Sparsity Based UWB Receiver Design in Additive Impulse Noise Channels

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***Abstract*—Ultra wide-band (UWB) technology is suitable for high data rate short range wireless communication, localization, and imaging techniques. In many applications, UWB devices may be operating in environments with impulse noise sources or narrow band interferers, called as impulse interferer. Impulse noise of high amplitude and random occurrences can overlap a UWB signal making UWB signal recovery difficult at the receiver end. The conventional UWB receiver is not optimal for impulse noise since they are designed for additive Gaussian noise assumption. In this paper, we propose a robust UWB receiver designed to mitigate the detrimental effects of impulse noise by exploiting the distinct characteristics of the signal and impulse noise. The bit error rate (BER) performance of binary phase shift modulated UWB pulses is demonstrated in the presence of impulse noise using the proposed receiver design. Simulation results establish robustness of the proposed method to the presence of additive impulse noise.**

I. INTRODUCTION

Ultra wide-band (UWB) communications at millimeter wave (mmWave) is a potential solution for connecting devices at high data rates. In fact, UWB is viewed as technology for Body Area Networks (BAN), Wireless Sensor Networks (WSN), Localization and Radio Frequency Identification (RFID) as the foundation of Internet of Things (IoT) and specifications for next generation consumer electronics. UWB communication can be one of unlicensed frequency band technology for low and medium range wireless personal area network (WPAN) and wireless local area network (WLAN). UWB impulse radio (IR) is a popular technique of low complexity devices for IoT applications.

UWB communication system's performance is deteriorated by environmental impulsive activities that can completely destroy a frame or a group of frames in the UWB transmission. For example, there are more chances of impulse noise occurrences in moving vehicles due to vehicle engine, other surrounding passing vehicles' ignitions, and switching in power line networks [1]. Another example is systems that use UWB technology for localization and imaging with more chances of being affected by impulse noise, e.g., in factories or exploration areas [2, 3]. Impulse noise has wide spectrum and the performance of a UWB system can be severely degraded depending upon the amplitude and duration of impulse. The large amplitude impulse noise generated in environment can propagate towards the transceiver and force the system to operate in nonlinear region since most receivers are designed with additive Gaussian noise assumption [4].

The above discussion establishes the need for designing robust UWB receivers for IoT applications in impulse noise affected channels. Before we delve further into this problem, we briefly discuss the effect of impulse noise and mitigation techniques in various areas of communication. Effect of impulse noise in power line communication (PLC) for single and multicarrier communication system is analyzed in [5]. BER approximation of UWB communication system in the presence of impulse interferers using distribution model is discussed in [6]. In these distribution models, first noise and interference signals are approximated using distribution models such as generalized Gaussian approximation, Laplace, or Middleton class A model, and later, BER is derived using the corresponding distribution model. The UWB communication system is also analyzed using limiter based Rake receiver in impulse noise [7]. However, generally, limiter based receiver is not optimum for a range of signal-to-noise ratio (SNR). To mitigate the effect of narrow band interference in PLC, UWB systems are analyzed using sparsity of the received signal in compressed sensing (CS) framework [8–10]. In [11], CS based UWB system is discussed in multipath channel, but without any impulse noise interference. In [5, 8, 10, 12], sparsity of UWB signal is exploited to mitigate impulsive interference or impulse noise assuming that it occurs in chunks within a fixed time duration only. In addition, it is assumed that the interference or impulse noise subspace is known in advance at the receiver that is neither practical nor represents the true nature of impulse noise.

In UWB communication, presence of impulse noise makes detection problem even harder since both the desired and the additive impulse noise signals are sparse in nature. Therefore, commonly used basis transformation based methods such as matched filter are not effective in mitigating impulse noise effect. Hence, in this work, we propose to employ a signal separation based method for removing impulse noise prior to the use of matched filter. The proposed method performs satisfactorily in low to moderate impulse noise scenarios.

We compare the performance of binary phase shift keying (BPSK) modulated UWB system using conventional matched (correlator) filter with the proposed receiver structure in impulse noise scenario. The proposed receiver structure has the following advantages: (a) proposed receiver structure is robust to additive impulse noise compared to the conventional matched receiver; (b) receiver structure utilizes received signal sparsity for signal separation and does not require prior knowledge of any signal subspace; and (c) the proposed receiver has better BER performance compared to the conventional matched receiver in additive impulse noise, while receivers in [4, 7] saturate with higher BER floor.

The paper is organized as follows. Basic review of impulse noise is provided in Section-II. In Section-III, the proposed receiver design using signal separation technique is discussed. Simulation results and discussion are presented in Section-IV. Lastly, conclusions are drawn in Section-V.

II. IMPULSE NOISE MODELS

There are various models to generate impulse noise. In this paper, we consider the two most commonly used Bernoulli Gaussian and α-stable impulse noise models.

A. *Bernoulli Gaussian impulse noise*

The impulse noise denoted by $i(t)$ can be represented as [13, 14]

$$i(t) = b(t)k(t), \tag{1}$$

where $b(t)$ is a binary random sequence represented as $(1-\kappa)$, $\kappa \in [0,1]$, and $k(t)$ is Gaussian noise with mean zero and variance σ_I^2. The combined Bernoulli Gaussian impulse noise can be modeled as

$$i(t) = (1-\kappa)\frac{1}{\sqrt{2\pi\sigma_I^2}}\exp\{-t^2/2\sigma_I^2\}. \tag{2}$$

If the value of κ is 1, the transmitted signal is not affected by impulse noise distortion during transmission. The value of parameters κ and σ_I can be used to model the duration and amplitude of impulse noise, respectively, in the system. The impulse noise model in (1) is called the Bernoulli Gaussian (BG) model.

B. *α-stable impulse noise*

Another useful model for impulse noise representation is α-stable distribution. Its characteristic function $\varphi(t)$ can be written as [4, 15]

$$\varphi(t) = \exp\{j\lambda t - \gamma|t|^{\alpha}[1 + j\beta sign(t) w(t,\alpha)]\}, \tag{3}$$

where $sign(t)$ is a signum function and

$$w(t,\alpha) = \begin{cases} \tan(\alpha\pi/2), & \text{if } \alpha \neq 1 \\ \frac{2}{\pi}\log|t|, & \text{otherwise.} \end{cases} \tag{4}$$

Parameters α, λ, γ, and β are exponent, location, dispersion, and symmetry parameters, respectively, of the characteristic function $\varphi(t)$. More details on α-stable noise can be found in [4]. In this paper, we have considered symmetric α-stable (SαS) distributions ($\beta = 0$) for the modeling of impulse noise. Without loss of generality, we consider Cauchy distribution of impulse noise with $\alpha = 1$ and $\beta = 0$, and the probability density function (pdf) given by

$$f_c(t) = \frac{1}{\pi}\left(\frac{\gamma}{\gamma^2 + (t-\lambda)^2}\right). \tag{5}$$

III. PROPOSED UWB RECEIVER DESIGN USING SPARSITY

Recently, sparse signal processing methods are increasingly being used in deconvolution, missing data estimation, signals separation, denoising, and many other problems. Since both the UWB signal and impulse noise are sparse, we propose a robust UWB communication receiver design based on signal separation method that exploits this sparsity to mitigate the impact of impulse noise.

For the proposed system model, we assume that the transmitted signal $s(t)$, impulse noise $i(t)$, and Gaussian noise $n(t)$ can be reconstructed from signals sampled at Nyquist rate. Thus, signals $s(t)$, $i(t)$, and $n(t)$ are denoted by vectors as $\mathbf{s} = \left[s(0), s(1), ..., s(N-1)\right]^T$, $\mathbf{i} = \left[i(0), i(1), ..., i(N-1)\right]^T$ and $\mathbf{n} = \left[n(0), n(1), ..., n(N-1)\right]^T$, where N is the total number of samples at Nyquist rate in a fixed time duration. Let us consider received signal $\mathbf{r}$ in the k^{th} frame as below

$$\mathbf{r} = \mathbf{s} + \mathbf{i} + \mathbf{n}; \quad \mathbf{r}, \mathbf{s}, \mathbf{i}, \mathbf{n} \in \mathbb{R}^N. \tag{6}$$

The transmitted UWB signal $\mathbf{s}$ is sparse due to few non-zero elements within a fixed time duration. Correspondingly, its sparsity can be defined as [16]

$$\text{sparsity}(\mathbf{s}) = \#\{k : s_k \neq 0, k = 1, 2, ..., N\}, \tag{7}$$

where a signal is called K-sparse if it has only K number of non-zero samples with $K << N$ [16].

The proposed UWB receiver is shown in Fig. 1. This receiver has an additional signal separation block that removes impulse noise before feeding the signal to the conventional matched filter structure (refer to Fig. 1). At the receiver, we apply morphological component analysis (MCA) for impulse noise separation as explained below.

Morphological component analysis (MCA) is a signal separation method that is generally used in image decomposition and audio decomposition. In MCA, it is assumed that the measured signal is a mixture of morphologically distinct signals that are sparse in some transform domain.

In the proposed work, resonance, duration, and oscillatory nature of UWB signal and impulse noise are considered to be the differentiating features for separation. UWB signal's amplitude and arrival time can be quasi-static (but predictable for a certain time duration) depending upon the operating environment. However, impulse noise has completely random amplitude and time of occurrence.

Hence, we note that MCA can be used in the proposed receiver design since both the UWB signal and the impulse noise are morphologically distinct and are sparse too. The objective function for MCA optimization can be represented as [17]

$$J(\mathbf{z}_1, \mathbf{z}_2) = ||\mathbf{r} - \mathbf{A}_1\mathbf{z}_1 - \mathbf{A}_2\mathbf{z}_2||_2^2 + \lambda_1||\mathbf{z}_1||_1 + \lambda_2||\mathbf{z}_2||_1 \tag{8}$$

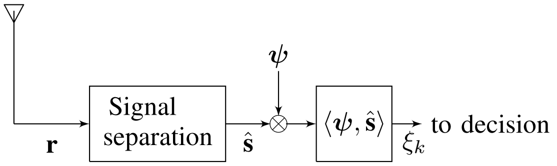

Fig. 1. Proposed receiver structure of UWB communication system

where λ_1 and λ_2 are the regularization parameters and, $\mathbf{A}_1$ and $\mathbf{A}_2$ are the sparsity bases for the desired signal and impulse noise, respectively. The objective function $J(\mathbf{z}_1, \mathbf{z}_2)$ is minimized with respect to $\mathbf{z}_1$ and $\mathbf{z}_2$. Signals (signal and impulse noise) are estimated using MCA as

$$\hat{\mathbf{s}} = \mathbf{A}_1 \mathbf{z}_1^* \quad \text{and} \quad \hat{\mathbf{i}} = \mathbf{A}_2 \mathbf{z}_2^* \tag{9}$$

where $(\mathbf{z}_1^*, \mathbf{z}_2^*)$ represent optimal values that minimize the cost function $J(\mathbf{z}_1, \mathbf{z}_2)$ in (8).

Equation (8) can be solved by using various algorithms such as matching pursuit, basis pursuit methods, iterated soft-thresholding algorithm, split augmented Lagrangian shrinkage algorithm (SALSA), etc. In this work, we apply SALSA because it is computationally efficient compared to matching pursuit and iterated soft-thresholding algorithms.

SALSA is effective in separating two sparse signals (that are different in some form) from their combination [17] and is used for solving linear inverse problems, large scale non-smooth optimization with fast convergence in denoising, deconvolution, signal separation. The procedure of solving (8) for impulse noise removal using SALSA is described in **Algorithm 1** below. Since the transmitted signal $\mathbf{s}$ is sparse in UWB, hence, $\mathbf{A}_1$ is considered to be the identity matrix. Transient signals having non-predefined shapes and frequencies that can be effectively transformed for sparse representation using short-time Fourier transform (STFT) [17]. Hence, for the impulse noise $\mathbf{i}$, $\mathbf{A}_2$ is the inverse STFT matrix. The window length to determine the size of the identity and STFT matrices for additive impulse AWGN and multipath channel (CM1) is considered to be 10 and 60 nanoseconds, respectively.

Algorithm 1 SALSA for signal separation

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Initialize: $\mu = 0.8, \mathbf{d}_1 = \mathbf{d}_2 = \mathbf{0}, \lambda_1 = \lambda_2 = 0.6, \mathbf{A}_1, \mathbf{A}_2$
Input: $\mathbf{r}, \mathbf{z}_2, \mathbf{z}_2$
For : # of iterations=50
$\mathbf{v}_i \leftarrow \mathbf{soft}(\mathbf{z}_i + \mathbf{d}_i, \lambda_i/\mu) - \mathbf{d}_i, \quad i = 1, 2$
$\mathbf{c} \leftarrow \mathbf{r} - \mathbf{A}_1\mathbf{v}_1 - \mathbf{A}_2\mathbf{v}_2$
$\mathbf{d}_i \leftarrow \frac{1}{\mu+2}\mathbf{A}_i^H\mathbf{c}, \quad i = 1, 2$
$\mathbf{z}_i \leftarrow \mathbf{d}_i + \mathbf{v}_i, \quad i = 1, 2$
End
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In **Algorithm 1**, $\mathbf{A}_i^H$ is the Hermitian transpose of $\mathbf{A}_i$, and **soft** is a soft-thresholding function defined as

$$\mathbf{soft}(x, T) = \max(1 - T/|x|, 0)x \tag{10}$$

In **Algorithm 1**, first the parameters λ_i, μ, and vector $\mathbf{d}_i$ are initialized. Next, we calculate vector $\mathbf{v}_i$ using the given input signal $\mathbf{z}_i$ and $\mathbf{d}_i$ using parameters λ_i and μ. The vector $\mathbf{c}$ is then calculated by using the updated vector $\mathbf{v}_i$ and the received vector. The vector $\mathbf{d}_i$ is then updated using the values of $\mathbf{c}$, $\mathbf{A}_i$ and μ. Finally, a new set of signals $\mathbf{z}_i$ are obtained using currently estimated value of vectors $\mathbf{d}_i$ and $\mathbf{v}_i$. This completes one iteration of the algorithm. In the next iteration, values are passed from previous iteration and loop runs for specified number (#) of iterations. After completing # of iterations, $\mathbf{A}_1\mathbf{z}_1$ has the desired estimated signal ($\hat{\mathbf{s}}$). This separated signal, $\hat{\mathbf{s}}$ is the input of the conventional correlator based receiver as shown in Fig. 1. The correlator output ξ_k for the k^{th} frame is given by $\langle \boldsymbol{\psi}, \hat{\mathbf{s}} \rangle$, where $\langle ., . \rangle$ is the inner product between $\boldsymbol{\psi}$ and $\hat{\mathbf{s}}$. To determine the transmitted data bit $d(k)$ of the k^{th} frame, correlator output ξ_k is mapped according to decision criterion:

$$d(k) = \begin{cases} -1, & \text{if } \xi_k \leq 0 \\ 1, & \text{otherwise} \end{cases} \tag{11}$$

IV. SIMULATION AND DISCUSSION

In this section, simulation results are presented to validate robustness of the proposed receiver. All simulation results are carried out using BPSK modulation and single pulse transmission per data symbol for single user. The transmitted UWB pulse $\boldsymbol{\psi}$ is the second derivative Gaussian pulse with pulse width parameter $\tau = 0.4$ nsec and corresponding analog pulse, $\psi(t)$ is expressed as [18]

$$\psi(t) = A(1 - 4\pi t^2/\tau^2)\exp(-2\pi t^2/\tau^2), \quad t \in \mathbb{R}, \tag{12}$$

where A is the pulse amplitude parameter that limits the transmitted pulse energy. Sampling frequency of 20GHz is assumed in simulations and BER performance results have been generated using an ensemble of 100 runs. Further, we have assumed that transmitter and receiver are synchronized and SNR corresponds to signal-to-background Gaussian noise ratio with a typical range of -10 to 20 dB, as in the UWB literature. In this paper, SINR is calculated using the ratio of received signal power to impulse noise power.

In Fig. 2, BG model for impulse noise is considered. As it can be seen from Fig. 2, we are able to separate the transmitted signal from the combined signal with good accuracy using the proposed algorithm. From observations in Fig. 2, we conclude that the proposed SALSA based signal separation technique is effective in removing high amplitude outliers from the received signal in the presence of Gaussian noise.

In Fig. 3, simulation results of BPSK modulated UWB system are shown using the conventional matched filter and the proposed receiver in impulse noise scenario. For these simulations, we considered impulse noise duration of 10% of the frame duration $T_f = 10$ nsec. From BER curves of Fig. 3, it is evident that short duration impulse noise can be separated using SALSA algorithm irrespective of the impulse noise amplitude. Further, it is observed that the BER performance of the proposed receiver is not much effected by the duration and amplitude of impulse noise. In fact, the BER performance of the proposed receiver is close to impulse noise free system performance and is free from BER floor as evident from

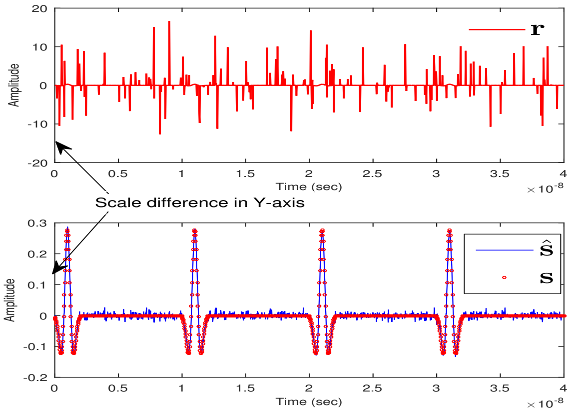

Fig. 2. The original transmitted signal $\mathbf{s}$, estimated signal $\hat{\mathbf{s}}$, and received signal $\mathbf{r}$ (combined signal) for a 40 nsec. time duration. In this simulation we have assumed signal to impulse noise ratio (SINR) is -30 dB with random occurrence of impulse noise samples and additive noise (background noise) at SNR 10 dB.

Fig. 3. Another important observation from Fig. 3 is that the conventional matched (correlator) receiver exhibits BER floor in all cases of different signal to impulse noise ratio (SINR) and that the BER floor depends on the impulse noise strength.

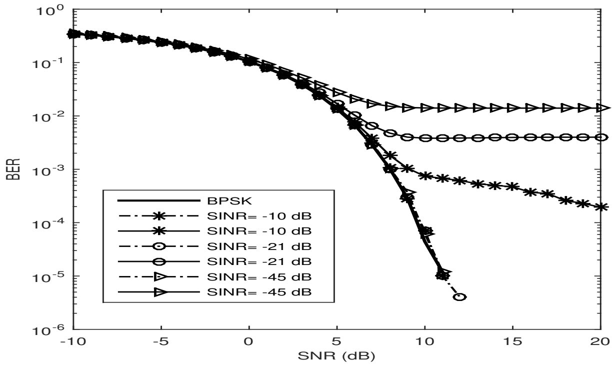

Fig. 3. BER performance of BPSK modulated UWB communication system in impulse noise scenario. The legend 'BPSK' represents the impulse noise free case, the solid and the dotted curves represent performance with the conventional matched and the proposed receiver in BG impulse noise, respectively. All BER curves (shown in dotted lines) using the proposed receiver overlap and are close to impulse noise free system (shown as solid line BPSK).

To verify that the proposed receiver design is generic for different impulse noise models, we also carried out simulation in α-stable noise case. The proposed receiver using signal separation method is shown to have improved performance as illustrated in Fig. 4. The improved performance can be quantified as 1.8, 0.8 and 0.5 decades at 11 dB in case-1, case-2, and case-3, respectively. Further, we observe that as the dispersion γ of α-stable impulse noise decreases, BER performance of the proposed receiver improves.

One of the most popular and simple technique to limit impulse noise is via the use of a limiter that was proposed in [4, 7]. Limiter based receiver exhibits error floor depending upon the limiter value. In order to ascertain the performance of the proposed system, we have simulated BER performance of UWB communication system in impulse noise environment using limiter and the proposed sparsity based signal separation method in Fig. 5. We note that the BER performance using the proposed receiver is better as compared to the limiter based method. The poor BER performance of limiter based approach at SNR greater than 7 dB can be attributed to the fact that the limiter introduces noise floor depending upon the dynamic range of the limiter. For clipping the outliers in the received signal, limiter value of ±2 is assumed in the simulation.

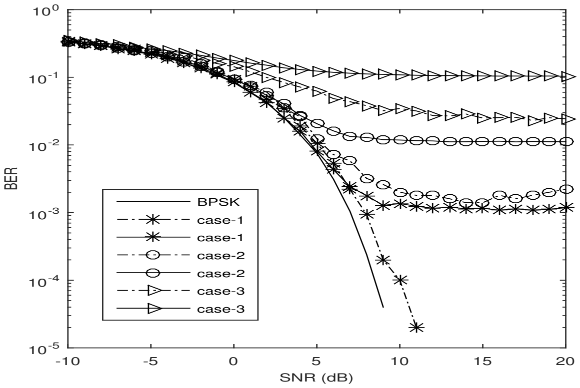

Fig. 4. BER performance of BPSK modulated UWB communication system. The legend 'BSPK' represents the impulse noise free scenario, and the solid and dotted curves represent performance with the conventional matched and the proposed receiver in α-stable impulse noise, respectively. Three cases of α-stable noise are considered. In case-1, SINR= -10 dB ($\gamma = 0.001$); case-2, SINR= -21 dB ($\gamma = 0.01$) and in case-3, SINR= -45 dB ($\gamma = 0.1$ in (5)) for α-stable additive noise in UWB system. We have calculated SINR using finite number of samples generated in simulation, although SINR does not exist theoretically except for $\alpha = 2$.

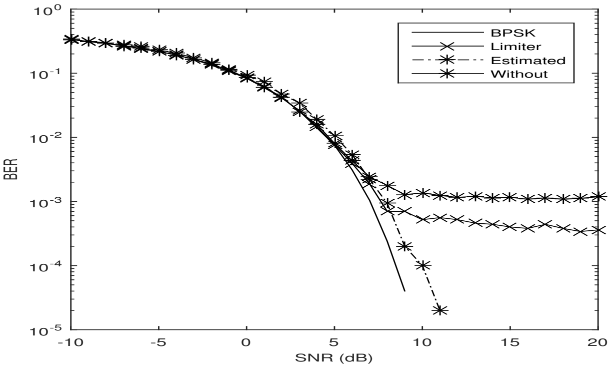

Fig. 5. BER performance of BPSK modulated UWB communication system. The legend 'BPSK' represents the impulse noise free case using the matched filter receiver. 'Limiter' and 'Estimated' BER curves represent performance with the limiter and the proposed signal separation method, respectively, and 'Without' represents the performance using the matched filter in α-stable impulse noise with $\gamma = 0.001$ in (5).

In order to assess the performance of proposed receiver in multipath channel, we simulated BER performance of BPSK modulated UWB system in CM1 channel model with additive impulse and AWGN noise. CM1 is a well known Line of Sight (LOS) channel model for UWB communication with parameters as specified in [19]. BER performance of BPSK using the proposed receiver, limiter based receiver (limiter is at the front end of the conventional receiver), conventional Rake receiver, and Rake receiver proposed in [7] is shown in Fig.

6. Performance of the proposed receiver is better as compared to limiter based and Guney (proposed in [7]) receivers. In this simulation, frame duration $T_f = 60$ nsec., limiter value ± 1 and two highest amplitude multipaths are considered with known channel impulse response at the receiver.

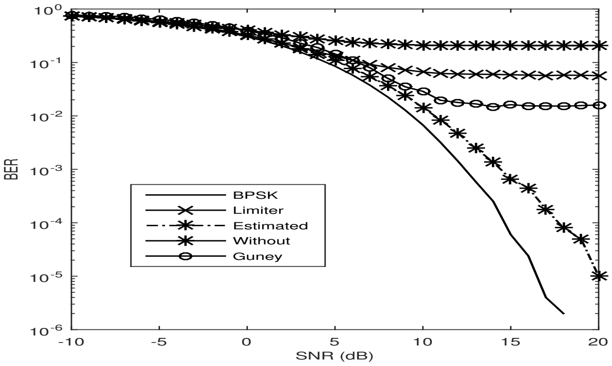

Fig. 6. BER performance of BPSK modulated UWB communication system in multipath CM1 channel model. The legend 'BPSK' represents impulse noise free performance with the conventional Rake receiver. 'Limiter' and 'Estimated' BER curves represent performance with the limiter and the proposed signal separation method before the Rake receiver, respectively, and 'Without' represents the performance using the conventional Rake receiver in impulse noise (BG) scenario at SINR= -10 dB. The legend 'Guney' represents the BER curve using Rake receiver in [7].

From the above simulations, it is evident that the BER performance of the proposed receiver is better as compared to the conventional matched receiver in both the BG and SαS additive impulse noise in Gaussian background noise. Simulations were carried using MATLAB on an Intel(R) Core(TM) i7-4790 CPU @ 3.6GHz with 8 GB RAM and 64 bit operating system. The proposed receiver took an addition 0.096887 seconds for 500 data frames compared to the conventional matched receiver. Thus, it is worth mentioning that the proposed UWB receiver has only a marginal increase in computational complexity compared to the conventional receiver with high gain of upto 2.2 decades at 10 dB and 1.8 decades at 11 dB in additive BG and SαS impulse noise, respectively.

V. CONCLUSION

The BER performance of BPSK modulated UWB system in the presence of impulse noise considering both BG and α-stable models is analyzed. A UWB communication receiver design using signal separation method is shown to perform better than the conventional matched receiver in impulse noise scenario as observed from simulation results. Further, it is also observed that the proposed receiver design is generic and can be used for different impulse noise models and channel conditions without any modification to the proposed receiver structure.

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