Parallel Interference Cancellation in Coded DS-CDMA Systems

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Abstract

This paper concerns the application of subtractive interference cancellation for an asynchronous uplink transmission in a DS-CDMA system employing different FEC coding strategies. Due to the inherent bandwidth expansion in CDMA systems, powerful low rate coding is possible. Therefore, the combination of convolutional and repetition codes (CCRPC) as well as a serial concatenation of a convolutional code, a Walsh code and a repetition code (SCCS) are considered. Besides a comparison of the different coding approaches, parallel interference cancellation (PIC) is applied to overcome the tremendous effect of multi-user interference (MUI) limiting the capacity of CDMA systems. In this context, different combinations of PIC and iterative SCCS decoding are examined.

Assuming perfectly known channel impulse responses for each user it turns out that the CCRPC scheme achieve near single user performance even in the case of high system loads. High interference levels degrade the performance of the SCCS considerably even when PIC is applied. Only for low system loads SCCS outperforms the other coding schemes.

1 Introduction

Code Division Multiple Access (CDMA) has been chosen in various modern communication systems [1, 2, 3, 4, 5, 6] as multiple access technique. One popular realization is the well-known single-carrier Direct-Sequence CDMA system (DS-CDMA) already embedded in the IS-95 standard [1]. Due to the inherent spreading, each user occupies a large bandwidth offering FEC coding with very low code rates and, therefore, high coding gains.

Up to now, a lot of work has been carried out concerning the trade-off between spreading and channel coding [7, 8]. Recently, it was pointed out by Frenger et al. [9] that spreading can be interpreted as simple repetition coding, i.e. spreading is nothing else than channel coding. Hence, the question arises if we can replace the weak repetition code by a stronger FEC code.

Specifically, we analyze the performance of two coding schemes for an uplink transmission over a frequency-selective Rayleigh fading channel. First, we consider a coding scenario consisting of a convolutional code and a simple repetition code (CCRPC). Second, the poor repetition code is mainly replaced by a more powerful Walsh-Hadamard block code that can be decoded efficiently by the Fast Hadamard transformation (FHT). Hence, we get a serially concatenated coding scheme (SCCS) that is iteratively decoded [10, 11].

Besides the task of finding strong codes of very low rate the question arises how the coding schemes behave in the presence of a multi-user detection (MUD) scheme. In contrast to a synchronous downlink transmission where orthogonal spreading sequences suppress multi-user interference (MUI) efficiently, pseudo-noise (PN) sequences are used for an asynchronous uplink transmission. Therefore, multi-user interference is the limiting factor concerning system capacity. In this paper, we apply parallel interference cancellation (PIC) assuming perfectly known channel impulse responses and identical average receive power for each user. The latter assumption is valid for systems with perfect power control so that no near-far problems occur.

The application of parallel interference cancellation leads itself to an iterative process including the FEC decoder and the interference canceller. Concerning the SCCS, it turns out that the receiver contains two nested loops allowing several realizations.

The paper is structured as follows: Section 2 describes the DS-CDMA transmission scheme and the different coding scenarios. Furthermore, simulation results for a single-user system and multi-user systems are presented. Next, the parallel interference cancellation scheme with the corresponding simulation results are discussed in sections 3 and 4. Finally, section 5 concludes the paper.

2 System Description

2.1 DS-CDMA

Figure 1 illustrates the structure of a typical DS-CDMA system for a single user j, $1 \leq j \leq J$. The remaining $J-1$ interfering users are summed up to the signal $\mathbf{i}$. The data stream $\mathbf{d}^{(j)}$ consists of binary information bits $d^{(j)}(k)$ each of duration T_d and is encoded by one of the coding schemes described in section 2.2. All coding schemes have the same overall code rate

$$R_c = \frac{1}{G_P} = \frac{1}{64}\,. \tag{1}$$

Therefore, the channel encoder performs the entire spreading with a total processing gain of $G_P = 64$. After encoding, the resulting sequence $\mathbf{b}^{(j)}$ with $T_b = T_d \cdot R_c$ is scram-

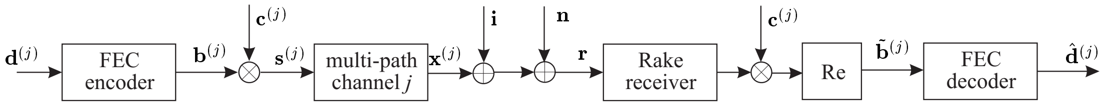

Figure 1: Typical structure of a DS-CDMA system with single-user detection

bled by a user-specific code $\mathbf{c}^{(j)}$ possessing the same chip duration $T_c = T_b$. Due to an asynchronous transmission in the uplink, we use simple pseudo-noise (PN) sequences for spreading. The scrambled signals of different users are transmitted over individual mobile radio channels.

According to Figure 1, a symbol $r(k)$ within the received sequence $\mathbf{r}$ can be expressed by

$$r(k) = \sum_{j=1}^{J} \sum_{l=0}^{L-1} h_l^{(j)}(k) \cdot s^{(j)}(k-l) + n(k) \tag{2}$$

where L describes the number of transmission paths of the mobile radio channel and $n(k)$ the background noise. Although each user is assigned to an individual channel, L is assumed to be the same for all users. Presupposing perfectly known channel coefficients $h_l^{(j)}(k)$ that remain unchanged during a time interval T_d, the corresponding symbol for user $j = 1$ at the input of the channel decoder can be devided into four parts

$$\tilde{b}^{(1)}(k) = \alpha(k) + \beta(k) + \gamma(k) + \eta(k)\ . \tag{3}$$

First, $\alpha(k)$ represents the desired coded information obtained by maximum ratio combining L different taps yielding a diversity gain and therefore enhancing the average signal-to-noise ratio at the input of the channel decoder. Next, $\beta(k)$ describes the path cross talk within the Rake receiver and $\gamma(k)$ the multiple access interference. Finally, the contribution of the background noise is denoted by $\eta(k)$. These four parts build the input signal of the channel decoder. Note that the de-spreading, i.e. integrating the descrambled signal over a duration T_b, is not performed in the Rake receiver but in the channel decoder.

2.2 Coding scenarios

The aim of this paper is to shed some light on the mutual influence of channel coding and multi-user detection. Therefore, we consider two different coding scenarios. They are introduced only briefly, a more detailed description can be found in [10, 11, 12].

The conventional coding system (CCRPC) employs a simple convolutional code (CC) of constraint length $L_c = 7$ and code rate $R_c^{cc} = 1/n$ followed by a repetition encoder (RPC). The latter one has the code rate $R_c^{rpc} = 1/N_P$ ensuring a constant entire processing gain of $G_P = 1/(R_c^{cc} \cdot R_c^{rpc}) = 64$. Therefore, the whole bandwidth expansion is already implemented in the channel encoder. Among a large variety of combinations between R_c^{cc} and R_c^{rpc} we have chosen two parameter configurations listed in Table 1. Decoding is simply performed by means of a correlator (RPC) and a Viterbi decoder (CC).

In order to improve the performance of the coding scheme, we replace the RPC by an interleaver and a Walsh code [13] performing the inner spreading and providing

	CC	WH	RPC
CCRPC	$R_c^{cc} = 1/2$	-	$R_c^{rpc} = 1/32$
$L_c = 7$	$R_c^{cc} = 1/8$	-	$R_c^{rpc} = 1/8$
SCCS	$R_c^{cc} = 1/2$	$R_c^{w} = 6/64$	$R_c^{rpc} = 1/3$
$L_c = 3$	$R_c^{cc} = 1/2$	$N = 600, 6000$	

Table 1: Coding parameters

low decoding complexity by the Fast Hadamard transform. Thus, the entire coding scenario describes a serial concatenation of a convolutional code, a Walsh code and a repetition code as depicted in Figure 2. At the receiver, the repetition code is decoded first. Then, an iterative decoding process starts consisting of an inner symbol-by-symbol Max-Log-MAP-decoder [14, 15] for the Walsh code and an outer Max-Log-MAP decoder for the convolutional code (refer to Figure 3). The extrinsic information of each decoder is extracted and fed to the successive decoder improving the performance compared with a single decoding iteration.

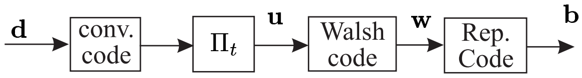

Figure 2: Encoder of serial concatenated coding scheme (SCCS)

Analyzing the SCCS it turns out that a convolutional code with $L_c = 3$ and $R_c = 1/2$ yields the best results in the context of suboptimal iterative decoding. It was combined with a rate $6/64$ WH code so that the code rate of the repetition code amounts $R_c^{rpc} = 1/3$. The interleaver Π_t between CC and Walsh encoder was randomly chosen with different lengths N. Table 1 depicts the parameters of the coding schemes under investigation.

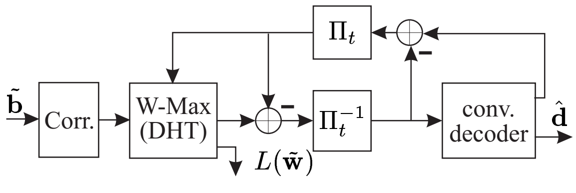

Figure 3: Decoder of serial concatenated coding scheme (SCCS)

2.3 Performance without PIC

In this subsection, we first present simulation results for single-user systems (SUS). A fully symbol-interleaved 4-path Rayleigh fading channel was used, i.e. the channel is assumed to remain unchanged for the duration $T_d = G_P \cdot T_c$ of one information bit. In the average, the transmitted signal's energy is spread equally over the 4 taps of the channel. Successive channel coefficients are assumed to be statistically independent.

Figure 4 depicts the corresponding simulation results. Please note that E_b denotes the energy per information bit $d^{(j)}(k)$ and not the energy of a coded bit $b^{(j)}(k)$. Obviously, at medium and high signal-to-noise ratios, the Walsh-coded SCCS outperforms the conventional schemes by 2 dB for an interleaver size of $N = 600$ and by 3 dB for $N = 6000$. At low signal-to-noise ratios, the conventional schemes perform better. Moreover, the CCRPC scheme with $R_c^{cc} = 1/2$ loses nearly 0.5 dB compared with $R_c^{cc} = 1/8$. Further reductions of R_c^{cc} lead only to minor additional gains.

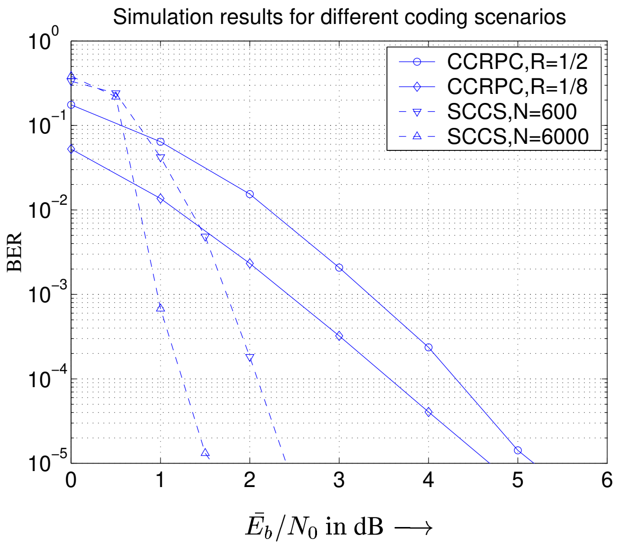

Figure 4: Simulation results for different coding schemes and $J = 1$ active user

The results discussed above represent the performance of a single-user system. However, expanding our considerations to J active users does not require additional simulations. We can tightly approximate the results for J active users by calculating an equivalent E_b/N_0 and exploit the results of the single-user system already depicted in Figure 4. Regarding a L-path Rayleigh fading channel with equal power distribution and a chip-synchronous transmission, the average signal-to-noise ratio on each channel tap is

$$\gamma = \frac{R_c E_b/N_0}{L + (JL-1)R_c E_b/N_0} . \tag{4}$$

Equation (4) takes into account the effects of multi-user interference and path cross talk. The Rake receiver performs the maximum ratio combining of L statistically independent taps. For a fixed channel, the signal-to-noise ratio is increased by a factor L. Furthermore, considering also the processing gain G_P that affects the suppression of interfering users as well as the path cross talk, we receive an equivalent measure of E_b/N_0

$$SNR^{equ}(E_b/N_0, J, L) = \frac{L E_b/N_0}{L + (JL-1)R_c E_b/N_0} . \tag{5}$$

Now, we can approximate the performance of multi-user systems in the absence of MUD techniques. From (5) with $J = 1$ and the simulation results shown in Figure 4 we know the function $P_b^{(J=1)}(SNR^{equ}(E_b/N_0, 1, L))$. Replacing $SNR^{equ}(E_b/N_0, 1, L)$ by $SNR^{equ}(E_b/N_0, J, L)$, we get the relationship

$$P_b^{(J)}(SNR^{equ}(E_b/N_0, 1, L)) =$$

$$P_b^{(J=1)}(SNR^{equ}(E_b/N_0, J, L)) . \tag{6}$$

Figure 5 shows the performance of the considered coding schemes for $J = 32$ active users. Simulation results are depicted as symbols whereas lines represent the application of (6). Obviously, a tight conformance can be observed. A comparison with Figure 4 visualizes the performance degradation due to MUI. The CCRPC schemes possess a high error floor caused by severe multiple access interference so that an error rate of $P_b = 10^{-4}$ cannot be reached. However, the SCCS especially with the larger interleaver is able to achieve error rates of $P_b = 10^{-5}$ in range $7 \text{ dB} \leq E_b/N_0 \leq 11 \text{ dB}$. Therefore, the SCCS provides acceptable performance even in the absence of multi-user detection schemes. As expected, the points of intersection between SCCS and CCRPC moved toward higher E_b/N_0 but they still lie in the range $10^{-1} < P_b < 10^{-2}$.

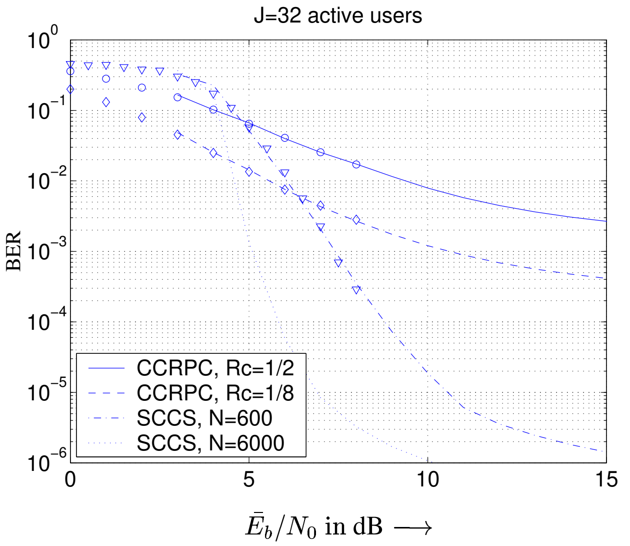

Figure 5: Performance of coding schemes for $J = 32$ active users

3 Parallel Interference Cancellation

Multi-user detection (MUD) schemes can be mainly devided into two groups, linear and nonlinear techniques [16]. Linear MUD schemes invert the correlation matrix $\mathbf{R}$ of the used spreading sequences according to the zero-forcing or the MMSE solution. The latter one supplies a compromise between sufficiently decorrelating the interfering signals and noise suppression. Due to the inversion of $\mathbf{R}$, the above mentioned methods presuppose a repetition code for spreading. Otherwise, the correlation matrix would be influenced by the coded data bits and calculating the inverse of $\mathbf{R}$ would require an estimation of the coded bits itself. Thus, to our knowledge, a joint implementation of linear MUD and decoding without a repetition code has not yet been realized and linear MUD cannot be applied for the SCCS.

Therefore, we consider nonlinear multi-user detection operating behind the FEC decoder. Generally, successive and parallel interference cancellation schemes are distinguished. The former technique is suitable for systems without power control where the power of the received signals vary in a wide range. This scenario is predestinated for the successive detection of all signals starting with the highest

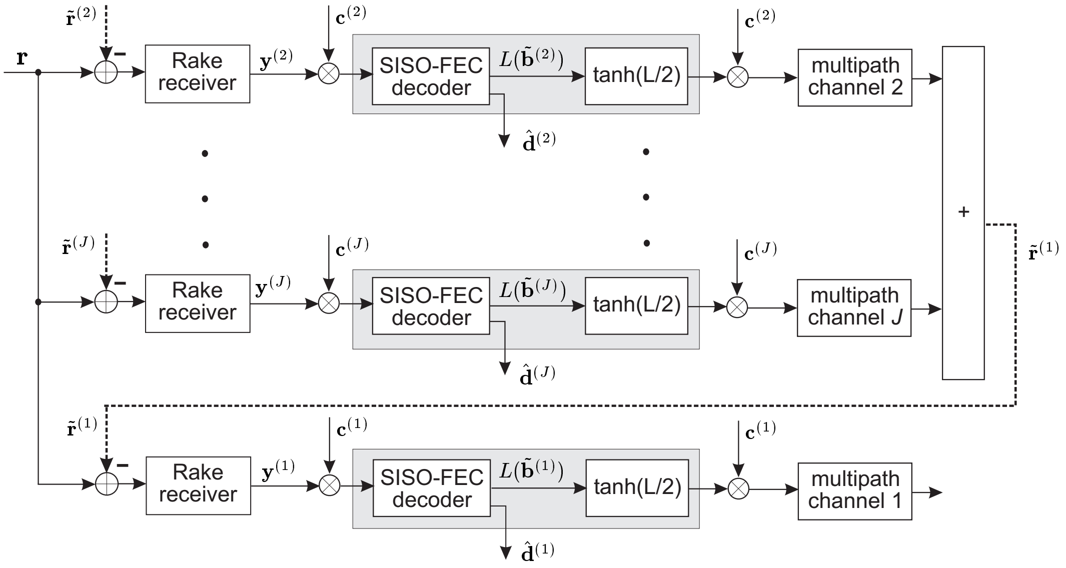

Figure 6: Principle structure of the parallel interference cancellation scheme

power signal and proceeding till the weakest signal has been detected. After each detection, the re-constructed version is subtracted from the channel output reducing the interference and allowing a more reliable detection of the remaining signals.

In this paper, we apply parallel interference cancellation (PIC) where all incoming signals are detected simultaneously. In contrast to the scheme described above, the PIC scheme requires a strong power control ensuring the same receive power for all incoming signals. The structure of the whole PIC system is depicted in Figure 6. A Soft-In/Soft-Out decoder delivers the estimated information bits $\hat{\mathbf{d}}^{(j)}$ as well as log-likelihood ratios $L(\tilde{\mathbf{b}}^{(j)})$ of the coded bits. Then, the expected values of the LLRs are calculated by the tanh-function. Afterwards, the received sequences are re-constructed by scrambling and re-transmitting over the individual 4-path Rayleigh fading channels. Finally, the sum $\tilde{\mathbf{r}}^{(1)}$ of all interfering signals regarding user $j = 1$ is subtracted from the received signal $\mathbf{r}$. In the absence of decoding errors, this difference is an estimate of the received signal of user $j = 1$ without multi-user interference. Therefore, passing this signal through the Rake and the channel decoder a second time should yield the performance of the single-user case. Due to decoding errors, the procedure described above has to be repeated several times.

Concerning the SCCS, it has to be mentioned that there exist several possibilities to calculate the LLRs $L(\tilde{\mathbf{b}}^{(j)})$. Instead of using the output of the convolutional decoder, we have exploited $L(\tilde{\mathbf{w}})$ at the output of the Walsh decoder. As depicted in Figure 3, it delivers not only soft estimates for the input bits $\mathbf{u}$ of the Walsh encoder but also a LLR for each coded symbol in a WH codeword. The expected values of these LLRs have to be repeated N_p times, scrambled and retransmitted over the multi-path channel.

The structure described above incorporates two nested loops so that two possible realizations exist. First, we can perform the iterative decoding for each user before carrying out the subtractive interference cancellation. This would guaranty a certain reliability of the reconstructed signal used for interference cancellation. Alternatively, we first carry out a loop consisting of Walsh decoding and subtractive interference cancellation several times before running the decoding loop. This would save some computational effort because the convolutional soft-in/soft-out decoder does not run so often. However, the second approach suffers from the inaccuracy of the reconstructed signal and performs much worse than the first one. Therefore, the next section presents only the results for the first PIC realization.

4 Simulation Results

As mentioned above, we used a fully symbol-interleaved 4-path Rayleigh fading channel in our simulations. Due to the multiplicity of parameter combinations, we restrict the presentation on the coding schemes CCRPC with $R_c^{cc} = 1/8$ and SCCS with $N = 600$. The results for these schemes and different number of active users are shown in Figures 7 and 8, respectively. It can be observed that the CCRPC scheme reaches the single user performance (SUS) even in the case of $J = 48$. Note that $J = 32$ active users lead to a 'full loaded system' when compared with half rate coded TDMA or FDMA systems. Contrarily, the SCCS scheme with $N = 600$ only reaches SUS performance for $J = 8$ and $J = 16$. Increasing the number of users to $J = 32$ leads to a loss of more than 1 dB at $P_b = 10^{-5}$.

A direct comparison of CCRPC and SCCS is shown in Figure 9. At a bit error rate of $P_b = 10^{-5}$ the SCCS outperforms the conventional scheme for $J = 16$ and $J = 32$ users. However, the gain for $J = 32$ is rather small and the point of intersection between CCRPC and SCCS is reached at $P_b = 6 \cdot 10^{-5}$. These relationships can be explained by regarding once again Figure 4. As already mentioned in section 2.3, the point of intersection is moving towards higher signal-to-noise ratios when J increases. Therefore, for large J the PIC scheme is working at SNRs where the CCRPC scheme outperforms the SCCS. It is expected for $J > 32$ that the SCCS performs worse. Concerning the computational costs it has to be mentioned that due to the small constraint length of the convolutional code in the SCCS it needs less computational power than the CCRPC scheme.

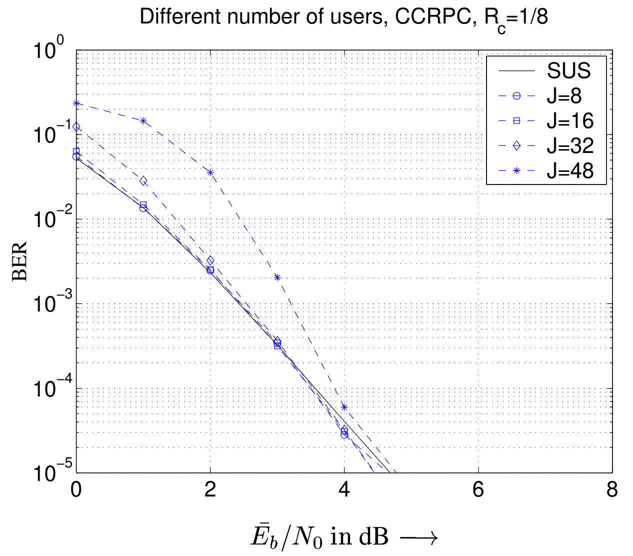

Figure 7: Performance of PIC for CCRPC and different number of users

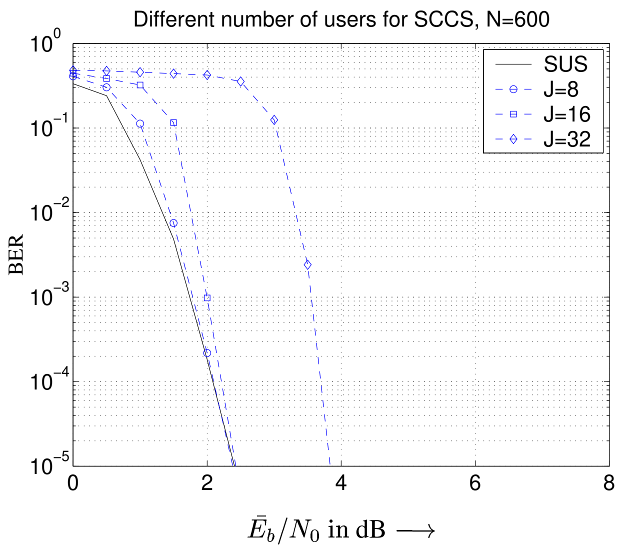

Figure 8: Performance of PIC for SCCS and different number of users

5 Conclusion

It has been shown that significant performance improvements can be achieved by replacing the weak repetition code inherent in many CDMA systems by a more powerful code, e.g. a Walsh code or a convolutional code of lower rate. Comparing CCRPC and SCCS, it turns out that SCCS performs better for medium and high signal-to-noise ratios. Even for high system loads, the SCCS is able to provide acceptable error rates without MUD. The application of parallel interference leads to remarkable gains. For the CCRPC scheme the performance of a single-user system is reached even for $J = 48$ users. Concerning the application of PIC for the SCCS, there remains a gap to the single-user system for high system loads. However, its performance is still superior to that of the CCRPC scheme.

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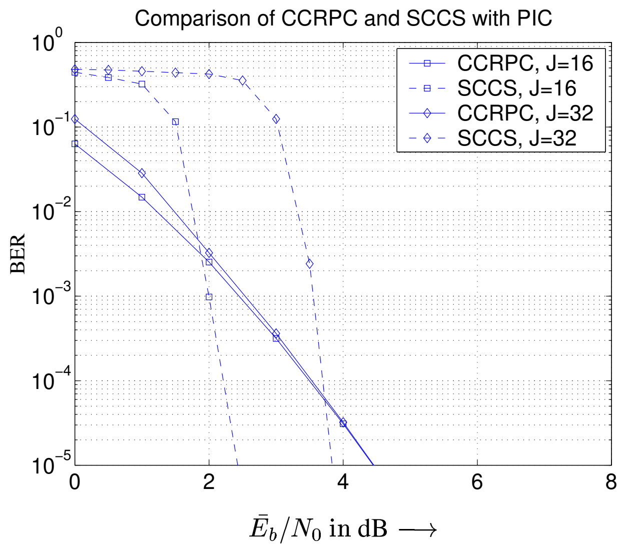

Figure 9: Comparison of CCRPC and SCCS with PIC

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