Digital Architecture for an Ultra-Wideband Radio Receiver

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***Abstract*— This paper presents analysis of a digital Ultra-wideband (UWB) radio receiver operating in the $3.1\ GHz$ to $10.6\ GHz$ band. Analog to digital converter (ADC) bit precision is analyzed on two types of UWB signals - OFDM UWB and pulsed UWB - all in the presence of Additive White Gaussian Noise (AWGN) and a narrowband interferer in the channel. This paper shows how probability of error and the bit resolution of the ADC can be scaled depending on the Signal to Noise Ratio (SNR), Signal to Interference Ratio (SIR), and the type of UWB signal. It also includes considerations on timing recovery for pulsed UWB.**

I. Introduction

UWB radio is a wireless technology that was recently approved for commercial use by the FCC. In [1], the UWB signals for communications applications are specified to have a minimum bandwidth of $500\ MHz$ within the $3.1\ GHz$ to $10.6\ GHz$ spectrum. This bandwidth may be utilized as a monolithic block (uni-band), or broken up into adjacent sub-bands (multi-band). In Section II, this paper will introduce the two UWB signals of interest. Section III presents the digital receiver architecture overview. Section IV presents the assumptions made for the simulations and analysis of ADC bit precision as applied to the two signals, both in the presence of AWGN and a narrowband interferer. Finally, Section V summarizes the results of the paper.

II. UWB Signal Definition

The only constraints upon the spectrum of a UWB signal are the minimum bandwidth ($500\ MHz$) and the maximum spectral density that can be transmitted [1]. There are several ways of modulating the signal in this bandwidth. The two analyzed in this paper are:

- Pulsed UWB: Information is transmitted as a collection of pulses with a small width and a very low duty cycle. Each user is assigned a different Pseudo-random Noise (PN) sequence that is used to encode the pulses in either position (PPM) [2] or polarity (BPSK) [3]. Channelization and processing gain are based on the PN code and the duty cycle.
- Orthogonal Frequency Division Multiplexing (OFDM) UWB: A collection of bits are transmitted at the same time, using synchronized orthogonal carriers. Each OFDM symbol has a cyclic prefix of a certain length that allows simple channel equalization [4].

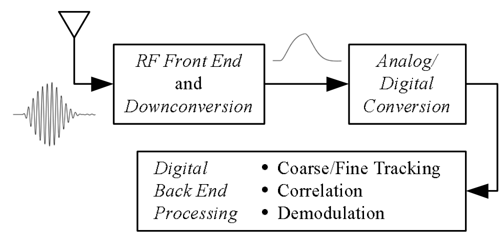

Fig. 1. Digital UWB Approach

III. Receiver Architecture

A block diagram of the receiver architecture is shown in Figure 1. A modulated signal is received by the RF front-end where it is filtered, amplified, and downconverted to a baseband signal. This signal is then sampled by a high-speed ADC. Once digitized, a variety of processing is done on the signal in order to extract the bitstream. A digital architecture allows high levels of programmability across all abstraction layers throughout the receiver.

A. Analog Front-End

The front-end begins with an electrically small wideband receive antenna designed to achieve linear phase, low Voltage Standing Wave Ratio (VSWR), wide beamwidth and high radiation efficiency throughout the entire band. Linear phase ensures constant group delay, minimizing signal distortion and spreading. Low VSWR values satisfy impedance matching requirements, which limit power loss due to reflection at the antenna terminals. Coverage area is maximized by targeting a monopole radiation pattern. Given the power constraints of UWB, the antenna design also targets high radiation efficiency such that the power received at the LNA is maximized.

After the antenna, there is a buffer to provide a wideband impedance match and mitigate bondpad capacitance. This is followed by two or more parallel Low Noise Amplifier (LNA) paths, each covering non-overlapping blocks of frequency within the UWB specification, in order to achieve the required dynamic range in frequency. The number of LNAs depends on the process that is used. The signal is then processed by I/Q demodulators. After the I/Q demodulator, a baseband Automatic Gain Control (AGC) and low-pass filter condition the signal before it is fed to the digital back-end. The local oscillator signal is generated by a Phase-Locked Loop (PLL). This front-end operates in one UWB channel at a time, and has a programmable center frequency and bandwidth which are digitally controlled in the LNA block. Thus, the LNA block should be able to tune and operate anywhere within the 3.1 GHz to 10.6 GHz band. Quadrature downconversion is necessary since pulsed UWB signals are transients instead of steady state sinusoids, thereby making coherent reception and frequency phase locking of the transmitter and receiver very difficult. In addition to the tunability of the LNA, the PLL should be able to hop frequencies quickly. The low-pass anti-aliasing filters will be adjusted according to the bandwidth that the LNA is configured to select. The AGC and subsequent amplification stages occur at baseband to save power and increase controllability and precision. The estimated power consumption of the analog front-end is less than 100mW, excluding the ADC, for a single-ended receiver.

B. Analog to Digital Conversion

Once the original pulse has been reconstructed at baseband, there still remains the task of digitizing it. This is not trivial due to the high bandwidth of the signal to be demodulated. The required speeds dictate the use of an interleaved FLASH ADC. These converters tend to be power hungry, their power scaling exponentially with bit precision [5]. Because of this, the precision used to detect the pulse becomes a critical parameter. The ability to scale bit precision, and thus power dissipation, based on the radio's environment is an attractive feature for low-power communication.

C. Digital Back-End Processing

An important part of the processing performed by the digital back-end is signal synchronization. The receiver achieves it by a two-step process. Coarse acquisition provides a rough estimation of the delay of the signal when nothing is known yet. Fine tracking refines this estimation after coarse acquisition has been achieved. These two steps will be explained in this section for the case of a pulsed UWB signal. The digital back-end can perform other tasks required for the demodulation of the signal. This includes channel equalization or the implementation of a RAKE receiver, but they will not be discussed here.

Figure 2 shows a block diagram of the coarse acquisition process. The input signal is correlated with a local template of the signal with a concrete delay. The result of the correlation is compared to a threshold. If the threshold is met, then coarse acquisition is declared. If the threshold is not met, then the input signal is correlated with a template with a different delay. In each comparison either the UWB signal is present (its delay is very close to the one tried) or is not. If the signal is present there is a probability of detecting it (P_d). If there is no signal present, there is still a probability of meeting the threshold due to noise and declaring a false acquisition (P_{fa}).

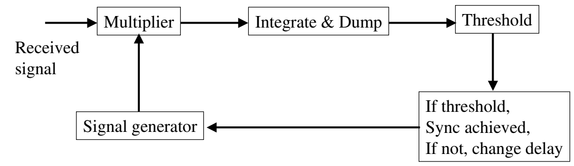

Fig. 2. Block diagram of the coarse acquisition process.

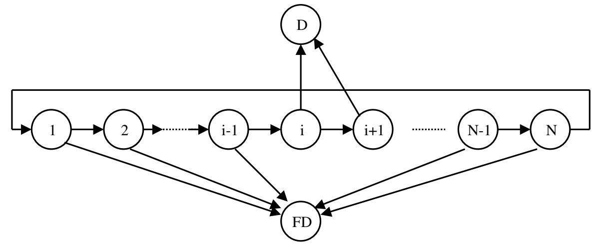

Fig. 3. Coarse acquisition process as a Markov chain.

Coarse acquisition can be understood as a Markov chain as seen in Figure 3. In each of the states depicted (except FD and D), a template with a different delay is correlated to the received signal. The initial state can be any number from 1 to N. The states i and $i+1$ are assumed in this figure to contain the pulses almost correctly aligned. If the pulse is detected there (probabilities $P_{d,i}$ and $P_{d,i+1}$), it goes to a correct detection (state D). The rest of the states do not contain pulses. Any detection in those states implies a false detection (state FD). This event happens with probability P_{fa}. If no signal is detected, each state can only jump to an adjacent one.

It was shown in [6] that the performance of coarse acquisition depends on the value of the threshold, since it also fixes the value of the P_{fa}. Table I shows the average number of trials before achieving coarse acquisition ($E[k]$) and the probability of achieving correct acquisition (P_{cd}) as a function of P_{fa}. The simulations where done for $N = 1550$[1]. It is observed that the probability of correct detection drops sharply when $P_{fa} \leq 10^{-3}$. This happens because P_{fa} becomes comparable to $1/N$, and in N trials more than one false alarm may easily arise. In order to ensure a reasonable probability of correct detection, P_{fa} must be lower than $1/N$.

If the data packet is long enough it may be necessary to include a fine tracking loop to cope with the effects of any frequency difference between transmitter and receiver clocks and of jitter. If the signal is pulsed, the effect of these

[1]This number corresponds to a pulsed UWB signal with a duty cycle of 2% and a code length of 31 pulses

irregularities in timing is that the position of the incoming pulses with respect to those generated in the receiver changes from one pulse to the next. The relative difference in frequency between transmitter and receiver clocks can be defined as:

$$k = \frac{\Delta f}{f_o} \tag{1}$$

If the pulse moves in any direction more than half of its width, V, half of the energy of the signal is lost. The number of pulses necessary for this to happen is:

$$n_{pulses} = \left\lfloor \frac{V f_o (1+k)}{2 N_f k} \right\rfloor \tag{2}$$

Where N_f represents the ratio from the distance between two consecutive pulses and V. If $k = 20\ ppm$, and $N_f = 50$, then $n_{pulses} = 250$. For data packets longer than this it is necessary to employ a fine tracking algorithm.

If fine tracking is totally performed in the digital domain (achieving the change of delay by dropping or advancing samples), it is possible to place all the jitter at the input of the DLL in our model. Usually, the transmitter and receiver have clocks with the same specifications. Both of them will have the same jitter. Modeling them as a Gaussian random variable with zero mean and standard deviation σ_{jitter}, the total jitter present in the system is a Gaussian process of zero mean and variance $\sigma^2_{total} = \sigma^2_{jitter} + \sigma^2_{jitter} = 2\sigma^2_{jitter}$. If the probability of losing a packet of 1000 bits due to synchronization problems is smaller than 10^{-2}, then this variance should be set so that the probability of achieving a deviation greater than the width of the pulse is smaller than 10^{-5} (value obtained using the union bound). For that:

$$Pr = 2N\left(\frac{\Delta t}{\sigma_{jitter}\sqrt{2}}\right) < 10^{-5} \tag{3}$$

Where $\sigma_{jitter} = 74\ ps$ for a pulse of width $2\ ns$.

IV. ADC Specification

A. Specifications of the Signals

For the ADC bit resolution simulations, the following signals are chosen so that each of them achieves a data-rate of $100\ Mbps$ with a bandwidth of $500\ MHz$:

- Pulsed UWB: Each bit of information is represented by one pulse of width $2\ ns$ and the distance between the beginning of two consecutive pulses is $10\ ns$.
- OFDM UWB with 256 carriers: Each OFDM symbol occupies, sampled at $1\ GHz$, 256 samples. In a heavy multipath environment, the expected RMS spread of the channel impulse response is approximately $25\ ns$ [1]. The cyclic prefix has been conservatively chosen to be greater than this value; it has a length of $54\ ns$ (54 samples). 31 bits of information are encoded in each symbol using repetition codes so that each bit is modulating more than one carrier in BPSK. In order to whiten the spectrum, the total number of carriers is divided into four blocks of 31 carriers, while reserving the remainder of them for channel estimation. The four blocks contain exactly the same bits of information, but each scrambled in a unique way. In order to obtain a real baseband signal, the symbols modulating the conjugate carriers are complex conjugates themselves.

These signals are sampled at a frequency of $1\ GHz$. Both signals provide the same data rate. Because they occupy the same channel, they have a similar processing gain. The following differences between the two signals should be highlighted:

- OFDM UWB inherently provides a simple mechanism of channel equalization. On the other hand, a receiver using pulsed UWB should also include an equalizer to mitigate the effects of the channel.
- Synchronization of the receiver is performed differently depending on the type of signal transmitted. This leads to different kinds of synchronization algorithms for the two signals. In the simulations shown in this section, it is assumed that the receiver has achieved perfect synchronization and no jitter or time errors are considered.

B. Automatic Gain Control

The presence of an ADC in the system implies the necessity of an AGC. It is assumed that this system has an instantaneous AGC in order to focus on the impact of quantization noise in the demodulation of the signal. The ADC model has a fixed input range, from -1 to 1. If the number of bits is b, then the quantization step is $\Delta = 2^{1-b}$. The AGC is calibrated with the assumption that, apart from the input signal, there is only AWGN at the input of the ADC. Then, the quantization noise can be assumed to be a uniform random variable of variance $\Delta^2/12$. This assumes that the total input signal amplitude is neither very large (avoiding saturation of the ADC) nor very small (in which the quantization noise tends to $\Delta^2/4$ as only the two smallest levels of the ADC are exerted). The AGC will avoid these extremes. The AGC scales its noisy input signal by a factor α such that the ADC is fed an *optimal* input mean square voltage of σ_o^2, given in Table II for different resolutions. Due to this block, it is safe to assume henceforth that the quantization noise power added by the ADC for all input SNR's is $\Delta^2/12$.

C. Digital Signal Processing

The detection of the bits will depend on the kind of signal received. Two types of receivers are considered:

- OFDM receiver [7]: After sampling the incoming signal, the samples corresponding to the same OFDM symbol are separated. The samples that belong to the cyclic prefix are removed. An FFT is performed over the rest

TABLE I

Model results

	Rect.		Triang.		Gauss.	
P_{fa}	$E[k]$	P_{cd}	$E[k]$	P_{cd}	$E[k]$	P_{cd}
10^{-3}	1930	0.42	1988	0.47	2016	0.48
10^{-4}	903	0.87	927	0.90	942	0.91
10^{-5}	801	0.98	809	0.99	821	0.99

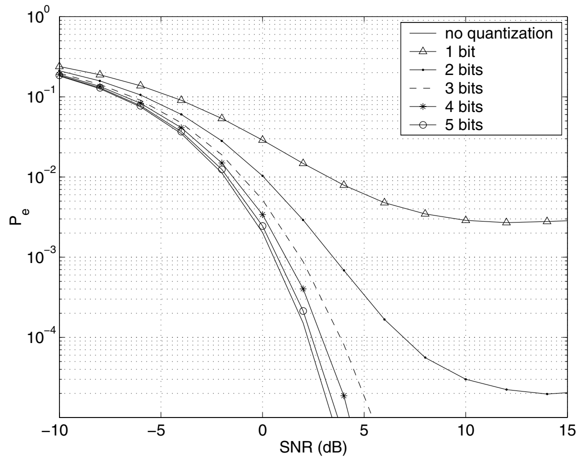

Fig. 4. P_e for the AWGN limited case, OFDM UWB

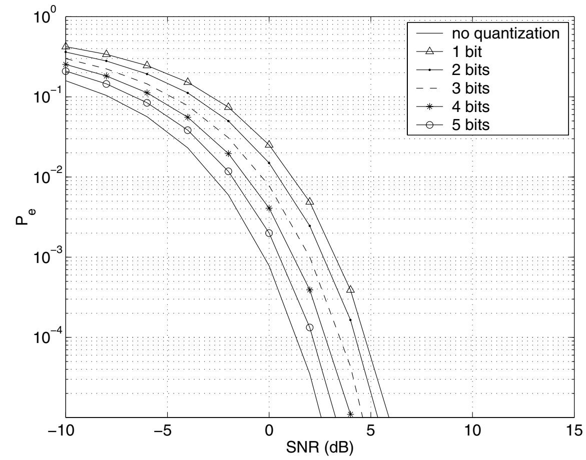

Fig. 5. P_e for the AWGN limited case, pulsed UWB

of the samples. Since each bit of information has been spread over several carriers, the coefficients of the FFT corresponding to those carriers are added. The sign of this number is related to the value of the data bit.

- Matched filter receiver [8]: After sampling, the incoming signal is correlated with a replica of the representation of the data bit. For pulsed UWB, the incoming signal is correlated with a representation of the pulse shape (in this case, a rectangular pulse). The sign of the correlation result indicates the value of the data bit.

D. AWGN Limited Case

Noise samples are uncorrelated. The ADC is preceded by an AGC which sets the power fed to the converter based on the *policy* described in the previous section. For each value of SNR simulated, $15 \cdot 10^6$ independent trials were carried out, based on which a probability of error P_e was assigned. These Monte Carlo simulations provide a standard deviation under 10% for a P_e of 10^{-5}, under 3% for a P_e of 10^{-4} and less than 1% for P_e greater or equal than 10^{-3}. The results are shown in Figure 4 for the OFDM UWB signal. Figure 5 represents the result for the pulsed UWB signal. In both cases, the results were obtained for ADC resolutions of 1, 2, 3, 4 and 5 bits. The curves for a 6-bit ADC were also obtained but since they are already very close to the ideal case with no quantization, they are not presented here. In both figures, the curve that represents the performance for the ideal case with no quantization is provided for comparison.

It is seen in these figures that the OFDM UWB signal performs slightly worse than the pulsed UWB signal. This difference is caused by the presence of a cyclic prefix in the OFDM UWB signals. This prefix reduces the real power used for detection of the information bit by the ratio of the prefix length to the sum of the OFDM symbol length and the prefix length.

TABLE II
σ_o VALUES SET BY AGC

ADC Resolution	σ_o
2	0.2850
3	0.2025
4	0.1425
5	0.1231

These simulations allow the comparison of the two different signals for two regimes:

- High SNR regime: In the case of OFDM UWB, as the SNR increases, P_e tends to a saturation value and cannot be reduced further. In the pulsed UWB, P_e can be made arbitrarily small by increasing the SNR. In the case of the OFDM UWB symbol, as the SNR increases, the only relevant noise term is the quantization noise that asymptotes to a constant value of $\Delta^2/12$. As an FFT of 256 points is performed, the demodulated symbol for each carrier contains noise that is the result of the combination with weights with different phases but the same amplitude of 256 samples of quantization noise. The result can be assumed to be Gaussian. In this case, P_e converges to the probability of error that corresponds to an SNR:
$$SNR = \frac{12 \cdot P_s}{\Delta^2} = 3 \cdot P_s \cdot 2^{2b} \tag{4}$$
For an OFDM UWB signal in the high SNR regime, each additional bit in the ADC will provide a better saturation P_e. In the case of pulsed UWB, a small number of samples is used for each bit. The effect of AWGN can be understood as a change of sign of the sample compared to the sign it should have. As the amplitude of the signal compared to the amplitude of the noise increases, the probability of changing the sign monotonically decreases and an arbitrarily low P_e is achieved.
- Low SNR regime: For the case of pulsed UWB, 1 or 2 bits are sufficient since the plots of these curves are close enough to the ideal case. Due to the saturation effect observed previously, the curves of OFDM UWB for a low number of bits are farther away from the ideal ones.

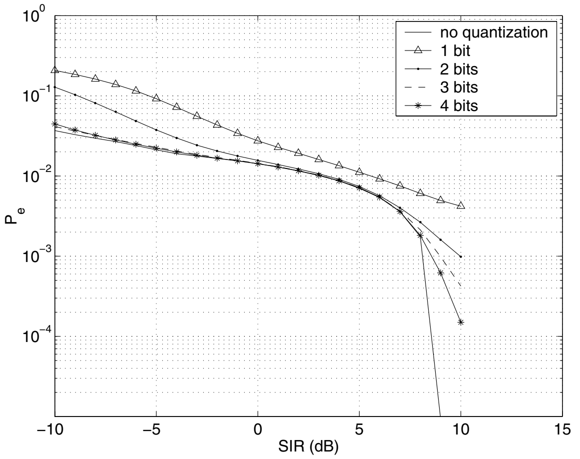

Fig. 6. P_e for the interference limited case, OFDM UWB

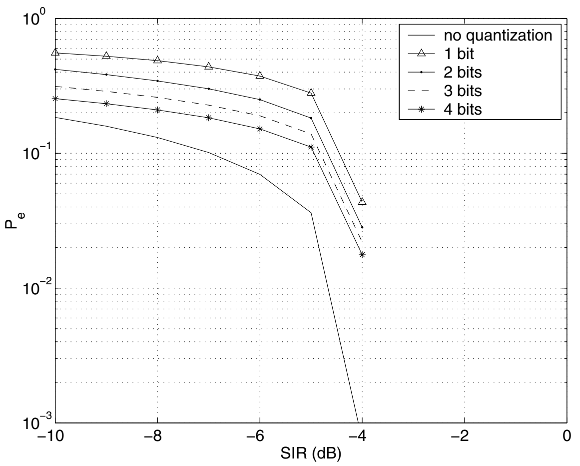

Fig. 7. P_e for the interference limited case, pulsed UWB

A P_e of 10^{-4} can still be achieved in the OFDM case by using an ADC of at least 3 bits.

E. Narrowband Interference Limited Case

The interference that is modeled here is narrowband in the real sense of the word, and is thus described by a pure sinusoid rather than as a modulated carrier with a finite data bandwidth. Thus, there are no abrupt changes of phase over the duration of both the representation of one information bit (in the case of pulsed UWB) or during the duration of an OFDM symbol, including the cyclic prefix, in the case of OFDM UWB. Its frequency is a uniform random variable in the range from 0 to half the sampling rate. Its initial phase is an independent uniform random variable from 0 to 2π. The Monte Carlo simulation provides the same precision as the simulations of the AWGN limited case. The simulation results are shown in Figures 6 (OFDM signal) and 7 (pulsed UWB).

P_e drops to zero for SIR values greater than those represented in the figure. This is because the interference is an amplitude limited signal and the amplitude is small enough so that the samples of the signal do not change. There is a threshold effect for $SIR = -3\ dB$ for pulsed UWB and for $SIR = 11\ dB$ for OFDM UWB. If the signal modulation is more complex, each bit incorporates a higher number of samples of the interference. For all of them, while 1 and 2 bits are still slightly far from the ideal curve, 3 or 4 bits comes close enough to it.

V. Conclusion

In this paper the specifications of a digital architecture for an UWB radio receiver have been analyzed. Digital approaches are preferred over analog for their flexibility. The specifications for the ADCs are relaxed by sub-banding the available bandwidth. The different elements of the receiver have been analyzed. From the point of view of the digital signal processing, several characteristics of the synchronization process have been presented. A good performance of the coarse acquisition is achieved if the probability of false alarm is below $1/N$. The precision of the ADC is a critical parameter since the power consumption of the ADC scales exponentially with the number of bits needed. The possibility of scaling bit precision depending on the channel conditions and the signal received is an attractive feature. It is shown that pulsed UWB signals need 1 or 2 bits in the presence of AWGN, and 4 bits in the presence of a narrowband interferer. OFDM UWB signals require 4 bits in the interference limited case and in the high SNR regime of the AWGN limited case. For the low SNR regime of the AWGN limited case, 1 or 2 bits is enough. Depending on the kind of signal received and the kind of environment (interference or AWGN), the ADC bit precision can be scaled to optimize power consumption.

Acknowledgment

This research is sponsored by Hewlett-Packard under the HP/MIT Alliance.

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