DELAY-BASED BPSK FOR PULSED-UWB COMMUNICATION

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ABSTRACT

This paper proposes a practical and effective modulation technique applicable to pulsed-UWB systems that mimics the desirable, continuous spectrum of a BPSK signal without requiring an inversion in the signal path. This technique can be used for scrambling the spectrum of a PPM signal, or as a replacement for BPSK signaling. It has been implemented in an all-digital, delay line based UWB transmitter in 90nm CMOS. An analysis of the spectral characteristics of the modulation technique is given, as well as simulation and measured results.

***Index Terms*—** UWB, pulse position modulation, PPM, binary phase shift keying, BPSK, phase scrambling.

1. INTRODUCTION

There is a wide range of pulse-based ultra-wideband (UWB) transmitter implementations found in literature, ranging in the modulation supported, the pulse widths and center frequencies, the pulse repetition frequency (PRF) range, and the sensitivity to process variation. This complicates a general comparison of UWB transmitters, such as transmitter energy/bit, when higher energy/bit transmitters may incorporate features that reduce the total *system* power consumption. This tradeoff is acceptable when the receiver dominates the overall energy/bit, which is typical in pulsed-UWB systems.

There is a class of pulsed-UWB transmitters that use a delay line to synthesize an RF pulse. This architecture has several desirable characteristics such as precise, and often tunable, control of the pulse width and center frequency. The architecture is ideal for integration in a CMOS process, and benefits from process scaling. Additionally, it is well suited for pulse position modulation (PPM), and has been adapted for BPSK with increased power consumption and area overhead [1][2]. In this paper, a modulation technique is proposed that achieves similar performance to BPSK systems, but with a simplified hardware implementation. It leverages existing resources in a delay-line-based UWB transmitter, without the additional overhead typically required for BPSK signaling. In the following sections, a more detailed motivation for the proposed signaling scheme is provided, and then it is described and analyzed in detail. In order to verify that this modulation is practical and effective, measured results are presented for signals synthesized with an arbitrary waveform generator, as well as results from a delay-line-based UWB transmitter RFIC.

2. MOTIVATION

BPSK is the most common modulation found in literature for pulsed-UWB systems. It offers a 3dB advantage in SNR over PPM, another modulation commonly found in literature for pulsed-UWB systems. In addition, the spectrum of BPSK modulated pulses does not contain any spectral lines, which is advantageous when maximizing transmit power while limited by the FCC mask. A PPM spectrum, however, will contain spectral lines even when modulated with random data. As shown in Fig. 1, the lines in the 2-PPM spectrum are 10log(*PRF*/1MHz) dB above the BPSK spectrum when keeping all other factors, in particular the total pulse energy, equal [3]. This results in a PPM transmitter having to lower its power by this factor relative to a BPSK transmitter in order meet the FCC mask. Therefore, higher-order PPM or BPSK scrambling in addition to PPM is used to eliminate these tones and thus

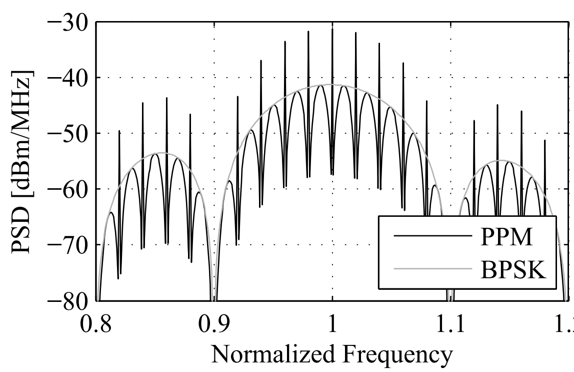

Fig. 1: Comparison of PPM and BPSK spectra with equal total pulse energy at a 10MHz PRF.

the need to reduce the power [4]. Because BPSK decouples the scrambling problem from the modulation, it is typically preferred over higher-order PPM, which adds complexity to the receiver hardware and synchronization algorithm.

BPSK modulation does come with added complexity and power consumption in the transmitter. This complexity leads to the use of RF amplifiers and mixers dissipating static power, or passive components that consume a relatively large die area. Power and area are two key constraints for which circuit designers go to great lengths to minimize at the expense of performance. PPM transmitters and receivers, however, offer an advantage in system complexity over BPSK. Pulse generation circuits become relatively cheap in terms of power and area, and a non-coherent receiver can be used which has lower energy/bit than coherent architectures.

It would therefore be advantageous to combine the spectral properties of BPSK signals with the implementation simplicity of a PPM transmitter. This can be achieved with the proposed *delay-based* BPSK (DB-BPSK) modulation.

3. DELAY-BASED BPSK CONCEPT

An illustration comparing DB-BPSK with conventional BPSK is shown in Fig. 2 with the reference pulses in black and "inverted" pulses in gray. The example pulses shown are 4-cycle square pulses having a *sinc* spectrum, centered at the frequency of the underlying 4-cycle RF tone. Conventional BPSK pulses are generated by inverting the reference pulse as shown on the left. DB-BPSK pulses are generated by instead delaying the reference pulse by half of the RF tone period as shown on the right. Conceptually, this delay appears to have the same effect as inversion, except for the half-cycles at the beginning and end of the pulses. As the number of cycles per pulse increases, the half-cycle extensions become a smaller fraction of the total pulse energy. Therefore, one would expect the performance of DB-BPSK to approach that of BPSK for increasing number of cycles per pulse. For more than 6 cycles per pulse, the spectrum of DB-BPSK pulses is similar to that of BPSK pulses in the mail lobe, making DB-BPSK suitable for scrambling a PPM pulse spectrum or communicating data.

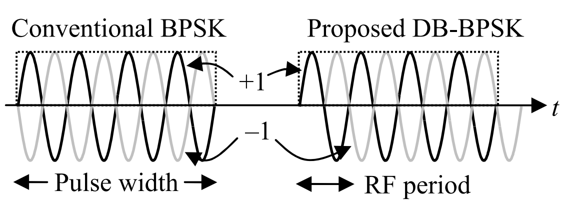

Fig. 2: Conventional and delay-based BPSK.

The DB-BPSK signaling scheme is further motivated by the number of pulse generators recently reported in literature that use a delay line to directly synthesize a UWB pulse in the 3.1-10.6GHz band [1][2][4]. Delay-line-based pulse generators are capable of generating precisely controlled and tunable pulses, and they offer the potential of an all-digital implementation for a higher level integration and no static power consumption. An architecture of a delay-line-based pulse generator is shown in Fig. 3. In order to synthesize a pulse using this architecture, the per-stage delay of the delay line is tuned to half of the desired RF cycle period. The edges from the delay line taps are then combined to form an RF pulse. This architecture is ideal for implementing DB-BPSK modulation with minimal overhead. Only one additional delay element and the ability to select edges from the delay line are required.

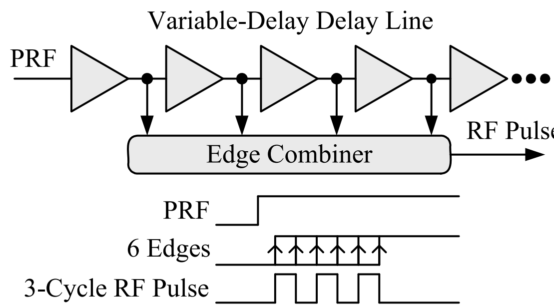

Fig. 3: Delay-line-based pulse generator architecture.

4. SIMULATION RESULTS

A summary of equations describing the spectrum of PPM, BPSK, and DB-BPSK signals is shown in Table 1 [3]. This assumes the signal is modulated by purely random data. $S(f)$ is the Fourier transform of the reference pulse, T_s is the pulse repetition interval equal to $1/PRF$, f_{RF} is the center frequency of the pulse, equal to the cycle frequency for the pulses shown in Fig. 2, and T_{ppm} is the PPM delay assuming a fixed time-hopping sequence. For each modulation scheme, the spectrum is divided into two components: a discrete and continuous part. The discrete part describes the magnitude of any spectral lines, as indicated by the delta functions in these equations. The continuous part is a smooth spectrum, which is the desirable component when considering the FCC mask. The total spectrum is the sum of these two parts. The BPSK (1) signal does not contain a discrete part, while the PPM (2) spectrum contains discrete tones spaced at twice the PRF. When BPSK scrambling is added to a PPM signal (3), the PPM tones are scrambled and the signal has only a continuous part, explaining why BPSK is often used for smoothing the spectrum of a PPM signal.

4.1. DB-BPSK for PPM Scrambling

Just as BPSK is applied to a PPM signal for scrambling, so can DB-BPSK. The spectrum for PPM + DB-BPSK (5) has a discrete and continuous part similar to a PPM spectrum

Modulation	Discrete Spectrum [W/Hz]	Continuous Spectrum [W/Hz]	
BPSK	0	$\frac{1}{T_s}\left\|S(f)\right\|^2$	(1)
PPM	$\frac{1}{4T_s^2}\cdot\sum_{n=-\infty}^{\infty}\left\|S\left(\frac{n}{T_s}\right)\left(1+e^{-j2\pi\frac{nT_{ppm}}{T_s}}\right)\right\|^2\delta\left(f-\frac{n}{T_s}\right)$	$\frac{1}{T_s}\left\|S(f)\right\|^2-\frac{1}{4T_s}\left\|S(f)\left(1+e^{-j2\pi fT_{ppm}}\right)\right\|^2$	(2)
PPM + BPSK	0	$\frac{1}{T_s}\left\|S(f)\right\|^2$	(3)
DB-BPSK	$\frac{1}{4T_s^2}\cdot\sum_{n=-\infty}^{\infty}\left\|S\left(\frac{n}{T_s}\right)\left(1+e^{-j\frac{n\pi}{f_{RF}T_s}}\right)\right\|^2\delta\left(f-\frac{n}{T_s}\right)$	$\frac{1}{T_s}\left\|S(f)\right\|^2-\frac{1}{4T_s}\left\|S(f)\left(1+e^{-j\frac{\pi f}{f_{RF}}}\right)\right\|^2$	(4)
PPM + DB-BPSK	$\frac{1}{4T_s^2}\cdot\sum_{n=-\infty}^{\infty}\left\|S\left(\frac{n}{T_s}\right)\left(1+e^{-j2\pi\frac{nT_{ppm}}{T_s}}\right)\left(1+e^{-j\frac{n\pi}{f_{RF}T_s}}\right)\right\|^2\delta\left(f-\frac{n}{T_s}\right)$	$\frac{1}{T_s}\left\|S(f)\right\|^2-\frac{1}{4T_s}\left\|S(f)\left(1+e^{-j\frac{\pi f}{f_{RF}}}\right)\left(1+e^{-j2\pi fT_{ppm}}\right)\right\|^2$	(5)

Table 1: Summary of discrete and continuous spectral components for PPM, BPSK, and DB-BPSK [3].

(2), with the addition of a $(1+e^{-j\pi f/f_{RF}})$ term. This term acts as a bandstop filter centered around f_{RF}, the center frequency of the pulse. At f_{RF}, the magnitude of this term is zero and the PPM + DB-BPSK equations collapse to those of a BPSK signal (1). At frequencies around f_{RF}, the filter term attenuates the unwanted lines of the spectrum.

The equations for the DB-BPSK scrambled PPM signal are plotted in Fig. 4, along with the PPM spectrum. The pulses have a center frequency of 1GHz, a PRF of 10MHz, and a PPM delay of 50ns. The pulse width is 10ns. In this example, the PPM tones are reduced by 10dB (10log(PRF/1MHz)) by using DB-BPSK scrambling. Note that there are some spectral lines beginning to appear on the sidelobes of the PPM + DB-BPSK pulse. This is due to the reduced filtering effect of the $(1+e^{-j\pi f/f_{RF}})$ term, which has been overlaid in the plot. These tones are sufficiently below the main lobe of the pulse and don't effect FCC compliance.

4.2. DB-BPSK for Communication

DB-BPSK modulation may also be used for communicating data with a coherent receiver. One would expect the system performance to be similar to BPSK, with some degradation due to the non-ideal inversion of DB-BPSK. The system shown in Fig. 5 was used to analyze the performance in Matlab.

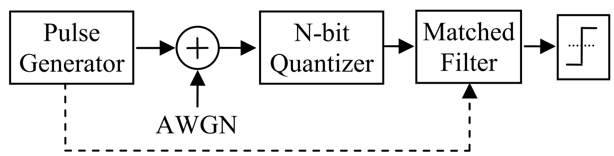

Fig. 5: Receiver architecture implemented in Matlab for BER performance simulations.

The results of the BER simulations are shown in Fig. 6 for BPSK and DB-BPSK modulation when using a 1-bit ADC or no ADC (∞-bits). In both cases the SNR loss from using DB-BPSK is only 0.2dB, which is considered a negligible loss in most UWB system link budgets.

5. HARDWARE VERIFICATION

This section presents measured results using an arbitrary waveform generator and custom RFIC in order to verify that DB-BPSK modulation is a practical and effective means for scrambling a PPM spectrum.

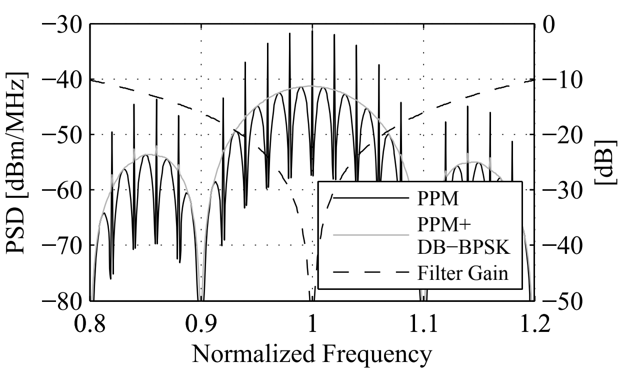

Fig. 4: Comparison of PPM and PPM + DB-BPSK spectra (left axis), along with the filter gain (right axis).

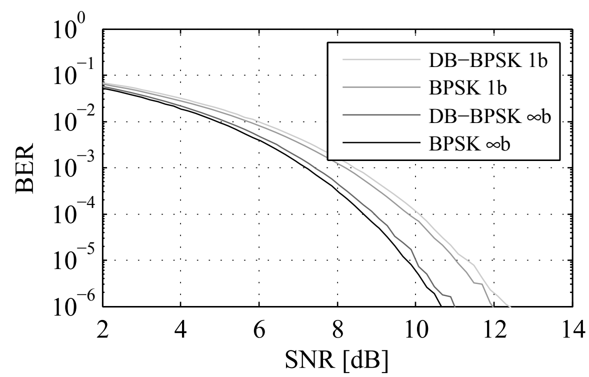

Fig. 6: Waterfall curves of a matched-filter DB-BPSK and BPSK system with a 1 bit ADC and no ADC.

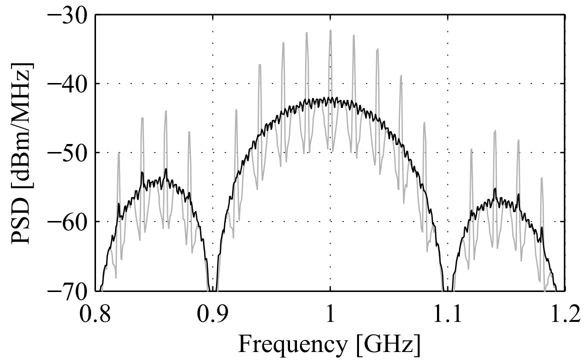

Fig. 7: Measured spectrum for PPM (gray) and PPM + DB-BPSK pulses (black) using the AWG.

5.1. Arbitrary Waveform Generator

A series of PPM and PPM + DB-BPSK modulated pulses were loaded into an arbitrary waveform generator (AWG) and the output was directly measured using a spectrum analyzer. The pulses have a center frequency of 1GHz, a PRF of 10MHz, a PPM delay of 50ns, and a DB-BPSK delay of 500ps. A long PN sequence is used to modulate the train of pulses. The AWG output is an 8-bit, 4GS/s DAC with an analog bandwidth of 1.2GHz. The spectrum analyzer directly measures the AWG output power in 1MHz bins. The measured spectra are shown in Fig. 7, which match very well with the spectra predicted by (2) and (5) and plotted in Fig. 4. The attenuation of the tones in the PPM spectrum is again 10dB (10log(*PRF*/1MHz)), and tones begin to appear in the side lobes of the PPM + DB-BPSK spectrum.

5.2. UWB Transmitter RFIC

DB-BPSK scrambling has also been implemented on a delay-line-based UWB transmitter RFIC targeting the 3.1-5GHz band [5]. The architecture of this transmitter is similar to Fig. 3, with additional programmability to selectively mask the edges sent to the edge combiner to implement the DB-BPSK time shift. The measured spectra of PPM modulated pulses, and PPM modulated pulses with DB-BPSK scrambling are shown in Fig. 8. The pulse center frequency is 3.45GHz and width is 2.6ns, with a 10MHz PRF. The tones in the PPM spectrum are completely canceled in the main lobe by DB-BPSK scrambling. The maximum power spectral density is reduced by 10dB by DB-BPSK scrambling, as expected for a 10MHz PRF. Note that without scrambling, the PPM spectrum exceeds the -41.3dBm/MHz FCC limit. The degradation in performance in the non-coherent PPM receiver due to DB-BPSK scrambling is negligible.

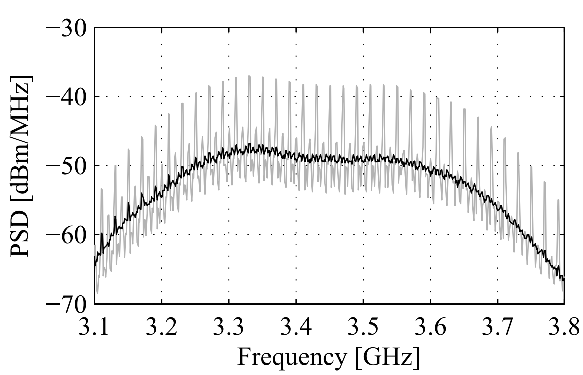

Fig. 8: Measured spectrum for PPM (gray) and PPM + DB-BPSK pulses (black) using the custom RFIC.

6. CONCLUSIONS

Delay-based BPSK can be applied to PPM pulse generators for scrambling the spectrum, or can be used to modulate data as a replacement for BPSK modulation with only a 0.2dB loss in system SNR. DB-BPSK is suitable for delay-line-based pulsed-UWB transmitters, which are gaining popularity due to their low-energy operation and precise pulse generation. The main hardware advantage of DB-BPSK is the simplification of the transmitter circuits required to generate it, and it has been demonstrated with an all-digital transmitter.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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