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Wideband VLF/LF Transmission from an Electrically-Small Antenna by Means of Time-Varying Non-Reciprocity via High-Speed Switches

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Abstract

We present a novel approach to transmitting wideband signals from electrically-small antennas (ESAs), with a focus on low frequencies where ESA limitations are most severe. Very low frequency (VLF) and low frequency (LF) signals have exceptionally long wavelengths, which make them well-suited to several critical applications but also difficult to generate. Conventional VLF/LF transmitters employ a resonant matching network that can achieve high efficiency, but only within a fundamentally narrow bandwidth. Here, we instead offer a time-varying matching technique that removes the need for resonance entirely. By actively manipulating reflections from the end of the antenna via high-speed switches, the antenna becomes non-reciprocal and is therefore matched to its generator. Moreover, because the matching occurs in the time-domain, this solution works over a very broad (orders of magnitude) frequency band, and therefore does not limit the system bandwidth. Numerical modeling of the transmitter confirms the theory of operation and suggests an improved performance over conventional antennas. In addition, experimental results demonstrate the ability to achieve non-reciprocity with high-speed switches, and indicate higher radiated power from a time-varying electrically-small VLF/LF transmitter prototype.

1 Introduction

The problem of designing compact, efficient, and broadband antennas capable of transmitting signals in the very low frequency (VLF, 3-30 kHz) and low frequency (LF, 30-300 kHz) bands has plagued engineers for decades. These bands are particularly challenging due to their exceptionally long wavelengths. For instance, attempting to build a standard quarter-wave monopole at 30 kHz would require an antenna to be 2.5 km long, which is roughly three times longer than the tallest building on Earth. Creating such an antenna would be highly impractical, and orienting the antenna in a horizontal configuration would be very inefficient due to ground currents limiting its radiation. Thus, any practical VLF/LF transmitter will be an electrically-small antenna (ESA), meaning the physical structure is much smaller than its operational wavelength, making it very difficult to generate broadband signals in an efficient manner.

However, VLF/LF waves are uniquely capable of carrying out various applications, including over-the-horizon communications, geophysical remote sensing, and underground detection, among others [1]. As such, despite the difficulties involved, there remains a compelling interest in designing antennas for long-wave frequencies that are compact and can broadcast at high-powers over a wide bandwidth. Here, we introduce a novel time-varying antenna that can achieve these qualities.

We begin by briefly reviewing the fundamental issues and limits encountered by conventional ESAs. We then introduce our time-varying solution and describe how it can overcome these limits. Finally, we present numerical results which indicate improved performance over conventional ESAs, as well as preliminary experimental data. Our time-varying antenna is limited in certain ways, namely its need for high-speed and high-power switches, but the limitations will ease as solid-state electronics continue to rapidly evolve in the coming years.

2 Limits of Electrically-Small Antennas

ESAs suffer from a steep efficiency-bandwidth trade-off. The low efficiency of an ESA can be understood by examining its impedance. Standard ESAs have a notoriously low radiation resistance and high input reactance [2]. Low radiation resistance leads to a small radiation efficiency, because only a small fraction of the dissipated power is usefully radiated away. In addition, high input reactance creates a severe impedance mismatch between the antenna and its generator, leading to a low matching efficiency. Thus, any solution that seeks to increase the efficiency of an ESA would ideally address both of these issues, but mitigating the input match provides the most room for improvement.

The narrow bandwidth of an ESA is characterized by the well-known Chu-Harrington limit [3]:

$$Q = \frac{1+2(ka)^2}{(ka)^3[1+(ka)^2]} \xrightarrow{ka \ll 1} \frac{1}{(ka)^3} \tag{1}$$

where Q is the radiation quality factor, a is the radius of the smallest sphere that can enclose the antenna, $k = 2\pi/\lambda$

is the operational wavenumber, and ka is thus the electrical size of the antenna. If $Q \gg 1$, which is normally the case for ESAs (i.e. antennas where $ka \ll 1$), then Q is inversely proportional to the antenna bandwidth. The Chu-Harrington limit therefore states that the bandwidth of antenna becomes increasingly narrower as the antenna gets smaller relative to its operational wavelength.

The Chu-Harrington limit is fundamental to linear time-invariant (LTI) antennas and is a natural consequence of creating a resonant matching network. Such a matching network improves the efficiency of an ESA by eliminating its large input reactance, but only does so at a single frequency, hence the trade-off with bandwidth. Moreover, any matching network used to achieve resonance at VLF/LF requires an enormous structure that is difficult to maintain. However, if one of the Chu limit's assumptions is broken, such as time-invariance, then the limit no longer applies. We contend that it is possible to create a time-varying ESA system with a bandwidth that goes beyond the Chu limit by providing an impedance match that does not rely on resonance. Our proposed system does not require a large structure to work, and can therefore achieve high-powers and wideband operation within a compact assembly. Time-varying systems have already shown the ability to achieve bandwidths beyond the Chu limit [4], but our solution is novel in that it does not rely upon resonance at all.

3 Time-Domain Matching Concept

Our proposed technique is to match the input impedance of an antenna by suppressing reflections via rapid variations of the antenna's conductivity over time. In a standard linear wire ESA, the back-and-forth propagation time is very short compared to the input wave period, causing the incoming and echo currents to nearly perfectly cancel each other at the antenna feed. Thus, the antenna has low current, implying a high impedance and a large mismatch. However, if the reflected current from the end of the antenna could be suppressed, then the impedance mismatch would be minimized. We propose to block reflections in this manner through a time-domain matching scheme, as shown in Figure 1.

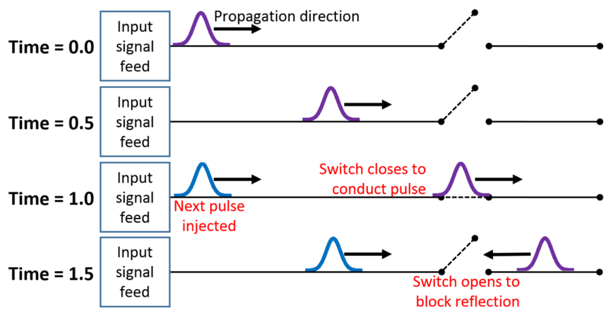

Figure 1. A diagram of the time-varying impedance matching technique, with four snapshots in time.

Here, a monopole ESA is embedded with a switch near its end and is fed by a train of current pulses. The first pulse propagates down the antenna in order to generate radiation. When the pulse nears the end of the antenna, the switch closes at precisely the right moment to allow it through, but then opens again to prevent it from returning back down the antenna. Thus, by trapping the pulse, it is prevented from canceling with the next incoming pulse in the train. If the timing is done carefully, the switch only closes again to allow the next pulse through, and the process repeats.

In order to encode low frequency information into the pulse train, the individual pulses could be samples of an arbitrary VLF/LF signal. This method of encoding is known as pulse amplitude modulation (PAM), and allows the antenna to transmit low frequency information while still performing the time-varying reflection suppression operation.

By encoding VLF/LF information into pulses and then blocking them from returning back down the antenna in this manner, the main issues endemic to ESAs are mitigated. First, the act of preventing the injected signal from returning to the feed creates a non-reciprocal network and causes the antenna to appear infinitely long, thereby eliminating the ESA's large input reactance and matching it to the VLF/LF source. In addition, since the input current does not get canceled out by any reflected current, the antenna develops a nearly uniform current profile, meaning its radiation resistance is improved as well. Finally, the biggest advantage of this matching scheme is that it occurs in the time-domain, meaning it can theoretically be done at any frequency. In fact, the antenna does not rely upon resonance at all, making it an inherently wideband solution.

4 Numerical Modeling

In order to confirm the behavior of the proposed matching scheme, a numerical model was created. Specifically, a monopole antenna was modeled as a one-dimensional transmission line by using the telegrapher's equations in a finite-difference time-domain (FDTD) formulation. A switch was then embedded in the antenna by varying the resistivity of the transmission line as a function of both length and time.

This model was used to perform the operation depicted in Figure 1 on a 1 m long antenna with a train of pulses whose amplitudes were modulated by a low-frequency sinusoidal envelope. The Fourier transform of the time-domain current waveform was then taken at each location along the antenna, and the sinusoidal frequency component of interest was extracted. The resulting current was then integrated along the full length of antenna in order to find the current moment (I_0L) at the frequency of interest. Finally, this value was plugged into the following equation [3]:

$$P_{\text{rad}} = \eta \left(\frac{\pi}{3}\right) \left|\frac{I_0 L}{\lambda}\right|^2 \tag{2}$$

where $P_{\rm rad}$ is the radiated power, η is the characteristic impedance of the medium surrounding the antenna, and $\lambda = c/f$ is the operational wavelength (with c being the speed of light, and f frequency). In this way, the radiated power of the low-frequency sinusoidal envelope could be calculated. This exercise was repeated over a range of frequencies for both the reflection-suppression antenna and for a conventional monopole (in which the transmission line resistance was always kept at zero). The results are plotted in Figure 2.

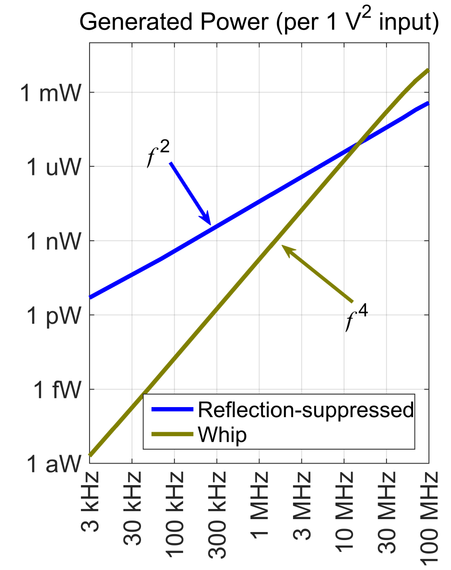

Figure 2. Simulated results for radiated power as a function of frequency for both a conventional (green) and a reflection-suppressed (blue) antenna.

The plot clearly demonstrates that the radiated power for a conventional antenna follows an f^4 frequency dependence, while that of the time-varying antenna only has an f^2 dependence. This difference can be explained by the large reactance of the antenna. It has been found that a standard electrically-small monopole's reactance $X_{\rm ant}$ is inversely proportional to frequency [5]. Thus, when this value gets plugged into Equation 2 (where $I_0 \approx V_0/|X_{\rm ant}|$), then $P_{\rm rad}$ gains an f^4 dependence. However, if the current is not a function of frequency, then Equation 2 instead predicts an f^2 dependence, which is the case for the time-varying antenna. These results suggest that the time-varying scheme has effectively eliminated the large input reactance to the ESA, providing a non-resonant match to the antenna that does not restrict bandwidth. The reflection-suppression antenna also provides an enormous improvement in radiated power at low frequencies, particularly in the VLF/LF bands.

5 Experimental Validation

In order to experimentally validate the proposed time-domain matching scheme, two sets of experiments were designed. The first confirmed the ability to create a time-varying non-reciprocal network, while the second sought to establish a VLF/LF communication link.

For the non-reciprocal network, the test setup was as follows. First, a function generator created a VLF/LF sinusoidal signal which was then fed to a rapidly varying switch that divided the signal into narrow pulses, creating a PAM waveform. The pulses then propagated along a transmission line representing the monopole antenna. Eventually, the pulses encountered another switch which closed to allow the pulses onto a second transmission line used for storage, but then opened to prevent the pulses from returning back to the generator.

Using this setup, we successfully demonstrated the ability to trap the individual pulses of a PAM waveform. The results were measured by an oscilloscope connected to the end of the storage transmission line, and were confirmed against both ideal and realistic circuit simulations performed in Keysight's Advanced Design System (ADS) software. The ideal simulations assumed perfect transmission lines and switches, while the realistic simulations used SPICE models and included non-idealities. The results are shown in Figure 3, with the ideal simulation in black, the realistic simulation in gray, and the measured results in blue.

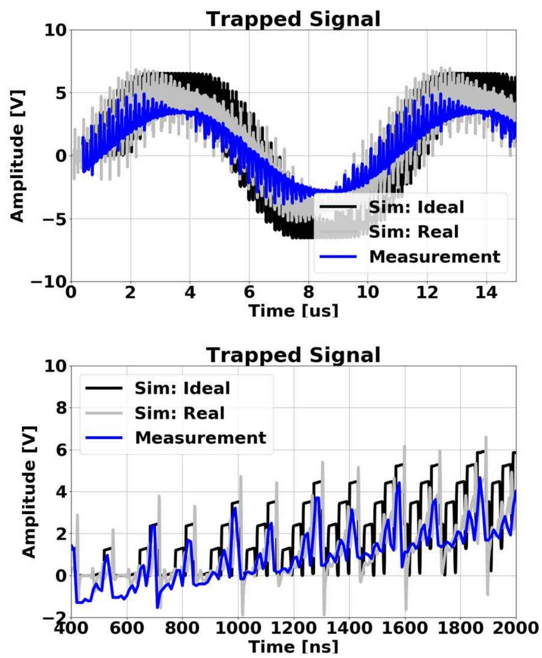

Figure 3. Simulated and measured data of trapped pulses from a PAM waveform.

The top plot shows that all three curves exhibit the same qualitative behavior, suggesting that the basic functionality is being met. The lower plot confirms this by zooming in on the first few trapped pulses. Looking first at the ideal data, there is initially only a single pulse trapped on the transmission line, bouncing back-and-forth indefinitely. Then another pulse of higher amplitude appears and both become trapped on the line. Then a third pulse is added, and so on, ultimately forming a staircase of trapped pulses that follow the envelope of the LF waveform. Although the more realistic data is messier, there are still clearly defined pulses appearing at all of the same times as the ideal scenario, meaning the circuitry worked as intended and successfully trapped pulses on the storage transmission line.

For the VLF/LF communication link, a low-power prototype of the time-varying ESA was constructed. The transmitter setup was nearly identical to the experimental apparatus described earlier, only the center transmission line was replaced with a 3 m long single-conductor wire to facilitate radiation from the pulses as they propagate towards the storage region. In order to receive the signals, the VLF/LF "AWESOME" receiver developed at Georgia Tech [6] was used with an air-core loop antenna to sense magnetic fields radiated by the transmitter. Both the transmitter and receiver were taken out to a field and a wireless link was established over a distance of roughly 5 m at 100 kHz. Preliminary results from the tests are shown in Figure 4.

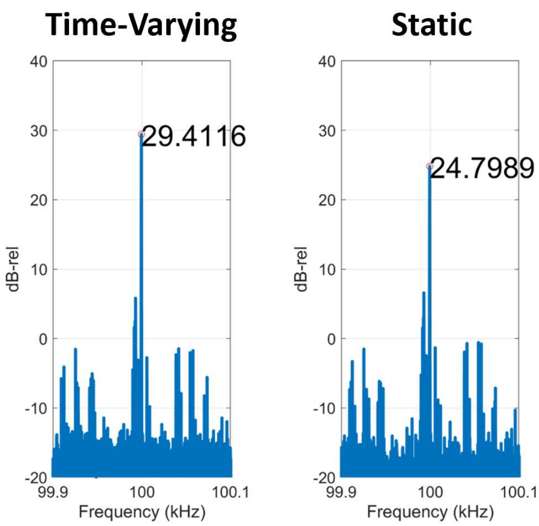

Figure 4. Received data from the transmitter operating in time-varying mode with the switch carefully timed (left) and in static mode with the switch kept on (right).

The left plot shows the received field with the output switch operating in the intended manner to trap pulses, while the right plot shows the received field with the switch kept closed, meaning pulses could go up and down the antenna freely without getting trapped. Comparing the two plots, there is a clear improvement of roughly 5 dB when the antenna is time-varying, implying that the act of trapping pulses near the end of the antenna results in a higher radiated power.

We attempted to take measurements as a function of distance from the transmitter in order to confirm that the fields followed the expected behavior of an electrically-small monopole in the near-field. However, we were only able to get to a distance of 25 m from the transmitter before the signal reached the receiver noise floor, which was not far enough away to establish a trend.

We therefore plan to increase the power handling of the transmitter by an order of magnitude in order to radiate over much longer distances. We are also working on an electric field sensor, which is better suited for communicating with the transmitter given their identical polarizations. We plan to detail these and other planned improvements in our presentation.

6 Conclusion

We introduce a new impedance matching scheme that enables wideband VLF/LF transmission from an electrically-small structure. The methodology leverages high-speed switches to suppress reflections, thereby providing a match in the time-domain that is independent of frequency and negates the need for resonance altogether. This technique presents a novel and exciting approach to antenna operation, and will hopefully lead to a new branch of antenna miniaturization research.

7 Acknowledgements

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