The Effects of Narrowband Interference on Finite-Resolution IR-UWB Digital Receiver

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Abstract—**Finite-resolution digital receiver is recently considered as a potential way to Ultra Wide Band (UWB) communication systems due to its ability of mitigating the challenge of Analog-Digital Converter (ADC). In this paper, the effects of narrowband interference (NBI) are investigated when finite-resolution digital receiver is used for Impulse Radio-UWB (IR-UWB) system. It is shown that finite-resolution receiver enlarges the impact of NBI. The lower resolution of the UWB receiver is, the more degradations NBI causes.**

Index Terms—**IR-UWB, narrowband interference, finite-resolution receiver.**

I. Introduction

The potential strength of UWB system lies in its use of extremely wide bandwidth, which results in many attractive properties, e.g., high transmission rate and accurate position location [1]. Due to its large transmission bandwidth, UWB systems need to coexist with a variety existing communication systems with relatively narrow bandwidth. Thus, these signals are called narrowband interference (NBI) signal in the view of UWB systems. The effect of NBI on various UWB systems based on analog matched filter were addressed by [1] and [2].

On the other hand, to implement digital UWB receiver, high sampling rate of analog-to-digital converter (ADC) is usually required for UWB signal [4][5], and causes large challenges, e.g., unfordable power for high resolution ADC [3]. For this purpose, finite-resolution digital UWB receiver with only one- or two-bit ADC, recently, were proposed by [4]-[6]. A common conclusion from their works is that full-resolution receiver are not recommended as its additional performance gains are too small to justify the increased implementation complexity. To the best of our knowledge, the effect of NBI on finite-resolution UWB receiver has not been investigated yet.

In this paper, we focus our attention on the effect of NBI on IR-UWB finite-resolution receiver. Two questions will be answered: 1) Whether does the finite-resolution receiver strengthen the harm resulted from NBI ? 2) How to model

the received symbol and evaluate the performance of finite-resolution receiver with NBI ? To answer above two questions, we derive bit error ratio (BER) performances of both full- and finite-resolution receivers with NBI. Through analysis, we induce a linear signal model for finite-resolution receiver and answer that two questions.

II. System Model and Analysis

To highlight the effect of NBI, we consider the reception of a single-user scenario IR-UWB system. Assume $p_{tr}(t)$ denote the unit-energy transmitted pulse shape at IR-UWB transmitter, which incorporates the possible time-hopping sequence or direct-sequence spreading code if they are used. Denote $h(t)$ as the dispersive channel response function. We assume a slow varying channel. Let $p_{rec}(t)$ denote the impulse response of low-pass filter (LPF) at the receiver with bandwidth B and gain 1. Then the received reference signal is

$$w(t) = p_{tr}(t) \otimes h(t) \otimes p_{rec}(t) \qquad (1)$$

where $\otimes$ denotes convolution. Therefore, the filtered IR-UWB signal with NBI at the receiver can be expressed as

$$r(t) = \sqrt{E_s} \sum_{k=0}^{\infty} d_k w(t - kT) + r_I(t) + n(t) \qquad (2)$$

where d_k is the kth transmitted symbol, which is equal to ± 1 with equal probability, $r_I(t)$ is the filtered NBI signal, which could be a single-carrier. E_s is the average transmission power and $n(t)$ is the Gaussian noise with zero-mean and variance $N_0/2$ per dimension. T is the impulse period. For convenience, we rewrite (2) as

$$r(t) = r_0(t) + r_I(t) + n(t) \qquad (3)$$

where $r_0(t)$ is the desired received signal

$$r_0(t) = \sqrt{E_s} \sum_{k=0}^{\infty} d_k w(t - kT) \qquad (4)$$

A. Full-Resolution Receiver

For a full-resolution receiver with channel state information, $r(t)$ will be fed into a matched filter. To reveal the effect of NBI, we only consider the receiver has no prior knowledge about the NBI. Hence, we employ a matched filter as

$$w_{mf}(t) = w(T - t), \ 0 \le t \le T \qquad (5)$$

The output of matched filter is sampled at time $t = kT, k = 0, 1, \cdots$. Thus, for the kth symbol, the sampled signal is

$$y[k] = \sqrt{E_s} E_w d_k + d_I[k] + n[k] \qquad (6)$$

where $y[k] = \int_{(k-1)T}^{kT} w(\tau)r(\tau)d\tau$, $E_w = \int_{(k-1)T}^{kT} w(\tau)^2 d\tau$, $d_I[k] = \int_{(k-1)T}^{kT} w(\tau)r_I(\tau)d\tau$ and $n[k] = \int_{(k-1)T}^{kT} w(\tau)n(\tau)d\tau$. Without loss of generality, we set $E_w = 1$. As d_k is equal to ± 1 with equal probability, then the bit error rate (BER) conditioned on $d_I[k]$ is

$$P_{mf} = \frac{1}{2}\left[\mathcal{Q}\left(\frac{\sqrt{E_s} + d_I}{\sqrt{N_0/2}} \right) + \mathcal{Q}\left(\frac{\sqrt{E_s} - d_I}{\sqrt{N_0/2}} \right) \right] \quad (7)$$

where we omit the subscript k for convenience and $\mathcal{Q}(x) = \int_x^{+\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$.

B. Finite-Resolution Receiver

For a finite-resolution digital receiver, the filtered signal is then sampled at Nyquist rate $T_s = 1/(2B)$, and quantized to b-bit resolution. Herein, b is usually less than 4 [5]. Yin *et al*[4] provided a linear Maximum Likelihood (ML) receiver, which is proved to be the optimal receiver of finite-resolution sampling[5][4], to demodulate the sampled signals. Unfortunately, it is difficult to obtain the exact BER performance of the optimal finite-resolution receiver. However, [4] also pointed out that a near-optimal finite-resolution receiver built on the idea of Matched Filter, which is proposed in [6], has approximately equal demodulation weights to optimal receiver in low and middle SNR regime. For very high SNR regime, although the optimal receiver outperforms the near-optimal receiver, both BERs are usually far less than 10^{-6} which is usually reliable enough to data transmission. Thus the near-optimal receiver achieves nearly the same performance to the optimal receiver during our interested SNR range. More importantly, the error performance of near-optimal receiver is easier to be derived. Thus, we herein use the BER of near-optimal receiver to evaluate the effect of NBI in our interested case.

Denote the b-bit quantized version of $r(t)$ as $\hat{r}(t) = Q_b(r(t))$. Set the output set of quantizer as $\{r_1, r_2, ..., r_{2^b}\}$ and quantizer level as $q_1, ..., q_{2^b - 1}$. Then $Q_b(r) = r_i$, if $q_{i-1} \leq r < q_i$. Since the quantization is a non-linear process, it is difficult to analyze the system performance. Thanks to the linearization method (Bussgang theorem) introduced in [7] and [8] for a Gaussian input, we can describe $\hat{r}(t)$ as

$$\hat{r}(t) = \alpha_b r(t) + v(t) \quad (8)$$

where $\alpha_b = E\{Q_b'(r(t))\}$ is the linear gain and $v(t)$ is the nonlinear distortion and follows normal distribution with zero mean and variance σ_b^2. Assume optimal quantizer is employed, where quantization levels are properly chosen so that overall quantization error is minimized (See [9] to find optimal $\{r_i\}$ and $\{q_i\}$), therefore, $\alpha_b = \sum_i \int (q_i - q_{i-1})\delta(r - q_i)f(r)dr$ where $f(r(t))$ is the probability density function of $r(t)$ and $\delta(x)$ is the Dirac delta function. So we also can obtain $\sigma_b^2 = E\{\hat{r}^2(t)\} - \alpha_b^2 E\{r^2(t)\}$. The near-optimal receiver provided in [6] could be expressed as $\text{sgn}(\hat{r}(t) \otimes \omega(T - t))$. Thanks to the linearization process, the sampled signal after matched-filter is modeled as

$$\hat{y}[k] = \sqrt{E_s}\alpha_b d_k + \alpha_b d_I[k] + \alpha_b n[k] + v[k] \quad (9)$$

where $v[k] = \int_{(k-1)T}^{kT} w(\tau)v(\tau)d\tau$ and $\alpha_b = E\{Q'(r(kT))\}$. Follow the derivation of (7), the BER of finite-resolution receiver conditioned on $d_I[k]$ is

$$P_{fr} = \frac{1}{2}\left[\mathcal{Q}\left(\frac{\sqrt{E_s} + d_I}{\sqrt{N_0/2 + \sigma_b^2/\alpha_b^2}} \right) \right. \\ \left. + \mathcal{Q}\left(\frac{\sqrt{E_s} - d_I}{\sqrt{N_0/2 + \sigma_b^2/\alpha_b^2}} \right) \right] \quad (10)$$

Note that if we substitute d_I with its absolute value $|d_I|$, the value of P_{fr} does not change. Therefore, we could analyze (7) and (10) with $d_I \geq 0$ or $|d_I|$. If the UWB system is designed for a desired reliability, e.g., $BER < 10^{-6}$, there should be

$$\frac{\sqrt{E_s} \pm d_I}{\sqrt{N_0/2}} \gg 0 \quad \text{and} \quad \frac{\sqrt{E_s} \pm d_I}{\sqrt{N_0/2 + \sigma_b^2/\alpha_b^2}} \gg 0$$

with high probability during an impulse period. It is also to say the linearization method used in this paper works well if the correlation between $r_I(t)$ and $w(t)$ is very small, which could be assured by proper design of $p_{tr}(t)$, e.g., direct-sequence spreading code. In this case, $\mathcal{Q}(x)$ is a convex function for $x > 0$. In following discussions, we thus only consider the reliable transmission case.

Remarks:

1) From (10), we can see that if σ_b^2/α_b^2 increases P_{fr} increases. Results derived by [7] show that quantizer with more bits causes a less σ_b^2/α_b^2. As a result, lower resolution (smaller b) receiver incurs higher BER. Also by (10) and (7), given $\mathcal{Q}(x)$ is a convex function, we can deduce that P_{mf} and P_{fr} increase as $|d_I|$ increases. Therefore, both finite-resolution sampling and NBI can degrade the system performance.

2) Also due to the property of convex function, we obtain

$$P_1 = P_{fr}(d_I \neq 0) - P_{fr}(d_I = 0) > 0$$
$$P_2 = P_{fr}(d_I = 0) - P_{mf}(d_I = 0) > 0$$
$$P_3 = P_{mf}(d_I \neq 0) - P_{mf}(d_I = 0) > 0$$

Moreover, P_1 and P_3 increases as $|d_I|$ increases and P_1 and P_2 increase as σ_b^2/α_b^2. Hence,

$$P_0(d_I) = P_{fr}(d_I) - P_{mf}(d_I) > 0$$

where P_0 increases as $|d_I|$ or σ_b^2/α_b^2 increases. As a result, there is

$$P_0(d_I \neq 0) - P_0(d_I = 0) > 0$$

and the difference increases as σ_b^2/α_b^2 increases. That is to say lower resolution receiver with the same NBI causes extra degradation incurred by NBI. In other words, finite-resolution receiver strengthens the impact of NBI and NBI enlarges the performance gap between full-resolution and finite-resolution receivers.

3) Compare (7) and (10), we found the only difference is that there is an extra term σ_b^2/α_b^2 in noise variance. Therefore, we can model the finite-resolution receiver as

$$\hat{y}[k] = \sqrt{E_s}d_k + d_I[k] + m[k] \quad (11)$$

Fig. 1.   BER performance of different receivers with SIR=-10dB
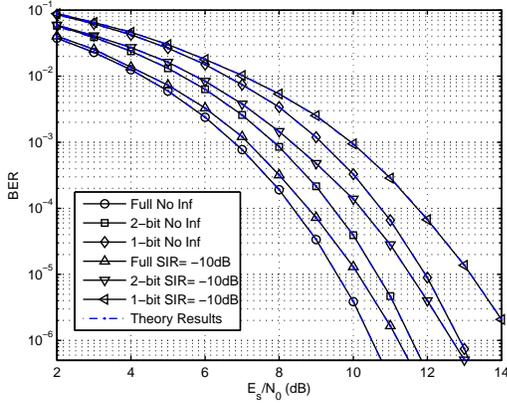

Fig. 2.   BER performance of different receivers with SIR=-15dB

where $m[k]$ is the equivalent Gaussian noise of finite-resolution receiver with zero-mean and variance $N_0/2 + \sigma_b^2/\alpha_b^2$. The linear signal model in (11) provides a general method to analyze finite-resolution receiver.

III. NUMERICAL RESULTS

In this section, we verify our theoretical results and remarks. We consider a second derivative Gaussian pulse with time constant $\tau = 0.16$ ns to meet regulation of UWB. We also assume there is no ISI and timing is perfect. The multi-path fading channel we used is the standard CM1 channel model[10]. The simulation parameters are as follows. The filter bandwidth was $B = 8$ GHz. Noise variance is $N_0/2 = 1/2$. We consider 1-bit and 2-bit (3-level [5]) finite-resolution receivers in our simulations. According to the optimal quantizer proposed in [9], we can obtain: $\alpha_1 = 0.7979$ and $\sigma_1^2 = 0.23$ for 1-bit receiver; $\alpha_2 = 0.8829$ and $\sigma_2^2 = 0.11$ for 2-bit receiver. To illustrate clearly, we define signal-noise ratio as SNR= $2E_s/N_0$ and signal-interference ratio as SIR= $E_s/E\{r_I(t)^2\}$. The carrier frequency of NBI is 5 GHz. We model the NBI as a BPSK modulation signal (a tone signal incurs the same performance due to [1]). Note that the simulation results in this paper are obtained through intensive Monte Carlo experiments. As it is difficult to derive the distribution of d_I, we have to average (7) and (10) over 10^8 realizations of d_I to calculate our theoretical results.

Fig. 1 and Fig. 2 show BER performances of different UWB receivers in a standard CM1 channel where NBI exits. In both figures, '**Full**' denotes full-resolution receiver, '**No Inf**' means no interference, and '**n-bit**' denotes finite-resolution receiver with n-bit sampling. First of all, we can see that our theoretical results fit the simulation curves closely for all cases. It verifies our analysis and the linear model. For a specific BER=10^{-5} without NBI, full-resolution receiver can save about 0.8 dB and 2.3 dB SNR respectively, compared with 2-bit receiver and 1-bit finite-resolution receiver. Obviously, as SIR increases BER of each receiver increases. Thus the item 1) of remarks is verified. When SIR= -10 dB and BER=10^{-6}, full resolution receiver loses about 0.7 dB, 2-bit receiver loses about 1.2 dB and 1-bit receiver loses about 1.5 dB than its corresponding receiver without NBI respectively. We also can
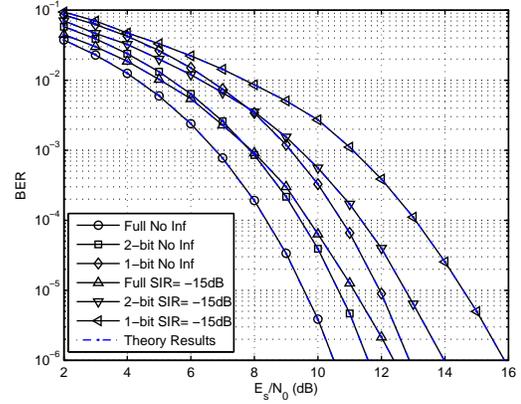
see from Fig. 2 that when SIR= -15dB and BER=10^{-6}, full-resolution receiver without NBI achieves about 2 dB gain over full-resolution with NBI, about 2.3 dB in the case of 2-bit receiver and about 3 dB in the case of 1-bit receiver. Through comparing, we find that finite-resolution receiver indeed enlarges the degradation incurred by NBI and lower resolution receiver causes greater enlargement.

IV. CONCLUSION

In this paper, we provided BER performances of both full-resolution and finite-resolution IR-UWB receiver in the presence of NBI. We found that both finite-resolution sampling and interference can degrade the receiver performance and finite-resolution receiver strengthens the harm of NBI.

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