multiple crossings of the threshold
    - Requires termination to the far end (suitable for buses)
    - The termination dissipates energy



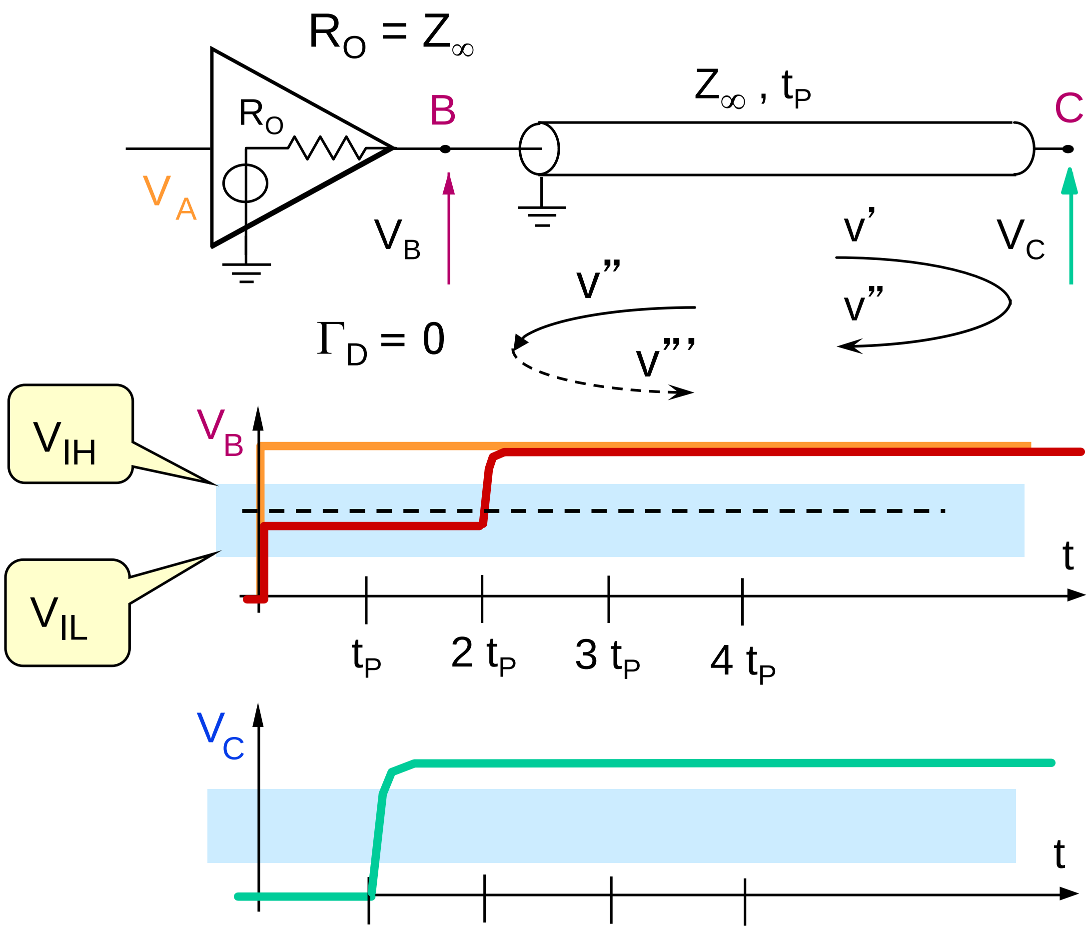


Adapted driver: $R_O = Z_\infty$

- $R_O = Z_\infty$ → driver-side adaptation
  - ♦ Adaptation at the Near End (possible series termination)
  - ♦ First step amplitude equal to half of the steady state voltage
  - ♦ The threshold V_T is crossed by the first reflection
    - Reflected Wave Switching (RWS)
- $\Gamma_D = 0$ → no reflection at the driver end
  - ♦ Suitable for point-to-point connections
- Compared to IWS
  - ♦ Slower
  - ♦ Lower consumption



Switching on the reflected wave



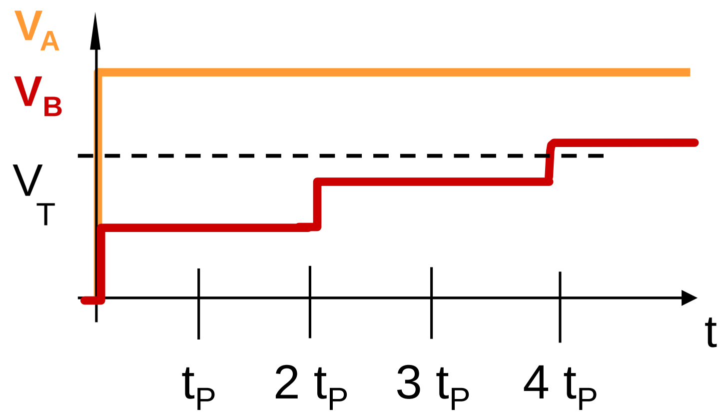
$\Gamma_T = 1$
$v' = v''$

$t_{TX} = 0 \ldots 2\ t_P$

$t_{TX} = t_P$

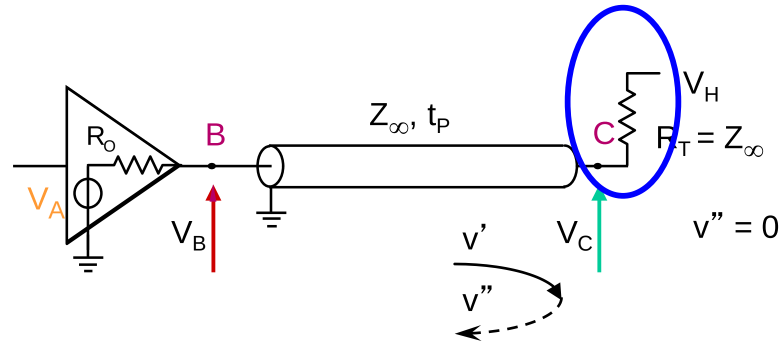
Low current driver: high R_O / Z_∞

- High R_O / Z_∞ ratio ($R_O > Z_\infty$)
  - Lower first voltage step
  - The first step cannot cross the threshold
- $\Gamma_T > 0$ → positive reflection on termination
- $\Gamma_D > 0$ → positive reflection on the driver
  - All reflected waves have the same polarity
  - Slow and monotonous change, no oscillations
  - Thresholds crossed after multiple reflections
- High t_{TX}, slow operation

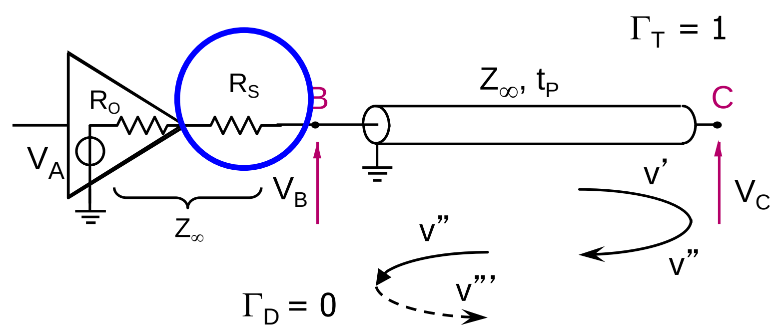


Types of termination

- Parallel termination
  - \+ Low delay
  - \+ Compatible with a driver connected to an intermediate point
  - \- High power consumption



- Series termination
  - \+ Low power consumption
  - \- Higher delay
  - \- Cannot be driven from an intermediate point (different impedances viewed from the driver towards the line)



Effects of capacitive load

- A capacitive load on the line
  - Reduces the characteristic impedance Z_∞
  - Reduces the propagation speed P
  - Reduces the first step amplitude
  - Increases dynamic power consumption P_D
- Must limit capacitive loads
  - Separation buffers
  - Surface Mount Devices (SMD)
  - Reduce length of PCB traces
  - Careful layout

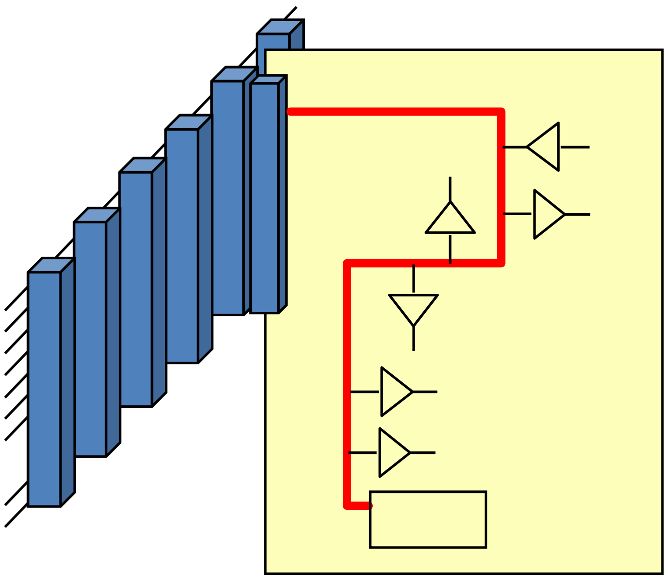
$$Z_\infty = \sqrt{\frac{L}{C}}$$

$$P = \sqrt{\frac{1}{LC}}$$

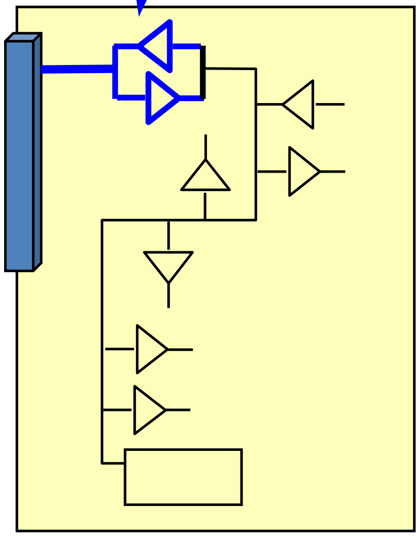
$$P_D = F\,V^2\,C$$

Multi-point connection (bus)

- Limit the stubs and capacitive loads
  - Do not connect directly the bus to the circuit boards
  - Use buffers or transceivers (close to the connector)



Wrong – high C



Correct – low C

Summary

- Incident Wave Switching
  - $t_{TXmin} = 0$, $t_{TXmax} = t_P$, $t_K = t_P$ (between RXs at line ends)
  - Fast
  - Static energy (dissipation in the terminations)
- Reflected Wave Switch (first reflection)
  - $t_{TXmin} = t_P$, $t_{TXmax} = 2\ t_P$, $t_K = t_P$ (between RXs at line ends)
  - Average speed, low power
  - Best for point-to-point connections
- Multiple Reflections Switching
  - $t_{TXmax} = N \cdot 2\ t_P$, N depends on voltage division at driver
  - Slow

Objectives of protocols at cycle level

- Registers have timing specifications (setup and hold)
- Electrical parameter propagation and spread change the temporal relationships (→ skew)
  - The skew modifies the set-up and hold times
  - It can cause metastability in flip-flops and registers
- To achieve high speeds
  - Minimize skew → this lecture
  - Ensure timing specifications: cycle level protocols
- Cycle-level protocols must guarantee correct information transfer despite skew-induced variations of temporal relations

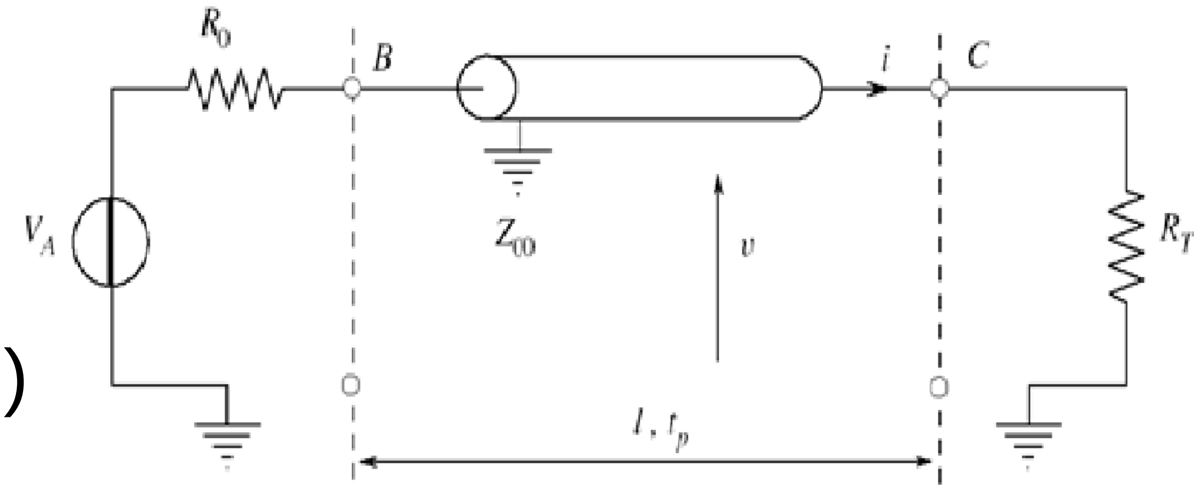
Exercise C3.1: transmission delay evaluation

- A point-to-point interconnection has:
  - $Z_\infty = 70\ \Omega$, $t_P = 10$ ns
  - Supply: $V_{AL} = 5$ V
  - Receiver: $V_{IHmin} = 3$ V, $V_{IHmax} = 4$ V
- Combinations for the other parameters

	a	b	c	d	e	f
R_O [Ω]	100	100	50	50	10	10
R_T [Ω]	∞	200	200	100	100	10

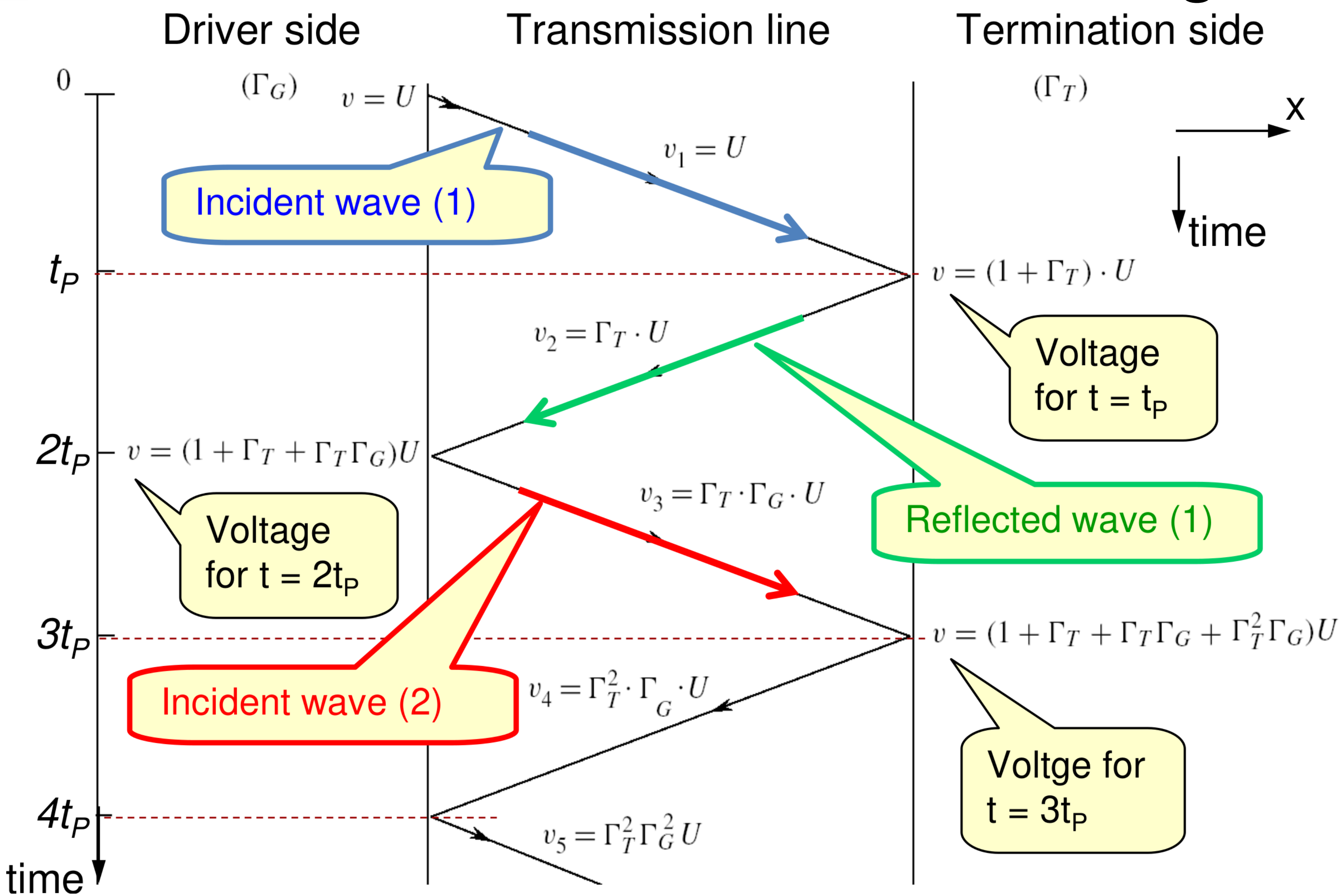
- For a low-to-high transition in the different cases
  - Draw the qualitative evolution of the driver and receiver signals
  - Calculate and compare the transmission time, t_{TX}, and skew, t_K

- Driver-end (near-end) reflection coefficient
  - $\Gamma_D = \frac{R_O - Z_\infty}{R_O + Z_\infty}$
- Receiver-end (far-end) reflection coefficient
  - $\Gamma_T = \frac{R_T - Z_\infty}{R_T + Z_\infty}$



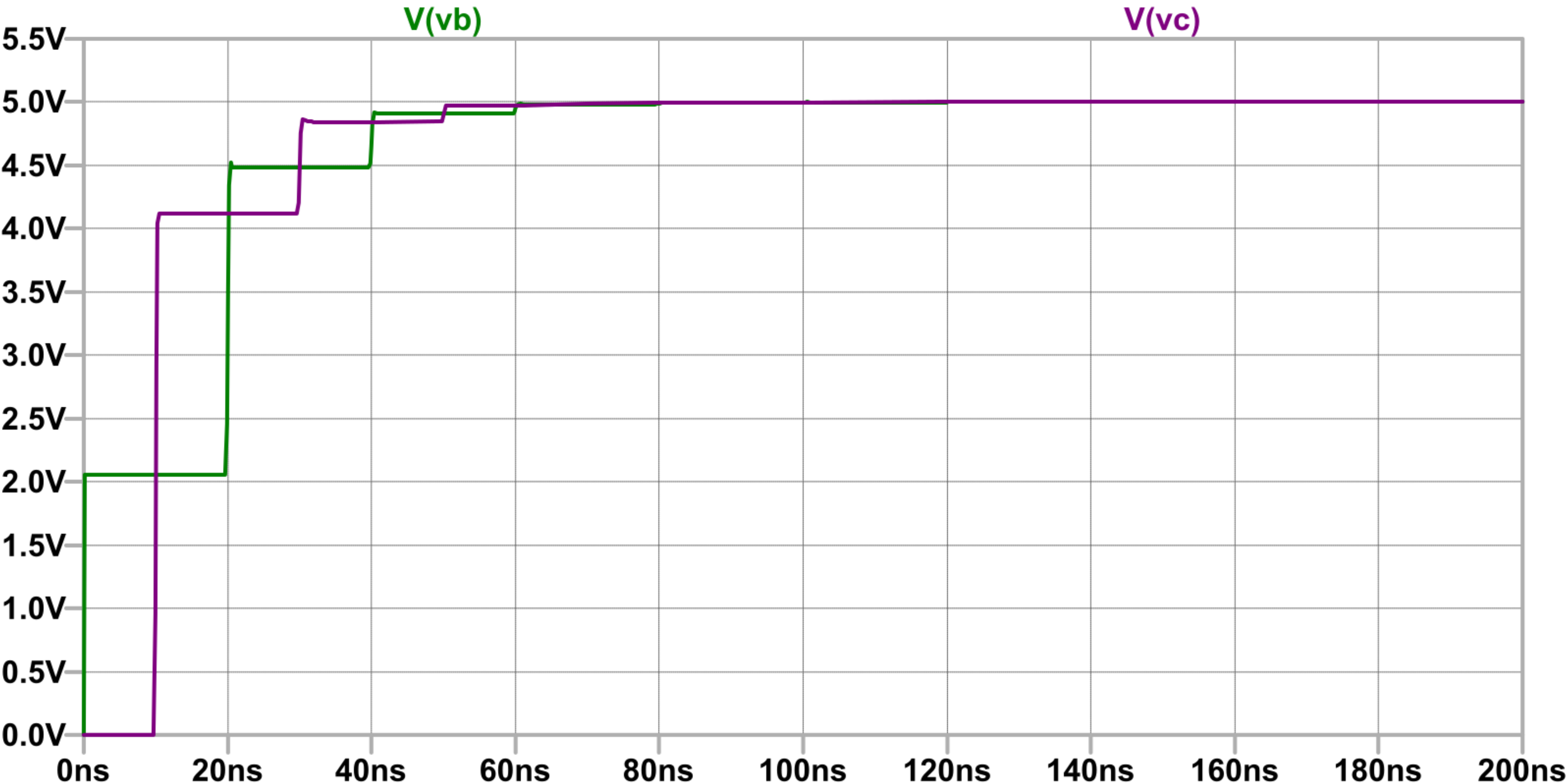
- Steady state line voltage $$V_{\text{steady}} = \frac{R_T}{R_O + R_T} V_A$$
- Incident wave $$v_1 = V_B(0) = \frac{Z_\infty}{R_O + Z_\infty} V_A$$
- First reflected wave $$v_2 = \Gamma_T v_1 = \frac{R_T - Z_\infty}{R_T + Z_\infty} v_1$$

Exercise C3.1: transmission delay evaluation: waves on the lattice diagram



Exercise C3.1: transmission delay evaluation: (a) – calculations

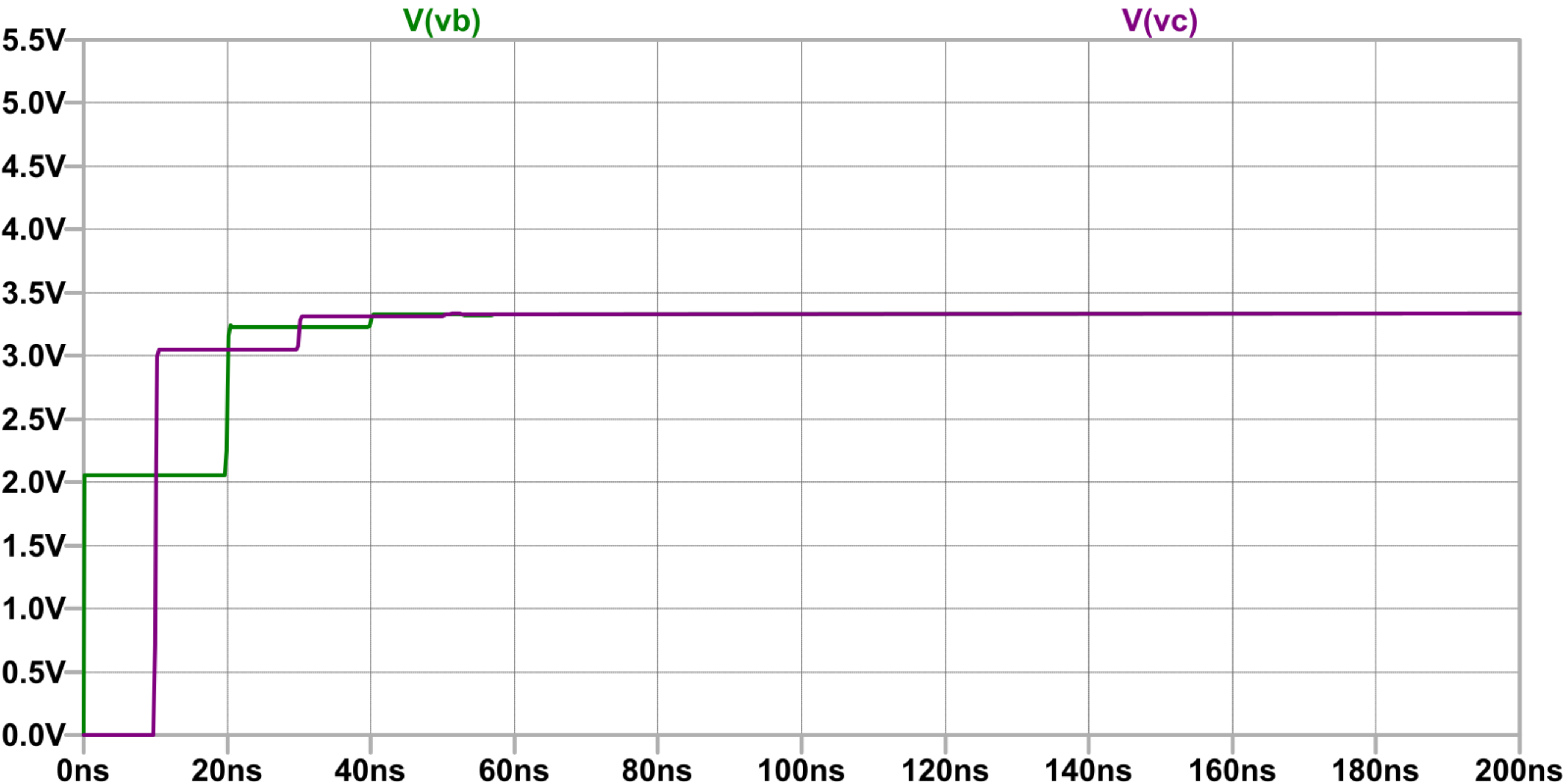
- $\Gamma_D = \frac{R_O - Z_\infty}{R_O + Z_\infty} = \frac{100\ \Omega - 70\ \Omega}{100\ \Omega + 70\ \Omega} = \frac{30\ \Omega}{170\ \Omega} = 0.18 > 0$
- $\Gamma_T = \frac{R_T - Z_\infty}{R_T + Z_\infty} = \frac{(R_T \to \infty) - 70\ \Omega}{(R_T \to \infty) + 70\ \Omega} = 1 > 0$
- $V_{\text{steady}} = \frac{R_T}{R_O + R_T} V_A = \frac{(R_T \to \infty)}{100\ \Omega + (R_T \to \infty)} \cdot 5\ \text{V} = 5\ \text{V}$
- $v_1 = V_B(0) = \frac{Z_\infty}{R_O + Z_\infty} V_A = \frac{70\ \Omega}{100\ \Omega + 70\ \Omega} \cdot 5\ \text{V} = 2.06\ \text{V}$
- $v_2 = \Gamma_T v_1 = 1 \cdot 2.06\ \text{V} = 2.06\ \text{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = 0.18 \cdot 1 \cdot 2.06\ \text{V} = 0.37\ \text{V}$
- $v_4 = \cdots$


V(vb)
V(vc)
5.5V
5.0V
4.5V
4.0V
3.5V
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
0ns
20ns
40ns
60ns
80ns
100ns
120ns
140ns
160ns
180ns
200ns

Exercise C3.1: transmission delay evaluation: (b) – calculations

- $\Gamma_D = \dfrac{R_O - Z_\infty}{R_O + Z_\infty} = \dfrac{100\ \Omega - 70\ \Omega}{100\ \Omega + 70\ \Omega} = \dfrac{30\ \Omega}{170\ \Omega} = 0.18 > 0$
- $\Gamma_T = \dfrac{R_T - Z_\infty}{R_T + Z_\infty} = \dfrac{200\ \Omega - 70\ \Omega}{200\ \Omega + 70\ \Omega} = 0.48 > 0$
- $V_{\text{steady}} = \dfrac{R_T}{R_O + R_T} V_A = \dfrac{200\ \Omega}{100\ \Omega + 200\ \Omega} \cdot 5\ \text{V} = 3.33\ \text{V}$
- $v_1 = V_B(0) = \dfrac{Z_\infty}{R_O + Z_\infty} V_A = \dfrac{70\ \Omega}{100\ \Omega + 70\ \Omega} \cdot 5\ \text{V} = 2.06\ \text{V}$
- $v_2 = \Gamma_T v_1 = 0.48 \cdot 2.06\ \text{V} = 0.99\ \text{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = 0.18 \cdot 0.48 \cdot 2.06\ \text{V} = 0.18\ \text{V}$
- $v_4 = \cdots$

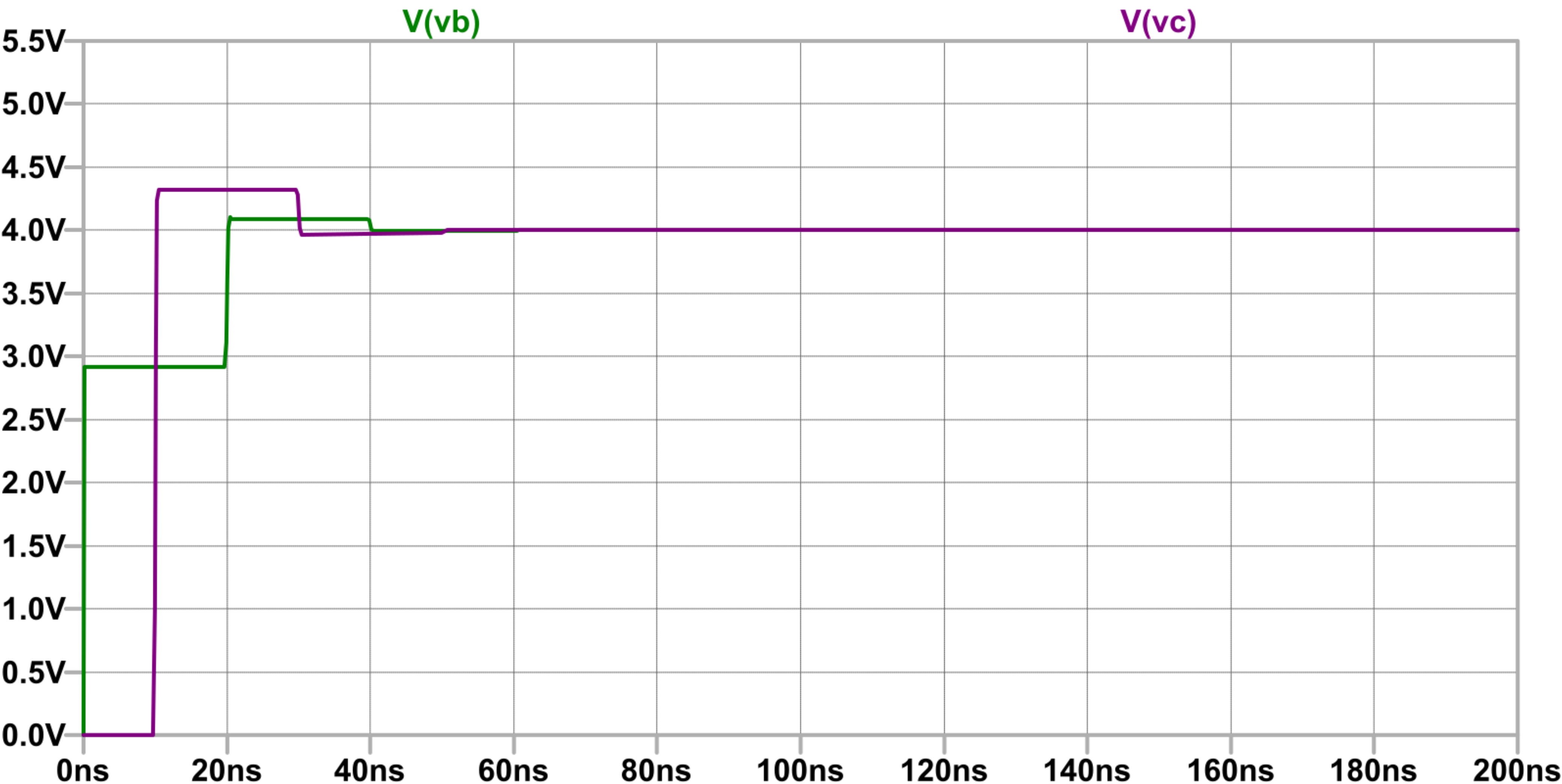
Exercise C3.1: transmission delay evaluation: waveforms (b)



Exercise C3.1: transmission delay evaluation: (c) – calculations

- $\Gamma_D = \dfrac{R_O - Z_\infty}{R_O + Z_\infty} = \dfrac{50\ \Omega - 70\ \Omega}{50\ \Omega + 70\ \Omega} = \dfrac{-20\ \Omega}{120\ \Omega} = -0.17 < 0$
- $\Gamma_T = \dfrac{R_T - Z_\infty}{R_T + Z_\infty} = \dfrac{200\ \Omega - 70\ \Omega}{200\ \Omega + 70\ \Omega} = 0.48 > 0$
- $V_{\text{steady}} = \dfrac{R_T}{R_O + R_T} V_A = \dfrac{200\ \Omega}{50\ \Omega + 200\ \Omega} \cdot 5\ \text{V} = 4\ \text{V}$
- $v_1 = V_B(0) = \dfrac{Z_\infty}{R_O + Z_\infty} V_A = \dfrac{70\ \Omega}{50\ \Omega + 70\ \Omega} \cdot 5\ \text{V} = 2.92\ \text{V}$
- $v_2 = \Gamma_T v_1 = 0.48 \cdot 2.92\ \text{V} = 1.40\ \text{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = -0.17 \cdot 0.48 \cdot 2.92\ \text{V} = -0.24\ \text{V}$
- $v_4 = \cdots$

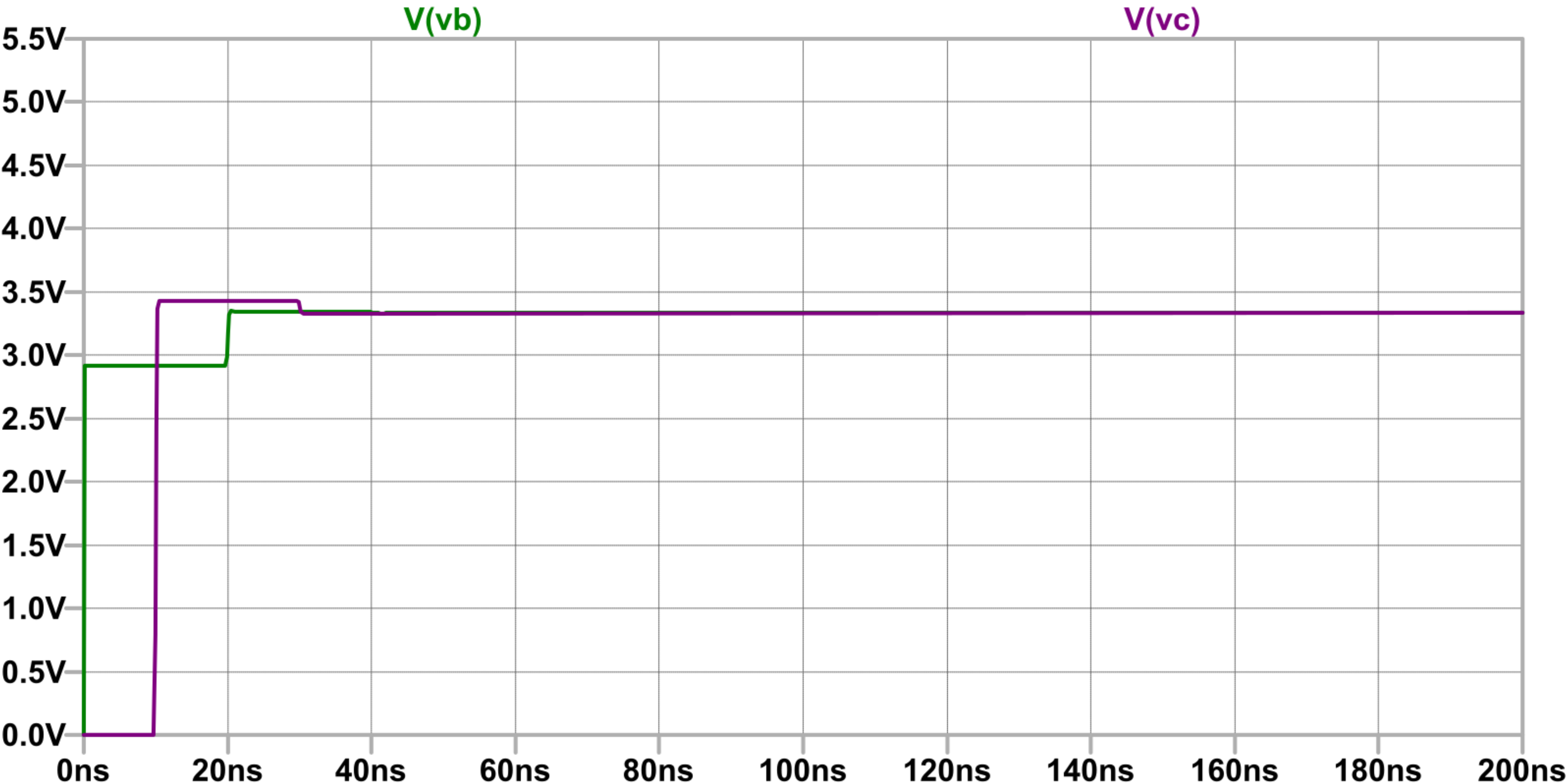
Exercise C3.1: transmission delay evaluation: waveforms (c)



Exercise C3.1: transmission delay evaluation: (d) – calculations

- $\Gamma_D = \dfrac{R_O - Z_\infty}{R_O + Z_\infty} = \dfrac{50\ \Omega - 70\ \Omega}{50\ \Omega + 70\ \Omega} = \dfrac{-20\ \Omega}{120\ \Omega} = -0.17 < 0$
- $\Gamma_T = \dfrac{R_T - Z_\infty}{R_T + Z_\infty} = \dfrac{100\ \Omega - 70\ \Omega}{100\ \Omega + 70\ \Omega} = 0.18 > 0$
- $V_{\text{steady}} = \dfrac{R_T}{R_O + R_T} V_A = \dfrac{100\ \Omega}{50\ \Omega + 100\ \Omega} \cdot 5\ \text{V} = 3.33\ \text{V}$
- $v_1 = V_B(0) = \dfrac{Z_\infty}{R_O + Z_\infty} V_A = \dfrac{70\ \Omega}{50\ \Omega + 70\ \Omega} \cdot 5\ \text{V} = 2.92\ \text{V}$
- $v_2 = \Gamma_T v_1 = 0.18 \cdot 2.92\ \text{V} = 0.53\ \text{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = -0.17 \cdot 0.18 \cdot 2.92\ \text{V} = -0.09\ \text{V}$
- $v_4 = \cdots$

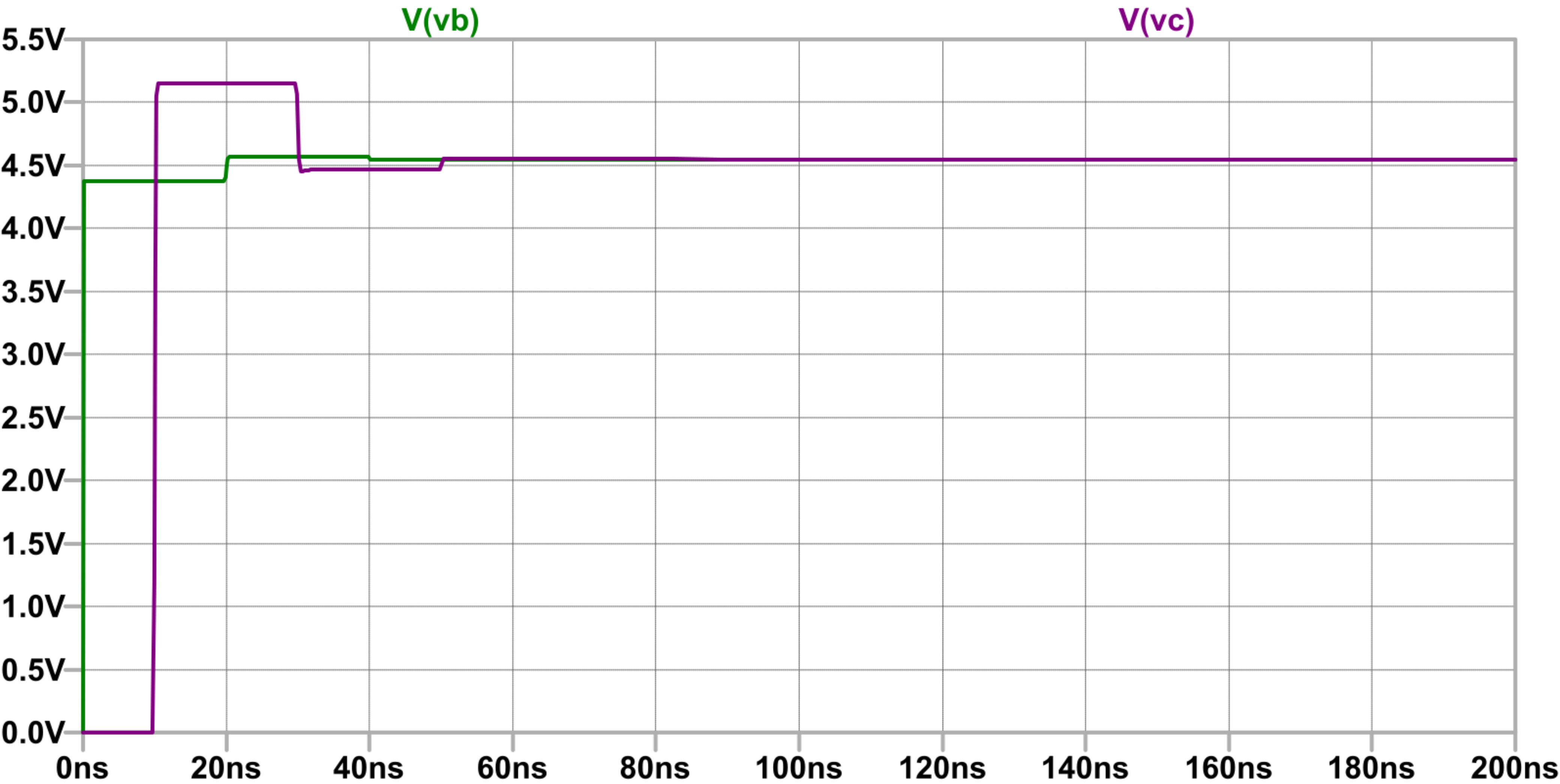
Exercise C3.1: transmission delay evaluation: waveforms (d)



Exercise C3.1: transmission delay evaluation: (e) – calculations

- $\Gamma_D = \dfrac{R_O - Z_\infty}{R_O + Z_\infty} = \dfrac{10\ \Omega - 70\ \Omega}{10\ \Omega + 70\ \Omega} = \dfrac{-60\ \Omega}{80\ \Omega} = -0.75 < 0$
- $\Gamma_T = \dfrac{R_T - Z_\infty}{R_T + Z_\infty} = \dfrac{100\ \Omega - 70\ \Omega}{100\ \Omega + 70\ \Omega} = 0.18 > 0$
- $V_{\text{steady}} = \dfrac{R_T}{R_O + R_T} V_A = \dfrac{100\ \Omega}{10\ \Omega + 100\ \Omega} \cdot 5\ \text{V} = 4.55\ \text{V}$
- $v_1 = V_B(0) = \dfrac{Z_\infty}{R_O + Z_\infty} V_A = \dfrac{70\ \Omega}{10\ \Omega + 70\ \Omega} \cdot 5\ \text{V} = 4.38\ \text{V}$
- $v_2 = \Gamma_T v_1 = 0.18 \cdot 4.38\ \text{V} = 0.79\ \text{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = -0.75 \cdot 0.18 \cdot 4.38\ \text{V} = -0.59\ \text{V}$
- $v_4 = \cdots$

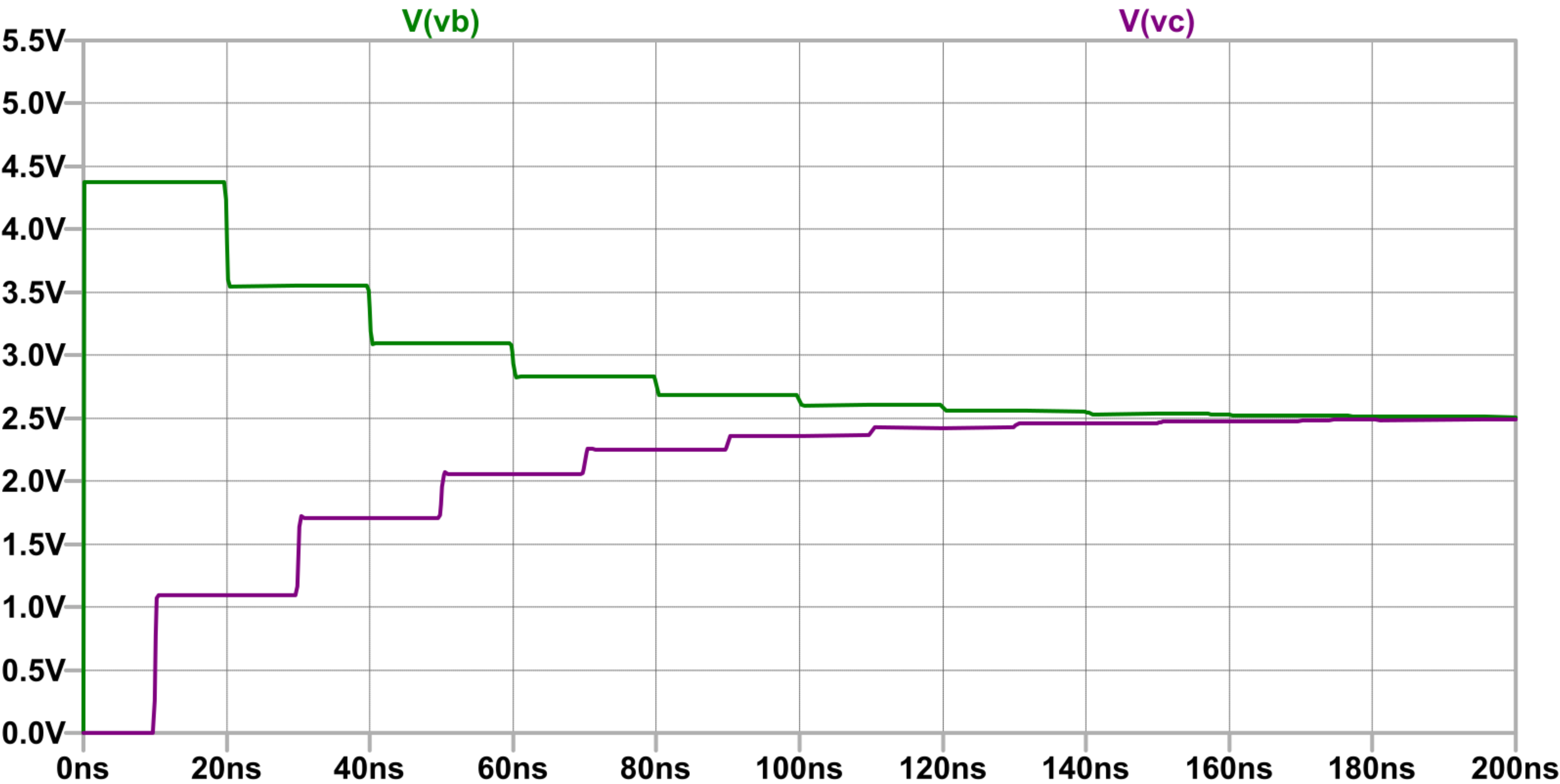
Exercise C3.1: transmission delay evaluation: waveforms (e)



Exercise C3.1: transmission delay evaluation: (f) – calculations

- $\Gamma_D = \dfrac{R_O - Z_\infty}{R_O + Z_\infty} = \dfrac{10\ \Omega - 70\ \Omega}{10\ \Omega + 70\ \Omega} = \dfrac{-60\ \Omega}{80\ \Omega} = -0.75 < 0$
- $\Gamma_T = \dfrac{R_T - Z_\infty}{R_T + Z_\infty} = \dfrac{10\ \Omega - 70\ \Omega}{10\ \Omega + 70\ \Omega} = -0.75 < 0$
- $V_{\mathrm{steady}} = \dfrac{R_T}{R_O + R_T} V_A = \dfrac{10\ \Omega}{10\ \Omega + 10\ \Omega} \cdot 5\ \mathrm{V} = 2.50\ \mathrm{V}$
- $v_1 = V_B(0) = \dfrac{Z_\infty}{R_O + Z_\infty} V_A = \dfrac{70\ \Omega}{10\ \Omega + 70\ \Omega} \cdot 5\ \mathrm{V} = 4.38\ \mathrm{V}$
- $v_2 = \Gamma_T v_1 = -0.75 \cdot 4.38\ \mathrm{V} = -3.29\ \mathrm{V}$
- $v_3 = \Gamma_D\ \Gamma_T\ v_1 = -0.75 \cdot (-0.75) \cdot 4.38\ \mathrm{V} = 2.46\ \mathrm{V}$
- $v_4 = \cdots$

Exercise C3.1: transmission delay evaluation: waveforms (f)



Exercise C3.2: parameter selection

- For the interconnection of exercise C3.1
  - Z_∞ = 70 Ω, t_P = 10 ns
  - Supply: V_{AL} = 5 V
  - Receiver: V_{IH} = 3 V
  - Cases:

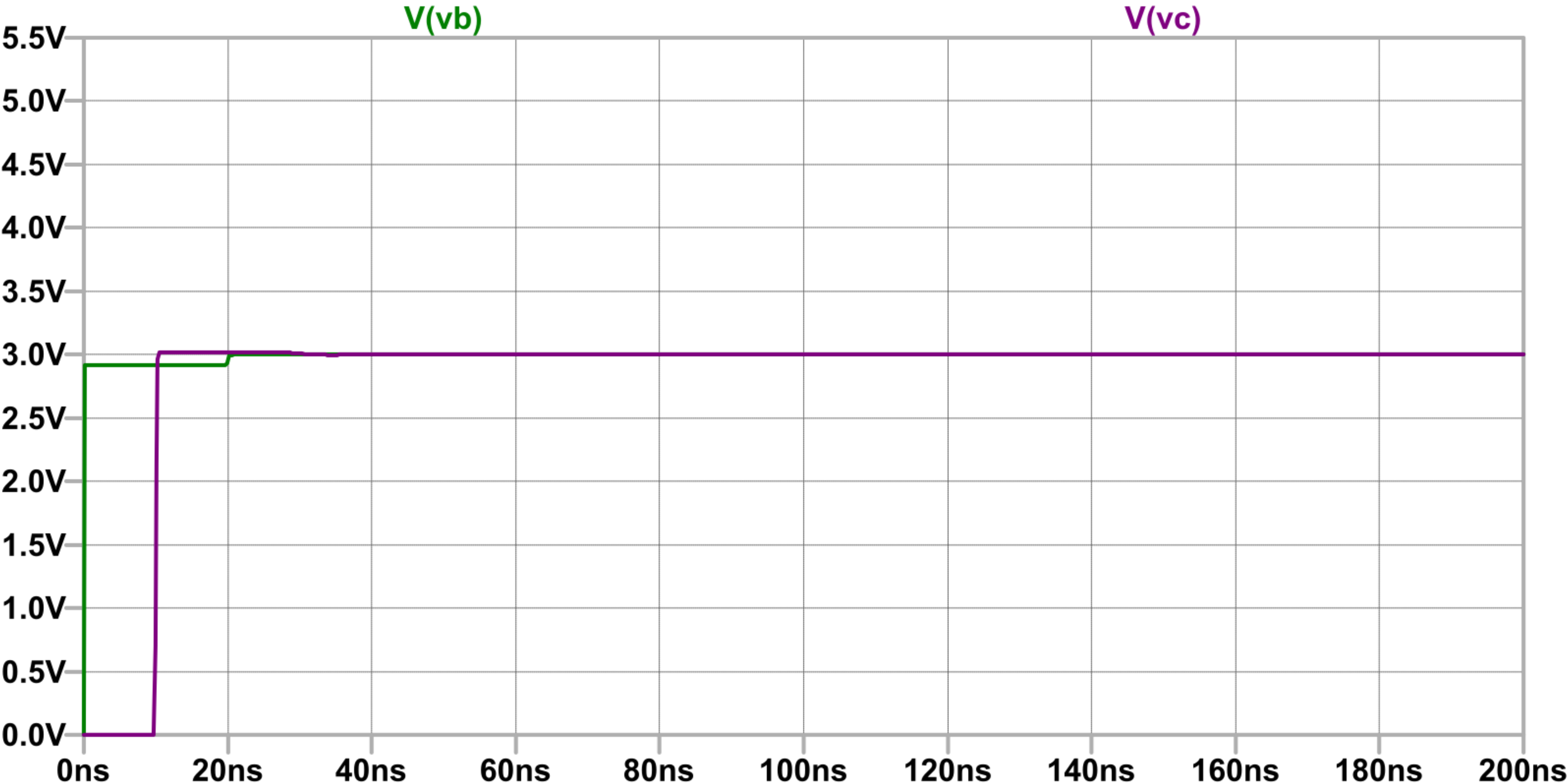
Cases:	a	b	c	d
Values of R_O [Ω]	100	70	50	10

- Choose the R_O values and determine the corresponding termination resistor R_T values (connected to 2.5 V) which guarantee:
  - Minimum static power consumption
  - Maximum speed

Exercise C3.2: parameter selection: calculations

- For fast transmission time, t_{TX}, we must have
  - $v_1 \geq V_{IH} > \frac{1}{2} V_A$; $v_1 = \frac{Z_\infty}{R_O + Z_\infty} V_A \geq V_{IH} \rightarrow R_O < Z_\infty$; $R_O = \begin{cases} 50\ \Omega & (c) \\ 10\ \Omega & (d) \end{cases}$
- Receiver steady state condition to decode the high level
  - $V_{\text{steady}} \geq V_{IH} \quad \rightarrow \frac{R_T}{R_O + R_T} V_A \geq \mathrm{V_{IH}} \rightarrow R_T \geq R_O \frac{V_{IH}}{V_A - V_{IH}}$
    - c) $R_O = 50\ \Omega \rightarrow R_T \geq 75\ \Omega$; d) $R_O = 10\ \Omega \rightarrow R_T \geq 15\ \Omega$
- For minimum static power consumption, we must have
  - $I_{\text{steady}} = \min\left(\frac{V_{\text{steady}} - 2.5\ \mathrm{V}}{R_O + R_T}\right) = \min\left(\frac{V_{IH} - 2.5\ \mathrm{V}}{R_O + R_T}\right)$
    - c) $R_O = 50\ \Omega \rightarrow I_{\text{steady}} = 4\ \mathrm{mA}$; d) $R_O = 10\ \Omega \rightarrow I_{\text{steady}} = 20\ \mathrm{mA}$
- Thus, the best combination is
  - c) $R_O = 50\ \Omega$ and $R_T = 75\ \Omega$

Exercise C3.2: parameter selection: waveforms



Lecture C3 – final check

- Define transmission time and skew and discuss on which parameters they depend on.
- How propagation time and the transmission time differ for a transmission line interconnection?
- What is the reflection coefficient Γ at termination for
  - Open circuit
  - Short circuit
- Lossless line steady state voltage depends on Z_∞?
- Define IWS and RWS.
- What is the effect of a capacitive load on the transmission time of an interconnection?