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Basic Principles of Electrically Small Antennas

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This tutorial looks at electrically small antennas, which have always been, and will continue to be, an important part of radio communications, especially in portable applications

Electrically small antennas have been an important part of communications engineering since the beginning. Whether they are small compared to the extremely long wavelengths used at the lowest radio frequencies, or intended to save space in GHz-range wireless devices, the basic principles are the same. This tutorial will review those principles, with primary attention to describing the performance tradeoffs of small size.

Definition of "Electrically Small"

There are various rules of thumb for considering an antenna to be electrically small. The most common definition is that the largest dimension of the antenna is no more than one-tenth of a wavelength. Thus, a dipole with a length of $\lambda/10$, a loop with a diameter of $\lambda/10$, or a patch with a diagonal dimension of $\lambda/10$ would be considered electrically small [1].

This definition makes no distinction among the various methods used to construct electrically small antennas. In fact, most work on these antennas involves selecting topologies suitable for specific applications, and the development of integral or external matching networks.

Common Applications

Most readers will be familiar with several common uses of small antennas. Loop antennas and short monopoles (whip) for medium-wave (AM broadcast) reception are common in home and vehicle entertainment systems. With wavelengths in the 200 to 600 meter range, these antennas far exceed the $\lambda/10$ criterion. Antennas for FM and television broadcast reception are sometimes reduced in size for convenience and portability.

The ubiquitous 315 or 433 MHz wireless remote control and telemetry systems for keyless entry, garage door openers, wireless doorbells and remote-reading thermometers rarely have "full-size" resonant antennas, since a wavelength is around 1 meter. A $\lambda/4$ monopole would be 17 cm long, and requires a similarly-sized counterpoise.

The developing RFID market demands low cost and small size. A 3 cm square RFID tag will have an antenna that is considered electrically small at any frequency below about 1 GHz. Handheld RFID readers will allow somewhat larger antennas, but will still fit the $\lambda/10$ criterion at many of the commonly used frequencies.

Finally, of course, are wireless phones, which now have integrated GPS, Bluetooth™ and other radio systems. Only the largest form factors can support antennas that are large enough to be outside the electrically small definition.

Small Antenna Types

The most common structures used in electrically small antennas are the short dipole (or equivalent monopole and ground place), the small loop, and the dielectrically-loaded patch. Each of these has many variations to fit the mechanical constraints of specific applications, but these three are an appropriate basis for understanding the issues involved in efficiency, impedance matching and radiation patterns. We will examine the topic using the classic dipole and loop as examples. For more information on electrically small patch antennas, readers are directed to Reference [2].

The Short Dipole

Figure 1(a) shows a short dipole antenna. At 100 MHz, a λ/10 dipole with a 1 mm conductor diameter has an impedance at the center feedpoint of 1.96 $-j1758$ ohms, as determined by NEC2 numerical modeling [3]. This low resistance and high capacitive reactance illustrates that a large impedance transformation will be required to match this antenna to a typical 50 ohm system.

The current distribution on a short dipole is a portion of the cosine current distribution seen on a half-wave resonant dipole. In this case, the current distribution is nearly triangular (Figure 1(b)). This current distribution results in the free-space radiation pattern of Figure 1(c), in a plane containing the antenna wire.

Note that the small size of this antenna does not greatly reduce the efficiency. The maximum gain of 1.77 dBi is only 0.37 dB less than a half-wave dipole's 2.14 dBi gain. However, this is only part of the efficiency story. As will be shown later, the matching system is the primary contributor to reduced efficiency in electrically small antennas.

The Small Loop

Figure 2(a) shows a small circular loop, with a diameter of λ/10. The radiation resistance of a small loop can be calculated from [4]:

$$R_r = 31{,}171\,(A/\lambda^2)^2$$

where R_r is radiation resistance, the number 31,171 is $320\pi^4$, with A (loop area) and λ (wavelength) in the same units.

Solving for a λ/10 diameter loop, where $A = \pi(\lambda/20)^2$, the radiation resistance is found to be 1.92 ohms. The actual feedpoint impedance will include the resistive loss of the conductor (with skin effect), plus the inductance of the loop, which will have a result in range of 3.0 $+j800$ ohms. The radiation pattern and gain are similar to the λ/10 short dipole.

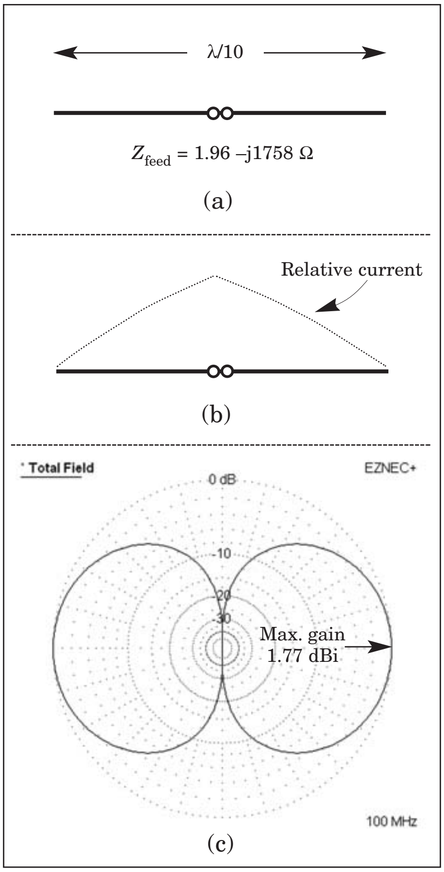

Figure 1 · Short dipole example: (a) dimensions and impedance; (b) current distribution, and (c) radiation pattern and gain.

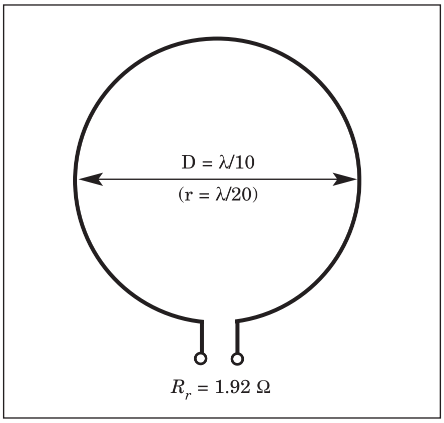

Figure 2 · A small loop also has a low radiation resistance.

Current distribution is nearly uniform on a small loop and does not reveal much about its behavior.

Impedance Matching Issues

The input impedance of both the short dipole and small loop has a small resistive component and a large reactive component. Of concern is the loss within the matching circuitry. Even with relatively high Q, large-value reactive components will have significant resistance that contributes to system loss.

For example, Figure 3(a) shows an ideal, lossless matching network to transform the 1.96 $-j1758$ ohms of the short dipole to 50 ohms system impedance. Mathematically, this provides a proper match, albeit narrowband.

However, ideal inductors do not exist. A practical Q for an inductor is between 50 and 200, depending on construction and effects of coupling to the surrounding environment. For a Q of 100, each inductor will have a resistive loss of X_L/Q, or 879/100 = 8.79 ohms. Since there are two inductors, the total additional resistance in series with the antenna input is 17.58 ohms. Ignoring the smaller loss from the capacitor, the finite Q of the inductors results in a loss of $20\log[1.96/(17.58+1.96)] = 21$ dB.

Figure 3(b) shows a modified matching network that accommodates the additional loss. The different values demonstrate how an empirically-derived matching network (e.g. determined by trial-and-error experimentation) can get results that are far from calculated network values that do not account for losses.

The matching process is similar for the small loop, except that the matching involves a large value of X_C instead of X_L. Since capacitors have much higher Q than inductors, it would seem that small loop matching would have lower losses than an equivalent dipole match. This is gen-

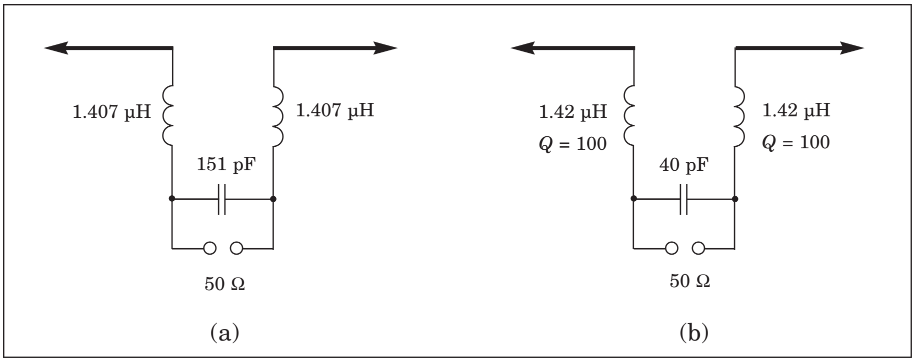

Figure 3 · Short dipole matching: (a) ideal lossless components, and (b) values required for practical inductors with a *Q* of 100.

erally true, but note that the loop example occupies an area much larger than the example dipole. A loop that is more comparable to the dipole in its physical dimensions will be smaller and have a lower value of R_r, which will increase matching network losses.

Mitigating the Loss Problem

Many technical papers and patents describe alterations in the structure of small antennas in ways that increase the radiation resistance and/or implement lower loss matching technqiues. Loading—the addition of capacitive or inductive elements, both lumped and integral to the antenna, is the most common group. Top hats, folded elements, 3-dimensional structures, dielectric foreshortening and other methods are commonly used to add electrical length to a small antenna, raising the radiation resistance.

Often—perhaps too often—the inefficiency of a small antenna is just included in the link budget calculations and overcome by increased system gain, transmit power or simply accepting reduced communication range. This may work for some applications, but all these consequences are detrimental to system performance, decreasing performance and shortening battery life. A useful reduction of losses in the antenna and matching network can be easy and cheap, but requires the designer to be aware that such an improvement can be obtained.

Hopefully, this tutorial raises the awareness of loss and efficiency issues with small antennas. The next step is to learn some of the options for getting better performance for future product designs.

References

1. D. Miron, *Small Antenna Design*, Newnes 2006.

2. R. Garg, P. Bhartia, Inder Bahl and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House 2001.

3. As implemented in EZNEC+ by Roy Lewallen, www.eznec.com.

4. J. Kraus, *Antennas*, McGraw-Hill 1950, Ch. 6, section 6-8.