NARROW-BAND INTERFERENCE SUPPRESSION IN DIRECT SEQUENCE SPREAD SPECTRUM SYSTEMS USING A LATTICE IIR NOTCH FILTER

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ABSTRACT

This paper proposes an algorithm for the suppression of narrow-band interference in direct sequence spread spectrum (DSSS) systems, based on the open loop adaptive IIR notch filtering. The center frequency of the interference is monitored on-line by the adaptive lattice IIR notch filter in [6] or by time-frequency analysis in [3]. The power of the interference signal is also estimated from the adaptive filters. Another lattice IIR notch filter is placed in front of the receiver, the notch of which is controlled by the frequency estimate to remove the interference. However, the IIR notch filter with the zeros on the unit circle also removes the information signal at the notch frequency while removing the interference and causes data distortion. Hence, the depth of the notch should also be adjusted for the trade-off between data distortion and effective interference reduction. The objective function for adjusting the depth of the notch is defined as the overall signal to noise ratio (SNR). The SNR is expressed as a function of filter parameters and the notch depth that maximizes the SNR is found. Simulation results show that the proposed algorithm yields better performance than the existing FIR notch filter [3] and the conventional FIR LMS algorithm with very long taps [1].

1. INTRODUCTION

The direct sequence spread spectrum technique employs the PN (pseudo noise) code to spread the data sequence over a much wider bandwidth than required. The processing gain from the spread spectrum inherently provides resistance to narrow-band interference (NBI). But when the interference is too strong to be protected by the processing gain, we need an additional narrow-band noise suppressor as a preprocessor. It has been shown that the NBI suppression capability of spread-spectrum systems can be further enhanced by employing adaptive filters prior to despreading [1]- [4]. Traditionally, linear prediction filters have been employed for reducing time-varying interferences [1]. Transform domain filtering was also studied extensively, and the techniques based on time-frequency analysis were proposed for highly nonstationary environments [2]. Short-time discrete fourier transform (DFT), Gabor, wavelet transforms or subband filter banks were applied in these cases. More recently, Amin [3] introduced the open-loop FIR adaptive notch filter for excising the interference. Amin also introduced the optimal algorithm for the adjustment of the notch depth of the FIR filter with respect to the interference power [4].

In general, IIR filters can provide frequency responses closer to an ideal notch filter than can FIR filters of the same length. Hence, we employ the IIR notch filter proposed in [5, 6] for more efficient suppression of NBI with less computational complexity, compared to the FIR filters. More specifically, the open loop adaptive filtering approach in [3] is applied to the IIR notch filter, which places the notch on the interference frequency. In order to find and track the instantaneous frequency (IF) of the interference where the notch frequency should be located, a frequency estimator such as the time-frequency distributions (TFD's) is also needed as in [3]. In our approach, another IIR notch filter of the same structure is employed for the IF estimation, which is used both as an adaptive line enhancer (ALE) for power estimation and as a frequency estimator by the adaptive algorithm in [6].

If the zeros of the notch filter are placed on the unit circle at the interference IF, the filter has infinite notch depth, and thereby leads to perfect excision of the interference. However, the infinite notch depth creates a problem such as self-noise [4], because the information is also completely removed at the notch frequency. The data distortion generated from infinte notch depth causes performance degradation below the case of "no excision" when the interference power is low. Hence, it is required to find the optimal notch depth for the trade-off between data distortion and effective interference reduction. In the proposed notch filter, two parameters related with the depth and width of the

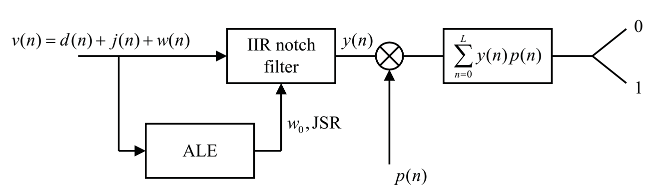

Figure 1: System block diagram

notch can be controlled to maximize the SNR at the filter output. For this purpose, the equation for the output SNR is derived as a function of filter parameters and the optimal notch depth is found for the given frequency and power of the interference. Simulation results show that the proposed algorithm provides better SNR and BER (bit-error-rate) performance than the interference suppresion techniques based on the FIR adaptive filters.

This paper is organized as follows. In Section 2, we review the lattice IIR notch filter. In Section 3, the SNR at the filter output and the adaptive algorithm are derived. In Section 4, simulation results are represented. Finally, Section 5 gives the conclusions.

2. LATTICE IIR NOTCH FILTER

The transfer function of the lattice IIR notch filter in [5] is given by

$$H(z) = \frac{N(z)}{D(z)} = \frac{1 + k_0(1+k_1)z^{-1} + k_1 z^{-2}}{1 + k_0(1+\alpha k_1)z^{-1} + \alpha k_1 z^{-2}} \quad (1)$$

where α is the pole-zero contraction factor, and k_0 determines the notch frequency. The variables k_1 and α control the depth and width of the notch, respectively. The block diagram of the proposed interference cancellation system is shown in Fig. 1. It is assumed that a tone interference and white Gaussian noise are added to a single DSSS signal. As shown in Fig. 1, the ALE is used for the estimation of the frequency and power of the interference, where other analysis methods such as TFD can also be used [3]. The ALE has the same structure as the IIR notch filter and the adaptive algorithm in [6] is used for the frequency estimation. Since the output of the ALE is the narrow-band signal at the interference frequency, we consider the power of the ALE output as the power estimate of the interference. The IIR notch filter reduces the time-varying interference by placing the notch on the interference frequency. It is also required to control the notch depth according to the interference power to prevent excess data distortion. The input to the IIR notch filter is modeled as

$$v(n) = d(n) + j(n) + w(n) \quad (2)$$

where $d(n)$ is the data signal multiplied by the PN code, $j(n)$ is a single tone interference represented by a sine wave with random phase, and $w(n)$ is white Gaussian noise. If the data signal has a normalized magnitude of 1 or -1 and the PN code is long enough, $d(n)$ can be considered as a sequence, $p(n)$, having independent-identical distribution with the same probability of being 1 or -1. Specifically, the input signal can be rewritten as

$$v(n) = p(n) + A\cos(w_0 n + \psi) + w(n) \quad (3)$$

where w_0 is the center frequency of the interference, and ψ is the random phase uniformly distributed over $[-\pi,\pi]$. Then, the output signal of the proposed IIR notch filter is given by

$$y(n) = H(z)v(n) \triangleq p_o(n) + j_o(n) + w_o(n) \quad (4)$$

where $p_o(n)$, $j_o(n)$, and $w_o(n)$ are the output components of the data, the interference, and Gaussian noise, respectively. It is noted that $p_o(n)$ is a distorted version of the information signal $p(n)$ due to the data distortion caused by information removal at the notch frequency of $H(z)$. Hence, it is required to adjust the depth of the notch in order to reduce data distortion while excising the interference effectively.

3. DERIVATION OF SNR AND ADAPTIVE ALGORITHM

For adjusting the filter parameters to have the optimal notch depth, it is required to express the output SNR as a function of the parameters, and find an optimal value that maximizes the SNR for the given environments. From the proposed model in the previous section, the output SNR can be defined as

$$\mathrm{SNR}_o = \frac{E[p^2(n)]}{E[(y(n)-p(n))^2]} \quad (5)$$

where $E[(y(n)-p(n))^2] = E[p^2(n)] - 2E[y(n)p(n)] + E[y^2(n)]$. If we assume that $p(n)$, $j(n)$, and $w(n)$ are independent of one another, $p_o(n)$, $j_o(n)$, and $w_o(n)$ are also independent. Hence, it follows that

$$\begin{aligned} E[y^2(n)] &= E[(p_o(n) + j_o(n) + w_o(n))^2] \\ &= \sum_{k=0}^{\infty} h_k^2 + \sigma_{j_o}^2 + \sigma_o^2 \end{aligned} \quad (6)$$

where h_k is the impulse reposponse of the IIR notch filter, and $\sigma_{j_o}^2$ and σ_o^2 are variances of $j_o(n)$ and $w_o(n)$, respectively. By the independence, $E[y(n)p(n)]$ can be given by

$$E[y(n)p(n)] = E[p_o(n)p(n)] = h_0. \quad (7)$$

From the eqs. (5)-(7), the output SNR is described as

$$\mathrm{SNR}_o = \frac{1}{\sum_{k=0}^{\infty} h_k^2 + \sigma_{j_o}^2 + \sigma_o^2 - 2h_o + 1}. \quad (8)$$

As stated previously, we need to express eq. (8) as a function of filter parameters. For this purpose, we first define $g(n)$ as

$$g(n) = \frac{1}{D(z)} w(n) \quad (9)$$

where $D(z)$ is the all-pole part of the notch filter as in eq. (1). Let $R_{gg}(n)$ be the autocorrelation of $g(n)$. Then $R_{gg}(0)$, $R_{gg}(1)$, and $R_{gg}(2)$ can be expressed as [6]

$$R_{gg}(0) = \frac{1}{(1-\alpha k_1^2)(1-k_0^2)}\sigma^2 \tag{10}$$

$$R_{gg}(1) = \frac{-k_0}{(1-\alpha k_1^2)(1-k_0^2)}\sigma^2 \tag{11}$$

$$R_{gg}(2) = \frac{k_0^2(1+\alpha k_1)-\alpha k_1}{(1-\alpha k_1^2)(1-k_0^2)}\sigma^2 \tag{12}$$

where $\sigma^2 = E[w^2(n)]$. Since $w_o(n) = N(n)g(n)$, the variance of $w_o(n)$ is given by

$$\begin{aligned}\sigma_o^2 &= \{1+k_0^2(1+k_1^2)^2+k_1^2\}R_{gg}(0)\\ &\quad+\{2k_0(1+k_1)^2\}R_{gg}(1)+2k_0R_{gg}(2).\end{aligned} \tag{13}$$

If we substitute eqs. (10)-(12) into eq. (13), σ_o^2 becomes

$$\sigma_o^2 = \frac{1+k_1^2-2\alpha k_1^2}{1-\alpha^2k_1^2}\sigma^2. \tag{14}$$

Moreover, since $\sigma_o^2 = E[w_0^2(n)] = \sigma^2\sum_{k=0}^{\infty}h_k^2$, we have

$$\sum_{k=0}^{\infty}h_k^2 = \frac{1+k_1^2-2\alpha k_1^2}{1-\alpha^2k_1^2}. \tag{15}$$

The next term, $\sigma_{j_o}^2$, in eq. (8) is the interference power after IIR notch filtering. Since $j(n)$ is a sine wave with center frequency w_0, the variance of $j_o(n)$ is given by

$$\sigma_{j_o}^2 = \frac{A^2}{2}|H(e^{jw_0})|^2. \tag{16}$$

If we have the exact interference frequency w_0, we let $k_0 = -\cos w_0$, and eq. (16) becomes

$$\sigma_{j_o}^2 = \frac{A^2}{2}\frac{(1-k_1)^2}{(1-\alpha k_1)^2}. \tag{17}$$

Hence, from eqs. (14), (15), and (17) the output SNR in eq. (8) is expressed in terms of filter parameters as

$$\text{SNR}_o = \frac{1}{(1+\sigma^2)\frac{1+k_1^2-2\alpha k_1^2}{1-\alpha^2k_1^2}+\text{JSR}\frac{(1-k_1)^2}{(1-\alpha k_1)^2}-1} \tag{18}$$

where JSR is the jammer to signal power ratio which is $A^2/2$ in our example. In order to maximize the SNR we need to find k_1 that minimizes the denominator of eq. (18), provided that α is set to a fixed value. The denominator can be expressed as a function of k_1, i.e.

$$f(k_1) = \frac{1+(1-2\alpha)k_1^2}{1-\alpha^2k_1^2}+B\frac{(1-k_1)^2}{(1-\alpha k_1)^2}-\frac{1}{1+\sigma^2} \tag{19}$$

where $B = \frac{\text{JSR}}{1+\sigma^2}$. In order to find the optimal k_1, we differentiate $f(k_1)$ and solve the following equation given by

$$\begin{aligned}f'(k_1) &= \alpha^2Bk_1^3+(2\alpha B-\alpha^2B+\alpha^2-\alpha)k_1^2\\ &\quad+(1-\alpha+B-2\alpha B)k_1-B=0.\end{aligned} \tag{20}$$

Since $f'(0) = -B < 0$ and $f'(1) = (\alpha-1)^2 > 0$, it is easily shown that the equation has at least one real root in the range [0,1]. The roots of eq. (20) is expressed as a function of JSR and we can choose one of the roots that corresponds to the optimal notch depth. Fig. 2 shows optimal k_1 obtained from the theoretical results in eq. (20) as the JSR is changed. Also shown in the Figure is the plot of experimentally obtained k_1 by extensive simulation. This shows that the optimal k_1 derived from the equation is in accordance with the experiments. It also verifies that k_1 approaches 1.0 as the JSR increases. In other words, the notch becomes deeper for stronger interferences and vice versa.

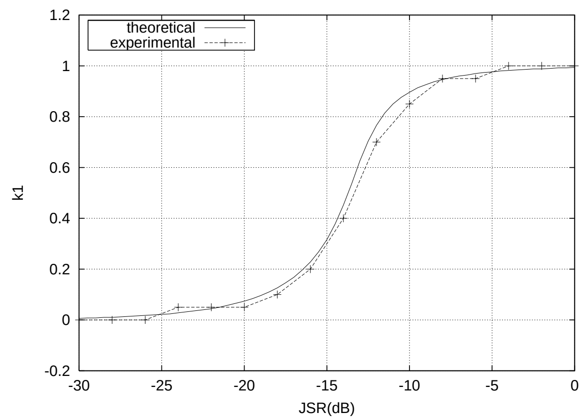

Figure 2: The variation of optimal k_1 with repect to JSR ($N_c = 128$, $\alpha = 0.85$, $\sigma^2 = 10dB$)

4. SIMULATION RESULTS

Fig. 3 shows the comparison of BER of DSSS systems for several algorithms (FIR LMS [1], FIR notch filter [3], and the proposed algorithm) when the interference is very strong. As verified in Fig. 2, k_1 is almost 1.0 in the case of the proposed algorithm for such strong interferences. The result shows that the proposed algorithm provides the lowest BER and is constant over a wide range of JSR. Fig 4 shows the results of SNR vs. JSR in order to demonstrate that the proposed algorithm effectively controls the notch depth to be deeper for the higher JSR. It shows that the proposed algorithm approaches the case of “full suppression” when the JSR is very high, because the notch becomes deeper for this case. On the other hand, it approaches the case of “without notch filter” when the JSR is low in order to prevent data distortion caused by notch filtering. Finally, Fig. 5 shows this relationship in terms of BER vs. JSR.

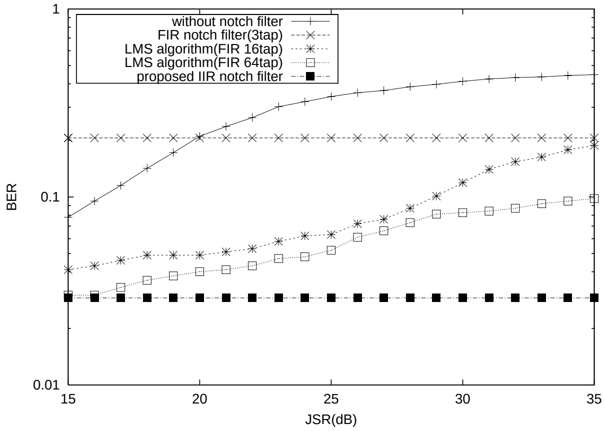

Figure 3: BER curve of several notch filters as JSR changes ($N_c = 128$, $\alpha = 0.85$, $\sigma^2 = 15dB$)

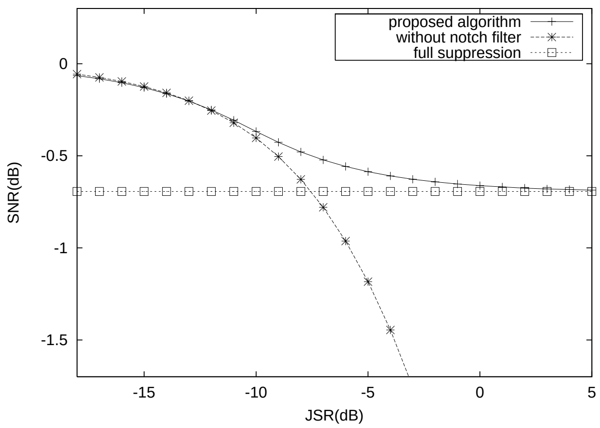

Figure 4: Comparison of SNR vs. JSR ($N_c = 128$, $\alpha = 0.85$, $\sigma^2 = 10dB$)

5. CONCLUSIONS

An IIR notch filter and an algorithm for the adjustment of filter coefficients have been proposed for the excision of narrow-band interference in DSSS systems. The zeros of the notch filter are adjusted to be placed on the frequency of the interference, using frequency estimators. However, if the zeros are on the unit circle, the notch depth is infinite and the filter removes the information as well as the interference. This causes data distortion and the performance of the receiver is degraded below the level of when no excision is performed. Hence, an adaptive algorithm for the given notch filter is proposed to adjust the depth of the notch as well as the notch frequency. For this purpose, we have derived the equation for the SNR as a function of filter parameters, and obtained the optimal notch depth for the given frequency and power estimates of the interference. As an estimator of the frequency and power, we employed the

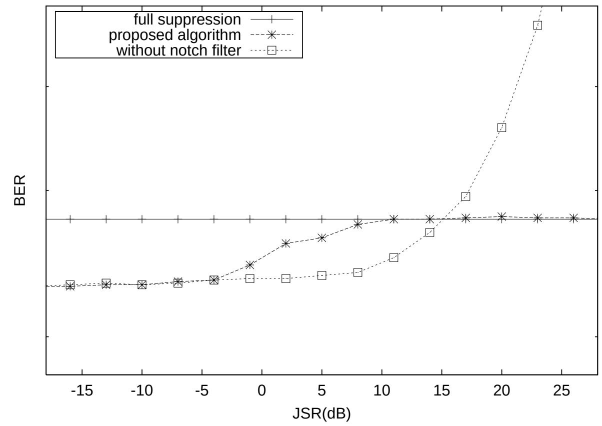

Figure 5: Comparison of BER vs. JSR ($N_c = 128$, $\alpha = 0.85$, $\sigma^2 = 10dB$)

IIR adaptive line enhancer of the same structure as the excisor [5, 6]. The estimates can also be obtained by other methods such as TFD [3]. The simulation results show that the proposed algorithm adjusts the depth of the notch effectively for the given JSR, and provides better SNR and BER than the conventional FIR notch filter and FIR LMS algorithm.

6. REFERENCES

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