Pulse Shapes That Outperform Traditional UWB Antenna/Waveform Combinations

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Abstract—Traditionally the Gaussian monocycle pulse and its higher derivatives have been proposed and deployed as impulse radio ultra-wideband (IR-UWB) pulses. Although relatively easy to generate in electronics, these pulses are ill-adapted to the sharp cutoffs in the US Federal Communications Commission (FCC) mask. The combination of these pulses with passband UWB antennas with steep roll-off improves power efficiency vis-à-vis the FCC mask. This approach is still quite sub-optimal and pulse shaping can provide marked improvement (to 3 dB) over the best traditional combinations.

We show that optimal design of UWB waveforms, when taking into account antenna gain profiles, improves the power efficiency of the pulses. Three typical antennas are considered. A nonlinear optimization process is used to design an efficient pulse for each antenna. The proposed optimization is based on the hybrid genetic algorithm and a sequential quadratic program. We demonstrate that this method finds efficient pulses under severe antenna distortion. Simulation results confirm that the optimally designed pulses have superior performance compared to the more common Gaussian monocycle and the Gaussian fifth-derivative pulse.

I. INTRODUCTION

Ultra-wideband (UWB) radio transmission has attracted much attention since its allocation of an unlicensed frequency band by the US Federal Communications Commission (FCC) in 2002 [1]. This wide but extremely power limited bandwidth, mainly from 3.1 to 10.6 GHz, allows very high data rate communications for close range applications, such as, cable replacement and high-definition (HD) video transmission at home. A major challenge in UWB system design is that the UWB pulses are highly power-limited compared to other conventional (narrowband) systems due to the FCC power spectral mask. The strict power limitations imposed by the FCC spectral mask necessitate spectral pulse shaping: designing spectrally efficient pulses that eke out most of the power available under the FCC mask. As with all communication systems, UWB system performance highly depends on the signal to noise (SNR) ratio. Therefore choosing efficient pulses for UWB communication systems is of critical importance.

The most common UWB pulses have been Gaussian monocycle and its higher order derivatives. Although traditionally employed for UWB systems, these shapes poorly exploit the permissible power under the FCC mask. When a Gaussian monocycle pulse is transmitted by a UWB antenna, the passband behavior of the antenna will modify the pulse spectrum and improve somewhat its power efficiency vis-à-vis the FCC mask. In this paper, we show that even in the case of the Gaussian $5^{th}$ derivative pulse, inherently superior to the Gaussian monocycle pulse in terms of meeting the FCC mask, it cannot reach the power efficiency of optimally designed pulses.

A widely used optimization method to find efficient UWB waveforms was proposed in [2]. In this approach, a convex formulation is used to optimize the coefficients of a digital finite impulse response (FIR) filter. Gaussian monocycle pulses form the building blocks of the filter. The pulses designed by this method are very efficient before transmission from an antenna. However, the antenna gain response distorts the pulses, degrading the power efficiency. In reference [3], the gain response of the antenna was measured and incorporated into the optimization process. The pulses obtained by this method are very efficient in terms of equivalent isotropic radiated power (EIRP), the parameter limited by the FCC spectral mask. The limitations existing in the linear optimization method proposed in [2] and [3], however, do not allow optimal pulse design in case of severe antenna distortion.

In [4] the genetic algorithm (GA) was used to optimize a linear combination of B-spline functions. The obtained UWB pulses, however, are not smooth and show excessive ripple. In this work, we propose a hybrid optimization process of the genetic algorithm and a sequential quadratic program (SQP) to design UWB pulses. In this method, we build the UWB waveforms by combining the Gaussian monocycle and its higher order derivatives. In contrast to the linear optimization method in [2], we optimize not only the weights, but also the delays, the full-width half-maximum (FWHM) pulse width and the derivation order. The GA is used as a global optimization process to solve this non-convex optimization problem. The output from the GA is fed to the SQP to improve the results, searching for a local optimum.

Ultra-wideband antenna design has been an active area of research for the antenna community. Many different antenna structures, mainly on printed circuit board (PCB), have been proposed. The impulse response of any antenna distorts the UWB pulses. In order to highlight the effect of pulse shaping and show the capability of our optimization technique to find efficient pulses for different antennas, we consider three antennas. The SkyCross UWB antenna, the circular monopole antenna [5], and the monopole antenna with two steps [6]. Efficient pulses are designed for each antenna by predistorting...
the UWB waveforms to compensate for the antenna gain response. The nonlinear optimization method proves to be more powerful for this purpose.

II. UWB PULSE DESIGN

In this section, we design efficient UWB waveforms that achieve high power efficiency values while their EIRP respects the FCC spectral mask. The power efficiency is defined as

\[ \text{PE} = \int_{F_p} EIRP(f) df \int_{F_p} S_{FCC}(f) df, \]

where \( S_{FCC} \) is the FCC spectral mask. The PE is calculated over the 3.1-10.6 GHz band. The EIRP is defined as \( EIRP = P_T(f) G_T(f) \), where \( P_T(f) \) is the transmit power spectral density and \( G_T(f) \) is the transmit antenna gain profile. To determine the EIRP, we use the Friis free space transmission formula in its simple form

\[ \frac{P_R(f)}{P_T(f)} = G_T(f) G_R(f) \left( \frac{c}{4\pi r f} \right)^2, \]

where \( P_R(f) \) is the receive power spectral density, \( G_R(f) \) is the receive antenna gain profile, \( c \) is the speed of light, \( r \) is the far field radial distance between the transmitter and the receiver [7]. To obtain transmitted EIRP we use similar antennas at transmitter and receiver and measure the channel frequency response using a network analyzer. No multipath reflection is allowed when measuring the channel frequency response. Using (2), as in [3], we define an effective spectral mask for a given antenna by

\[ M(f) = \frac{c S_{FCC}(f)}{4\pi f_0^2 \sqrt{S_{21}(f)}}, \]

where \( S_{21}(f) \) is the channel frequency response. The power spectral density of the UWB pulse should respect the effective mask instead of the FCC mask. Note that the effective mask is antenna dependent. We use two different optimization methods to maximize the total average power under the newly defined mask.

A. A Linear Optimization Process

This method was proposed in [2] for use with the FCC mask, and was later used with the effective spectral mask in [3]. The optimal pulse is synthesized using a digital finite impulse response (FIR) filter structure. Gaussian monocycle pulses form the building blocks of the filter. Given a filter with taps, the optimal pulse is expressed as

\[ x(t) = \sum_{k=0}^{L-1} w[k] g_m(t - kT_0), \]

where \( T_0 \) is the tap spacing, \( \{w[k]\}_{k=0}^{k=L-1} \) are the filter tap coefficients to be determined by the optimization process and \( g_m(t) = t \exp \left( -2(t/\tau)^2 \right) \) is the Gaussian monocycle pulse with pulse duration of about \( 4\tau \).

The optimization problem is stated as

\[ \max \int_{F_p} |X(f)|^2 df, \quad f \in F_p \]

subject to \( |X(f)|^2 \leq M(f), \quad f \in F_p \)

where \( X(f) \) is the Fourier transform of \( x(t) \). Equation (5) defines a non-convex optimization problem which can be transformed into a convex finite linear optimization problem by using the autocorrelation of \( w \) [3]. The problem can be solved using a convex cone optimization program such as the Matlab SeDuMi optimization tool [8].

B. A Nonlinear Optimization Process

In general, the optimization method in the previous section finds a better fit to the mask by increasing the number of taps. However, being limited to optimizing only the weights of the monocycle pulses in (4), it does not result necessarily in a best fit. In this section, we use a hybrid optimization based on the genetic algorithm and SQP. We synthesize the optimal pulse as

\[ x(t) = \sum_{k=0}^{L-1} w[k] g_k(t - T_k), \]

where \( g_k \) can be the Gaussian monocycle pulse or one of its higher order derivatives. Each Gaussian pulse can have a different FWHM. The delay between the Gaussian pulses, \( T_k \), is also considered as a variable. Therefore, the pulse is synthesized with many more degrees of freedom compared to the linear optimization method. Particularly, using higher order derivatives can be important for the optimization program. By differentiating a Gaussian pulse, its spectrum shifts towards the higher frequencies. Intuitively, different derivation orders in the summation (6) explore different frequency regions over the UWB bandwidth.

The optimization problem is the same as the problem stated in (5). It involves nonlinear, non-convex optimization with many variables. This type of optimization problem is generally difficult to solve, and we turn to the genetic algorithm. The fitness function is the integral in (4). The population size is set to 200 and the algorithm continues subject to a certain error tolerance.

The output from the GA is then used as the initial point in the SQP in the MATLAB optimization toolbox. This nonlinear constrained optimizer improves the results obtained from the GA.

In the next section we will use this method to find optimal pulses under different effective masks.

III. ANTENNAS AND EFFICIENT UWB PULSES

For high data-rate indoor applications the antennas are required to be omni-directional and small. Printed circuit board (PCB) antennas are great candidates for UWB antennas. Ideally, a UWB antenna should have a flat frequency response from 3.1 to 10.6 GHz but unfortunately this is not possible. The frequency response of the antenna distorts UWB pulses.
To measure the antenna frequency response, two similar antennas are used for line-of-sight (LOS) transmission in lab environment over a distance of 65 cm and a height of 120 cm off the ground. The antennas are placed in their peak radiation direction in the azimuth plane. Note FCC regulations require peak EIRP measurements over all directions. For these antennas, the azimuth was the direction of greatest gain. The channel response, $S_{21}(f)$, is measured by a vector network analyzer (VNA-N5230A). The VNA captured 6401 points across a span of 0.2 to 12 GHz and averaged 16 times to improve the dynamic range. Observation of the channel over longer periods of time shows no differences in the response and we conclude that the channel is non-varying.

For (2) to be valid, there should be no reflections in the channel measurement. We place electromagnetic absorbers around the antennas, however as this is not an anechoic chamber, some reflections still occur. These reflections are eliminated by signal processing per the following. The inverse Fourier transform of the channel frequency response provides the channel impulse response. We keep the LOS impulse and truncate all the reflections. By taking the Fourier transform of this response, we find a smooth channel response with no reflections that can be used in (3).

Before transmission by the antennas, the pulses are amplified using a power amplifier with an average gain of 25.7 dB over the bandwidth of interest. The frequency response, $S_{21}(f)$, is measured for this antenna using the VNA. This response is also used in (3) to compensate for the distortion caused by the amplifier.

The commonly used Gaussian monocycle and the Gaussian 5th derivative are shown in Fig. 1. Before transmission from antenna, the spectral efficiency of the Gaussian monocycle and the Gaussian 5th derivative are 1% and 40%, respectively. While common wisdom in that a Gaussian monocycle combined with a passband antenna response can boost the power efficiency of the monocycle over the FCC mask, this approach is far from optimal. Even when using the Gaussian 5th derivative pulse, the passband antenna cannot provide the same level of power efficiency as a pulse shaped to adapt to the antenna response and sculpted to match the FCC mask.

In this section, we choose three typical UWB antennas. An efficient pulse is designed for each antenna after finding the corresponding effective masks. We will compare the performance of these optimally designed pulses with the Gaussian monocycle and the Gaussian 5th derivative pulse.

A. The SkyCross Antenna

The commercially available 3.1-10 GHz omni-directional SkyCross SMT-3TO10MA antenna is shown in Fig. 2.a1. This antenna has small size and is azimuth omni-directional. It consists of a wideband monopole and a self-contained matching structure. The antenna has a -10 dB bandwidth from 3.7 to 9 GHz. Fig. 2.a2 shows the measured frequency response of the antenna. The antenna passes the whole UWB bandwidth but has a non-flat response. Based on the measured frequency response, the effective mask is calculated using (3) and shown in Fig. 2.a3. An efficient UWB pulse is designed using the linear optimization method. We use 8 taps in (4), and $T_0$ and $\tau$ are 38.5 and 58.5 ps, respectively. The nonlinear optimization program results in a similar pulse for this antenna. The EIRP closely respects the FCC spectral mask (Fig. 2.a3). The power efficiency is 70%. The pulse in the time domain is plotted in Fig. 2.a4.

B. The circular monopole antenna

The circular disc monopole antenna was first proposed in [9]. It is a printed antenna fed by a 50 $\Omega$ microstrip line. The antenna is fabricated on the FR4 substrate with a thickness of 1.5 mm. The transfer function of this type of antenna was studied in [5]. It is shown that the transfer function at boresight suffers a notch at high frequencies due to degradation of the antenna pattern, i.e., the antenna is not omni-directional and radiates to the sides.

In [5] reducing the size of the substrate is proposed to leave just a small gap between the radiator and the substrate edges. This smaller antenna shows more omni-directionality at high frequency and does not have the mentioned notch. We fabricated an antenna to these specifications. The antenna is shown in Fig. 2.b1. Fig. 2b2 shows the measured frequency response of the antenna. The frequency response covers up to 9 GHz. The effective mask is found and the nonlinear optimization program is used to design an efficient UWB pulse. The pulse is shown in the frequency domain (Fig. 2.b3) and in the time domain (Fig. 2.b4). We achieve $PE = 58\%$. Higher power efficiencies are possible by increasing $L$ in (6), but imply more complicated pulses in the time domain.

C. The monopole antenna with two steps

The monopole antenna with two steps and a circular slot, proposed in [6], follows the same principles as the circular monopole antenna, and was fabricated in house. The antenna is shown in Fig. 2.c1. The added steps increase the antenna perimeter which lowers the first resonant frequency. The antenna has a return loss less than -10 dB from 3 to 11.4 GHz. Fig. 2.c2 shows the measured frequency response of the antenna. We can see that the frequency response is limited to

![Fig. 1. Commonly used UWB pulses. (a) the Gaussian 5th derivative, (b) the Gaussian monocycle, and (c) The corresponding spectra normalized to respect the normalized FCC spectral mask.](image-url)
Fig. 3 compares the Gaussian monocycle, the Gaussian 5\textsuperscript{th} derivative and the EIRP-optimized pulses vis-à-vis the FCC spectral mask for each of the three antennas. We can see that the monocycle pulse has to be greatly attenuated to respect the FCC mask. Consider the SkyCross antenna (Fig. 3a) which has good out-of-band rejection and a passband within the FCC limits (Fig. 2.a2). When this antenna filters the Gaussian monocycle pulse, the EIRP of the transmit pulse has just 4% power efficiency. This clearly illustrates that the antenna is not an effective filter for the Gaussian monocycle pulse transmission. In this case, adding a UWB passband filter improves the PE [10].

The EIRP of the Gaussian 5\textsuperscript{th} derivative respects the FCC spectral mask for all three antennas, with no need for addi-
V. CONCLUSION

The Gaussian monocycle and the Gaussian 5th derivative, common UWB pulses, do not have good FCC mask coverage. By studying the bandpass characteristics of UWB antennas, we designed UWB pulses that efficiently exploit the FCC spectral mask. To do so, a linear and a nonlinear optimization program were used. The programs take into account the effects of the power amplifier and the antenna to maximize the transmitted power, while respecting the FCC spectral mask. The nonlinear optimization method was more efficient than the linear method when the antenna severely distorted the pulse.

Table 1 shows numerical values of the power efficiency and the absolute power for the Gaussian monocycle, the Gaussian 5th derivative and the EIRP-optimized pulses. Among all the pulses, the pulse designed for the SkyCross antenna has the highest power efficiency. The highest pulse shaping gain goes to the monopole antenna with two steps with 17.7 and 2.9 dB improvement over the Gaussian monocycle and the Gaussian 5th derivative, respectively. The latter antenna, although worse than the circular monopole antenna in terms of bandwidth, results in a higher power efficiency. Therefore, the nonlinear pulse shaping method is effective in compensating severe antenna distortion.

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Given the frequency response of each antenna, a unique pulse was designed for each antenna. The FCC-optimized pulses showed up to 17.7 dB improvement over the Gaussian monocycle and 2.9 dB improvement over the Gaussian 5th derivative. This result confirms that the antenna alone is not an appropriate filter to boost the power efficiency of the monocycle over the FCC mask; this approach is far from optimal. Even when using the Gaussian 5th pulse, the passband antenna cannot provide the same level of power efficiency as a pulse shaped to match the FCC mask. The energy improvement in UWB pulses directly improves the receiver signal-to-noise ratio and extends the reach of the communication link.

REFERENCES