ORBAN MICROWAVE

BASICS OF ELECTRICALLY SMALL ANTENNAS

INTRODUCTION

“Small Is Beautiful” is the rallying cry of electronic design that has guided designers since the end of the Second World War. The rise of consumer electronics and computing has been the driving force behind miniaturization. Consumers want small devices capable of being carried in a pocket and useful computers need to pack the largest numbers of computing elements (gates) into the smallest possible space. Today we are experiencing profound personal, societal, and technical changes as a result of this program of miniaturization. One device that resists this process of efficient miniaturization is the antenna.

Definition of an electrically small antenna (ESA)

An antenna is classed as an electromagnetic transducer. It converts an electrical signal from one form (a guided wave) into another form (radiation). It does this by coupling the guided wave mode, be it from a coaxial cable or some other waveguide, into a radiation mode. How the well the antenna performs is strictly related to the physics of electromagnetic radiation. Radiation is most efficient when the antenna elements have dimensions that are near or greater than one-half of a wavelength in free space. The efficiency of coupling into the radiation mode is facilitated by apertures that are large with respect to wavelength. Larger antennas also allow operation over wider bandwidths. When an antenna is much smaller than a wavelength, coupling into the radiation mode is weaker. Small antennas achieve radiation by building up intense electric and magnetic fields in the vicinity of the antenna to counteract the weak coupling into radiation modes. As we will see, this poses certain challenges to the designer.

An electrically small antenna is generally defined by its largest dimension being less than one sixth to one tenth of a wavelength. The critical design parameters are feedpoint impedance bandwidth, radiation efficiency and antenna “smallness”. Note that these design parameters are mutually conflicting. You can have any two of these parameters to the exclusion of the third. Illustration 1 graphically shows the permissible combinations for a small antenna. Most ESA designs attempt to maximize radiation efficiency and smallness at the expense of bandwidth. Other ESA designs are less concerned with radiation efficiency and go for larger bandwidth and small size (in, e.g. nearfield RFID or proximity coupled communications applications – not really antennas in the strict sense).

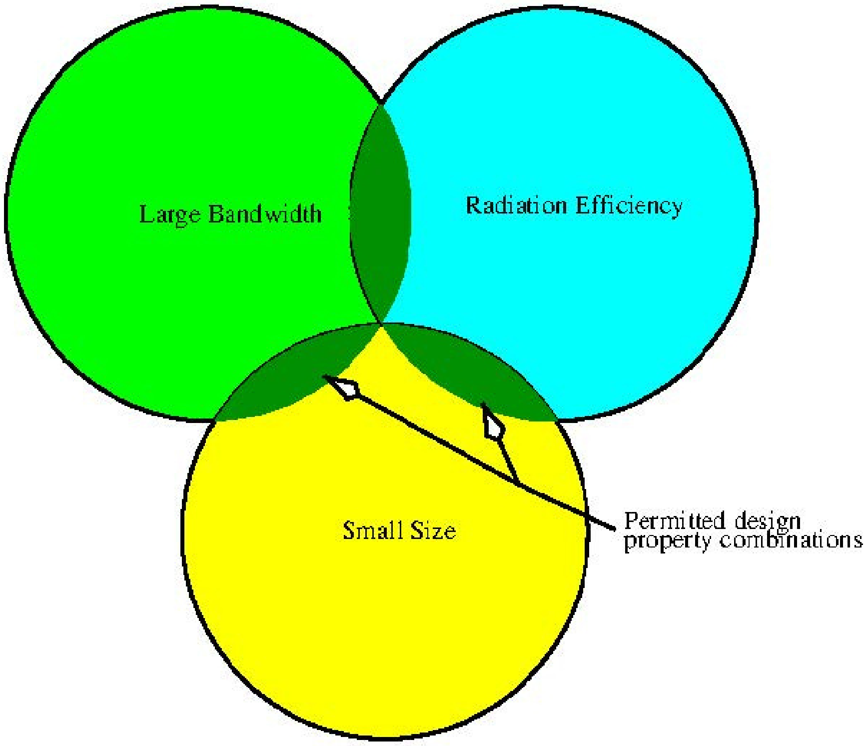


Illustration 1: Venn diagram showing the design parameters. The dark green area shows the permissible parameter combinations.

Bandwidth

Small antennas, because of the inefficient coupling to radiation modes, will usually have a large Q-factor. A large percentage of the field energy is "stored" in the near field zone of the antenna and leaks out with difficulty – hence the high Q. Generally speaking, Q is defined in terms of bandwidth as

$$Q=\frac{f}{\Delta f},$$

where f is the center frequency and Δf is the impedance bandwidth of the antenna feed. The Q-factor of the small antenna is readily approximated by the Chu-Harrington limit [1]-[3]:

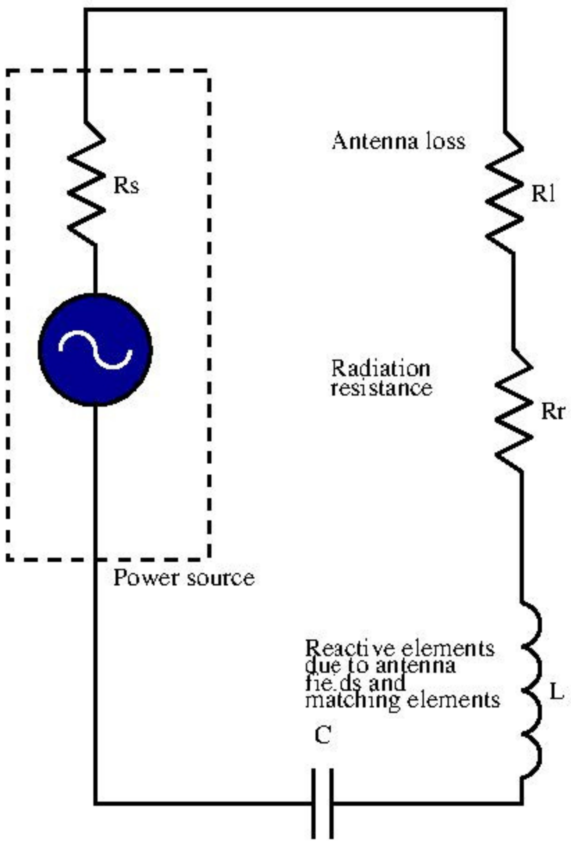
$$Q\propto\frac{\lambda^3}{a^3}.$$

Hence, as the antenna size becomes smaller than the wavelength λ, the Q-factor rises precipitously. For example, a dipole antenna of length 0.1λ would have a Q of around 1000. If the antenna could be matched to 50 ohms, it would have a bandwidth of around 0.1%. If the center frequency is 1GHz, we are talking about a 1MHz maximum bandwidth under ideal conditions. In reality, the antenna (and its associated matching networks) will have a Q-factor much lower than this ideal. This is no reason to celebrate, though, because the reduced Q is due entirely to losses and inefficiencies in the antenna system (i.e. radiated power/input power = radiation efficiency).

Radiation efficiency

One way to conceptualize antenna performance is to visualize the antenna system and its matching network as a lossy tuned circuit, as in Illustration 2.

Illustration 2: Antenna conceptual model.



We see the power source on the left. The source resistance is usually 50 or 75 ohms in most applications. Internal losses (from copper loss, component loss, dielectric loss in the antenna) are represented by the loss resistance Rl . Power transfer into useful radiation is represented by the radiation resistance Rr . The inductor and capacitor represent reactive components to the antenna feedpoint impedance as well as any possible reactive matching circuit components and do not contribute to loss. The Q-factor defined in terms of energy and power dissipation of this series resonant circuit (not including the source resistance) is

$$Q = \frac{X_L}{R_l + R_r}$$

where XL is the inductive reactance. Looking at the the case of a λ/10 dipole, the radiation resistance is Rr=1.9 ohms and capacitive reactance is XC=1758 ohms. We can use a series inductor with XL=1758 ohms to cancel the capacitive reactance and make the antenna resonate with a Q=916. The loss resistance Rl will include the inevitable losses in the capacitor and inductor as well. A typical Q factor found on a data sheet for an RF capacitor might be 150 and for a good RF inductor, 50. Q factors in this type of circuit add like

$$\frac{1}{Q_T} = \frac{1}{Q_r} + \frac{1}{Q_L} + \frac{1}{Q_C}$$

where QL and QC are the inductor and capacitor Qs, respectively. Hence, the total QT=1/(1/916 + 1/50 + 1/150) = 36! The amount of power that is actually radiated (the radiation efficiency) is

Antenna size

There are a number of ways to reduce antenna size. Typically, the radiating element can be coiled up, looped or meandered, or the antenna can be fashioned from a high permittivity dielectric. One old method of constructing an electrically small antenna is to employ a high permeability ferrite as the core of a coil. To summarize, size reduction strategies include using:

- **ferrite loops**
- **single or multi-turn air-core loops**
- **normal mode helicals with and without dielectric loading**
- **loaded mono/dipoles**
- **meandered patterns**
- **dielectric resonator and patches on high permittivity substrates**

ESA menagerie | Ferrite loops

Ferrite loop antennas are one of the oldest (since the mid 20th century) small antennas that still find use in portable long, medium and shortwave receivers as well as automatic radio-controlled clocks that use the DCF77 or WWVB (among other) longwave time signals. Ferrite loop antennas are magnetic dipoles. The ferrite core raises the radiation resistance to a level acceptable for reception and permits resonance to be achieved by tuning using capacitors of an acceptable value.

These types of antennas are used almost exclusively in receive applications because losses are significant. The losses incurred in these antennas tend to be less of a problem than in UHF antennas and above, because external interference and noise in the kHz and low MHz bands is much higher than noise generated in even a lossy antenna. However, attempted use in a transmit application of any significant power would result in overheating of the ferrite rod with very little radiation taking place.

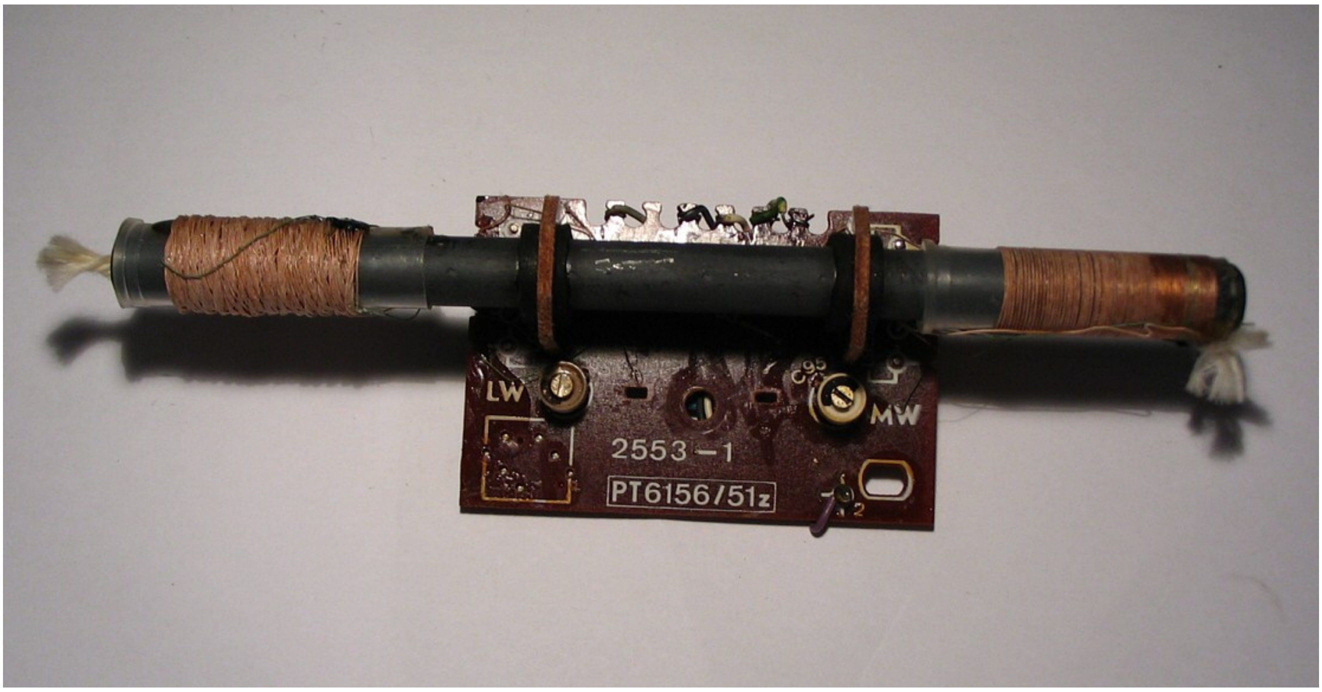


Illustration 3: Ferrite loop antenna. From Wikipedia: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1142082.

Air-core loop antennas

These antennas are often found in direction finding applications and narrowband transmit-receive systems. The size of these antennas with respect to wavelength is larger than the ferrite loops, but the dimensions are usually still very small compared to wavelength. Some of the very earliest AM receivers used multi-turn loops, as seen in Illustration 4.

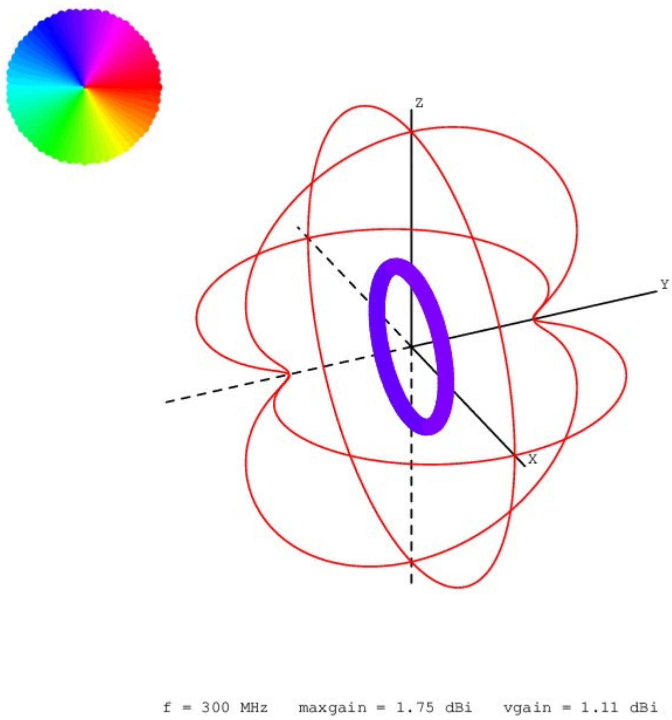
Illustration 4: Loop antenna from 1920s AM radio. From https://www.radiomuseum.org/forumdata/users/4942/loop_replaces_aerial/1920s%20Loop%20antenna.jpg

These antennas are usually very easy to fabricate and can be tuned to a particular frequency using variable capacitors. Like the ferrite antenna, these antennas behave like magnetic dipoles and hence have nulls along a line perpendicular to the loop area. Hence, they can be used in direction finding “sniffer” receivers like the one in Illustration 5.

Illustration 5: Loop antenna used in direction finding receiver. From Wikipedia: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8843029.

As in all short dipoles, small loops exhibit very small radiation resistance, however, in this case, with large inductive reactance. The radiation resistance for a one-tenth wavelength diameter loop is about 1.9 ohms with an inductive reactance XL = 800 ohms. We can make the system resonant, but the losses in the antenna conductor and the matching network will permit an efficiency of a few percent. If used in transmitting applications, the high voltages present on the feed tuning capacitor can cause breakdown and failure as well as provoke arcing in the air around the feed. Small loop antennas tend to be very narrowband, often exhibiting bandwidths of less than 1%. The resulting gain is slightly higher than for an isotropic radiator: 1.75dBi (Illustration 6).

Illustration 6: Radiation pattern for the λ/10 diameter small loop. Computed using NEC2 [2].



As expected, the radiation has dips along the axis of rotation of the loop, broadside to the wire loop.

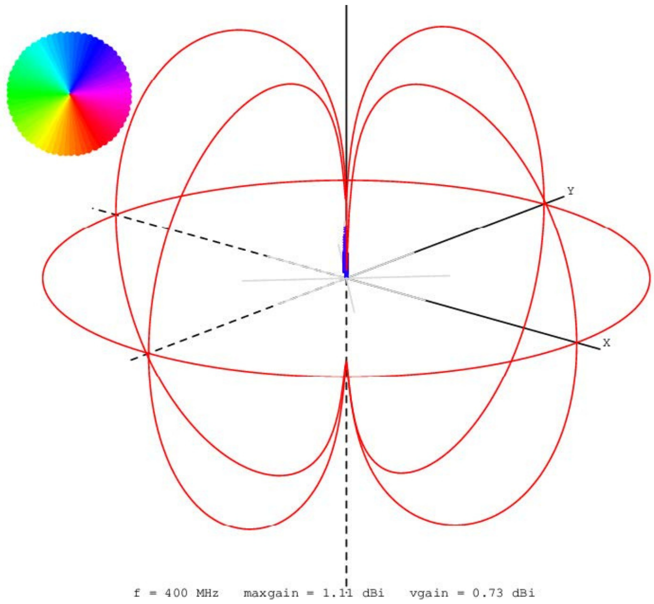
Normal mode helical antennas

This is another class of small antenna that is found in many portable radio applications as a "whip" or "rubber ducky" antennas (Illustration 7). Since the windings of these antennas are much smaller than a wavelength, they produce continuous inductive loading along their lengths. These antennas are very useful for mobile and portable HF to VHF applications, where a full quarter wave monopole is not convenient.

Illustration 7: Normal mode helical antenna. From Wikipedia: https://commons.wikimedia.org/wiki/File:UHF_CB_with_rubber_ducky_exposed.jpg

It the conductor length is tuned correctly, these antennas can be made self-resonant. They tend to radiate in an omnidirectional pattern broadside to the winding axis. The radiation pattern has a minimum along the antenna axis and is azimuthally omnidirectional, much like the small dipole. Feedpoint impedance bandwidth, consistent with other ESAs, is narrow and depends on the Chu dimension/wavelength ratio. The example pattern in Illustration 8 is for a 0.15λ long helix whose winding is around ½ wavelength long over a finite ground plane. Gain is very low (approximately 1.1dBi) and radiation resistance is 9 ohms at resonance.

Illustration 8: Example normal mode helix radiation pattern. Note low 1.1dBi gain. Nulls are along axis of helix.



Care must be taken in the design for transmitting applications that the radiation resistance is sufficient to keep the antenna Q low enough to prevent arcing at the top of the antenna. If coupling to the free space radiation mode is weak, you will essentially have a Tesla coil with a plasma discharge at the top!

Loaded mono- and dipoles

By lumping inductance and/or capacitance at strategic points along a dipole or monopole antenna, we can make the antenna resonant while simultaneously reducing its size considerably.These antennas are very common in mobile applications under 50MHz. Schematically, the technique is straightforward.

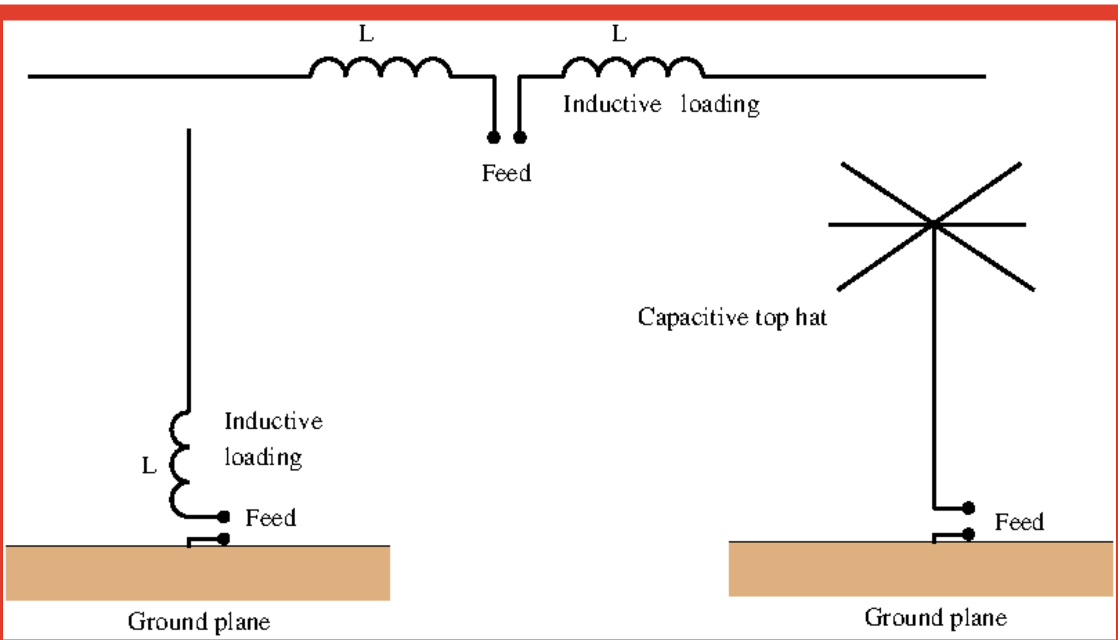


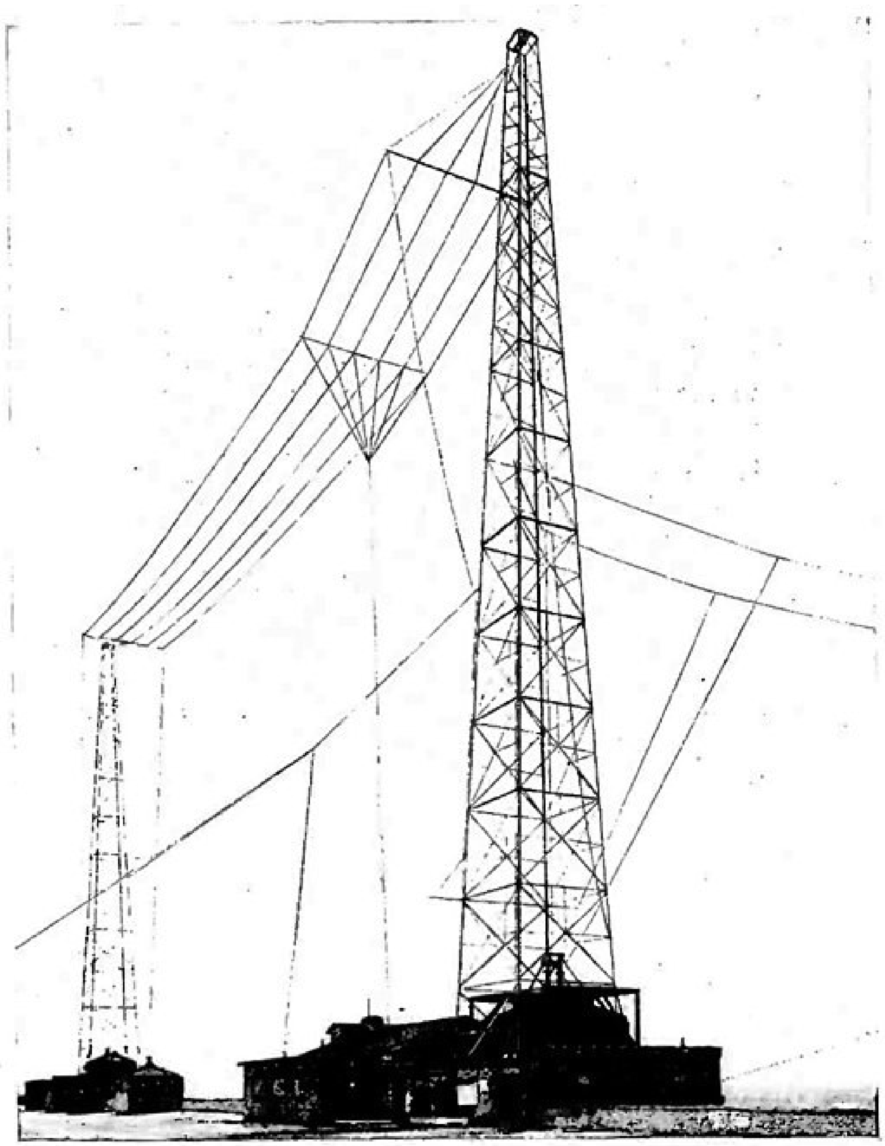
Illustration 9: Dipole and monopoles with inductive and capacitive loading.

By placing an inductor near the feed, the antenna resonates at a frequency determined by the lumped inductance and the capacitance of the wire after the inductor. The radiation resistance is principally determined by the shortened wire part of the antenna. The length of this wire must be sufficient to guarantee a sufficient radiation resistance for efficiency as well as avoiding the Tesla coil effect (arcing) when used in transmit applications. Often, one finds the loading coil placed in the center of the monopole to improve the radiation resistance and, hence, antenna efficiency. Many mobile and hand-held radios use inductive loading in monopoles.

Loaded mono- and dipoles... Continued

Alternatively, one can capacitively load the top of the antenna, increasing its effective electrical length. Some of the earliest long-wave antennas used this method (Illustration 10). Modern VLF transmission systems (like time signals and VLF communications) still use these types of antennas.

Illustration 10: WBZ T-antenna, ca. 1925 with top capacitive loading. From Wikipedia: https://commons.wikimedia.org/wiki/File:Wire_T_antenna_station_WBZ_1925.jpg



Radiation resistance is generally low (a few ohms in most applications), but top arcing is less of a problem because the capacitance has the effect of lowering the antenna Q significantly. This is because conductor losses in the feed and vertical wire contribute significant losses. The current in the vertical is higher than in the inductively loaded antennas, meaning I2R losses are also higher. Matching circuit components contribute to further degradation of antenna efficiency. For these applications, operating wavelengths of hundreds or thousands of meters make ¼ or ½ wave antennas impractical. Top loading makes broadcast over narrow bands practical for very low frequencies if one is disposed to accepting some inefficiency.

Meandered antennas

One convenient way to design small resonant antennas is to “fold up” the familiar dipole antenna by meandering the conductor as seen in Illustration 11.

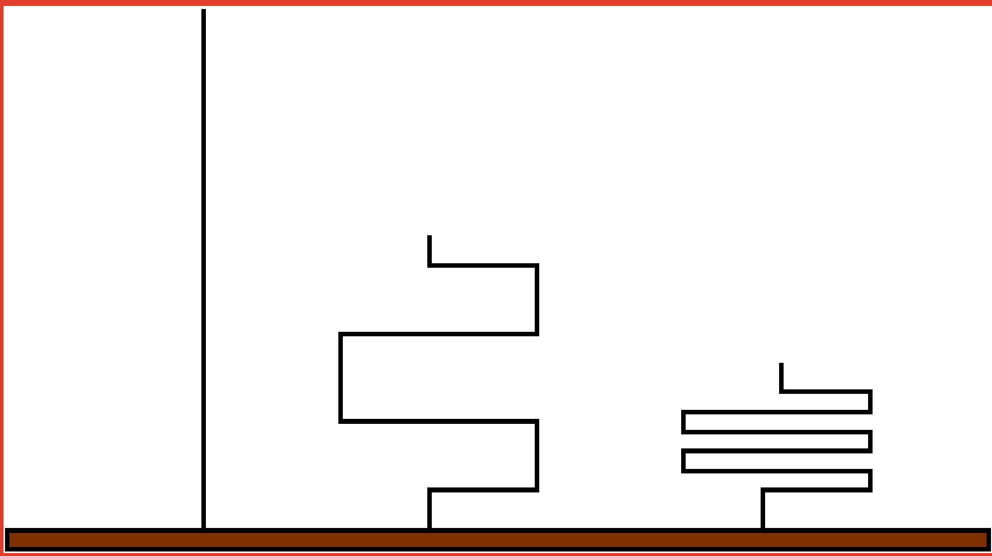


Illustration 11: Illustration of wire antenna meandering to reduce size. Monopole is on left and progressively folded antennas are to the right.

For comparison, a straight half-wave dipole antenna has a radiation resistance around 73 ohms and a maximum directivity of 2.15dBi (Illustration 12).

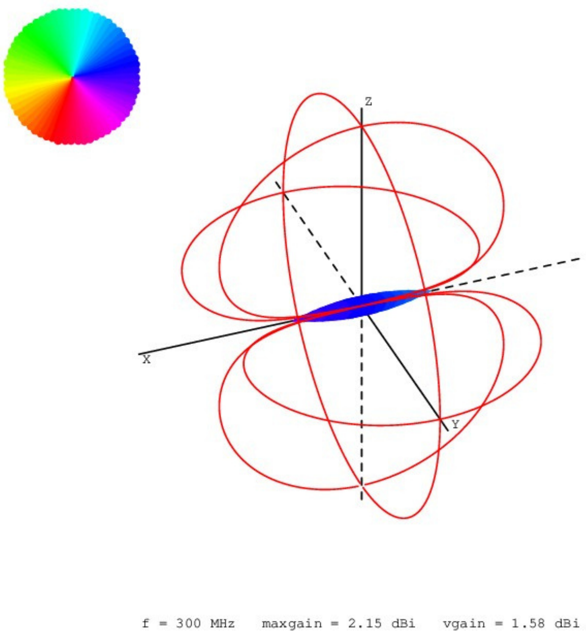


Illustration 12: Radiation pattern of 1/2 wave dipole. Gain is 2.15dBi for lossless antenna.

A meandered dipole with physical length 0.06λ exhibits a much lower radiation resistance of around 5 ohms at resonance. Note that the electrical length of the folded wire is of the order 0.5λ.

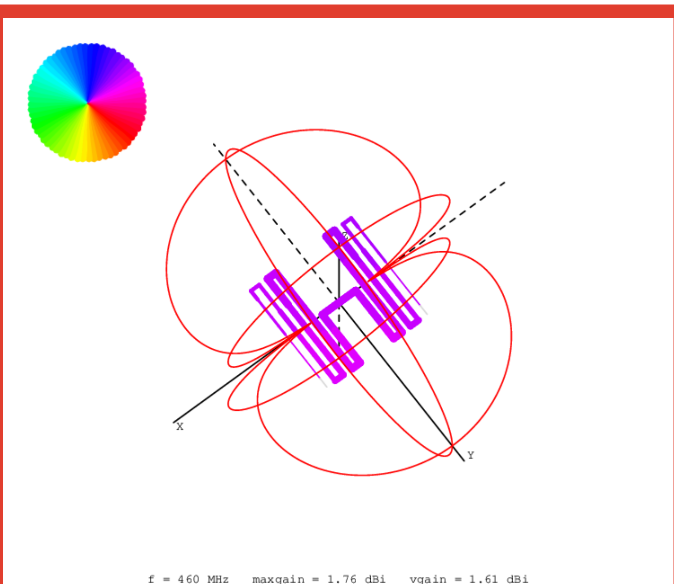


Illustration 13: Radiation pattern of meandered antenna. Gain is 1.76dBi; very close to the gain of the small loop antenna.

Again, we see the doughnut shaped small dipole radiation pattern with nulls along the axis of the antenna.

Dielectric resonator antennas

Dielectric loaded and dielectric resonator antennas find use in hand-held applications such as GNSS receivers, where compactness is highly desirable. Furthermore, ceramics tend to be temperature stable and low loss, permitting efficient narrow band operation.

In Illustration 14 we have placed a metal patch on a block of high permittivity ceramic material (Dk = 81). The ceramic pulls the resonant wavelength to around 10% of that of free space, making this arrangement similar to a small dipole.

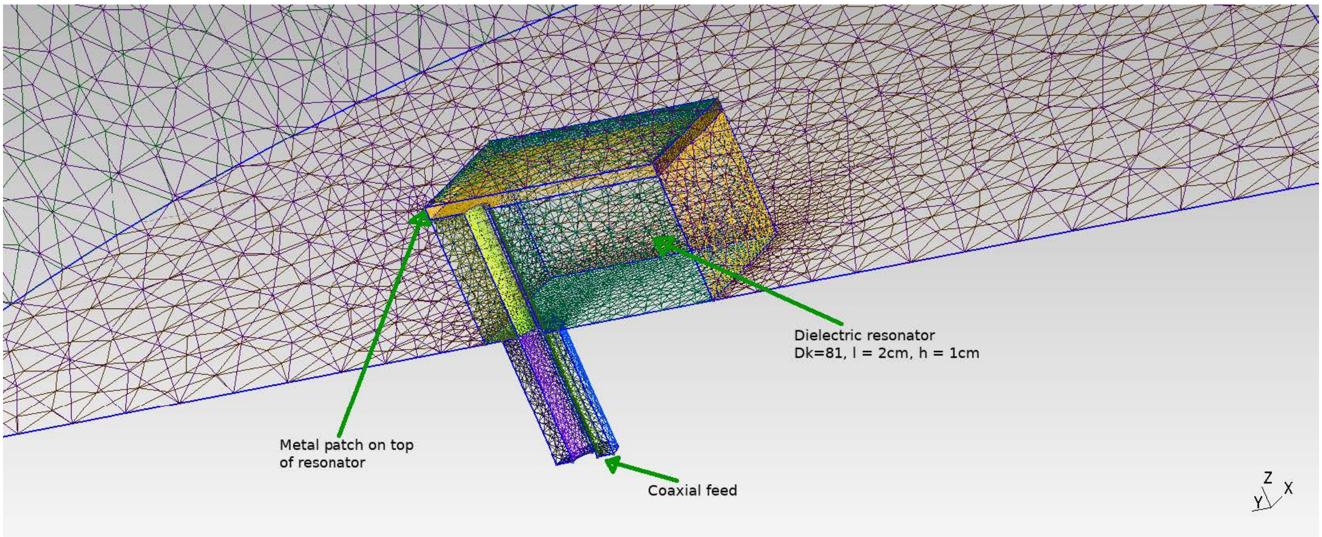
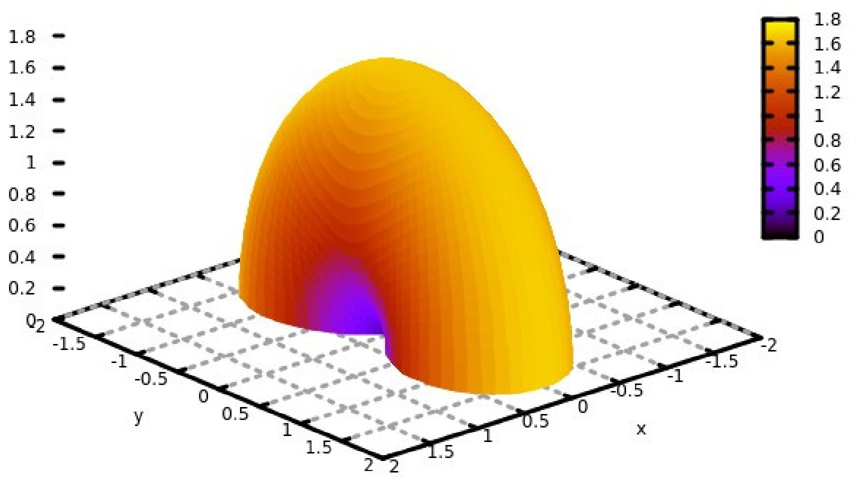


Illustration 14: Simulation model for high Dk small dielectric antenna. One half of the geometry is shown, with a perfect magnetic conductor symmetry wall in the YZ plane (x=0, x-axis into the page).

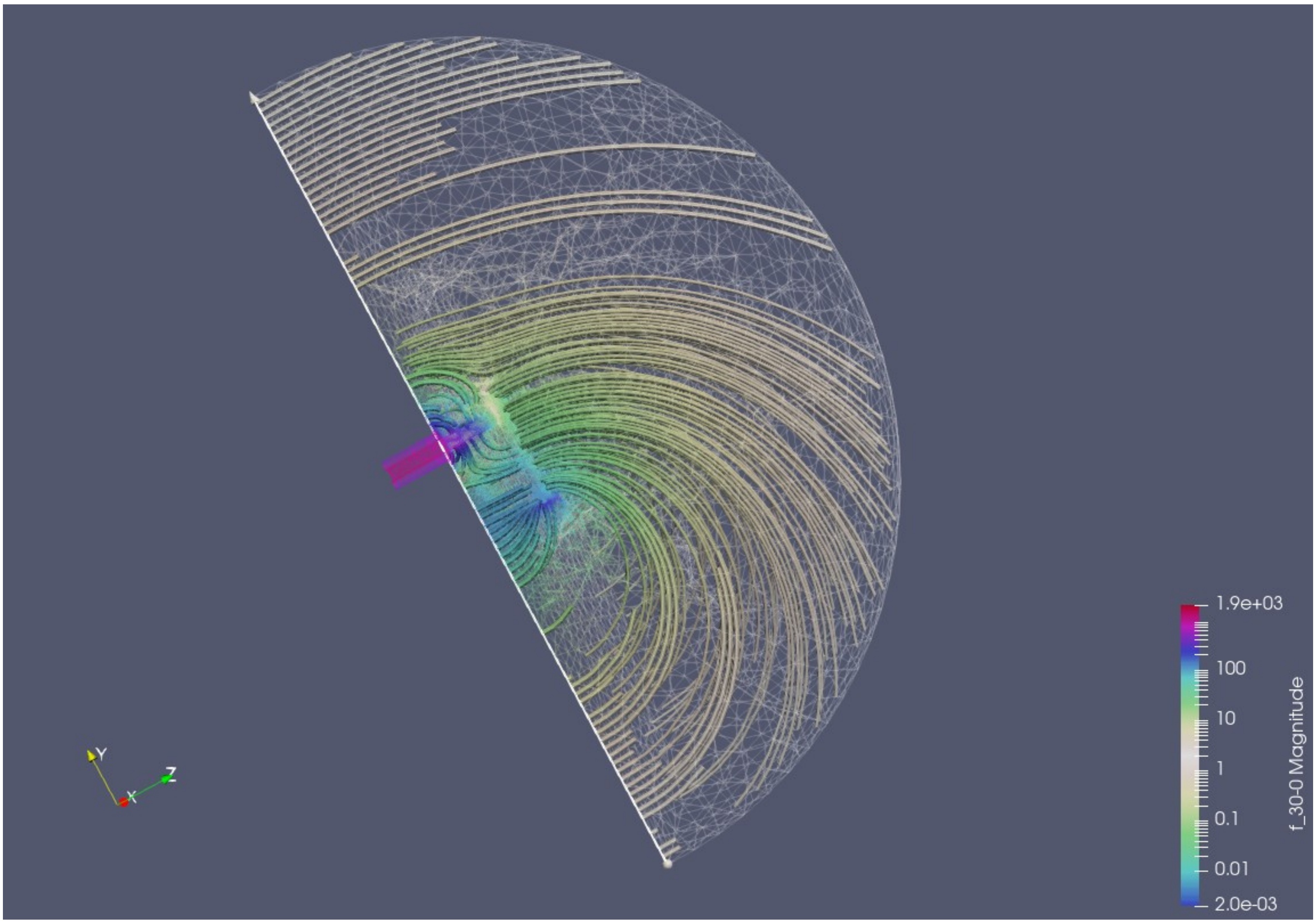
To achieve significant radiation, intense fields are built up inside the dielectric and high currents flow on the top patch. Assuming lossless materials, computed radiation resistance is around 0.6 ohm at the fundamental resonance of 720MHz. Bandwidth is about 1%. At this frequency, the antenna size is about λ/20.

Illustration 15: Radiation pattern for small dielectric antenna. Scale is linear and maximum gain corresponds to 2.5dBi.



The gain for the lossless antenna, seen in Illustration 15 is around 2.5dBi. The pattern is the familiar “doughnut” shape of the small dipole. The nulls are located at the sides of the patch. To further illustrate the radiation, Illustration 16 shows the electric lines of force at a time instant.

Illustration 16: Electric field lines around dielectric resonator antenna. Field solution using finite element solver suite [5].



Summary On Following Page

SUMMARY

ORBAN MICROWAVE

There is nothing magic about small antennas. The designer must juggle the conflicting tradeoffs to produce the desired performance. Generally, useful small antennas share these characteristics:

• A dipole-like radiation pattern that is omnidirectional.

• Low gain, usually less than the ½ wave dipole. Overall antenna gain (including losses encountered in matching circuits) will be less than an ideal isotropic radiator. -2 or -3dBi is not uncommon for low cost ceramic resonator antennas and worse for ferrite and loop antennas.

• Narrow operational bandwidth – exactly how narrow depends on the type of antenna, but 2-3% or less is typical in many practical applications. Do not be fooled by small antennas promising wide bandwidth. They are more resistor than antenna!

• High internal power loss with respect to radiation power – since strong resonance is needed to force power out of a small antenna, low antenna feed and matching circuit Q factors dominate. Most power is lost in the antenna instead of radiated into space.

So, with all these downsides, why use small antennas?

• Low-cost portable applications, like handheld GNSS receivers or satellite phones.

finite element solver suite [5].

• Short range, low power communications in high interference environments. Some inefficiency can be tolerated to keep size and cost down.

• For cases where full-sized antennas are impractical – low frequency broadcast where wavelengths can be hundreds or thousands of meters. Some form of size reduction based on loading makes the antenna realizable.

Designing small antennas that perform well in the field requires attention to a number of details, like temperature stability, power handling and noise. Power handling and noise are linked to losses in the antenna and are particularly important to optimize for VHF, UHF and above. Typically, that means low loss materials need to be used to fabricate the antennas and careful matching that minimizes loss is crucial. Small receive antennas below 30MHz or so can usually tolerate more loss, since external incoming noise radiation at these frequencies exceeds internal antenna and receiver noise by a large margin in most cases.

References

[1] L. J. Chu, "Physical limitations of omnidirectional antennas," MIT Tech. Report 64, May 1948.
[2] R. F. Harrington, "Effects of antenna size on gain, bandwidth and efficiency," J. Nat. Bureau Standards, 64D pp. 1-12, 1960.
[3] H. Wheeler, ""Small antennas," IEEE Trans. Antennas Propagat., vol AP-24, no. 4, pp. 462-469, 1975.
[4] NEC2, Numerical Electromagnetics Code, https://www.nec2.org
[5] Fenics Project, https://fenicsproject.org/community/