Time-Domain Matching for Broadband VLF/LF Electrically-Short Radiators

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***Abstract*—Electrically-short antennas traditionally suffer from a very narrow bandwidth due to fundamental limits inherent to frequency-domain impedance matching. Here, we present an alternative time-domain technique that matches the antenna's input impedance via reflection suppression and is thus broadband by nature. We detail results of a low-power prototype and its improvement in efficiency compared to a standard electrically-short dipole. We also discuss an effort to upgrade the prototype to high-power operation for long-distance applications. Our focus is on the VLF/LF band from 1-500 kHz, where conventional beacons require top hats that can span thousands of acres, yet deliver very small bandwidths.**

***Keywords*— electrically-short antenna, radiation efficiency, bandwidth, impedance matching, VLF**

I. INTRODUCTION

There has long been a desire to miniaturize antennas, and a tremendous amount of effort has been expended in pursuit of this goal. Most research has been focused on optimizing the well-known efficiency-bandwidth tradeoff that becomes problematic when an antenna is significantly smaller than its wavelength of operation. For electrically short antennas, this tradeoff is described by the Chu-Harrington limit [1,2].

This tradeoff arises from the fact that the radiated power from an electrically-short, fixed-length dipole falls off with frequency by a factor of f^4. One f^2 factor of the roll-off is an inescapable law of physics, while the other f^2 factor is due to impedance mismatch. The latter can be mitigated through careful engineering but doing so implicitly narrows the bandwidth. For instance, top hat antennas currently utilized for transmission in the VLF band achieve at best 1% bandwidth, and require massive structures covering several square miles. Wider bandwidths can be achieved with resistive loading, but then the f^2 roll-off is not mitigated and the antenna's radiation efficiency suffers, so the problem is a choice between efficiency and bandwidth.

A broadband impedance matching solution would benefit a wide host of applications, particularly in the area of VLF engineering. VLF waves have a unique set of properties that make them suitable for a wide range of applications, including global communications, navigation systems, subterranean imaging, and over-the-horizon radar among others.

Recent attempts to miniaturize VLF antennas include the generation of electromagnetic fields via mechanical motion [3]. However, an electrical solution would be simpler and more robust. Time-varying techniques in particular have begun to show promise [4] and could potentially usher in an entirely new era of antenna engineering.

II. TIME-DOMAIN APPROACH

We have developed a technique to control the input impedance of an antenna by suppressing reflections via rapid variation of the antenna's conductivity over time. Viewing the antenna as a transmission line terminated by an open circuit stub, its input impedance should increase as its length is decreased relative to the operational wavelength. However, if reflections from the open circuit termination could be suppressed, then the transmission line would appear infinitely long, rendering the antenna's input impedance irrelevant. This would, in turn, eliminate the f^2 mismatch roll-off factor and improve efficiency, but without the cost of narrow-bandwidth since the matching is being performed in the time-domain, making it a frequency-independent solution.

The proposed technique has been simulated with an FDTD model, in which the current moment of the antenna was used to determine its radiated power as a function of frequency. The results of this simulation on a 1-meter antenna are shown in Figure 1, where the benefit of suppressing reflections can clearly be seen, particularly in the lower frequency range.

In order to realize this transmission scheme, the signal of interest is initially broken up into a series of pulses by sampling the input waveform with a switch. Each resulting pulse then propagates down the length of the antenna to generate the

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desired radiation. However, once each pulse reaches the end of the antenna where it would normally reflect back downward, a segment of the antenna is instead switched to a high impedance so that the pulse cannot travel back. The pulse then re-reflects away from the high-impedance section and thus does not cancel out the next incoming pulse; the original pulse is effectively trapped. By repeating this procedure for each pulse, the amount of reflection is severely minimized, and the efficiency is dramatically improved.

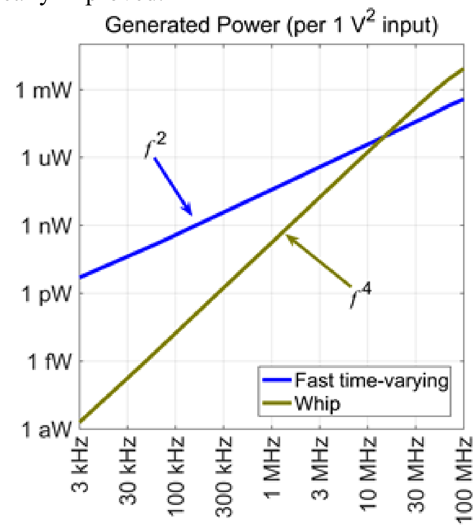

Figure 1. FDTD simulation of our time-varying antenna compared to a standard whip antenna.

This temporal variation in impedance along the antenna can be achieved in several ways. One proposed method is to use a plasma as the conducting channel. The plasma channel could be ionized and deionized to control impedance. This method would allow for very high currents in theory. However, in practice, controlling plasmas on nanosecond time-scales is an exceedingly difficult task. A second method involves replacing a portion of the antenna with a reflective switch. This method is limited by the power-handling and speed of the switch. However, with a unique switch designed to handle both high-power and fast-switching, the desired antenna can be reasonably achieved.

III. IMPLEMENTATION

A proof of concept was constructed using a FET-based switch for reflection suppression. The radiating element took the form of a single-wire transmission line similar to that described by Goubau [5]. Using a 3-meter transmitting antenna (significantly shorter than the radiated wavelength), we were able to measure >20 dB improvement in magnetic field strength for a 30 kHz signal at a distance of 25 meters from the reflection-suppressed antenna, as compared to a conventional antenna of the same length. The result is shown in Figure 2.

Figure 3 shows the spectrogram of a measured magnetic field chirp swept from 60 to 100 kHz and transmitted via the reflection-suppressed antenna, demonstrating the broadband capability of the proposed method. All measurements were taken using the AWESOME VLF and LF receiver, which is capable of greater than 1 fT/rt-Hz sensitivity [6,7]. With this sensitivity and planned improvements for higher transmit power, we believe that we should be able to detect signals at km-scale distances.

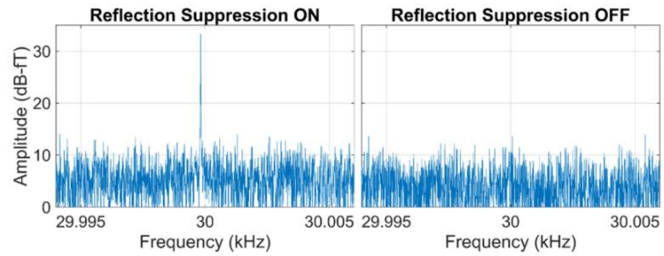

Figure 2. Measured field strength at a 25-meter distance shows >20 dB improvement using reflection suppression compared to a conventional antenna.

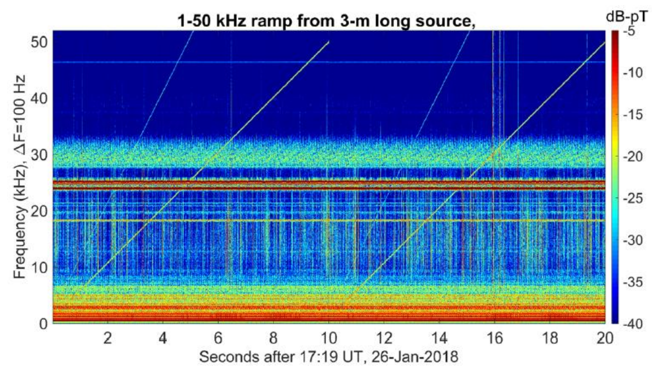

Figure 3. Measured frequency sweep transmitted using reflection suppression, highlighting the broadband nature of the technique.

IV. FUTURE PLANS

We are currently pursuing several methods to increase the output power of our switch-based system. This includes designing a high-power RF switch; optimizing the impedance match to the single-wire transmission line; and improving our timing algorithm. We will detail these improvements and further results in this presentation.

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