# Digital Subscriber Lines (xDSL) Twisted-pair channel modeling

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# Talk overview

- Introduction to DSL (digital subscriber line)
- Twisted-pair channel modeling
- Transceiver front-end noise
- Channel capacity
- Hybrid circuits

# Types of DSL

- IDSN (integrated services digital networks)
  - Started 1985 at AT&T
  - Used bandwidth : 80 kHz
  - Basic rate ISDN transports 160 kb/s
  - loop length up to 18 kft (5.5 km)

# Types of DSL

- HDSL (high bit-rate DSL)
  - Started 1988 at AT&T
  - Used bandwidth : 200 kHz
  - basic HDSL rate: 800 kb/s
  - loop length up to 12 kft (3.7 km)

# Types of DSL

- ADSL (asymmetric DSL)
  - Started 1989 at Bellcore
  - Used bandwidth : 1 MHz
  - ADSL3: <9 Mb/s downstream, <1 Mb/s upstream
  - loop length up to 12 kft (3.7 km)

# Types of DSL

- VDSL (Very-high-bit-rate DSL)
  - Started 1994
  - Used bandwidth : 15 MHz
  - 52 Mb/s for <1 kft
  - 13 Mb/s for <12 kft

# Subscriber loop environment

- connects central office (CO) and end user
- designed for 4 kHz voice band
- ringing voltage up to 140 volts
- Plain Old Telephone Service (POTS), analog phones
- different wire gauge, installations (aerial,. . .)

# Bridged taps

- open wire connected in parallel to loop
- used for reaching future customers
- unterminated $\longrightarrow$ reflections
- $\longrightarrow$ signal loss, distortions
- 80% of US loops have bridged taps

# Loading coils

- series inductor in twisted pair loop
- used for extending beyond 18 kft
- flattens frequency response across voice band
- low pass filtering
- blocks xDSL signals
- 15% of US loops have loading coils

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# Two-port modeling

- yields accurate results for DSL <20 MHz
- loop consists of cascade of different wire types

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \Phi \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{1}$$

# Two-port modeling

with

(2)
$$T(f) = \frac{V_2}{V_1} = \frac{1}{A + B\frac{I_2}{V_2}}$$

and $V_2/V_1 = Z_2 = Z_L$ the load impedance yields

(3)
$$T(f) = \frac{Z_L}{AZ_L + B}$$

# Two-port modeling

Transfer function $H(f)$

$$(4)\ \frac{V_L(f)}{V_s(f)} = H(f) = \frac{V_L(f)}{V_2(f)}\frac{V_2(f)}{V_S(f)} = \frac{Z_1}{Z_1 + Z_S}T(f)$$

with $Z_1 = V_1/I_1$, input impedance of two-port

# Equivalent circuit

deriving the ABCD parameters

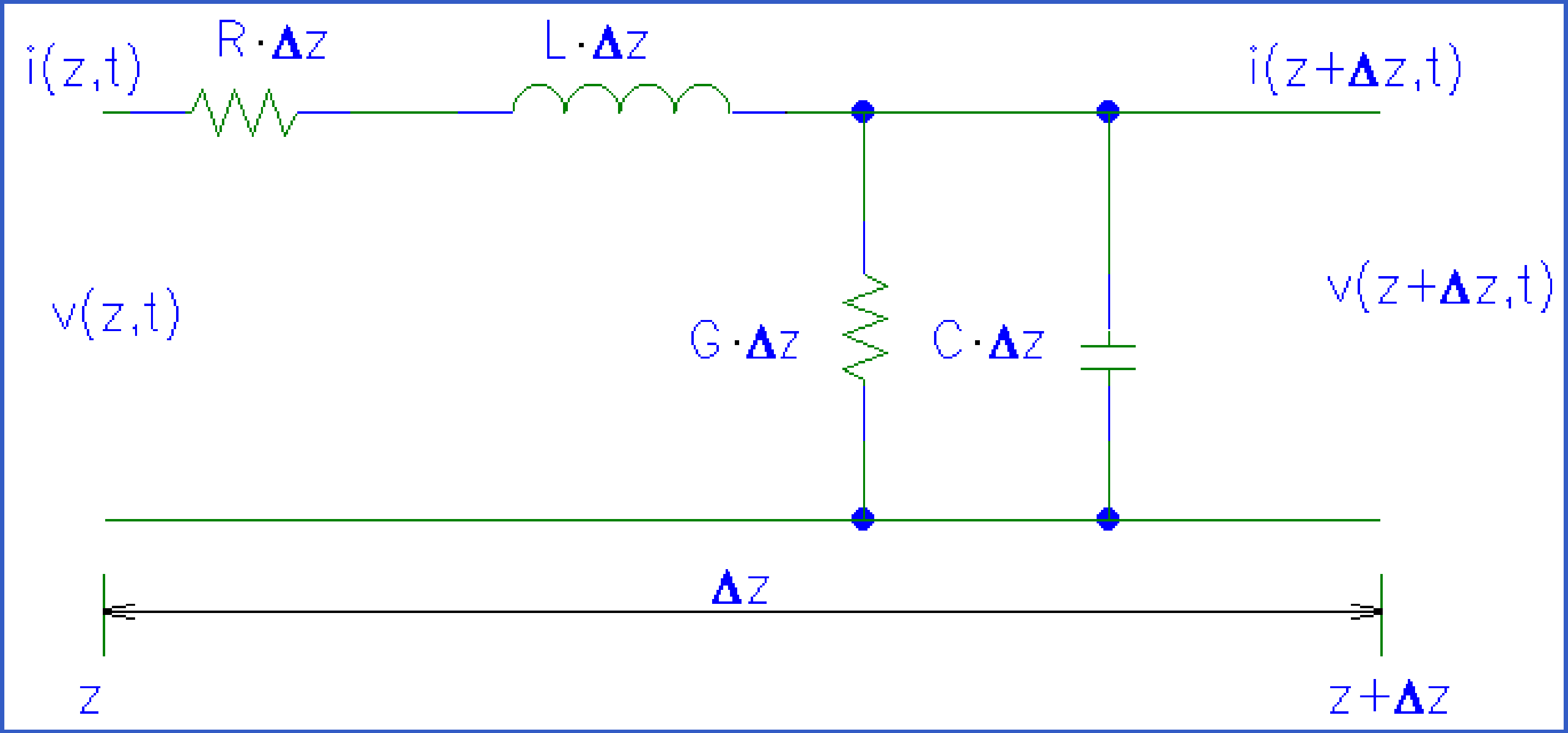


Figure 1: The transmission line equivalent ciruit.

# Transmission line equation

(5) $$-\frac{\partial v(z,t)}{\partial z} = Ri(z,t) + L\frac{\partial i(z,t)}{\partial t}$$

(6) $$-\frac{\partial i(z,t)}{\partial z} = Gv(z,t) + C\frac{\partial v(z,t)}{\partial t}$$

# Time harmonic equations

with

$$v(z,t) = \Re\left[V(z)e^{j\omega t}\right], \quad i(z,t) = \Re\left[I(z)e^{j\omega t}\right] \tag{7}$$

$$-\frac{dV(z)}{dz} = (R+j\omega L)I(z), \quad -\frac{dI(z)}{dz} = (G+j\omega C)V(z) \tag{8}$$

# Time harmonic equations

combining gives

$$\frac{d^2V(z)}{dz^2} = \gamma^2 V(z), \qquad \frac{d^2I(z)}{dz^2} = \gamma^2 I(z) \tag{9}$$

with

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} = \sqrt{ZY} \tag{10}$$

- frequency dependent propagation constant $\gamma$
- attenuation constant $\alpha$
- phase constant $\beta$

# Time harmonic equations

Solutions are

$$V(z) = V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z} \qquad I(z) = I_0^+ e^{-\gamma z} + I_0^- e^{\gamma z}. \tag{11}$$

Characteristic impedance

$$Z_0 = \frac{V_0^+}{I_0^+} = \frac{V_0^-}{I_0^-} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{12}$$

# Matrix form

for a given wire length $d$

$$\begin{bmatrix} V(0) \\ I(0) \end{bmatrix} = \begin{bmatrix} \cosh(\gamma d) & Z_0 \sinh(\gamma d) \\ \frac{1}{Z_0} \sinh(\gamma d) & \cosh(\gamma d) \end{bmatrix} \begin{bmatrix} V(d) \\ I(d) \end{bmatrix}$$

(13)

# Characteristic functions

with $V(d)/I(d) = Z_L$

(14)
$$T = \frac{1}{\cosh(\gamma d) + \left(\frac{Z_0}{Z_L}\right)\sinh(\gamma d)}$$

and input impedance $V(0)/I(0)$

(15)
$$Z_1 = Z_0 \frac{Z_L + Z_0 \tanh(\gamma d)}{Z_0 + Z_L \tanh(\gamma d)}$$

# Characteristic functions

(16) $$H(f) = \frac{Z_1}{Z_1 + Z_S} T(f)$$

and therefore

$$H(f) = \frac{Z_0 / \cosh(\gamma d)}{Z_S \left[ \frac{Z_0}{Z_L} + \tanh(\gamma d) \right] + Z_0 \left[ 1 + \frac{Z_0}{Z_L} \tanh(\gamma d) \right]}$$

(17)

# Bridged taps

$$\Phi_2 = \begin{bmatrix} 1 & 0 \\ 1/Z_{bt} & 1 \end{bmatrix} \tag{18}$$

when terminated with open circuit

$$Z_{bt} = Z_{0t}\frac{\cosh(\gamma d)}{\sinh(\gamma d)} \tag{19}$$

# Loading coils

(20)
$$\Phi_{coil} = \begin{bmatrix} 1 & j\omega L_{coil} \\ 0 & 1 \end{bmatrix}$$

when terminated with open circuit

(21)
$$Z_{bt} = Z_{0t} \frac{\cosh(\gamma d)}{\sinh(\gamma d)}$$

# Overall two-port

$$\Phi = \Phi_0 \Phi_1 \cdots \Phi_N \tag{22}$$

and the source voltage divider is

$$\Phi_0 = \begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \tag{23}$$

# RCLG are frequency dependent

Approximate measurement fittings valid up to 20 MHz:

- resistance $R(f) = a + b\sqrt{f}$
- inductance $L(f) = c + \frac{d}{\sqrt{f}}$
- conductance $G(f) \propto f$
- Capacitance is approximately constant

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# Transceiver front-end noise

- Near end Cosstalk (NEXT)
- Far end Crosstalk (FEXT)
- Impulse noise (CO switching,...)

# NEXT/FEXT

- NEXT: Crosstalk between a receiving path and a transmitting path a DSL transceiver at the same end of two different subscriber loops
- FEXT: crosstalk between a receiving path and a transmitting path a DSL transceiver at opposite ends of two different subscriber loops
- can be modeled by Unger model

# Useful links

- Online book about DSL at www.paradyne.com
- ADSL - forum www.adsl.com
- Html-bases documentation of the talk http://snape.inw.tu-graz.ac.at/talks/dsl/