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.

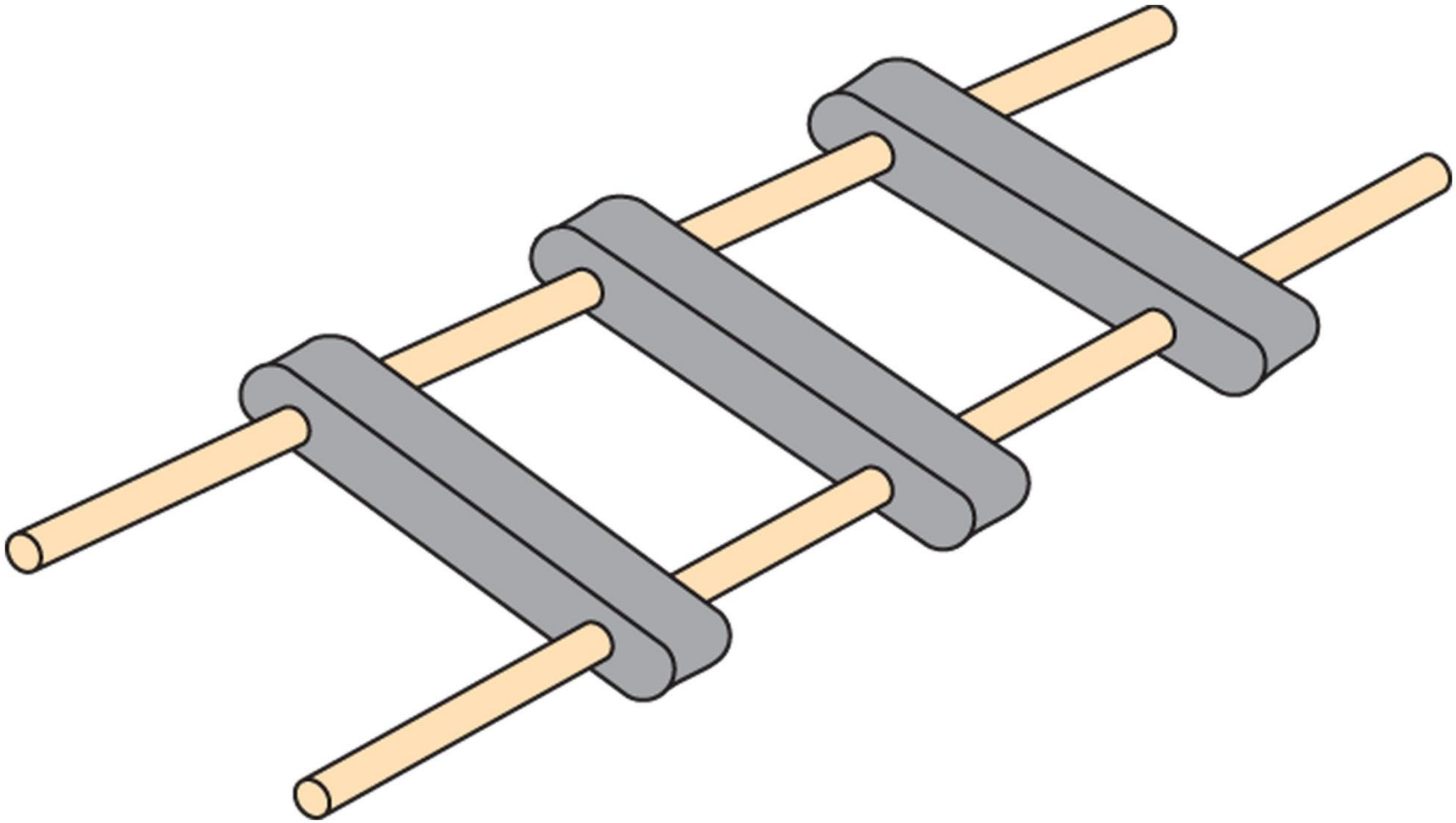
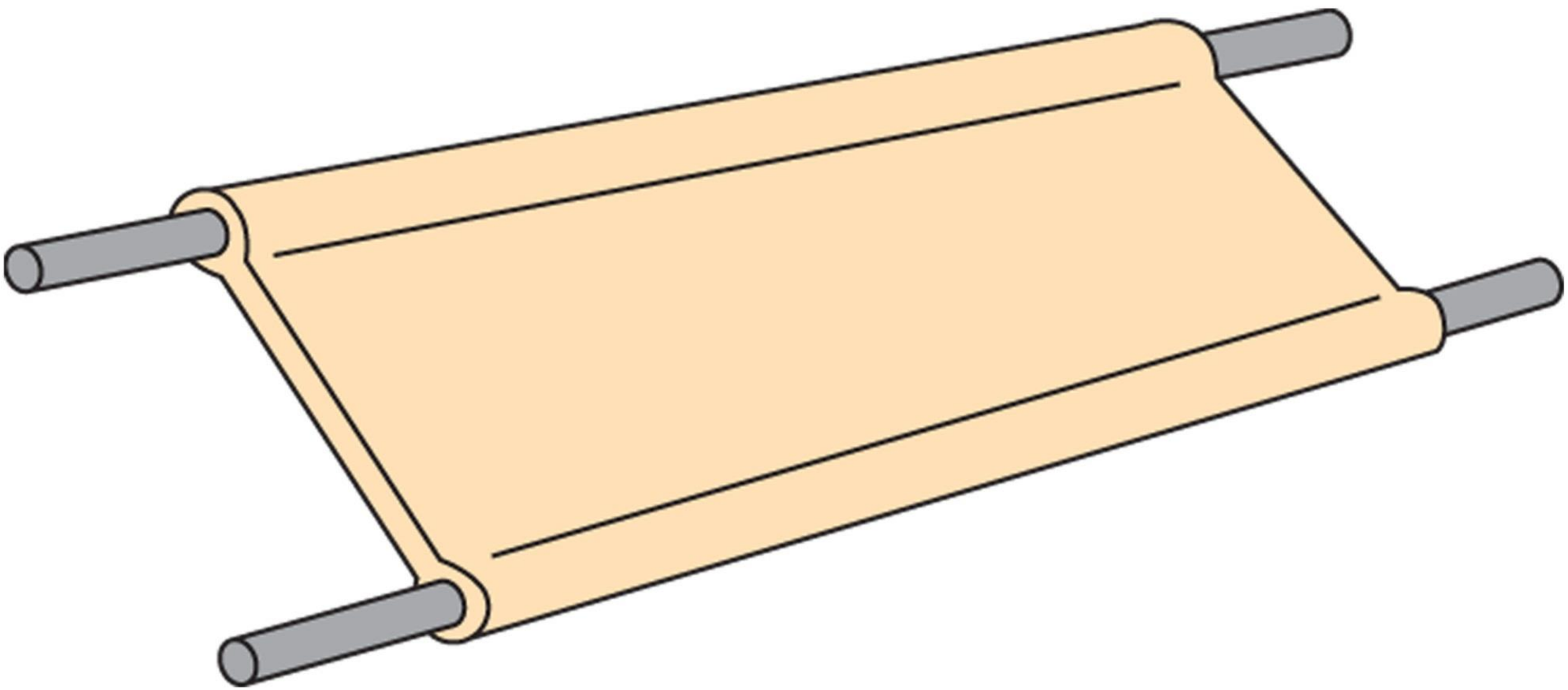


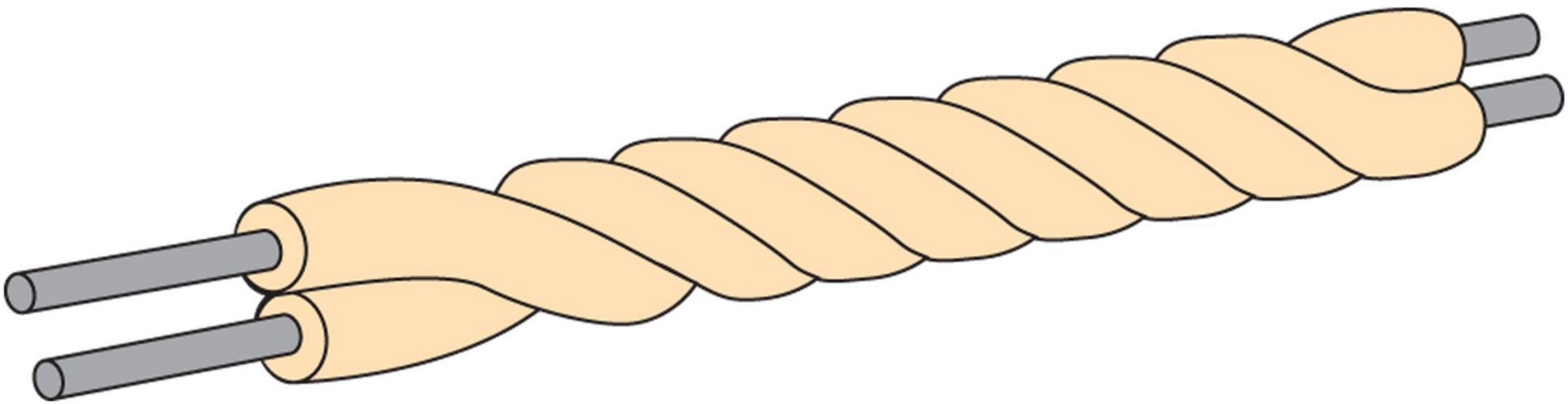
Figure 12-2 Two-wire ribbon-type lines.



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_- wires make differential signal of (V_+ - V_-)
  - Interference impose upon one wire most likely affect both wires becoming a common mode signal

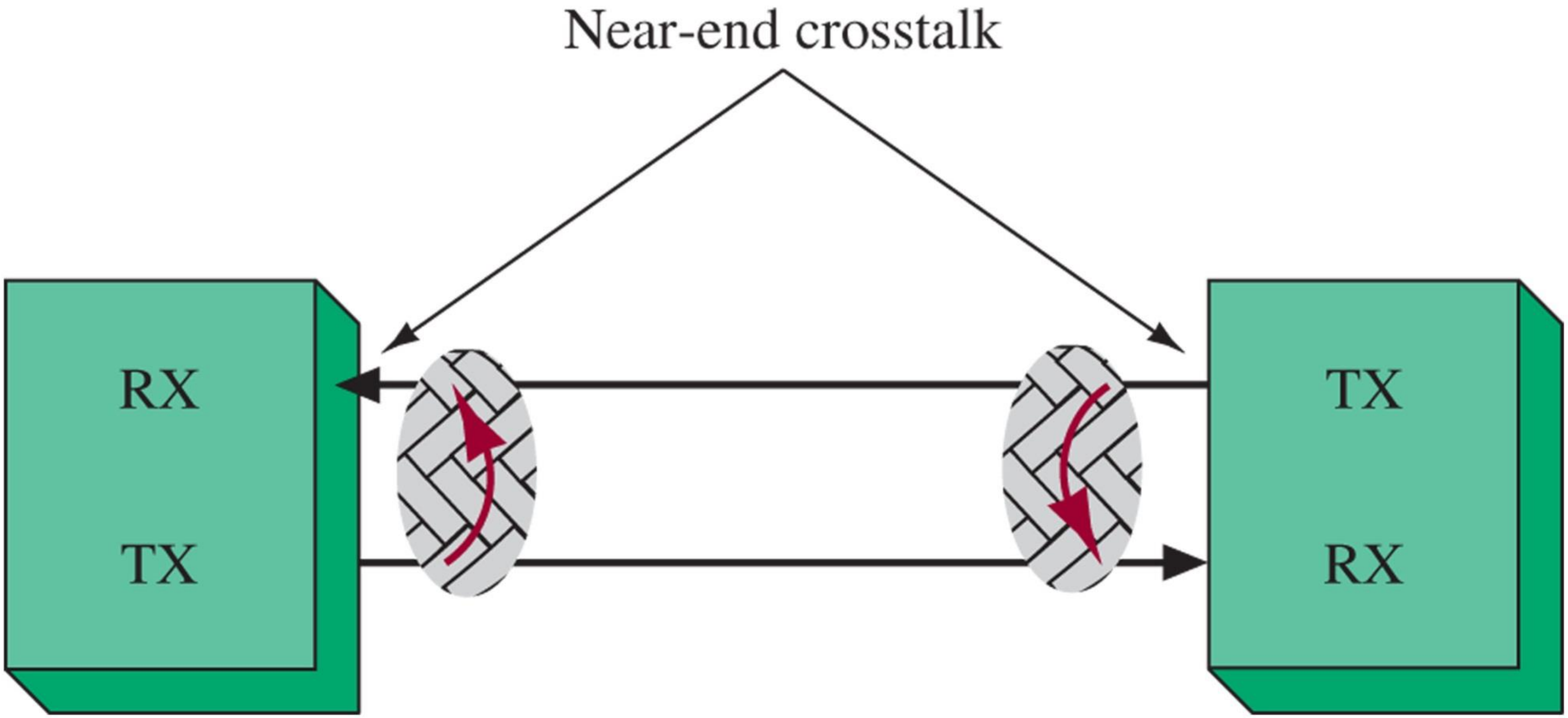
UTP Cable Parameters

- **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**

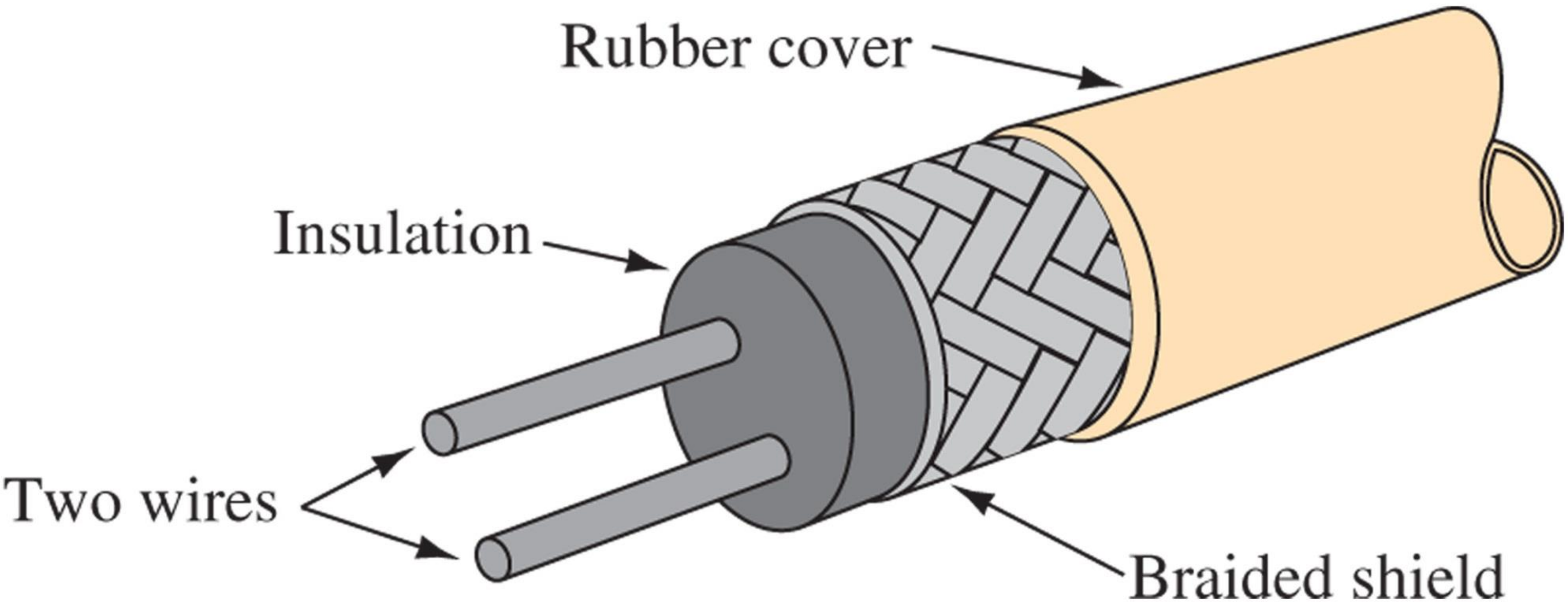
Figure 12-4 A graphical illustration of near-end crosstalk.



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.

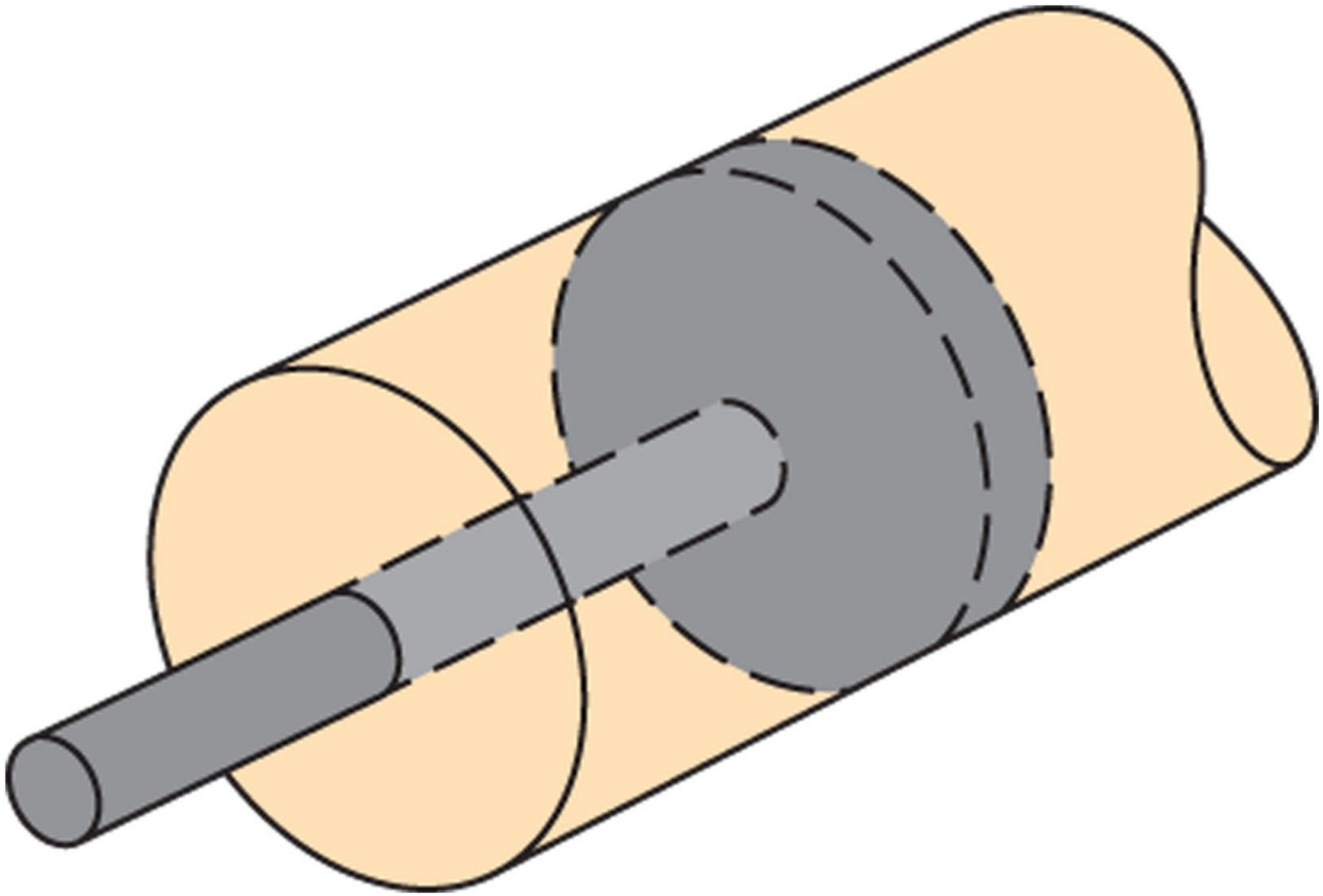
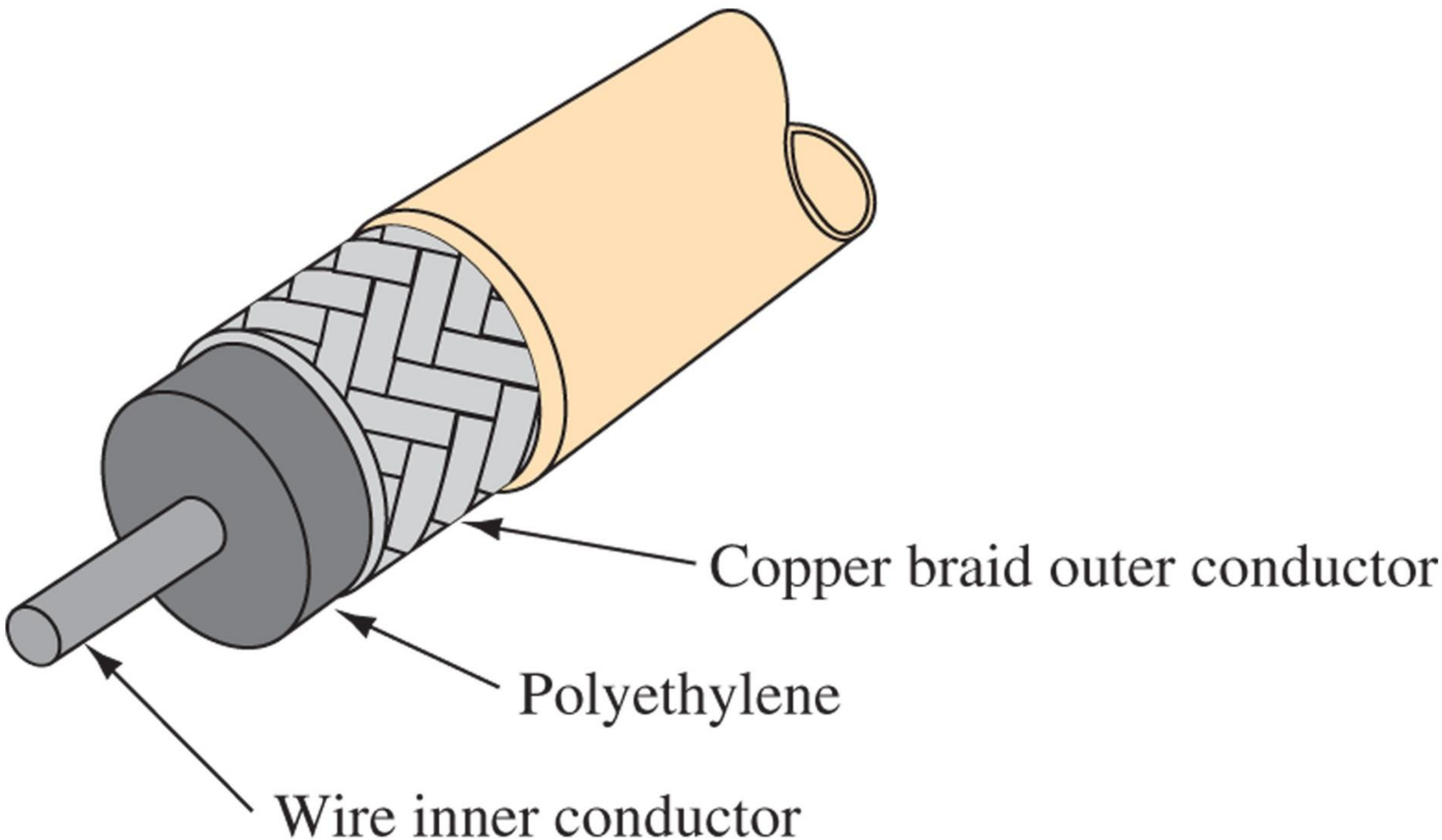


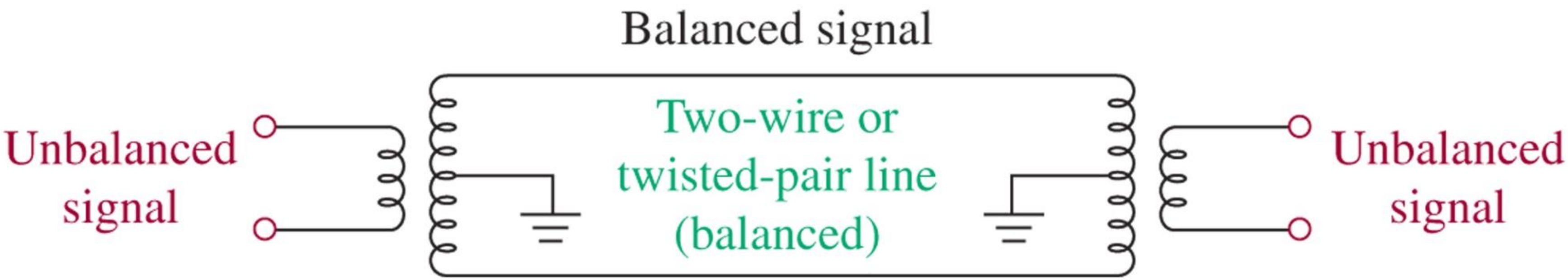
Figure 12-7 Flexible coaxial.



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)**

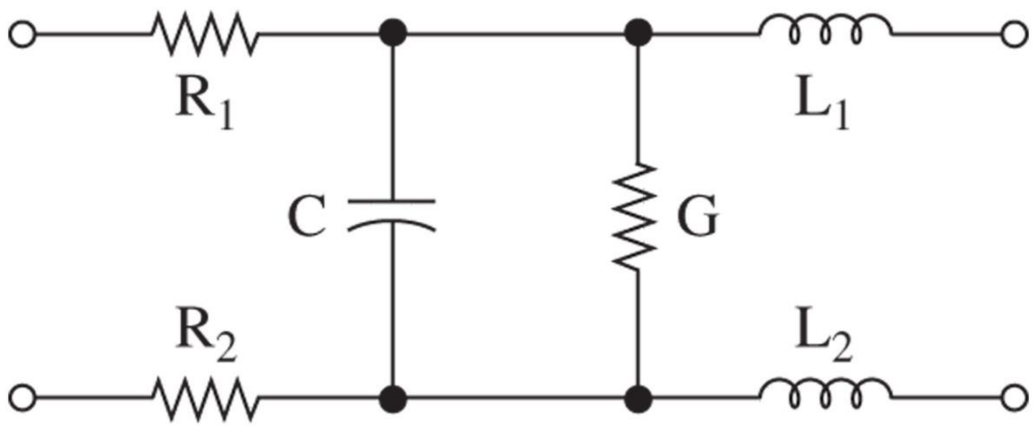
Figure 12-8 Balanced/unbalanced conversion.



Electrical Characteristics of Two-Wire Transmission Lines

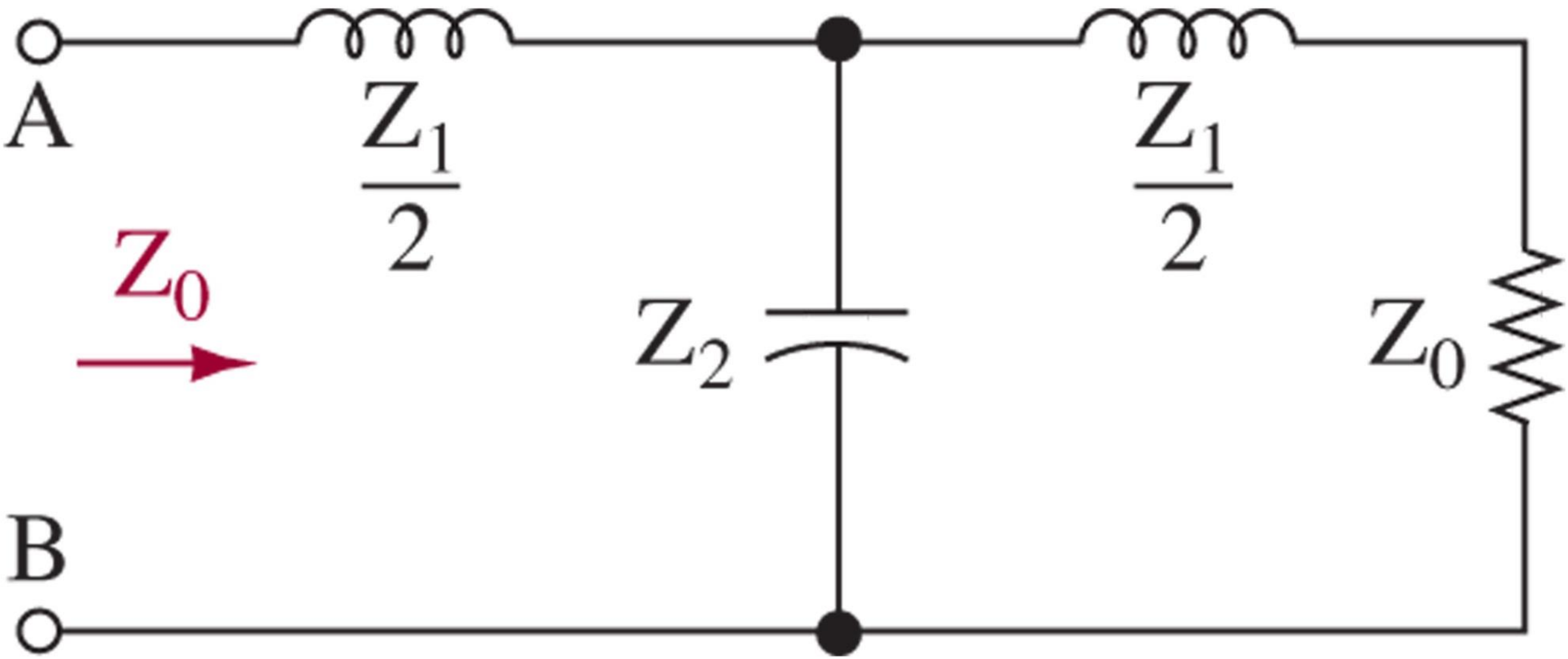
- Capacitance arise between two lines since they are conductors with electric fields (long capacitor)
- Inductance occurs in each line due to magnetic field from moving charge
- Some conductance exists between lines since insulator resistance is not really infinite
- Equivalent circuit of a small line 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.



L_1 = inductance of top wire
L_2 = inductance of bottom wire
R_1 = resistance of top wire
R_2 = resistance of bottom wire
G = conductance between wires
C = capacitance between wires

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:**

$$Z_0 \cong \frac{276}{\sqrt{\epsilon}} \log \frac{2D}{d}$$

Where:

D: spacing between wires (center-to-center)

d: diameter of one of the conductors

ϵ: dielectric constant of insulating material relative to air

- **And for a coaxial line:**

$$Z_0 \cong \frac{138}{\sqrt{\epsilon}} \log \frac{D}{d}$$

Where:

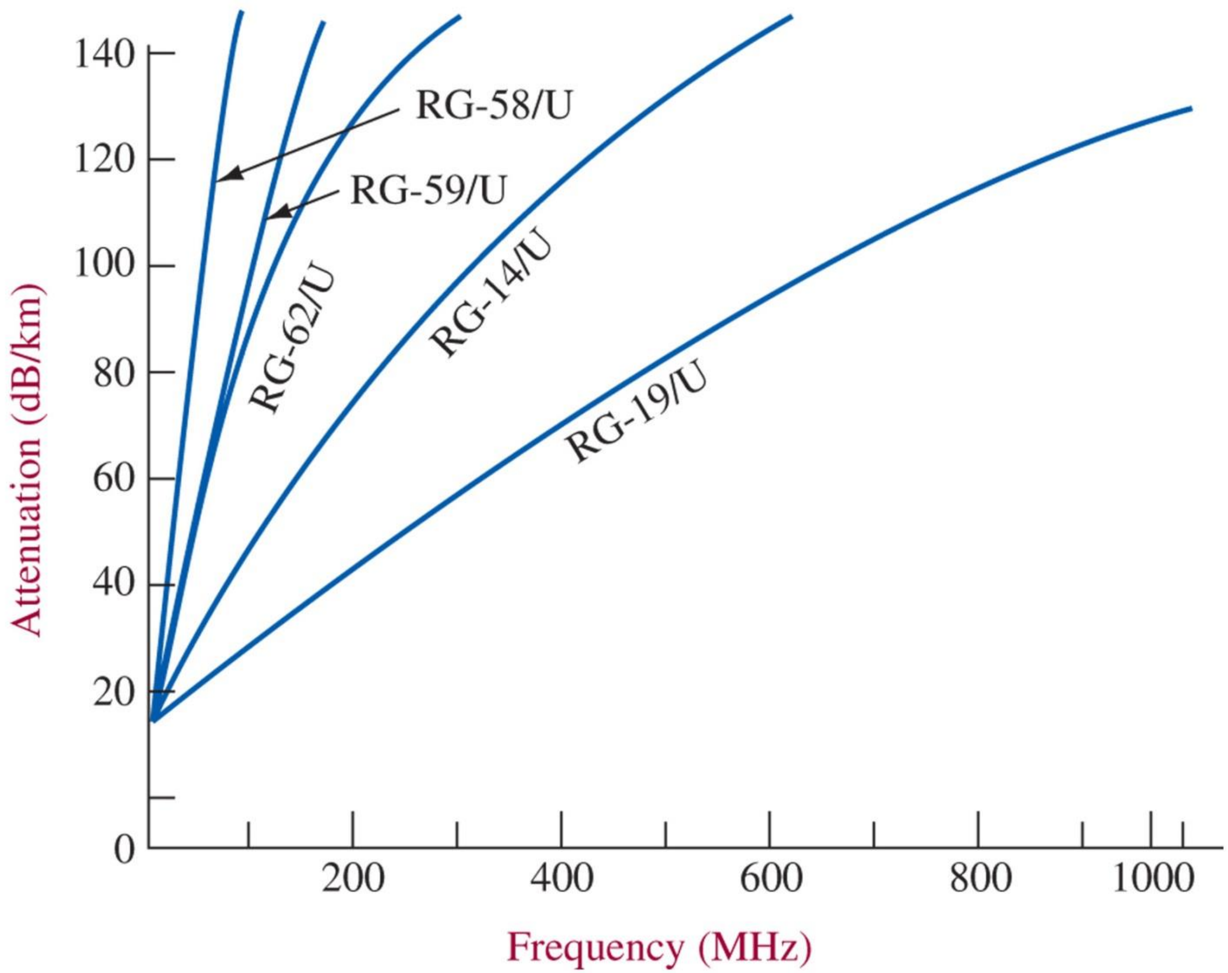
D: inner diameter of outer conductor

d: outer diameter of inner conductor

Transmission Line Losses

- **Losses in <u>practical</u> 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 know 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:

$$V_p = d/\sqrt{LC}$$

Where:

d: 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:**

  $\lambda = V_p / f$

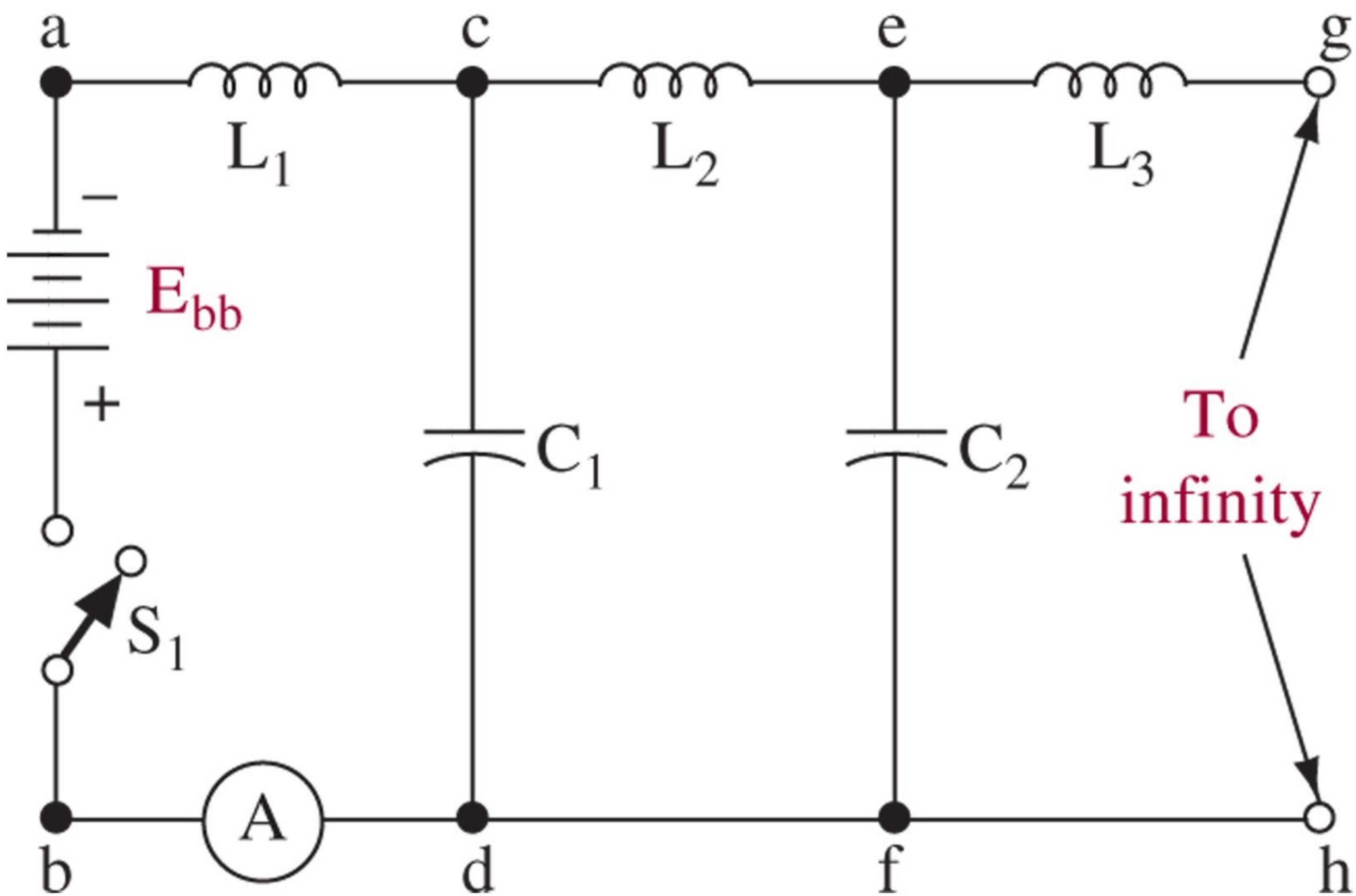
  Where:

  V_p : velocity of propagation

  f: frequency

- **In space, the velocity of propagation becomes the speed of light ($V_p = c = 3 \times 10^8$ 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 <u>open-circuit</u> 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 <u>reflection</u>**

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

Resonant Transmission Line – Cont'd

- **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.

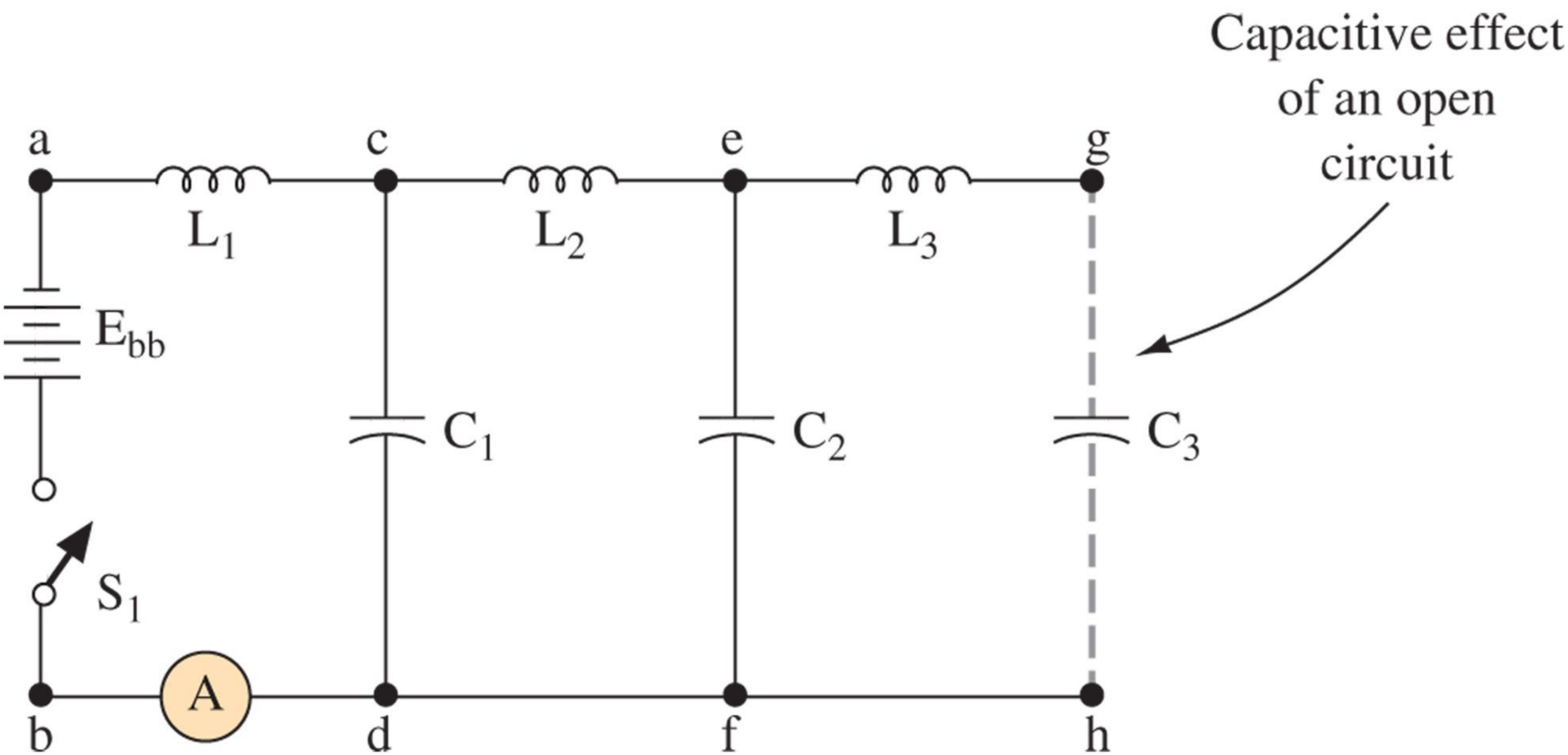
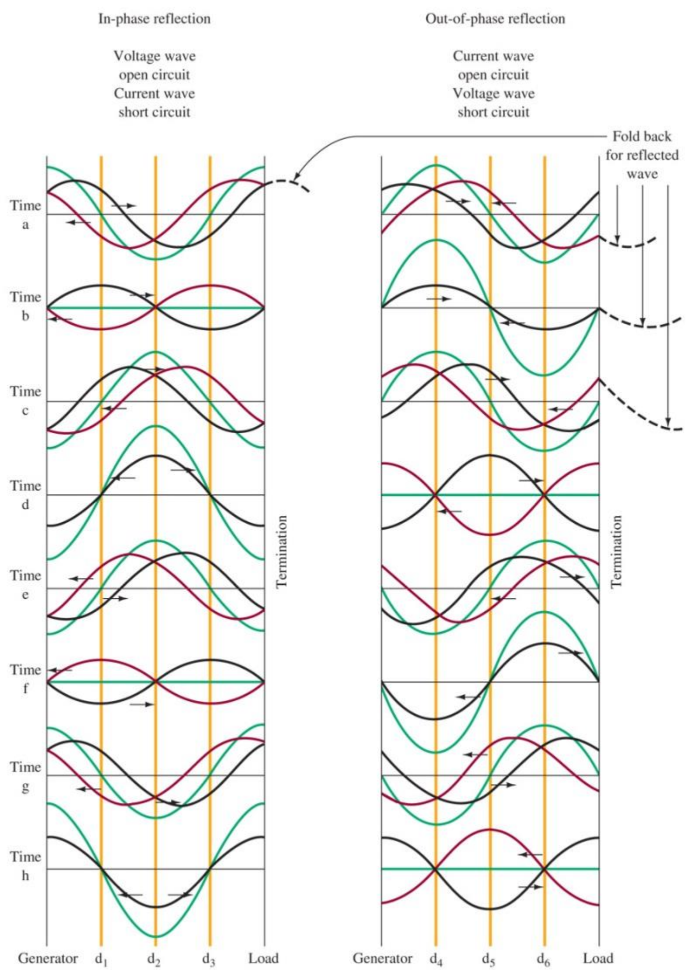


Figure 12-19 Development of standing waves.



Reflection Coefficient (Γ)

- **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:

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

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

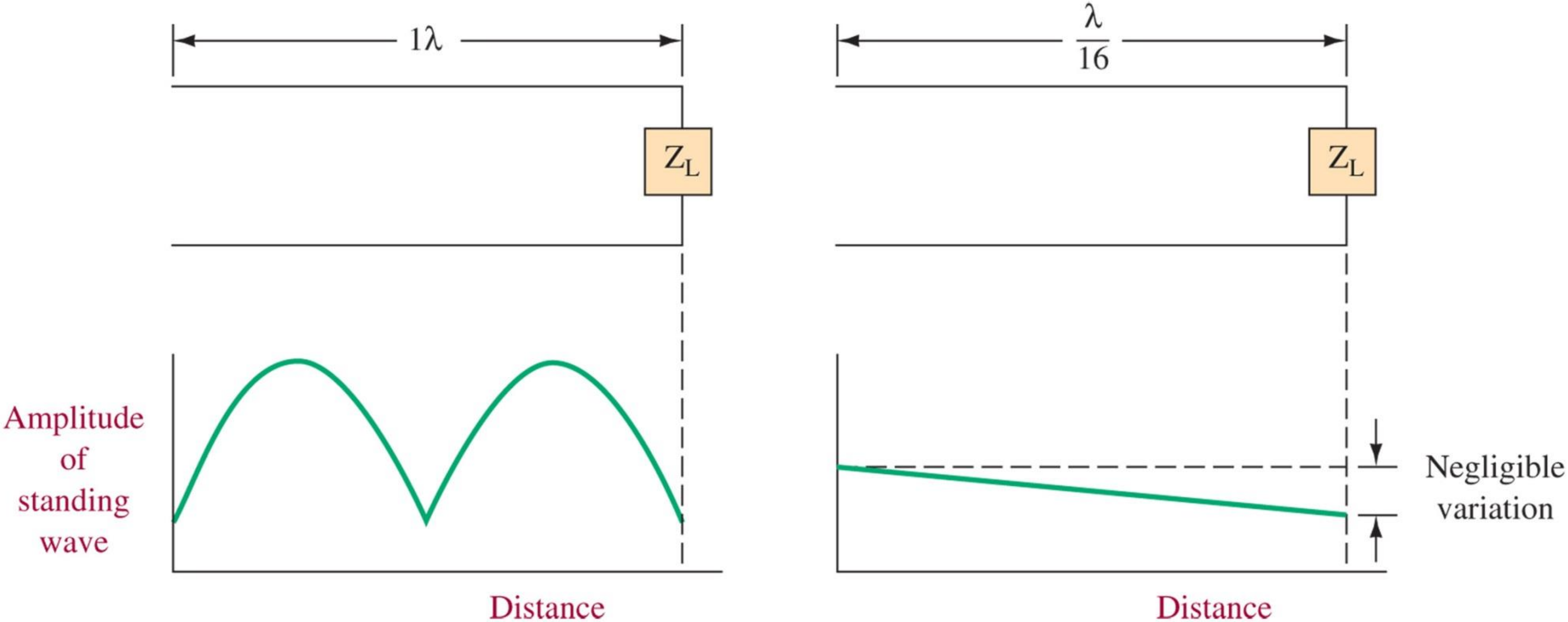
$$\text{VSWR} = R_L / Z_0 \quad (\text{if } R_L \geq Z_0)$$

$$\text{VSWR} = Z_0 / R_L \quad (\text{if } R_L < Z_0)$$

Electrical Length

- **Defined as the length of a line in wavelengths (not physical length)**
- **It is important because when reflections occurs, the voltage maximums occur at $\lambda/2$ 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