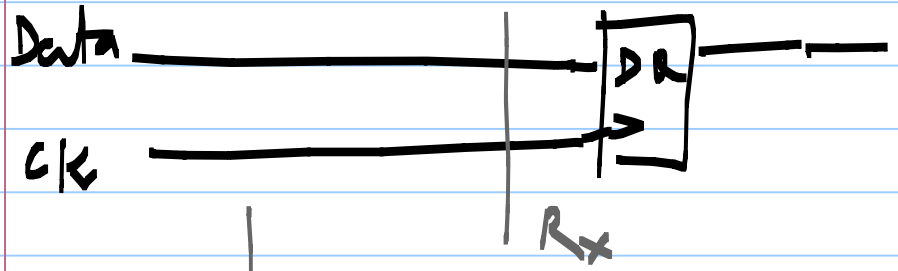
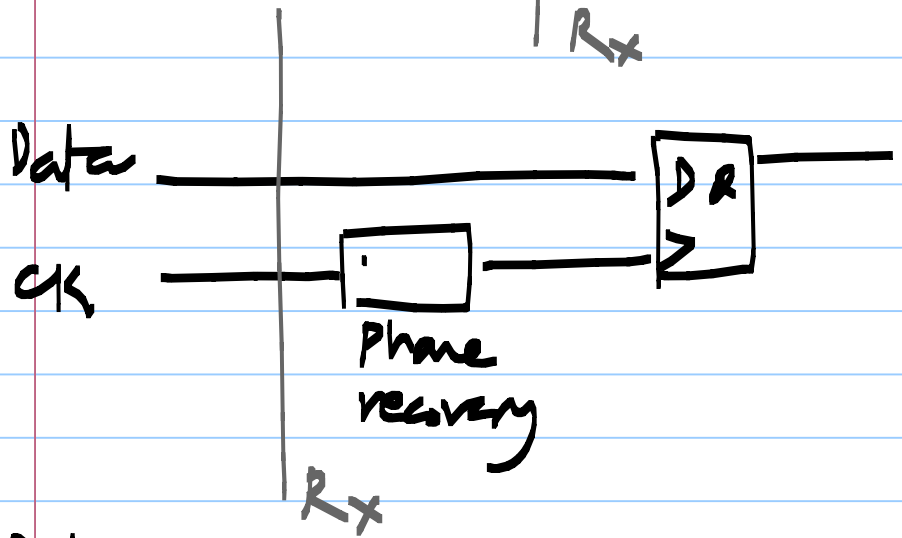
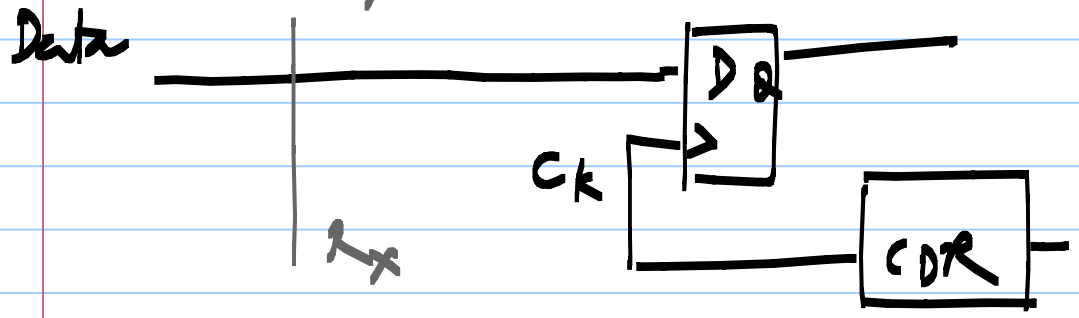
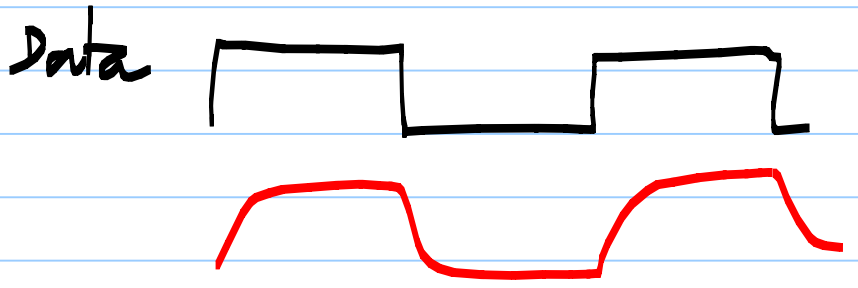
Digital communication





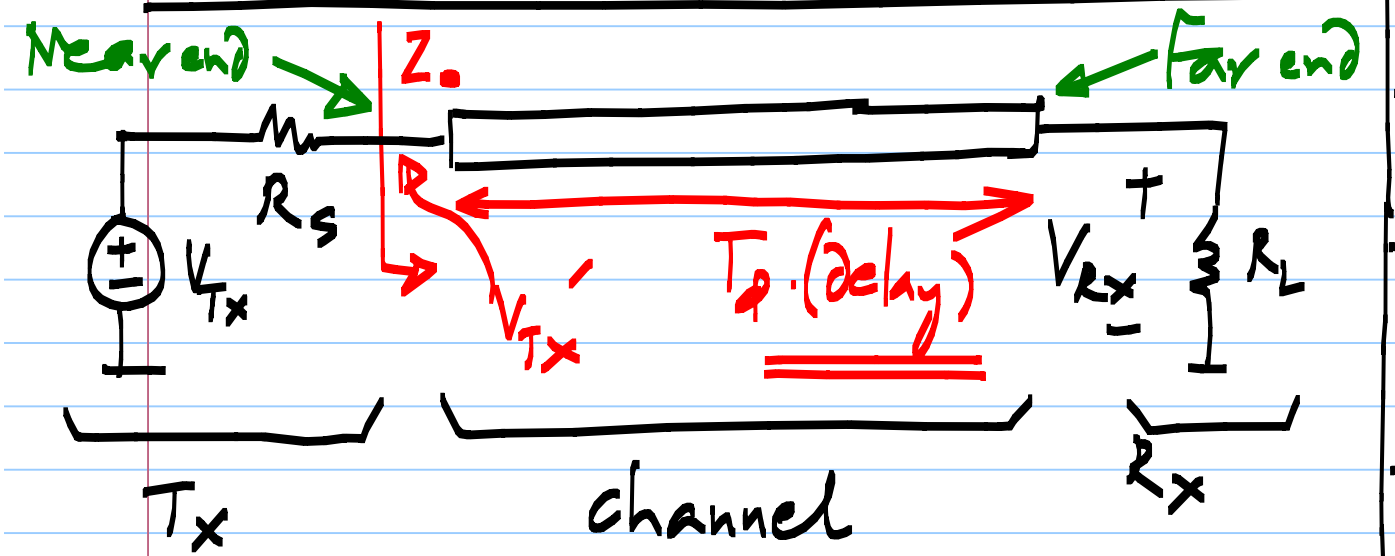


Ideal



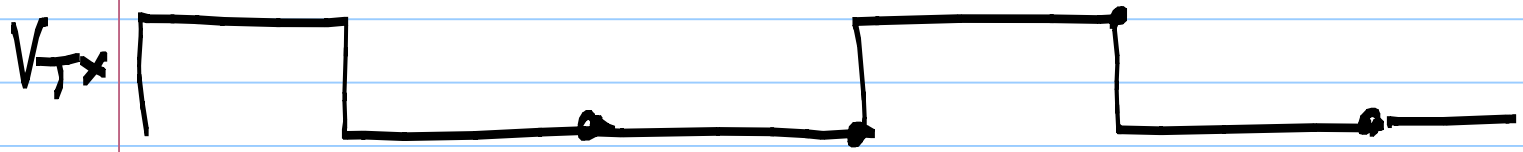
Data is in "good enough" condition

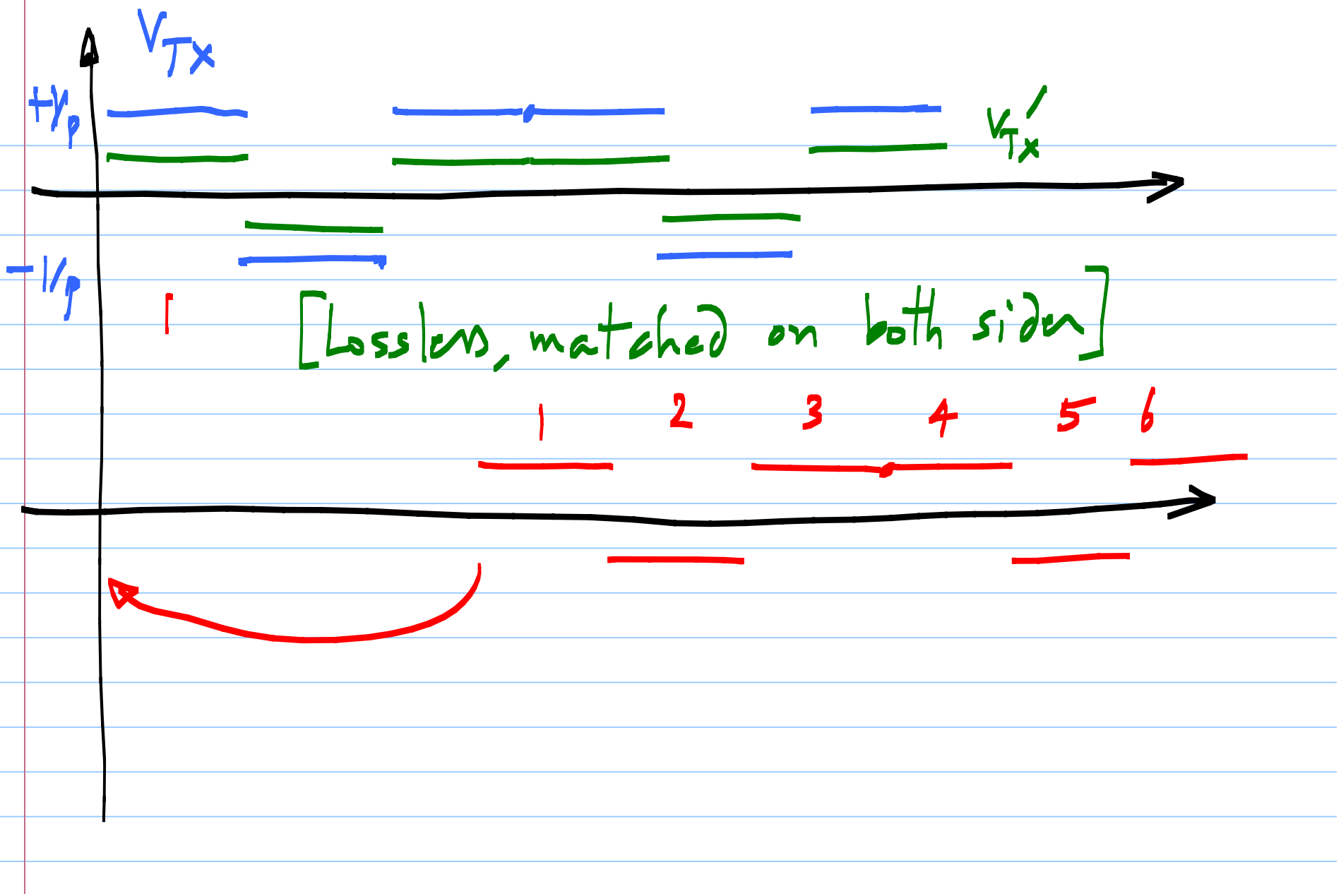
Data transmission through a channel

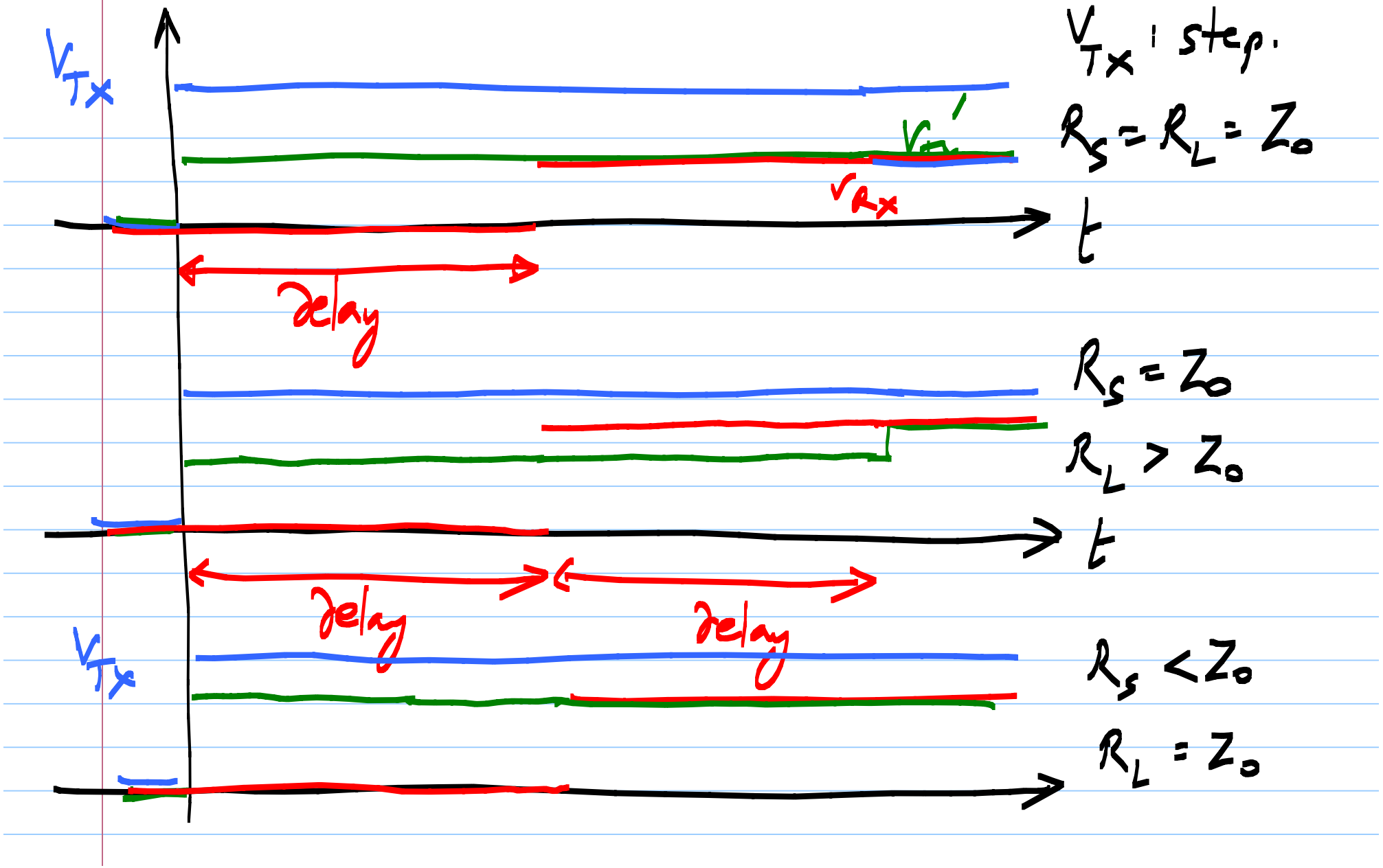


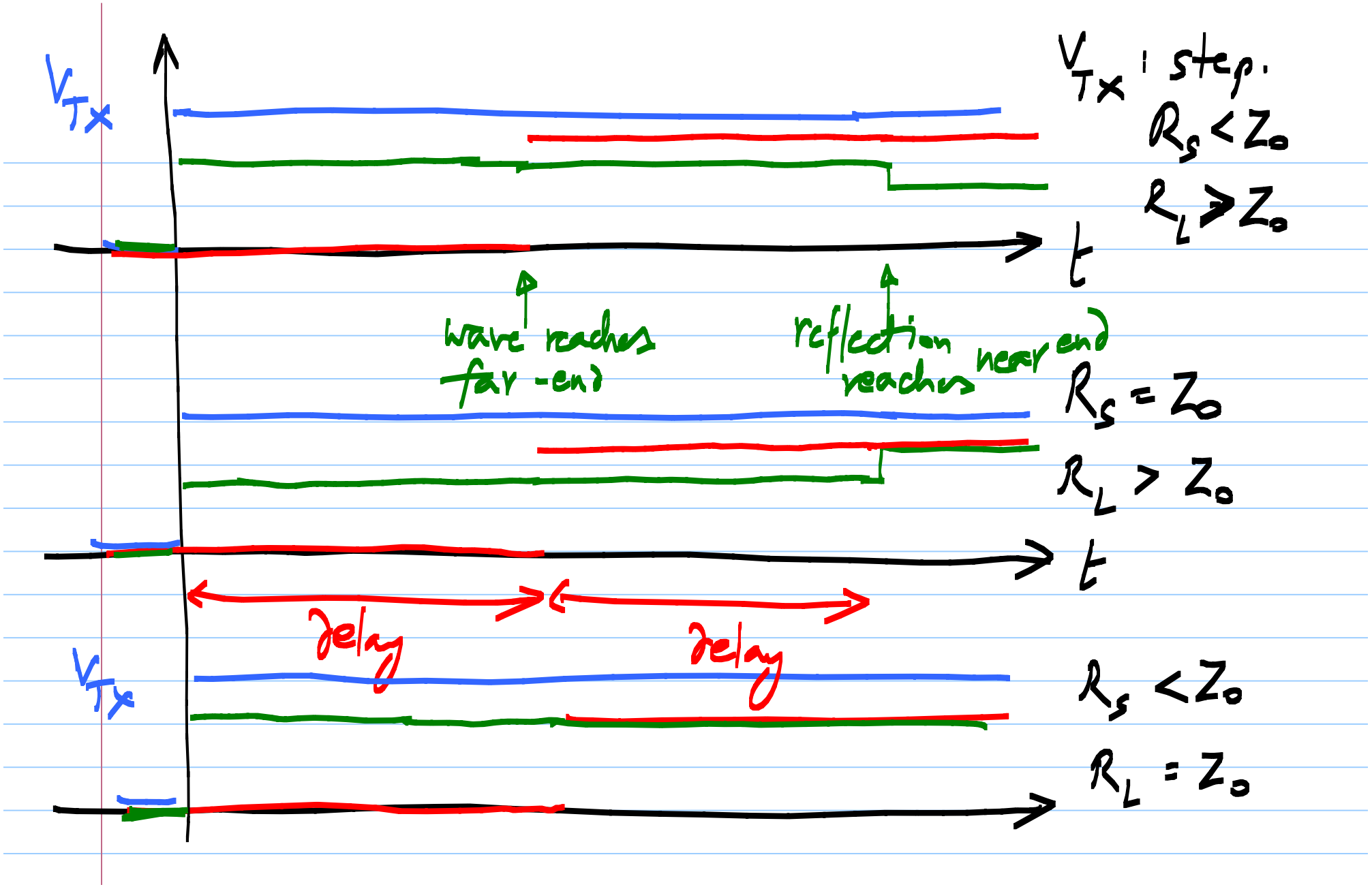
- on-chip
- chip-to-chip (cm to m)
- on a board
- cables
- optical fiber

Transmission line of char. impedance Z_0, $R_s = R_L = Z_0$

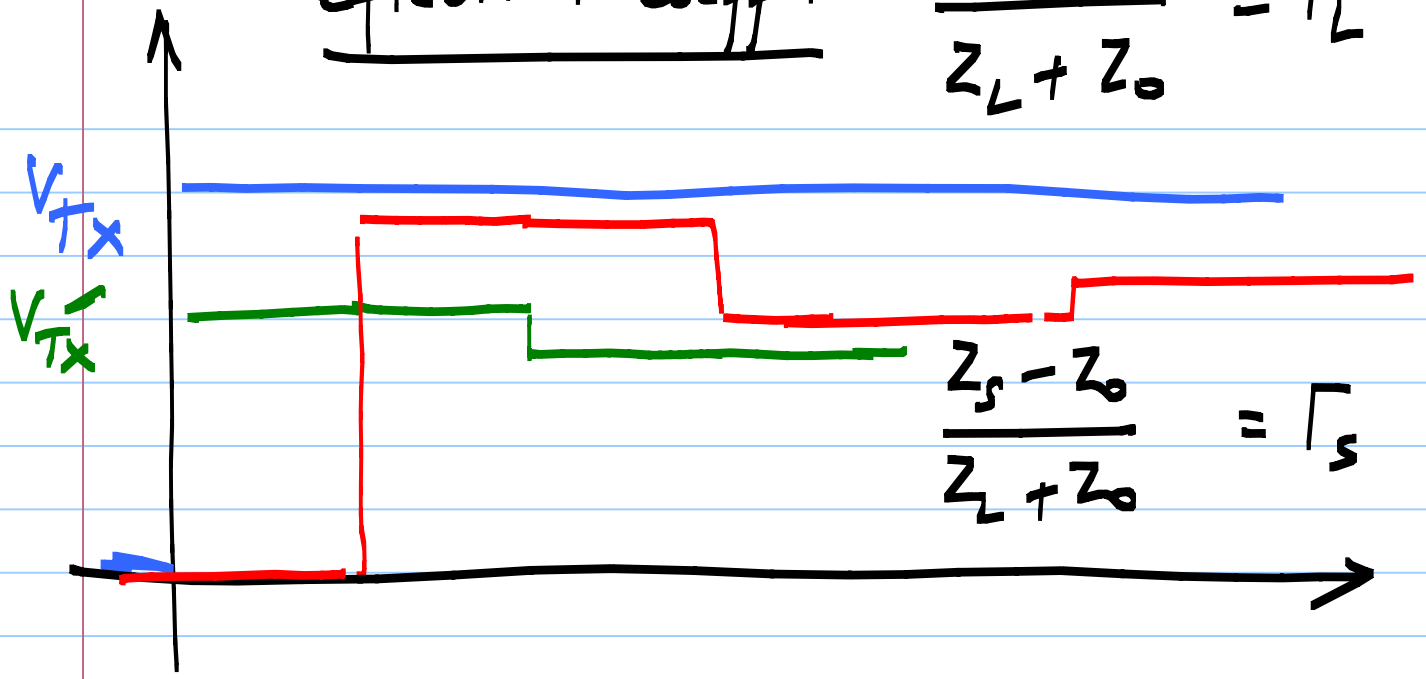



V_{Tx}
$+V_p$
$-V_p$
V_{Tx}'
1
[Lossless, matched on both sides]
1
2
3
4
5
6


V_{Tx}
V_{Tx} : step.
$R_s = R_L = Z_0$
v_{Rx}
v_{Rx}'
t
delay
$R_s = Z_0$
$R_L > Z_0$
t
delay
delay
V_{Tx}
$R_s < Z_0$
$R_L = Z_0$


V_{Tx}
V_{Tx} : step.
$R_s < Z_0$
$R_L > Z_0$
t
wave reaches far-end
reflection reaches near end
$R_s = Z_0$
$R_L > Z_0$
t
delay
delay
V_{Tx}
$R_s < Z_0$
$R_L = Z_0$

Reflection Coeff: $\frac{Z_L - Z_0}{Z_L + Z_0} = \Gamma_L$



Real Z_0

Real termi-nations

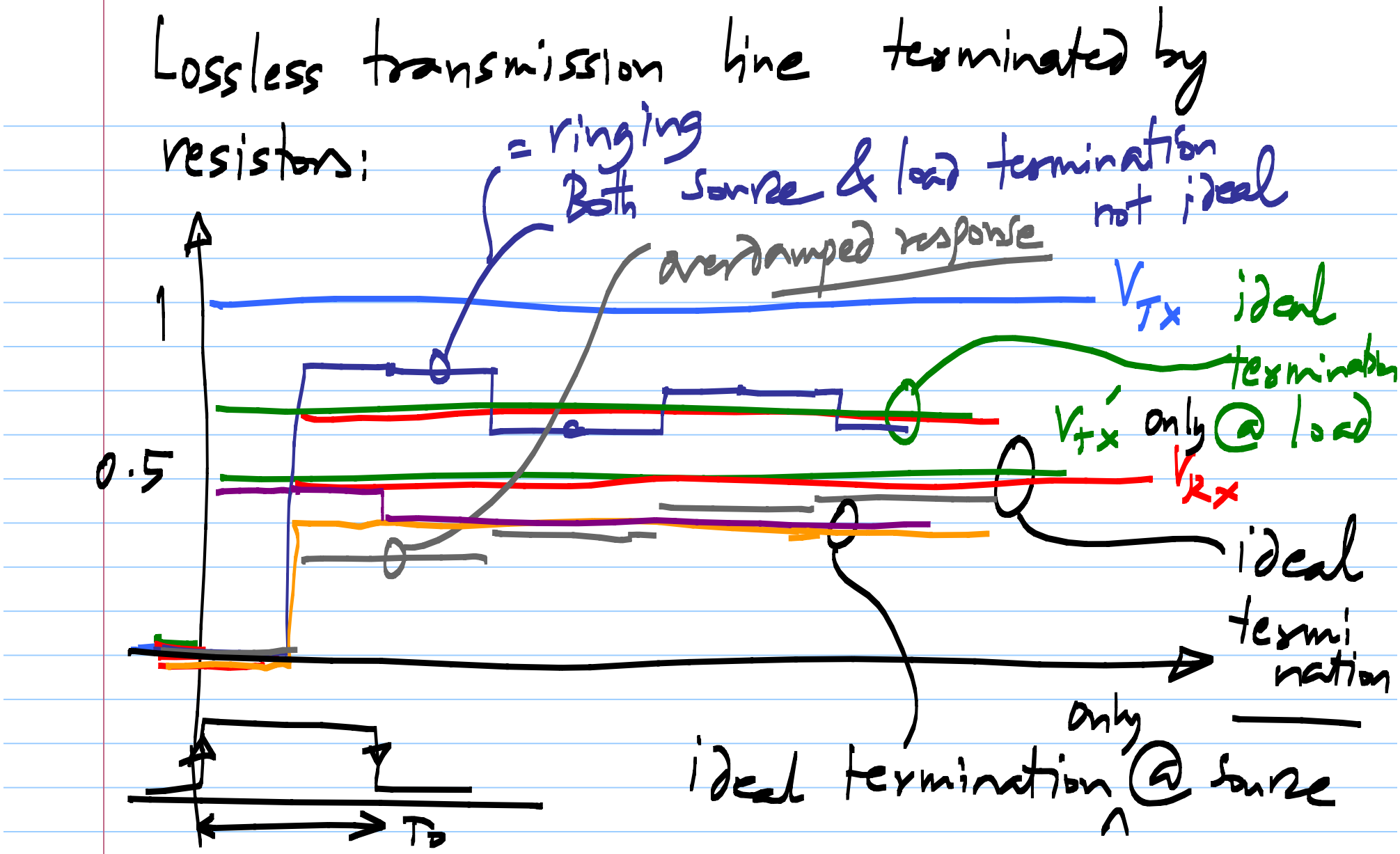
R_s, R_L

$R_s < Z_0$

$R_L > Z_0$

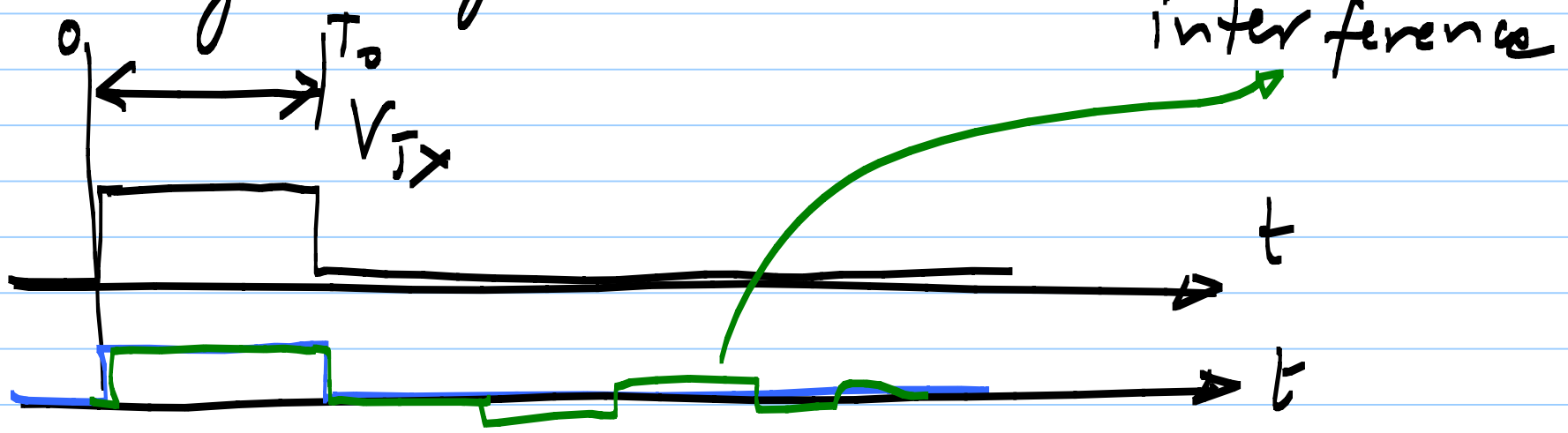
Steady-state $V_{Rx} = \frac{R_L}{R_L + R_s} \cdot V_{Tx}$

$t = 0^+$ $V_{Tx}' = \frac{Z_0}{Z_0 + R_s} \cdot V_{Tx}$


Lossless transmission line terminated by resistors:
= ringing
Both source & load termination not ideal
overdamped response
1
0.5
V_{Tx} ideal termination
V_{Tx} only @ load
V_{Rx}
ideal termination
only @ source
T_D

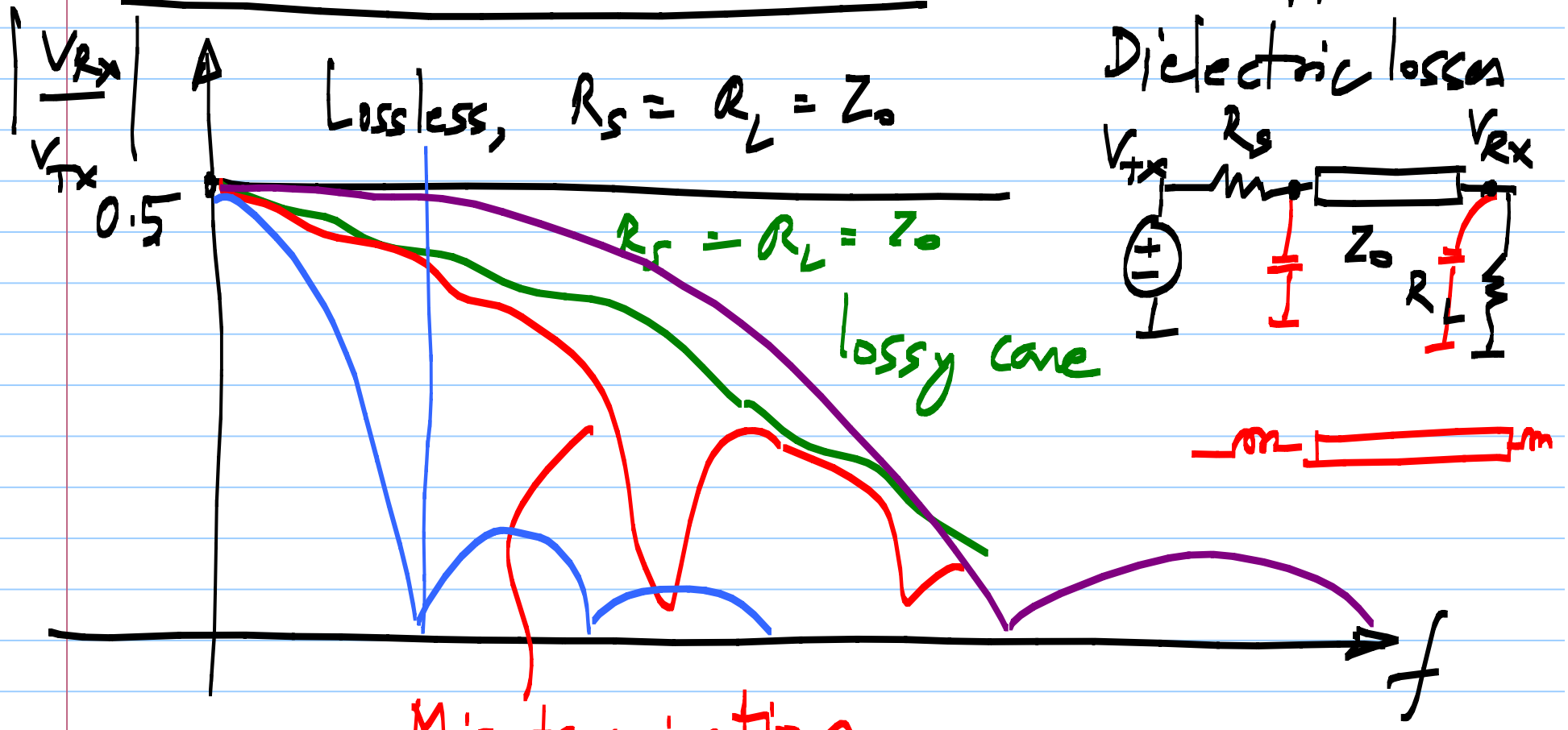
Ideal T-line with m/s-termination

- Ringing (under-damped)
- over-damped
- Delay > symbol interval ⇒ inter-symbol interference

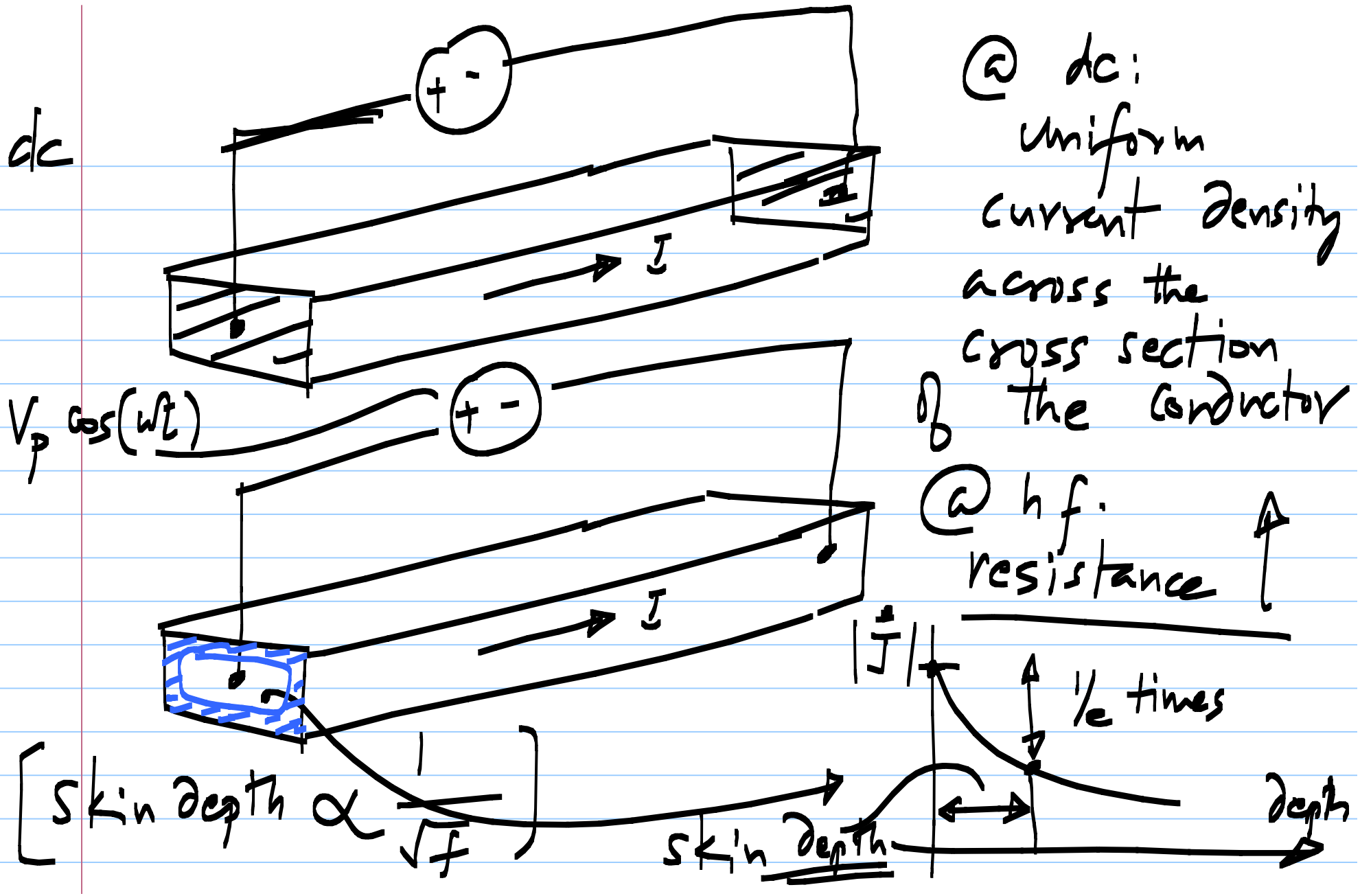


Freq. dependent termination (parasitic cap.) Freq. dependent [skin effect]

Transmission line: losses

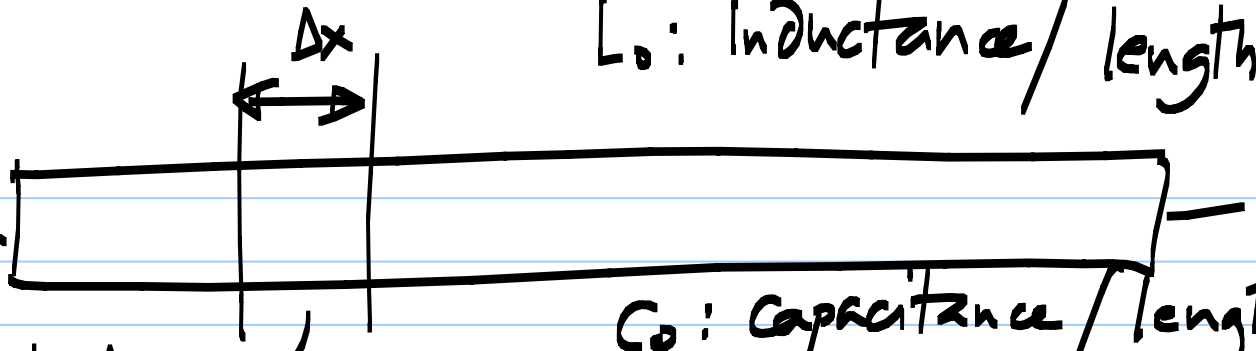


Dielectric losses


dc
+ -
I
$V_p \cos(\omega t)$
+ -
I
[skin depth $\propto \frac{1}{\sqrt{f}}$]
@ dc:
uniform
current density
across the
cross section
of the conductor
@ hf:
resistance
$|\vec{J}|$
1/e times
skin depth
depth

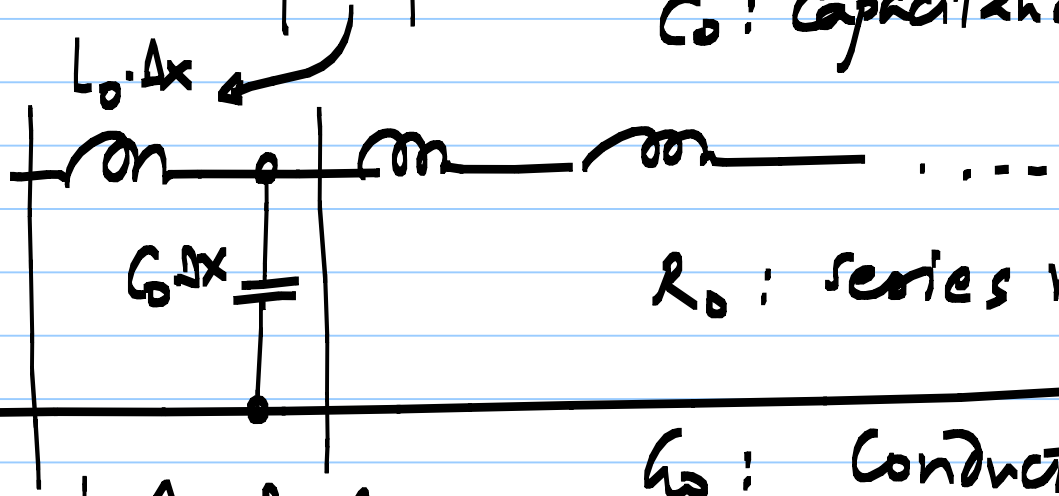
$\frac{L_0}{R_0} = \frac{C_0}{G_0}$ X

Freq. independent



L_0 : Inductance / length

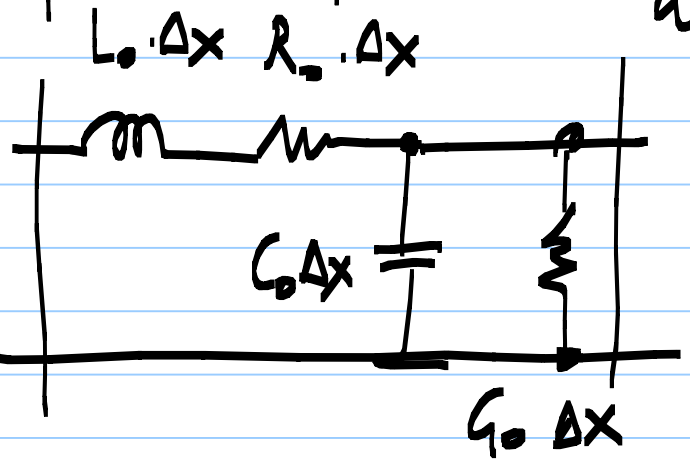
C_0 : Capacitance / length



R_0 : series resistance / length

G_0 : Conductance / length

Lossless Line



Lossy Line

Rectangular data: $x(t) = \sum a_n \, p[t - nT_0]$

$S_x(f) \propto |P(f)|^2$

bits $\{a_n\}$