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# Distributed and Centralized Iterative Detection of Self-Encoded Spread Spectrum in Multi-Channel Communication

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# Distributed and Centralized Iterative Detection of Self-Encoded Spread Spectrum in Multi-Channel Communication

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*Abstract:* **We propose self-encoded spread spectrum with two different iterative detection methods in multi-channel communication. The centralized iterative detection outperforms the iterative detection distributed over multiple channels. The results show that self-encoded spread spectrum with the centralized iterative detection is an excellent candidate for cognitive radio network.**

*Index Terms:* **Cognitive radio (CR), iterative detection (ID), multi-channel, self-encoded spread spectrum (SESS).**

## I. INTRODUCTION

The outage and coded outage of cooperative networks have been studied in [1] and [2] for multiple relay network. Their extension to the outage probability of cognitive transmission was analyzed in [3] by examining the impact of spectrum sensing overhead on system performance. In addition, cognitive transmission with multiple relays by jointly considering the spectrum sensing phase and the data transmission phase was explored in [4]. Cognitive multiple access with cooperation was also shown to provide significant performance gains over conventional relaying strategies [5]. Spectrum sensing cognitive-carrier sense multiple access (CSMA) based on CSMA was examined in [6] where carrier sensing was used for both spectrum sensing and interference control. In order to efficiently utilize the radio spectrum, the multiple access scheme of cognitive radio networks (CRN) was considered together with physical layer transmission schemes in [7]. A primary networks with the coexistence of multiple secondary networks was studied in multiple cognitive CSMA with collision avoidance (CSMA/CA) networks [8]. Moreover, enhanced CSMAs continuously sensed the channel and assigned bands to users in [9]. A cognitive radio (CR) system with primary bands and sub-bands in each primary bands was investigated to evaluate the performance of spectrum handoff and channel reservation [10]. In fact, the primary users have the priority to use the spectrum and can reclaim any sub-bands temporarily used by cognitive users. Therefore, the CRN organized by multiple CRs has been considered as an emerging wireless communication technology [7]. In this paper, we consider multi-channel banks where several CRs are assigned to a cognitive user.

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An efficient iterative receiver structure was proposed for decoding multiuser information data in a convolutionally coded asynchronous multipath direct sequence code division multiple access (DS-CDMA) system in [11]. The iterative receiver performed two successive soft-output decisions, achieved by a soft-input soft-output (SISO) multiuser detector and a bank of single user SISO channel decoders, through an iterative process. Simulation results demonstrated that the low-complexity turbo multiuser iterative receiver offers performance approaching that of the single-user channel at high signal-to-noise ratio (SNR). Another iterative receiver for joint detection and decoding of CDMA signals was presented in [12]. The simulation results were shown to achieve very close performance to that of the single user system for some range of SNRs. This range of SNR depended on the number of users sharing the channel, the cross correlation matrix, and the forward error correction (FEC) code constraint length. On the other hand, for convolutionally encoded system with both Viterbi and turbo decoding as well as for uncoded schemes, minimum mean squared error (MMSE) iterative successive parallel decision feedback (DF) receivers for DS-CDMA systems were proposed in [13]. The results showed that the detection scheme can offer considerable gains as compared to existing DF and linear receivers.

A class of equalizer that can be used in conjunction with error-control coding was developed for intersymbol interference (ISI) channels [14]. The nonlinear equalizers have an effective complexity comparable to the decision-feedback equalizer (DFE), yet asymptotically achieve the performance of maximum-likelihood sequence detection (MLSD). For the same dispersive channels an iterative block DFE (IBDFE) was proposed in [15] which operates iteratively on blocks of the received signal. As an extension of [16], the iterative detection of DFE in [15] transmits data arranged according to a format that allows the use of discrete Fourier transform (DFT) both for the feed forward (FF) and feed back (FB) filters, i.e., cancellation was performed in the frequency domain (FD). Meanwhile, for joint multiuser detection and multichannel estimation (JDE) of DS-CDMA, two efficient iterative receiver structures were presented with tractable complexity in [17]. The proposed JDE receivers have excellent multiuser efficiency and are robust against errors in the estimation of the channel parameters. However, training sequences are required for the JDE schemes to converge. As a unified approach to joint iterative parameter estimation with interference cancellation (IC), and least-squares (LS) joint optimization method was developed for estimating the linear receiver filter front-end, the IC and the channel parameters for uplink CDMA systems in multipath channels in [18].

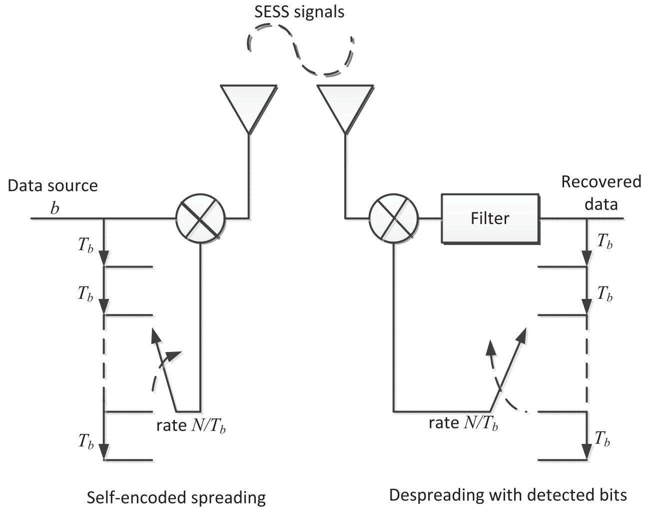


Fig. 1. SESS transmitter and receiver structure.

Self-encoded spread spectrum (SESS) system has been introduced in [19]. Unlike conventional pseudo noise (PN) sequence, SESS derives the spreading sequence from the time-varying source data itself. In SESS, the despreading sequence is constructed from the detected data bits at the receiver. Therefore, the detection error introduces chip errors in the despreading sequence that causes self-interference. It is obvious that the transmitted bit can be detected by correlation detection in the current bit duration. In SESS system, it can also be detected again later since the same bit exists in the future $N$ transmitting spreading sequences. The latter detection method is called iterative detection (ID). Unlike [11] and [12], SESS ID can be used with or without channel coding. SESS ID also improves system performance significantly without decision feedback proposed in [13]–[15] or training sequences in [17]. However, we can combine the unified IC method [18] and SESS ID for further improvement of SESS systems. Moreover, SESS ID provides the time diversity especially in fading channel at the expense of processing delay. The SESS is discussed in multiple access system in [20] and multiple-input and multiple-output (MIMO) system in [21].

In this paper, we explore SESS ID with multi-channel that can be applied to CRN. SESS ID with multi-channel provides the time diversity as well as the frequency diversity. The rest of the paper is organized as follows. In Section II, we present the system model for SESS ID with multi-channels. Section III analyzes the proposed system. Simulation results are presented in Section IV. Section V concludes the paper.

## II. SYSTEM MODEL

Fig. 1 shows the SESS transmitter and receiver structure. The current bit is spread by the output of a delay register which stores the previous $N$ bits of transmitted data, where $N$ is the processing gain, $N/T_b$ is the chip rate, and $T_b$ is the bit duration. From the diagram, we can see that the current bit will also exist in the next $N$ spreading sequences when new data are transmitted. At the receiver, we employ a similar process to obtain the detected bits, and use them to refresh the despreading sequence. We also need the next $N$ detected bits for iterative detection which requires $N$ bit time delay. We can express the spreading code $\mathbf{sp}(0)$ in the transmitter and the despreading code $\mathbf{dsp}(0)$ at the receiver during the $0\text{th}$ bit interval as

$$\mathbf{sp}(0) = [b(-1), b(-2), \cdots, b(-N)] \tag{1}$$

$$\mathbf{dsp}(0) = [d(-1), d(-2), \cdots, d(-N)] \tag{2}$$

where the bold-faced letter indicates a vector. Considering a binary communication, $b(i) \in \{1, -1\}$ and $d(i) \in \{1, -1\}$. $b(-m)$ is the $m\text{th}$ previous transmitted bit, and $d(-m)$ is the $m\text{th}$ previously detected bit using correlation. The spread spectrum sequence $\mathbf{sc}$ by the current bit $b(0)$ during the $0\text{th}$ bit time is

$$\mathbf{sc}(0) = b(0) \cdot [b(-1), b(-2), \cdots, b(-N)]. \tag{3}$$

In our multi-channel system, the SESS transmitter transmits the signal through CR channels with low transmit power. When SESS transmitter senses more than one vacant channels, the total transmit power is split into the available channels while maintaining the same total power. At the receiver, each matched filter receives the channel output separately and performs the correlation detection. Let us assume that we have $n$ multiple channels for detection. In the $k\text{th}$ channel, the fading parameter is $f_k(0)$ during the $0\text{th}$ bit time. Thus the $k\text{th}$ channel output is

$$\mathbf{r}_k(0) = \frac{1}{\sqrt{n}} f_k(0)\mathbf{sc}(0) + \mathbf{n}_k(0) \tag{4}$$

where $\mathbf{n}_k$ is noise of the channel $k$. It is important to reduce the transmit power in each channel by $n$ to maintain the same transmit power with a single channel system. At the receiver side, we first obtain the correlation detection output $de_k(0)$ using the despreading code:

$$de_k(0) = \mathbf{dsp}_k(0) \times \mathbf{r}_k^T(0) \tag{5}$$

where $[\cdot]^T$ represents the transpose operation of the matrix and '$\times$' denotes the matrix multiplication operation. The value $de_k(0)$ will be used in the despreading code $d(i) = \text{sign}(de_k(i))$. In SESS, the information bit exists also in the next $N$ spreading sequences. Thus, we can achieve the time diversity by iterative detection. To realize the iterative detection, we need a matrix to store the spread sequences that are received, and the correlation outputs. The block $\mathbf{D}_k$ which is $(N+1) \times N$ matrix to save the spread sequences can be expressed as

$$\mathbf{D}_k = \begin{pmatrix} r_k(0,1) & r_k(0,2) & \cdots & r_k(0,N) \\ r_k(1,1) & r_k(1,2) & \cdots & r_k(1,N) \\ \vdots & \vdots & \vdots & \vdots \\ r_k(N-1,1) & r_k(N-1,2) & \cdots & r_k(N-1,N) \\ r_k(N,1) & r_k(N,2) & \cdots & r_k(N,N) \end{pmatrix} \tag{6}$$

where $r_k(i,j)$ is the $j\text{th}$ spread chip in the $i\text{th}$ future bit at the $k\text{th}$ channel output. We also need to save the $N \times 1$ column vector of the correlation output. The $N \times 1$ block $\mathbf{d}_k$ which is used for ID is composed of the correlation output $de_k$ from (5), that is,

$$\mathbf{d}_k = \begin{pmatrix} de_k(1) \\ \vdots \\ de_k(N-1) \\ de_k(N) \end{pmatrix}. \tag{7}$$

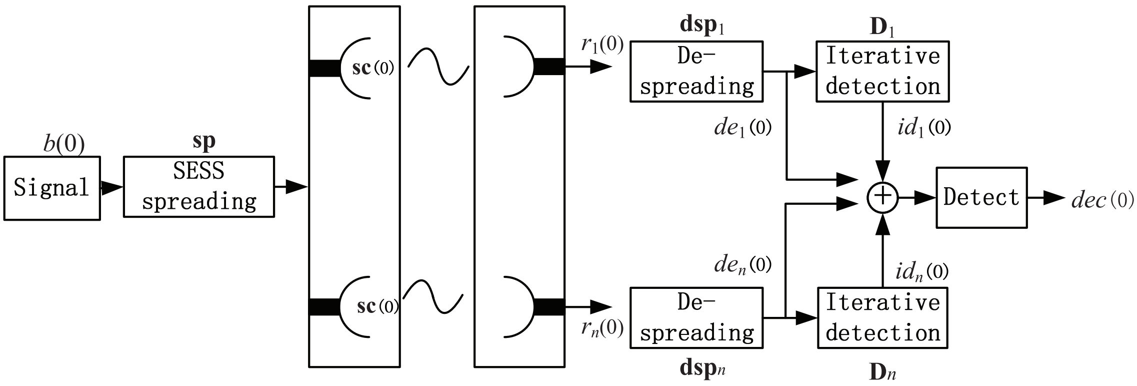


Fig. 2. Distributed SESS ID in multi-channel CRN.

In the block of $\mathbf{D}_k$, the first row is equal to $\mathbf{r}_k(0)$ and is used to calculate the correlation output value $de_k(0)$. The next $N$ rows are employed for the iterative detection $id_k(0)$. We take the diagonal terms from the second row to the $(N+1)\text{th}$ row from the block $\mathbf{D}_k$ to construct the row vector $\mathbf{v}_k$:

$$\mathbf{v}_k = [r_k(1,1), r_k(2,2), \cdots, r_k(N,N)]. \quad (8)$$

There are two different method to combine the detected signal to achieve the multi-channel diversity gain. One is to maintain the separate iterative detection block $\mathbf{D}_k$ in each channel and combine the ID output per channel later. The other is to maintain one integrated iterative detection block $\mathbf{D}$ and use it for the iterative detection for all channels. In this paper, we will name the former as the distributed SESS ID and the latter as the centralized SESS ID.

### *A. Distributed SESS ID*

Fig. 2 shows the system model of the distributed SESS ID. The fading vector $\mathbf{f}_k$ is

$$\mathbf{f}_k = [f_k(1), f_k(2), \cdots, f_k(N)] \quad (9)$$

where $f_k(i)$ is the fading parameter during the $i\text{th}$ bit duration at the $k\text{th}$ channel. Consequently, the iterative detection output value $id_k(0)$ is

$$id_k(0) = \mathbf{v}_k \times \mathbf{d}_k. \quad (10)$$

Equation (10) presents the result of iterative detection value in the $k\text{th}$ channel. In the proposed distributed SESS ID, we combine the multiple channel outputs in (10). As shown in Fig. 2, we combine the soft detection output values from all $n$ channels to make the final decision:

$$dec(0) = \text{sign}\left[\sum_{k=1}^{n}(de_k(0) + id_k(0))\right]. \quad (11)$$

Equation (11) is the final detection for $b(0)$ which contains the correlation detection output and the iterative detection output from all channels. This achieves the double diversity of time and frequency for the multi-channel SESS communication system.

### *B. Centralized SESS ID*

Fig. 3 shows the system model of the centralized SESS ID. In this model, all channels share the same despreading sequence and iterative detection block. Unlike the distributed SESS ID, all correlation output values in (5) add together to update despreading code:

$$de(0) = \sum_{k=1}^{n} de_k(0). \quad (12)$$

Block $\mathbf{D}_k$ in (6) are added together for the iterative detection as

$$\mathbf{D} = \sum_{k=1}^{n} \mathbf{D}_k. \quad (13)$$

We can then obtain the diagonal elements from the second row to the $(N+1)\text{th}$ row of $\mathbf{D}$:

$$\mathbf{v} = \sum_{k=1}^{n} \mathbf{v}_k. \quad (14)$$

The bits for ID is

$$\mathbf{d} = \sum_{k=1}^{n} \mathbf{d}_k \quad (15)$$

or

$$\mathbf{d} = \begin{pmatrix} de(1) \\ \vdots \\ de(N-1) \\ de(N) \end{pmatrix}. \quad (16)$$

The main difference between the distributed SESS ID and the centralized SESS ID comes from the vector $\mathbf{v}$ in (14). We can now obtain the ID output value of the centralized SESS ID as

$$id(0) = \mathbf{v} \times \mathbf{d}. \quad (17)$$

The final detection value is

$$dec(0) = \text{sign}[de(0) + id(0)]. \quad (18)$$

Equations (13) and (15) show that the block $\mathbf{D}$ and the correlation output combined from all channels have been employed for the ID.

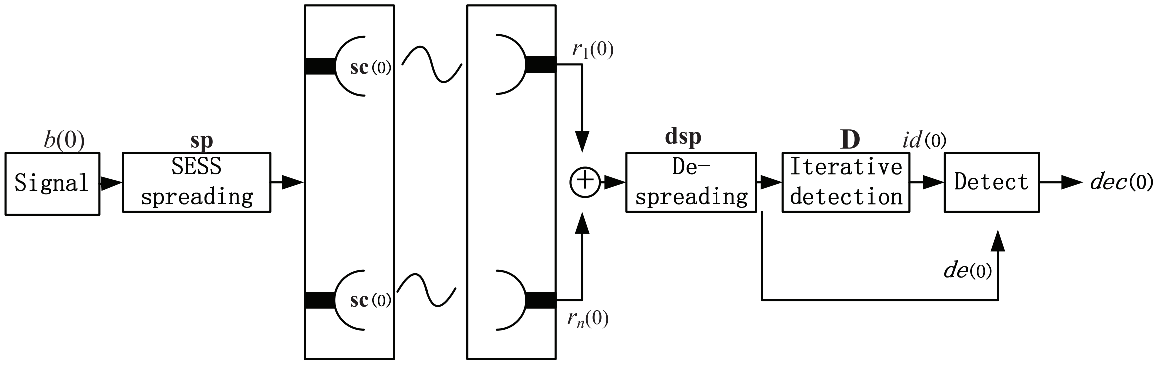


Fig. 3. Centralized SESS ID in multi-channel CRN.

## III. SYSTEM ANALYSIS

For simplicity, we will consider the system of high SNR with negligible noise power. Let us consider SESS with the distributed ID first. Equation (8) becomes under the noiseless assumption:

$$\mathbf{v}_k = [f_k(1)b(0)b(1), f_k(2)b(0)b(2), \cdots, f_k(N)b(0)b(N)]. \quad (19)$$

Equation (10) then becomes

$$id_k(0) = \mathbf{v}_k \times \mathbf{d}_k = b(0)\sum_{i=1}^{N} f_k(i)b(i)de_k(i) \quad (20)$$

and $de_k(i) = f_k(i)d(i) = f_k(i)b(i)$. Therefore,

$$id_k(0) = b(0)\sum_{i=0}^{N} f_k^2(i)b^2(i) = b(0)\sum_{i=0}^{N} f_k^2(i) \quad (21)$$

since $b^2(i)$=1, for all $i$. Now, the ID part of (11) can be expressed as

$$id(0) = \sum_{k=1}^{n} id_k(0) = b(0)\sum_{k=1}^{n}\sum_{i=0}^{N} f_k^2(i) = b(0)\sum_{i=1}^{N}\sum_{k=1}^{n} f_k^2(i) \quad (22)$$

which is equivalent to maximal ratio combining. The average of $id(0)$ is

$$E[id(0)] = \sum_{k=1}^{n} E[id_k(0)] = b(0)\sum_{k=1}^{n}\sum_{i=0}^{N} E\left[f_k^2(i)\right] = nNb(0) \quad (23)$$

where $E[\cdot]$ indicates the expectation operation with respect to fading. $f_k(i)$ is taken to be an independently and identically distributed Rayleigh fading distribution with unit power.

We can apply a similar process to SESS with the centralized ID in (14) and (17). Again, considering the scenario without noise

$$\mathbf{v}_k = [f_k(1)b(0)b(1), f_k(2)b(0)b(2), \cdots, f_k(N)b(0)b(N)] \quad (24)$$

and

$$\mathbf{v} = \sum_{k=1}^{n}\mathbf{v}_k = \left[b(0)b(1)\sum_{k=1}^{n} f_k(1), b(0)b(2)\sum_{k=1}^{n} f_k(2), \cdots, b(0)b(N)\sum_{k=1}^{n} f_k(N)\right]. \quad (25)$$

At high SNR, (16) can be written as

$$\mathbf{d} = \begin{pmatrix} de(1) = \sum_{k=1}^{n} f_k(1)b(1) \\ \vdots \\ de(N-1) = \sum_{k=1}^{n} f_k(N-1)b(N-1) \\ de(N) = \sum_{k=1}^{n} f_k(N)b(N) \end{pmatrix}. \quad (26)$$

Therefore, the combining process can be expressed as

$$id(0) = \mathbf{v} \times \mathbf{d} = b(0)\sum_{i=1}^{N}\left[b(i)\sum_{k=1}^{n} f_k(i)\right]^2 = b(0)\sum_{i=1}^{N}\left[\sum_{k=1}^{n} f_k(i)\right]^2. \quad (27)$$

It can be seen that (27) has a larger gain than (22) since there are cross-product terms. The average of the $id(0)$ of the centralized SESS ID can be determined as

$$E[id(0)] = b(0)E\left[\sum_{i=1}^{N}\left[\sum_{k=1}^{n} f_k(i)\right]^2\right] = b(0)\sum_{i=1}^{N}\sum_{k=1}^{n} E\left[f_k^2(i)\right] + b(0)\sum_{i=1}^{N}\sum_{k=1}^{n}\sum_{\substack{l=1 \\ l\neq k}}^{n} E[f_k(i)]\,E[f_l(i)] = nNb(0)[1+(\pi/4)(n-1)]. \quad (28)$$

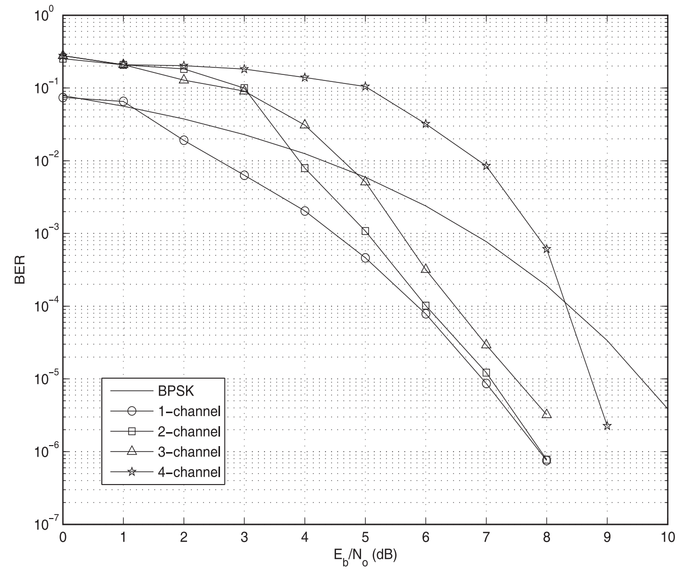


Fig. 4. SESS with distributed ID, $N = 64$, and AWGN channel.

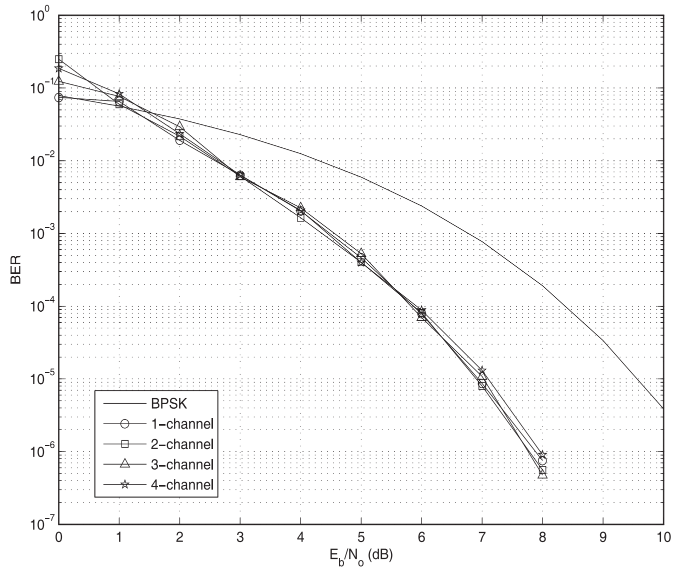


Fig. 6. SESS with centralized ID, $N = 64$, and AWGN channel.

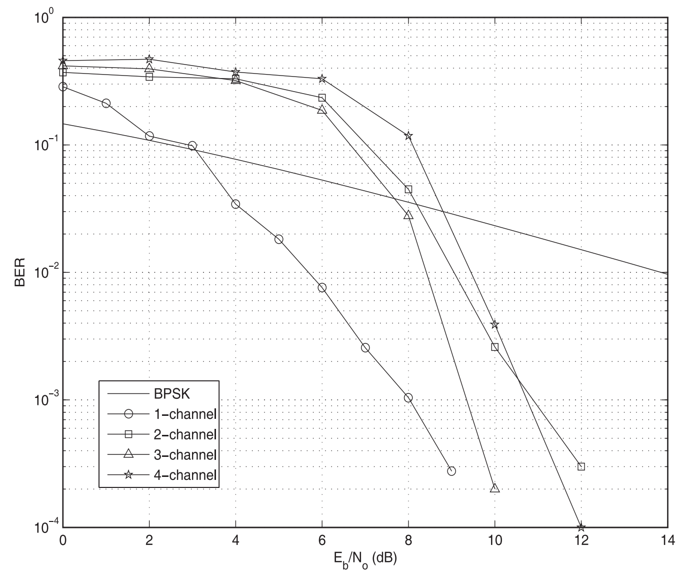


Fig. 5. SESS with distributed ID, $N = 64$, and Rayleigh fading channel.

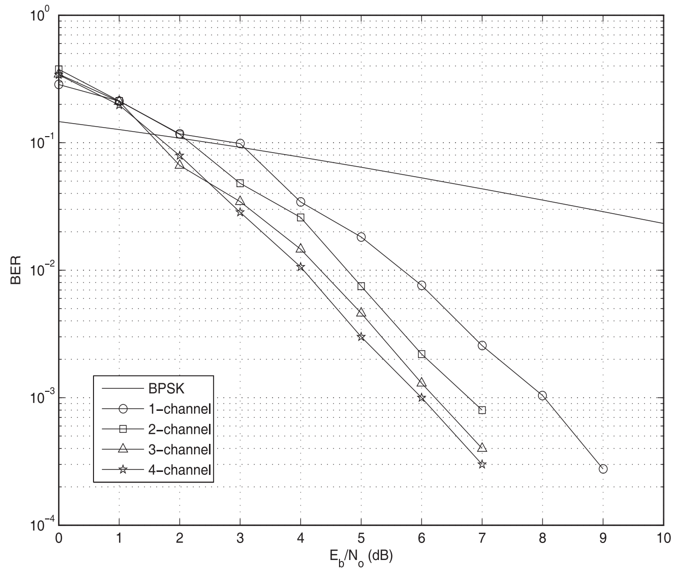


Fig. 7. SESS with centralized ID, $N = 64$, and Rayleigh fading channel.

Notice that we have applied the average of the Rayleigh fading, $E[f_k(i)] = \sqrt{\pi/2}\sigma$ and $\sigma^2 = 1/2$, to maintain the unit average power. Comparing (23) and (28), we find that the average power enhancement of the centralized SESS ID over the distributed SESS ID is $[1 + (\pi/4)(n-1)]$ at high SNR.

## IV. SIMULATION RESULTS

In this section, we present the BER performance of the two different SESS ID methods in additive white Gaussian noise (AWGN) and Rayleigh fading channels. Fig. 4 shows the simulation results of the distributed SESS ID in AWGN channel. The plots show that the distributed SESS ID with a single channel exhibits nearly 3 dB gain over binary phase shift keying (BPSK) at high SNR. The 3 dB gain comes from the ID in addition to the correlation detection. We observe that the BER deteriorates as the number of channels increases from the reduced transmit power per channel. The reduced SNR introduces the self-interference that comes from the chip errors in the despreading code at the receiver. Fig. 5 displays the BER of the distributed SESS ID in Rayleigh fading channel. Since the self-interference is dominant over the diversity gain, the performance does not necessarily improve as the number of channels increases. A similar effect can also be seen in Fig. 4.

Fig. 6 shows the BER of the centralized SESS ID in AWGN channel. The plots show that the multi-channel performance is identical to that of the single channel. The 3 dB gain over BPSK has been achieved regardless of the number of channels since there is no diversity without fading. Fig. 7 shows the BER of the centralized SESS ID in Rayleigh fading channel. Unlike the distributed SESS ID the performance clearly improves as the number of channels increases. A comparison of the results in Figs. 4 and 5 to Figs. 6 and 7 clearly shows that the centralized SESS ID outperforms the distributed SESS ID in both AWGN and Rayleigh fading channels. In AWGN channel, the centralized SESS ID provides a uniform BER that is 3 dB better than BPSK regardless of the number of channels. Under Rayleigh fading, the BER performance of the centralized SESS ID improves as the number of channels increases, although the margin reduces with the number of channels. Frequency diversity is dominant over self-interference in the centralized SESS ID. However, the converse is true in the distributed SESS ID. In fact, the centralized SESS ID exhibits negligible self-interference under AWGN and Rayleigh fading.

## V. CONCLUSION

In this paper, we compared two different SESS ID methods in multi-channel communication that can be applied to CRN. We showed that the centralized SESS ID outperforms the distributed SESS ID in both AWGN and Rayleigh fading channels. Unlike the distributed SESS ID, the diversity gain is dominant over self-interference in the centralized SESS ID. Simulation results demonstrated superior performance of the centralized SESS ID due to analytical power gain at high SNR. The proposed SESS ID is thus an excellent candidate for CRN.

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