APPENDIX D
Dipoles for Dummies (as well as for all the rest of us without a Ph.D. in electromagnetics)

Why is this appendix on antenna theory in a book on electromagnetic compatibility engineering? Because an understanding of some basic antenna theory is helpful for all electrical engineers, especially those involved in electromagnetic compatibility (EMC). After all, if a product radiates, or is susceptible, to electromagnetic energy, it is an antenna even if you call it something else such as a microprocessor, an integrated circuit (IC), a printed circuit board (PCB), a power cord, or an RS-232 cable.

An important characteristic to remember about antennas is reciprocity. Reciprocity means that if a structure (antenna) radiates well, then it will also pick up energy well, and vice versa. What prevents an antenna from radiating will also prevent an antenna from picking up energy. Therefore, the same techniques can be used to solve both emission and susceptibility problems.

D.1 BASIC DIPOLES FOR DUMMIES

A dipole is a basic antenna structure that consists of two straight collinear wires (arms or poles) as depicted in Fig. D-1. The first thing to notice about a dipole is that it has two parts, hence, the term "di" in its name.

How can we explain the fact that it is possible to drive current into a dipole when the ends are open, and we, therefore, do not have a closed loop? The simplest way to resolve this seeming dilemma, without getting involved with electromagnetic field theory, is to consider the parasitic capacitance between the two arms (poles) of the antenna as the return current path, as shown in Fig. D-2. At high frequency, this capacitance will represent a low impedance. Current through this uncontrolled parasitic capacitance represents radiation.

Therefore, *a dipole requires two parts to radiate* and *the amount of radiation will be proportional to the dipole current*. Note also from Fig. D-2

Electromagnetic Compatibility Engineering, by Henry W. Ott

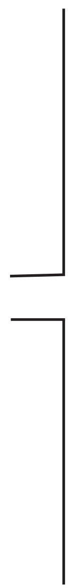

FIGURE D-1. Dipole antenna.

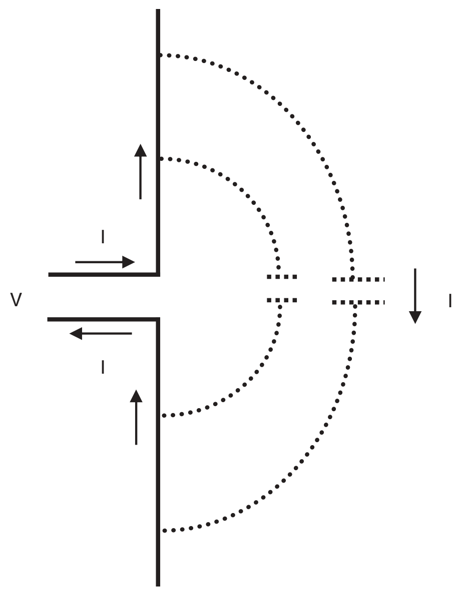

FIGURE D-2. Current in a dipole antenna flows through the capacitance between the arms (poles).

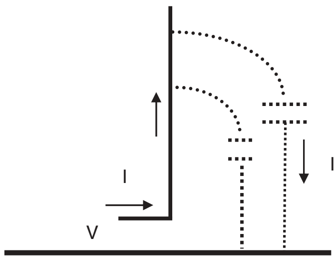

FIGURE D-3. Monopole antenna, showing the arm (pole) and the reference plane.

that *a dipole does not require a "ground" to work*, just capacitance between the two arms.

A good analogy is to consider what happens when we clap our hands. Clapping launches an acoustic wave, whereas a dipole launches an electromagnetic wave. It takes two hands to clap, just like it takes two arms for a dipole to radiate.

What about a monopole; does it only need one part to radiate? The answer is no; a monopole also needs two parts. A monopole is just a dipole cut in half, as we shall see. The second part is normally a reference plane located below the one arm (pole) as shown in Fig. D-3. If you do not provide the reference plane (which is the second part of the antenna), then the monopole will find something to work against, usually the largest metal object around. The current path for a monopole is through the parasitic capacitance betweeen the one arm of the monopole and the reference plane as shown in Fig. D-3. Note that the reference plane does not have to be a plane, and it does not have to be grounded. Any metal object with capacitance to the pole will do just fine, regardless of its shape. Other examples of monopole antennas configurations are shown in Fig. D-4.

Note that even in the case of the monopole, "no ground" is needed to operate.

Referring to our clapping hands analogy again, consider the case where you are asked to clap with one hand in your pocket. You take your free hand and find something to clap against such as your knee, a desk, a table, or wall; that is exactly how a monopole works.

Therefore, *the way to make an antenna (dipole or monopole) is to have a radio frequency (rf) potential between two pieces of metal*. The capacitance between the two pieces of metal will provide the current return path.

The way to prevent radiation is to connect the two halves of the antenna together so that they are at the same potential. By the way, it does not matter what potential the halves are at, as long as a potential difference does not exist between them.

Returning to the clapping analogy, if you put your two hands together and wrap duct tape around them (equivalent to holding the two arms of the dipole at the same potential), then you no longer can separate your hands and clap.

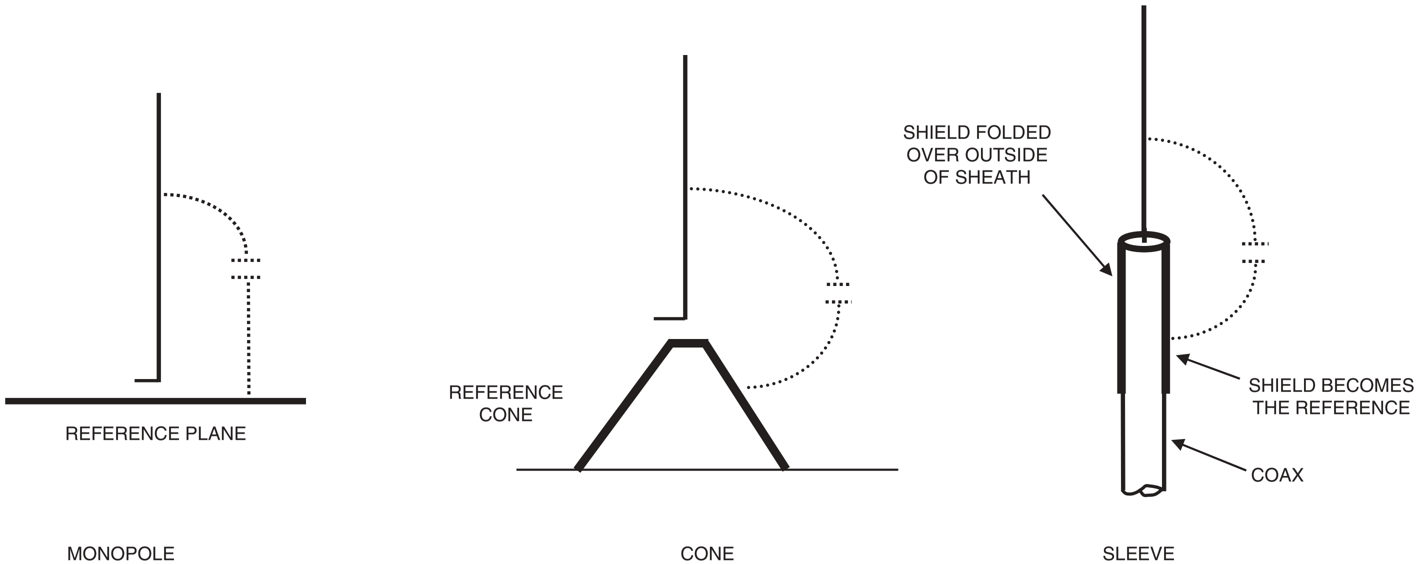

FIGURE D-4. Some variations of the basic monopole antenna.

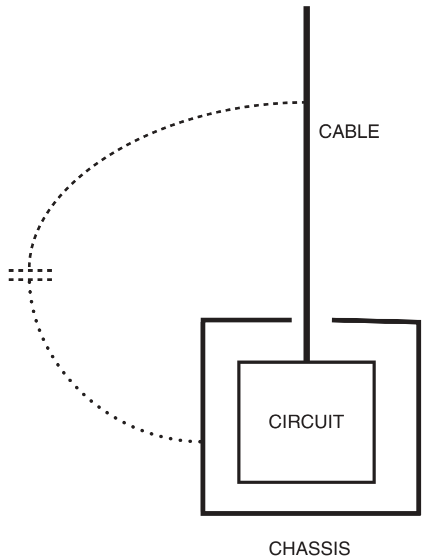

FIGURE D-5. A product in a metallic enclosure, with an attached cable.

So what does all of this have to do with EMC, you ask? It turns out quite a bit! Let us consider a simple product in a metallic enclosure with a single cable attached as shown in Fig. D-5. To make it more interesting, let us assume that we put the product on a rocket and launch it into space so that it is now orbiting the earth. I think under these circumstances we can bypass a discussion of how we should ‘‘ground’’ the product!

However, if a potential difference exists between the chassis and the cable, we have produced a monopole antenna (the cable is the arm of the monopole and the chassis is the reference plane), and the cable will radiate. This potential difference is referred to as a common-mode voltage.

Because we do not want a difference of potential to exist between the cable and chassis, how we connect the internal circuit to the chassis becomes important. *The internal circuit's reference (often called ‘‘circuit ground’’) should be connected to the chassis as close to where the cable terminates as possible* to minimize the voltage between the cable and chassis. This connection must provide a low impedance at rf frequencies. Any impedance between the circuit reference and the chassis will produce a voltage drop and will cause the assembly to radiate. In practice, this ground-to-chassis connection is often made with poorly placed metal standoffs and can be of considerable impedance. Seldom is the connection optimized for EMC purposes. This connection and how it is made is *critical* to the EMC performance of the product (see Section 3.2.5).

A second possibility to reduce the cable radiation is to place capacitors between all the cable conductors (even the ones we call ground) and the chassis, to short out the rf potential between the cable and chassis.

Third, we could use a common-mode choke (ferrite core) on the cable to raise the cable's common-mode impedance and hence to reduce the cable current produced by the common-mode voltage between the chassis and cable.

Last, but not least, we could shield the cable and terminate the shield properly (360° connection, see Section 2.15) to the chassis. In this case, the cable effectively does not leave the enclosure. You can think of the cable shield as just an extension of the chassis, and how well it does or does not behave in this manner is a strong function of the shield-to-chassis connection.

Note in the above example it matters not what potential the chassis is at with respect to the earth or any other arbitrary reference, only the difference of potential between the chassis and the cable matters.

Now, let us take our product out of orbit and bring it back to earth. Does it matter how we ground the chassis to some external reference, such as the earth or the power line ground? No, not from an EMC perspective! The same criteria, as when we were in orbit, still applies, our only requirement is to have no common-mode voltage between the cable and the chassis.

D.2 INTERMEDIATE DIPOLES FOR DUMMIES

OK, so now you know something about how dipole and monopole antennas work. Let us look into the matter a little more and determine the current distribution along the length of a monopole antenna. The same result will also be applicable to a dipole if we apply the result to each of the dipole arms individually.

Let us assume that we drive a current I into the base of the monopole antenna as shown in Fig. D-6. The current at the top of the antenna must be zero. Therefore, the current varies from I at the base to zero at the top. If the antenna is short compared with a quarter of a wavelength (e.g., less than 1/10 wavelength), the current distribution will be linear from base to tip. If the

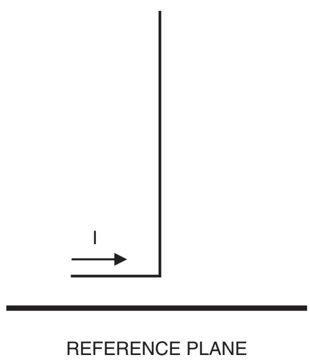

FIGURE D-6. Current feeding a monopole antenna.

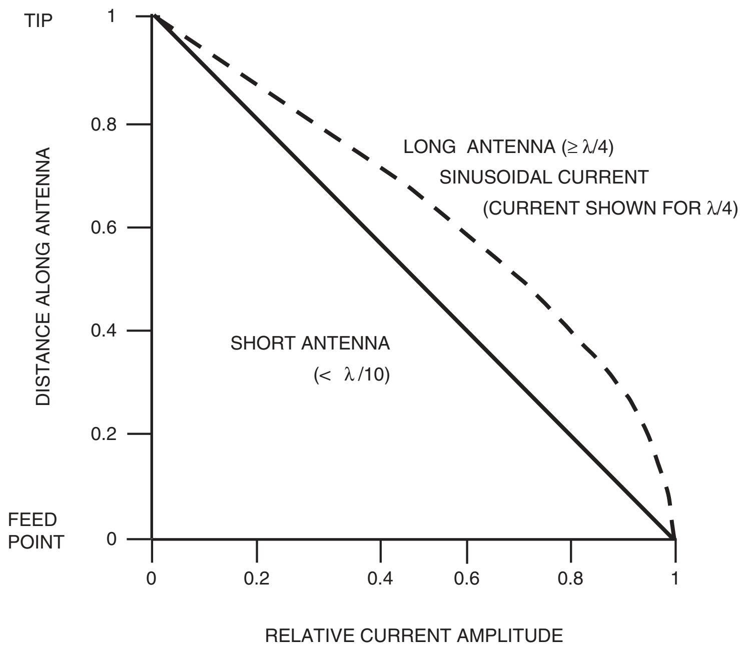

FIGURE D-7. Current distribution on a monopole antenna.

antenna is long, then the current distribution will be sinusoidal. This is show in Fig. D-7.

Clearly, the antenna does not radiate uniformly along its entire length. The bottom millimeter will radiate the maximum, and the top millimeter will hardly radiate at all. The average current will be 0.5 I for a short antenna, and 0.637 I for a quarter wavelength long antenna. Compared with an ideal antenna (one having uniform current along its entire length), a short dipole will produce half as much radiation, and a quarter wavelength long dipole will produce 64% as much radiation.

This leads directly to the concept of effective length or effective height of an antenna. If the effective length (in meters) is multiplied by the incident electric field strength (in V/m), it will give the voltage picked up by the antenna. For an ideal (uniform current distribution) dipole or monopole, the effective length will be equal to the actual length of the antenna. For a short dipole (monopole), however, the effective length will be equal to one half its actual length.

How could we make the antenna more efficient? By increasing the average current! That means forcing more current up to the top of the antenna. Because the current is flowing through the parasitic capacitance between the antenna arm and the reference plane, we have to increase the capacitance from the top of the antenna to the reference plane.

Figure D-8 shows what is often called a "top hat" or capacitive loaded antenna. By adding a large piece of metal at the top, we can increase the

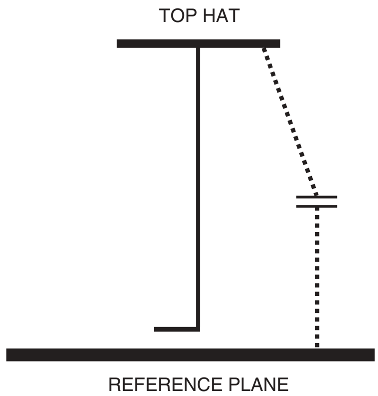

FIGURE D-8. Capacitive loaded monopole antenna.

capacitance from the top of the antenna to the reference plane and thereby increase the current flowing up to the top of the antenna. The "top hat" can be a metal disk, radial wires, or a metal sphere. It does not matter what shape it is as long as it increases the capacitance from the top of the monopole to the reference plane.

As was mentioned before, the same approach can be used with a dipole, only in the dipole case we must apply the "top hat" to the ends of both arms. The resulting antenna is then often referred to as a "dumbbell" antenna; see Fig. D-9.

Therefore, we can conclude that *adding metal (capacitance) to the end(s) of a dipole or monopole antenna will increase its radiation efficiency*. Because the tophat adds capacitance, it will also decrease the resonant length (see Section D.3.2) of the antenna, because the antenna will now have some current at the top. This can be deduced by studying Fig. D-16.

Again you can ask the question, what does this all have to do with EMC? What it has to do with EMC is that you want to make sure you do not configure your product in such a way that you produce a "top hat" antenna.

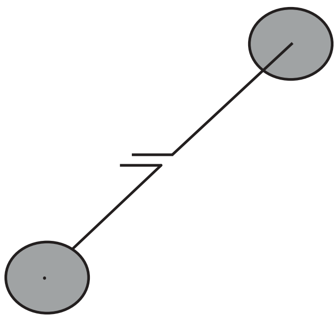

FIGURE D-9. Capacitive loaded dipole antenna.

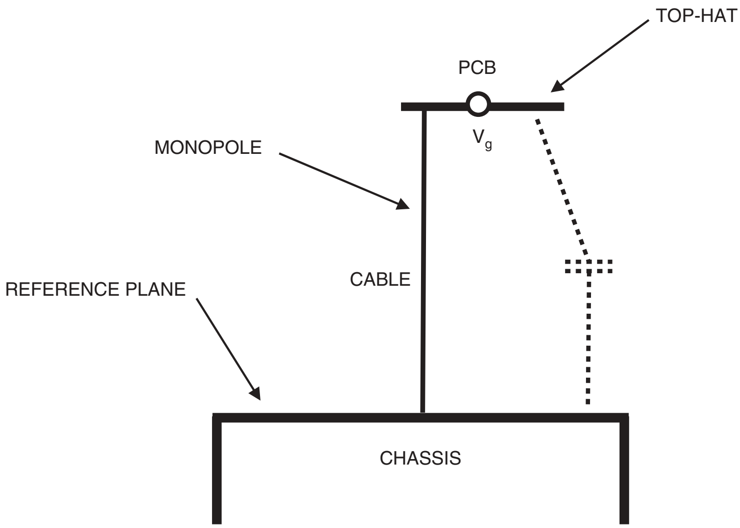

FIGURE D-10. A PCB mounted a distance above a metal chassis forms a top-hat antenna.

Consider the product depicted in Fig. D-10, which consists of a PCB connected to the end of a long cable and mounted a significant distance above a metal chassis. We have just created a "top hat" antenna and the structure will radiate efficiently. The cable is the monopole, the chassis is the reference plane, and the PCB is the "top hat." Therefore, *when a PCB is mounted in a product with a metal chassis, it should be mounted as close to the chassis as possible and have its reference (ground) connected to the chassis.*

A similar situation exists when a daughterboard is mounted above a PCB as shown in Fig. D-11. This is not as bad as the case shown in Fig. D-10, because the dimensions are much smaller, however, it can also, on occasion, be a problem. The solution is also simpler in this case; just connect the daughter-board ground to the motherboard ground through multiple metal standoffs or by some other means.

Figure D-12 shows an interesting example. It is similar to the example of Fig. D-5, but this time the product is in a plastic enclosure instead of a metal box. In

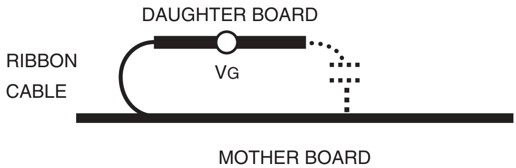

FIGURE D-11. A daughter board mounted above a PCB forms a top-hat antenna.

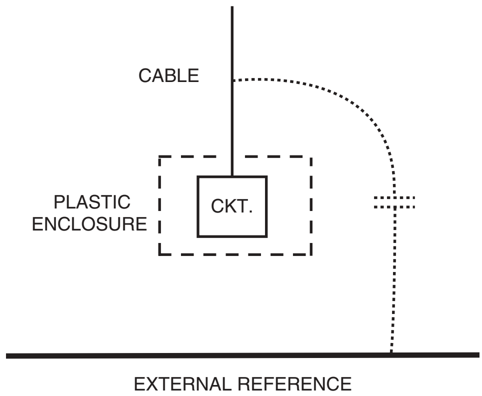

FIGURE D-12. A product in a plastic enclosure, with an attached cable.

this situation, the product does not provide a reference plane for the monopole to work against, so that the monopole will have to find something external to the product to act as its reference plane. This reference plane could be the actual ground (earth) or a metal table, file cabinet, or other metal object in the vicinity. In each location where the product is placed, the reference plane could be something different. Under these circumstances, how do you eliminate the common-mode radiation?

In this case, you may be better off by intentionally providing the other half of the antenna (the reference plane) as part of the product, instead of letting it find something different in each installation. One way to do this would be to add a metal plate, as shown in Fig. D-13, to the bottom of the plastic enclosure and then short out the monopole to this plate. This plate does not have to be thick or heavy (metal foil will do), but it should be large to have maximum

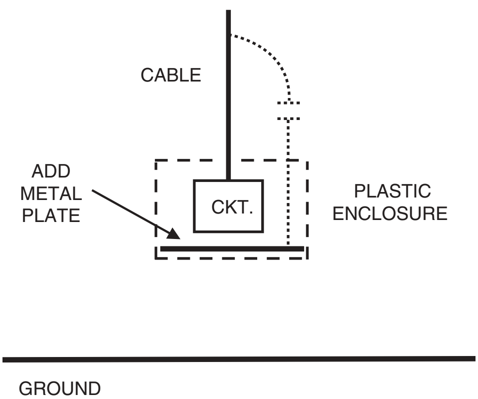

FIGURE D-13. A product in a plastic enclosure with the addition of a metal reference plate.

capacitence to the pole. At this point, the question is usually asked, how large? The answer is simple, as large as the enclosure will allow.

D.3 ADVANCED DIPOLES FOR DUMMIES

If you followed the discussion so far, you now know quite a bit about dipoles and are ready to move to the advanced class. Here we will determine the impedance of a dipole antenna. The impedance is important because it affects the ability to couple energy into, or extract energy from, the antenna structure.

D.3.1 Impedance of a Dipole

Referring to Fig. D-2, we can determine that one of the elements of the antenna impedance will be a capacitor. We also know that the wire arms of the antenna must have inductance, and this inductance will be in series with the capacitance.

If the antenna radiates, then energy will be lost, and this lost energy must be accounted for in our model. The only component that will dissipate power is a resistor, so let us add that to our model in series with the inductor and capacitor. *Therefore, the equivalent circuit for a dipole antenna becomes a series R, L, C network* as shown in Fig. D-14. We call the resistance R_R the "radiation resistance" because it represents the energy that is lost as radiation.

From Fig. D-14, we observe that a dipole is actually a series resonant circuit. At frequencies below resonance, the impedance will be capacitive, at frequencies above resonance it will be inductive, and at resonance it will be resistive.

The impedance of a monopole is one half that of a dipole. This can be deduced by studying Fig. D-15. Figure D-15A shows a dipole antenna and its impedances. If we cut the dipole in Fig. D-15A in half and add a reference plane, along the cut then we form a monopole antenna as shown in Fig. D-15B. The monopole inductance and resistance will be one half that of the dipole, and the capacitance will be twice that of the dipole.

D.3.2 Dipole Resonance

Refering to Fig D-14 we can conclude that below the resonant frequency the input impedance to the antenna will be large (> 1000 Ω) because of the

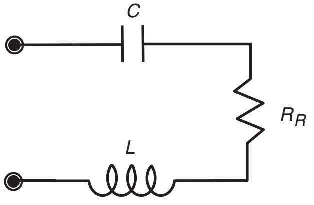

FIGURE D-14. The impedance of a dipole is a series R-L-C circuit.

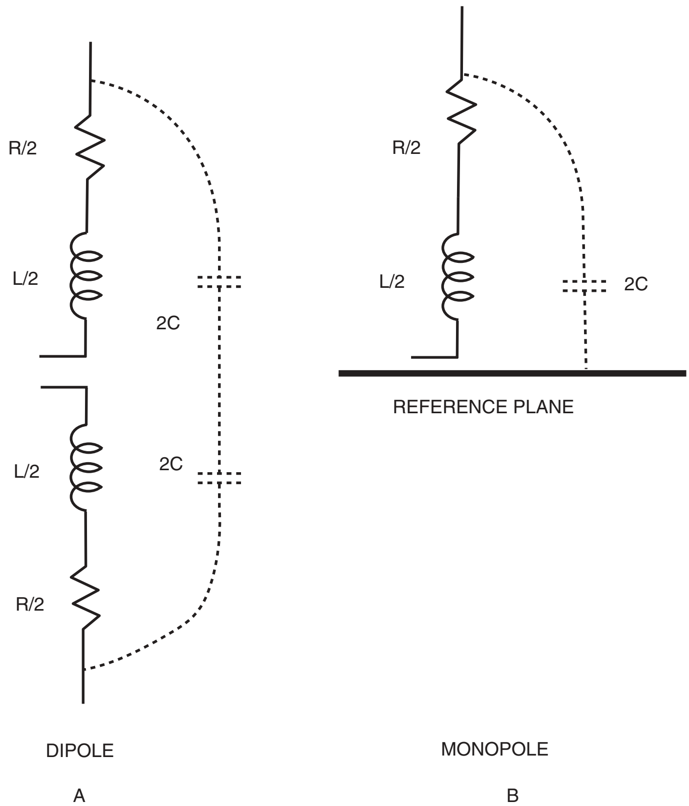

FIGURE D-15. (*A*) Dipole impedance, (*B*) monopole impedance. A dipole cut in half is equivalent to a monopole.

impedance of the capacitor. Above the resonant frequency, the impedance will also be large ($> 1000\ \Omega$) because of the impedance of the inductor. At resonance, however, the impedance will be low (around 70 Ω for a dipole and 35 Ω for a monopole) because, at resonance, the inductive reactance will cancel the capacitive reactance, which leaves just the radiation resistance.

It will be difficult for the common-mode voltage (or any other voltage for that matter) to drive much current into the antenna when the input impedance is large. However, it will be easy to drive current into an antenna at resonance, when the impedance is low. Therefore, dipole (monopole) resonance is important with respect to EMC. *At the resonant frequency, it is much easier to couple energy into or extract energy from the antenna, and it will therefore be a more efficient radiator or receptor of electromagnetic energy*.

As it turns out, the resonant frequency of a dipole (or monopole) is related to its length. Resonance will occur when the length of one of the antenna arms (elements) is one quarter wavelength. Therefore, a dipole will be resonant when its overall length is equal to one half a wavelength, and a monopole will be resonant when its length is one quarter wavelength.

Why this is so can best be understood by recalling the discussion relating to Fig. D-7, with respect to the current in a monopole. At any point in time, the current distribution along the length of a conductor will be sinusoidal as shown in Fig. D-16A. The required boundary condition for an antenna element is that the current at the tip be zero. Figure D-16B shows various length antenna elements placed such that the current at the tip will be zero. As can be observed, the current at the base will be maximum when the element is a quarter of a wavelength long. The highest current point also represents the lowest impedance point; hence, this represents the resonant length.

If the antenna element is shorter than a quarter wavelength, then the current at the base will be lower; hence, a higher impedance and the element will be below resonance. If the antenna element is longer than a quarter wavelength, then the current at the base will also be lower; hence, a higher impedance and the element will be above resonance.

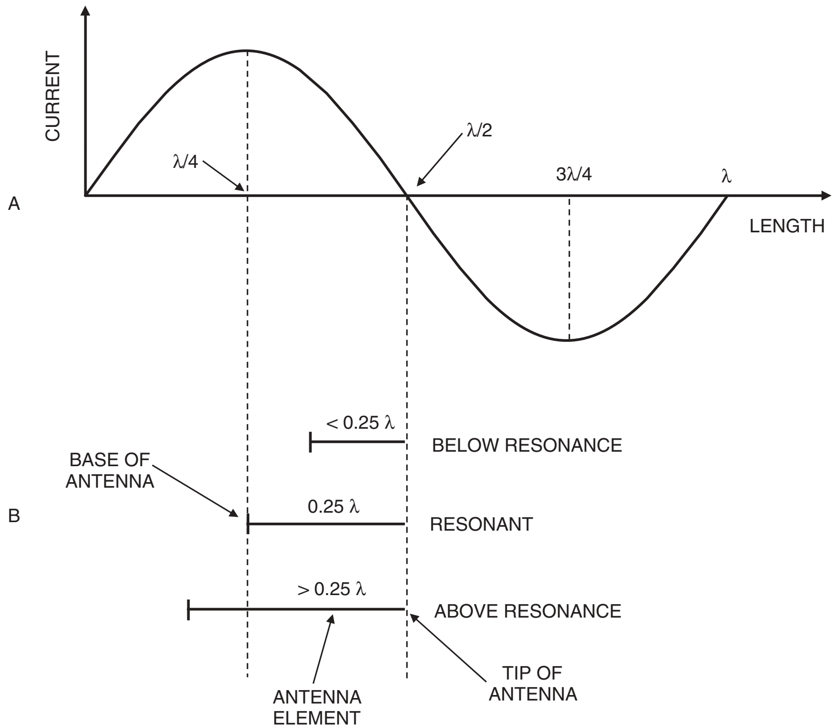

FIGURE D-16. (A) Current distribution along the length of a conductor. (B) Current distribution on various length antenna elements.

Additional resonances will also occur when the element length is equal to odd multiples of a quarter wavelength. This can be deduced from Fig. D-16 by extending the sine wave of current to the left (Fig D-16A) and then moving the base of the antenna (Fig D-16B) to the next current peak. At these frequencies, the cable radiation will also be increased because of the resonance.

D.3.3 Receiving Dipole

Figure D-17A shows a dipole antenna exposed to an electric field E. Figure D-17B shows the equivalent circuitry for the receiving dipole of Fig. D-17A, where Z_A represents the dipole impedance (Fig. D-14) and R_L is the load impedance. If the dipole has an effective length of L_e, then the voltage induced into the antenna when exposed to the electric field E will be

$$V_i = L_e E, \tag{D-1}$$

regardless of the length of the antenna or whether the antenna is resonant.

The voltage across the load R_L at the terminals of the antenna will be equal to

$$V_L = \left(\frac{R_L}{R_L + Z_A}\right) V_i = \left(\frac{R_L}{R_L + Z_A}\right)(L_e E). \tag{D-2}$$

From Fig. D-14, we know that the impedance Z_A is equal to

$$Z_A = R_R + X_L - X_C, \tag{D-3}$$

which is frequency dependent. The antenna impedance Z_A will be large at frequencies above and below resonance, and it will be small at resonance, where the second and third terms cancel, which will leave just the radiation resistance R_R. Therefore, V_L will be a maximum at resonance (where Z_A is small) and will decrease at frequencies above and below resonance (where Z_A is large).

Notice from the above three equations, and Fig. D-17B, that the voltage induced into the antenna V_i is frequency independent, whereas the voltage V_L at the antenna terminals is frequency dependent. Therefore, the problem is not that a nonresonant antenna will not pick up a voltage, rather the problem is that the picked up voltage cannot be coupled out of the antenna because of the large magnitude of the antenna impedance Z_A, when the antenna is not resonant.

D.3.4 Theory of Images

Let us compare the performance of the dipole and monopole as radiators. For example, let us assume that we measure the field at a point in space d meters

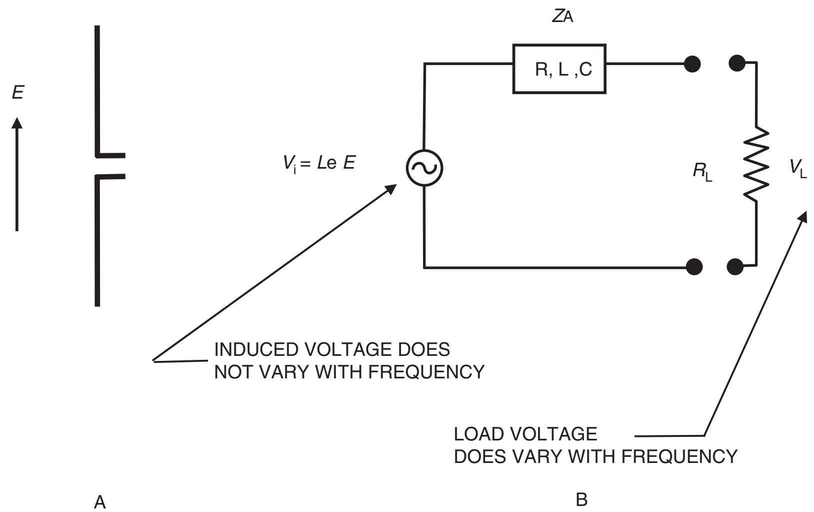

FIGURE D-17. (A) Receiving dipole, (B) equivalent circuit of a receiving antenna.

from, and at a 45° angle from the axis of a dipole shown in Fig. D-18A. How will this compare with the field measured at a similar point the same distance away from a monopole of one half the length and carrying the same current as the dipole as shown in Fig. D-18B.

To answer this question, we can use the theory of images. The easiest way to understand the theory of images is to consider something that we are all

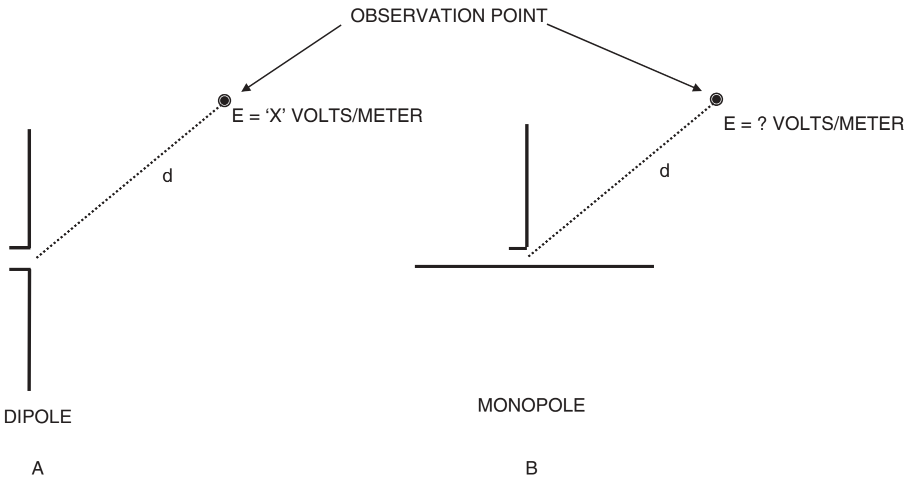

FIGURE D-18. (A) Transmitting dipole, (B) transmitting monopole.

familiar with—a mirror. After all, light is electromagnetic energy similar to what we have been discussing, except of a much higher frequency.

If you look into a mirror (a reflective surface), what do you see? You see yourself! If you move three steps back from the mirror, what does your image do? It also moves three steps back. Therefore, a mirror produces an image of the object in front of it, and that image is located as far behind the mirror as the object was in front of the mirror.

The same thing happens with a monopole above a reference plane (a reflective surface). The reference plane produces an image of the monopole as far below the plane as the antenna is above the plane. Saying it slightly differently, the field produced at any point in space, in the upper hemisphere, by a conductor perpendicular to a reflective plane is equivalent to the field that would be produced by the originally conductor plus a second identical conductor located an equal distance below the plane, as the original conductor is above the plane, but without the plane present. Figure D-19 shows this equivalence. Therefore, the monopole is equivalent to the dipole in the upper hemisphere.

The answer to our original question is then, that as long as we limit ourselves to considering the fields in the upper hemisphere, *the monopole and the dipole produce the exact same field at the observation point*.

D.3.5 Dipole Arrays

Dipoles do not have to be used individually; rather, they are often combined in various ways to modify their radiating or receiving characteristics. Two common dipole arrays are a Yagi and a log periodic.

A Yagi antenna consists of a single driven dipole, a number of slighter shorter parasitic dipoles called directors located in front of the active dipole, and a single slightly longer dipole called a reflector located behind the active

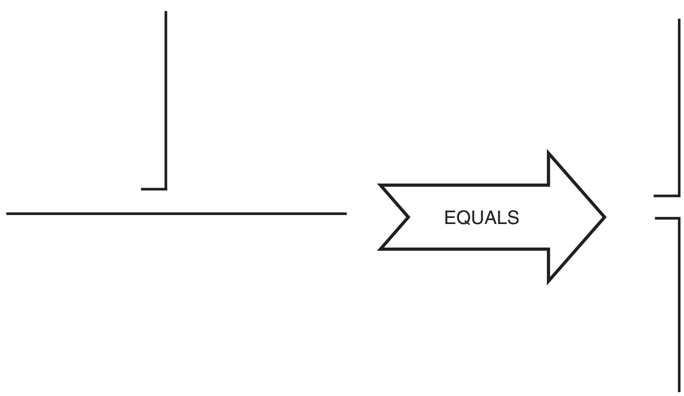

FIGURE D-19. Dipole–monopole equivalence.

dipole, as shown in Fig. D-20. The objective of a Yagi is to increase the gain of the antenna. Because an antenna is a passive structure, the only way to obtain gain (i.e., more energy in one direction) is to take the energy from somewhere else, that is, reduce the energy in another direction, which decreases the beamwidth and increases the directivity of the antenna. An optimized Yagi antenna will provide about 10 dB of gain over a dipole. Yagi's are commonly used as very high frequency (VHF) TV antennas.

A log periodic antenna is an array of driven elements that decreases in length and spacing as shown in Fig. D-21. The log periodic is fed from the front with the feed-line crisscrossing between antenna elements. The purpose of a log periodic antenna is to produce an antenna that will operate efficiently over a

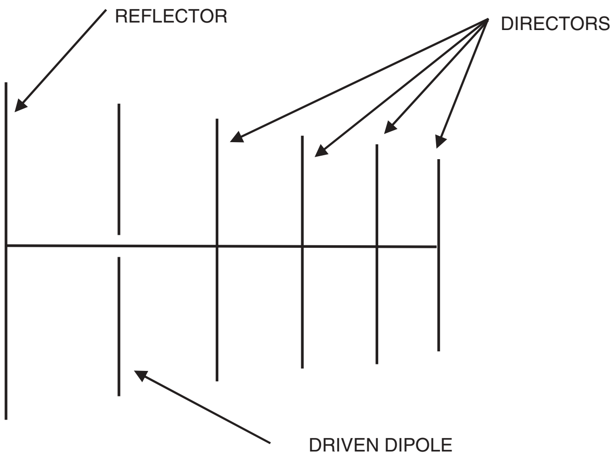

FIGURE D-20. Yagi antenna.

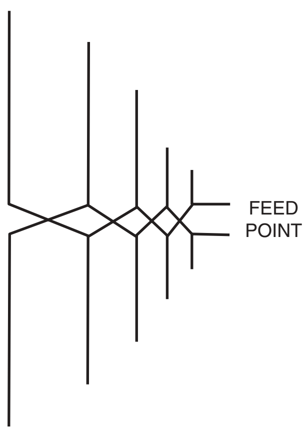

FIGURE D-21. Log periodic antenna.

large frequency range. At different frequencies, a different dipole becomes the active element. Because the impedance of a dipole is large at frequencies off of resonance, the nonresonant dipoles draw little or no current from the feed line.

A log periodic antenna has fairly uniform impedance and radiation pattern from the resonant frequency of the longest element to the resonant frequency of the shortest element. A single log periodic antenna is often used for EMC testing over the frequency range of 300 to 1000 MHz.

D.3.6 Very High-Frequency Dipoles

At very high frequencies (>1 GHz), the size of a resonant dipole is small; at 3 GHz it is equal to 2 in. Therefore, it will pick up or radiate little energy because from Eq. D-1, the induced voltage is equal to the incident field strength E times the effective length L_e, which is less then the actual length of the antenna. If the dipole is made larger, then its impedance will be high, and we will not be able to couple energy to it or extract energy from it. What can be done to solve this dilemma? How about using a small resonant dipole with a big reflector behind it to concentrate a lot of energy at the focal point, where we will locate the small dipole as shown in Fig. D-22. This increases the field strength E at the dipole, which increases the voltage that it picks up. We just made a commonly used satellite-receiving antenna.

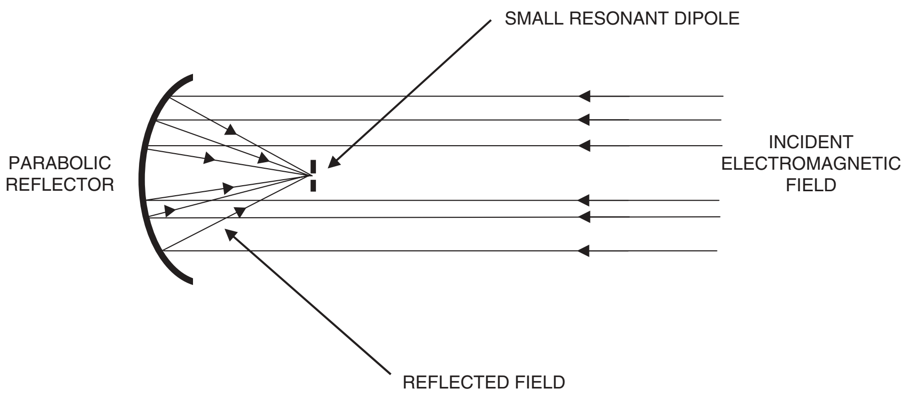

FIGURE D-22. A small dipole with a parabolic reflector makes an effective, very high-frequency antenna.

SUMMARY

- A dipole (or monopole) antenna requires two parts.
- The magnitude of the radiation will be proportional to the dipole (or monopole) current.

- A dipole (or monopole) antenna does not require a ground to work.
- A monopole is just a dipole in disguise.
- The way to make a dipole (or monopole) antenna is to have an rf potential between two pieces of metal.
- The way to prevent radiation is not to have a potential difference between the two halves of the antenna.
- The internal circuit reference (ground) of a product should be connected to the chassis as close to where the cable enters/leaves the product as possible.
- The effective length (effective height) of an antenna is defined as the ratio of the voltage induced into the antenna (not the terminal voltage), to the magnitude of the incident electric field.
- Adding metal (capacitance) to the end(s) of a dipole or monopole antenna will increase its radiation efficiency.
- A PCB should be mounted as close to a metal chassis as possible, and have its ground connected directly to that chassis.
- A plastic enclosure for an electronic product should contain a metal reference plane.
- The equivalent circuit of a dipole (or monopole) is a series R–L–C circuit.
- The impedance of a monopole is one half that of a dipole.
- At the resonant frequency, it is much easier to couple energy into an antenna and, therefore, it will be a more efficient radiator (or receptor) at this frequency.
- Antenna resonance occurs when the element(s) of the antenna are one quarter wavelength long.
- Multiple resonances will occur at frequencies that are odd-numbered harmonics of a quarter wavelength frequency.
- A monopole and dipole both radiate the same field.

FURTHER READING

German, R. F. and Ott, H. W. *Antenna Theory Simplified*. One-Day Seminar, Henry Ott Consultants, 2003.

Iizuka, K. "Antennas for Non-Specialists." *IEEE Antennas and Propagation*, February 2004.