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ULTRA WIDEBAND SURFACE WAVE COMMUNICATION

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Abstract—Ultra Wideband (UWB), an impulse carrier waveform, was applied at HF-VHF frequencies to utilize surface wave propagation. Due to the low duty cycle of the pulse, the energy requirements are significantly reduced. UWB involves the propagation of transient pulses rather than continuous waves which makes the system easier to implement, inexpensive and small. The use of surface wave propagation (instead of commercial SHF UWB) extends the communication range. The waveform, transmitter, receiver, modulation and channel characteristics of the novel system design will be presented.

1. INTRODUCTION

Ultra Wideband (UWB) technology is vastly different from classical radio transmission. The extremely short pulses are generated at baseband and are transmitted without the use of a carrier. The short pulses of electromagnetic energy translate to very wide transmission bandwidths in the frequency domain. The Federal Communications Commission (FCC) defines UWB as a signal with either a fractional bandwidth of 20% of the center frequency or 500 MHz. Due to the low duty cycle of the pulse the energy requirements are significantly reduced. Due to the low power spectral density the system has a low probability of intercept (LPI).

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The FCC has allocated 7,500 MHz of spectrum for unlicensed use of UWB in the 3.1 to 10.6 GHz frequency band [1]. UWB was considered a solution for the IEEE 802.15.3a standard for low complexity, low cost, low power consumption and high data rate connectivity for wireless personal area networks [2]. This tremendous commercial potential led to a great number of research in UWB antennas [3], signaling [4–6] and propagation [7, 8].

Distributed Sensor Networks (DSN) are emerging as a significant military technology both on land and sea. DSN provides pervasive sensing and intelligence that is critical to knowledge of the battlespace. UWB is an attractive solution for DSN because it is inexpensive, uses little power and has a low LPI. However commercial UWB is designed only for a distance of about 15 ft. The application of ultra wideband communications at HF-VHF was investigated [9, 10]. At HF-VHF, low elevation propagation is accomplished via surface wave. Using surface wave propagation, instead of commercial SHF UWB, extends the communication range between sensors.

2. SIGNAL DESIGN

There are two general categories of UWB signals, impulse or multicarrier. The impulse UWB is the pure form where a single pulse, or Gaussian of energy is transmitted for a short duration.

$$f(t) = \exp\left[-t^2/2\sigma^2\right] \tag{1}$$

where σ is the standard deviation of the Gaussian pulse in seconds. The pulse width, τ_p is related to the standard deviation as $\tau_p = 2\pi\sigma$.

However the Gaussian waveform is not a transmittable pulse due to the non-existence of the derivative at $t = 0$. In other words the frequency domain contains a DC component that does not propagate. For UWB systems, a Gaussian modulated sinusoidal pulse or other pulse shaping methods are more practical for better spectral control [11]. The Gaussian modulated waveform is given by:

$$f(t) = \exp\left[-t^2/2\sigma^2\right]\cos(2\pi f_c t) \tag{2}$$

where f_c denotes the center frequency and the pulse width is $2\pi\sigma$.

The fourier transform of the waveform (2) is given by:

$$F(\omega) = \frac{1}{2}\sigma\sqrt{2\pi}\left[\exp\left[\frac{-\sigma^2(\omega-\omega_0)^2}{2}\right] + \exp\left[\frac{-\sigma^2(\omega+\omega_0)^2}{2}\right]\right] \tag{3}$$

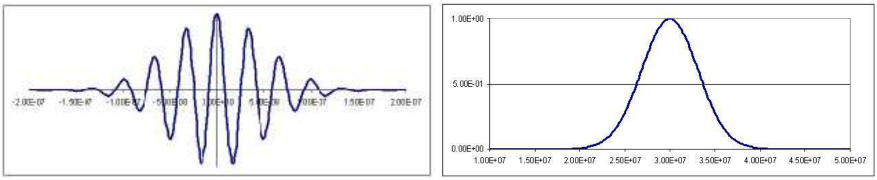

Figure 1. Gaussian Modulated input signal and corresponding frequency spectrum ($\tau_p = 320\,\text{ns}$, $f_c = 30\,\text{MHz}$).

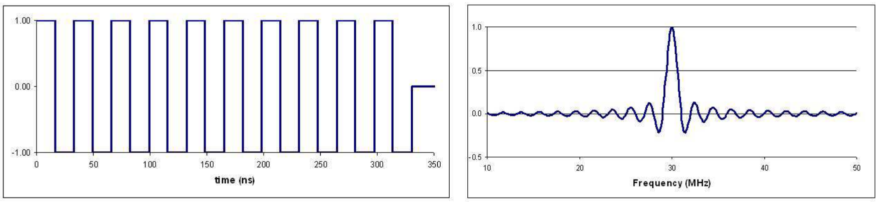

Figure 2. Square pulse train and corresponding frequency spectrum ($\tau_p = 320\,\text{ns}$, $f_c = 30\,\text{MHz}$).

Although the Gaussian modulated sinusoidal pulse is ideal for spectral control it requires pulse shaping. For this application a simple TTL pulse stream was used for the waveform. This was easy to generate using a MOSFET as a high power switch. This waveform can be written as follows with time period τ and center frequency, f_c.

$$f(t) = rect\left({}^{t}\!/_{\tau}\right)\cos(2\pi f_c t) \tag{4}$$

The Fourier transform of the above waveform is given by:

$$F(\omega) = \frac{\tau}{2}\left[\sin c\left(\frac{(\omega-\omega_0)\tau}{2\pi}\right) + \sin c\left(\frac{(\omega+\omega_0)\tau}{2\pi}\right)\right] \tag{5}$$

The center frequency chosen for the system is 30 MHz with a 5 MHz bandwidth. This corresponds to a pulse width of approximately 320 ns with a modulation rate of 33 ns.

3. PULSE DISPERSION

Propagation in the HF band is by various means; sky wave and ground wave. Skywave is reflected from the ionosphere which could provide communications over long skip distances that may be thousands of miles in length. The ground wave component includes the direct wave, indirect (reflected) wave and surface wave. When the antenna is located at the surface of the earth the direct wave and indirect wave cancel out leaving only the surface wave. The surface wave propagation provides beyond line of sight communications.

The well known expression for the vertical electric field, E_z, of a vertical electric dipole (VED) of length ds and time harmonic current, $Ie^{j\omega t}$, at the surface of the Earth is [12]:

$$E_z = \frac{j\omega\mu_0 Ids}{2\pi}\frac{e^{-jk_2\rho}}{\rho}F(p) \tag{6}$$

where ρ is the distance along the surface of the Earth from the source, $\omega{=}2\pi f$, μ_0 is the permeability of free space and k_2 is the propagation constant and is given by $\omega\sqrt{\mu_0\varepsilon_0}$. The above equation assumes a flat homogeneous earth with conductivity, σ_c, and displacements currents are neglected. The Sommerfeld attenuation function, F, for frequencies such that $\varepsilon_0\omega/\sigma_c \ll 1$ is given by [12]:

$$F(p) = 1 - j\sqrt{\pi p}e^{-p}erfc(j\sqrt{p}) \tag{7}$$

where p is known as the numerical distance, and erfc is the complementary error function. For good ground conductivity, such as seawater, the numerical distance can be reduced to [13]:

$$p = (k\rho/2)(\varepsilon_0\omega/\sigma_c) \tag{8}$$

The theory of ground wave propagation has been developed for time harmonic fields. However UWB is a carrier free or impulse communication waveform. Therefore the general equation for ground wave attenuation does not apply. The Sommerfeld attenuation is for a single frequency where UWB is for a broad range of frequencies. Each frequency may have differing attenuation thus distorting the waveform. However, the distortion of transient electromagnetic energy as it propagates over the surface of the Earth is a subject that has been studied [14–17] for use in the areas of lightning strike detection, geophysics and detection of nuclear bursts [18].

The corresponding time dependant field is obtained from the inverse Fourier transform.

$$e(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E(\omega)e^{j\omega t}d\omega = \frac{\mu_0 Ids}{2\pi\rho}A(t-\rho/c) \tag{9}$$

Where [17]:

$$\begin{aligned} A(t) &= \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)e^{-j\omega t}d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left(1-j\sqrt{\pi}\omega q e^{(j\omega q)^2} erfc(j\omega t)e^{-j\omega t}\right)d\omega \\ &= \frac{t}{2q^2}\exp\left(\frac{-t}{4q^2}\right)u(t) \end{aligned} \tag{10}$$

where $q^2 = p/\omega^2$. $A(t)$ is by definition the impulse response of the Sommerfeld attenuation function. The vertical electric field response of the UWB signal is then simply the convolution of the impulse response and the Gaussian modulated pulse [17].

$$E_z(t) = \frac{\mu_0}{2\pi\rho}B(t-\rho/c) \tag{11}$$

$$B(t) = \frac{\exp\left(-t^2/2\sigma^2\right)\omega^2}{2pA^{1/2}}\left(\frac{1}{2A^{1/2}}-\frac{B}{2A}\exp\left(\frac{B}{4A}\right)erfc\left(\frac{B}{2A^{1/2}}\right)\right) \tag{12}$$

where

$$A = \frac{1}{2\sigma^2}+\frac{\omega^2}{4p} \quad \text{and} \quad B = j\omega_0 - \frac{2t}{2\sigma^2} \tag{13}$$

And p is the numerical distance, and $2\pi\sigma$ is the width of the pulse.

To examine what happens in terms of pulse broadening we need to examine the coefficient of t^2 in the exponential term. This term is then related to the pulse width resulting in:

$$2\pi\sigma = 2\pi\sqrt{\frac{1}{2}\left(\frac{1}{2\sigma}-\frac{q^2}{\sigma^2(2q^2+\sigma^2)}\right)^{-1}} \tag{14}$$

The pulse broadening over seawater with a conductivity of 4 S/m can be shown in Figure 3.

From Figure 3 the pulse does broaden over distance with a greater impact on the shorter pulses. For this application for the proposed distances of operation there is minimal impact on the pulse shape.

4. TRANSMITTER DESIGN

Antennas exhibit varying performance versus frequency hence acting much like a filter. For UWB applications the antenna must radiate

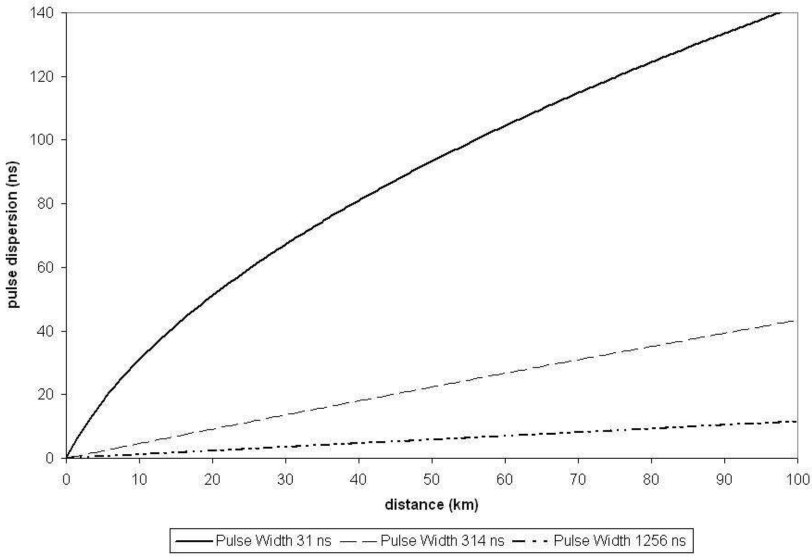

Figure 3. Pulse dispersion over seawater versus distance for various pulse widths.

effectively over the required frequency spectrum. In addition, to prevent distorting the pulse, the antenna should produce radiation fields with constant magnitude and phase shift that varies linearly with frequency. Resonant antennas are considered poor choices for traditional UWB applications [3, 19].

Since DSN platforms will typically be small, an electrically small antenna (a quarter wave monopole for 30 MHz would be 2.5 meters long) is required. The traditional means of providing high-level signal to the feed of a short monopole antenna is to use a 50-ohm transmitter together with a suitable impedance matching network. Such an approach can provide significant feed voltage but has both limited bandwidth and is highly susceptible to detuning when placed in a highly variable environment such as the sea surface. The chosen solution was to develop an active antenna, where active devices are integrated in the passive antenna to improve antenna performance. The circuit design utilizes a high-voltage RF Power MOSFET as a low duty cycle switch to convert a voltage source of 200 Vdc to a 1000 Vp-p RF waveform. The MOSFET is used as a high power switch. The signal drive source, a 30 MHz square wave, is applied directly to the gate of the MOSFET. The MOSFET drain is directly connected to the antenna. The drain is also connected to a 200 Vdc source through an inductor. The inductor is chosen such that together with the MOSFET drain-source capacitance (C_{ds}), and the antenna's capacitance, it comprises a parallel resonant circuit during the MOSFET's cutoff period. This resonant circuit, however, is non-linear due to the effect drain-source voltage (V_{ds}) has upon drain-source capacitance (C_{ds}). This non-linearity together with the large C_{ds} results in an effective Q that is low enough to enable significant bandwidth yet still provides the required antenna feed voltage over the anticipated range of antenna impedance. Due to the MOSFET's relatively large C_{ds} the circuit is relatively immune to changes in antenna impedance.

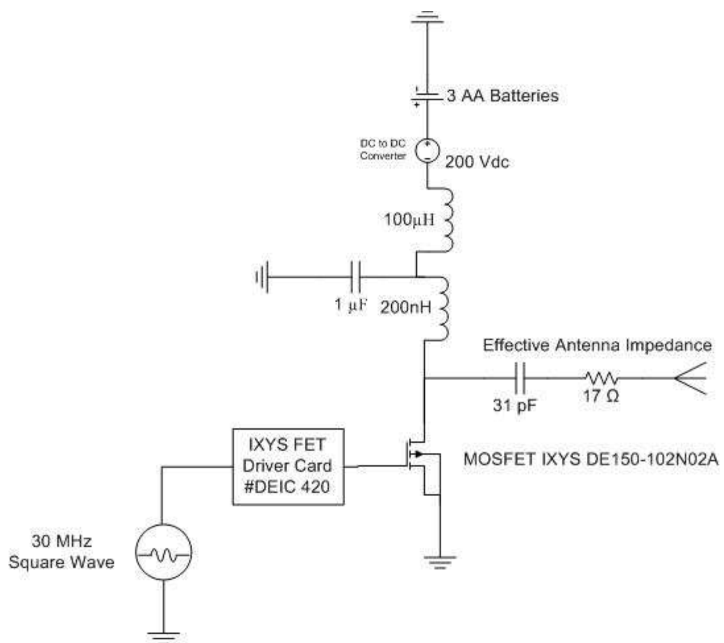

Figure 4. Transmitter circuit diagram.

5. RECEIVER

The receiver consists of a monopole antenna, a filter matching the bandwidth of the signal, low noise amplifier and an envelope detector. Detection of the UWB signal is performed by threshold detection. The threshold detection (also known as energy detection) is a much simpler design which is better suited for a low-cost, low complexity sensor system. This type of receiver integrates the energy contained within a pulse period to determine if a pulse is present. A threshold energy level is set, and if the energy detected is above this threshold then the decision is a bit has been sent. The energy detector used was a Schottky diode. By loading the Schottky diode with a resistive load increases the decay rate.

6. COMMUNICATION CHANNEL CHARACTERIZATION

Data was measured over seawater at a one mile distance at Naval Undersea Warfare Center's Fishers Island Facility. Measurements of the received field strength were made from a monopole antenna with constant voltage as a function of frequency from 2 to 30 MHz. The electric field strength increased with the square of the frequency and 3/2 power of antenna height. Additional tests showed the received field was seen to be directly proportional to the applied voltage. Based on this data the empirical equation of the received field as a function of driving voltage, antenna length and frequency is:

$$E_v = 20\log\left(\frac{E_{in}}{180}\right) + 46 + 30\log\left(\frac{L}{36}\right) + 40\log\left(\frac{F_{\mathrm{MHz}}}{10}\right) \tag{15}$$

where E_v = vertical electric field in dB//1µV/m at a distance of 1 mile, E_{in} = applied voltage in volts p-p, L = transmit antenna length in inches and F_{MHz} = frequency in MHz. The comparison of measured to analytical data is shown below.

The signal-to-noise ratio (SNR) at the receiver is given by

$$\mathrm{SNR} = E_v - Atten - NSD - 10\log(B) \tag{16}$$

where SNR is the received signal to noise ratio in the receiver bandwidth in dB, E_v is the vertical electric field at a distance of 1 mile (dB//1µV/m) as given by Equation (14), *Atten* is the attenuation beyond one mile, *NSD* is the noise spectral density (1 Hz bandwidth) and B is the receiver bandwidth in Hz. Surface wave attenuation over seawater can be easily referenced [20]. Noise at the HF band can be atmospheric, man-made and galactic. Atmospheric noise values vary as a function of frequency, time of day, season, and location on the earth's surface and decreases with increasing frequency. Since this system application is for ocean communications we assumed that the man-made noise sources will be negligible. Therefore we assumed Galactic noise levels and assumed the received is external noise limited. The noise factor, noise above kTB, for galactic noise is given by [21]:

$$F_a = 52.0 - 23.0\ \log(F_{\mathrm{MHz}}) \tag{17}$$

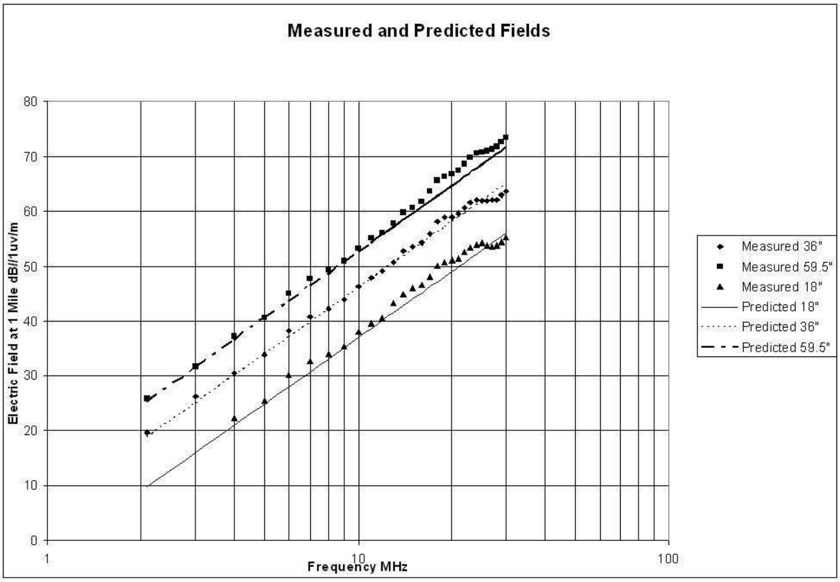

Figure 5. Predicted levels based on empirical equation compared to measured values.

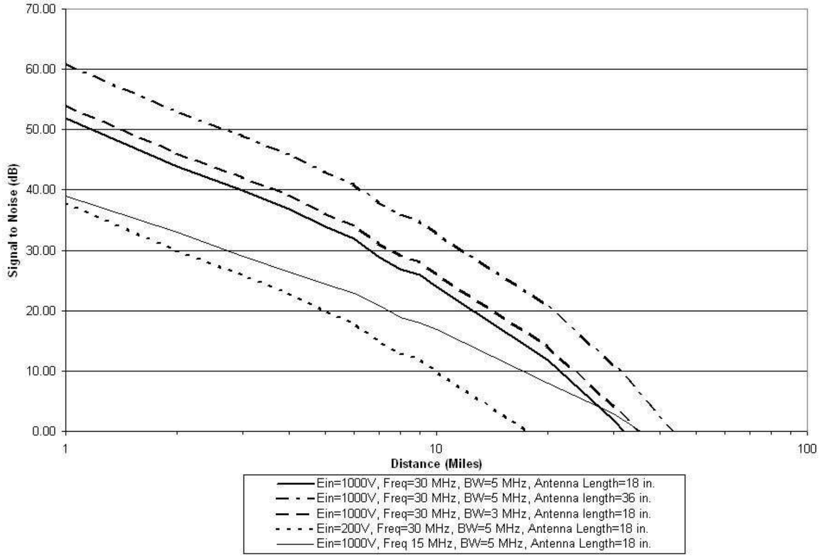

Figure 6. Plot of signal to noise ratio (SNR) for varying system parameters.

The performance of the UWB surface wave communication system can be shown for varying parameters such as transmitting antenna length, bandwidth and power.

From Figure 6 one can see that longer transmit antenna length, greater transmit power and smaller bandwidth improves system performance. The higher frequency which has less noise but greater attenuation is better at shorter distances. As distance increase the attenuation becomes an issue and lower HF frequencies would have to be used.

7. CONCLUSION

The UWB surface wave communication system is a solution for small platforms such as remote sensors since it is simple, inexpensive, requires low power and occupies a physically small package. The system does not meet FCC guidelines [1] but could be used for military purposes or in international waters. The limited range of 20 miles minimizes interference with other systems.

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