American Journal of Signal Processing 2020, 10(1): 10-18
DOI: 10.5923/j.ajsp.20201001.02

Mitigation of Continuous Wave Narrow-Band Interference in QPSK Demodulation Using Adaptive IIR Notch Filter

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Abstract A Continuous Wave Narrow-Band Interference (CW-NBI) can reduce the effective signal-to-noise ratio (SNR), and the quality of the Signals-of-Interest (SoI) in any wireless transmission such as in a Digital Video Broadcasting (DVB-S2) receiver. Therefore, this paper proposes a novel low-complexity anti-jamming filter to mitigate unknown CW-NBI. The approach is to develop a robust least-mean-squared (LMS) algorithm for mitigating CW-NBI in QPSK demodulation but could be used in any communication system. The proposed filter is based on two open-loop Adaptive lattice Notch Filter (ALNF) structure and an LMS algorithm. Each ALNF is composed of a second-order Infinite-Impulse-Response (IIR) filter. The first ALNF is used to estimate the Jamming to Signal Ratio (JSR) and the frequency of the interference. In contrast, the second ALNF is used to remove the interference and adjust the depth of the notch according to the estimated JSR. On the other hand, the LMS algorithm is used to obtain and then track the interference. Simulation results show the performance of the proposed IIR notch filter with the LMS algorithm in reducing and mitigating interference. Also, it provides better output SNR of the notch filter for a given value of JSR and BER performance. For example, at the JSR value of -6 dB, the SNR output of the proposed IIR notch filter was enhanced by 9 dB compared to the case without a filter when $E_b/N_o = 20\ dB$.

Keywords CW-NBI, SNR, QPSK, ANF, ALNF, IIR, LMS, JSR, DVB-S2

1. Introduction

As the telecommunication systems technology is expanding, human-made Radio Frequency Interference (RFI) is continuously increasing. The radio frequency (RF) spectrum is a decisive part of wireless communication. Wireless and satellite systems use the RF spectrum to communicate with ground stations, aircraft, and/or other satellites. As the RF spectrum is a limited resource shared by numerous systems, and taking into account the increasing number of users in terrestrial and space applications, it leads to the RF-crowded spectrum, which is suffering from different unintentional RFI and intentional acts such as jamming. CW-NBI impacts the wireless communications signal at the receiver side, leading to 1) Degradation of the Quality of Service (QoS) of the communication system, 2) Decrease the signal to noise ratio (SNR) and increase the bit error rate (BER), 3) Reduce the quality of the Signals-of-Interest (SoI) drastically. In order to remove or reduce strong CW-NBI, various mitigation techniques have been proposed to mitigate CW and narrowband interference with communication signals such as prediction error filters [1-3], transform domain techniques [4-8], and adaptive notch filters [9-13]. The two approaches in narrowband interference suppression adaptive notch filters are classified into time-domain (TD) and frequency-domain (FD). In TD, papers [14-17] present methods for recovering a single-tone CW narrowband interference using an adaptive lattice IIR notch filter form. The linear prediction is considered as traditional time-domain filtering to remove the time-varying NBI [13]. In contrast, the nonlinear prediction methods considering the non-Gaussian environment [18-21] shown that the nonlinear prediction method achieves a higher SNR than the linear prediction method. The disadvantage of the conventional linear and nonlinear prediction filters requires longer tap filters to mitigate the effect of narrowband interference effectively, which increases the system's complexity [14]. In FD, [22] proposed an N-sigma excision method to reject CWI. Also, FD and the space-time technique increase the hardware complexity and not suitable for mobile devices [23]. Paper [24] presents a comparative performance analysis of two adaptive notch filtering algorithms in GPS, But the disadvantage of this method the trade-off between the quality of interference

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Published online at http://journal.sapub.org/ajsp

removing and the computational complexity of the system. The ANF is useful for the detection and mitigation of jamming signals [25]. Paper [23] presents a novel algorithm for ANF based on direct IIR notch filter form structure, in contrast, the lattice form IIR notch filter provides better convergence properties, and more accurate frequency estimation compared to the direct form implementations [14,16,17]. The notch filter has proved to be an efficient mitigation technique for CW-NBI [15]. In literature, notch filters have been used for removing interference in different types of applications such as biomedical [26], GNSS applications, GPS receiver, and DSSS systems [14,15].

IIR notch filter has constrained zeros on the unit circle, which makes the notch more "depth into infinite" that can remove the interference completely. But the disadvantage of this method creates self-noise caused by eliminating some of the useful signals at the notch frequency while removing the interference [14,16]. Self-noise is briefly described in [27]. To reduce the self-noise, Choi [14] proposed a Narrowband interference suppression technique using open-loop adaptive IIR notch filter in DSSS systems by controlling the depth of the notch according to the estimated JSR and CWI frequency. This will lead to maximizing the output SNR. However, in this paper, the approach is based on proposing a new LMS algorithm for mitigating CW narrowband interference in QPSK demodulation. This LMS algorithm is developed to obtain and then track the interference and adjust the depth of the notch according to the estimated JSR and CWI frequency.

The rest of this paper is organized as follows. Section 2 describes the QPSK modulated baseband signal model in the presence of the CWI "system model,". Whereas Section 3 describes and reviews the adaptive lattice IIR notch filter (ALNF), and proposing a new LMS algorithm for mitigating CW-NBI in QPSK demodulation. The optimal notch depth to maximize the output SNR of the notch filter is described in Section 4. Section 5 presents the simulation results and performance analysis. Finally, Section 6 concludes this paper.

2. QPSK Modulated Baseband Signal and Interference Signal, Models

In this section, a QPSK modulated baseband signal and interference signal models are presented, as in Figure 1. A MATLAB simulation model is used to generate a QPSK signal and CW-NBI at different SNR and JSR.

The received signal (input to IIR notch filter) in the presence of interference can be modelled as follows:

$$r(t) = S(t) + W(t) + J(t) \tag{1}$$

QPSK modulated baseband signal model is as follow:

$$S = IChannel + \mathrm{j}QChannel \tag{2}$$

The CWI is one class of narrowband interference and one of the most common sources of interference. CWI can be modelled as a sinusoidal wave in time, such as single and multiple NBI. When the case of CWI is considered, $J_{cwi}(t)$, Can be modelled as given below [15].

$$J_{multi\ -cwi}(n) = \sum_{n=1}^{m} A_i \cos(2\pi f_i t + \theta_i) \tag{3}$$

Where m is the number of CWI and $A_i, f_i, and\ \theta_i$ are the amplitudes, the frequencies, and the random phases uniformly distributed over $[-\pi, \pi]$, respectively.

In this work, a case of a single interfering is considered and thus $m = 1$. The received signal $(r(t))$ is then sampled and analog to digital converted, leading to

$$r(nT_s) = S(nT_s) + W(nT_s) + J(nT_s) \tag{4}$$

In the rest of this paper, the sampling interval T_s will be ignored for ease of notation and the equation (4) will be adopted as given below

$$r(n) = S(n) + W(n) + J(n) \tag{5}$$

Where S(n) is the desired QPSK modulated baseband signal, W(n) is white Gaussian noise, and J(n) is CW narrowband interference.

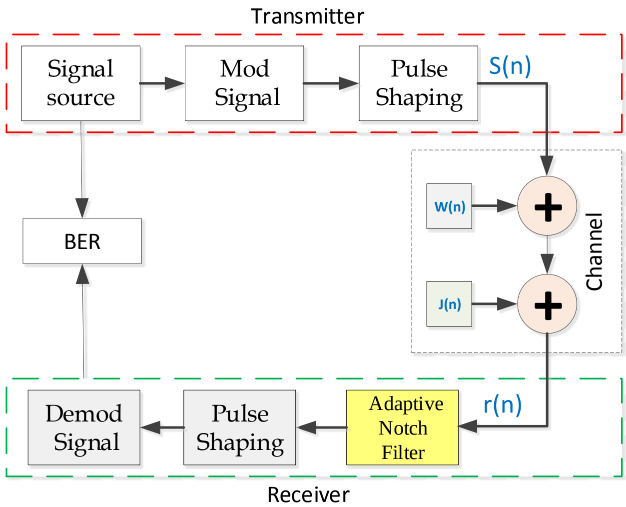


Figure 1. Block Diagram of the System Model

3. Review ALNF and Proposed LMS Algorithm for Mitigating CW-NBI

In this section, the structures of the IIR notch filter is briefly presented. The adaptive IIR notch filter has been used and describes as Adaptive Line Enhancer (ALE) for enhancing the sinusoids corrupted by noise [16]. The IIR notch filter requires much less filter length than the Finite Impulse Response (FIR) and more widely used. Also, it can remove the interference signal or NBI efficiently [28]. The IIR notch filters can also obtain frequency response closer to ideal notch filter compared to FIR notch filters using the same length, [14]. The ANF is a common method used for estimating and tracking unknown frequencies of sinusoids degraded by noise. It has two main forms, direct and lattice forms [29]. In this paper, a system model consists of two adaptive lattice IIR notch filters, $H_1(z)$, and $H_2(z)$ for interference cancellation, which shown in Figure 2. In this system, assumed single-tone CWI and white Gaussian noise are added to QPSK modulated baseband signal as described in Eq.(5). In literature [14,16], the lattice IIR notch filter seems to have better performance than the direct IIR notch filter form. In general, the notch filter has proved to be an efficient mitigation technique for CW-NBI [15,30].

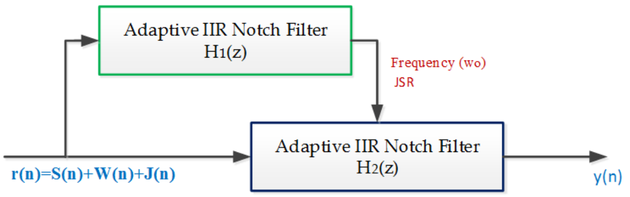


Figure 2. System block diagram of the anti-jamming filter

The adaptive lattice IIR notch filter structure $H_1(z)$ and the LMS algorithm is used to estimate JSR and the frequency of the interference by using the transfer function of the lattice notch filter in Choi [14] is given by Eq.(5).

$$H_1(z) = \frac{N_1(z)}{D_1(Z)} = \frac{1+2k_o Z^{-1}+Z^{-2}}{1+k_o(1+\beta)Z^{-1}+\beta Z^{-2}} \quad (6)$$

Where $0 < \beta < 1$ is the pole-zero contraction factor that adjusts the width of the notch. k_o is related to the notch frequency that decides to reject the CWI, and ω_o, is defined as $k_o = -\cos(\omega_o)$.

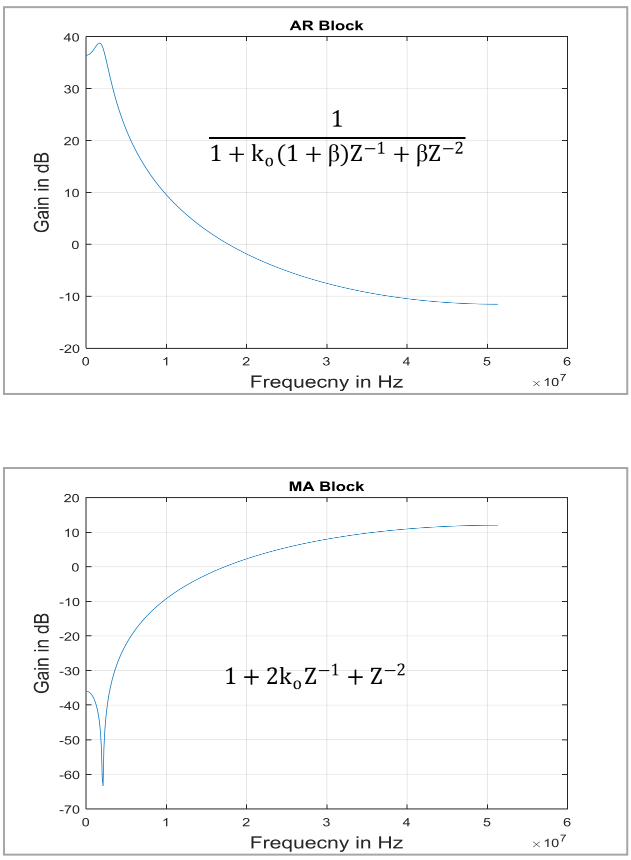


Figure 3. Adaptive IIR notch filter structure

The transfer function of $H_1(z)$ consists of two parts, the auto-regression (AR) block and the moving average (MA) block, which described in Figure 3. The MA block can remove the signal on the interference center frequency as well as the signal located near the interference frequency where the transmitted data are located. Thus, as AR and MA blocks are used simultaneously, the filter can reject only the interference frequency signal so that they reduce the information signal loss [15].

The transfer function of $H_1(z)$ has one notch frequency and zero on the unit circle, which resulting in-depth into infinite.

By taking the inverse Z-transform of $H_1(z)$, it is accessible to an illustration that the filter output can be expressed as given by:

$$y(n) = x(n) + 2k_o x(n-1) + x(n-2)$$
$$-k_o(1+\beta)y(n-1) - \beta y(n-2) \quad (7)$$

The filter goal is to minimize the output power of the filter $E[y^2(n)]$. In this work, equation (12) is the developed LMS algorithm for the proposed adaptive notch filter, which based on the gradient-based method of steepest descent. As we are trying to minimize the mean-squared output energy level $E[y^2(n)]$ instead of minimizing the mean-squared error MSE which is given by

$$k_o(n+1) = k_o(n) - \mu[dy(n)^2/dk_o(n)] \quad (8)$$

Differentiating the output mean-squared w.r.t $k_o(n)$

$$k_o(n+1) = k_o(n) - 2\mu y(n)[dy(n)/dk_o(n)] \quad (9)$$

From equation (7) the gradient function $\left(\frac{dy(n)}{dk_o(n)}\right)$ can be derived as

$$\left[\frac{dy(n)}{dk_o(n)}\right] = -2x(n-1) + (1+\beta)y(n-1) \quad (10)$$

Substinting into equation (9)

$$k_o(n+1) =$$
$$k_o(n) - 2\mu y(n)[-2x(n-1) + (1+\beta)y(n-1)] \quad (11)$$

$$k_o(n+1) = k_o(n) - 4\mu y(n)[x(n-1) - \left[\frac{(1+\beta)}{2}\right]y(n-1) \quad (12)$$

where μ is the convergence factor that controls speed and convergence stability. In equation (12), we can see the simplicity and ease of calculation of the LMS algorithm, which allows the filter weight to be updated averaging, squaring, or differentiating.

Since the normalized notch frequency f_N and k_o are related by $k_o = -\cos(\omega_o)$ where $\omega_o = 2\pi f_N$, then the estimated frequency at sample n is given by

$$\hat{f}_N(n) = \frac{1}{2\pi} arccos(\hat{k}_o(n)) \quad (13)$$

The estimated frequency $\hat{f}_N(n)$ is used to place notch by calculating $k_o = -\cos(2\pi \hat{f}_N)$. Also, using $H_1(z)$ to estimate JSR, by subtracting the output of the notch filter from the received signal as is given by

$$JSR_{dB} = 10\log_{10}\{|r[n] - y[n]|^2\} \quad (14)$$

These parameters are required for the design of IIR notch filter $H_2(z)$ to control k_1 based on the estimation of JSR by $H_1(z)$ to maximize the output SNR at $H_2(z)$. The transfer function of the lattice notch filter $H_2(z)$ [14] is given by

$$H_2(z) = \frac{N_2(z)}{D_2(Z)} = \frac{1+K_0(1+K_1)Z^{-1}+K_1Z^{-2}}{1+K_0(1+\beta K_1)Z^{-1}+\beta K_1 Z^{-2}} \quad (15)$$

where, k_1 is controlling the depth of the notch filter and depends on the estimated JSR by $H_1(z)$ and β is controlling the width of the notch filter. There are many implementation schemes for obtaining $H_2(z)$. But this work implement $H_2(z)$ [14] by cascading all-pole and all zero lattice IIR filter, as shown in Figure 4. If we set k_1=1, the result of the transfer function $H_2(z)$ will be the same as the transfer function $H_1(z)$, which has zero on the unit circle hence resulting in-depth into infinite of the notch that can remove the interference completely. As stated previously, with infinite depth of the notch filter, the interference is removed completely, but it creates self-noise at the notch filter caused by eliminating some of the useful signals. Hence, the depth of the notch (k_1) should be adjusted with the interference power. Therefore, the IIR notch filter $H_1(z)$ and $H_2(z)$ can be performed using the same structure, and the notch of Eq.(15) can be placed on the IF by copying k_o of the IIR notch filter $[H_1(z)]$ that is tuned to IF by Eq.(12).

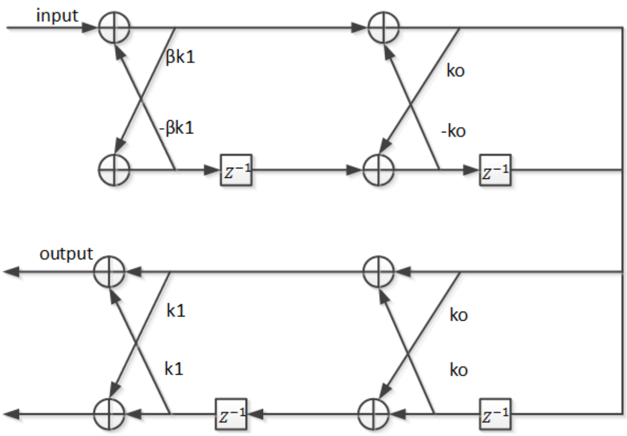


Figure 4. The lattice IIR notch filter structuration

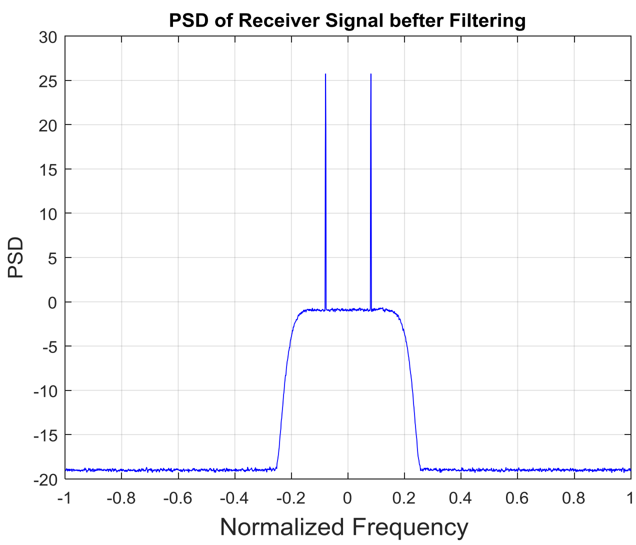


Figure 5. The power spectrum of received signal before filtering

The output of the IIR notch filter $H_2(z)$ can be expressed as

$$y(n) = S_o(n) + W_o(n) + J_o(n) \quad (16)$$

Where $S_o(n)$, $W_o(n)$, and $J_o(n)$ are the output components of the desired QPSK modulated baseband signal, white Gaussian noise, and CW narrowband interference, respectively.

Figure 5 and Figure 6 show the power spectrum of the received signal before and after filtering. From these figures, with infinite depth of the notch filter, the interference is removed completely, but some of the useful signals are also removed while removing the interference. Hence, in order to minimize loss of the useful signal, the depth of the notch (k_1) should be adjusted, which described in the section (4).

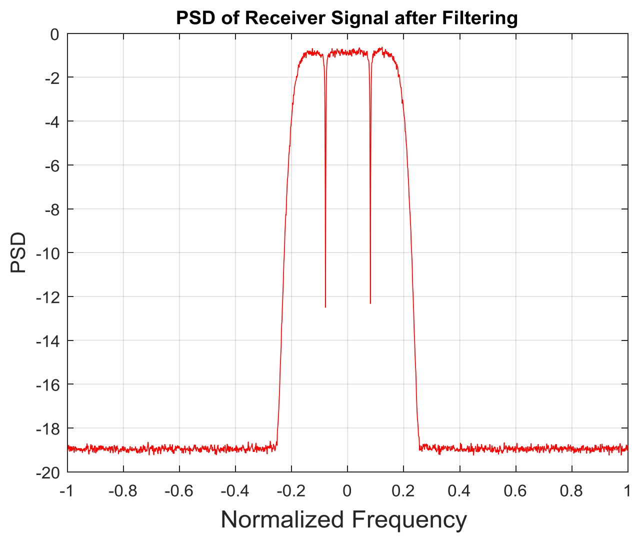


Figure 6. The power spectrum of the received signal after filtering

4. Optimal Value of the Notch Depth to Maximize the Output SNR

Papers [1,8] expressed the output SNR of the notch filter as a function of parameters as given by

$$SNR_{out} = \frac{E[S^2(n)]}{E[(y(n)-S(n))^2]} \quad (17)$$

Where $y(n)$ is the output of the IIR notch filter $H_2(z)$. The SNR_{out} finally can be expressed in terms of the filter parameters as [14], given by Eq.(18).

$$SNR_{out} = \frac{1}{(1+\sigma^2)\left(\frac{(1+k_1^2-2\beta k_1^2)}{1-\beta^2 k_1^2}\right)+JSR\left(\frac{(1-k_1)^2}{(1-\beta k_1)^2}\right)-1} \quad (18)$$

Where σ^2 is the AWGN variance and JSR equals $\frac{A^2}{2}$.

Assuming the first part of equation (18) is equal to D, as shown in equation (19), which called self-noise of the notch.

$$D = (1+\sigma^2)\left(\frac{(1+k_1^2-2\beta k_1^2)}{1-\beta^2 k_1^2}\right) \quad (19)$$

From equation (18), the SNR output is affected by JSR as well as D. As the depth of the notch (k_1) increases, D shows a large value. In order to maximize SNR output, the optimal

k_1 need to be found to minimizes denominator in equation (18) with a fixed value of β. The denominator in equation (18) can be expressed as a function of the depth of the notch (k_1) after some modification.

$$f(k_1) = \left(\frac{(1+k_1^2-2\beta k_1^2)}{1-\beta^2 k_1^2}\right) + G\left(\frac{(1-k_1)^2}{(1-\beta k_1)^2}\right) - \frac{1}{(1+\sigma^2)} \quad (20)$$

Where $G = \frac{JSR}{(1+\sigma^2)}$. To find the optimal k_1, we differentiate $f(k_1)$ and solve $f'(k_1) = 0$ for all possible roots of k_1 as

$$f'(k_1) = \beta^2 G k_1^3 + [2\beta G - \beta^2 G + \beta^2 - \beta]k_1^2 + [1 - \beta + G - 2\beta G]k_1 - G = 0 \quad (21)$$

The equation (21) has at least one real root in the range [0 1] that given the optimal k_1 as a function of JSR.

5. Simulation Results and Performance Analysis

In this section, the simulated performance of the proposed system is investigated in terms of the SNR output of the notch filter for varying JSR and the SOI power (E_b/N_o). A single tone CWI of 0.04 rad center frequency is considered in this work. However, it can be any value in the range of [0-1]. The simulations are run for 1e6 data bits, for the narrowband interference, β is chosen to be 0.98, which gives more satisfying results for various situations. Large β is known to give more accurate estimates of JSR and frequency from the notch filter (H_1z), but slower convergence and tracking [16].

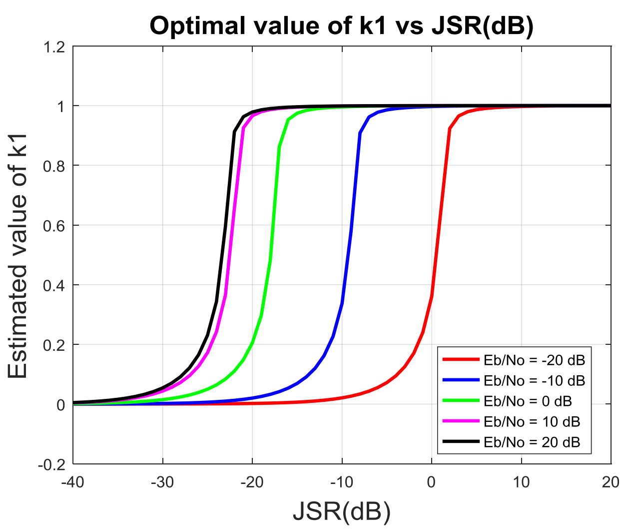


Figure 7. Optimal value of k1 vs. JSR with $\beta = 0.98$

Figure 7 and Figure 8 show the estimated optimal value of k_1 as a function of JSR, with different (E_b/N_o) power and a fixed width of the notch filter "β." From this figure, the k_1 approaches 1 as the JSR increases. In addition, the result shows that the increasing of JSR to approach k_1=1 also depend on (E_b/N_o) power and β, so as E_b/N_o and β decreased, the JSR increasing to approaches k1=1.

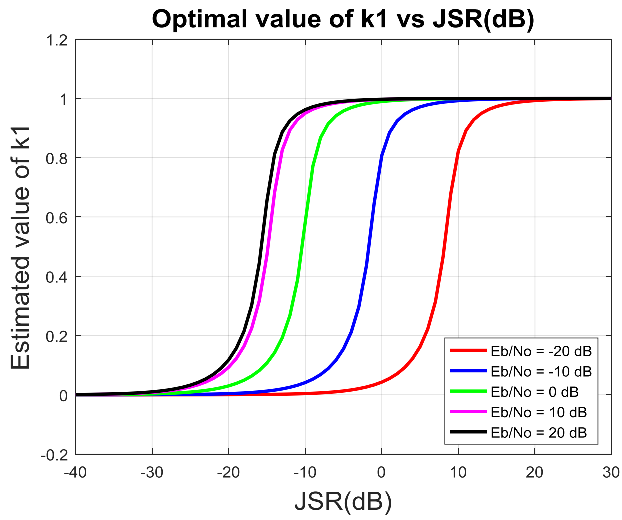


Figure 8. Optimal value of k1 vs. JSR with $\beta = 0.90$

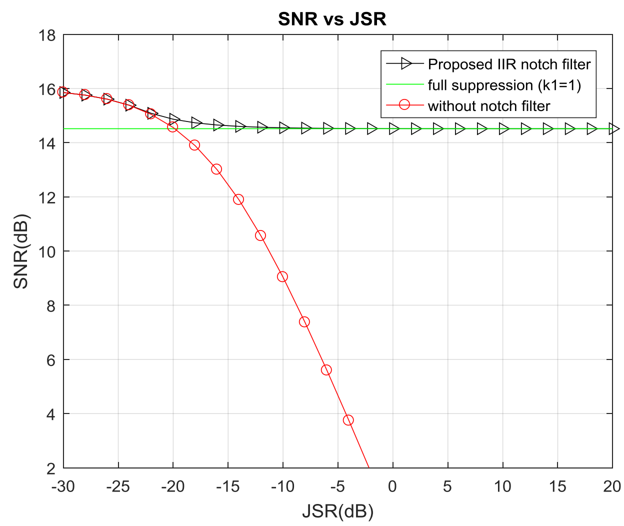


Figure 9. SNR vs. JSR with $\beta = 0.98, \frac{E_b}{N_o} = 20\ dB$

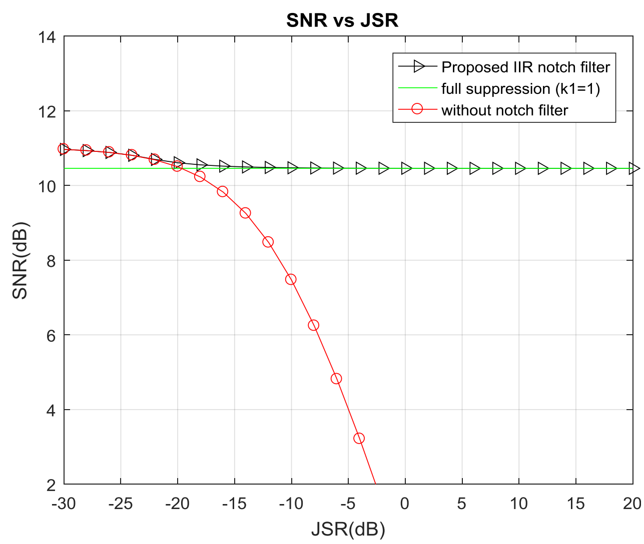


Figure 10. SNR vs. JSR with $\beta = 0.98, \frac{E_b}{N_o} = 15\ dB$

Figure 9 and Figure 10 shown the outcome of SNR vs. JSR by controlling the depth of the notch. Thus, the result shows the proposed IIR notch filter achieves the same output of the SNR as without filter for small values of JSR. The notch becomes deeper for higher JSR while it becomes smaller for a lower value of JSR; the filter is capable of controlling the notch depth deeper and achieves better suppression for higher JSR. The full suppression means in this work is k1=1.

Figure 11 shows that the depth of the notch is depended on the estimated jamming to signal ratio and the frequency of the interference, with $E_b/N_o = 20$ dB.

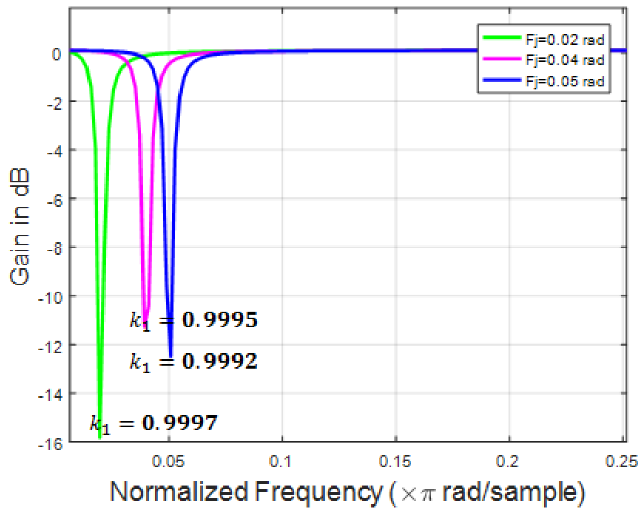


Figure 11. Depth of the notch with estimated JSR

Figure 12 shows the Bit Error Rate (BER) performance vs. JSR, when the simulations run at different JSR values (-15 dB to 15 dB) and with a fixed value of E_b/N_o power (15 dB and 20 dB). The result shows the compared with the Proposed IIR notch filter algorithm and without notch filter "no filtering."

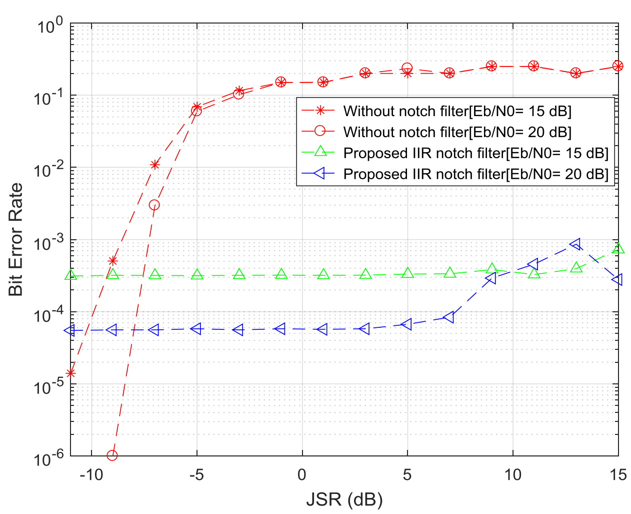


Figure 12. BER vs. JSR with $\beta = 0.98, \frac{E_b}{N_o}[15\,dB, 20dB]$

Figure 13 and Figure 14 show the BER performance vs. E_b/N_o, when the simulations run as E_b/N_o values changes (-20 dB to 10 dB) and with a fixed values of Jamming power (15 dB and 20 dB).

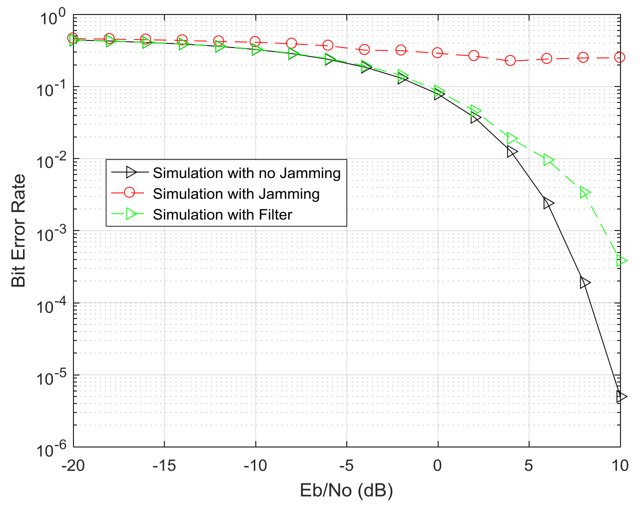


Figure 13. BER vs $\frac{E_b}{N_o}$ with $\beta = 0.98, JSR = 20dB$

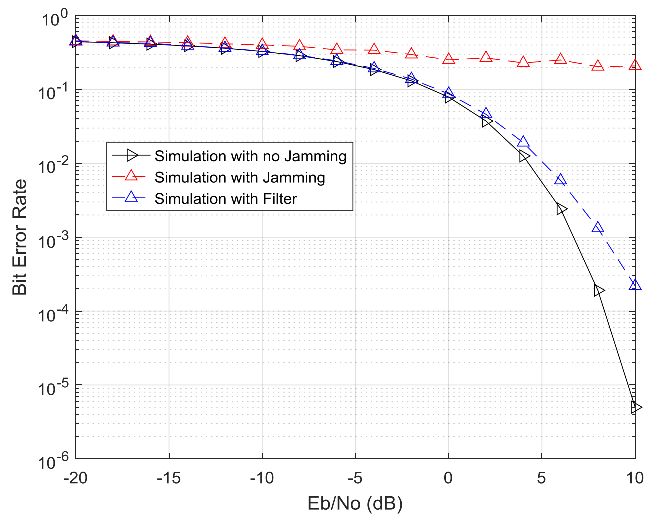


Figure 14. BER vs $\frac{E_b}{N_o}$ with $\beta = 0.98, JSR = 15dB$

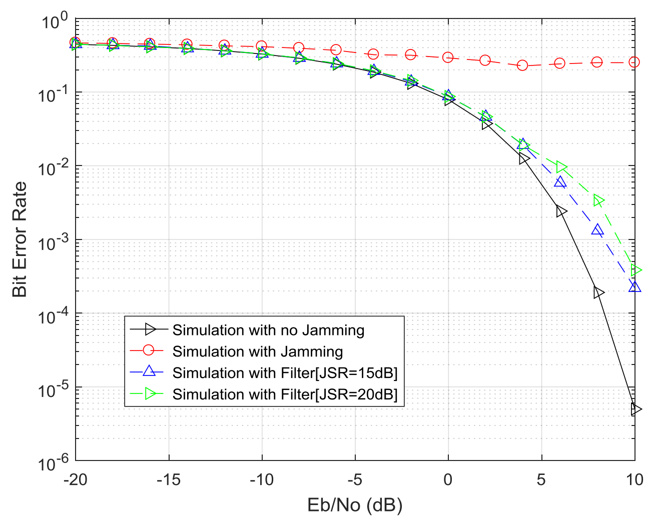


Figure 15. BER vs $\frac{E_b}{N_o}$ with $\beta = 0.98, JSR = 20dB$

Figure 15 shows the BER performance vs. E_b/N_o, when the simulations run as E_b/N_o values changes (-20 dB to 10 dB) and a fixed value of Jamming power (20 dB and 15 dB) with estimated the depth of the notch (k_1).

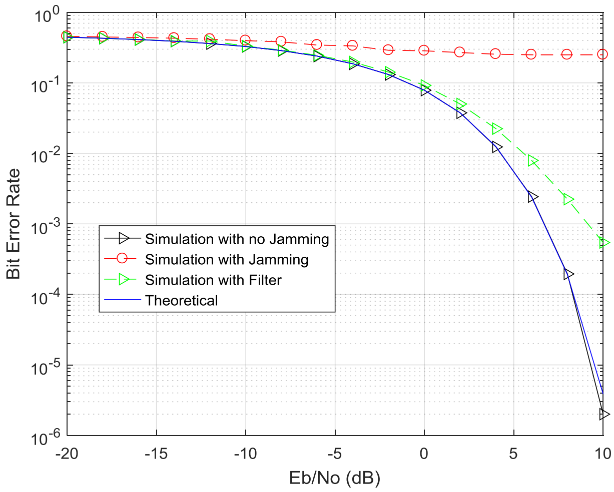
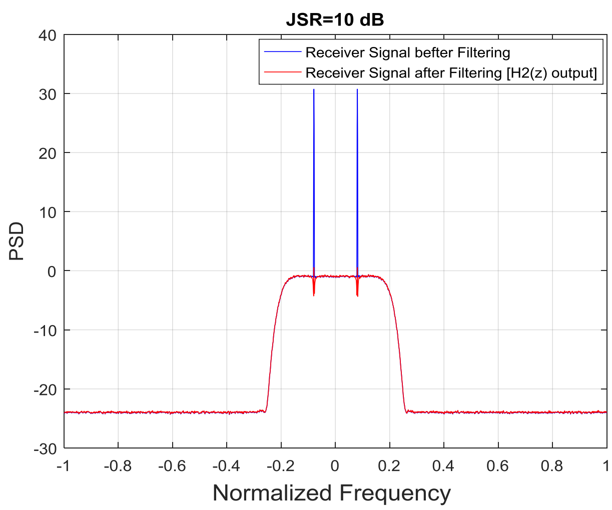
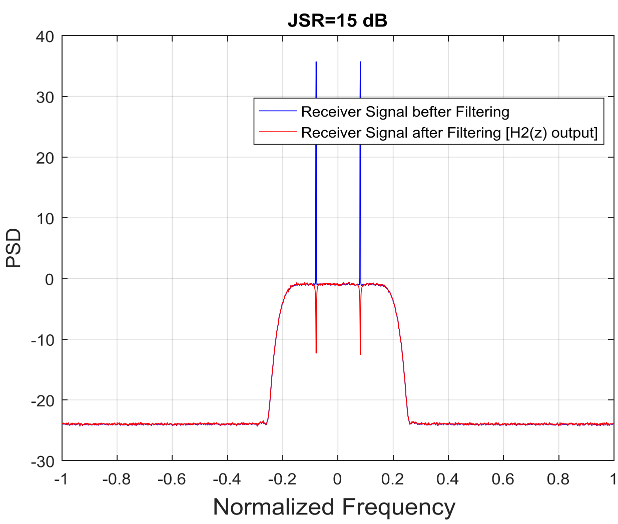


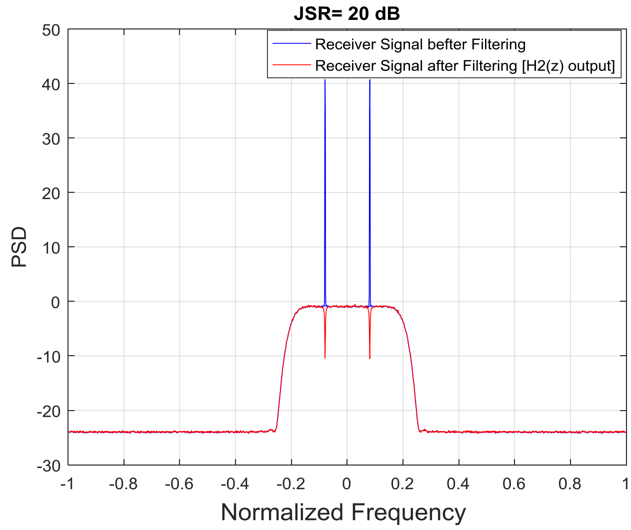
Figure 16. BER vs $\frac{E_b}{N_o}$ with $\beta = 0.98, JSR = 15\ dB$



(a)



(b)



(c)

Figure 17. Input and output PSD of the notch filter with, $\frac{E_b}{N_o} = 20\ dB$, $\beta = 0.98$: (a) $JSR = 20dB$, (b) $JSR = 15dB$, (c) $JSR = 20dB$

Figure 16 shows the BER performance vs. E_b/N_o, when JSR = 15 dB. From this figure, the simulation with no jamming is matched the theoretical.

Figure 17 shows the power spectrum of the received signal before and after filtering. From these figures, with the adjusted depth of the notch filter (k_1), the interference is removed according to the estimated JSR.

6. Conclusions

This paper proposed an IIR notch filter that improved the performance of the system for CW-NBI suppression. The filter comprises two ANF structures and an LMS algorithm working in parallel. The first IIR notch filter detects the interference in the received signal, and then the second IIR notch filter removes the interference and adjusts the depth of the notch according to the estimated power of the interference. The notch becomes deeper for higher JSR to reduce the effect of stronger interference while becomes smaller for a lower value of JSR. Thus, as a conclusion, the proposed IIR notch filter can effectively detect CW-NBI and adjust the depth of the notch for any given value of JSR and provides better BER performance. Also, it maximizes the SNR output of notch filter for lower and higher values of JSR with different values of (E_b/N_o) power. Therefore, this technique can be applied in a DVB-S2 receiver or any other communication and navigation receivers.

ACKNOWLEDGEMENTS

The work reported in this paper was done under AVIO 601 - Interference Mitigation in Satellite Communication, project of LASSENA, ÉTS.

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