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Signal integrity

Lecture #8
Electronic measurements

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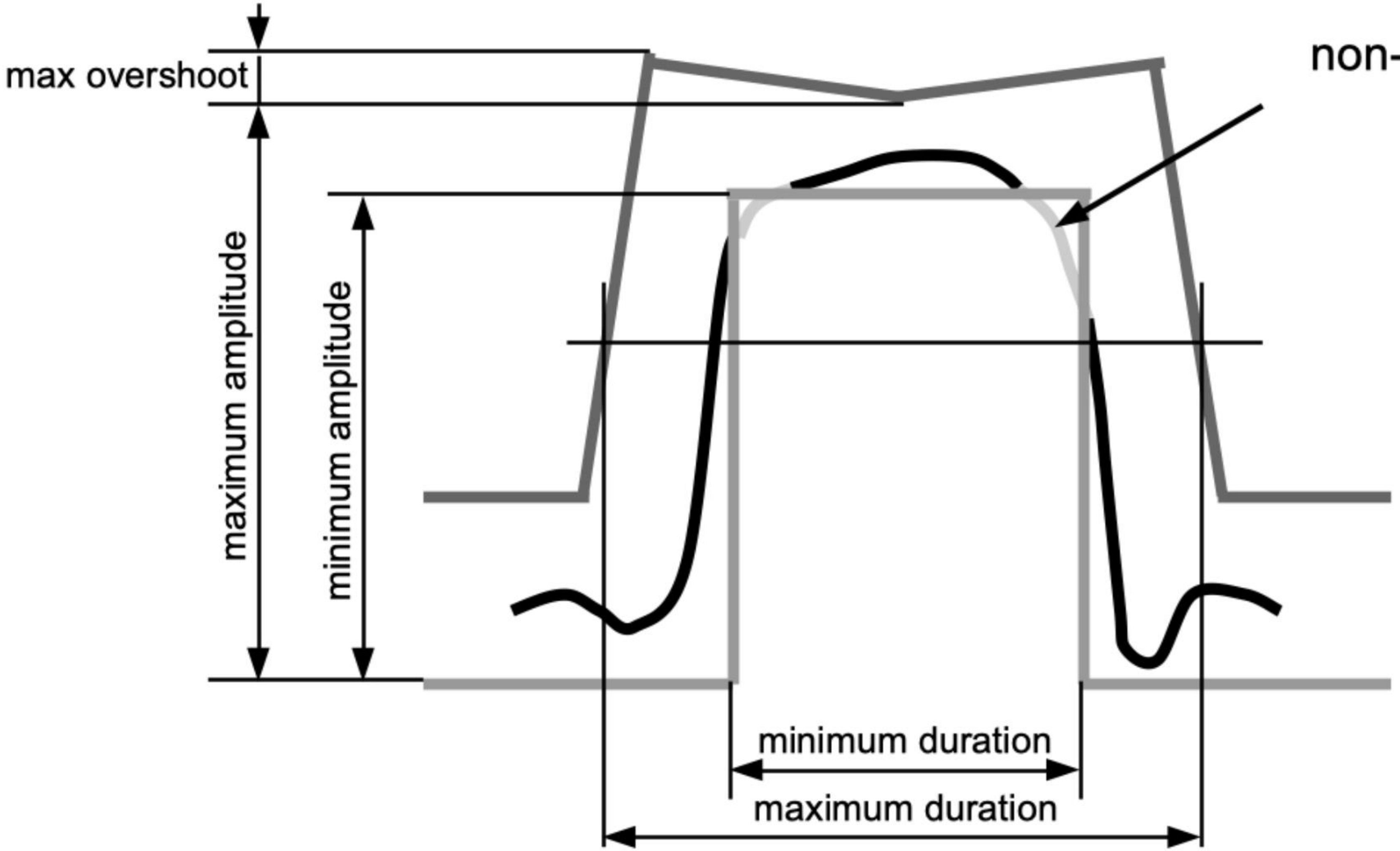
Signal integrity

- Signals exchange → **pre-defined waveforms**
- **Digital signal**:
  - Alternation between two voltage levels
  - Very short switching intervals → Set-up time
  - Permanence in the levels for a suitable time → Hold time

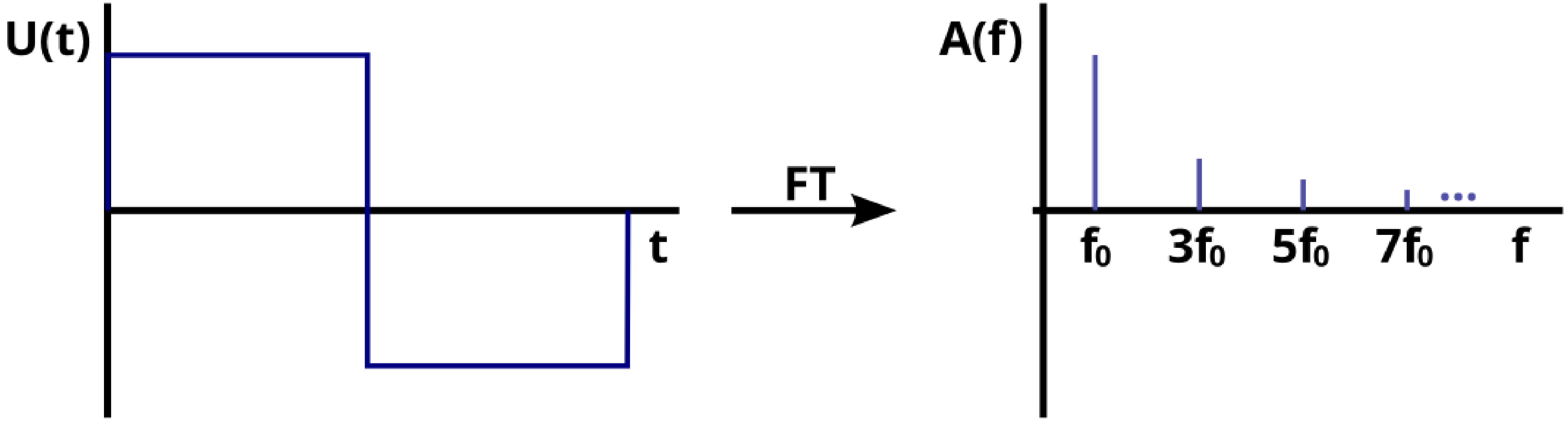
- **Shape specifications**:
  - Rise and fall times
  - Pre-shoot
  - Overshoot

Waveform masks



Signal integrity

- Example: ideal symmetric square wave
- $T = 200$ ns
- Fundamental frequency $f_s = 5$ MHz



- Oscilloscope with a 100 MHz bandwidth → up to 19 harmonics within the bandwidth

Signal integrity

- **Real** symmetric square wave → non-zero rise and fall times t_s
- **Trapezoidal** waveform
- **Time domain**: convolution in the between an "ideal" square wave and a rectangular pulse having length t_s
- **Frequency domain**: multiplication of the square wave spectrum and the spectrum $W(f)$ of a rectangular pulse:

$$W(s) = \frac{\sin \pi f t_s}{\pi f t_s}$$

Great attenuation at frequencies over $1/t_s$

- $t_s = 20$ ns → Limiting frequency 50 MHz
- $t_s = 5$ ns → Limiting frequency 200 MHz

Time Domain Reflectometry (TDR)

- Diagnostic technique employed when interconnections between components can be treated as **TRANSMISSION LINES**
- Analysis and troubleshooting of **high-speed digital systems**

- Voltage level transitions → **Transient** phenomena
- Poorly matched devices → Multiple **reflections**

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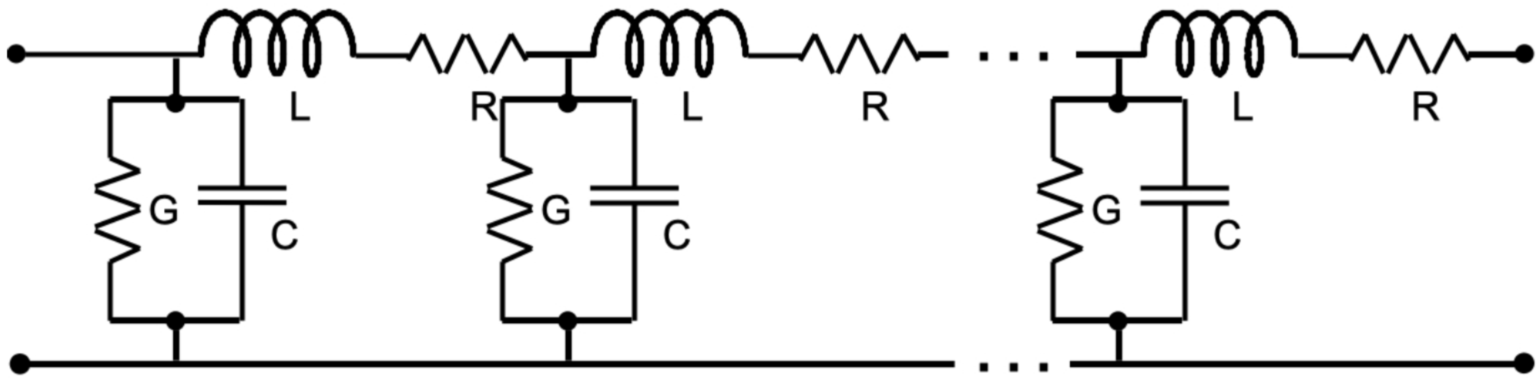
Unintended changes *in logic states*

Delays *in reaching stable voltage levels*

PROPAGATION TIME

Time Domain Reflectometry (TDR)

- Microstrip line → Transmission line



- Each segment of infinitesimal length
- Characteristic impedance

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

- R, L, C and G per unit length

Time Domain Reflectometry (TDR)

- **Ideal behaviour** → Delay
- **Impedance mismatches** → Reflections

Mismatched load at the opposite end of a line

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Reflection

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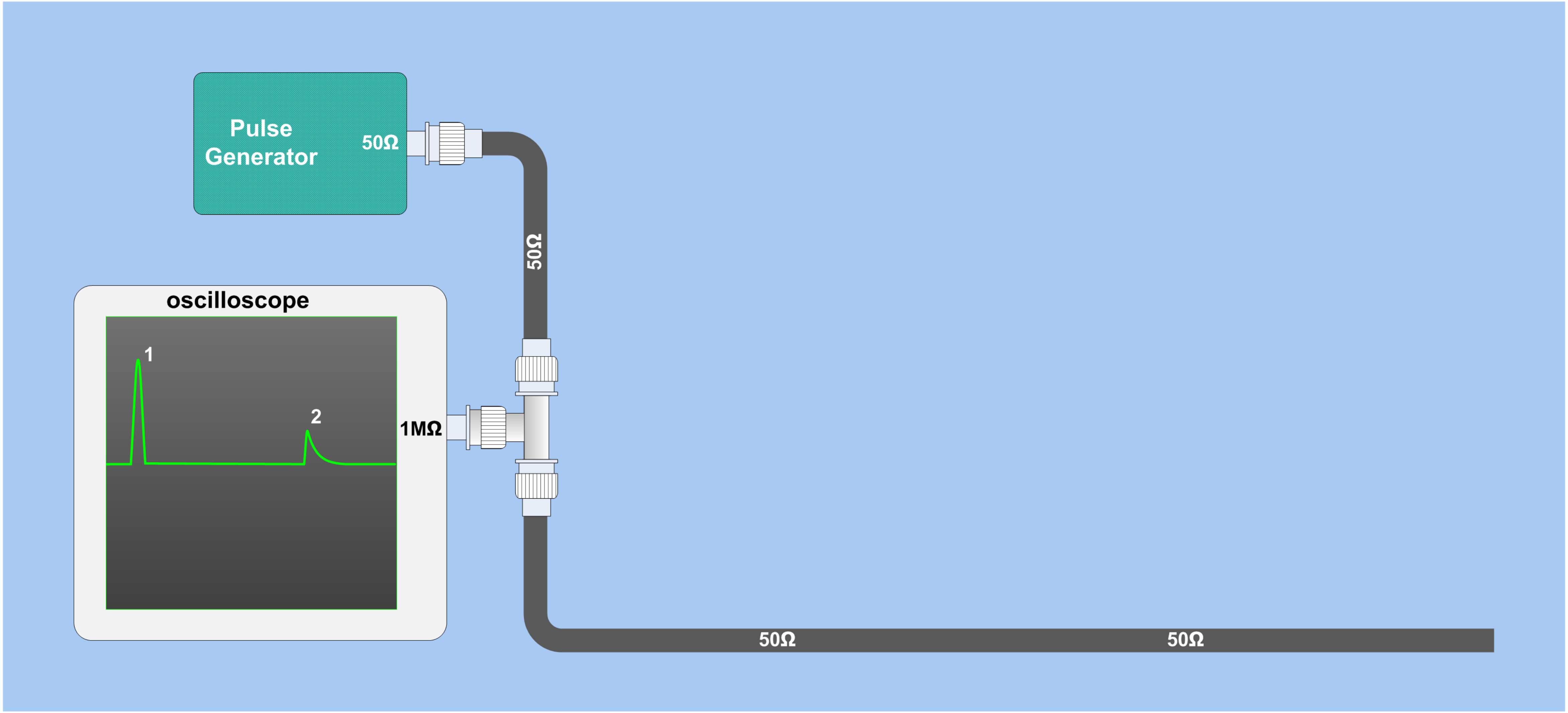
Time required to reach the measurement point from the reflection point proportional to the distance

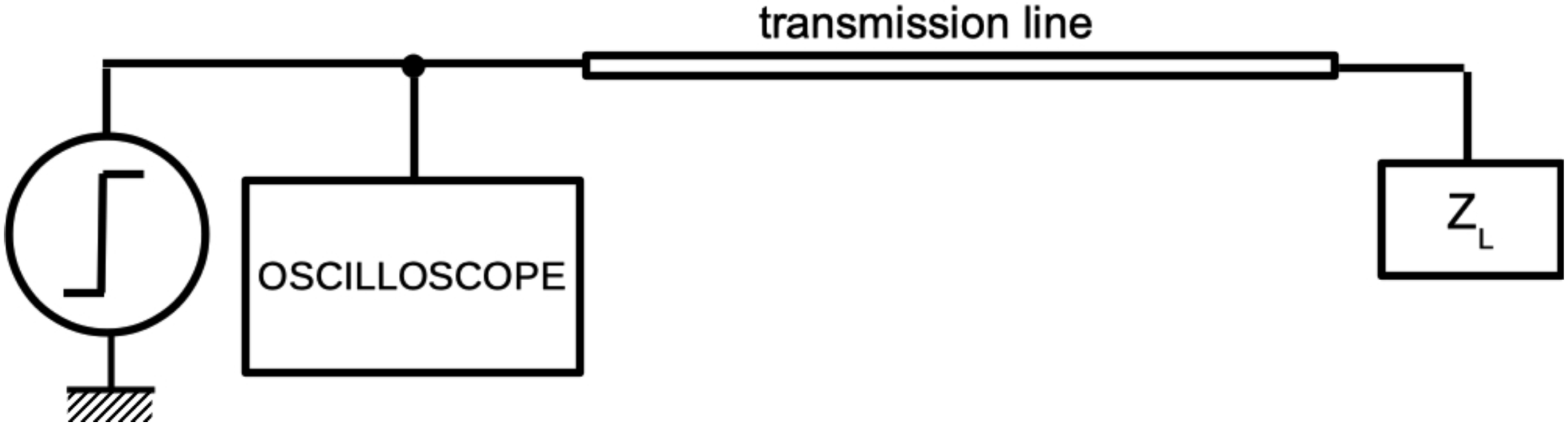
- Short, broadband test signals (Pulses or sharp edges)

TDR measurement



TDR measurement

- Instruments:
  - Oscilloscope
  - Broad band signal generator



TDR measurement

- The signal generator produces a test signal having a **very short length**
- The generator output impedance must be **matched** to the characteristic impedance of the transmission line under test
- **Only one end** of the transmission line needs to be accessed for measurement
- Although the observed trace shows the response of a whole transmission line, **individual reflection components** contributed by different points along the line can be separated in time, and originating points can be located

- Finite speed $v = \frac{c}{\sqrt{\epsilon_r}}$ where ϵ_r dielectric constant of the propagation medium
- **Coaxial cables** → polyethylene: $\epsilon_r \cong 2.3$
- **Microstrip lines** → partly in resin/fibreglass, partly in air

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TDR measurement

- **Test signal amplitude** E_i
- **Unmatched load impedance** Z_L at the end of the line
- If $\boldsymbol{Z_L \neq Z_0}$ → Partial or total reflection

- **Reflection coefficient**

$$\rho(\omega)\frac{E_r}{E_i} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

- x_d **distance** of the reflection point from the generator
- $\tau_d = x_d/v$ **time required** by the test signal to reach the reflection point
- $\Delta t = 2\tau$

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TDR measurement

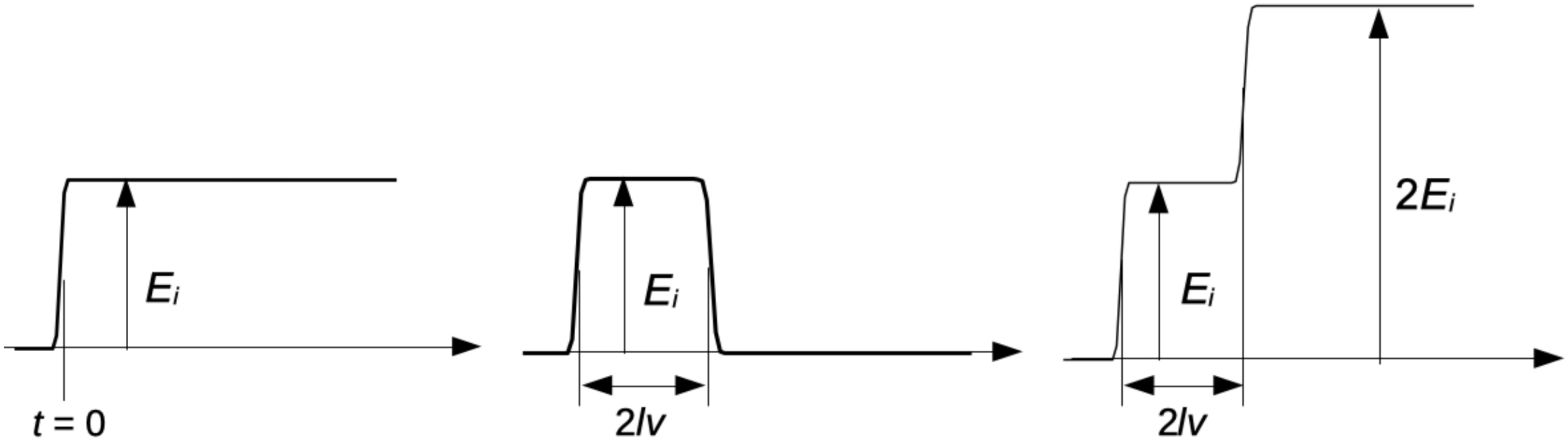
- **Lossless transmission** line of length l
- $R = 0$ and $G = 0$
- $Z_0 = \sqrt{L/C}$ is **purely resistive**
- If $R_L = Z_L$ purely resistive ρ is **real** and the **reflected wave is summed** to the incident
- $-1 \leq \rho \leq 1$

- A mismatched termination allows to estimate the **electrical length of the line**

$$l = (v \cdot \Delta t)/2$$

TDR measurement

- $R_L = Z_0 \Rightarrow \rho = 0 \Rightarrow E_r = 0 \Rightarrow E_r + E_i = E_i$
- $R_L = 0 \Rightarrow \rho = -1 \Rightarrow E_r = -E_i \Rightarrow E_r + E_i = 0$
- $R_L = \infty \Rightarrow \rho = 1 \Rightarrow E_r = E_i \Rightarrow E_r + E_i = 2E_i$

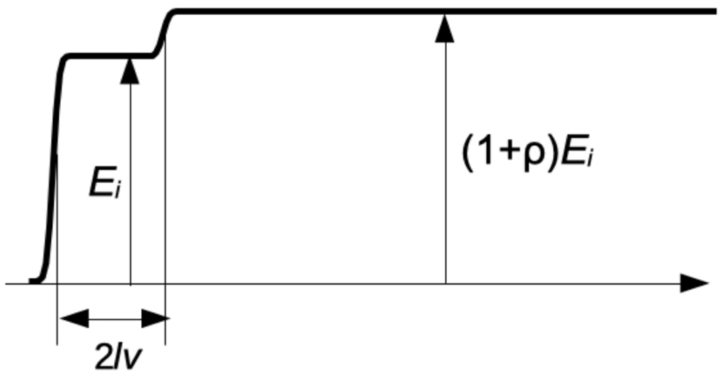


(a) matched load; (b) short circuit; (c) open circuit.

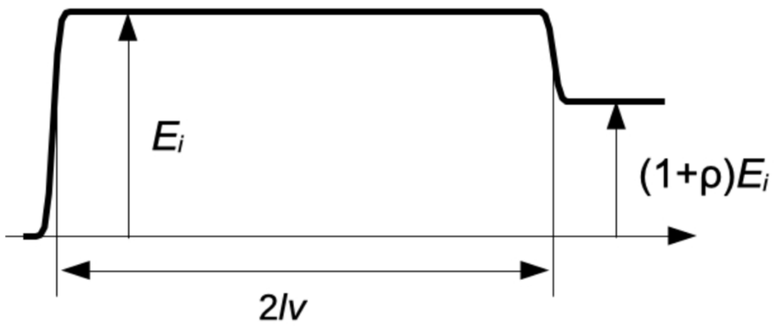
TDR measurement

- Resistive termination

$$\frac{E_i+E_r}{E_i} = 1+\rho \quad \text{where} \quad 1+\rho = \frac{2R_L}{R_L+Z_0}$$



(a) $R_L > Z_0$;



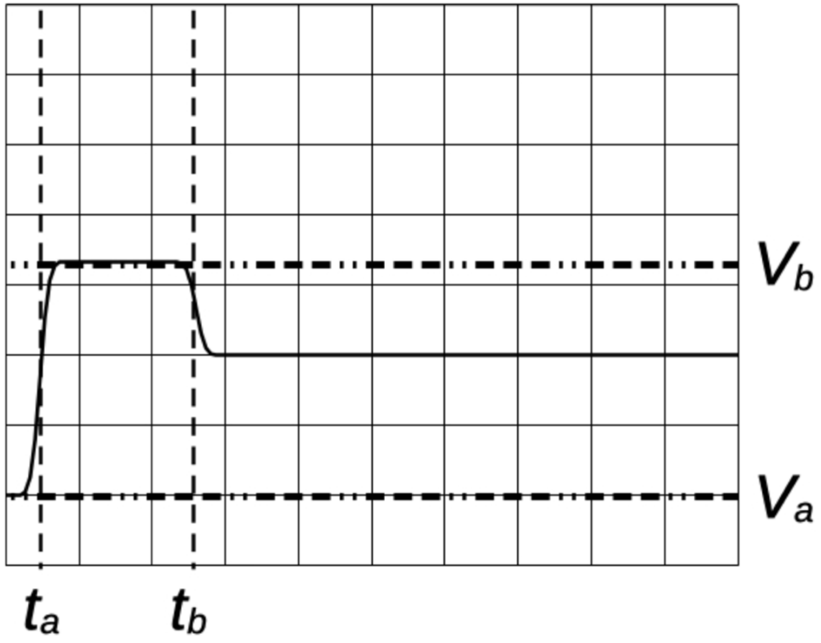
(b) $R_L < Z_0$;

- Normalized load resistance $r_L = R_L/Z_0$, $V_1 = E_i$ and $V_2 = E_i + E_r$

$$\frac{V_2}{V_1} = 1+\rho = \frac{2r_L}{r_L+1} \quad \text{from which} \quad R_L = r_L \cdot Z_0 = \frac{V_2/V_1}{2-V_2/V_1} \cdot Z_0$$

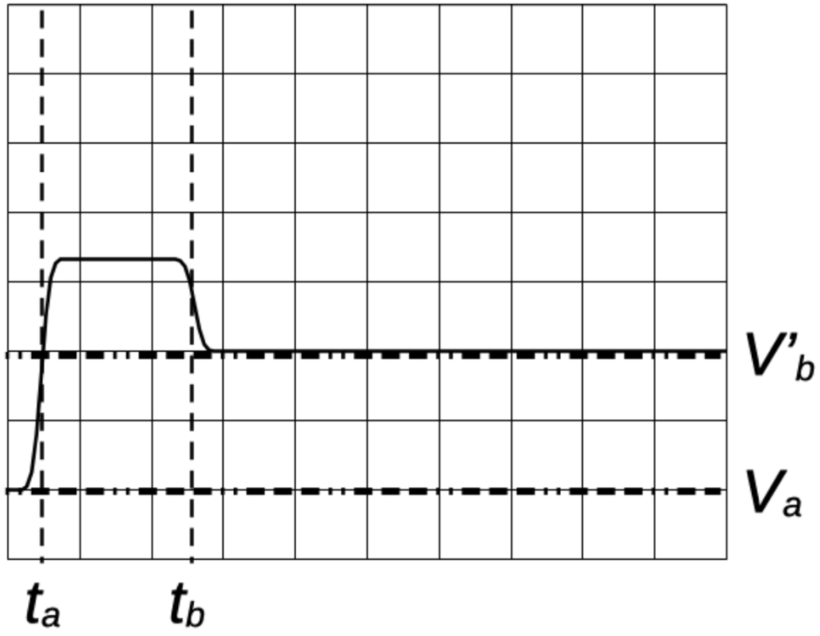
TDR accuracy analysis

- **Measurement accuracy** depending on specific points in the trace
- **Amplitude cursor positions** on the constant voltage levels



(a) amplitude cursors measuring E_i;

$$E_i = V_b - V_a = V_1$$



(b) amplitude cursors measuring $E_i + E_r$;

$$E_i + E_r = V_b' - V_a = V_2$$

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TDR with reactive line termination

- **Generic load impedance Z_L**
- Fourier transform of an **incident step** $V_i(\omega) = E_i/(j\omega)$

$$V_r(\omega) = \frac{E_i}{j\omega} \cdot \frac{Z_L(\omega) - Z_0}{Z_L(\omega) + Z_0}$$

- After Δt the reflected wave is added to E_i:

$$\frac{E_i}{j\omega} \cdot [1 + \delta(\omega)] = \frac{E_i}{j\omega} \cdot \frac{Z_L(\omega)}{Z_L(\omega) + Z_0}$$

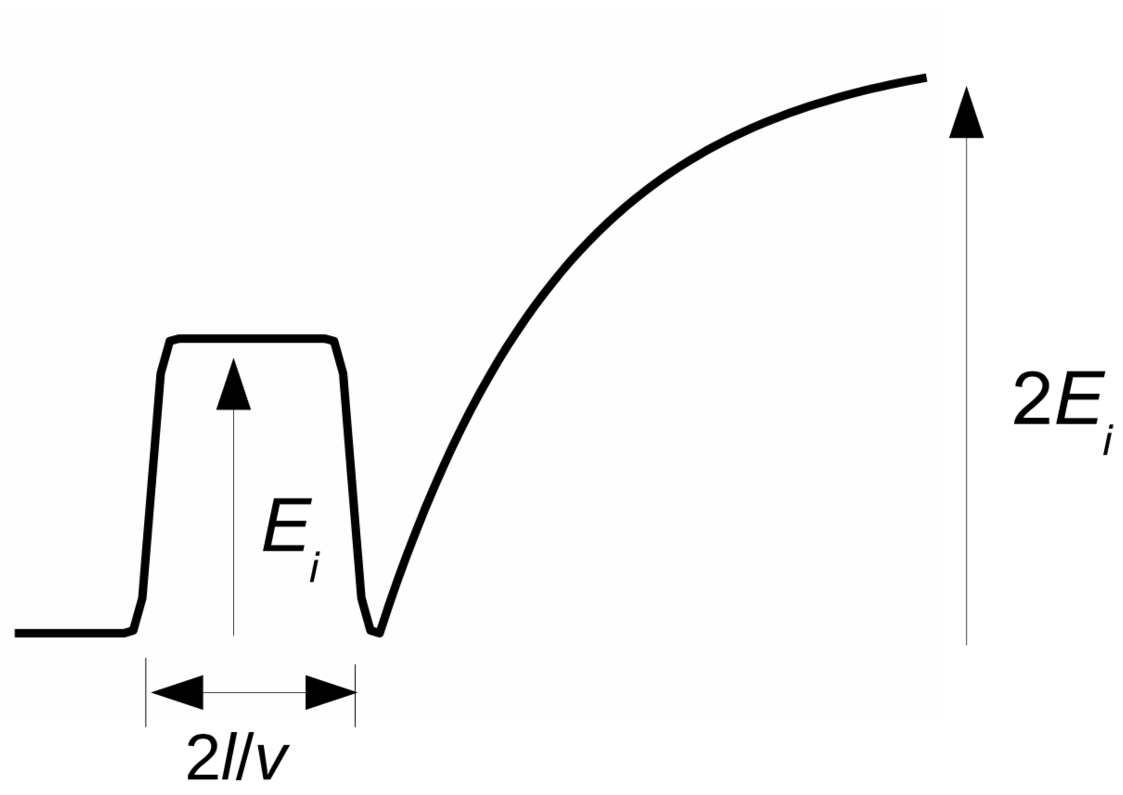
TDR with reactive line termination

- **Capacitance C_L**
- Waveform shape → Inverse transform of:

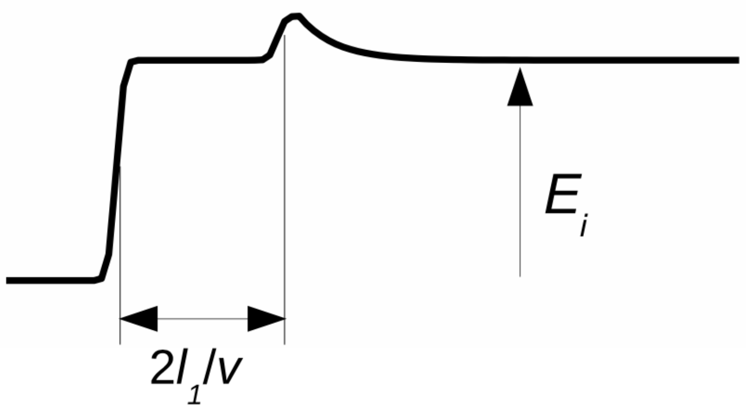
$$\frac{E_i}{j\omega} + \frac{E_i}{j\omega} \cdot \frac{\frac{1}{j\omega C_L} - Z_0}{\frac{1}{j\omega C_L} + Z_0} = \frac{E_i}{j\omega} \cdot \frac{1}{1 + j\omega C_L Z_0}$$

- Junction between 2 cables with a connector introducing a series **inductance L_C**
- In general, **all possible load configurations** composed of either a series or a parallel of a resistance and a reactive quantity (capacitance or inductance) can be analyzed in this way

TDR with reactive line termination



(a) capacitive load;



(b) effect of a junction where an inductive effect is introduced by the connector.

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TDR systems specifications

- **Bandwidth** → Step as close as possible to the ideal behaviour
  - Short rise time
  - No overshoot
  - No oscillations

- **Test signal rise time** determines the minimum discernible separation
- **Propagation speed** of 15/20 ns/cm → sub-ns rise times for PCB analysis

- **Time resolution** → Sampling intervals of the same order of magnitude as the test signal rise time
- **Square wave** → Final steady state value to be reached in each half-period

Laboratory activity

- **Instruments**:
  - Keysight 33600A or Tektronix AFG 3101 **signal generator**
  - Coaxial cable
  - Keysight DSOX1102G (100 MHz) or MSOX3024T (200 MHz) digital **oscilloscope**
  - accessories and passive components

- Broad-band **signal generator**, providing either short pulses or steps with short rise time, whose output impedance should match the characteristic impedance of the transmission line under test (50 Ω)
- **Oscilloscope** with comparable bandwidth, connected to the line under test in parallel to the test signal generator

Laboratory activity

- Transmission line → **Long coaxial cable**
- Typical conditions → microstrip lines → Broad band instrumentation

TIME RESOLUTION

- Test signal: **SQUARE WAVE**
  - Any amplitude (ex. 1 V)
  - Period long enough to avoid superposition of the TDR responses from consecutive voltage steps (frequency below 10 kHz)
- Oscilloscope in **high impedance** (T-connector)
- Connection between the oscilloscope and the line under test as short as possible

Laboratory activity

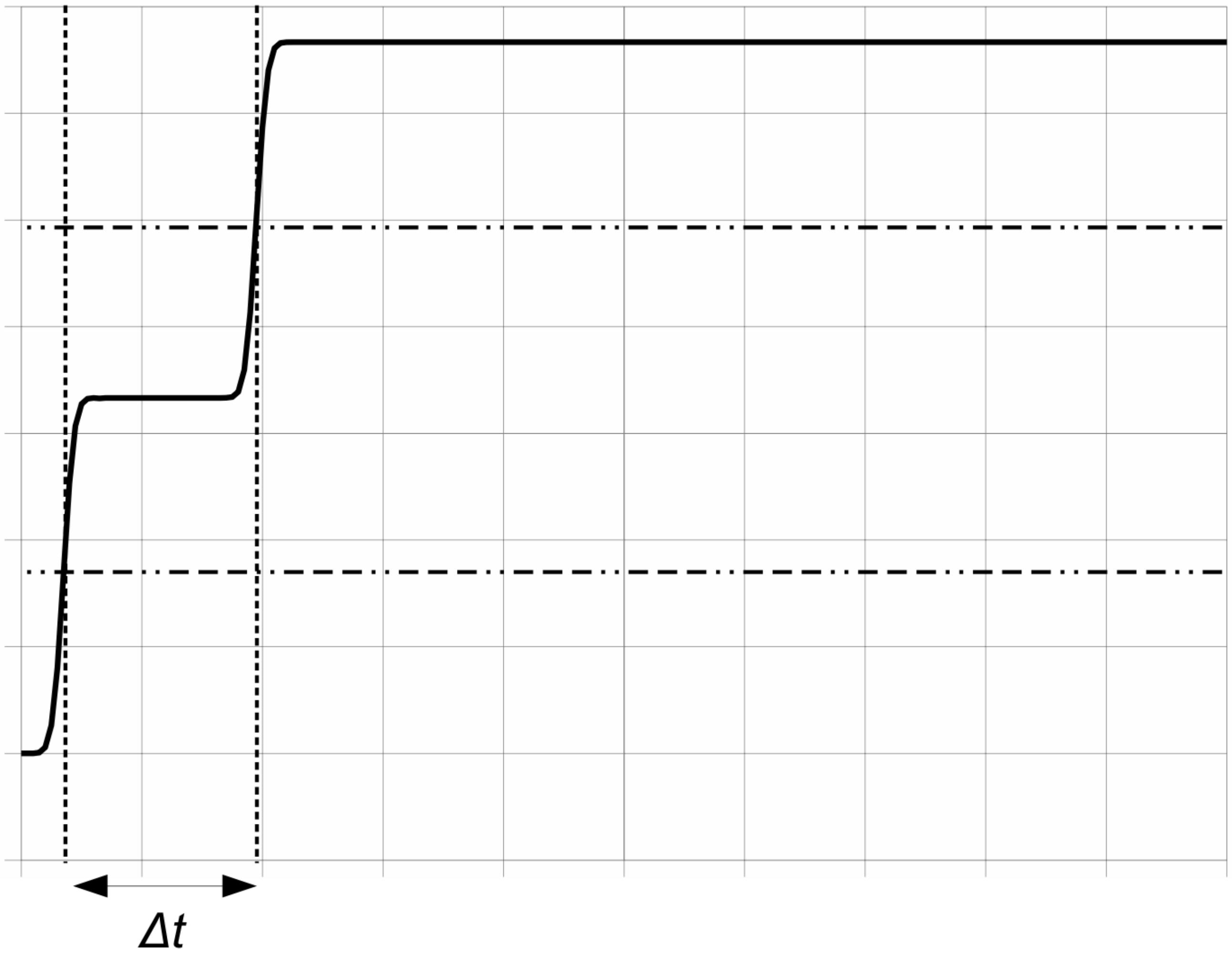
- **Measuring the length of a line**

- Coil of coaxial cable
- One end connected to the T of the oscilloscope
- The opposite end open $\rightarrow Z_0 = \infty$, $\rho = 1$

- Measurement of the delay between the incident and reflected wavefront
- $l = (v \cdot \Delta t)/2$
- $v = c/\sqrt{\epsilon_r} \rightarrow \epsilon_r = 2.3$ for polyethylene $\rightarrow v \cong 2 \times 10^8$ m/s

Laboratory activity

- Measuring the length of a line



Laboratory activity

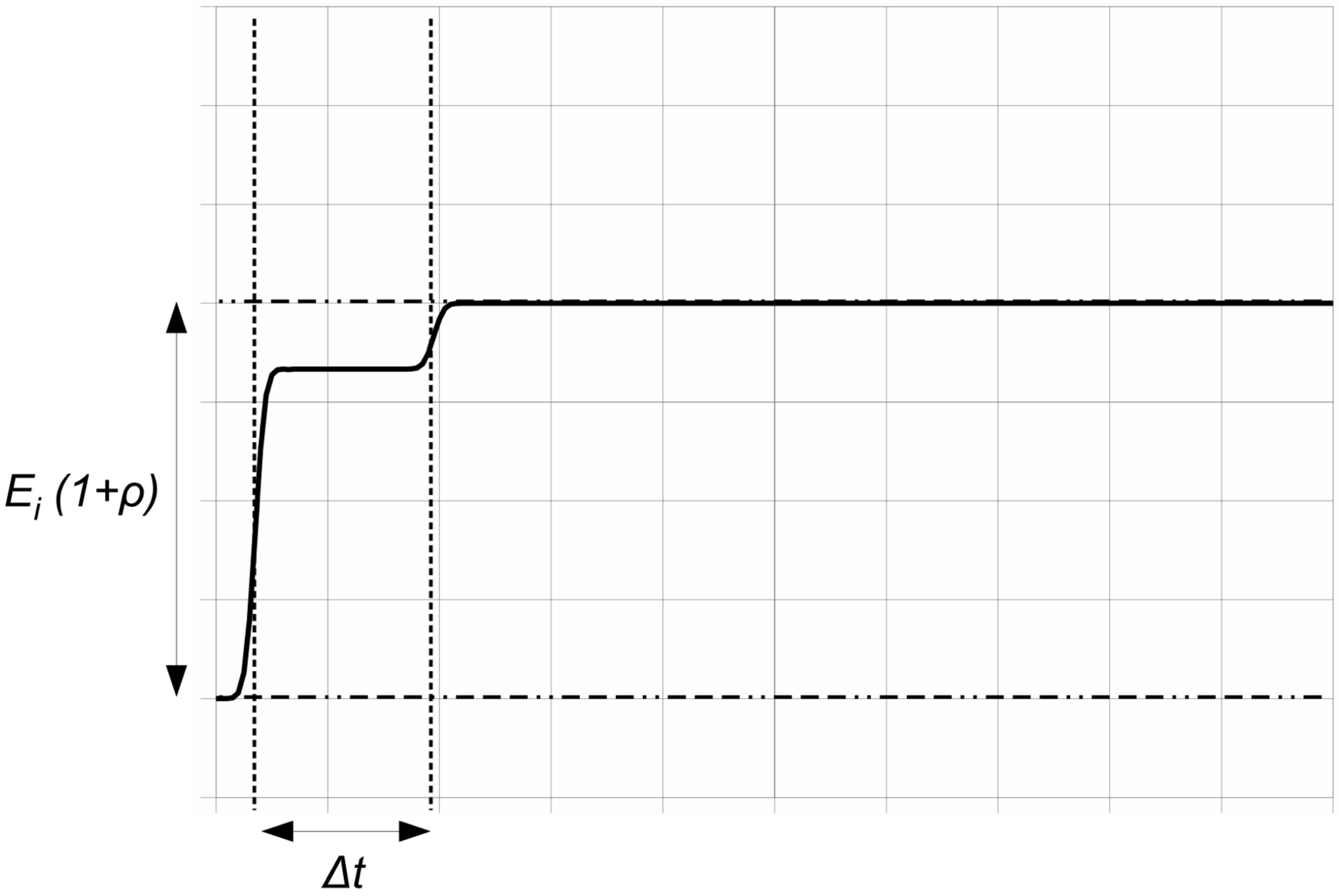
- **Verification of length measurement accuracy**

- **Incremental measurement**: a cable of known length is joined to the longer one
- Length difference is measured by TDR
- $\tau = \Delta t' - \Delta t$

- Time resolution Δ_t

Laboratory activity

- **Line termination impedance: resistive load**



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Laboratory activity

- **Line termination impedance: capacitive load**

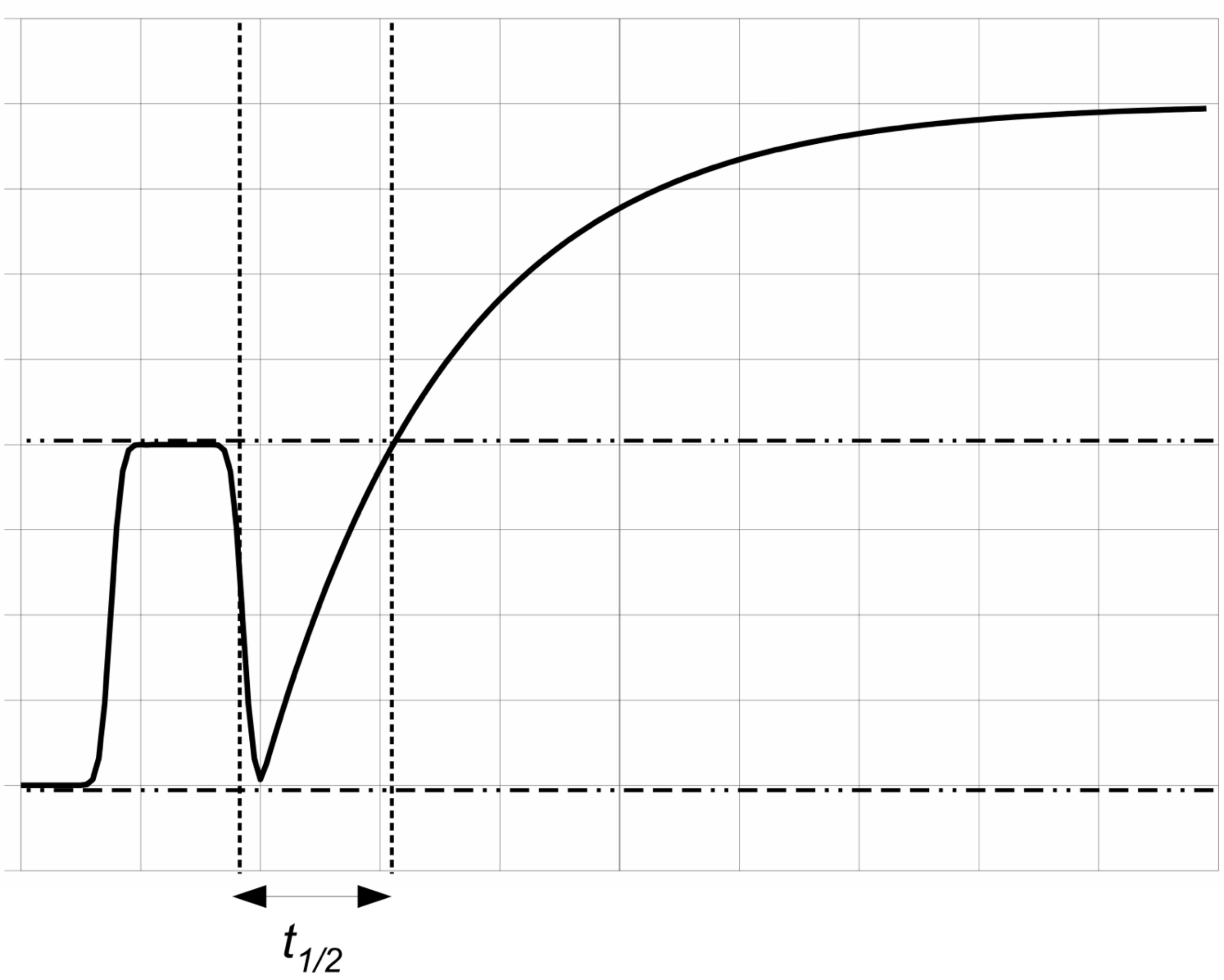
- $v(t) = 2E_i\left(1 - e^{-\frac{1}{Z_0 C_L}}\right)$

- Time to half-value $t_{\frac{1}{2}}$

- $e^{-\frac{1}{Z_0 C_L}} = \frac{1}{2}$ from which $Z_0 C_L = \frac{t_{\frac{1}{2}}}{\ln 2} \cong t_{\frac{1}{2}} \cdot 1.4$

Laboratory activity

- **Line termination impedance: capacitive load**



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