IEEE Conference on Ultra Wideband Systems and Technologies, pp. 248-252, May 2004, Kyoto, Japan

Toward Digital UWB Radios: Part I – Frequency Domain UWB Receiver with 1 bit ADCs

Hyung-Jin Lee[1], Dong Sam Ha[1], and Hyung-Soo Lee[2]

[1]VTVT (Virginia Tech VLSI for Telecommunications) Lab
Department of Electrical and Computer Engineering
Virginia Tech, Blacksburg, VA 24061
E-mail: {hlee, ha}@vt.edu

[2]Radio and Broadcasting Laboratory
Electronics and Telecommunications Research Institute
Yuseong-Gu, Daejon Korea
E-mail: hsulee@etri.re.kr

ABSTRACT:

Our UWB receiver, based on the frequency domain approach, samples spectral components of the received signal at the pulse repetition rate, and it effectively increases the sampling rate through digital signal processing in the frequency domain [1,2]. In this paper, we investigate employment of 1-bit ADCs for our UWB receiver and propose to use the confidence levels of the individual line spectrum in the correlation operation. Our simulation results indicate that the performance of our receiver with 1-bit ADCs is degraded by only 3 dB at BER of 10^{-1} compared to ideal ADCs and is comparable with a conventional receiver that uses an analog correlator.

1 INTRODUCTION

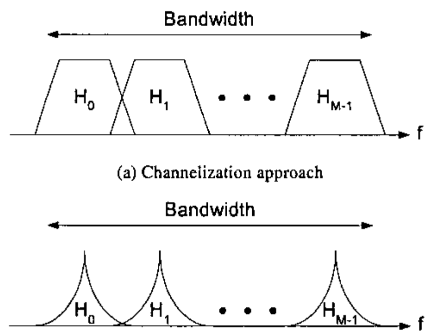
For implementation of digital UWB radios, the challenge stems from the fact that UWB is based on extremely narrow pulses, and direct over-sampling of such pulses requires extremely high-speed analog-to-digital converters (ADCs), often in the order of 10 GHz. Due to the need for prohibitively fast ADCs, all existing UWB receivers resort to an analog correlation approach [3]. The analog approach prohibits exploiting the advantages of digital communications for UWB receivers.

A brute force approach for digital UWB radios is parallel operation of ADCs, in which each ADC is responsible for sampling one temporal point of the received signal [4]. The parallel approach places a high demand on synchronization between multiple ADCs, and the need for precise control of the sampling time for each ADC renders the approach problematic. Another approach is to channelize the received signal into several subbands by means of a bank of bandpass filters as shown in Figure 1 (a) [5]. This approach allocates a frequency band to each ADC associated with a bandpass filter, and the ADC down-samples the filter outputs by a factor M, where M is the number of subbands. The down-sampled outputs are up-sampled by extending the data, and a digital synthesizer reconstructs the signal. The channelization creates several bandpass signals, which allow each ADC to operate at much lower speed. However, the approach requires high performance bandpass filters to avoid aliasing and distortion, and such bandpass filters are complex in hardware. Another method, proposed in [6], also relies on channelization of the received signal. The method shifts the center frequency of each subband to the zero frequency by means of a bank of local oscillators and mixers. As a result, the same lowpass filter can be applied to each subband. In addition to the need for local oscillators and mixers, this method suffers from the same problems of the previous one.

We also investigated a new UWB receiver architecture based on the frequency domain approach, which relaxes the ADC speed requirement [1, 2]. Our frequency domain approach samples spectral components of the received signal at the pulse repetition rate, but it effectively increases the sampling rate through digital signal processing in the frequency domain. It should be noted that the ADC outputs of the previous two methods are sampled signals in the time domain, while the ADC outputs for our method are spectral components in the frequency domain. Figure 1 contrasts the characteristics of the filters for two approaches. As shown in Figure 1, our method does not require the ideal, flat-top bandpass filters necessary for

0-7803-8373-7/04/$20.00 ©2004 IEEE

the time-domain sampling, and hence it does not incur the aliasing problem.



(a) Channelization approach

(b) Frequency domain approach

Figure 1: Characteristics of Bandpass Filters for the Two Approaches

Both approaches, channelization and frequency domain, alleviate the speed requirement of ADCs, but the ADC speed still remains as a critical issue, especially for a high data rate such as 480 Mbps as mandated by the IEEE 802.15.3a standard. Further, a faster speed ADC consumes a large amount of power.

In this paper, we propose to use 1-bit ADCs to address the problem for our UWB receivers. 1-bit ADCs, or equivalently comparators, are lower in circuit complexity, faster, and much more power efficient compared with higher resolution ADCs. Further, the 1-bit ADCs are inherently linear and eliminate various non-liner effects faced such as integral and differential non-linearity errors. However, the use of 1-bit ADCs degrades the system performance. The major objective of the paper is to devise a method to minimize the system performance degradation while employing 1-bit ADCs. According to our simulation results, our method affects the SINR (signal to interference noise ratio) by about only 3 dB at BER = 10^{-1} as compared to ideal ADCs. So the benefits of 1-bit ADCs can justify the performance degradation for many applications. Further, the high speed achievable for 1-bit ADCs enables a designer to adopt a higher processing gain to boost the system performance.

The paper is organized as follows. Section 2 reviews the architecture of our frequency domain UWB receiver and its operation. We describe the proposed method in Section 3 and present simulation results in Section 4. Section 5 concludes the paper. While this paper is limited to issues related to employment of 1-bit ADCs, our companion paper covers other functions of our receiver such as synchronization, intersymbol interference (ISI) cancellation [7].

2 BACKGROUND

As an early work, we investigated a new architecture for impulse-based UWB receivers employing the frequency domain approach [1, 2]. The key idea for the proposed method is to extract the frequency components of the received signal and to perform signal processing in the frequency domain to increase the effective sampling rate. The proposed receiver architecture relaxes the speed requirement of analog-to-digital converters and the bandwidth requirement of LNAs (low-noise amplifiers). The proposed frequency domain approach also leads to simple rake receivers and correlators. We briefly review the receiver architecture.

2.1 Overall Architecture

Figure 2 shows the overall architecture for our impulse-based UWB receiver. The proposed UWB receiver consists of multiple ***narrowband*** LNAs, a frequency domain sampler, an energy harvester block, and a decision block. The energy harvester performs baseband signal processing such as synchronization, correlation and rake operation in the frequency domain, which results in efficient hardware.

A frequency-domain sampler consists of multiple filter banks followed by multiple ADCs as shown in Figure 2. Each filter bank f_i captures the spectral component of the frequency f_i of the received signal, where $f_i = kF_0$ for some integer k and *f_i is an in-band frequency*. The fundamental frequency is determined by the observation window period T_p such that $F_0=1/T_p$. For example, suppose we observe each received pulse for 2 ns with the pulse repetition rate of 100 Mbps and the in-band frequency spectrum ranges from 3.1 GHz to 5.1GHz. $F_0=1/(2\text{ns})$ = 500 MHz, which requires four filter banks with the center frequencies of 3.5 GHz, 4 GHz, 4.5 GHz, and 5 GHz. A salient point of the proposed frequency domain sampler is that the ADC speed is determined by the pulse repetition rate, not the over-sampling rate. So ADCs for our receiver operate at 100 MHz for the previous example.

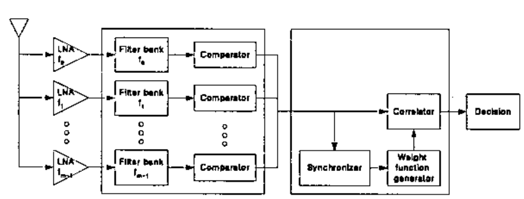


Figure 2: Architecture of the Proposed UWB Receiver

The structure of a filter bank is shown in Figure 3, and a filter bank captures one in-band spectral component f_i of the received signal and generates real and imaginary values of the spectral component. The block with a transfer function of $\frac{s}{s^2+(k\omega_o)^2}$ can be implemented using a passive LC resonator. The two outputs of a filter bank are sampled by two ADCs at the sample rate of $1/T_p$. Note that the filter banks should be reset after sampling.

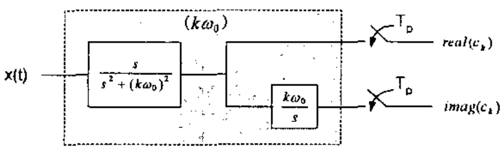


Figure 3: A Filter Bank

A key design issue for the proposed UWB receiver design is the resolution of ADCs. Higher resolution ADCs improves the system performance, but dissipate larger power in addition to higher circuit complexity. To address the problem, we investigate use of 1-bit ADCs in this paper.

2.2 Correlation Operation

To recover a symbol in the time domain, the received signal $r(t)$ is correlated with a template signal $\tilde{r}(t)$. Ideally, the template signal matches the received signal for best performance. A correlation operation in the time domain is a multiplication in the frequency domain as shown in (1).

$$A(\tau) \equiv \int r(t)\tilde{r}(t+\tau)dt = F^{-1}\{R^*(f)\tilde{R}(f)\} \quad (1)$$

where $R^*(f)$ is the conjugate of the frequency spectrum of the received signal. So our frequency domain UWB receiver performs a multiplication between the line spectrum (extracted by filter banks) of the received signal $R^*(f)$ and that of a template signal $\tilde{R}(f)$. The sum of real terms out of the multiplication is the correlation result for $\tau = 0$.

3 PROPOSED METHOD FOR SPECTRAL CODE CORRELATION

An important issue for employment of 1-bit ADCs is generation of template signals. Several schemes are proposed for acquisition of template signals. A simple scheme uses the transmitted pulse shape, but it does not account for the channel condition and results in poor performance [3]. A better approach, which is considered in our design, is to dynamically generate a template signal during each preamble.

A template signal can be obtained as the ensemble average of a sequence of received signals during a preamble period. In case of employment of multi-bit ADCs, the line spectrum of the template signal is average values of those individual multi-bit ADCs outputs. When 1-bit ADCs are employed, the ADCs capture only the sign bits of the line spectrum. Therefore, those ADC outputs fail to yield the line spectrum of the template signal using only the sign bits. To circumvent the problem, we propose to compute the confidence levels of the individual line spectrum of the template signal and to use the confidence levels as weights in the correlation operation.

3.1 Confidence Level of the Line Spectrum

The pair of 1-bit ADCs for a filter bank samples only the signs of the real and imaginary spectral components. To make the analysis tractable, *we assume that the noise of an output of a filter bank is AWGN (additive white Gaussian noise) and the two noise terms of real and imaginary outputs are independent.*

The Fourier coefficient extracted from a filter bank k for a received signal $r(t)$ at certain time under complex AWGN is expressed as (2).

$$R_k = A_k e^{j\theta_k} + N_k, \text{ where } N_k = n_k + j\,\eta_k. \quad (2)$$

Thus, the real and imaginary signals of a filter bank before sampling can be formulated as below.

$$I_k = A_k \cos\theta_k + n_k \quad (3.1)$$

$$Q_k = A_k \sin\theta_k + \eta_k \quad (3.2)$$

The I_k and Q_k terms represent the real and imaginary terms. The probability density functions (PDF) of both n_k and η_k are the same as $p(n) = \frac{1}{\sqrt{\pi N_0}} e^{-n^2/N_0}$. Therefore, the conditional PDFs of noise n, under the transmission of $R_k = A_k e^{j\theta_k}$ are:

$$p(n \mid A_k \cos\theta_k) = \frac{1}{\sqrt{\pi N_0}} e^{-(n-A_k\cos\theta_k)^2/N_0} \quad (4.1)$$

$$p(n \mid A_k \sin\theta_k) = \frac{1}{\sqrt{\pi N_0}} e^{-(n-A_k\sin\theta_k)^2/N_0} \quad (4.2)$$

The probabilities for detecting the real signal as '1' and '-1' for 1-bit ADCs are obtained as:

$$P(1|A_k\cos\theta_k)=\int_0^{\infty}p(n|A_k\cos\theta_k)dn$$
$$=\frac{1}{\sqrt{\pi N_0}}\int_0^{\infty}\exp\left[-\frac{(n-A_k\cos\theta_k)^2}{N_0}\right]dn \quad (5.1)$$
$$=\frac{1}{\sqrt{2\pi}}\int_{-\frac{A_k\cos\theta_k}{\sqrt{N_0/2}}}^{\infty}e^{-x^2/2}dx$$
$$=Q\left(-\frac{A_k\cos\theta_k}{\sqrt{N_0/2}}\right)=1-Q\left(\frac{A_k\cos\theta_k}{\sqrt{N_0/2}}\right)$$

$$P(-1|A_k\cos\theta_k)=\int_{-\infty}^{0}p(n|A_k\cos\theta_k)dn$$
$$=Q\left(\frac{A_k\cos\theta_k}{\sqrt{N_0/2}}\right) \quad (5.2)$$

In the same manner, the probabilities for detecting the imaginary signal are obtained as:

$$P(1|A_k\sin\theta_k)=1-Q\left(\frac{A_k\sin\theta_k}{\sqrt{N_0/2}}\right) \quad (6.1)$$

$$P(-1|A_k\sin\theta_k)=Q\left(\frac{A_k\sin\theta_k}{\sqrt{N_0/2}}\right) \quad (6.2)$$

Therefore, the expected values for the real and imaginary signals for the 1-bit ADC can be calculated from (5) and (6) and are given below.

$$E[I_k]=P(1|A_k\cos\theta_k)-P(-1|A_k\cos\theta_k)$$
$$=1-2Q\left(\frac{A_k\cos\theta_k}{\sqrt{N_0/2}}\right) \quad (7.1)$$

$$E[Q_k]=P(1|A_k\sin\theta_k)-P(-1|A_k\sin\theta_k)$$
$$=1-2Q\left(\frac{A_k\sin\theta_k}{\sqrt{N_0/2}}\right) \quad (7.2)$$

where $E[I_k]$ and $E[Q_k]$ are expected values of the real and imaginary terms, respectively. The expected values indicate the confidence level of the spectrum for an extracted Fourier coefficient R_k and are 1 for a noiseless channel. To increase the confidence level, the outputs of the 1-bit ADCs are averaged over a preamble sequence for each packet of data.

The two expected values of a filter bank indicate the confidence level of the spectral component and are called *weight terms* of the spectral component. The weight W^k for a filter bank k is defined as $W^k=E[I_k]+jE[Q_k]$ for the associated spectral component and is used in section 3.2.

3.2 *Spectral Code Correlation*

Instead of performing correlation with the received signal and a template as described in Section 2.2, we propose a new method called spectral code correlation in this paper. The channel spectral code S_i^k of a filter bank k for a transmitted data symbol D_i is defined as the outputs of 1-bit ADCs in the following manner.

$$S_i^k=\mathrm{sgn}(I_k)+j\ \mathrm{sgn}(Q_k)\big|_{D_i} \quad (9.1)$$

$$\mathbf{S}_i=[S_i^0\quad S_i^1\quad\cdots\quad S_i^{M-1}] \quad (9.2)$$

where M is the total number of the filter banks. The weight function $\mathbf{W}$ is a collection of weights for individual filter banks and is expressed as below.

$$\mathbf{W}=\left[W^0\quad W^1\quad\cdots\quad W^{M-1}\right] \quad (10)$$

The weight function reflects the confidence level on the individual line spectrum of the symbol code. Now, the correlation is performed between the symbol code $\mathbf{S}_i$ and the conjugate version of the weight function $\mathbf{W}$ for the transmit symbol D_i, and the sign of the real term is examined to estimate the sent values as formulated in (11).

$$\tilde{D}_i=real\left\{\mathbf{S}_i\mathbf{W}^{*'}\right\}$$
$$=real\left\{[S_i^0\quad S_i^1\quad\cdots\quad S_i^{M-1}]\begin{bmatrix}W^{0*}\\W^{1*}\\\vdots\\W^{M-1*}\end{bmatrix}\right\}$$
$$=real\left\{\sum_{m=0}^{M-1}S_i^mW^{m*}\right\}$$
(11)

where $\tilde{D}_i$ is the estimated transmit symbol.

The number of filter banks for our receiver is small; for example, it is three to six for our systems. So the circuit complexity of the proposed method is low. In the following section, we present our simulation results for the proposed system.

4 SIMULATION RESULTS

We described a method to use 1-bit ADCs for our UWB receiver based on the frequency domain approach. Other key functions such as synchronization, ISI cancellation schemes for our frequency domain UWB receiver are described in our companion paper [7]. We simulated the performance of our UWB receiver for two different cases: 1-bit ADCs and ideal ADCs. We also simulated a system with a conventional analog receiver that uses an analog correlator in an environment without ISI in which all multipath signals die out before the next pulse is received. It should be noted that a spreading gain is not applied to any of the systems.

- Pulse repetition interval: 10 ns
- Modulation scheme: BPSK (Binary Phase Shift Keying)
- Packet size: 100 Kbits for 1 ms duration
- Preamble size: 1 Kbits for 10 μs duration
- Channel model: CM4 of IEEE 802.15.3a
- Signal bandwidth: 3.1 – 5.16 GHz
- Observation window size: 3 ns
- Number of filter banks: 6

Figure 4 shows the simulation results. The simulation results indicate the employment of 1-bit ADCs degrades the performance of our receiver by about only 3 dB at BER of 10^{-1} compared to ideal ADCs. The degradation of the performance by 3 dB should be considered as small, since the quantization noise increases by 6 dB per reduction of one bit. The performance of our receiver with 1-bit ADCs is comparable to that of the analog correlator receiver, even if ISI is not considered for the analog receiver. The superiority of our receiver is attributed to the effectiveness of the rake operation and channel equalization. (Refer to [1] and [7] for details.)

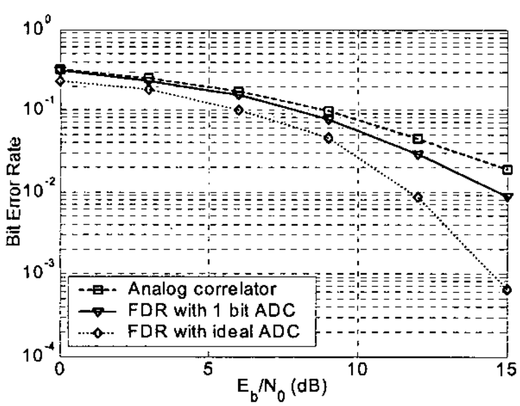


Figure 4: Performance of our receiver and an analog correlator receiver

5 CONCLUSION

Our UWB receiver, based on the frequency domain approach, samples spectral components of the received signal at the pulse repetition rate, and it effectively increases the sampling rate through digital signal processing in the frequency domain [1,2]. We investigated employment of 1-bit ADCs for our UWB receiver in this paper and proposed to use the confidence levels of the individual line spectrum in the correlation operation, which is readily computed from a preamble sequence. Our simulation results indicate that the performance of our receiver with 1-bit ADCs is degraded by only 3 dB at BER 10^{-1} compared to that for ideal ADCs, and the performance is comparable with a conventional analog receiver. Further, the performance of our receiver can be enhanced easily by increasing the number of filter banks. Considering the advantages of 1-bit ADCs over multi-bit ADCs such as low hardware complexity and power dissipation, our receiver with 1-bit ADCs is promising for many applications such as wireless senor networks and RF ID.

6 REFERENCE

[1] H.-J. Lee, D.S. Ha, and H.-S. Lee, "A Frequency-Domain Approach for All-Digital CMOS Ultra Wideband Receivers," *IEEE Conference on Ultra Wideband Systems and Technologies*, pp. 86-90, November 2003.

[2] H.-J. Lee and D.S. Ha, "Frequency Domain Approach for CMOS Ultra-Wideband Radios," *IEEE Computer Society Annual Symposium on VLSI*, pp. 236-237, February 2003.

[3] R.A. Scholtz and M.Z. Win, "Impulse Radio," Invited Paper, *IEEE PIMRC '97*, Helsinki, 1997.

[4] O'Donnell, M. Chen, S. Wang and R. W. Brodersen, "An Integrated, Low-Power, Ultra-Wideband Transceiver Architecture for Low-Rate, Indoor Wireless Systems," *IEEE CAS Workshop on Wireless Communications and Networking*, September 2002.

[5] S.R. Velazquez, T.Q. Nguyen, and S.R. Broadstone, "Design of Hybrid Filter Banks for Analog/Digital Conversion," *IEEE Transactions on Signal Processing*, Vol. 4, pp. 956–967, April 1998.

[6] W. Namgoong, "A Channelized Digital Ultrawideband Receiver," *IEEE Transactions on Wireless Communications*, Vol. 2, No. 3, pp. 502-510, May 2003.

[7] H.-J. Lee, D.S. Ha, and H.-S. Lee, "Toward Digital UWB Radios: Part II – A System Design to Increase Data Throughput for a Frequency Domain UWB Receiver," *IEEE Conference on Ultra Wideband Systems and Technologies*, May.2004.