Performance of Self-Encoded Spread Spectrum under Pulsed-Noise Jamming

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***Abstract* - In this paper, we study the performance of self-encoded spread spectrum (SESS) system under pulsed noise jamming and show that iterative detection can improve the bit-error rate (BER) performance significantly. We first verify that the jamming performance of SESS with correlation detection is similar to conventional Direct Sequence Spread Spectrum (DSSS) system. We then show that the performance improves by approximately 7dB when the correlation detection is combined with the iterative detection. The results demonstrate that iterative detection has the potential to completely mitigate the effect of jamming on the BER performance of SESS under pulsed-noise jamming.**

***Index terms* – Direct sequence spread spectrum, self-encoded spread spectrum, iterative detection, pulsed-noise jamming.**

I. INTRODUCTION

Conventional direct sequence spread spectrum system employs pseudo-noise (PN) code generators which are typically linear feedback shift register circuits that generate maximal-length or related sequences [1,3,4]. In contrast, self-encoded spread spectrum (SESS) employs non-deterministic spreading codes that have been generated from the random information source and provide unique advantages over traditional PN-coded systems [5-6]. Our work has shown that iteration detection can exploit the modulation memory of SESS signals to achieve not only signal gain in AWGN channels, but also time diversity gain with robust BER performance in fading channels [7].

In this paper we analyze the performance of SESS system under jamming. Pulsed-noise jamming has been shown to be effective against direct sequence spread spectrum (DSSS) system and is often used in electronic counter measure operations [2,3]. A pulsed-noise jammer (PNJ) can be defined as a jammer that turns on with just sufficient power to degrade spread spectrum system performance significantly, but does not totally annihilate the receiver when it is "on". PNJ typically transmits a band-limited Gaussian noise pulse whose power spectral density (PSD) just covers the spread spectrum bandwidth (W). When the jammer is "on," the one-sided received jammer power spectral density is given by N_j/ρ, where N_j is the average jamming PSD, ρ is the jamming duty cycle or the fraction of time during which the jammer is "on" [1-4]. The results of our study demonstrate that iterative detection has the potential to completely mitigate the effect of pulsed-noise jamming on the BER performance of SESS.

In the following, Section II briefly describes SESS system. The BER performance analysis with the correlation detection under worst-case pulsed-noise jamming is carried out in Section III. Section IV describes the iterative detection and analyzes the performance of the combined correlation detection and iterative detection. Section V shows that iterative detection has completely mitigated the effect of jamming on the BER.. The paper concludes with Section VI.

II. SELF-ENCODED SPREAD SPECTRUM

Fig. 1 shows a block diagram of SESS where the current symbol of duration T is modulated at the chip rate of N/T by N previous symbols that have been stored in the N shift registers. The self-encoded spreading chip sequence generated from the random symbols is not only independent of current symbol, but also changes dynamically from one symbol to next. The symbol and chip are bipolar values of +1 and -1.

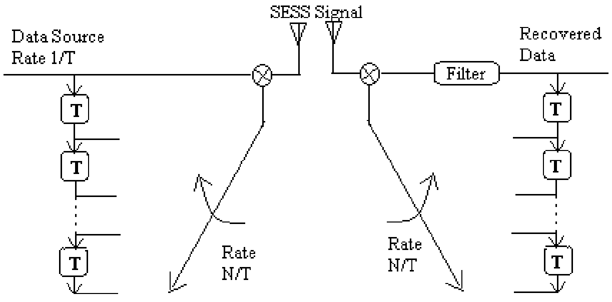

Fig. 1 Self-encoded spread spectrum system.

At the receiver, the feedback demodulator performs the reverse operation for symbol recovery by means of correlation detection. The received signal is correlated with the binary chip sequence, also of +1 or -1 values, that has been obtained from the delay registers in the

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receiver. The recovered data are fed back to the delay shift registers, also of N taps, to provide an estimate of the spreading sequence required for signal de-spreading.

III. PERFORMANCE ANALYSIS

In this section, we analyze the BER performance of the above SESS system with correlation detection in a pulsed-noise jamming environment. We assume that synchronization between transmitter and receiver has been achieved. From Fig. 1, the recovered symbols are used to estimate the spreading sequence which in turn is used to de-spread the received signals. Thus, with a small value of N a chip error that propagates through the shift registers would be shifted out quickly. On the other hand N must be large enough so that the signal degradation due to chip errors will be small. The chip errors in the receiver registers attenuate the de-spread signal strength and can be regarded as self-interference. The average BER of SESS system in AWGN channel can be expressed as [3]

$$P_b = Q\left(\left(1-\frac{2l}{N}\right)\sqrt{\frac{2E_b}{N_o}}\right) \tag{1}$$

where l is to the number of chip errors in the de-spreading sequence, and N is the chip length. The effect of pulsed-noise jamming can be incorporated into (1) in order to determine the worst-case performance, in a manner similar fashion to the PNJ model for DSSS in [1]. Thus, the probability of error of SESS with the correlation detection can be written as

$$P_b = (1-\rho)Q\left(\left(1-\frac{2l}{N}\right)\sqrt{\frac{2E_b}{N_o}}\right) + \rho Q\left(\left(1-\frac{2l}{N}\right)\sqrt{\frac{2E_b}{N_o + N_j/\rho}}\right) \tag{2}$$

Without loss of generality, we can assume that the performance is dominated by jamming. As a result, the first term in (2) can be ignored as it only represents the effect of channel noise when the jammer is off. Also, for large N, the ratio l/N approaches P_b. The expression for the error probability then becomes:

$$P_b = \rho Q\left(\left(1-2P_b\right)\sqrt{\frac{2E_b}{N_j/\rho}}\right) \tag{3}$$

Using the upper bound of the Q-function, we can set the derivative of the above equation with respect to ρ to zero and solve for the worst-case jamming duty cycle ρ according to [1]:

$$\rho = \frac{N_j}{2E_b(1-2P_b)^2} \tag{4}$$

Thus, the worst-case jamming duty cycle is inversely proportional to the signal-to-noise ratio (SNR). The BER performance under worst-case jamming can be found by substituting ρ back into (3) to obtain:

$$\begin{aligned} P_b &= \frac{Q(1)N_j}{2E_b(1-2P_b)^2} \\ P_b(1-2P_b)^2 &= \frac{Q(1)}{2E_b/N_j} \cong \frac{0.083}{E_b/N_j} \end{aligned} \tag{5}$$

It is clear that under normal conditions where P_b is much smaller than 0.5, equation (5) is well-approximated by $P_b = Q(1)/(2E_b/N_j)$. Thus, the BER performance of SESS with correlation detection is similar to DSSS under worst-case pulsed-noise jamming.

The BER performance for various ρ can be determined numerically from the non-linear BER expression given by (3). The theoretical calculations based on this expression are shown in Fig. 2, demonstrating excellent agreement with the simulation results that have been obtained with a spreading length of $N = 64$. In the simulations, the bits are subjected to jamming with a probability equal to ρ . The worst-case performance has been plotted in Fig. 2 as the heavy line that is tangent to the BER curves of ρ values that vary from 1.0 to 0.16%. The linearly inverse relationship is characteristics of the worst-case performance under pulsed-noise jamming [1]. In fact, the performance analysis in (2) can be easily shown to describe the worst-case BER in Fig. 2. Thus, the results show that the BER performance of SESS with correlation detection is similar to DSSS.

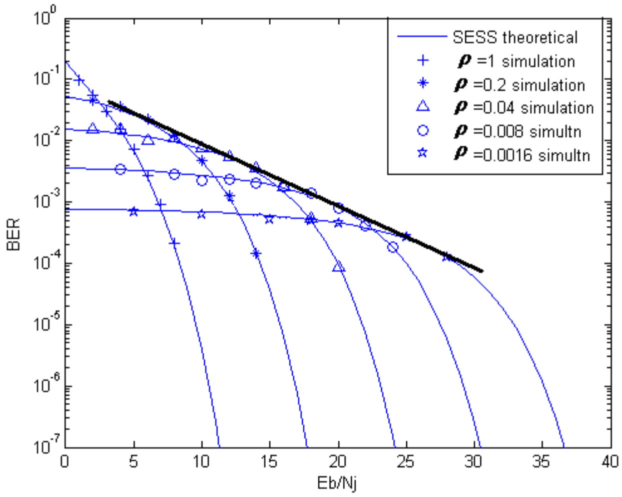

Fig. 2 Jamming performance of SESS with correlation detection.

IV. ITERATIVE DETECTION

Because there is memory in SESS-modulated signals, it is natural to consider using the maximum likelihood sequence estimation (MLSE) detection based on the Viterbi algorithm. MLSE detection improves the system performance by estimating the sequence of received signal. However, the number of states in the optimum Viterbi detection grows exponentially with the spreading factor as 2^N, making it impractical to implement for large *N*. The sub-optimal iterative detector can reduce the complexity to a linear order of the spreading factor.

We proceed to describe the iterative detection by writing the SESS signal as

$$\begin{aligned}
s_1 &= e_0 e_1 + e_{-1} e_1 + \ldots \quad \ldots. + e_{-N+1} e_1 \\
s_2 &= e_1 e_2 + e_0 e_2 + \ldots.. \quad .. \; . + e_{-N+2} e_2 \\
s_3 &= e_2 e_3 + e_1 e_3 + \ldots.. \quad \ldots\ldots + e_{-N+3} e_3 \\
&\quad . \qquad\qquad\qquad\qquad . \\
s_N &= e_{N-1} e_N + e_{N-2} e_N + \ldots. \quad \ldots. + e_0 e_N \\
s_{N+1} &= e_N e_{N+1} + e_{N-1} e_{N+1} + \ldots \; \ldots. + e_1 e_{N+1}
\end{aligned}$$

Notice that the current detected bit e_1 is not only related to previous *N* information bits which are stored in the delay shift registers, $e_{-N+1},\ldots e_0$, but also related to *N* future transmitted signals $s_2,\ldots s_{N+1}$. It is also easy to see that there is one chip for every *N* future transmitted signals $s_2,\ldots s_{N+1}$that contains the information about e_1. By incorporating future transmitted signals together with previous detected bits, we expect to improve the performance over the feedback correlation detector, which only estimates the current bits by correlating with *N* previous detected bits.

Fig. 3 illustrates the block diagram of iterative detection in SESS that employs the output of the correlation detection to re-estimate the current bit with *N* future received bits. Notice that the re-estimated, iterative detection output is combined with correlation detection output to increase the signal strength (by 3 dB). The recovered data experiences a delay of *N* bits and the structure partly resembles a Rake receiver with *N* fingers.

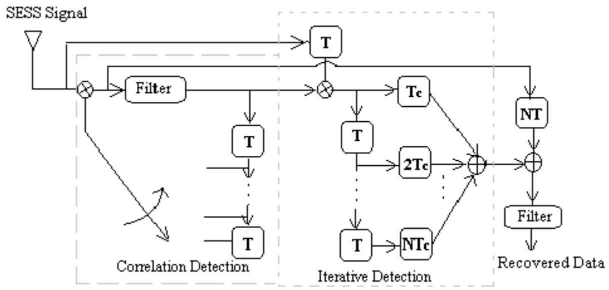

Fig. 3 SESS with iterative detection.

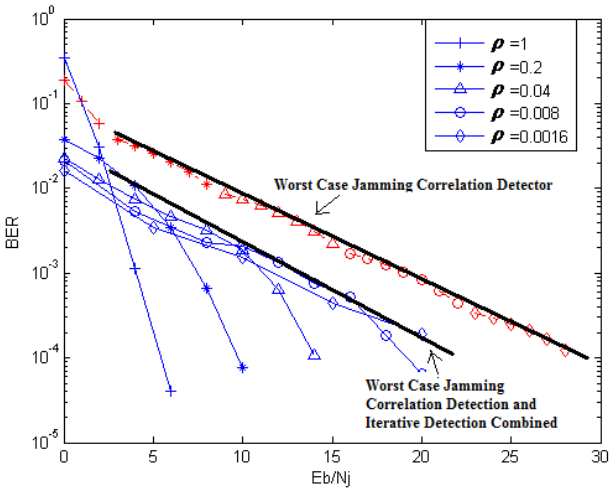

Fig. 4 Performance of SESS with and without iterative detection.

Fig. 4 shows the BER of the combined detection scheme described in Fig. 3 for $N = 64$. The simulation results show that the performance gain is nearly 7dB compared to correlation detection.

The results in Fig. 4 suggest that the output of correlation detection is significantly less reliable than the iteration detection output. Since each bit is subjected to jamming with a probability equal to ρ , the performance of correlation detection can be seriously degraded in worst-case jamming by adjusting ρ according to the SNR in (2). The iterative detection on the other hand accumulates the signal for the current bit from the *N* chips that have been spread out over *N* future bits. These *N* chips are less likely to experience jamming in all of them, making the iteration detection more reliable – especially as the worst-case ρ values become smaller for larger SNR. The performance of the iteration detection only is studied in the next Section.

V. PERFORMANCE OF ITERATIVE DETECTION ONLY

The noisy signal with jamming arriving at the receiver, denoted by r_k, is given as

$$r_k = s_k + J_k + a_k \tag{6}$$

The variable s_k represents the SESS transmitter output signal. J_k is the Gaussian jamming noise with zero mean and variance N_j / ρ , and a_k is the additive Gaussian noise with zero mean and variance $N_o/2$. Let x_k be the content of the delay registers at the k^{th} received bit, then the output of the correlation detection for the k^{th} bit can be represented as

$$\begin{aligned}
y_k &= x_k r_k \\
&= x_k s_k + x_k J_k + x_k a_k
\end{aligned} \tag{7}$$

Since the jamming and additive Gaussian noises have zero mean, the BER of the correlation detection can obtained simply as:

$$P_b = Q\left[(1-2P_b)\frac{E[y]}{\sqrt{Var[y]}}\right] \qquad (8)$$

The second term in (7) contains the jamming noise. Since we are considering iterative detection output only, it is clear that we can combine N chips from each of the N future bits to obtain the single bit energy E_b. Furthermore, it is unlikely that all of the N chips are jammed, and the jamming term in (7) can be represented as follows. Let e_k be the chip energy of the bit, that is e_k is equal to E_b/N, then

$$\begin{aligned} J_k x_k &= \sum_{k=0}^{N-1}[e_k(\rho(e_k+N_j)+(1-\rho)e_k)] \\ &= \sum_{k=0}^{N-1}[\rho e_k + \rho e_k N_j + (1-\rho)e_k] \qquad (9) \\ &= \sum_{k=0}^{N-1}[e_k(\rho N_j + 1)] \end{aligned}$$

$$Var[J_k x_k] \cong \rho P_s \widetilde{P}_j = P_s N_j$$

Thus, the variance of the jamming term at the iterative detection output is independent of jamming duty cycle ρ. This implies that BER of SESS with iterative detection alone is independent of ρ. Thus, as N increases, the iterative detection which depends upon the large number of chips (that have been spread out over N bits) will render the effect of jamming negligible. It follows that for sufficiently large values of N, the BER with iterative detection approaches the AWGN performance even under worst-case jamming.

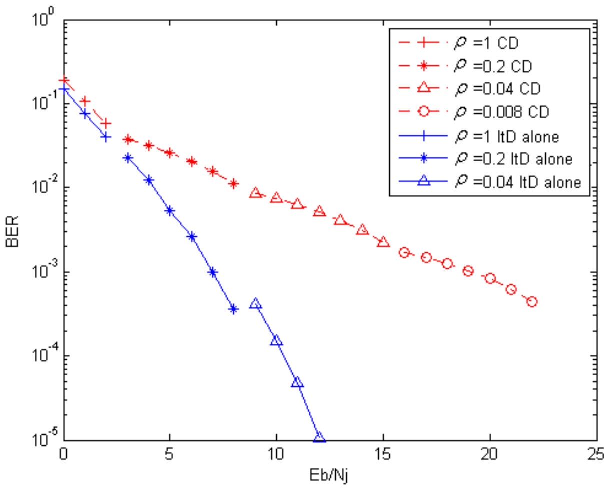

Fig. 5 Performance of SESS with iterative detector (ItD) only, N = 64.

Fig. 5 compares the BER performance of iterative detector (ItD) only in PNJ environment with correlation detector (CD) for various jamming duty cycle. It is clear that iterative detection performs much better than correlation detection. The results also verify the plot from Fig. 4, that the combined correlation and iterative detection would be worse than the iterative detection only.

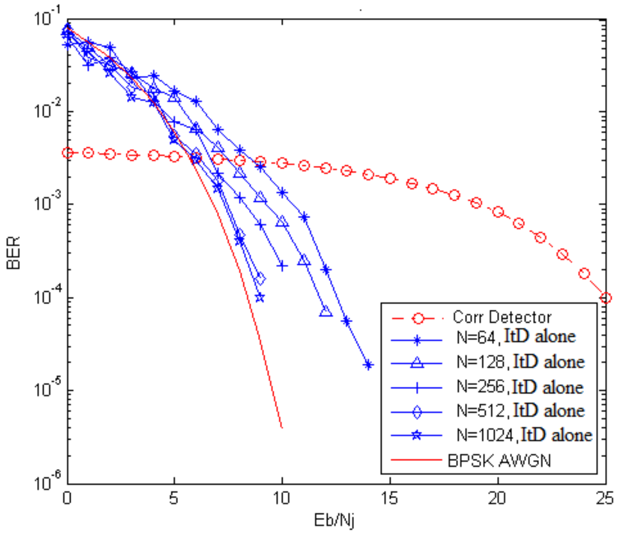

Fig. 6 Performance of SESS for various N, ρ = 0.008.

Fig. 6 shows the BER performance with iterative detector only under ρ = 0.8% for various spreading factors. The plots show that as the spreading length increases, the BER improvement approach BPSK in AWGN. Thus, for sufficiently large N, the iterative detection can potentially mitigate the effect of jamming completely. Also note that increasing the spreading length does not improve the correlation detection performance.

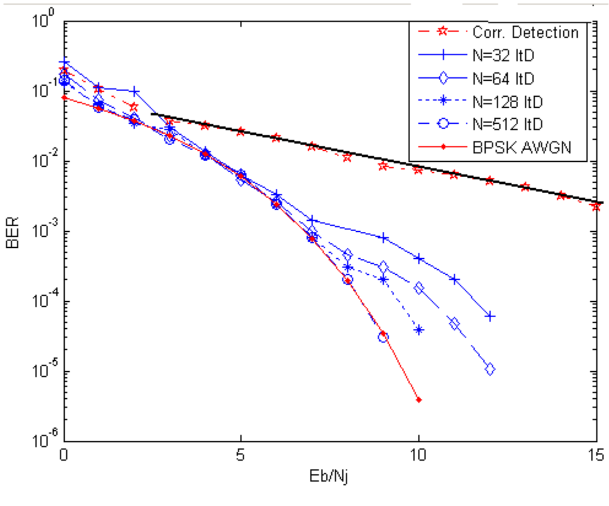

Fig. 7 Worst-case jamming performance of SESS for different N.

Finally, Fig. 7 compares the performance of iterative detection and correlation detection with various spreading factors under worst-case pulsed-noise jamming condition. The worst-case correlation detection curve does not depend on N as expected. On the other hand, the iterative detection approaches the AWGN performance as N increases. In particular for N = 512, the iteration detection has completely mitigated the effect of worst-case jamming.

VI. CONCLUSION

In this paper, we determined the performance of self-encoded spread spectrum system under pulsed noise jamming and showed that iterative detection can improve the bit-error rate performance significantly. The jamming BER performance of SESS with correlation detection has been derived and shown to be similar to conventional direct sequence spread spectrum system. The results showed that the performance improves by approximately 7dB when the correlation detection is combined with the iterative detection. Most significantly, the results demonstrated that iterative detection has the potential to completely mitigate the effect of jamming on the BER performance of SESS under worst-case pulsed-noise jamming.

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