Chapter 12: Transmission Lines

EET-223: RF Communication Circuits
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Introduction

• A transmission line can be defined as the conductive connections between system elements that carry signal power.

• At low frequencies transmission is very straightforward (short-circuit), but at higher frequencies the make-up of the connection starts having appreciable effect on circuit action that results on strange behaviour (losses, radiation, reflection, etc.)
Two Wire Open Transmission Line

- Can be used as transmission line between antenna & transmitter or antenna & receiver
- Parallel two-wire line (Fig 12-1)
  - Spaced from 0.25 - 6 inches apart
- Twin Lead or two-wire ribbon-type line (Fig 12-2)
  - Low loss dielectric (e.g. polyethylene)
Figure 12-1  Parallel two-wire line.
Figure 12-2  Two-wire ribbon-type lines.
Twisted Pair Transmission Lines

• Refer to Fig 12-3
• Consists of two insulated wires twisted to form a flexible line without the use of spacer
• Not used at high frequencies because of high losses occur in rubber isolation
• Losses increase when line is wet
Figure 12-3 Twisted pair.
Unshielded Twisted Pair (UTP) Transmission Lines

- Widely used for computer networking
- Most commonly used standard is UTP category 6 (CAT6) and 5e (CAT5e):
  - Frequencies up to 100 MHz
  - Maximum length of 100 meters
  - Four color coded pairs of 22/24 gauge wires
  - Terminated with RJ45 connector
- Provide differential signal noise rejection:
  - $V_+ \& V_- \text{ wires make differential signal of } (V_+ - V_-)$
  - Interference impose upon one wire most likely affect both wires becoming a common mode signal
UTP Cable Parameters

• Attenuation: amount of loss in the signal strength as it propagates down a wire (negative dB gain)
• Crosstalk: unwanted coupling caused by overlapping electric and magnetic fields
• Near-End Crosstalk (NEXT): measure of level of crosstalk or signal coupling within an cable
  – Graphical illustration at Fig 12-4
  – Measured in dB; the larger (closer to negative infinite), the better
  – Crosstalk more likely at wire ends because transmit signals are stronger while receive signals are weaker
UTP Cable Parameters – Cont’d

• Attenuation-to-Crosstalk Ratio (ARC): combined measurement of attenuation and crosstalk
  – Large value indicates greater bandwidth
  – Measurement of the quality of the cable

• Delay Skew: measure of difference in time between the fastest and slowest wire pair in a UTP cable
  – Critical on high-speed data transmission where data on a wire pair must arrive at the same time

• Return Loss: measure of ratio of transmitted power into a cable to amount of power returned/reflected
Figure 12-4  A graphical illustration of near-end crosstalk.
Shielded Pair Transmission Lines

• See construction at Fig 12-5
• Consists of parallel conductors separated from each other and surrounded by solid dielectric
• Conductors are contained within copper braid shield that isolates from external noise pickup and prevents radiating to and interfering with other systems
• Principal advantage is that the conductors are balanced to ground, so capacitance between the cables is uniform throughout the length of the cable
Figure 12-5  Shielded pair.
Coaxial Transmission Lines

• Consists of single transmission line surrounded by conductive, ground shield (concentric conductors)

• Two types of lines:
  – Rigid or Air Coaxial (see Fig 12-6)
  – Flexible or Solid Coaxial (see Fig 12-7)

• Advantages:
  – Minimizes radiation losses
  – Minimizes external noise pickup

• Disadvantages:
  – Expensive
  – Prone to moisture problems
Figure 12-6  Air coaxial: cable with washer insulator.
Figure 12-7 Flexible coaxial.

- Copper braid outer conductor
- Polyethylene
- Wire inner conductor
Balance vs Unbalance Transmission Lines

• **Balance Lines:**
  – Used on two-wire open, twisted pair and shielded pair lines
  – Same current flows in each wire but 180° out of phase
  – Noise or unwanted signals are pickup by both wires, but because 180° out of phase, they cancel each other (called Common Mode Rejection or CMR)

• **Unbalance Lines:**
  – Used on coaxial lines
  – Signal carried by center conductor with respect to grounded outer conductor

• **Balance/Unbalance conversion can be done with baluns circuit** (see Fig 12-8)
Figure 12-8  Balanced/unbalanced conversion.
Electrical Characteristics of Two-Wire Transmission Lines

- Capacitance arise between two lines since they are conductors with electric fields (long capacitor)
- Inductance occurs in each line due to magnetic field from moving charge
- Some conductance exists between lines since insulator resistance is not really infinite
- Equivalent circuit of a small line section is shown in Fig 12-9
- Typically, the values of conductance and resistance can be neglected resulting in circuit at Fig 12-10
Figure 12-9  Equivalent circuit for a two-wire transmission line.

\[ \begin{align*}
L_1 &= \text{inductance of top wire} \\
L_2 &= \text{inductance of bottom wire} \\
R_1 &= \text{resistance of top wire} \\
R_2 &= \text{resistance of bottom wire} \\
G &= \text{conductance between wires} \\
C &= \text{capacitance between wires}
\end{align*} \]
Figure 12-10  Simplified circuit terminated with its characteristic impedance.
Characteristic Impedance ($Z_0$)

- Aka Surge Impedance
- It is the input impedance of an infinitely long transmission line
- It can shown that it is equal to:

$$Z_0 = \sqrt{\frac{L}{C}}$$

Where:

L: inductance reactance of the line
C: capacitive reactance of line
Characteristic Impedance \( (Z_0) \) – Cont’d

• For a two-wire line it can be computed as:

\[
Z_0 \approx \frac{276}{\sqrt{\varepsilon}} \log \frac{2D}{d}
\]

Where:

- \( D \): spacing between wires (center-to-center)
- \( d \): diameter of one of the conductors
- \( \varepsilon \): dielectric constant of insulating material relative to air

• And for a coaxial line:

\[
Z_0 \approx \frac{138}{\sqrt{\varepsilon}} \log \frac{D}{d}
\]

Where:

- \( D \): inner diameter of outer conductor
- \( d \): outer diameter of inner conductor
Transmission Line Losses

• Losses in practical lines cannot be neglected
• The resistance of the line causes losses:
  – The larger the length, the larger the resistance
  – The smaller the diameter, the larger the resistance
• At high frequencies, current tends to flow mostly near surface of conductor, effectively reducing the cross-sectional area of the conductor. This is known as the Skin Effect (see Fig. 12-11)
• Dielectric losses are proportional to voltage across dielectric and frequency. Limit maximum operation to ~18 GHz
Figure 12-11  Line attenuation characteristics.
Propagation of DC Voltage Down a Line

• Propagation of a DC Voltage down a line takes time because of the capacitive & inducive effect on the wires (see model circuit on Fig 12-12)

• The time of propagation can be computed as:

\[ t = \sqrt{LC} \]

• The velocity of propagation is given by:

\[ V_p = \frac{d}{\sqrt{LC}} \]

Where:

\[ d: \text{distance to travel} \]
Propagation of DC Voltage Down a Line – Cont’d

- A wave travels through a medium at a constant speed, regardless of frequency.
- The distance traveled by a wave during a period of one cycle (called *wavelength*) can be found as:
  \[ \lambda = \frac{V_p}{f} \]
  
  Where:
  
  \( V_p \): velocity of propagation
  
  \( f \): frequency

- In space, the velocity of propagation becomes the speed of light \( V_p = c = 3 \times 10^8 \text{ m/s} \)
Figure 12-12  DC voltage applied to a transmission line.
Non-Resonant Transmission Line

- Defined as a line of infinite length that is terminated with a resistive load equal to its characteristic impedance
- The voltage (DC or AC) takes time to travel down the line
- All energy is absorbed by the matched load (nothing reflected back)
Resonant Transmission Line

• Defined as a line that is terminated with an impedance that is NOT equal to its characteristic impedance

• When DC voltage is applied to a resonant line terminated on an open-circuit load (see Fig 12-16):
  – Open circuit load behaves like a capacitor
  – Each capacitor charges from current through previous inductor
  – Current keeps flowing into load capacitor making voltage across larger than voltage across previous one
  – Current flows in opposite direction causing reflection
Resonant Transmission Line – Cont’d

• When DC voltage is applied to a resonant line terminated on a short-circuit load:
  – Same sequence as open-circuit case until current reaches short-circuit load
  – Incident voltage is reflected back out of phase (180°) so that resulting voltage at load is zero

• Differences between open and short circuit load cases are:
  – Voltage reflection from open circuit is in phase, while from short circuit is out of phase
  – Current reflection from open circuit is out of phase, while from short circuit is in phase
When the applied signal is AC, the interaction between incident and reflected wave results in the creation of a new wave called **standing wave**

- Name is given because they apparently remain in one position, varying only in amplitude
- Standing wave is simply the superposition (sum) of the incident and reflected waves
- See illustration Fig 12-19
- Notice that Standing Waves maximums occur at $\lambda/2$ intervals
Figure 12-16  Open-ended transmission line.
Figure 12-19  Development of standing waves.
Reflection Coefficient ($\Gamma$)

- The ratio of reflected voltage to incident voltage is called the *reflection coefficient* and can be computed as:

$$\Gamma = \frac{E_r}{E_i} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Where,

- $E_r$: magnitude of reflected wave
- $E_i$: magnitude of incident wave
- $Z_L$: load impedance
- $Z_0$: characteristic impedance
Voltage Standing Wave Ratio

• As seen before, standing wave is the result of an incident and reflected wave

• The ratio of maximum to minimum voltage on a line is called the voltage standing wave ratio (VSWR) or simply standing wave ratio (SWR)

• In general, it can be computed as:

\[
VSWR = SWR = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}
\]

• And for the case of a purely resistive load \(R_L\):

\[
VSWR = \frac{R_L}{Z_0} \quad \text{(if } R_L \geq Z_0)\\
VSWR = \frac{Z_0}{R_L} \quad \text{(if } R_L < Z_0)
\]
Electrical Length

• Defined as the length of a line in wavelengths (not physical length)
• It is important because when reflections occur, the voltage maximums occur at λ/2 intervals
• If line is too short, reflection still occurs but no significant voltage variation along the line exists (see example of this situation in Fig 12-24)
Figure 12-24 Effect of line electrical length.
Effect of Mismatch ($Z_L \neq Z_0$)

- Full generator power doesn’t reach load
- Cable dielectric may break down because of high voltage from standing waves
- Increased $I^2R$ power losses resulting because of increased current from standing waves
- Noise problems increased by mismatches
- “Ghost” signals can be created