

A Bidirectional Processing Receiver for Layered Space-Time MIMO Systems

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Resumo—Neste artigo, é apresentada uma nova estrutura de receptor para sistemas MIMO (do inglês, *multiple-input multiple-output*) baseados em cancelamento não-linear de interferência. A ideia principal do receptor proposto está no uso de uma abordagem bidirecional para o processamento do sinal, em que filtragem espacial e subtração de interferência iniciam simultaneamente na primeira e última camada de detecção, prosseguindo sucessivamente até a camada central de forma paralelizada. O receptor bidirecional proposto tem duas vantagens principais comparado aos detectores SIC (do inglês, *successive interference cancellation*): i) o atraso de processamento pode ser reduzido pela metade fazendo-se uso de uma unidade de processamento paralelo e ii) o desempenho em termos de taxa de erro de bits pode ser melhorado consideravelmente em decorrência do maior ganho de diversidade obtido nas camadas de detecção. Além disso, o receptor bidirecional proposto exibe desempenho semelhante ao do receptor com retro-processamento recursivo proposto recentemente em [6], mas com um tempo de processamento menor. Resultados de simulação são fornecidos para confirmar o mérito do receptor proposto em termos de taxa de erro de bits não-codificada.

Palavras-Chave—Sistemas MIMO, processamento bidirecional, cancelamento sucessivo de interferência, multiplexagem espaço-temporal.

Abstract—In this paper, we present a new receiver structure for layered space-time multiple-input multiple-output (MIMO) systems based on non-linear interference cancellation. The main idea of the proposed receiver is to use a bidirectional processing approach, where spatial filtering and interference subtraction start simultaneously at the first and last layers and proceed successively towards the central layer in a parallelized manner. The proposed bidirectional processing receiver has two main advantages compared to traditional successive interference cancellation (SIC) detectors: i) the processing delay can be reduced by a factor of two at the expense of a parallel processing unit and ii) the bit-error-rate performance can be considerably improved due to the increased diversity gain obtained across the detection layers. Moreover, our bidirectional processing receiver exhibits the same performance as the recently proposed backward recursion based receiver [6] at a reduced processing time. Simulation results are provided to confirm the merits of the proposed receiver in terms of uncoded bit-error-rate.

Keywords—MIMO systems, bidirectional processing, successive interference cancellation, space-time multiplexing.

I. INTRODUCTION

Multiple input multiple output (MIMO) antenna systems have been a topic of intense research during the last decade due

to their capability to provide high data rates and robustness to wireless links. MIMO is considered a mandatory technology to be employed in the upcoming wireless communication systems, such as 3G+ and 4G, for achieving the envisaged quality of service (QoS) levels [1]. Despite the well-known trade-off between diversity and multiplexing whenever a MIMO structure is considered [2], the goal of maximizing the data rate is achieved by means of spatial multiplexing schemes. Contrary to diversity schemes, where most of the signal processing is performed at the transmitter, multiplexing schemes use the receiver as the processing unit for interference cancellation purposes [3]. Typical solutions are zero forcing (ZF) and minimum mean square error (MMSE) receivers for the linear spatial filtering, and successive interference cancellation (SIC) as non-linear interference cancellation scheme [4]. Although very simple, the SIC receiver suffers from the problem of error propagation since the first detected layer must have a good temporal coding. Further, during detection, the initial layers have lower diversity orders, since the amount of interference is proportional to the the number of non-detected layers at this point [4].

In order to improve detection performance, some works have proposed iterative methods for processing the information and extracting more diversity during the receiver signal processing for interference cancellation. The method of [5] performs an iterative maximal ratio combining (MRC)-vector after the interference cancellation stage in order to improve performance over the traditional spatial multiplexing scheme, also known as vertical bell-labs layered space-time (VBLAST) structure. In a recent work [6], an enhanced SIC-based detection algorithm for layered space-time multiplexing schemes in MIMO systems has been proposed, which consists in adding a backward recursion in traditional non-linear interference cancellation detectors in order to provide an improved diversity order at the receiver to all layers.

In this paper, we present a new receiver structure for layered space-time MIMO systems based on non-linear interference cancellation. The main idea of the proposed receiver is to use a bidirectional processing approach, where spatial filtering and interference subtraction start simultaneously at the first and last layers and proceed successively towards the central layer in a parallelized manner. The proposed bidirectional processing receiver has two main advantages compared to traditional SIC detectors. First, the processing delay can be reduced by a factor of two at the expense of a parallel processing unit. Second, the bit-error-rate performance can be considerably improved due to the increased diversity gain obtained across the detection layers. Our results also shown

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that the bidirectional processing receiver exhibits the same performance as the recently proposed backward recursion based receiver [6] at a reduced processing time.

The rest of this paper is organized as follows. In Section II the system model is described. The rationale of the layered detection is discussed in Section III while Section IV is devoted to the explanation of the proposed bidirectional processing receiver. Simulation results corroborating the merits of the proposed receiver are shown in Section V and the paper is concluded in Section VI.

II. SYSTEM MODEL

We consider a transmitter equipped with an M -element antenna array and a receiver equipped with an N -element antenna array ($N \geq M$). The wireless channel matrix is assumed to have rich scattering and undergo flat-fading. The fading between each transmit and receive antenna pair is assumed to be independent. A quasi-static block fading model is assumed. Furthermore, the total transmit power is fixed and equally divided across the transmit antennas. Ideal symbol timing and pulse shaping are assumed at the transmitter and receiver. Thus, we can relate the transmit and receive symbols in a given symbol period in complex baseband form as:

$$\mathbf{x} = \sqrt{\frac{E_s}{M}} \mathbf{H} \mathbf{s} + \mathbf{v}, \quad (1)$$

where \mathbf{H} denotes the $N \times M$ channel matrix, \mathbf{x} denotes the complex received vector of dimension $N \times 1$, \mathbf{s} denotes the transmitted symbol vector having dimension $M \times 1$, \mathbf{v} is the additive white circularly symmetric complex gaussian noise samples with zero mean and variance $\sigma_v^2 = N_0/2$ per dimension and E_s/M is the energy of a symbol radiated from each transmit antenna.

III. LAYERED SPACE-TIME INTERFERENCE CANCELATION DETECTORS

In order to separate the signals received from the several transmit antennas at the receiver, interference cancellation detection algorithms should be considered to detect the co-channel signals. Initially, detection techniques were proposed in the literature based on the conventional linear nulling, which consider one layer as the desired, one per turn, and the other ones are treated as interferers. The nulling vectors in each turn are calculated following a given criterion such as ZF and MMSE [7].

In ZF criterion the decision for the i -th layer is made nulling the other $M-1$ layers, and the nulling spatial filter \mathbf{W} is given by

$$\mathbf{W}^H = \sqrt{\frac{M}{E_s}} \mathbf{H}^\dagger = \sqrt{\frac{M}{E_s}} (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H, \quad (2)$$

where \mathbf{H}^\dagger is the Moore-Penrose generalized inverse matrix [8] and $(\cdot)^H$ is the Hermitian operator.

Considering the MMSE criterion the nulling spatial filter \mathbf{W} is found minimizing the following cost function

$$J_{\text{MMSE}} = E\{\|\mathbf{W}^H \mathbf{x} - \mathbf{s}\|^2\}, \quad (3)$$

such that

$$\mathbf{W}^H = \sqrt{\frac{M}{E_s}} [\mathbf{H}^H \mathbf{H} + \sigma_v^2 \mathbf{I}_M]^{-1} \mathbf{H}^H, \quad (4)$$

where \mathbf{I}_M is an $M \times M$ identity matrix. As in the ZF criterion, the output vector for the i -th layer of the MMSE detector is y_i given by

$$y_i = \mathbf{w}_i^H \mathbf{x}, \quad (5)$$

where \mathbf{w}_i^H is the vector associated with the i -th row of the matrix \mathbf{W} . Both linear nulling detectors, ZF and MMSE, could improve their performance if an additional step is considered after the nulling of interference [7].

A superior detector performance for layered space-time MIMO schemes can be reached if the contribution of the detected layers to the the received signal is reconstructed and canceled. Assuming correct decisions (ideal case without error propagation), the resulting signal is free from the interference of the layers already detected, yielding better estimates of the remaining symbols, which improves the whole performance of the detector. This detector is known in the literature as SIC or nulling and canceling detector.

In SIC, the layers are detected sequentially. Initially, the received signal \mathbf{x} goes through a nulling detector for the first layer (we can apply ZF or MMSE criteria), whose output is used to produce a hard estimate of the symbols at this layer, \hat{s}_1 . Then, the contribution of the first layer to the received signal is estimated and cancelled, generating the signal \mathbf{x}_2 . This process is recursive until the last spatial layer is reached. In general, at the i -th layer, the signal \mathbf{x}_i , hopefully free from the interference of layers $1, \dots, i-1$, goes through a nulling detector that tries to mitigate the interference from layers $i+1, \dots, M$. A hard estimate of the symbol at this layer, \hat{s}_i , is then produced, based on the output of the detector. Then, the contribution of this layer to the "received signal" \mathbf{x}_i is estimated and canceled. This procedure yields a modified received signal given by

$$\mathbf{x}_{i+1} = \mathbf{x}_i - \hat{s}_i \mathbf{h}_i, \quad (6)$$

where \mathbf{h}_i is the i -th column of the channel matrix \mathbf{H} corresponding to the channel gains associated to layer i , and $\hat{s}_i \mathbf{h}_i$ represents the estimated interference from the i -th layer. The result is that \mathbf{x}_{i+1} is free from the interference coming from layers $1, \dots, i$. This signal is then fed into the linear detector for the $(i+1)$ -th layer and the process is repeated until layer M .

Note that the performance of SIC can be improved if the layers are detected in an appropriate order, resulting in the ordered successive interference cancellation (OSIC) algorithm [9]. Indeed, one of the disadvantages of SIC is that the signal associated with the first detected layer may exhibit a lower received signal-to-noise ratio (SNR) than some other layer. This may increase the probability of detection errors, which can propagate through the recursive detection process, degrading performance of the overall receiver. This problem can be mitigated if the layers are ordered by decreasing SNR, so that the first layer to be detected is that with the highest SNR.

A. Performance of Layered Space-Time Interference cancellation

In [10], the performance of MIMO linear MMSE spatial filtering followed by SIC was evaluated. The authors of [10] derive simple expression to evaluate the performance of low-complexity SIC algorithm. Basically, the performance of each layer of a MIMO linear MMSE followed by SIC with uniform mean power over all the transmit antennas is equivalent to that of a MIMO linear MMSE spatial filtering system with 1 transmit antenna and $N - M + i$ receive antennas, where the $(i + 1)$ -th layer is considered to be free from the interference coming from layers $1, \dots, i$ [10].

Using this result, we can claim that the diversity order is increased for each layer in the MIMO linear MMSE spatial filtering followed by SIC canceling approach. Clearly, this is unfair to the first layers to be detected by the algorithm since these layers will not obtain the full diversity order at the receiver. In order to overcome this issue we propose the backward recursion technique in non-linear interference cancellation detectors. As an illustration we will consider the SIC detector using the MMSE spatial filtering and the VBLAST spatial multiplexing scheme.

IV. PROPOSED BIDIRECTIONAL RECEIVER

In order to improve the performance of SIC based detectors in layered space-time multiplexing schemes, we propose to extend the canceling approach for the first layers using two SIC algorithm running in different directions where one of the algorithm acting from the first layer towards to M -th layer, meanwhile the other algorithm acting from the M -th layer towards to the first layer. This way, at each iteration the spatial filter estimates two symbols. Therefore, at the $M/2$ -th iteration, all the symbols are estimated and at the others $M/2$ iterations the two bidirectional SIC algorithms cancel the inter-layer interference. The bidirectional SIC algorithm is summarized in Algorithm 1 using a MMSE spatial filter. However, this idea could be extended straightforwardly to the ZF receiver.

In Algorithm 1, $Q(\cdot)$ denotes the quantization operation in accordance with the modulation in use, \hat{s}_i and \hat{s}_j is the estimation of the symbol at the first stage of the receiver in the i -th and j -th layer, y_i and y_j is the output of the MMSE filter at the i -th and j -th layer respectively. The variables \hat{s}'_i and \hat{s}'_j correspond to the estimated symbols at the second stage of the receiver in layer i and j respectively. Note that, in Figure 1, there are two SIC's acting at the first stage. Due to this, the receiver obtain an estimative of all M symbols in $M/2$ iterations. The next $M/2$ iterations are in the second stage, responsible to eliminate all the inter-layer interference. This way the full diversity order is achieved not only in the last layer as in the traditional SIC, but in all layers.

Another structure of receiver based in non-linear interference cancellation is the SIC with backward recursion [6]. It provides a gain of performance over classical SIC, implementing a backward recursion in non-linear interference cancellation detector in order to improve the diversity order. The algorithm 2 shows the functionality of the receiver

Algorithm 1 MMSE bidirectional SIC detector

MMSE spatial filtering:

$$\mathbf{W}^H = \sqrt{\frac{M}{E_s}} [\mathbf{H}^H \mathbf{H} + \sigma^2 \mathbf{I}_M]^{-1} \mathbf{H}^H$$

for $i = 1$ to $M/2$ **do**

$$j = M + 1 - i$$

$$y_i = \mathbf{w}_i^H \mathbf{x}_i$$

$$y_j = \mathbf{w}_j^H \mathbf{x}_i$$

$$\hat{s}_i = Q(y_i)$$

$$\hat{s}_j = Q(y_j)$$

$$\mathbf{x}_{i+1} = \mathbf{x}_i - \hat{s}_i \mathbf{h}_i - \hat{s}_j \mathbf{h}_j$$

end for

$$\hat{\mathbf{s}} = [\hat{s}_1 \hat{s}_2 \dots \hat{s}_M]^T$$

for $i = M/2 + 1$ to M **do**

$$j = M + 1 - i$$

$$\mathbf{x}_i = \mathbf{x}_j - [\mathbf{h}_j, \dots, \mathbf{h}_{i-1}] [\hat{s}_j, \dots, \hat{s}_{i-1}]^T$$

$$\mathbf{x}_j = \mathbf{x}_j - [\mathbf{h}_{j+1}, \dots, \mathbf{h}_i] [\hat{s}_{j+1}, \dots, \hat{s}_i]^T$$

$$y_i = \mathbf{w}_i^H \mathbf{x}_i$$

$$y_j = \mathbf{w}_j^H \mathbf{x}_j$$

$$\hat{s}'_i = Q(y_i)$$

$$\hat{s}'_j = Q(y_j)$$

$$\hat{s}_i = \hat{s}'_i$$

$$\hat{s}_j = \hat{s}'_j$$

end for

$$\hat{\mathbf{s}}' = [\hat{s}'_1 \hat{s}'_2 \dots \hat{s}'_M]^T$$

Algorithm 2 MMSE SIC detector with backward recursion

MMSE spatial filtering:

$$\mathbf{W}^H = \sqrt{\frac{M}{E_s}} [\mathbf{H}^H \mathbf{H} + \sigma^2 \mathbf{I}_M]^{-1} \mathbf{H}^H$$

Forward Recursion:

$$\mathbf{x} \leftarrow \mathbf{x}_1$$

for $i = 1$ to M **do**

$$y_i = \mathbf{w}_i^H \mathbf{x}_i$$

$$\hat{s}_i = Q(y_i)$$

$$\mathbf{x}_{i+1} = \mathbf{x}_i - \hat{s}_i \mathbf{h}_i$$

end for

Backward Recursion:

$$\hat{s}'_i = \hat{s}_M$$

for $i = M$ to 2 **do**

$$\mathbf{x}'_{i-1} = \mathbf{x}_{i-1} - [\mathbf{h}_i \dots \mathbf{h}_M] [\hat{s}'_i \dots \hat{s}'_M]^T$$

$$y'_{i-1} = \mathbf{w}_{i-1}^H \mathbf{x}'_{i-1}$$

$$\hat{s}'_{i-1} = Q(y'_{i-1})$$

end for.

proposed in [6]. The forward recursion is the same as classical SIC detection. At the $(M - 1)$ -th backward recursion layer, a modified received signal \mathbf{x}'_{M-1} is formed from \mathbf{x}_M by subtracting out the interference from the M -th layer. A new estimate of the k -th symbol transmitted at the $(M - 1)$ -th layer is then obtained by means of spatial filtering. The backward recursion proceeds similarly for the subsequent layers $M - 2, \dots, 2$. Both techniques has the same goal, to achieve the full diversity order to all space-time layers. However, the bidirectional SIC needs of M iterations to subtracting out the interference from the all layers, on the other hand, the backward SIC needs of $2M$. Therefore,

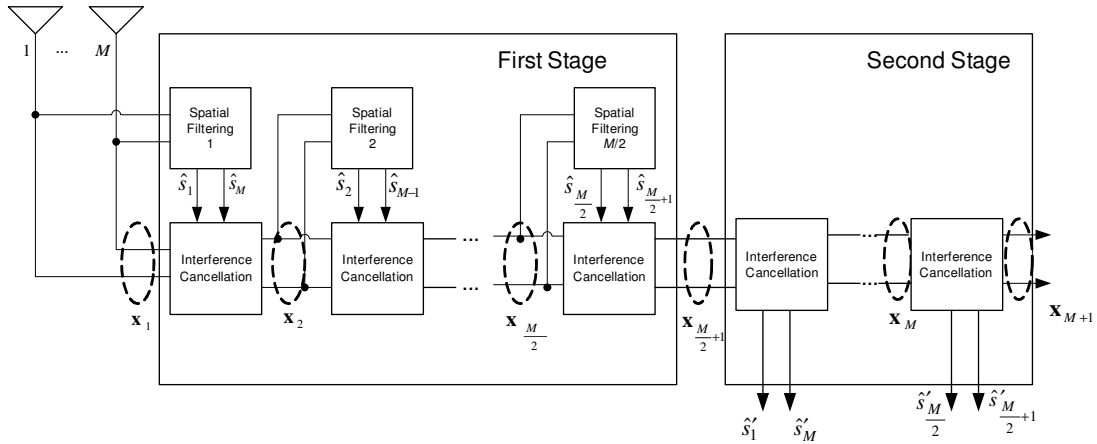


Fig. 1. Structure of Bidirectional SIC receiver.

the bidirectional SIC provides the same performance of the backward SIC in a shorter processing time.

V. SIMULATION RESULTS

In this section, we evaluate the bit error rate (BER) performance of the classical SIC, backward recursion based SIC, and the proposed bidirectional SIC receiver, using a VBLAST architecture, by means of numerical results from Monte Carlo simulations. Finally, we compare the time processing of the three receiver algorithms.

Figure 2 presents the per layer BER performance of bidirectional SIC. In this case, we assume VBLAST architecture with four transmit and four receive antennas (VBLAST 4x4) using quadrature phase shift keying (QPSK) modulation. As we can see in Figures 2 and 3, the overall diversity order is increased since all layers achieve the same BER performance. The increase in the diversity order provided by the bidirectional SIC can be obtained using SIC with backward propagation [6]. It is observed in Figure 4 that both algorithms have the same uncoded BER. Moreover, both techniques provide a power gain of 6.5 dB compared to the traditional SIC receiver, due to the maximal diversity order obtained in the four layers.

The results of Figures 2, 3 and 4 are obtained by considering the perfect estimation of the output symbols at the output of the spatial filter. Since estimation errors always occur in practice, in Figure 5 we evaluate the impact of a non-perfect estimation of the symbols. Note that both algorithms present the same BER performance and they lose 6 dB of SNR in relation to the system with perfect symbol estimation.

As we can see the bidirectional SIC and SIC with backward propagation have the same BER performance. However, the bidirectional SIC has an advantage, it is the processing time. Table I shows measurements of the overall processing time of the three receiver algorithms. We measured the processing time with the “tic toc” function of the Matlab simulation software. Ten thousand runs have been used to average the overall processing times.

Note that processing time of the bidirectional SIC receiver is lower than that of the backward recursion based SIC.

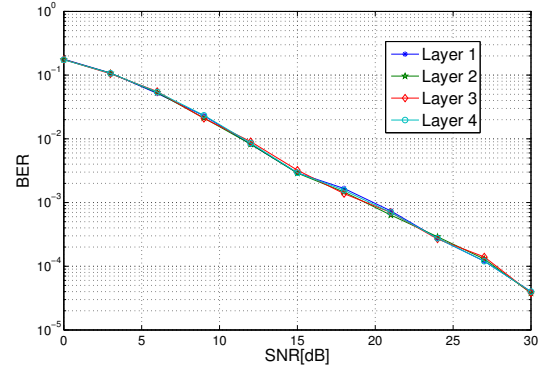


Fig. 2. BER performance per layer of Bidirectional SIC.

This is because the algorithm 2, it provides the maximal diversity to the system in $2M$ iterations, whereas the algorithm 1 does in M iterations. On the other hand, although the number of iterations is the same in both traditional SIC and bidirectional SIC, the algorithm 1 performs more operations at each iteration, which explains the time difference among the second and third columns of the table. As expected, the processing time increases using the VBLAST architecture as the number of transmitting/receiving antennas increase from 6 to 8. Moreover, the difference in processing time between bidirectional SIC and backward recursion based SIC increases with the diversity order. It is important to highlight that the increase on the diversity order results in a better BER performance. The BER of the VBLAST 6x6 is shown in Figure 6. Note the performance improvement of the three detectors in relation to Figure 4.

VI. CONCLUSIONS AND PERSPECTIVES

We have proposed a bidirectional SIC receiver for space-time multiplexing MIMO systems, where spatial filtering and interference subtraction start simultaneously at the first and last layers and proceed successively towards the central layer in a parallelized manner. This strategy provides to all layers of a spatial multiplexing scheme an improved

TABELA I
MEASURED TIME PROCESSING OF TRADITIONAL SIC, BIDIRECTIONAL SIC AND BACKWARD SIC.

	SIC (μ s)	Bid. SIC (μ s)	SIC w/ Back. prop. (μ s)
VBLAST 4x4	8.75	117.64	126.16
VBLAST 6x6	89.07	135	145.79
VBLAST 8x8	171.37	219.91	276.57

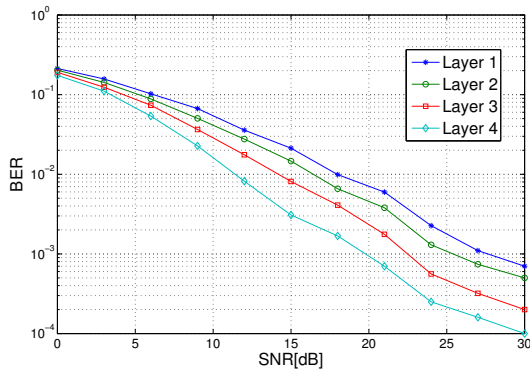


Fig. 3. Per-layer BER performance of traditional SIC.

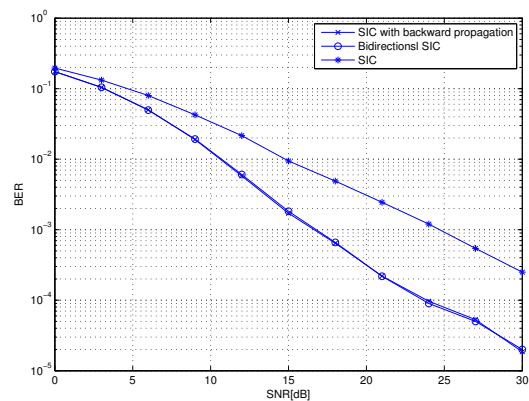


Fig. 6. BER performance of Bidirectional SIC and SIC with and without backward propagation, using a V-Blast 6x6 architecture.

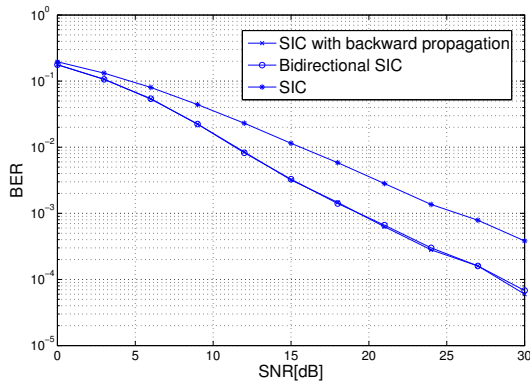


Fig. 4. Performances of bidirectional SIC, traditional SIC, and backward recursion SIC.

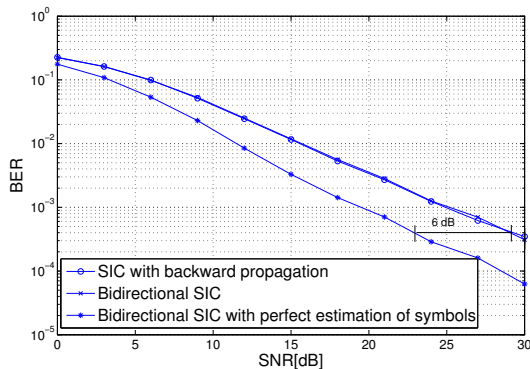


Fig. 5. BER performance of Bidirectional and SIC with backward propagation compared to the system with perfect estimation.

the backward recursion based receiver at a reduced processing time. Perspectives of this work include an extension of this idea to ordered SIC detection and the use of an iterative bidirectional recursion relying on turbo processing.

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diversity order at the receiver, leading to lower error rates than the traditional SIC detector, and the same performance as