Some Perspectives on the Design of Electrically Small Antennas

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The purpose of this paper is to review some guidelines for the design of transmitting antennas constrained by physical dimensions and performance objectives. Principal among these objectives are the impedance bandwidth, the radiated power, and the efficiency.

Wheeler was the first to define the fundamental limitations of electrically small antennas (H. A. Wheeler, *Proc. IRE*, 1947, 1479-1484) for which the radius of the circumscribing sphere is less than the *radianlength* $\ell = \lambda/2\pi$. For present purposes, we will define this as a circuit-theoretic approach and note that in circuit theory it is assumed that all elements are electrically small and phase shift only occurs across discrete elements such as *R, L* and *C*. Note that such a region also defines the extent of quasi-static field theory.

Subsequently, theoretic limits (R. M. Fano, *Jour. Franklin Inst*., 259, 1950, 57-83, 139-154) were established for the broadband matching of arbitrary impedances such as the *RL* and *RC* circuits of small dipoles and loops. Lopez indicates that double tuning is the most practical application of this idea (A. R. Lopez, *IEEE Ant. Prop. Mag*., 46, 2004, 88-90).

The same fundamental limits on small antennas noted by Wheeler were developed by Chu (L. J. Chu, *J. Appl. Phys*., 1948, 1163-1176) who approached the problem from a wave-theoretic point of view. In particular, Chu noted that the cutoff radius $r_c = \lambda/2\pi$ (the same as Wheeler's radianlength) of the two lowest-order spherical modes of radiation, the TM_{10} and TE_{10} modes. Since the physical extent of an electrically small antenna is within this boundary, it cannot radiate very well and therefore may be regarded as a lossy reactor, *L* or *C*, with a small amount of damping due to radiation. As noted by Best (S. R. Best, *IEEE Ant. Prop. Mag*., 2015, 38-47) the widest bandwidth is achieved by moving the antenna conductors to the very limits of the spherical boundary, a spherical coil.

Finally, we see the application of hybrid methods in which printed-circuit elements are combined to form multi-resonant antennas. In this case, a multiplicity of elements mimic the characteristic modes and broaden the bandwidth (H. Stuart, S. Best, A. Yaghjian, *IEEE Ant. Wireless Letters,* 6, 2007, 460-463).

Although contemporary developments did not alter the fundamental limitations noted by Wheeler and Chu, they did offer new insights into the optimum design of small antennas. Circuit-theoretic methods seem to be more appropriate for longer wavelengths where discrete circuit components are applicable; hybrid methods are more appropriate at shorter wavelengths where printed circuits and integrated devices are used. In both cases, wave theory ultimately governs the bandwidth limitations based on fundamental physics.