Antennas and Propagation

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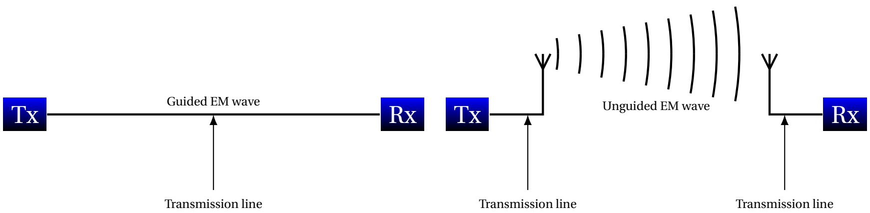
Lecture notes are fully based on books, Balanis [1] Kraus *et al.* [4], and Rao [9]. Some diagrams are directly from the books. These are acknowledged by inserting the citation.

Contents

1 Introduction

What is an Antenna?

An antenna is a device for radiating and receiving radio waves. The antenna is the transitional structure between free-space and a guiding device.



(a) Guided or wire-line communication. (b) Radio or wireless communication.

Figure 1: Unguided and guided EM wave propagation.

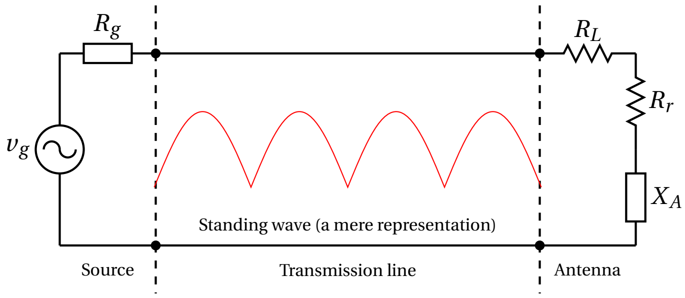


Figure 2: Transmission line Thevévenin equivalent of antenna system

Transmission Line Thevévenin Equivalent of Antenna System

Quantities in Fig. 2:

- The transmission line is represented by a line with characteristic impedance Z_c .
- The antenna is represented by a load $Z_A = (R_L + R_r) + jX_A$ connected to the transmission line.
- The load resistance R_L represents the conduction and dielectric losses associated with the antenna structure.
- R_r, the radiation resistance, represents radiation by the antenna.
- The reactance X_A represents the imaginary part of the impedance associated with radiation by the antenna.

Maximum Power Transfer

Losses in practical systems:

- Conduction-dielectric losses due to the lossy nature of the transmission line and the antenna.
- Losses due to reflections (mismatch) losses at the interface between the line and the antenna.

If we neglect mismatch, maximum power is delivered to the antenna under conjugate matching.

Standing Waves

- Due to the interference between the forward wave and the reflected wave, *standing waves* are created: energy pockets.
- This makes the transmission line an energy storage device than a wave guiding and energy transport device.
- If the maximum field intensities of the standing wave are sufficiently large, they can cause arching inside the transmission lines.

Reducing Losses

The losses due to the line, antenna, and the standing waves are undesirable.

- Line: select a low loss line.
- Antenna: reduce the loss resistance R_L.
- Standing waves: match the impedance of the antenna (load) to the characteristic impedance of the line.

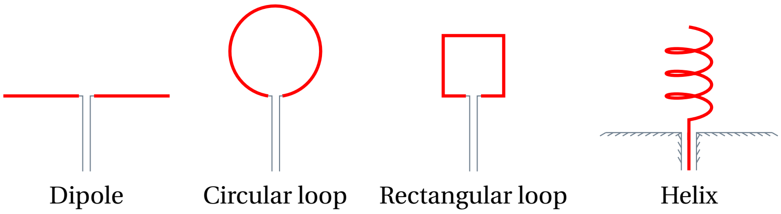
2 Types of Antennas

Antenna Types by Physical Structure

A good antenna would radiate almost all the power delivered to it from the transmitter in a desired direction or directions. A receiver antenna does the reciprocal process, and delivers power received from a desired direction or directions.

- Wire antennas
- Aperture antennas
- Microstrip antennas
- Antenna arrays
- Reflector antennas
- Lens antennas

Wire Antennas



Aperture Antennas

Pyramidal horn

Conical horn

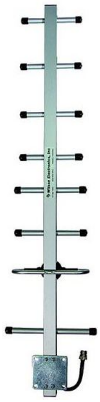
Pictures are from [10].

Microstip Antennas

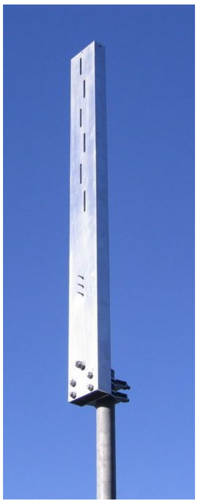
Mobile phone antenna [7]

Antennas Arrays

Reflector array [8]



Yagi Uda [2]



Slotted waveguide [3]

Reflector Antennas

Reflector [5]

Reflector [6]

Other Categorizations

- Narrow band versus broadband
- Size in comparison to the wavelength (e.g., electrically small antennas)
- Omni-directional versus directional antennas
- Polarization (linear, circular, or elliptic)

Antennas at a Glance

Circuit Quantities

- Antenna impedance Z_A
- Radiation resistance R_r
- Antenna temperature T_A

Physical Quantities

- Size
- Weight
- Current distribution

Space Quantities

- Field patterns
- Polarization: LP, CP, EP
- Power pattern
- Beam area
- Directivity
- Gain
- Effective aperture
- Radar cross-section

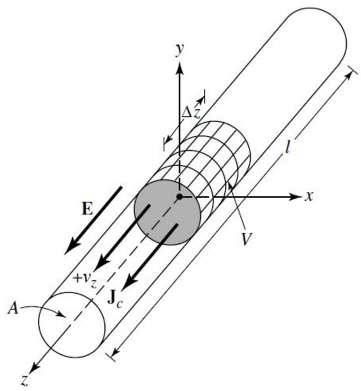
3 Radiation Mechanism

How Is Radiation Accomplished?

- How are electromagnetic fields generated by the source, contained and guided within the transmission line and antenna, and finally "detached" from the antenna to form a free-space wave?

Single-Wire: Current Density, Current

Conducting wires are are characterized by the motion of electric charges and the creation of current flow. Assume that an electric volume charge density, q_v (coulombs/m^3), is distributed uniformly in a circular wire of cross-sectional area A and volume V.



Charge uniformly distributed in a circular cross section cylinder wire.

- Current density in a volume with volume charge density q_v (C/m^3):

$$J_z = q_v v_z \quad (\text{A/m}^2). \tag{1}$$

- Surface current density in a section with a surface charge density q_s (C/m^2):

$$J_s = q_s v_z \quad (\text{A/m}). \tag{2}$$

- Current in a thin wire with a linear charge density q_l (C/m):

$$I_z = q_l v_z \quad (\text{A}). \tag{3}$$

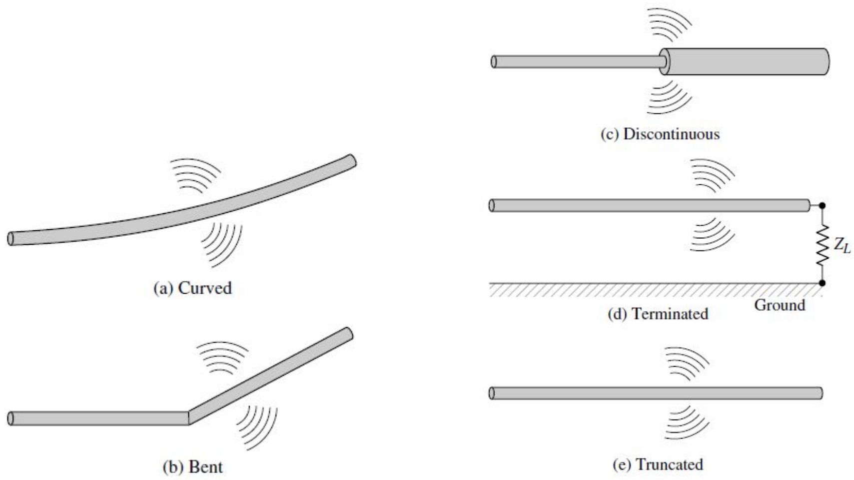


Figure 3: Wire Configurations for Radiation

Thin Wire

If the current is time varying, then the derivative of the current of 3 can be written as

$$\frac{dIz}{dt} = q_l \frac{dv_z}{dt} = q_l a_z \tag{4}$$

where a_z (m/s^2) is the acceleration. If the wire is of length l, then

$$l\frac{dIz}{dt} = lq_l \frac{dv_z}{dt} = lq_l a_z \tag{5}$$

Equation 5 is the basic relation between current and charge, and it also serves as the fundamental relation of electromagnetic radiation.

$l\frac{dIz}{dt} = lq_l \frac{dv_z}{dt} = lq_l a_z$
To create radiation, there must be a time-varying current or an acceleration (or deceleration) of charge.

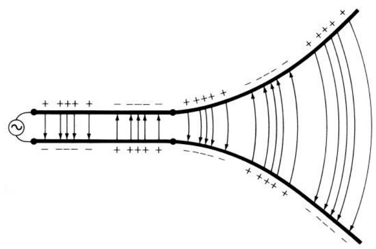
- We usually refer to currents in time-harmonic applications while charge is most often mentioned in transients.
- To create charge acceleration (or deceleration) the wire must be curved, bent, discontinuous, or terminated.
- Periodic charge acceleration (or deceleration) or time-varying current is also created when charge is oscillating in a time-harmonic motion.

1. If a charge is not moving, current is not created and there is no radiation.
2. If charge is moving with a uniform velocity:
   (a) There is no radiation if the wire is straight, and infinite in extent.
   (b) There is radiation if the wire is curved, bent, discontinuous, terminated, or truncated.
3. If charge is oscillating in a time-motion, it radiates even if the wire is straight.

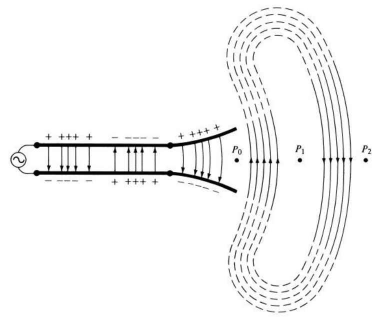
Two-Wires

- Applying a voltage across the two-conductor transmission line creates an electric field between the conductors.
- The movement of the charges creates a current that in turn creates a magnetic field intensity.

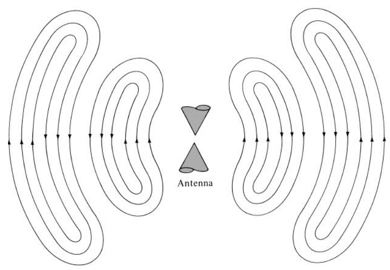
- The creation of time-varying electric and magnetic fields between the conductors forms electromagnetic waves which travel along the transmission line.



- The electromagnetic waves enter the antenna and have associated with them electric charges and corresponding currents.
- If we remove part of the antenna structure,free-space waves can be formed by “connecting” the open ends of the electric lines.

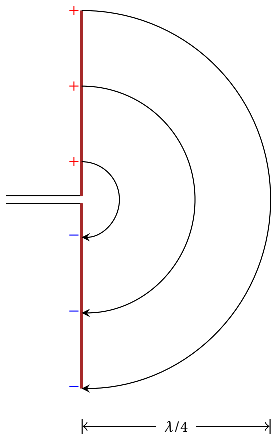


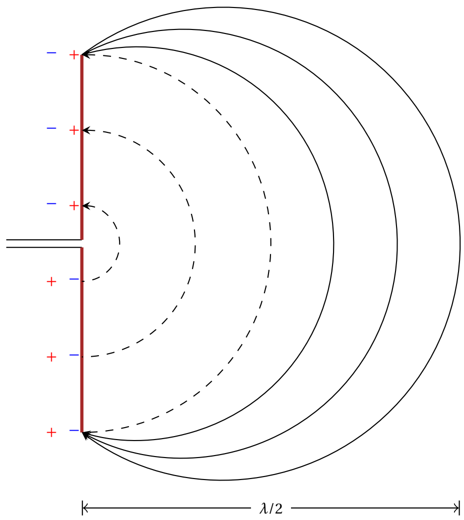
- If the initial electric disturbance by the source is of a short duration, the created electromagnetic waves travel inside the transmission line, then into the antenna, and finally are radiated as free-space waves, even if the electric source has ceased to exist.
- If the electric disturbance is of a continuous nature, electromagnetic waves exist continuously and follow in their travel behind the others.
- However, when the waves are radiated, they form closed loops and there are no charges to sustain their existence.
- Electric charges are required to excite the fields but are not needed to sustain them and may exist in their absence.



Dipole: Example to Illustrate the Creation of Free-Space Waves

- How are the electric lines of force are detached from the antenna to form the free-space waves?
- Consider the example of a small dipole antenna where the time of travel is negligible.


+
+
+
−
−
−
λ/4


− +
− +
− +
+ −
+ −
+ −
λ/2

During the fist $T/4$

The charge has reached a maximum.
Lines have traveled outwardly a radial distance $\lambda/4$.

↓

During $T/4$ to $T/2$

The original three lines travel an additional $\lambda/4$.
The lines created by the opposite charges travel a distance $\lambda/4$.
The charge density begins to diminish, leading to neutralization.

↓

At $T/2$

There is no net charge on the antenna.
The lines must have been forced to detach themselves from the conductors and to unite together to form closed loops.

↓

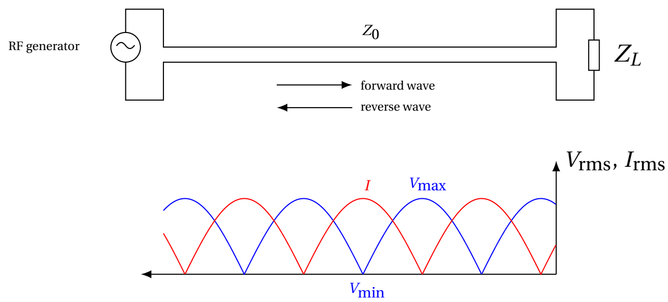
Beyond $T/2$

The process repeats.

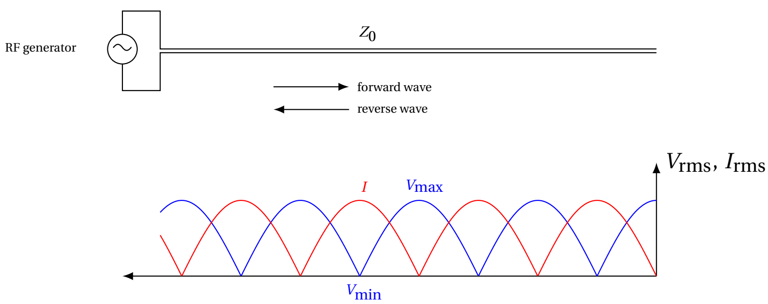
4 Current Distribution on a Thin Wire Antenna

- Let us consider the geometry of a lossless two-wire transmission line.
- The movement of the charges creates a traveling wave current, of magnitude $I_0/2$, along each of the wires.
- When the current arrives at the end of each of the wires, it undergoes a complete reflection (equal magnitude and 180° phase reversal).
- The reflected traveling wave, when combined with the incident traveling wave, forms in each wire a pure standing wave pattern of sinusoidal form.

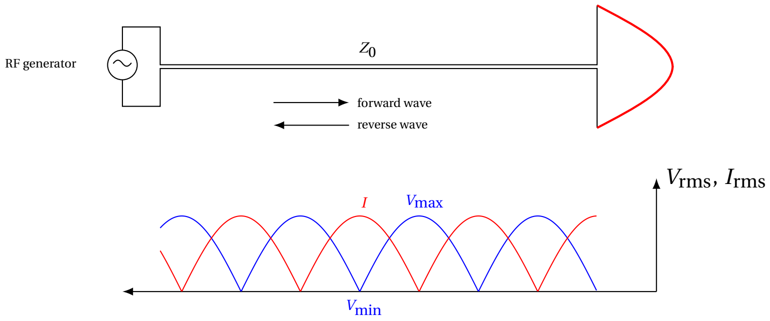
Standing Waves



Standing waves on a transmission line.

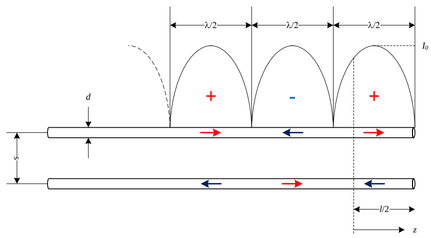


Open circuit transmission line.

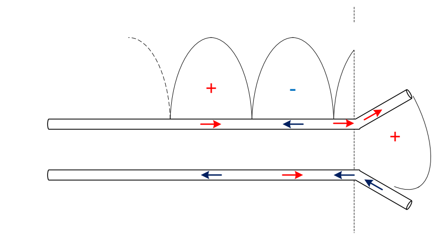


Radiation from a half-wave dipole.

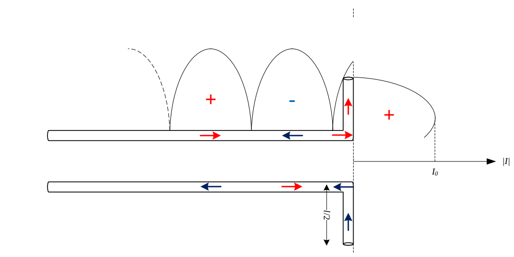
- For the two-wire balanced (symmetrical) transmission line, the current in a half-cycle of one wire is of the same magnitude but 180° out-of-phase from that in the corresponding half-cycle of the other wire.
- If s is also very small ($s \ll \lambda$), the two fields are canceled.
- The net result is an almost ideal, non-radiating transmission line.

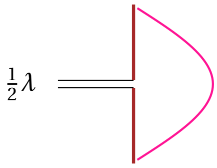


- When the line is flared, because the two wires of the flared section are not necessarily close to each other, the fields do not cancel each other.
- Therefore ideally there is a net radiation by the transmission line system.

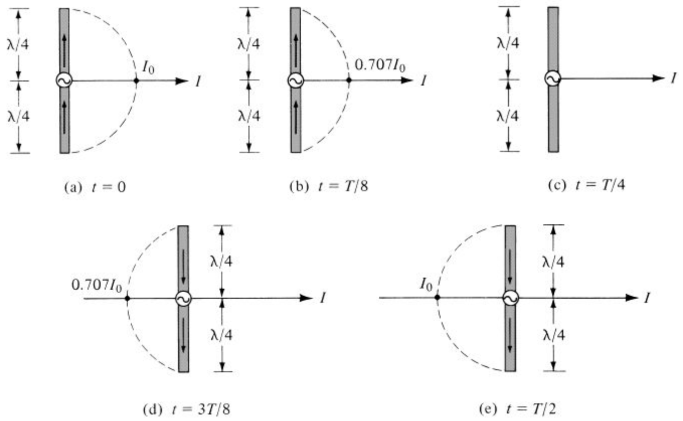


- When the line is flared into a dipole, if s not much less than λ, the phase of the current standing wave pattern in each arm is the same throughout its length. In addition, spatially it is oriented in the same direction as that of the other arm.
- Thus the fields radiated by the two arms of the dipole (vertical parts of a flared transmission line) will primarily reinforce each other toward most directions of observation.





The current distributions we have seen represent the maximum current excitation for any time. The current varies as a function of time as well.



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