Electrically Small Antennas' Design Criteria and Measurement Challenges

Majid Manteghi
Virginia Polytechnique and State University, Blacksburg, VA 24060, USA
(manteghi@vt.edu)

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***Abstract*— The contrast between the design criteria for electrically small transmit and receive antennas is studied in this work. On the transmit side, radiation efficiency (ohmic loss plus return loss) and data throughput are critical. However, a higher impedance mismatch on the receiving front end may reduce ohmic loss and expand the frequency bandwidth. So, a calculated mismatch can be added to improve the performance of the receiving ESA by lowering the overall noise figure and widening the frequency bandwidth. These contradictory design criteria suggest utilizing separate transmit and receive antennas to improve the transmitter and receiver performances.**

Keywords*— *Bode-Fano limit; Chu's limit; electrically small antennas; wideband impedance matching

I. Introduction

Wireless technology has provided novel and innovative solutions to new challenges in our everyday lives, therefore boosting our quality of life. Nevertheless, many solutions, such as IoT devices and sensor networks, must shrink with time. Although the shrinking of specific radio components is a technological issue, some miniaturization aspects contradict physical laws and cannot always be resolved by technological advancement. One of these issues involves the fundamental limits of antennas [1, 2]. As a result, bandwidth, radiation efficiency, and antenna miniaturization factor cannot be concurrently maximized. Despite this, the need for electrically small (ESA), wideband, high-efficiency antennas continues to increase.

Numerous measurement tools with standardized antenna characterization instructions and a substantial quantity of supplementary materials are available for antenna characterization. However, ESA characterization remains a challenging field of research. Furthermore, there must be a balance between the design characteristics, including frequency bandwidth, radiation efficiency, miniaturization factor, and radiation pattern of an ESA. Consequently, this work emphasizes the significance of each parameter for transmitting and receiving ESAs.

II. Design requirements for Electrically Small Transit and Receive Antennas

According to Wheeler's definition, an ESA may be contained inside a sphere with a diameter of λ/π or less. λ/π is also an approximate range used to describe the reactive nearfield of the antenna [3]. Therefore, any disturbance, including the feeding network, environmental variations, and lossy medium (such as the human body), can directly alter the current distribution of the ESA. Consequently, any item connected to the ESA or within its reactive nearfield may significantly impact its parameters, including its resonant frequency, input impedance, radiation pattern, and frequency bandwidth.

Before discussing the design criteria for electrically small antennas, we investigate the following two equations [4]:

$$\mathbf{E}(\mathbf{r}) = -j\omega\mu\frac{e^{-jkr}}{4\pi r}\int_V\left(\bar{\bar{\mathbf{I}}} - \hat{r}\hat{r}\right)\cdot\mathbf{J}(\mathbf{r}')e^{k\hat{r}\cdot\mathbf{r}'} \qquad (1)$$

$$\frac{\Delta f}{f_0} = \frac{\pi}{Q \times \max(\ln 1/|\Gamma|)} \qquad (2)$$

where $\bar{\bar{\mathbf{I}}}$ represents the unit dyadic, and Γ represents the reflection coefficient of a lossy reactive component. Equation (1) demonstrates that the intensity of the radiated electric field at the far zone is proportional to the volume integral of the source multiplied by $e^{k\hat{r}\cdot\mathbf{r}'}$. In the case of ESA, the volume is limited, and the source's magnitude must increase considerably to raise the strength of the electric field. Typically, resonant topologies are used to obtain such a large current. A high ohmic loss is generally the consequence of a strong current in a confined area. Consequently, ESAs have relatively poor radiation efficiency. On the transmitting side, the radiation efficiency (ohmic loss + return loss) is the essential metric besides the frequency bandwidth.

On the receiving side, however, the signal-to-noise ratio (SNR) is just as important as the frequency bandwidth. Equation (2) demonstrates that a mismatched antenna may improve frequency bandwidth for a given quality factor [5, 6]. However, the antenna mismatch does not affect the signal-to-noise ratio, SNR, since it simultaneously reradiates the signal and noise. Therefore, the noise figure of the front end (low noise amplifier and filter) plays an essential role in the receiving antenna. A parametric amplifier was suggested as a matching circuit and front-end combination in [5] to satisfy mismatch and low-noise matching conditions. It is easy to show that for the desired Γ the optimum impedance for matching circuitry at the resonant frequency is computed as:

$$R_{opt} = \frac{1+|\Gamma|^2}{1-|\Gamma|^2}R_A \Longrightarrow R_{opt} = R_A\coth\frac{\pi f}{Q\Delta f} \qquad (3)$$

where R_A is the antenna's impedance's real part at the center frequency. However, higher-order matching circuits may be designed to meet Bode-Fano criteria. The second equation in (3) is obtained by substituting Γ from equation (2) into the first equation in (3) for a zero-order matching circuitry. For example, if the antenna's quality factor is 100 and a 10% rational bandwidth is wanted, the real part of the matching circuit should be 3.28 times the impedance of the antenna: $R_{opt} = 3.28\, R_A$ at the resonant frequency. Increasing the input impedance of the matching circuit decreases the ohmic loss, which indirectly enhances the system's noise figure:

$$P_{loss} = \frac{V_{oc}^2}{2\left(R_r + R_{ohm} + R_{opt}\right)} \tag{4}$$

where $V_{oc} = \mathbf{E}^{inc} \cdot \mathbf{l}_{eff}$ and R_{ohm} represents antenna loss and $\mathbf{l}_{eff}$ is the effective length of the antenna.

Given the preceding explanation, the transmitting and receiving ESA design criteria are contradictory. Therefore, designing two distinct ESAs for the transmitter and receiver seems to be the ideal solution.

III. ESA Input Impedance Measurement Challenges

Due to the intense reactive field around the antenna, traditional methods to shield the feeding cable from the antenna current, such as utilizing Balanced-Unbalanced, balun circuitries, are impractical for ESAs. For example, the electric/magnetic field (in the case of electric/magnetic ESA, such as monopole/loop antenna) couples to the balun structure, and the cable attached to the balun causes erroneous readings [7]. Consequently, the feeding cable and the instrument connected to the feeding cable become components of the radiating structure (Figure 1). As a result, the measured input impedance or radiation pattern is not exclusive to the ESA. Therefore, several attempts have been made to precisely characterize an ESA's input impedance and bandwidth [8, 9].

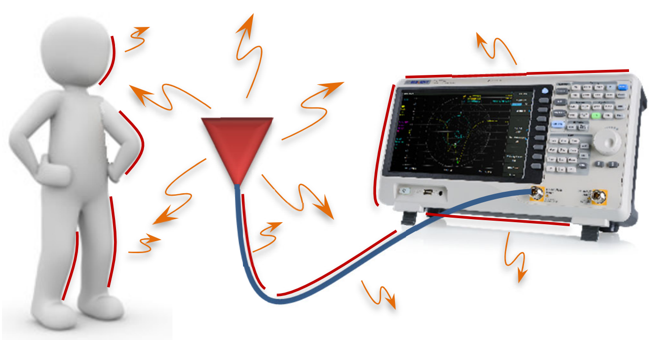

Fig. 1 Due to the strong reactive nearfield of an ESA, the whole measurement apparatus may constitute a component of the radiating structure.

[10] presents a calibration-free measuring approach based on the Singularity Expansion Method [11] (SEM). The AUT is successively connected to an open, short, and matched load. For each load, the antenna's impulse response is determined by excitation with electrostatic discharge and measurement of the radiated field using an oscilloscope.

IV. ESA Radiation Pattern Measurement Challenges

Typically, the radiation pattern of a standalone ESA is the spherical harmonic $Y_1^0(\theta,\varphi)$ or simply $\sin\theta$ associated with TE_{01}/TM_{01} for a magnetic/electric ESA. However, one may need to measure an ESA's radiation pattern and polarization. For example, measuring a circularly polarized ESA's axial ratio is challenging.

One may attach a miniature source (oscillator) to the AUT's port and measure the radiated field inside an anechoic chamber. The source and its battery should be much smaller than the AUT to avoid altering the radiation pattern. In [12], another approach based on frequency mixing is proposed. A tiny low-frequency source and its battery are connected in parallel with a nonlinear device, such as a diode, to the port of the AUT. An external RF source illuminates the antenna via the measuring probe during rotation. A spectrum analyzer samples the probe and measures the offset frequency's magnitude as the radiation pattern's square.

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