ADAPTIVE ANTENNA FOR GROUND PENETRATING RADAR

A.A. Lestari, A.G. Yarovoy, L.P. Ligthart
International Research Centre for Telecommunications-Transmission and Radar
Faculty of Information Technology and Systems
Delft University of Technology
Mekelweg 4, 2628 CD Delft, The Netherlands
a.lestari@its.tudelft.nl a.yarovoy@its.tudelft.nl l.p.ligthart@its.tudelft.nl

ABSTRACT

In this paper a concept in designing an adaptive antenna for ground penetrating radar is presented along with its preliminary simulation results. The antenna considered is an array of wire dipoles arranged to form a wire bow-tie antenna. The input impedance of bow-tie antennas is known to be dependent mostly on their flare angle. For antennas situated on the ground, maximal radiation into the ground can be obtained if their input impedance is optimized with respect to the ground impedance. Bow-tie antennas can therefore be optimized to radiate maximum power into a certain type of ground by adjusting their flare angle. In a first approach, without matching the antenna to feeding line, it is found numerically that there exists a certain angle at which this antenna radiates maximal power into the ground for all types of ground. In this case, adaptation to the ground by varying flare angle is still not fully realized. In our future research, another approach will be used, in which the antenna is matched to the feeding line within the whole spectrum of input pulse in order to obtain a more effective adaptation to the ground.

Key words: GPR, adaptive antenna, bow-tie antenna, wire dipole, array antenna, moment method, NEC-code.

INTRODUCTION

Antenna plays a key role in most of ground penetrating radar (GPR) systems. The general performance of GPRs using impulse radar for buried object detection depends significantly on the ability of the antenna to radiate impulses into the ground with a minimal degree of distortion and loss. It is commonly known that impulse-GPR antennas should be able to produce minimal late-time ringing caused by internal reflections in order to avoid masking of targets. Resistive loading and absorbers have been widely used to overcome internal reflections at the expense of radiation efficiency. An alternative technique which allows high radiation efficiency using a combination of slots and absorbers has been proposed (Lestari, A.A., Yarovoy, A.G., Ligthart L.P., 2000). Furthermore, due to their ultra-wideband property GPR antennas are notably sensitive to external electromagnetic interference. To deal with this problem, shielding is usually employed by sacrificing the antenna bandwidth. Problems related to reflections at the air-ground interface also have to be addressed, meaning that dielectric materials are generally utilized to obtain a transition between the free space and ground for reducing reflections at the interface. However, the unavailability of materials having a variable dielectric constant limits this approach since the electrical property of ground varies considerably. In this paper we concentrate on the problem of obtaining optimal transmission of radiated energy by a single antenna into various types of ground with different electrical properties.

It is widely understood that antenna performance can be seriously affected by the presence of the ground in the neighborhood of the antenna. For GPR antennas the situation can be more difficult as they are usually situated in a close vicinity of the ground. Since the electrical property (dielectric constant and conductivity of various types of ground) ranges considerably, the difficulty lies in having an antenna which would be able to radiated maximal energy into the ground for all ground types. For example, an antenna designed to optimally radiate into sand might degrade when operated on clay, and vise versa. Therefore, from a practical point of view it is desirable to have an antenna which is adaptive to any ground type in the sense that depending on the ground type something in the antenna can be externally adjusted in order to obtain maximal radiation into the ground. In our opinion, adaptation to the ground should be made at the feedpoint (i.e., matching the antenna impedance with respect to feeding line) and inside the antenna (i.e., matching the antenna impedance with respect to ground impedance), as well as in the front of the antenna (in order to further reduce ground reflections). To obtain a well-functioning adaptive GPR antenna, those three matching aspects should be present within the whole frequency spectrum of input pulse. In this paper we discuss only the second aspect, i.e., matching the antenna impedance with respect to ground impedance. The other two are the topics of our future research.

WIRE BOW-TIE ANTENNA

Solid metal bow-tie antennas are commonly employed in GPR due to their reasonable ultra-wideband property and simplicity. The input impedance of sufficiently long bow-tie antennas, which are the limiting case of biconical antennas, is known to be frequency independent and depends only on their flare angle (Carrel, R.L., 1958). This property is attractive as the starting point in designing an adaptive antenna for GPR. If the bow-tie is constructed to have a variable flare angle, a value of input impedance that is optimal with respect to the intrinsic impedance of the ground can be obtained by varying the flare angle. In this case the bow-tie is optimally coupled to the ground and radiates maximal energy into the ground with small ringing.

The solid metal bow-tie antenna is here approximated by a number of wires in order to make the changing of flare angle more easily realizable in practice. An example of this wire bow-tie consisting of 6 straight wires on each arm is shown in Figure 1. The wire elements have equal lengths and spacing and are connected mutually at the feedpoint. It can be seen that this antenna is basically an array of identical straight wire dipoles having a common feedpoint and equal angular separation. This geometry simplifies the analysis since the antenna can be treated as simply a number of interconnected dipoles. In addition, it is also attractive because resistive loading or microwave absorbing materials can be more easily applied at the ends of each dipole element in order to suppress internal reflections.

The antenna here is expected to be used with a 0.8-ns monocycle pulse generator. The input pulse, shown in Figure 2, is a 0.8-ns monocycle sampled directly from the generator and transformed into the frequency domain using the Fast Fourier Transform (FFT). As it can be seen, the radiated energy concentrates at around 1 GHz and becomes insignificant for frequencies above 3 GHz.

Intuitively, it can be said that if the wire bow-tie consists of many elements it would approximate a solid metal bow-tie better. However, the number of elements should in practice be limited because too many elements are not practical if small flare angles are required. The main model of the wire bow-tie reported here consists of 6 identical dipole elements having a half-length of 0.25 m which allows a sufficient temporal separation between the 0.8-ns monocycle and its end reflection. The wires are chosen to be very thin with a radius of 0.5 mm in order to make small flare angles still realizable.

NUMERICAL MODEL

To analyze the antenna we use the method of moments by means of the Numerical Electromagnetics Code NEC-2 of the Lawrence Livermore Laboratory. The objective of the analysis is to determine the optimal flare angle for each ground type, which in time domain would result in the highest maximum amplitude of the radiated pulse in the ground. In our work we assume that the antenna will be long enough to allow separation in time between the main pulse and reflections at the antenna ends, which can be suppressed by means of loading. Thus, we concentrate only on the main pulse and disregard the reflections. Calculations of input impedance and radiated fields of the antenna situated in the free space and on the ground are carried out in the frequency domain. The time domain response of the antenna is obtained using the inverse Fast Fourier Transform (IFFT) according to

$$E(t) = \mathrm{IFFT}\,[E(w) \times V_{in}(w) \times \{1+G(w)\}] \qquad (1)$$

where $E(t)$, $E(w)$, $V_{in}(w)$ and $G(w)$ are the radiated field in time domain, the radiated field in the frequency domain, the input pulse used, and the reflection coefficient at the antenna terminal, respectively. The reflection coefficient is calculated as

$$G(w)=[Z_i(w) - Z_0] / [Z_i(w)+Z_0] \qquad (2)$$

where $Z_i(w)$ is the antenna input impedance and Z_0 is the transmission line's characteristic impedance. The factor $1+G(w)$ is included in (1) in order to obtain the actual input voltage at the antenna's terminal when a transmission line with a characteristic impedance Z_0 is used as feeding line.

Calculations in the frequency domain are carried out from 50 MHz up to 5 GHz with a 50-MHz step giving in total 100 frequency-domain data. For the IFFT purposes these data are extended up to 1000 data, resulting in a 50-GHz upper limit. In time domain the 50-MHz frequency step determines a 20-ns time window and the 50-GHz upper limit fixes a 0.02-ns time step, which for the dimension of the antenna and the distance to the observation point are still acceptable. In this investigation we only consider the situation when the antenna is in contact with the ground in order to avoid complex interactions between antenna and ground if the antenna is elevated. However, unfortunately when the antenna is too close to the ground NEC-2 gives inaccurate field calculations for distances smaller than 1 wavelength. Hence, the observation point cannot be located near the air-ground interface because the input pulse possesses significant low frequency contents. As a consequence of this, the observation point is located in the ground, 2 meters below the feedpoint. At this distance, for most of the frequencies within the 50 MHz - 5 GHz range

NEC-2 uses Norton's asymptotic approximations for ground fields, which are less accurate than numerical evaluation of Sommerfeld integrals. However, since in the ground we are interested mainly in the amplitude of the transmitted pulse only, this approach is still deemed to be acceptable.

NUMERICAL ANALYSIS

The input impedance of this antenna in the free space as a function of flare angle at 1 GHz is shown in Figure 3. It can be seen that the input resistance is maximal at a very small flare angle and decreases almost linearly as the flare angle increases while the input reactance remains relatively constant. The resistance can be varied up to more than 180 Ohms within the 180-degree range of the flare angle. This result is encouraging since it shows the possibility to vary the input impedance to a large extent by only changing the flare angle.

The time domain response of the 6-element wire bow-tie is depicted in Figure 4, for cases where the flare angle is 10° or 90°. The antenna radiates into two different media representing clay (ε_r=16, σ=30 mS/m) and sand (ε_r=4, σ=4 mS/m). Empirical values of dielectric constant (ε_r) and conductivity (σ) of various types of soil considered here are obtained from literature (Baum, C.E., 1999). In Figure 4 it can be seen that the main pulse still preserves its shape in both ground types. The end reflection, which possesses significant high frequency contents, is still pronounced in sand but decays more rapidly in clay. The magnitude of the main pulse in clay is smaller than in sand due to a larger effective propagation path and larger ohmic losses. It can also be seen that the amplitude of the radiated pulse is obviously affected by the change in flare angle. This is an important fact since we are interested in finding the optimal value of flare angle for various values of ε_r and σ that would give the highest maximum amplitude of the radiated pulse in the ground. For this purpose we take an additional set of ε_r and σ representing another type of clay (ε_r=25 and σ=60 mS/m).

Variation of the normalized maximum amplitude of the radiated pulse in the ground as functions of flare angle for the three ground types is plotted in Figure 5. It is obvious that in all three cases the antenna has an optimal flare angle of around 20 degrees, at which radiation is maximal for the three types of ground. Here the optimal flare angle varies only marginally for different ground types because in this case the antenna is still not matched to the feeding line. This results in non-negligible reflections at the feedpoint within the whole spectrum of the input pulse for all flare angles. As a result, for a certain ground type, the factor $1+G(w)$ in (1) varies only slightly with different flare angles, as shown in Figure 6. This in turn causes the optimal flare angle to remain more or less at the same value for different types of ground. This situation is not yet optimal since adaptation to the ground by varying the flare angle is not fully realized. In our future research we will investigate the situation where for a certain flare angle the antenna is matched to the feeding line (e.g., by using a particular frequency independent matching device). In this case, the factor $1+G(w)$ would have a wider variation and accordingly for different ground types the strongest radiation would occur at different flare angles. Thus, adaptation to the ground by varying the flare angle would be more effectively realized.

If for a fixed flare angle the number of elements is varied the antenna shows a behavior as depicted in Figure 7. We can see that the maximum amplitude of the radiated pulse increases asymptotically as number of elements increases. In the case of a 10°-flare angle, the amplitude reaches more or less its maximum value at about 14 elements. In this situation the wire bow-tie approaches a solid metal bow-tie. As it can be seen, 9 elements already result in about 90% of the maximum amplitude of a solid bow-tie. Thus, without using too many elements, the wire bowtie radiates already almost as strong as a solid bowtie. This result illustrates the way in which a decision regarding the number of elements to be used can be made.

CONCLUSIONS

A concept in designing an adaptive antenna for ground penetrating radar is introduced. To elucidate this concept, a numerical analysis of a wire bow-tie antenna situated on the air-ground interface is carried out. The analysis makes use of the method of moments by employing the Numerical Electromagnetics Code NEC-2. The time-domain radiated pulse in the ground is computed from the calculated frequency-domain fields using the inverse Fast Fourier Transform. In the case of the antenna is not matched to the feeding line, it is found that for various ground types the antenna radiates maximum power into the ground at a certain flare angle. In this situation, adaptation to the ground by varying flare angle is not fully realized. In our future research the analysis will be made for the case of the antenna is matched to the feeding line within the whole spectrum of input pulse. This approach should improve the adaptation to the ground by means of variation in flare angle.

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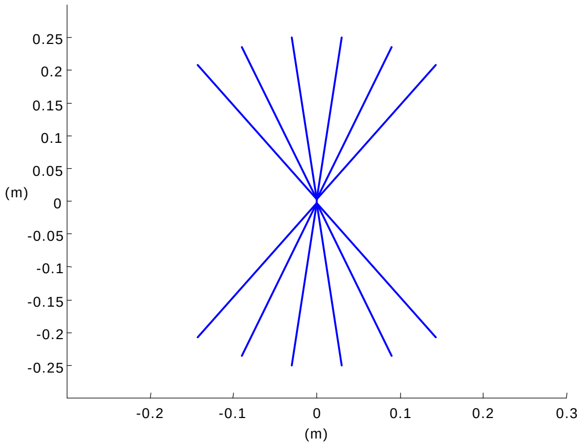
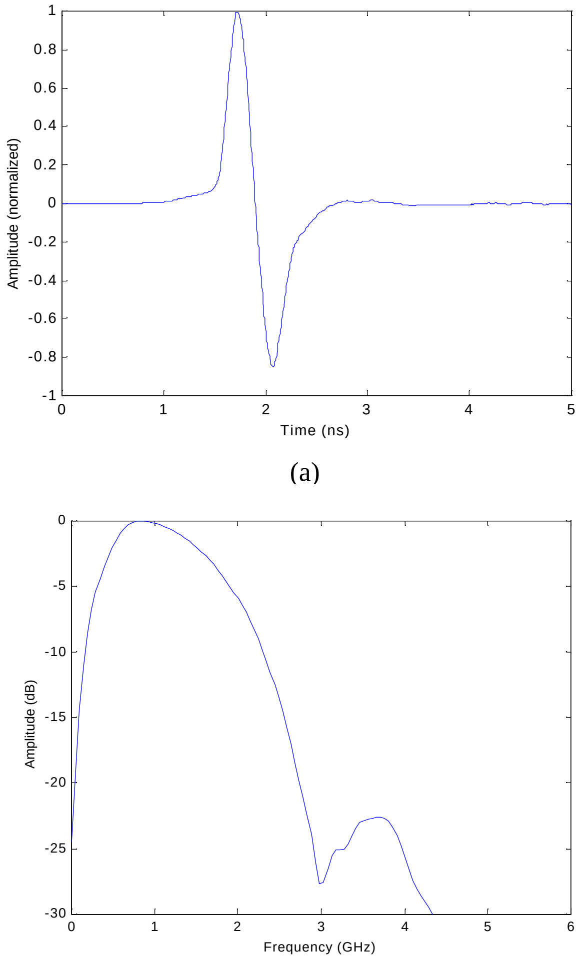


Figure 1: A 6-element wire bow-tie antenna.



(a)

(b)

Figure 2: Input pulse used: a 0.8-ns monocycle (a) and its frequency spectrum (b).

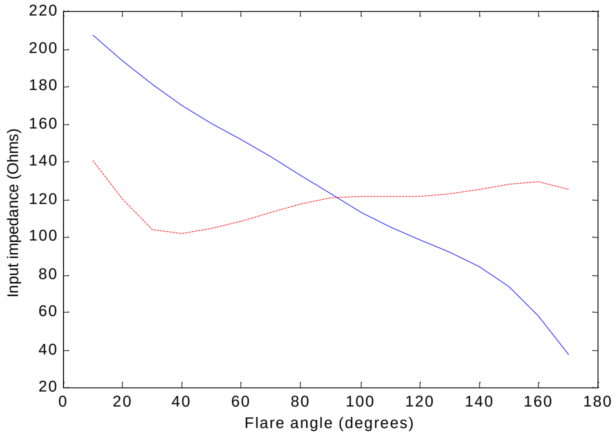
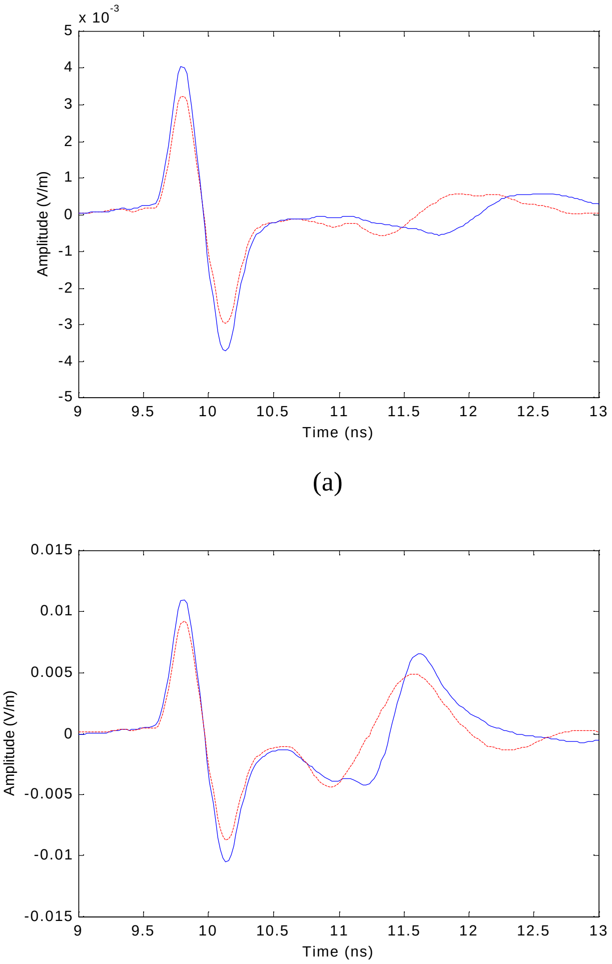


Figure 3: Input impedance of a wire bow-tie antenna in the free space as a function of flare angle at 1 GHz (resistance: solid/blue line, reactance: dashed/red line). The antenna consists of 6 identical dipole elements having a half-length of 0.25 m.



(a)

(b)

Figure 4: Time-domain electric fields of the 6-element wire bow-tie antenna in the ground 2 meters below the feedpoint, when the flare angle is 10° (solid/blue line) and 90° (dashed/red line). The antenna is situated on clay (ε_r=16, σ=30 mS/m) (a) and sand (ε_r=4, σ=4 mS/m) (b).

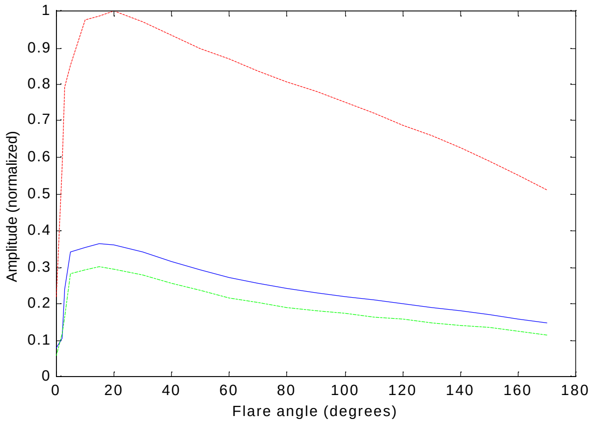


Figure 5: Normalized maximum amplitude of the main pulse radiated into the ground from the 6-element wire bow-tie as functions of flare angle when the ground type is sand (ε_r=4, σ=4 mS/m, dashed/red line), clay #1 (ε_r=16, σ=30 mS/m, solid/blue line) and clay #2 (ε_r=25, σ=60 mS/m, dash-dotted/green line).

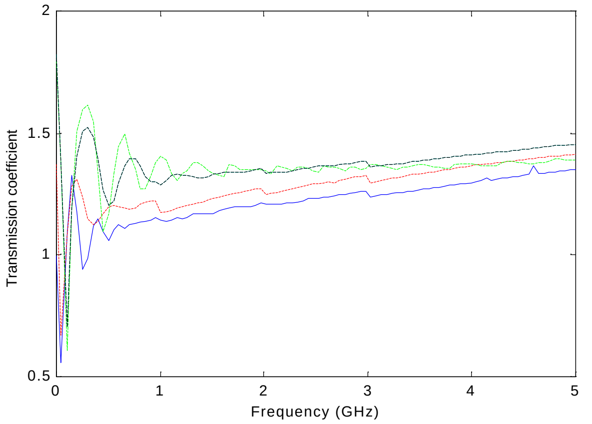


Figure 6: Absolute value of the transmission coefficient {*1+G(w)*} as functions of frequency, when the antenna is: on sand and flare angle=90° (dotted/black line), on sand and flare angle=10° (dash-dotted/green line), on clay #1 and flare angle=90° (dashed/red line), on clay #1 and flare angle=10° (solid/blue line). The characteristic impedance of feeding line is assumed to be 50 Ohms.

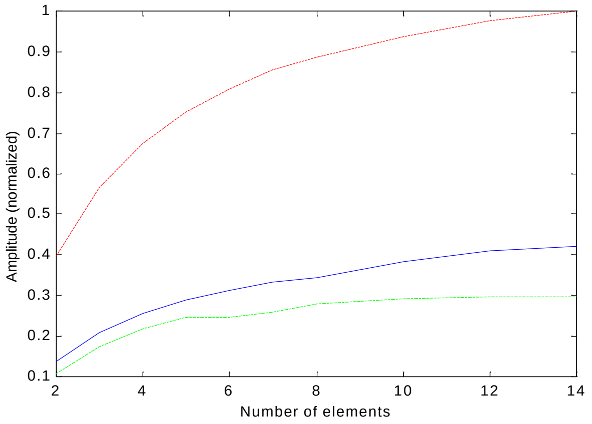


Figure 7: Normalized maximum amplitude of the pulse radiated from the wire bow-tie into the ground as functions of number of elements when the ground type is sand (ε_r=4, σ=4 mS/m, dashed/red line), clay #1 (ε_r=16, σ=30 mS/m, solid/blue line) and clay #2 (ε_r=25, σ=60 mS/m, dash-dotted/green line). The flare angle is fixed to be 10°.