A METHOD OF OBTAINING ANTENNA OVERALL EFFICIENCY FROM ANTENNA COMPUTER SIMULATIONS

Marcio SILVA, Jovan LEBARIC, Richard ADLER, and Peter CUTSUMBIS
Naval Postgraduate School - Department of Electrical Engineering
Monterey, California, USA, 93943-5121
lebaric@nps.navy.mil

1. Introduction

This paper presents a method for determining the overall antenna efficiency of antennas simulated using computational electromagnetics software. The antenna efficiency for a transmitting antenna is defined as the ratio of power radiated by the antenna toward the intended target and power delivered to the antenna input terminals. This paper expands this definition by presenting how to obtain the three components of the overall antenna efficiency [2,3] from antenna data obtained by computer simulation. The three components of the antenna overall efficiency are:

- the input efficiency,
- the internal efficiency, and
- the output (beam) efficiency.

The input efficiency is related to the antenna-to-transmission-line-matching problem. The internal efficiency is an indication of thermal losses within the antenna. The output efficiency is a measure of the antenna directivity in the solid angle subtended by the intended targets. The overall antenna efficiency is a product of the three efficiencies defined above, each of which is a function of frequency. The data required for the calculation of the three constituent efficiencies can be obtained from an antenna simulation program such as NEC (Numerical Electromagnetics Code) [1] or its PC variant GNEC.

2. The Overall Antenna Efficiency

The antenna overall efficiency (η), for a specific frequency, is a non-dimensional value greater than zero and less than one, as defined in Equation 1 [4]. The variables involved are the power radiated by the antenna $P_{radiated}$, the power delivered to the antenna $P_{incident}$, and their difference, the power "lost" P_{lost}:

$$\eta = \frac{P_{radiated}}{P_{incident}} = \frac{P_{incident} - P_{loss}}{P_{incident}} = 1 - \frac{P_{loss}}{P_{incident}} \quad (1)$$

The "lost" power P_{lost} has three components as well:

$$P_{loss} = P_{reflected} + P_{dissipated} + P_{off\text{-}target} \quad (2)$$

Where:

- $P_{reflected}$ is the portion of the power reflected off the antenna terminals (because of the antenna mismatch to the feed transmission line) that is lost in transmission line attenuation and transmitter internal resistance.
- $P_{dissipated}$ is the power dissipated as heat within the antenna
- $P_{off\text{-}target}$ is the power radiated by the antenna into solid angle regions that do not include the target.

Substituting Equation 2 into Equation 1, the "generic" formula for antenna efficiency η is obtained:

$$\eta = 1 - \frac{P_{reflected} + P_{dissipated} + P_{off\text{-}target}}{P_{incident}} \quad (3)$$

Figure 1 illustrates the antenna power flow for the above equation.

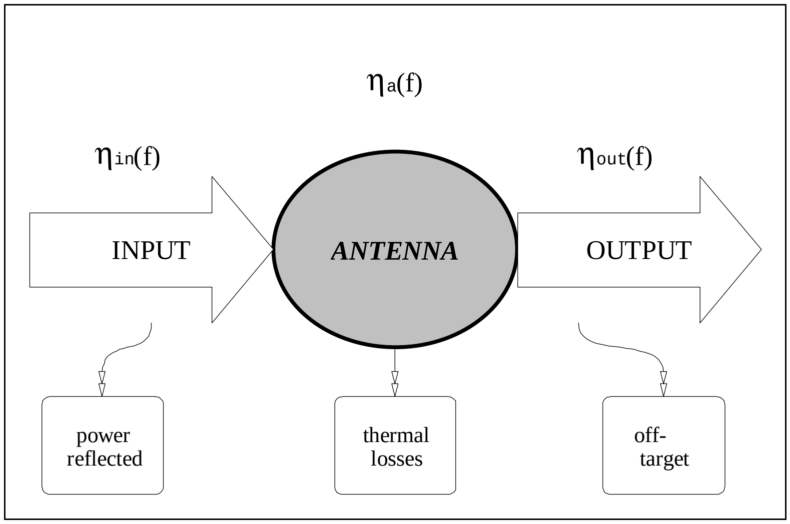

Figure 1 – Antenna Power Flow Illustration

An antenna simulation program typically does not provide the powers in Equation 3 directly. However, the equation for the antenna overall efficiency can be rewritten as a product of three constituent efficiencies that can be determined from the antenna data supplied by the program. The three constituent efficiencies are the input efficiency η_{in}, the antenna internal efficiency η_a, and the antenna output or beam efficiency η_{out}. In order to derive a formula for overall antenna efficiency in terms of these three constituent efficiencies, the antenna can be modeled as three subsystems in series:

- the "input" subsystem with the efficiency η_{in}
- the antenna "internal" subsystem with the efficiency η_a
- the "output" subsystem with the efficiency η_{out}

as shown below.

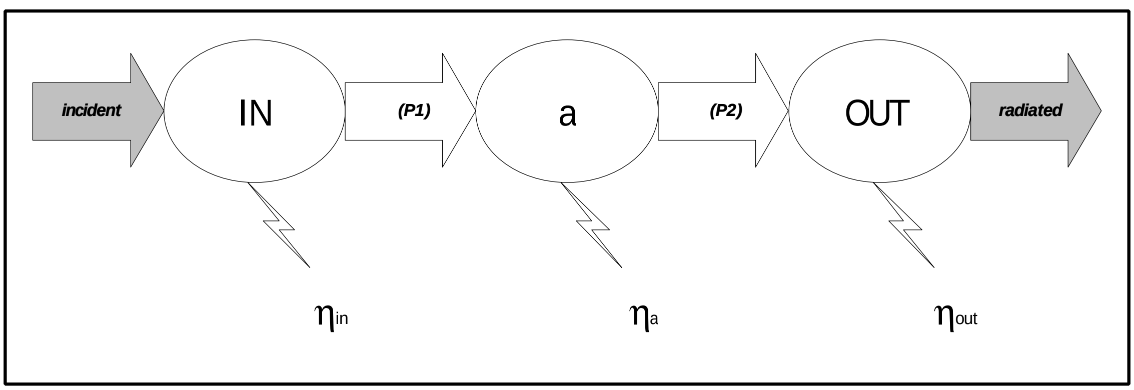

Figure 2 – Antenna Efficiency Model

The efficiencies for each subsystem are:

$$\eta_{in} = \frac{(P1)}{P_{incident}} \qquad \eta_a = \frac{(P2)}{(P1)} \qquad \eta_{out} = \frac{P_{radiated}}{(P2)}$$

Where $P_{incident}$ is the total power delivered to the antenna by the transmitter and transmission line, and $P_{radiated}$ is the power radiated power into the target's solid angle. Multiplying the three efficiencies defined above we obtain (after the cancellations of P1 and P2) the expression for the antenna overall efficiency:

$$\eta = \frac{P_{radiated}}{P_{incident}} = \eta_{out} \cdot \eta_a \cdot \eta_{in} \tag{4}$$

The antenna efficiency is therefore a product of the input efficiency, the internal efficiency, and the output or beam efficiency. We will now discuss how the three efficiencies can be obtained from the antenna simulation data generated by the GNEC code. A similar procedure can be adopted for any antenna simulation program with antenna impedance and antenna gain outputs.

3. The Antenna Input and Internal Efficiencies

Antenna input efficiency η_{in} can be obtained from antenna input impedance data or from antenna VSWR data. Since GNEC provides a text file with antenna input impedance (the real and imaginary parts) as a function of frequency, the values of input impedance can be extracted using a simple parsing program. From extracted values of antenna input impedance, Z(f), and selected transmission line characteristic impedance, Z_0 and, ignoring any antenna tuner circuits between the transmitter and the transmission line, the values of the reflection coefficient at the antenna $\Gamma(f)$ can be calculated.

GNEC antenna simulation ➔ GNEC's text format report of Z(f) ➔
Parsing the input impedance Z(f) text file ➔…
… ➔ table of (Z , f)➔ table of (G , f) ➔ h_{in}(f)

Figure 3 – Process for Determining the Antenna Input Efficiency h_{in}

The calculated reflection coefficient can be used for a "conservative" estimate of the antenna input efficiency $\eta_{in}(f)$:

$$\eta_{in}(f) = 1 - |\Gamma(f)|^2 \qquad (5)$$

GNEC output file includes the antenna internal efficiency data. Therefore, the internal efficiency can be obtained by parsing the GNEC output file directly to extract the internal efficiency data. Note that a properly designed antenna should have a very high (close to 1) internal efficiency. Indeed, of the three constituent efficiencies, the internal efficiency is typically the highest and can be approximated as equal to 1.

4. The Antenna Output Efficiency

The antenna output efficiency or beam efficiency [3] is a function of the antenna directivity. The η_{out} is defined as the ratio of the radiated power in the solid angle containing the target as viewed from the antenna, P_{target}, to the total power radiated by the antenna, P_{total} [2,3,4]. The antenna gain can be used to determine the antenna output efficiency, instead of using powers or directivity, when the internal efficiency is close to 1. This is accomplished by forming the ratio of the antenna average gain for the entire 4π steradian space (or for the 2π steradian space for antennas above an infinite ground plane), and the antenna average gain for the solid angle defined as the "target sector":

$$\eta_{out} = \frac{P_{target}}{P_{total}} = \frac{G_{\Omega}}{G_0} \qquad (6)$$

To speed up calculations for antennas with one or more planes of symmetry, GNEC can calculate the average gain by integrating the radiated power over a sector of space determined by the range of elevation and azimuth angles (which define a solid angle). The result is then multiplied by 4π and divided by the solid angle of integration to obtain the average gain. The integration has to be performed twice, once for the average gain G_0 and once for the target sector average gain G_{Ω} (the ranges of integration are different). Note that the average gain G_0 for a lossless antenna should be 1.0 if the antenna is in free space and 2.0 over perfectly conducting ground. If the values of average gain from GNEC are not 1.0 or 2.0, the root-mean-square error of G_0 is an indication of modeling inaccuracy. The procedure for determining the antenna output (beam) efficiency from the GNEC simulation is presented in the Figure 4.

GNEC simulation➔ output report (.nou file) ➔ parsing the report➔…
…➔ obtain G_W, its solid angle a, and G_o as a function of frequency➔ …
…➔ compute G_W(f) and the RMS_{error} of the G_o(f) ➔ table of (h_{out} , f) ➔ h_{out}(f)

Figure 4 – Procedure for Deriving the Antenna Output Efficiency (h_{out})

6. Example

This section presents an example of the use of the method. Two copper wire dipoles (horizontal and vertical) 50 cm long and 10 mm in diameter were simulated in free-space from 200 to 400 MHz using GNEC [1]. The pre-defined solid angle (target) was chosen as $\pm 45^{o}$ in azimuth and elevation and a 50 Ω feed impedance was used in input efficiency calculations. The results of the simulation for overall efficiency are presented in Figure 5 and in Table 1.

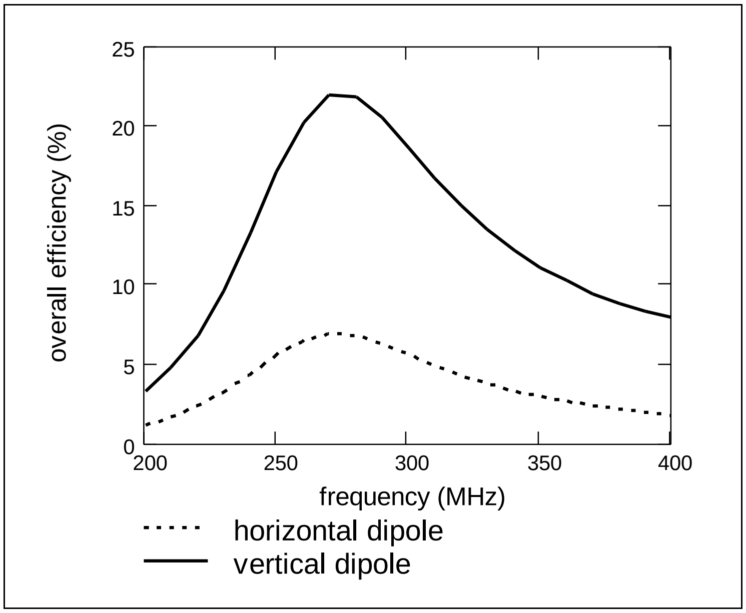

Figure 5 – GNEC Simulation Results

	Vertical Dipole	Horizontal Dipole
Overall Efficiency Average in the Band	12.9 %	3.8 %
Lower cutoff Frequency	220 MHz	220 MHz
Upper Cutoff Frequency	400 MHz	400 MHz
Overall Efficiency at the center frequency	21.9 %	6.9 %

Table 1 – Example of the Antenna Overall Efficiency Analysis

As expected, the vertical dipole has higher overall efficiency because its pattern is omni-directional in azimuth, which directly affects the beam efficiency. Also as expected, both dipoles have the same bandwidth, based on ½ of the respective average efficiencies.

7. References

1. Burke, G., *Numerical Electromagnetics Code – Part I: User's Manual*, Lawrence Livermore National Laboratory, January 1992.
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3. Balanis, C., *Antenna Theory: Analysis and Design*, 2nd ed., John Wiley & Sons, 1997, ISBN 0471592684
4. Miller, C., *Low Band VHF antenna Design for the Grumman EA-6B Aircraft*, Master's Thesis, Naval Postgraduate School, Monterey, California, USA, June 1999.