Chapter 8 : ON THE AIR

Radio waves are combinations of electric and magnetic fields and therefore they are usually called electromagnetic waves. Antennas convert electrical energy into electric and magnetic fields for transmission, and electromagnetic energy to electrical energy for reception.

Antennas are combinations of pieces of conductors of specific lengths (sometimes area) and shapes. There are many different types of antennas for numerous applications. A fundamental antenna form is a *dipole* antenna. We use a dipole in TRC-10.

Antennas belong to the class of devices called *transducers*. Transducers convert one form of energy into another. Loudspeaker, for example, is a transducer which converts electrical energy into sound (or mechanical) energy, and microphone converts sound into electrical energy. Antennas provide transduction between electrical and electromagnetic energy.

What follows in this chapter is a descriptive theory of electromagnetics and antennas.

8.1. Antenna concept

In electronic circuits, capacitors, inductors, other components and their interconnections are small compared to the wavelength at the frequency used. We defined wavelength λ as

λ= (3.0 E+8 m/sec)/f

where 3.0 E+8 m/sec is the velocity of electromagnetic waves (and also light) in free space, f is frequency in cycles/second (Hz) and wavelength is in meters. Wavelength can also be interpreted as the distance electromagnetic wave travels in one full cycle.

When the circuit dimensions are small compared to the wavelength, most of the electromagnetic energy generated by the circuit is confined to the circuit. It is either conserved for the desired purpose or converted to heat. When the dimensions of the components or the interconnections become large (e.g. comparable to the wavelength) part of the energy escapes into space in form of electromagnetic waves. This part of the energy used in the circuit appears as lost (or “dissipated”) energy to the circuit, whereas it provides a source for the electromagnetic waves in space.

Antennas are devices, which makes use of this conversion-and-escape mechanism to produce radio waves as efficiently as possible.

8.1.1. Radiation from an antenna

A dipole antenna is made up of two pieces of conductor wires or poles aligned together with a small isolating gap in between. A dipole is shown in Figure 8.1. The generation of electromagnetic waves by a dipole is also shown in the same figure, conceptually.

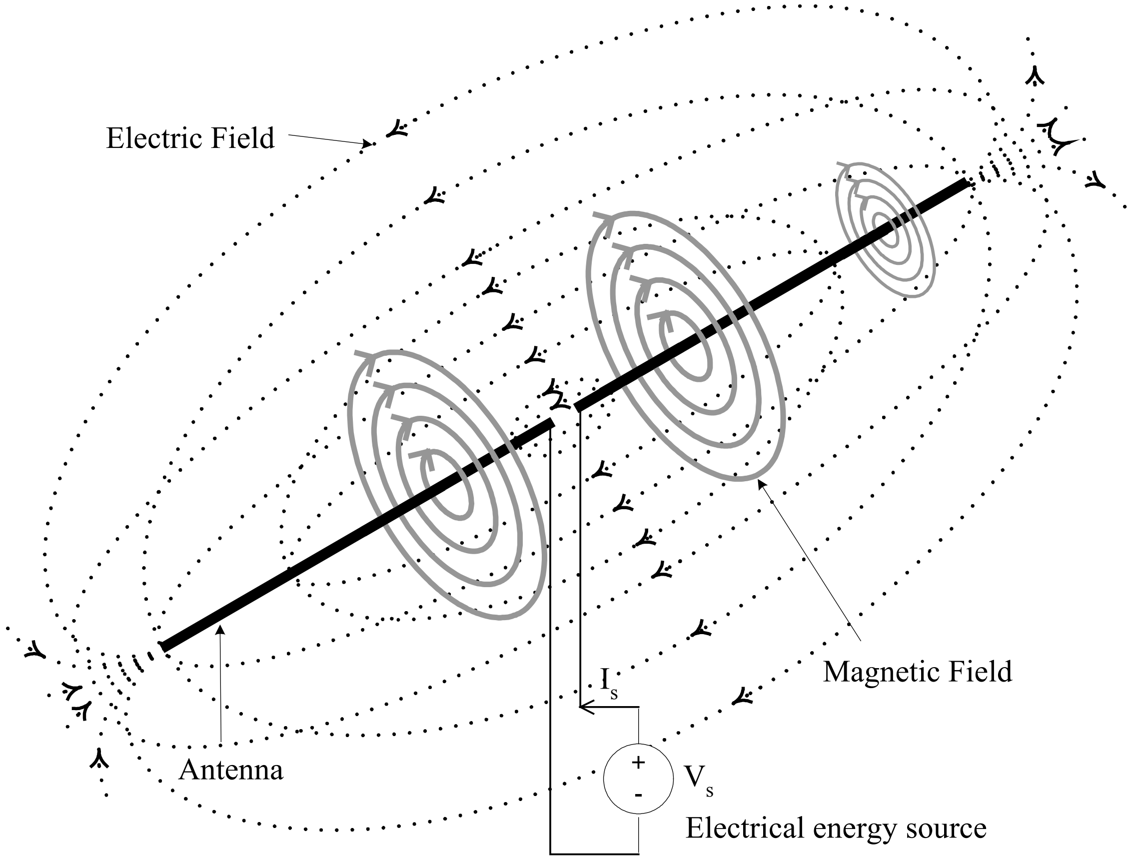


Figure 8.1 Dipole antenna and radio wave generation concept

When a voltage source V_s is connected to these two conductors across the gap, as shown in Figure 8.1, an electric field between the entire surfaces of two conductors is produced due to the potential difference between them. This field is time varying when the source is a non d.c. source. Its frequency is equal to the frequency of the voltage source. Electric field is denoted by letter **E** and it has units of V/m.

The electric field extends to the entire space, but its strength decreases as the observation distance from the dipole increases. The electric field is strongest near the gap.

The two conductor surfaces constitute a *distributed* capacitance across the terminals at which the voltage source is applied. This phenomenon is depicted in Figure 8.2(a). The current I_s supplied by the source, leaks from one conductor to the other along the length of the conductor, through the capacitive path. The current amplitude decreases as we move along the conductor. Current diminishes at the tip of the conductor. A typical current distribution along the antenna is given in Figure 8.2(b).

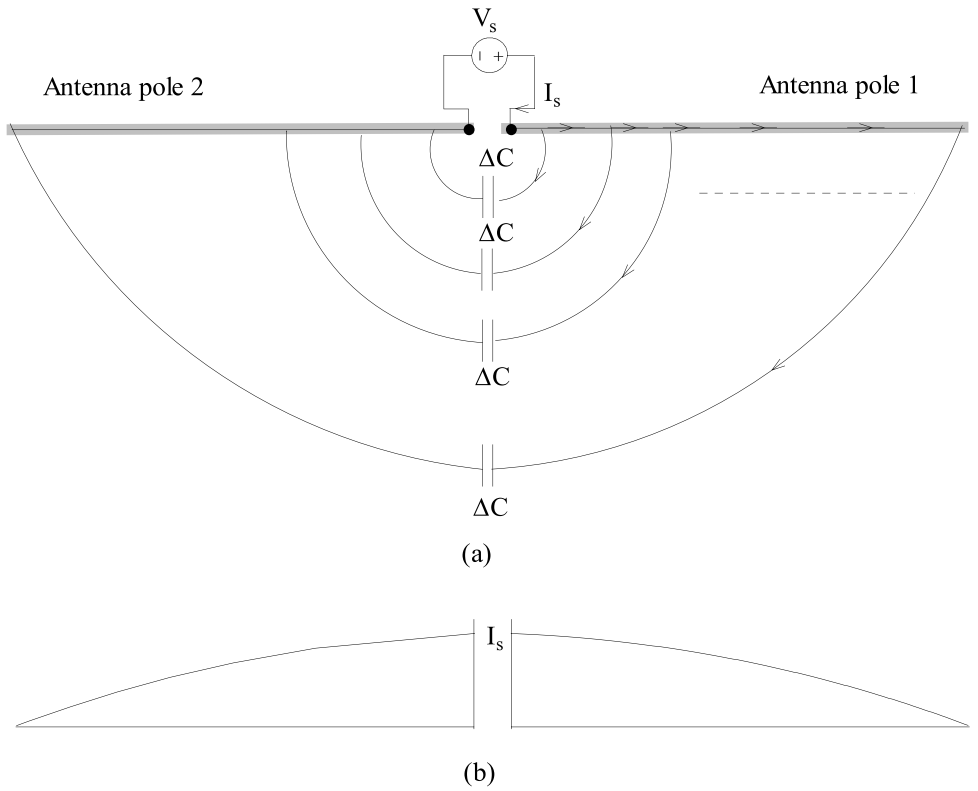


Figure 8.2 (a) Distributed capacitance on antenna, and (b) current amplitude distribution along antenna

The current along the antenna produces a magnetic field shown in Figure 8.1. Again, the frequency of the magnetic field is the same as that of the voltage source. Letter **H** denotes the magnetic field and it has units of A/m. Electric and magnetic fields have magnitude and direction and hence they can be modeled as vectors.

During propagation in space, some components of **E** and **H** vectors decay very quickly away from the dipole. Only *orthogonal* components (mutually perpendicular components) of the electric and magnetic fields are maintained during propagation at far away distances. When we observe the electromagnetic wave emanating from a dipole at a large distance, the equal phase surfaces (the surface defined by electric and magnetic waves which have the *same* phase; the fields which have the same phase must have left the antenna at the same instant- phase is like age), called *wavefront*, appear like concentric spheres. The center of these spheres, which is called the *phase center*, coincides with the center of the isolating gap in the dipole. This is shown in Figure 8.3.

The direction of propagation in this figure is outward from the center. The electromagnetic wave generated at some instant gets away from the dipole in all directions, at a speed of 3.0 E+8 m/sec.

Now let us take a closer look at the field shown on the patch over the spherical surface, in Figure 8.3. If the radius of the sphere is very large compared to the rectangular patch (which is a very realistic assumption for practical antenna discussions), the patch approximately defines a planar surface. We can define a

Cartesian plane on which electric field coincides with x-axis and magnetic field coincides with y-axis. This is shown in Figure 8.4.

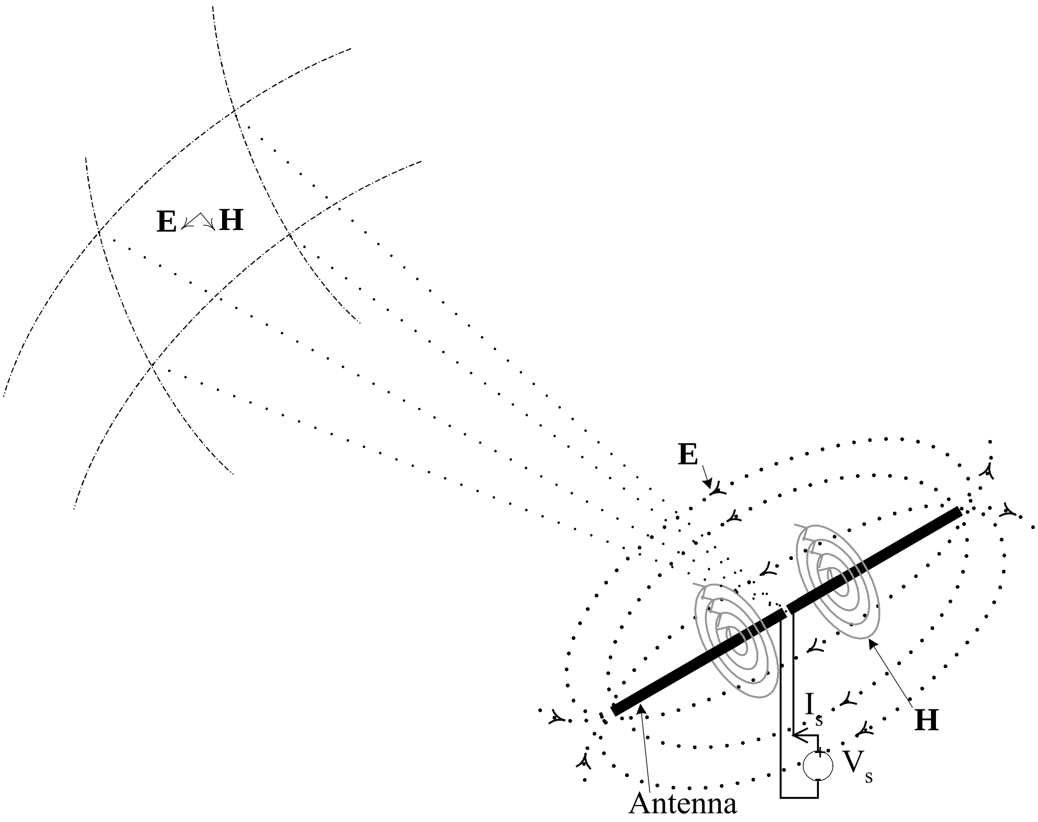


Figure 8.3 Radio wave far away from the source dipole

With E_x and H_y are phasors of the electric and magnetic fields respectively, and $\mathbf{a}_x$ and $\mathbf{a}_y$ are unit vectors in x and y directions, we can write the two field vectors as

$\mathbf{E} = E_x\mathbf{a}_x$

and

$\mathbf{H} = H_y\mathbf{a}_y$

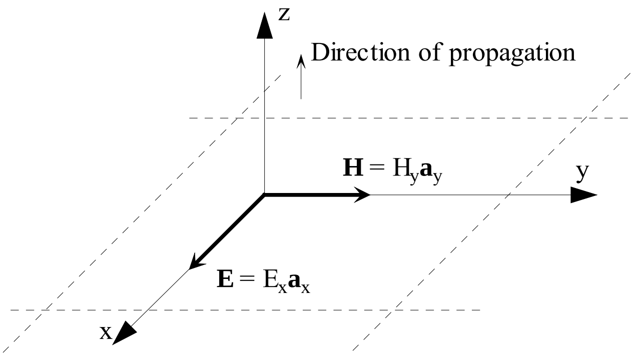


Figure 8.4 Orthogonal electric and magnetic fields and the direction of propagation

E_x and H_y in an electromagnetic wave propagating in space are related to each other as

$E_x/H_y = \eta_o = (\mu_o/\varepsilon_o)^{1/2}$.

Here μ_o and ε_o are the permeability and the permittivity of the free space (and air), respectively. Their values are

$\mu_o = 4\pi\times10^{-7}$ H/m

and

$\varepsilon_o = 8.85$ E-12 F/m.

η_o is called the wave impedance and can be calculated as

$\eta_o \approx 377\ \Omega \approx 120\pi\ \Omega$.

As a matter of fact, the speed of light is also related to permeability and permittivity of free space as

$c = 1/(\mu_o\varepsilon_o)^{1/2}$.

There is a continuous flow of energy in the direction of propagation in electromagnetic waves. This power flow is quantified in terms of *power density* of the electromagnetic wave. The average power density in z direction of the wave depicted in Figure 8.4, is given in terms of the product of the electric field phasor and the complex conjugate of magnetic field phasor as

$P_{em} = \mathrm{Re}\{E_xH_y^*/2\} = |E_x|^2/(2\eta_o)$.

The unit of power density is W/m^2. The total power over an area can be calculated by integrating $|E_x|^2/(2\eta_o)$ over that area.

Antenna, which radiates in all directions with equal preference is called *omnidirectional* antenna. For example, a dipole whose length is very small compared to the wavelength can be approximated as an omnidirectional antenna. The electric field is uniformly distributed over the spherical equal phase surface, in such antennas. At a distance r from the antenna, the power density is uniform over the sphere and is given as

$P_{em} = P_o/(4\pi r^2)$

where P_o is the power delivered to the antenna and $4\pi r^2$ is the area of the sphere (conservation of energy). Hence the electric field at that distance becomes

$|E_x| = [2\eta_oP_o/(4\pi r^2)]^{1/2} = (60P_o)^{1/2}/r$

where P_o is in watts and r is in meters. For example, a transmitter delivering 10 mW to an omnidirectional antenna generates electric field strength of 0.8 mV/m at 1 km distance, in space.

8.1.2. Receiving antenna

Antennas are reciprocal devices. They behave similarly in reception. When a dipole is exposed to an electromagnetic wave whose electric field is aligned with the antenna, a voltage is developed across the isolating gap. A receiving antenna in an electromagnetic wave is shown in Figure 8.5.

The open circuit voltage between the two conductors is the potential difference between them. The potential of each conductor is the potential at its mid-point. The dipole has a length of ℓ meters (where ℓ is very small compared to wavelength). Hence the received voltage is approximately given as

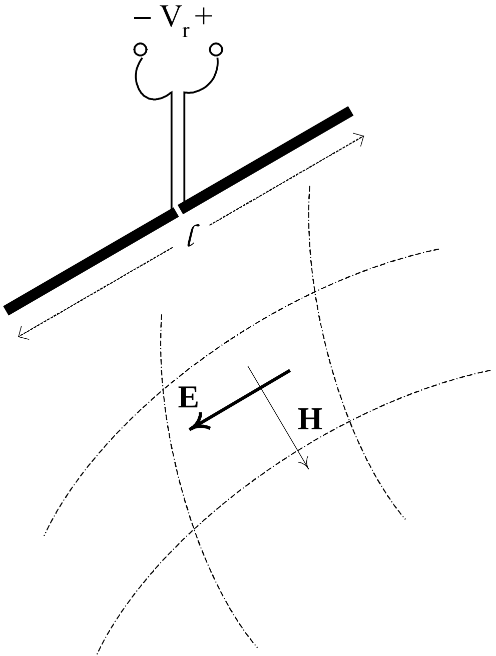


Figure 8.5 Receiving dipole

$V_r = E_X(\ell/2)$.

For example, the open circuit voltage developed across a 1.2 m long dipole is 0.48mV when the incident field is 0.8 mV/m.

8.2. Antenna impedance

The energy radiated from an antenna appears as lost energy to the circuit, which drives it. As far as the circuit is concerned, the antenna is not different than a piece of circuit with a resistive component, which converts the same amount of energy into heat. It is customary to associate the energy radiated from an antenna by a resistance. This resistance is called *radiation resistance*.

8.2.1. Self impedance

The radiation resistance of a short dipole of length ℓ, far away from other conductors, is given approximately in Ω as

$$R_r \approx 80\pi^2(\ell/2)^2/\lambda^2 = 20\,\pi^2(\ell/\lambda)^2.$$

The effective capacitance between the two conductors depends on the diameter of the conductor, as well as its length. This capacitance can be calculated for a cylindrical conductor of radius a as

$$C_d = \pi\varepsilon_o(\ell/2)/[\ln(\ell/2a)-1],$$

where both ℓ and a are in meters.

These equivalent values allow us to model a short dipole by means of an equivalent circuit given in Figure 8.6.

The radiation resistance (at 29 MHz) and the equivalent capacitance of a 1.2 m long dipole with 2.5 cm diameter are 2.7 Ω and 5.8 pF, respectively.

8.2.2. Mutual impedance

Presence of conductors in the vicinity of an antenna affect its radiation impedance. Conductor pieces, ground, which is a poor conductor are all effective on antennas radiation impedance. Estimation of this effect is a rather involved process, and usually requires the spatial positioning of these non-antenna related conductors to be accounted by numerical techniques.

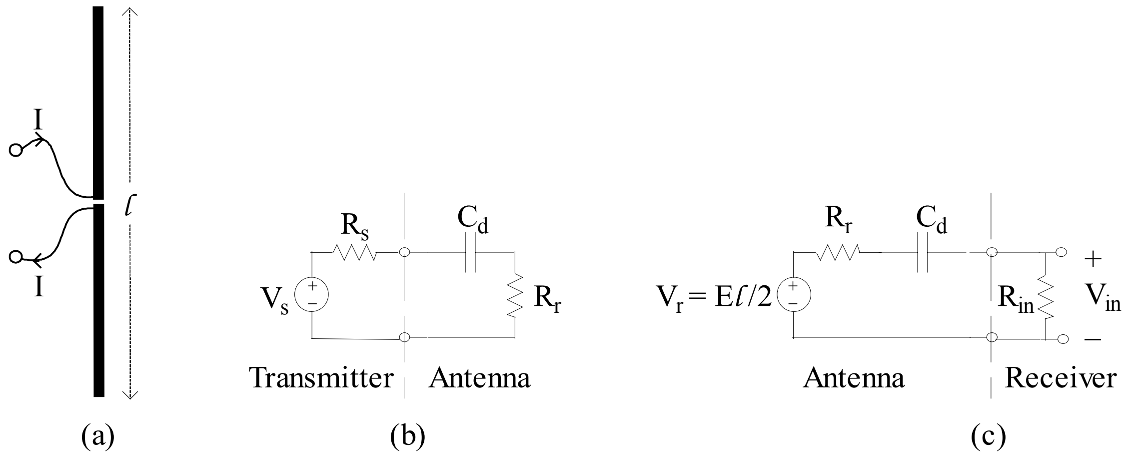


Figure 8.6 (a) Short dipole, (b) equivalent circuit of transmitting antenna, and (c) equivalent circuit of receiving antenna

8.3.Half wave dipole

A dipole antenna whose length is a half wavelength exhibits a resonance (actually 0.48 λ long dipole). We leave the rigorous analysis of this antenna to more advanced texts on antennas. However, we can discuss the resonance concept for a λ/2 dipole from the circuit theory point of view.

Lengths of the poles in a λ/2 dipole are considerably larger than that of short dipoles. A λ/2 dipole at 29 MHz is 5.2 m long. The inductance of the current path along the poles becomes significant due to this larger length. The Figure 8.2(a) is redrawn for a λ/2 dipole in Figure 8.7. The distributed inductance and capacitance combines to produce an equivalent series resonance at f = (3.0E+8)/λ Hz, where wavelength λ is in meters.

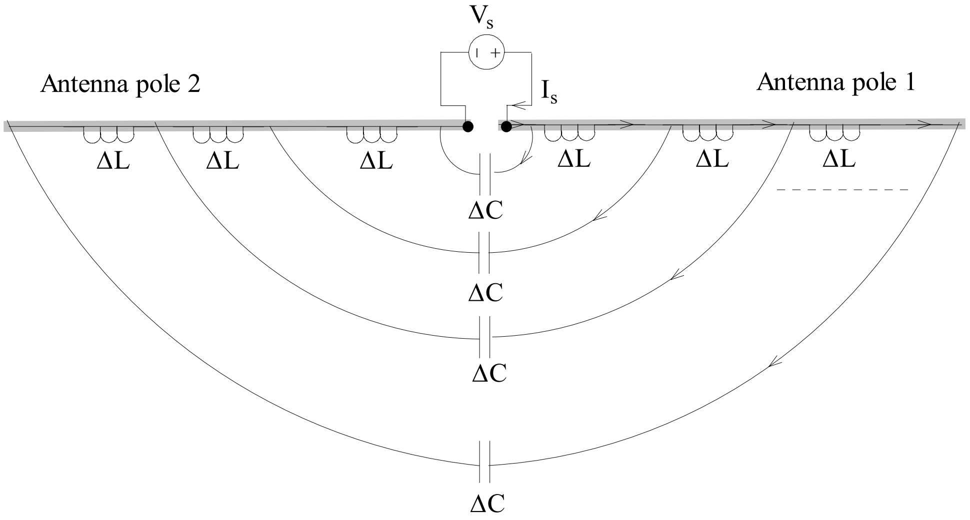


Figure 8.7 Half wave dipole interpreted as a distributed LC circuit

A half wave dipole has the properties of a transmission line as far as input impedance is concerned. The resonance can be modeled as a series resonance with 73 Ω resistance for a half wave dipole in space. The conducting objects in its near vicinity affect the antenna impedance, as in form of mutual impedance. Since the antenna cannot be far away from ground, the mutual impedance effects pull this resistance to about 50 Ω.

The bandwidth of half wave dipoles are significantly larger compared to what can be obtained in short dipoles. The quality of resonance at this resonance depends on the diameter of the conductor. Q decreases as the diameter increases. Q is less than 6 for an antenna of 2.5 cm diameter at 29 MHz.

8.4. Monopole antenna

Monopole or *whip* antennas are probably the most commonly encountered antennas. Car radio antennas mobile phone antennas are all this type of antennas. Monopole antennas are derived from dipoles, by eliminating half of the dipole using a reflective *ground plane*. This is shown in Figure 8.8.

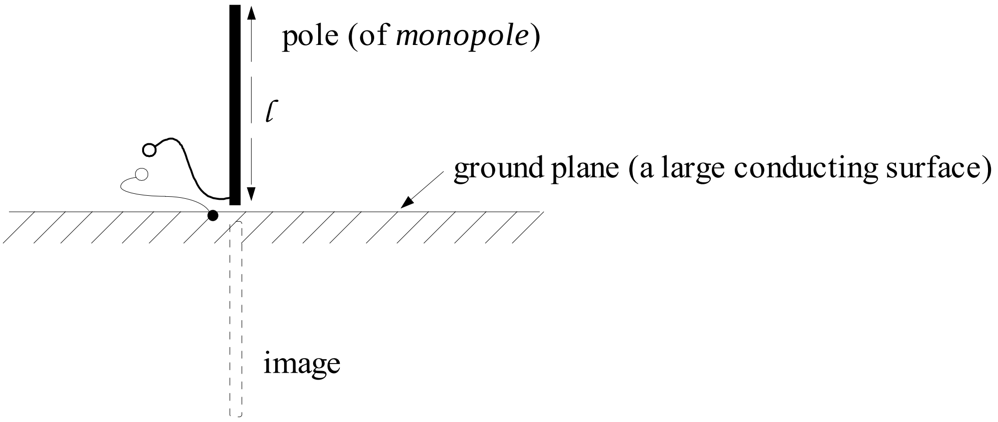


Figure 8.8 Monopole antenna

Conducting surfaces behave like mirrors to electromagnetic waves. As a direct result of this physical property, a pole of length ℓ placed on a conducting surface behaves like a dipole of length 2ℓ electromagnetically. Electrical connections are between the pole and the ground plane. The radiation resistance of a short monopole of length ℓ is, however,

$$R_r \approx 40\pi^2(\ell/\lambda)^2,$$

which is twice as much as the resistance of a dipole of length 2ℓ. The radiated power in an antenna is

$$P_r = R_r I^2/2.$$

For the same input current I, a dipole (of length 2ℓ) radiates a total power P_r to the entire space, while a monopole (of length ℓ) radiates only to *half* space, hence a total power of $P_r/2$. Therefore the radiation resistance of monopole is twice as much as the radiation resistance of an equivalent dipole.

Similarly a monopole antenna of length $\lambda/4$ placed on a large conducting surface behaves like a half wave dipole.

The effective capacitance between the conductor (of length ℓ and radius a) and the ground plane in a monopole antenna is given by

$$C_m = 2\pi\, \varepsilon_o\, \ell\, /\, [\ln(\ell/a) - 1],$$

where C_m is in farads and both ℓ and a are in meters.

In fixed stations where the antennas are installed in places like roofs of buildings, it is possible to simulate a ground plane to an acceptable level by properly designed conducting frame. It is almost never possible to have a large planar conducting surface (compared to the wavelength), on which an antenna can conveniently be placed in mobile stations. The radiation resistance of a monopole is always determined by the mutual impedance of the ground reference in such systems. This can be limited to the dimensions of the casing of a hand-set in case of mobile phones.

Nevertheless, the expression given above is a good approximation to the radiation impedance.

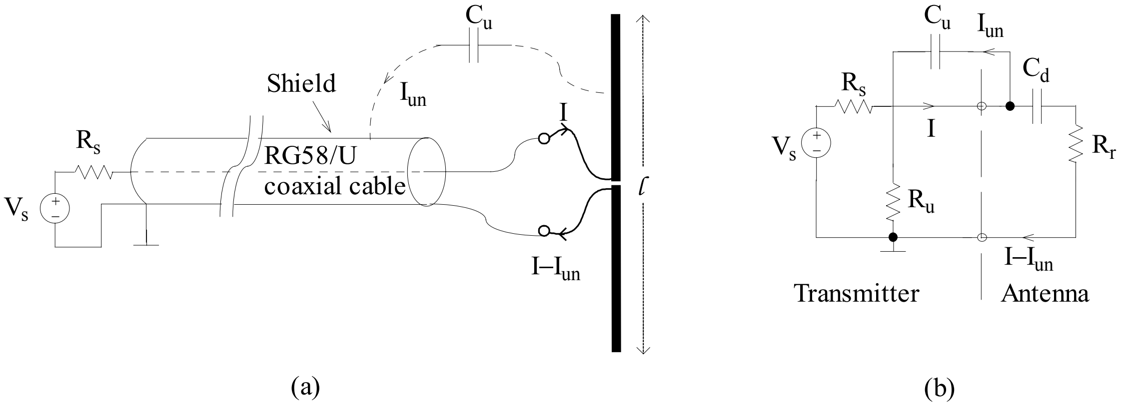
8.5. Antenna feeders

Antenna is an electromagnetic transducer, which must be supplied with electrical energy through its electrical terminals. This electrical connection is called *feeder*. Antennas are classified in two groups as *balanced* and *unbalanced*, as far as their electrical input are concerned.

Dipoles are balanced antennas. The input current I of the antenna flows only through the impedance determined by the antenna parameters R_r and C_d, as shown in Figure 8.6. Now if we feed this antenna using an unbalanced feeder like a coaxial cable, we affect the equivalent circuit observed at the antenna terminals. This is depicted in Figure 8.9. One pole is connected to the center conductor of the coaxial line and the other is connected to the shield (the outer conductor) and hence to ground in this case, as shown in Figure 8.9(a). Since there is a direct electrical connection between one pole and the shield, the unbalanced capacitance C_u between the other pole and the shield (it is not balanced by the a similar capacitance between the shield and directly connected pole to it) cause part of the supplied current I_{un} to flow through a path which is not between the poles. Hence while the current fed to the isolated pole is I, the current that returns from the other pole is $I – I_{un}$. The two *antenna currents* become unbalanced.

The shield of the coaxial line behaves like an extension of the lower pole and also contributes to the radiated energy in an uncontrolled manner. This part also has an uncontrolled radiation resistance R_u, which depends on the length, position and shape of the coaxial line. The equivalent circuit of the resulting antenna system is given in Figure 8.9(b).

Another way of looking at this combination is that the shield of the coaxial line, together with the pole connected to it, serves as the ground reference for the isolated pole. This converts the dipole into a monopole with a very poorly designed ground plane.



(a) (b)

Figure 8.9 (a) Dipole (balanced) driven by an unbalanced feeder and (b) equivalent circuit

Such a feeding configuration is very undesirable for dipoles. Dipoles must be driven by appropriate means, which suits to their balanced nature.

Considerations are different for monopoles. Monopole antennas have a single isolated element and operate with ground reference to start with, as shown in Figure 8.8. The capacitive component in the radiation impedance is between the pole and the ground plane, anyway. They are unbalanced antennas. When the coaxial line feeder is connected to the antenna the center conductor is connected to the pole and the *grounded* shield is connected to the ground plane. This combination is proper for a monopole.

8.5.1. Balanced-unbalanced transformation

A straightforward way of driving balanced antennas is to use a balanced feed line like *twin-lead transmission lines*. This approach, of course, requires a balanced transmitter output. These are used extensively in HF for outdoor antenna systems.

The other approach is to convert balanced antenna input into unbalanced load and use coaxial lines. This is more common and is also applicable at higher frequencies. We use *bal*anced-to-*un*balanced transformation, or *balun* in short, in TRC-10 antenna feeder.

The goal of using a balun is to minimize the unbalanced current component in the antenna. Consider the circuit given in Figure 8.10(a). When large series impedance like a large inductance is inserted, this large impedance isolates the pole and the shield at the radiation frequency. The stray capacitance between this pole and the shield now becomes significant also. The equivalent circuit of this case is given in Figure 8.10(b).

The current that flows into the antenna is now balanced. The effect of the shield of the coaxial cable decreased down to the effect of any conductor in the vicinity of the antenna, and it contributes only to the mutual impedance marginally ($C_u/2$).

On the other hand, large series impedance also impedes the current to the antenna radiation resistance. Coupling any power to the antenna becomes difficult.

There are numerous very clever implementations of baluns. The large inductance is often implemented as a winding of a transformer. A typical balun feeder is given in Figure 8.10(c). This kind of balun is called *current balun*. The turns ratio of the transformer is 1:1 (*n:n* in the figure to indicate that actual inductance is large), and therefore $V_2 = V_1$. We can write the voltage across the coaxial line V_t in terms of the voltage delivered to antenna, V_a, we obtain

$$V_t = V_1 + V_a - V_2.$$

Since $V_1 = V_2$, the voltage that appears across the coaxial line is the antenna potential, $V_t = V_a$. Antenna impedance (both *mutual* and *self* impedance) appears across the coaxial line, but through a very large series impedance imposed by the windings of the balun transformer.

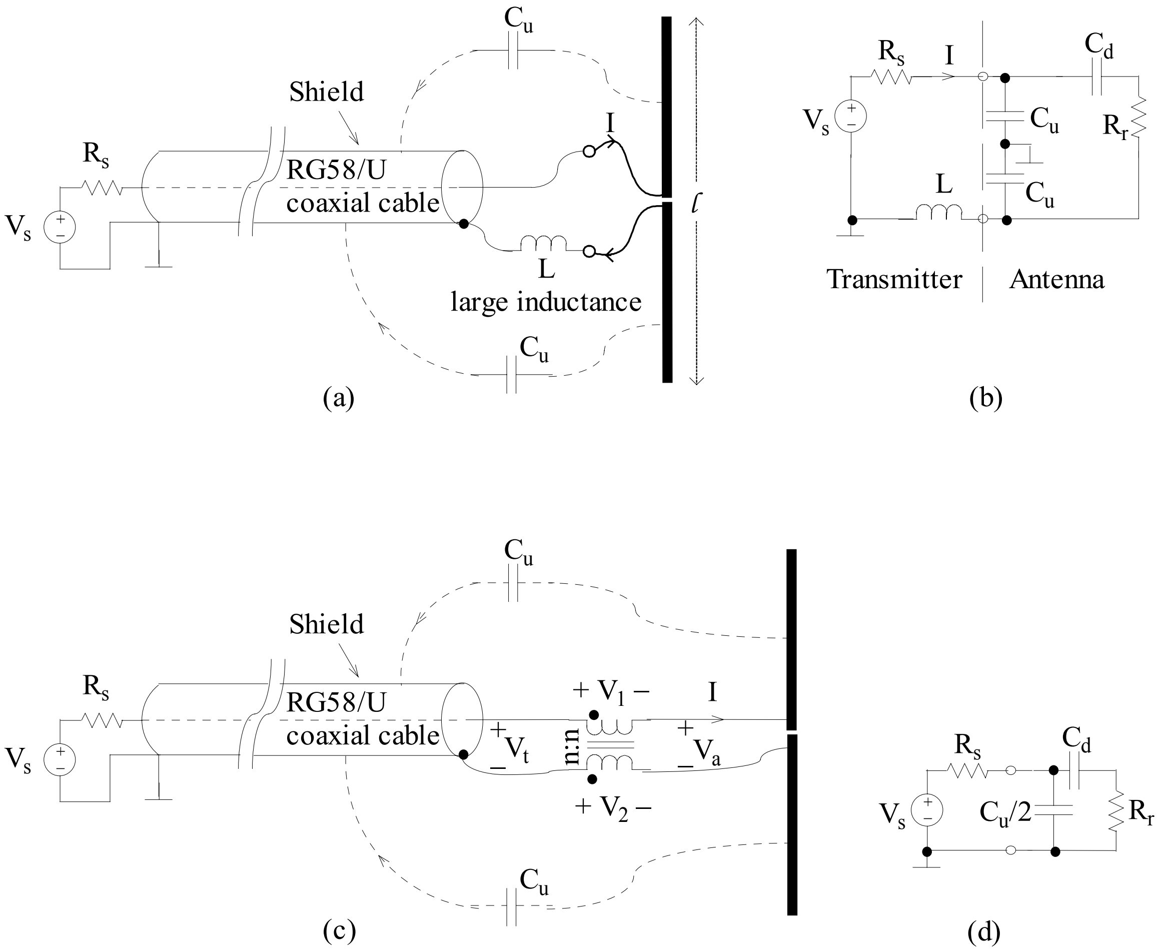


Figure 8.10 Inserting a large series impedance minimizes unbalance current; (a) connections and (b) equivalent circuit, (c) current balun and (d) equivalent circuit of current balun feeder

If the antenna is connected to the line by means of an isolating transformer, the balanced-unbalanced conversion is also maintained. The transformer can also serve to convert the antenna input resistance into nominal termination impedance, like 50 Ω. Quite often the antennas are $\lambda/2$-dipoles or $\lambda/4$-monopoles and impedance conversion is not necessary.

The transmitter output of TRC-10 is unbalanced and its output resistance is 50 Ω. therefore it can drive a $\lambda/4$-monopole by a simple connection of a coaxial line. A $\lambda/4$-monopole at 29 MHz requires a 2.5 meter long pole and ground plane wiring. For laboratory testing, we use a portable dipole of 1.2 meter length.

8.5.2. TRC-10 short dipole feeder

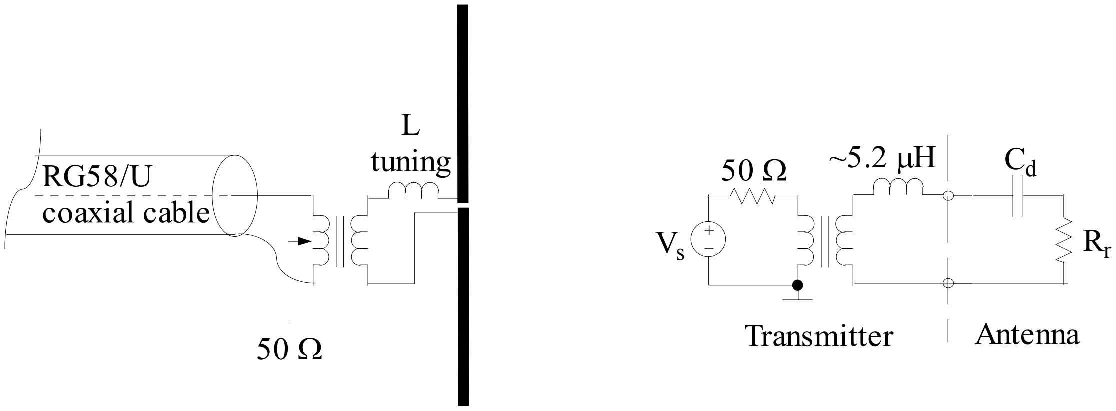
The equivalent circuit of a short dipole of length 1.2 meter at 29 MHz comprises series connected resistance and capacitance. The diameter of the poles is 2.5 cm. The values of radiation resistance and capacitance are calculated in Section 8.2.1 as 2.7 Ω and 5.8 pF, respectively. Hence radiation impedance becomes

$Z_a = 2.7 - j950\ \Omega$

at 29 MHz, approximately. The reactive part must be tuned out at the frequency of transmission, in order to make most use of available power. The inductance needed for this purpose is about 5.2 μH. Tuning out the capacitance is the first step. The radiation resistance must then be matched to the TX output impedance, which is 50 Ω. We also need a transformer. The resulting feeder circuit is depicted in Figure 8.11.

The series resonant circuit has a very high Q (≈ 350). It is not possible to have a tuning inductance virtually without any loss at this frequency. The loss resistance of the inductor is in series with the radiation resistance and decreases the efficiency of radiation in this configuration. Another complication is the fact that, a very narrow 3-dB bandwidth of the antenna makes optimum power transfers over the entire 28-29.7 MHz range impossible without extra tuning.

If we consider the case when the dipole length is longer, for example 2.4 meters, the life becomes simpler. For such a dipole, radiation resistance and the capacitance are 10.5 Ω and 10 pF approximately. The radiation resistance is now significantly higher and, consequently, the series loss resistance of the tuning inductor is less effective. Also the Q of the antenna is lower, at about 50, and hence, tuning is much simpler.



(a) (b)

Figure 8.11 Short dipole feeder of TRC-10; (a) connections and (b) equivalent circuit

If we can maintain the length of the dipole at its λ/2 resonance length, then the feeding becomes a simple balun problem, free from bandwidth and matching constraints.

We neither live in houses of five meter ceiling height, nor we work in such environment. Our gadgets, including antennas, have to live with our shortcomings. Hence the test antenna length is limited to 1.2 meters. On the other hand, as we experience in the exercises of this chapter, two wishful parties who want to communicate using a pair of TRC-10 can do so even with un-tuned feeders, *for testing purposes*. Mother nature is on our side!

8.6. Using amateur frequency bands

National regulation authorities tightly regulate transmission at any frequency. You are allowed to use the transmitters you built in amateur bands, provided your transmitter satisfies the emission requirements. The equipment that can be used in other bands must have “type approval”.

The operators using transmitters are also required to have amateur licenses. If you intend to use your TRC-10 for purposes other than the requirements of this course, you must contact your national regulatory agency and obtain an amateur license.

8.7. Bibliography

Electromagnetic theory is the founding subject in electronics. A good understanding of electromagnetic theory is essential for good electronic engineering. Antennas and propagation builds on electromagnetic theory and is a fundamental field in electronic engineering. There are many texts on these subjects with a lot of detailed analysis of almost every aspect.

As far as handling simple practical antenna problems with almost no electromagnetic theory background, *The ARRL Antenna Handbook* is a good source. Also Chapter 20 of *The ARRL Handbook* provides a concise overview of such problems.

8.8. Laboratory Exercises

1. Construct the dipole using two aluminum pipes (of 2.5 cm diameter and 60 cm length) and 10 cm long polyamide stud. Place the antenna handle in between as shown in Figure 8.12. and fix the structure using two screws.

2. The total antenna capacitance is somewhat higher than the dipole capacitance because of mutual impedance, as we discussed in Section 8.5.1. Hence tuning coil can be less than 5.2 μH. Allowing few pF for mutual capacitance, a tuning coil of about 4 μH must be sufficient.

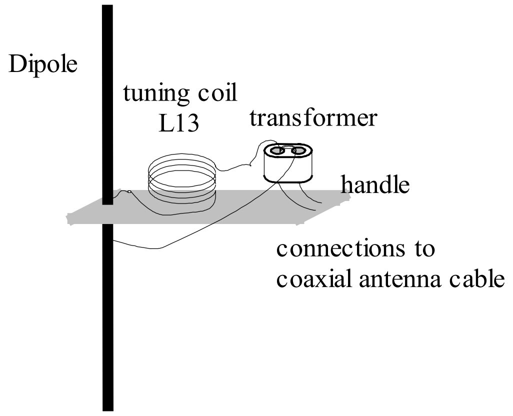


Figure 8.12 Antenna connections

The coil former for tuning inductor L13 is a piece of plastic tube of 16 mm diameter. Cut grooves on the coil former so that you can fix one end of the winding after tuning. Cut about a meter of 0.5 mm diameter enameled wire and wind 17 tight turns on this coil former so that the length of the coil is 1 cm. Fix the winding by means of a tape. Strip enamel on both ends and cover them by solder completely. Fix one end of the inductor to the screw on one of the poles, by making a loop around the screw. Tighten the screw. Fix this end of the coil on the coil former and fix the coil former on the antenna handle using glue. Work the other end into the groove such that the winding is tightly fitted on the cylindrical surface and its length is fixed.

Remove the tape. You can now increase the length of the coil by moving the end in the groove. This provides a means of tuning the antenna. This coil is your *antenna tuner*.

The loss resistance of the coil is in series with the radiation resistance and comparatively larger than the radiation resistance. The best way to find out the total impedance is to measure it. However it is not a straightforward laboratory procedure to measure an antenna radiation resistance at 30 MHz. Instead we shall estimate the loss resistance, assuming that the Q of the coil is about 70.

We can assume the coil loss resistance r_s as approximately 10 Ω.

3. The transformer core BLN1728-6 has 18 nH/turn^2 inductance constant, when the winding is applied from one hole to the other. This shape of core enables low leakage transformers even with low permeability materials, which can be used at higher frequencies. Wind 10:5 winding on BLN1728-6. Strip enamel on all four ends and cover them by solder completely. Solder one lead of the 5-turn secondary to the free end of the coil. Connect other lead to the remaining pole. Again make a loop around the screw.

   The approximate equivalent circuit of the antenna is given in Figure 8.13. The magnetizing inductance of the transformer is referred to secondary in this circuit. The impedance Z_s has two resonance frequencies. The series resonance is near

   $\omega_s = (L13C_d)^{-1/2}$.

   The parallel resonance is in the vicinity of

   $\omega_p = [(L13+L_s)C_d]^{-1/2}$,

   and is lower than the series resonance. We use the series resonance of this circuit.

   Solder the free end of the coaxial cable (the other end is terminated by a BNC) across the primary terminals of the transformer.

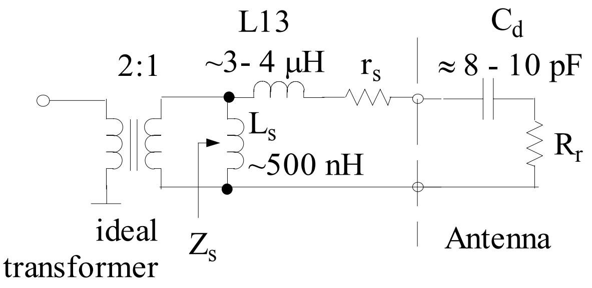


Figure 8.13 Equivalent circuit of the antenna and the feeder.

4. Connect your antenna to your TRC-10 using RG58/U coaxial cable and BNC connector. Switch the power on. Try to tune to the frequency of the test transceiver, which transmits a continuous tone signal. You can extend the length of the tuning inductor to tune your antenna precisely at this reception frequency. Check if you can improve the reception (for example, does the received continuous tone sound increase?) by tuning the antenna.

5. Switch TRC-10 to transmit mode and check if the test receiver receives your signal.

6. Make the microphone connection to the circuit by connecting J12. Find a partner and try to meet at a frequency and communicate. You can use calibration table you produced for coarse tuner in Chapter 7. You may have to re-tune the tuning inductor for a better signal.

8.9. Problems

1. Assume we want to use a dipole antenna, which has a radiation resistance of 10 Ω with TRC-10. Calculate the total length of the antenna. Calculate the antenna capacitance C_d if the diameter of the poles is 1 cm. Calculate the inductor required to tune this capacitor at 29 MHz. What is the Q of this antenna?

2. Calculate the power delivered to R_r in Figure 8.13 at the series resonance. Assume that the transmitter shown in Figure 8.11(b) drives the transformer primary and the peak amplitude V_s of the source is 4.5 V.

3. For the transmitted signal in problem 2, calculate the distance at which the received open circuit signal is 100 µV peak, assuming that the receiver is also a TRC-10 with a similar antenna and feeder.

4. Assume that we do not use L13 at all, but tune C_d by an appropriately chosen L_s. Calculate the value of L_s required to tune out C_d of TRC-10 antenna, in a parallel resonance. Calculate the power delivered to R_r in Figure 8.13 at the parallel resonance. Assume that the transmitter as shown in Figure 8.11(b) drives the transformer primary and the peak amplitude V_s of the source is 4.5V.

5. A short dipole of length 20 cm is used as the antenna of a mobile set at 150 MHz. What is the open circuit voltage generated at a receiving antenna, when another set transmits 2 W at 3 km distance?