MODELING AND SIMULATION OF A DIPOLE ANTENNA FOR UWB APPLICATIONS USING EQUIVALENT SPICE CIRCUITS[1]

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ABSTRACT

This paper presents results of research on modeling and simulation of a simple λ/2 dipole antenna for wideband and ultra wideband applications. Although dipole and monopole antennas are not necessarily the best candidate for UWB antennas, they are easy to manufacture and low-cost. The performance penalty in frequency domain UWB systems may be quite acceptable.

The simple and intuitive electrical equivalent schematic of the dipole antenna presented here can be used in any SPICE simulator and yields fast and qualitative good results without the need for electromagnetic simulation tools.

In order to validate the model, both frequency domain and time measurements were performed in the laboratory on a system comprising two λ/2 dipoles with a resonant frequency f_0 = 1.25 GHz in a line-of-sight arrangement.

The simplified model presented here yields qualitatively good results in a limited frequency band (0 – 1.2 f_0) and gives acceptable results when used in the time domain to assess UWB pulse distortion.

1. INTRODUCTION

In a UWB communication system, the antennas act as major pulse-shaping filters. Bandwidth limitations of the antennas show up as a frequency-domain transfer function and as time-domain distortion of the received pulse, requiring a more advanced detection mechanism in the UWB receiver.

Research conducted at CSEM has shown the dominant influence of the antennas on the measured overall transfer function from transmitter to receiver. Each antenna has its own particular signature in both time and frequency domain. For a λ/2 dipole, the frequency domain signature resembles that of a bandpasss function around the resonant frequency f_0.

Section 2 presents an equivalent narrow-band SPICE model of the half wavelength dipole.

In section 3, this model is validated using both time and frequency domain measurements using a TDR signal generator.

Section 4 shows simulation and measurement results for a real monocycle UWB signal applied to the dipole antennas.

Section 5 presents conclusions and topics for further investigations.

2. EQUIVALENT SPICE ANTENNA MODEL

Figure 1 shows the wire dipole that was used for the measurements. It is made out of 1 mm silver-plated copper wire. Dipole length is 115 mm.

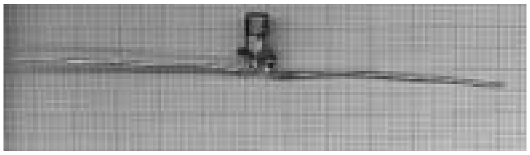

Figure -1: The λ/2 dipole antenna with resonant frequency f_0 = 1250 MHz.

Its reflection coefficient S11 when mounted on a tripod 1.4 m (6 λ) above the floor as measured on a HP8753D network analyzer is shown in Figure-2.

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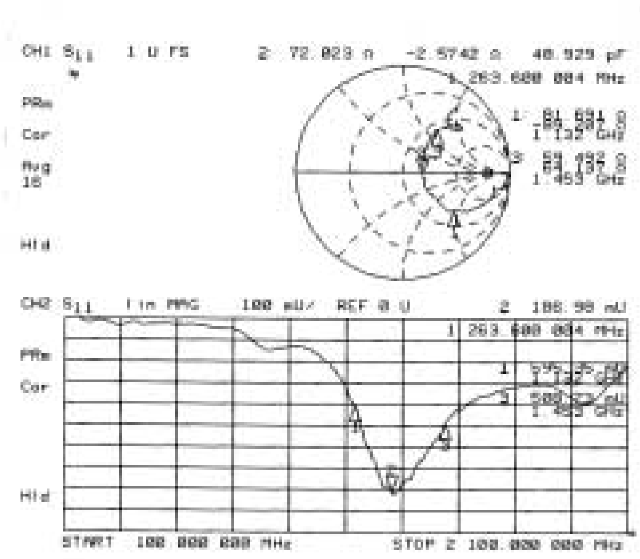

Figure -2: S11 of the λ/2 dipole antenna at a height of 1.4 m above the floor.

A simple and intuitive SPICE model for the half wavelength dipole antenna based upon the impedance measurements is shown in Figure-3. The antenna is modeled by the series resonant circuit constituted by inductance L_1, capacitance C_1, the radiation resistance R_r and the loss resistance $R_{l.}$. This circuit has its minimum impedance (R_r + R_l) at the resonant frequency f_0. The equivalent antenna impedance Z_a, resonant frequency f_0 and quality factor Q can be written as

$$Z_a = \frac{V}{I} = (R_r + R_l)\left(1 + j\omega \frac{L}{(R_r + R_l)} - j\frac{1}{\omega(R_r + R_l)C}\right) \tag{1}$$

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

$$Q = \frac{\omega_0 L}{R_r + R_l} = \frac{1}{R_r + R_l}\sqrt{\frac{L}{C}} \tag{3}$$

The major assumptions of this simplified model are the constant radiation resistance R_r and loss resistance R_l.

The power “dissipated” in the radiation resistance corresponds to the actually radiated power. The source V_{RX} represents the received voltage due to external electromagnetic waves. Note that this simple series-resonant circuit model takes only into account the 1st antenna resonance around f_0. Adding capacitor C_2 improves the model performance above f_0. This model is applicable for frequencies below and around the resonant frequency f_0 (typically DC – 1.2 f_0). Resistor R_1 (1 MΩ) is only present to ensure DC convergence in SPICE. Voltage source V_{TX} and resistor R_s (50 Ω) represent the transmitter.

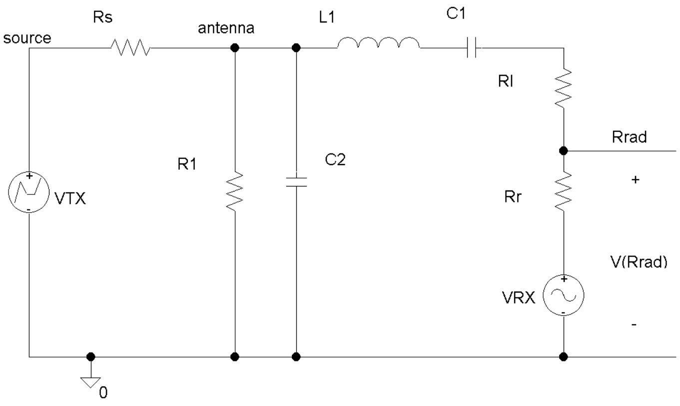

Figure -3: Electrical equivalent of a λ/2 dipole antenna connected to a 50 Ω source.

The quality factor Q for a λ/2 monopole antenna is typically in the order of 4 - 5, whereas the radiation resistance R_s is about 73 Ω and the loss resistance Rl is typically 2Ω, yielding a radiation efficiency of 97 % at f_0.

Modeling this 1.25 GHz antenna according to the equivalent schematic of Figure-3 yields the following component values:

L_1 = 46.5 nH
C_1 = 350 fF
C_2 = 50 fF
R_r = 73 Ω
R_l = 2 Ω

Both R_r and R_l were measured at the resonant frequency f_0. The loss resistance was measured by completely enclosing the antenna in a closed metallic cylinder that prevents any radiation. This method was first suggested by Wheeler [1] and constitutes a relatively simple method to measure antenna loss resistance and efficiency. Two tins made out of tinned iron of 75 mm diameter and 105 mm height were soldered together to completely enclose the antenna. The impedance measurements were made on a HP4291A RF Impedance Analyzer using the low impedance test head.

3. TDR MEASUREMENTS VERSUS SIMULATION RESULTS

In order to test the validity of the SPICE model, a benchmark was defined using two of the described 1.25 GHz dipoles in a line-of-sight communication link of 70 cm (3 λ) distance. The antennas were mounted on tripods giving them a height of 1.4 m. The transfer S21 was measured on a HP8753D network analyzer. The line-of-sight distance between the two dipoles equals 70 cm

Figure-4 shows the equivalent circuit used to simulate this 70 cm line-of-sight channel in PSpice.

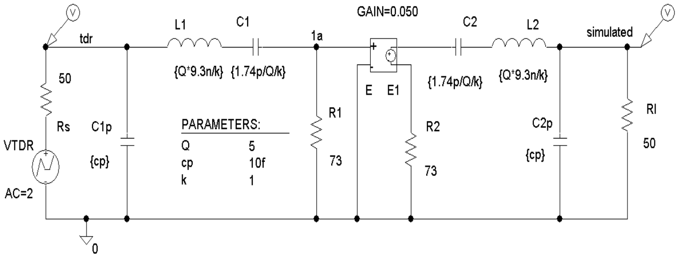

Figure -4: SPICE circuit representing two dipole antennas and a 70 cm line-of-sight channel.

The transmission antenna is represented by components L1-C1-R1-C1p and the reception antenna by components L2-C2-R2-C2p. The loss resistance of the antennas was omitted from this simulation. The path loss is accounted for by controlled source E1. Path loss is assumed to be frequency independent which is a reasonable assumption for line-of-sight applications. The propagation delay was not included in this model, but can be accounted for by a transmission line of appropriate length.

The source VTDR is a 2 V AC source for the frequency domain (AC) simulations and a piecewise linear (PWL) source reading a file containing the digitized TDR response. The TDR used is the 18 GHz HP54753A TDR module from a HP 54750A digitizing oscilloscope. The TDR waveform was save to a disk, imported into MATLAB and exported as a PWL file readable by PSpice.

Figure 5 shows both simulation and measurement results. Measurement results from the S21 measurement, using the Z:Trans conversion option of the network analyzer, were used as data points for an EFREQ source in PSpice, allowing for direct comparison of the results in Probe. It can be seen that up about 1.2 f_0 simulation and measured results correspond quite well. Above 1.5 GHz, this simple model, taking only into account radiation occurring around the first resonant frequency f_0 of the antenna, is too pessimistic in its transfer function. Extension of this model to higher bandwidths is currently under investigation.

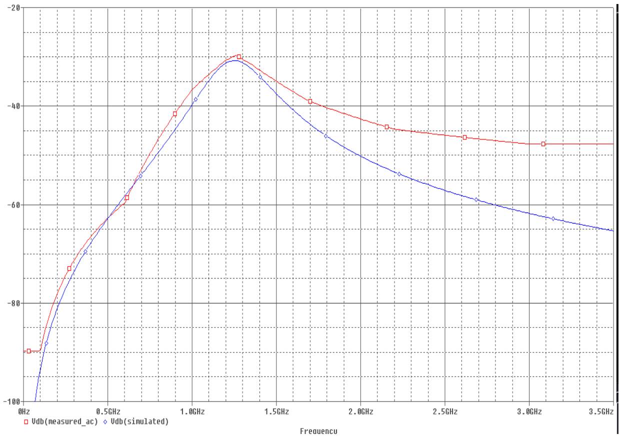

Figure-5 Simulated and measured frequency domain transfer for two λ/2 dipoles spaced 70 cm apart.

The simulated and measured time-domain response of this line-of-sight system are shown in Figure-6.

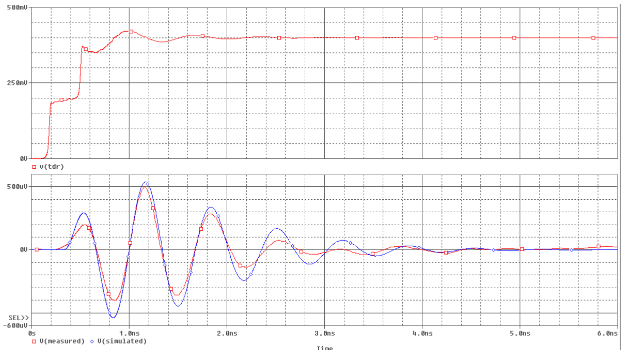

Figure-6 Simulated TDR pulse and simulated and measured time domain transfer for two λ/2 dipoles spaced 70 cm apart.

We see a qualitatively good agreement between simulated and measured waveforms for the first 3 cycles of the pulse response. Afterwards, the simulated results are no longer coherent with the measurements. By lowering the quality factor Q of the antenna equivalent circuit, this can be improved, yet at the expense of inaccuracies during the first few cycles of the pulse response. Clearly, the SPICE model has its limitations also in the time domain.

4. GAUSSIAN MONOCYCLE SIMULATION AND MEASUREMENT

As a last exercise, the time domain performance of the SPICE model was investigated using a DC-free Gaussian monocycle as shown in Figure-7. This signal was generated by an Avtech AVE1-PS monocycle generator.

Figure-7 Measured UWB monocycle pulse waveform

followed by a 3 dB attenuator and a parallel shorted transmission line stub of 17 mm length. This signal was digitized and used as input file for the PWL source in the SPICE simulation. Figure-8 shows simulation results.

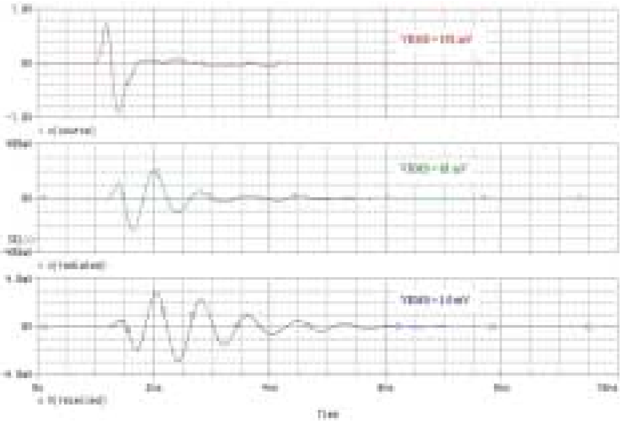

Figure-8 Simulated pulse transfer from source up to radiated signal and received signal.

The upper waveform is the Gaussian monocycle as generated in the transmitter. A pulse repetition time of 10 ns was used in the simulation yielding a waveform with RMS value equal to 192 mV.

The middle trace shows the hypothetical signal as one can imagine it across the radiation resistance of the antenna. It can be seen that not all the energy is radiated, since this would correspond to an RMS voltage of 91 mV.

The lower trace shows the received signal at the end of the 70 cm line-of-sight link, it has an RMS value of 1 mV. Simulated signal attenuation in terms of RMS value of the waveforms corresponds to 39 dB, which is about 10 dB higher than the narrow-band transfer at the dipole's resonant frequency of 1250 MHz.

Figure 9 shows the receiver's antenna response to this waveform. A reflection causes a second smaller signal starting 6 ns after the main response, corresponding to a path difference of 1.8 m.

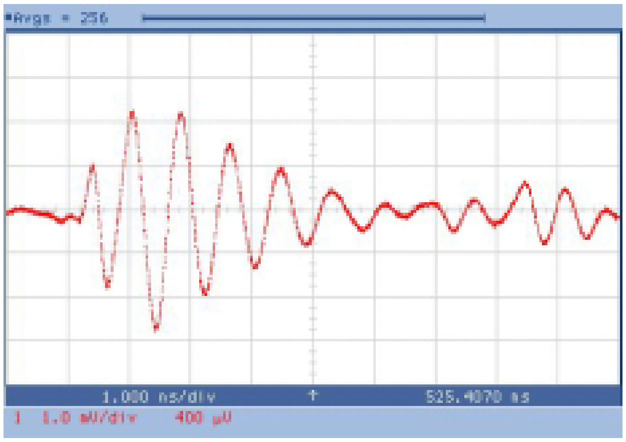

Figure-9 Measured monocycle response at receive antenna.

A comparison with the lower trace in Figure-8 shows good correspondence between simulation and measurement results. The echo after 6 ns doesn't occur in the simulation since a pure line-of-sight situation is assumed. Addition of a transmission line, a multiplier and a summer circuit to the SPICE equivalent circuit allows for simulation of this reflection.

5. CONCLUSIONS

An equivalent SPICE model for a dipole and a line-of-sight link using two dipole antenna has been presented. Despite its limitations (assuming a constant radiation and loss resistance) it performs well from DC up to 1.2 times the antenna resonant frequency.

A comparison of measured and simulated signals using signals from a TDR module and a UWB monocycle generator show a qualitatively good correspondence.
Clearly, this simplified equivalent circuit model is useful for a first investigation of the UWB performance of dipole antennas in an electrical circuit simulator like SPICE. It needs further refinements to implement the frequency-dependency of both radiation and loss resistance as well as the multiple resonances of the dipole antenna.

Further research will therefore focus on more wideband modeling of the dipole and hopefully on SPICE modeling of wideband antennas.

6. REFERENCES

[1] H.A. Wheeler, "The Radiansphere Around a Small Antenna", Proceedings of the IRE, Vol. 47, August 1959.