STANFORD

Supplementary Lecture 4A

Transmission-Line Channels

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Announcements & Agenda

- Goals
  - Familiarize, or reacquaint, interested students/researchers to obtain an $H(f)$ for a transmission line
  - Permit construction of real or complex baseband-equivalent channels for analysis.

This is first of 3 short lectures online

S4A: Transmission Line

S4B: Waveguide

S4C: Wireless (with antennas)

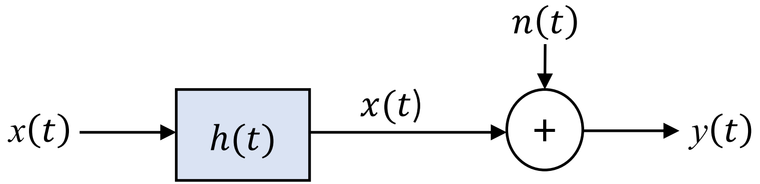
- Topics
  - Filtered AWGN
  - 2-port network review & transmission line
  - Phases and delays
  - Cascades
  - Example use rlcg379.m

Finding H(f)

[Section 1.3.8](#)

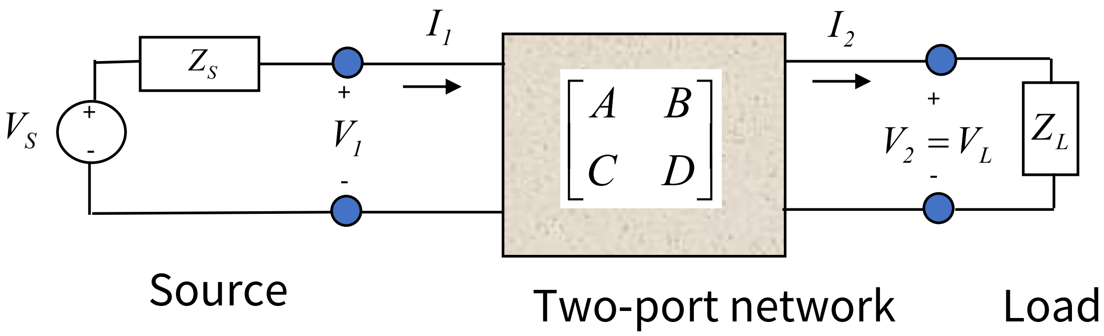
Computation of H(f)

- **Channel filter** $h(t) \leftrightarrow H(f)$ from electromagnetic modelling.



- **Noise:** AWGN often specifies a PSD, like -174 dBm/Hz
  - This is room temperature noise $k \cdot T$ (Boltzman constant x Kelvin temperature).
  - Often ADC quantization and/or background noises lifts this to numbers like -150 dBm/Hz , or "noise figure" in dB increases this level
  - Unrelated radio noises can "color" the noise (must measure $S_{noise}(f)$) and then can model with noise-whitening receiver that changes $H(f) \leftrightarrow S_{noise}^{-1/2} \cdot H(f)$

Supplementary – 2-port Network



$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \underbrace{\begin{bmatrix} A & B \\ C & D \end{bmatrix}}_{\Phi} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

- **Overall Transfer Function follows.**
  - By cascading sections

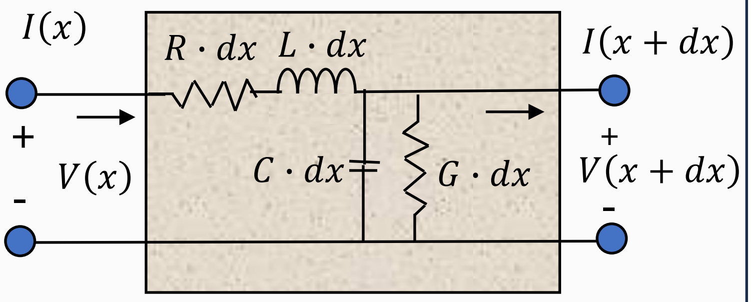
$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \left(\prod_{i=1}^{N-1} \Phi_i \right) \cdot \begin{bmatrix} V_N \\ I_N \end{bmatrix}$$

- **Overall Transfer Function is:** $\frac{V_L}{V_S} = \frac{Z_1}{Z_1 + Z_S} \cdot \frac{Z_L}{A \cdot Z_L + B}$ where $Z_1 = \frac{A \cdot Z_L + B}{C \cdot Z_L + D}$

Transfer function = "Insertion Loss" + 6db (IL = measure w & w/o 2-port present)

Supplemenary – Transmission Line

- Cascade sections and integrate.
- Propagation constant is
  - $\gamma = \sqrt{(R + j\omega L) \cdot (G + j\omega C)}$
- Characteristic Impedance is
  - $Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$
- RLCG 1.3.8 tables



Incremental 2-port network – integrate over length d

$$\frac{V_L}{V_S} = \frac{Z_0 \cdot sech(\gamma \cdot d)}{Z_0 \cdot \left[{}^{Z_0}/_{Z_L} + tanh(\gamma \cdot d)\right] + Z_0 \cdot \left[1 + {}^{Z_0}/_{Z_L} \cdot tanh(\gamma \cdot d)\right]}$$

Appendix E (when complete) provides more details. The length is d .

Velocity, Phase, and Delay

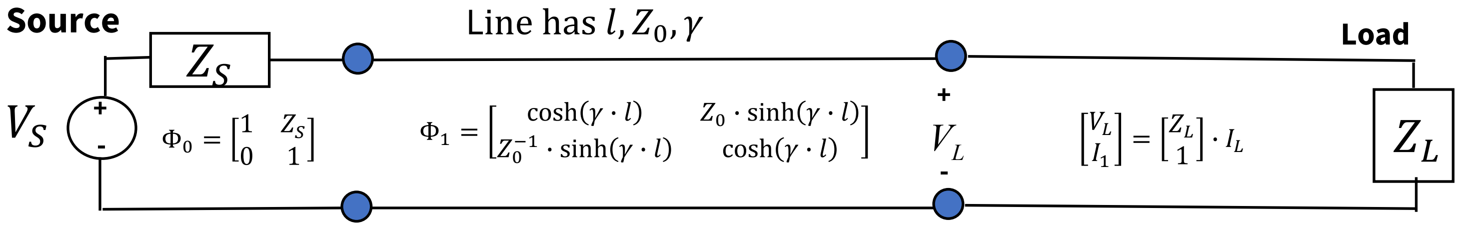
- $cos(\omega \cdot t + \theta)$ = sinusoid propagating (whatever amplitude)
- **Phase delay** is $\tau_p = -\frac{\theta}{\omega}$; **phase velocity** is $v_p = -\frac{\omega}{\beta}$
- **Group delay** is $\tau_g = -\frac{d\theta}{d\omega}$; **group velocity** is $v_g = -\frac{d\omega}{d\beta}$
- Lossless (R=G=0), then $c_{tl} = \frac{1}{\sqrt{LC}} \leq c = 3\times10^8\ m/s$
  - $c_{tl} = \sqrt{v_p \cdot v_g}$

Average Group Delay & RMS Delay Spread

- **Average group delay** $\langle \tau_g \rangle = \frac{\int_0^\infty t \cdot |h(t)|^2 \cdot dt}{\int_0^\infty |h(t)|^2 \cdot dt}$

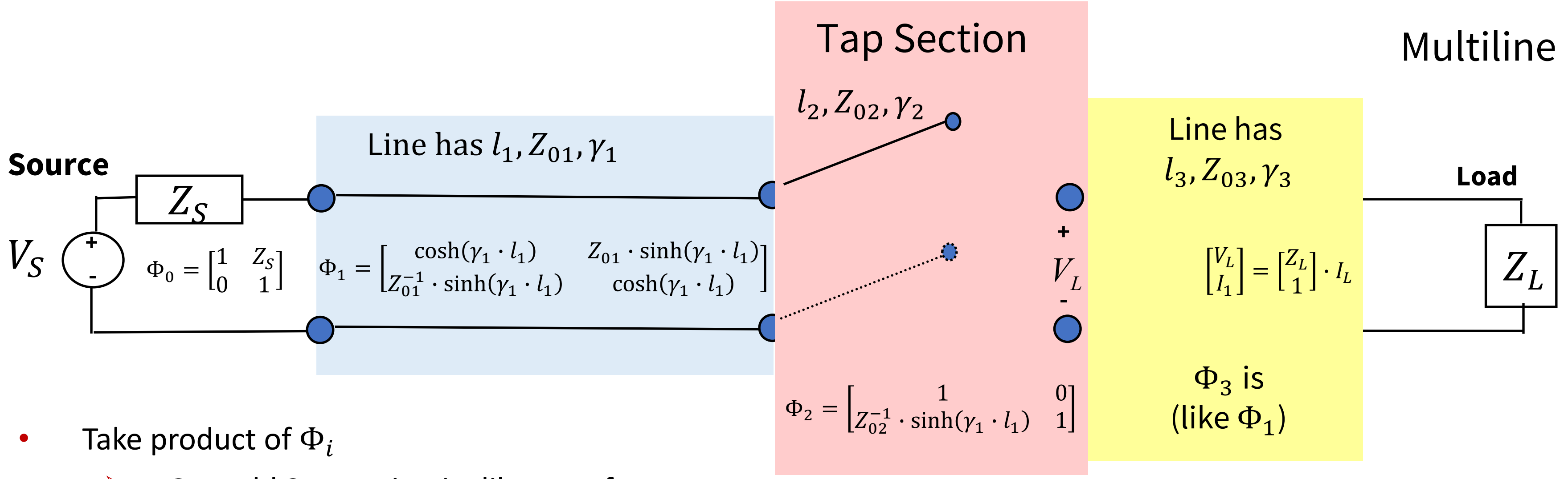
- **Average group delay** $\tau_{rms} = \frac{\int_0^\infty (t - \tau_g)^2 \cdot |h(t)|^2 \cdot dt}{\int_0^\infty |h(t)|^2 \cdot dt}$

Single Line or Sections



Single line

Multiline

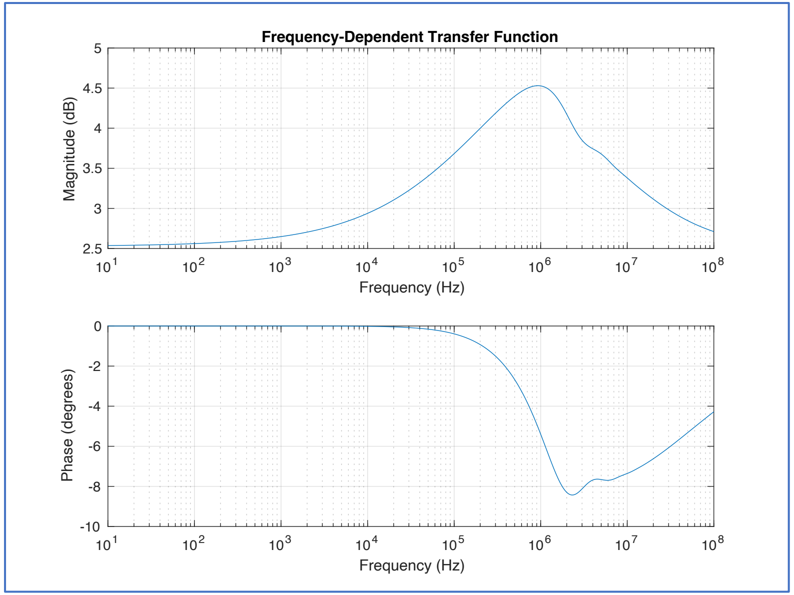


- Take product of Φ_i
  - Can add 2-port circuits like transformers
  - or "baluns" (impedance matching circuits between trans line and waveguide), etc

Example

- Matlab rlcg379.
  - Inputs R,L,C,G,l,Z_s,Z_L,ff
  - Outputs H,Zin, ABCD
  - Also plots magnitude and phase on log(f) scale

```
f = logspace(1, 8, 1000);
R = 0.1 + 0.01 * sqrt(f); % Example: Resistance in ohms/m
L = 1e-6 * ones(size(f)); % Example: Inductance in H/m
C = 100e-12 * ones(size(f)); % Example: Capacitance in F/m
G = 1e-9 * ones(size(f)); % Example: Conductance in S/m
l = 10; % Length in meters
Z_s = 50; % Source impedance in ohms
Z_L = 100; % Load impedance in ohms
H,Z_in,ABCD]=rlcg379(R,L,C,G,l,Z_s,Z_L,f);
size(ABCD) % =        2        2      1000
```



- Insertion loss, divide by 2
  - If Z_s ~matches Z_in

End Supplementary Lecture 4A