SIMPLE MODELS FOR EXPLAINING ANTENNA RECEPTION AND SCATTERING IN THE TIME DOMAIN

Glenn S. Smith

School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250, USA
Email: glenn.smith@ece.gatech.edu

ABSTRACT

With modern numerical methods, the accurate analysis of wire antennas is routine; however, these methods do not offer physical models for interpreting the results. It is the premise of this paper that the simplest physical model for understanding the radiation and reception by wire antennas is one based in the time domain. In an earlier paper, a methodology was presented for treating transmitting antennas, and in this paper it is extended to treat receiving/scattering antennas. First, an expression is obtained for the reception/scattering by a basic traveling-wave element; then, more complicated antennas are viewed as combinations of these elements.

OVERVIEW

With modern numerical methods, the analysis of simple wire antennas is routine. Accurate results can be obtained in both the time and frequency domains using several different methods, e.g., the method of moments (MoM) and the finite-difference time-domain (FDTD) method. While these methods provide accurate numerical results, they do not offer physical models for interpreting these results. In other words, they do not offer the user a simple approach for describing and cataloging the phenomena associated with radiation. Often, very simple models can be used for this purpose. At this point, an example might be helpful. We still use sinusoidal current on a dipole as a physical model for understanding time-harmonic radiation from this antenna, even though we know that the results calculated from this current, e.g., input impedance, are not nearly as accurate as those obtained from the numerical methods.

It is the premise of this paper, and earlier work by the author [1-3], that the simplest physical model for understanding the radiation and reception by wire antennas is one based in the time domain, viz., excitation of an antenna with a pulse. This approach is particularly relevant for instruction, because the time-domain explanation for the radiation from a wire antenna (a dipole) complements the traditional time-domain explanation for propagation on a transmission line (parallel wire line), which is one of the first electrodynamics problems presented to students.

In an earlier paper, a method was presented for obtaining the electromagnetic field of simple wire transmitting antennas with a general, assumed distribution of current [2]. An analytic expression was first obtained for the field of a basic traveling-wave element. Then a more complicated antenna was viewed as a combination of basic traveling-wave elements, and the electromagnetic field of the antenna was obtained as a superposition of the fields of the elements. When the current/charge was a narrow pulse in time, the field at a point in space was shown to be associated with a traveling wave of current passing a particular point on the antenna at an earlier time. Using this observation, a simple analogy was constructed between the radiation from these antennas and the radiation from a moving point charge (bremsstrahlung and synchrotron radiation).

In this paper, the method will be extended to treat the reception and scattering of an electromagnetic plane wave by simple wire antennas. As for the earlier paper, the purpose is instruction, so the emphasis is on the physical aspects of the problem and the insight that can be gained by studying graphical results for the current and field. First, the basic traveling-wave element is analyzed as a receiving antenna. Expressions are obtained for the current/charge on the element and the scattered electromagnetic field of the element (both the near field and the far field). Next, the dipole receiving antenna is analyzed as a superposition of four basic traveling-wave elements, and expressions for the current/charge on the dipole and scattered electromagnetic field are obtained. The relationship between the performance of the dipole antenna on reception and on transmission is also examined. Finally, the scattering from a straight wire (dipole without a load) is analyzed, again by treating the structure as a superposition of basic traveling-wave elements. The phenomenon of resonant scattering is explained, and its importance in determining the back scattering cross section of the wire is discussed.

THE BASIC TRAVELING-WAVE ELEMENT

As stated above, the building block for the method is the basic traveling-wave element; all other structures are analyzed in terms of this unit. Fig. 1 shows schematic drawings for this element; it is aligned with the z axis and is of length h. When the element is transmitting, as in Fig. 1a, there is a source of current, $I_s(t)$, at the bottom and a perfect termination at the top, and when the element is receiving, as in Fig. 1b, there are perfect terminations at both ends. For the *transmitting element*, a traveling wave of current (a pulse) leaves the source and propagates along the element at the speed of light, c, until it reaches the termination, where it is totally absorbed. Thus, the current distribution along the element is

$$I(z,t) = I_s(t - z/c)\,. \quad (1)$$

For the *receiving element*, the electric field, $\vec{E}^i$, of the normally incident plane wave acts as an incremental source of current, i.e., $dI_s = \Upsilon E_z^i dz$, at every point along the element. The resulting current distribution is then

$$I(z,t) = c\Upsilon\left\{2\xi^i(t) - \xi^i(t - z/c) - \xi^i[t - (h - z)/c]\right\}, \quad (2)$$

where Υ is a constant with the units of siemens, and ξ^i is the integral of the incident electric field:

$$\xi^i(t) = \int_{t'=-\infty}^{t} E^i(t')dt'\,. \quad (3)$$

Analytical expressions for the complete electromagnetic field, as well as simpler asymptotic expressions for the far-zone field, are available for both cases (transmission and reception) [2, 3].

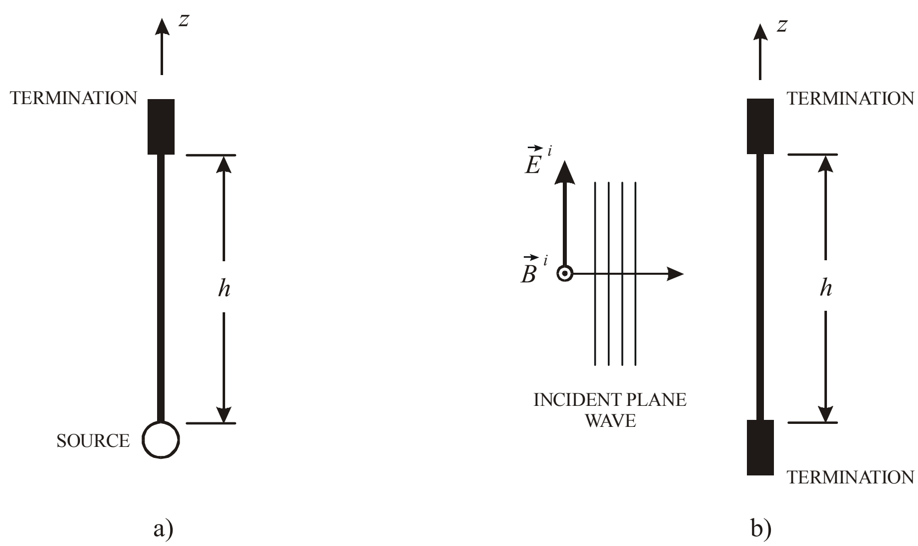

Fig. 1. Geometry for the basic traveling-wave element: a) as a transmitting antenna, and b) as a receiving antenna.

AN EXAMPLE: THE DIPOLE RECEIVING ANTENNA

Because of the limited space, the method can be illustrated by only one example: the dipole receiving antenna with a matched load shown in Fig. 2a. This antenna can be modeled using the four basic traveling-wave elements shown in Fig. 2b: the two receiving elements, 1 and 3, and the two transmitting elements, 2 and 4, that account for the reflection of the current of the receiving elements at the open ends of the dipole. An electromagnetic quantity for the dipole, e.g.

the current distribution or the field, is computed by superimposing the corresponding quantities for the four elements. Thus, the current distribution on the top arm of the dipole, $0 \le z \le h$, is

$$I(z,t) = c\Upsilon \left\{ 2\xi^i(t) - \xi^i(t - z/c) - 2\xi^i\left[t + (z-h)/c\right] + \xi^i\left[t + (z-2h)/c\right] \right\}. \quad (4)$$

For illustrative purposes, the incident electric field is chosen to be a differentiated Gaussian pulse in time:

$$E^i(t) = -\sqrt{2}e^{1/2}E_o(t/\tau)e^{-(t/\tau)^2}, \quad (5)$$

with the characteristic time, τ, for the pulse being $\tau/\tau_a = 0.076$, where $\tau_a = h/c$ is the time for light to travel the length of the dipole's arm.

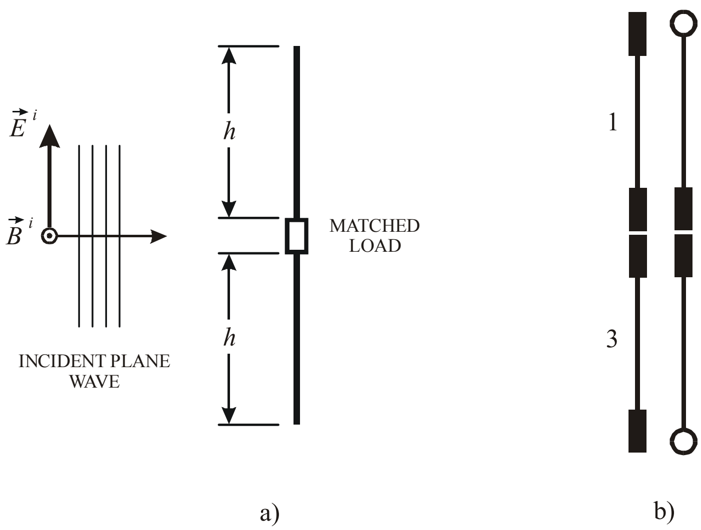

Fig. 2. a) Dipole receiving antenna, and b) represented by a group of four basic traveling-wave elements.

Fig. 3 shows the current (4) on the top arm of the dipole as a function of the normalized time, t/τ_a, and the normalized position, z/h. This graph is a series of one-dimensional plots (current versus time); each plot is for a fixed spatial position. The plots are vertically displaced by an amount proportional to the position to show the progression of the signal along the element. When the incident wave reaches the dipole, at around $t/\tau_a = 0$, a uniform current is produced with the amplitude $+2$. At the same time, pulses of current with the amplitudes -2 and -1 leave the top end and the bottom end of the arm, respectively. The former travels down the arm of the dipole at the speed of light until it reaches the load, where it is totally absorbed. The latter travels up the arm of the dipole at the speed of light until it reaches the open end where it is totally reflected. It then travels down the arm of the dipole at the speed of light until it reaches the load, where it is also totally absorbed.

Fig. 4 shows the scattered electric field surrounding the dipole receiving antenna at three times: $t/\tau_a = 0.5$, 1.5, and 2.5. These graphs were produced by summing the fields of the four basic traveling-wave elements shown in Fig. 2b. Here, the logarithm of the magnitude of the electric field is plotted on a gray scale, and the range of values displayed is 100:1. In Fig. 4a, three spherical wavefronts are evident: W_1 and W_1' centered on the ends of the dipole, and W_2 centered on the load. These wavefronts originated when the pulses of current, shown in Fig. 3, left the ends of the dipole and the load at $t/\tau_a = 0.0$. Away from the ends of the dipole, there is a cylindrical wavefront W_C, which is caused by the superposition of the spherical wavefronts of the incremental sources, dI_s, distributed along the element, as in Huygens' principle. In Fig. 4b, the pulses of current that left the load at $t/\tau_a = 0.0$ have reached the open ends of the dipole and have been reflected from the open ends creating the spherical wavefronts W_3 and W_3' (at $t/\tau_a = 1.0$). In addition, the pulses of current from the ends of the dipole have reached the load and have been absorbed creating the spherical wavefront W_4 (at $t/\tau_a = 1.0$). Finally, as shown in Fig. 4c, the pulses of current that were reflected at the open ends of the dipole at $t/\tau_a = 1.0$ have reached the load and have been absorbed creating the spherical wavefront W_5 (at $t/\tau_a = 2.0$). After this time, no additional wavefronts are produced, and the existing wavefronts expand outwardly at the speed of light.

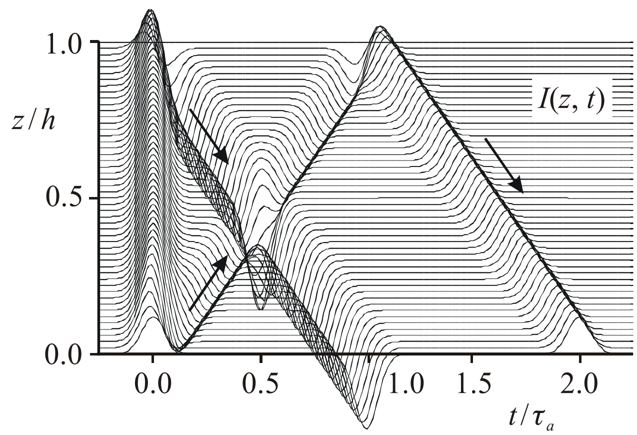

Fig. 3. Development of the current along the top arm of the dipole receiving antenna.

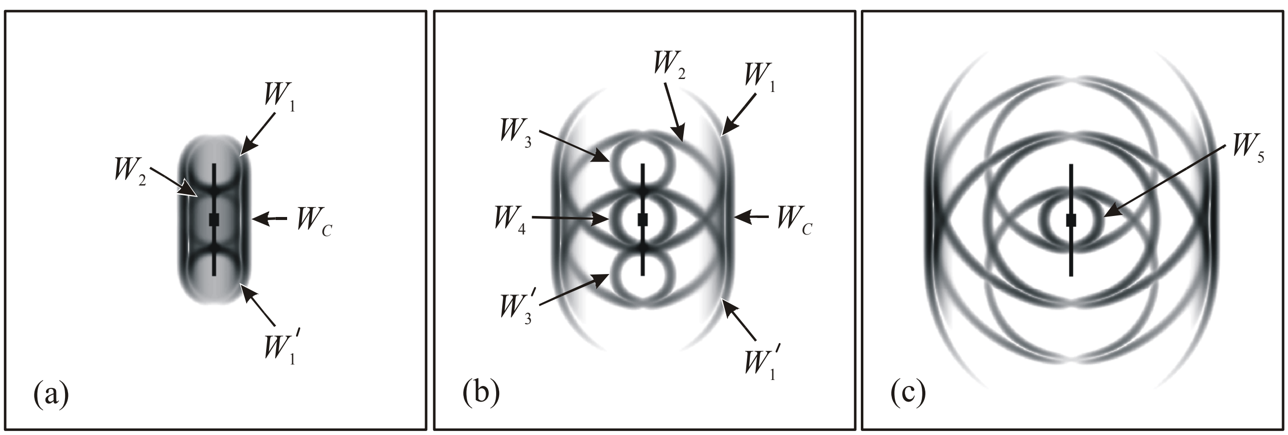

Fig. 4. Magnitude of the scattered electric field surrounding the dipole receiving antenna at three times: a) $t/\tau_a = 0.5$, b) $t/\tau_a = 1.5$, and c) $t/\tau_a = 2.5$

ACKNOWLEDGEMENT

The author is grateful for the support provided by the John Pippin Chair in Electromagnetics that furthered this study.

REFERENCES

[1] G.S. Smith, *An Introduction to Classical Electromagnetic Radiation*, Cambridge: Cambridge Univ. Press, 1997.
[2] G.S. Smith, "Teaching antenna radiation from a time-domain perspective," *Am. J. Phys.* vol. 69, pp. 288-300, March 2001.
[3] G.S. Smith, "Teaching antenna reception and scattering from a time-domain perspective," to be published in *Am. J. Phys.,* 2002.