

Overloading Scheme for Cellular DS-CDMA using Quasi-Orthogonal Sequences and Iterative Interference Cancellation Receiver

Preetam Kumar and Saswat Chakrabarti

Abstract—Overloading is a technique to accommodate more number of users than the spreading factor N . This is a bandwidth efficient scheme to increase the number users in a fixed bandwidth. One of the efficient schemes to overload a CDMA system is to use two sets of orthogonal signal waveforms (O/O). The first set is assigned to the N users and the second set is assigned to the additional M users. An iterative interference cancellation technique is used to cancel interference between the two sets of users. In this paper, the performance of an overloading scheme in which the first N users are assigned Walsh-Hadamard orthogonal codes and extra users are assigned the same WH codes but overlaid by a fixed (quasi) bent sequence [11] is evaluated. This particular scheme is called Quasi-Orthogonal Sequence (QOS) O/O scheme, which is a part of cdma2000 standard [12] to provide overloading in the downlink using single user detector. QOS scheme are balance O/O scheme, where the correlation between any set-1 and set-2 users are equalized. The allowable overload of this scheme is investigated in the uplink on an AWGN and Rayleigh fading channels, so that the uncoded performance with iterative multistage interference cancellation detector remains close to the single user bound. It is shown that this scheme provides 19% and 11% overloading with SDIC technique for $N=16$ and 64 respectively, with an SNR degradation of less than 0.35 dB as compared to single user bound at a BER of 0.00001 . But on a Rayleigh fading channel, the channel overloading is 45% (29 extra users) at a BER of 0.0005 , with an SNR degradation of about 1 dB as compared to single user performance for $N=64$. This is a significant amount of channel overloading on a Rayleigh fading channel.

Keywords—DS-CDMA, Iterative Interference Cancellation Orthogonal codes, Overloading.

I. INTRODUCTION

THE number of users supported in a DS-CDMA cellular system is typically less than spreading factor (N), and the system is said to be underloaded. Overloading is a technique to accommodate more number of users than the spreading factor N . This is an efficient way to increase the number users in a fixed bandwidth, which is of practical

interest to mobile system operators. Infact this type of channel overloading is provisioned in the 3G standard [1].

Among the approaches described in the literature, the most efficient ones use multiple sets of synchronous orthogonal codes [2] [3]. In synchronous CDMA system, synchronism between signatures can be maintained in the downlink of cellular systems with relative ease and hence, orthogonal signatures (Walsh functions) are used in the downlink of IS-95 and UMTS mobile radio standards. Even in the uplink of UMTS, usage of orthogonal signatures has been advocated to realize multi-code channelization. Also, with multicarrier-CDMA, the signal alignment can be maintained for much weaker synchronization requirements, by application of an appropriate cyclic prefix and single-tap equalization. This makes the study of CDMA systems with time aligned signatures and hence overloading justified for both uplink and downlink transmission.

When number of active users, K exceeds N , the system becomes overloaded and the signatures are no longer orthogonal. This leads to multiple access interference (MAI). In an overloaded system, a conventional matched filter receiver is not optimal, due to the high level of MAI. Multiuser detection (MUD) is required in order to obtain a satisfactory performance of the users. The nonlinear MUD's such as multistage parallel interference cancellation (PIC) and successive interference cancellation (SIC) [3], have good complexity- performance trade-off as compared to other MUD's. Hence these MUDs are suitable for overloaded systems. Thus, the problem of overloading DS-CDMA systems may be stated as: how to increase the number of spreading codes, or the number of users K , without increasing the dimension N , while keeping MAI in minimum, to ensure low complexity of the receiver.

It is interesting to note that several studies have been made in the recent past to understand, analyze and counter the detrimental effects of overloading. Almost all studies consider the uplink or reverse link and several studies suggest usage of appropriate multiuser detection (MUD) schemes at the base station receiver. For example, a method of accommodating $K = N + M$ users in an N -dimensional signal space that does not compromise the minimum Euclidean distance of the orthogonal signaling has been presented in [4] for AWGN channel. A tree-like correlation coefficient structure of user signatures suitable for optimal multiuser detection has been proposed in [5]. In another approach, two sets of orthogonal

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codes which are orthogonal within the sets is introduced in [6]. In this paper, the orthogonal sets are generated using Walsh- Hadamard (WH) codes, where the same WH code set is scrambled with set specific scrambling sequence (s-O/O). An

iterative multistage detection technique has been proposed to cancel the interference between the two sets of user. In [7], it is shown that for uncoded BPSK modulated CDMA signal with $N=64$, an overloading of 11% can be achieved in an AWGN channel for s-O/O scheme. Recently, the performance of an overloading scheme where only one orthogonal set is scrambled is evaluated in [8]. Another kind of receiver simplification is presented in [9], where signals are divided into groups that are orthogonal to each other. A new overloading scheme using hybrid techniques has been proposed in [10], where the spreading codes and transmission modes are different for the two sets to increase the overloading performance. The attractive property of overloading scheme was the incentive to integrate a particular type of O/O, called quasi-synchronous sequences (QOS) [11], into cdma2000 standard [12].

In this paper, we have evaluated the BER performance of QOS overloading scheme with hard decision (HDIC) and soft decision (SDIC) interference cancellation receivers in the uplink over an AWGN and Rayleigh flat fading channel. The paper is organized as follows. In the next section, we describe the system model for the O/O overloading scheme. In section-3 we explain the process of iterative interference cancellation in overloaded system. Simulation results are presented and discussed in Section-4. Finally, we present the conclusion of this paper.

II. SYSTEM MODEL

In the sequel we will consider the DS-CDMA system with processing gain N and the number of users $K (=M+N)$. The waveforms of the first signal set in O/O scheme are assigned to the first N users, and M waveforms from the second set are assigned to the next M users. We assume that signal spreading is performed by means of user-specific spreading sequences. Let us denote by $\mathbf{S} = [\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_K]$ the $N \times K$ matrix containing the K signature sequences of length N associated to the K users (denoted by $\mathbf{s}_k = (s_{1k}, s_{2k}, \dots, s_{Nk})^T$). We can also write: $\mathbf{S} = [\mathbf{S}_1 \mathbf{S}_2]$ with \mathbf{S}_1 and \mathbf{S}_2 respectively of size $N \times N$ and $N \times M$ corresponding to the matrices of sequences attributed to set 1 and set 2 users. Here, we consider schemes where the sequences assigned to users in the same group are orthogonal. In this work, we have considered QOS O/O scheme, where the signatures of the set 1 users are the Walsh-Hadamard sequences $\mathbf{WH}_N^{(k)}$ of order N , and the signatures of set 2 users are obtained by the same Walsh-Hadamard sequences by means of a (quasi-) bent sequence $\mathbf{Q} \in \{1, -1\}^N$ [11]. QOS are balanced O/O sets, so that the correlation between set 1 and set 2 users is equalized. These QOS minimize the maximum correlation between the set1 and set 2 users

The following notations are used to describe the transmission model:

- $\mathbf{x} = (x_1, x_2, \dots, x_K)^T$ is the set of BPSK transmitted bits associated to the K users during a given CDMA bit period,
- $\mathbf{A} = \text{diag}(a_k, k \in \{1, \dots, K\})$ is the matrix whose coefficients a_k denote the k th user's complex channel attenuation,
- $\mathbf{r} = (r_1, r_2, \dots, r_N)^T$ is the received signal block.

Assuming that the channel attenuations do not vary within one symbol interval, the received signal block can be written as follows:

$$r_n = \sum_{j=1}^K s_{nj} a_j x_j + z_n \quad n = 1, \dots, N \quad (1)$$

This is equivalent to:

$$\mathbf{r} = \mathbf{S} \mathbf{A} \mathbf{x} + \mathbf{z} \quad (2)$$

where $\mathbf{z} = (z_1, z_2, \dots, z_N)^T$ is the vector of AWGN samples of variance $\sigma_z^2 = N_0$.

We notice that the case of an AWGN channel is obtained by taking $\mathbf{A} = \mathbf{I}_K$. The Rayleigh fading channel model can be described by fading amplitudes generated according to $a_k = a_k^{(I)} + j a_k^{(Q)}$, where $a_k^{(I)}$ and $a_k^{(Q)}$ are independent zero-mean real Gaussian distributed random variables with variance $\sigma_{a_k^{(I)}}^2 = \sigma_{a_k^{(Q)}}^2 = 1/2$ [14].

III. ITERATIVE INTERFERENCE CANCELLATION RECEIVER

In this work, an iterative interference cancellation receiver is used to remove the MAI between the two sets. The basic principle of this receiver is to iteratively remove the estimated interference from each set due to the users of other set in multiple stages such that near single user performance is achieved.

Let us consider the k th user to be detected. If we correlate the received signal with the sequence assigned to the considered user (despreading operation), we obtain:

$$v_k = \sum_{n=1}^N r_n s_{nk}^* a_k^* = |a_k|^2 x_k + I(k) + z_k' \quad (3)$$

$$\text{where } I(k) = \sum_{j=1, j \neq k}^K x_j \sum_{n=1}^N s_{nj} a_j s_{nk}^* a_k^* \quad (4)$$

$$z_k' = \sum_{n=1}^N z_n s_{nk}^* a_k^* \quad (5)$$

and the superscript $*$ denotes complex conjugation.

We observe that z_k' is a Gaussian noise, with the same variance as \mathbf{z} . Furthermore, we notice that because of the orthogonality of the spreading sequences in each set of users, the expression of the interference caused by the other users on the k th user reduces to:

$$I(k) = \sum_{j=N+1}^K x_j \sum_{n=1}^N s_{nj} a_j s_{nk}^* a_k^* \quad \text{for } k = 1, 2, \dots, N \quad (6)$$

$$I(k) = \sum_{j=N}^K x_j \sum_{n=1}^N s_{nj} a_j s_{nk}^* a_k^* \quad \text{for } k = N+1, 2, \dots, K \quad (7)$$

These expressions are used in the iterative interference cancellation presented in the next section.

B. Soft-Decision Interference Cancellation

First of all, the correlator outputs, i.e. the v_k 's, must be computed for each user ($k = 1, 2, \dots, K$).

First iteration: To begin with, the v_k 's obtained for set-1 users ($k = 1, 2, \dots, N$) are divided by $|a_k|^2$ and sent to the detector, which provides the first estimations $\hat{x}_j^{(1)}$ ($j = 1, 2, \dots, N$) of set-1 symbols. Next, the estimated interference of set-1-users on each set-2 user is synthesized by substituting $\hat{x}_j^{(1)}$ for x_j in (7). The estimated interference terms are subtracted from the values of v_k associated to the set-2 users ($k = N+1, \dots, K$). The resulting signals are then sent to the detector after division by $|a_k|^2$, giving symbol decisions $\hat{x}_j^{(1)}$ ($j = N+1, \dots, K$) for the set-2 users. In an AWGN channel, we consider $a_k = 1, k \in \{1, \dots, K\}$.

Iteration i ($i > 1$): The symbol decisions made for set-2 users in the $(i-1)$ th iteration ($\hat{x}_j^{(i-1)}, j = N+1, \dots, K$) are used to synthesize the interference from these users on each set-1 user, by substituting for $\hat{x}_j^{(i-1)}$ for x_j in (6). The estimated interferences are subtracted from the v_k 's obtained for set-1 users ($k = 1, 2, \dots, N$). After dividing by $|a_k|^2$, improved decisions $\hat{x}_j^{(i)}$ ($j = 1, 2, \dots, N$) are made for the symbols transmitted by the set-1 users. These decisions are next used to synthesize the interference from set-1 users on each set-2 user by using (7). The estimated interferences are subtracted from the v_k 's associated to the set-2 users ($k = N+1, \dots, K$). After dividing by $|a_k|^2$, the symbol decisions corresponding to set-2 users at iteration i ($\hat{x}_j^{(i)}, j = N+1, \dots, K$) are computed.

To make soft decisions, we have used the piecewise linear function described in [7] as the nonlinearity involved in the decision device, except for the last iteration, where hard decisions are made. The piecewise linear function is parameterized by θ and has the following expression:

$$\phi(x) = \begin{cases} x/\theta & |x| < \theta \\ \text{sgn}(x) & |x| \geq \theta \end{cases} \quad (8)$$

The value of θ is selected so as to minimize the bit error rate (BER) after 10 iterations. This non-linearity is used in the

detector to provide the soft values corresponding to BPSK symbols.

For HDIC, the decision function is defined as

$$\phi(x) = \text{sgn}(x) = \begin{cases} -1 & x < 0 \\ +1 & x > 0 \end{cases} \quad (9)$$

In the last iteration of SDIC, we take hard decisions as given in (9). For HDIC scheme, in all iterations, we take hard decisions.

IV. SIMULATION RESULTS

This section presents the Monte-Carlo simulation results of the QOS overloading scheme with SDIC receiver. In this way, we can consider that steady-state performance has been reached, given that increasing the number of iterations would not provide a significant improvement. The BER performance of hard decision (HDIC) and soft decision interference cancellation (SDIC) has been evaluated. The number of iterations has been fixed to 4 and 10 for HDIC and SDIC respectively. The value of the parameter θ is 0.7 for SDIC and it is fixed for all iterations. The simulation has been carried out in MAT-Lab to evaluate the BER performance of the proposed scheme in an AWGN and Rayleigh fading channels.

In order to compare the performance of these schemes, we define the critical overload as the maximum achievable channel overload $\beta_{\max} = M_{\max} / N = (K_{\max} - N) / N$ with interference cancellation receiver, so that the SNR degradation as compared to a single user system at an average BER of 10^{-5} is less than 0.35 dB in an AWGN channel. For Rayleigh fading channel, critical overload is defined such that the SNR degradation for an average BER of $5 \cdot 10^{-4}$ is less than 1 dB. It has to be emphasized that the receiver does not require any kind of user sorting to yield the desired overloading performance. As a consequence, this measure guarantees that the mean BER performance remains close to that of the ideal BER curve provided that $M < M_{\max}$. It is worth noting that the BER performance in case of perfect interference cancellation is identical to the performance of a non-overloaded system where the users are orthogonal, and also to the performance of a single-user system. The BER achieved by a single-user transmitting over a Rayleigh fading channel is given by [13]:

$$P_{e_b} = \frac{1}{2} \left(1 - \frac{1}{\sqrt{1 + N_0 / E_b}} \right) \quad (9)$$

First, we will evaluate the overloading performance of the new scheme in an AWGN channel, where the matrix, $\mathbf{A} = \mathbf{I}_K$. We have assumed equal power and equal phase users over an AWGN channel. In Fig. 1, the BER performance of QOS overloading scheme is shown, when we use hard decisions to estimate the interference in all iterations, i.e., hard decision interference cancellation (HDIC) receiver, for $N=16$. It is observed that the amount of channel overload is only 6% (1 extra user), with an SNR degradation of less than 0.35 dB at a BER of 10^{-5} as compared to single user

bound. Even if, we increase the channel overloading to 12 % (2 extra user), the SNR degradation is considerably high. If we increase the spreading factor N from 16 to 64, we observe from Fig. 2, that the amount of overloading increases to 9%, i.e. we are able to overload 6 extra users ensuring a BER of 10^{-5} at an SNR of less than 10 dB. So, the critical overload is 6% for $N=64$ with HDIC receiver.

To increase the critical overload of QOS scheme, we use soft decisions to estimate the interference (8). In Fig. 3, BER performance of SDIC receiver is shown for $N = 16$ at 19% (3 extra users) overloading. It is observed that 19% overloading can be achieved, with about 0.35 dB SNR degradation at an average BER of 10^{-5} . If we increase the overloading further, the SNR degradation is more than 0.35 dB. We can ensure a BER of 10^{-5} for all users, if the channel overload is less than or equal to 19% and hence we can obtain a critical overload of 19% for $N=16$.

In Fig. 4, the same SDIC receiver is simulated for $N = 64$. It is observed that an overloading of only 11% can be obtained with a SNR degradation of less than 0.35 dB at an average BER of 10^{-5} . Hence, the critical overload is reduced to 11%, when spreading factor is increased from 16 to 64. If we increase the overloading further to 19% or more, a BER error floor is reached.

In Fig. 5, the BER performance of QOS scheme with conventional matched filter and SDIC receiver on a Rayleigh fading channel is shown for $N=16$. Fig. 4 also shows the theoretical single-user BER performance over a Rayleigh fading channel. It can be observed that the SNR degradation at a BER of $5 \cdot 10^{-4}$ is about 1 dB at 19% channel overload. If the channel overload is increased to 25%, a BER error floor is reached. So, we can obtain 19% channel overloading on a Rayleigh fading channel with the SDIC receiver for $N = 16$.

Fig. 6 shows the BER performance for $N=64$ at 45% (29 extra users) channel overloading. The SNR degradation at a BER of $5 \cdot 10^{-4}$ is about 1 dB at 45% channel overload. Thus, we observe that the overloading performance tends to improve considerably with increasing N from 16 to 64. The BER degradation occurring with $N = 16$ disappears on the curves corresponding to $N = 64$ on Rayleigh fading channel.

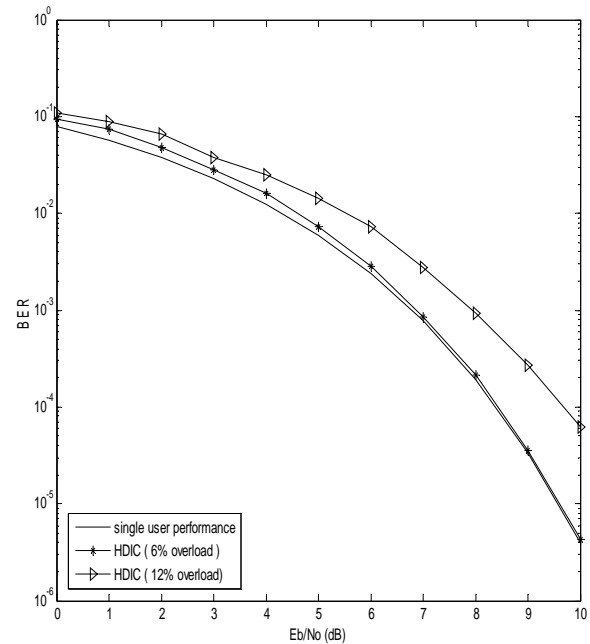


Fig. 1. BER performance of QOS overloading scheme with hard decision interference cancellation (HDIC) receiver for $N=16$ over an AWGN channel

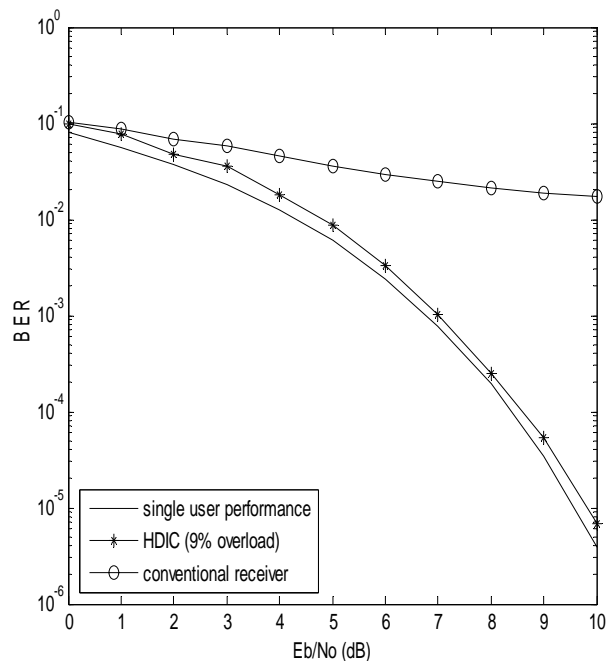


Fig. 2. BER performance of QOS overloading scheme with hard decision interference cancellation (HDIC) receiver for $N = 64$ over an AWGN channel

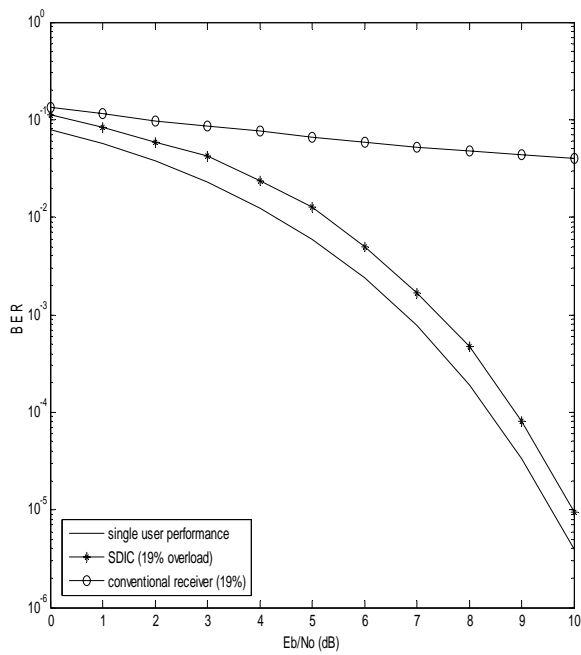


Fig. 3. BER performance of QOS overloading scheme with soft decision interference cancellation (SDIC) receiver for $N=16$ over an AWGN channel

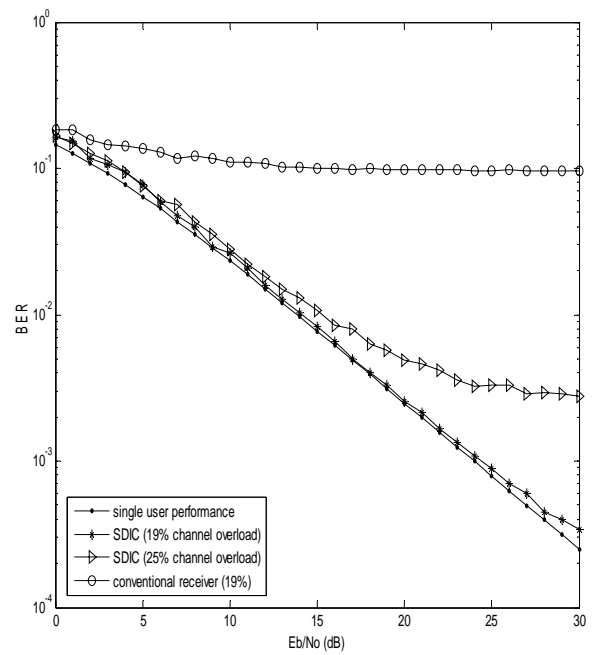


Fig. 5. BER performance of QOS with 19% and 25% overload and SDIC receiver over a Rayleigh fading channel for $N=16$

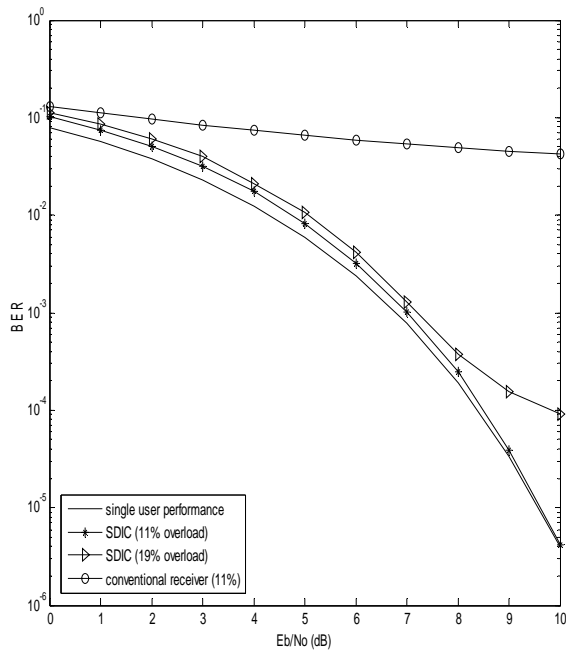


Fig. 4. BER performance comparison of QOS overloading scheme with SDIC receiver for $N=64$ over an AWGN channel

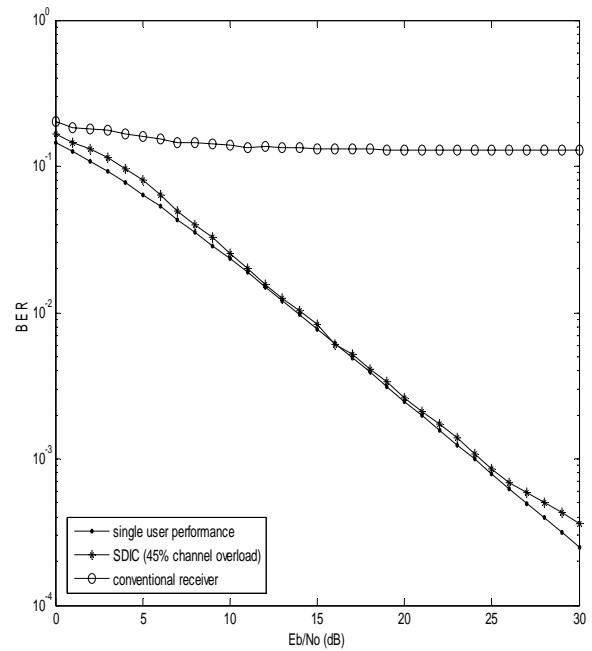


Fig. 6. BER performance of QOS scheme with 45% overload with SDIC receiver over a Rayleigh fading channel for $N=64$

V. CONCLUSION

Efficient use of the available radio spectrum is an important requirement for future wireless communication. Overloading is an efficient way to increase the capacity of a DS-CDMA system. In this work, overloading performance of QOS scheme is evaluated. The channel overloading of 19% is obtained on an AWGN with soft decision interference cancellation (SDIC) at a BER of 10^{-5} with less than 0.35 SNR degradation as compared to single user performance, for $N=16$. For $N=64$, the critical load is only 11%. But it is observed that QOS scheme with soft decision interference cancellation (SDIC) can overload the DS-CDMA systems by 45% (29 extra users) at BER of 5×10^{-4} for $N=64$, with an SNR degradation of about 1 dB on a Rayleigh fading channel.

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