

SIC receiver in a mobile MIMO-OFDM system with optimization for HARQ operation

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Abstract—We study the benefits of successive interference cancellation (SIC) receivers over linear receivers for multiple input - multiple output (MIMO) orthogonal frequency-division multiplexing (OFDM) systems. SIC receivers optimized for hybrid automatic repeat request (HARQ) operation are presented and analyzed.

I. INTRODUCTION

OFDM serves as the air interface for many upcoming mobile communication systems, such as 3GPP LTE. Multiple antenna techniques for the transmitter and the receiver (multiple input – multiple output, MIMO) are required to reach the high desired spectral efficiencies or peak data rates.

In MIMO spatial multiplexing (SM) transmission systems with M antennas at the transmitter (Tx) and N antennas at the receiver (Rx), up to $\min(M,N)$ independent data streams can be transmitted. Commonly, information bits of these data streams are grouped into transport blocks (TB), and these TBs are separately encoded, so that we have independent code words (CW) for the data streams. A successive interference cancellation (SIC) receiver can detect and decode the CWs of the data streams in such a way that if the CW of one data stream is successfully decoded (indicated by a cyclic redundancy check (CRC) code), the decoded data is then re-encoded, remodulated, etc., and cancelled from the originally received signal. Thus, interference is reduced for the remaining data streams. Note that in this paper we are looking at SIC Rx that do cancellation only after the *correct* decoding of CWs, as opposed to another kind of SIC Rx that perform cancellation based on undecoded data streams [1]. Therefore, here, interference cancellation cannot introduce errors that propagate through the detection process as for SIC Rx operating on undecoded data streams. One aspect in this paper is the performance gain of SIC Rx over linear Rx.

Commonly, mobile communication systems use a hybrid automatic repeat request (HARQ) scheme. If the CW relating to a certain TB cannot be correctly decoded at the Rx, a retransmission for this TB is initiated. At the Rx, the retransmitted data is com-

bined with the previously transmitted data in a HARQ buffer and a new decoding attempt is performed. The data in the HARQ buffer is stored in the form of log-likelihood ratios (LLR), so that data from retransmissions can be simply added to the data already in the HARQ buffer.

For SIC Rx, however, it may happen that decoding attempts for a certain CW are performed before and after the cancellation of other data streams. Therefore, there are different LLRs available in the various decoding attempts. If LLRs are simply added to the HARQ buffers, these may contain the superposition of “interference-containing” and “interference-free” LLRs. Therefore, we study a new SIC Rx optimized for HARQ operation for which LLRs in the current transmission time interval (TTI) are written to an additional buffer. Decoding is performed on the combined LLRs from this additional buffer and the HARQ buffer with the LLRs from previous transmissions.

Further, in the SIC process it may happen that a data stream is correctly decoded after a certain number of transmissions. In this case, the interference cancellation cannot only be performed in the current TTI, but also in previous TTIs if there are other remaining undecoded data streams. We show such a new SIC Rx.

II. SYSTEM DESCRIPTION

A. MIMO-OFDM SYSTEM

Fig. 1 shows a block diagram of the considered MIMO-OFDM system with M Tx antennas at the base station (BS) and N Rx antennas at the mobile station (MS). Here, we focus on downlink transmission, however the basic concepts are in principle also valid for uplink transmission. An input bit stream is first serial-to-parallel (S/P) converted, and forward error-correction (FEC) channel encoding is performed on the resulting M parallel streams. The FEC encoding is controlled by some Tx HARQ functionality as described in subsection II.B.

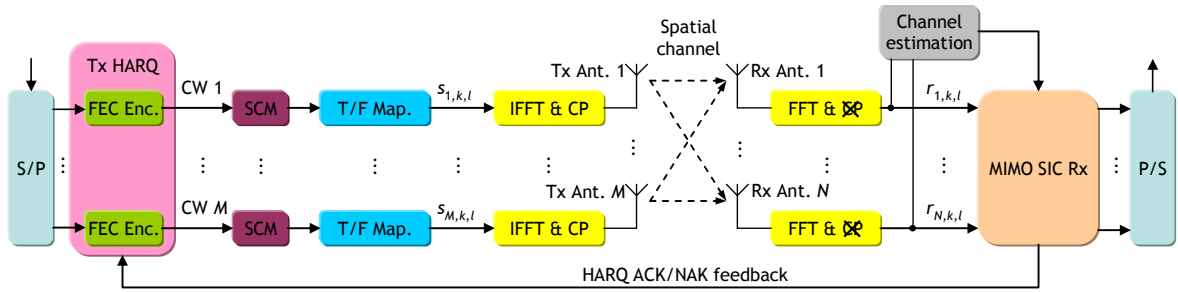


Fig. 1. MIMO-OFDM system with successive interference cancellation receiver

Single-carrier modulation (SCM) maps the encoded bits to complex-valued quadrature amplitude modulated (QAM) symbols, and the time/frequency (T/F) mapper puts these QAM symbols on the respective subcarriers l in OFDM symbols k . Thus we get the transmit column vectors $\mathbf{s}_{k,l} = [s_{1,k,l} \ s_{2,k,l} \ \dots \ s_{M,k,l}]^T$. We use 3GPP LTE OFDM parameters for the 5-MHz bandwidth system [2], i.e a 512-point IFFT/FFT for multi-carrier modulation/demodulation, 300 subcarriers with a 15-kHz spacing, and 14 OFDM symbols per 1-ms TTI. The cyclic prefix (CP) lengths are 4.69 μs or 5.21 μs for twelve or two out of the 14 OFDM symbols, respectively. FEC CWs span the full TTI.

For the simulations performed in this paper we use a spatial fading channel with a Vehicular A power-delay profile at a MS velocity of 120 km/h. Correlation between the Tx and Rx antennas is captured by the Kronecker correlation model [3] with correlation coefficients of $\rho_{Tx} = 0.1$ at Tx and $\rho_{Rx} = 0.7$ at Rx side.

After transmission over the channel and multi-carrier demodulation by the FFT and CP removal we have the MIMO SIC Rx, which is explained in more detail in subsections C and D. A channel estimation (CE) block provides estimates of the channel transfer function to the Rx. CE is either assumed to be ideal or is uses linear interpolation based on pilot signals according to 3GPP LTE [2].

B. HARQ AND CHANNEL ENCODING

Commonly, in mobile communication systems a HARQ scheme is used. The information bits of a TB are first appended by some bits from an error-detection code (e.g. CRC code), and then channel encoding for FEC is performed on the block of information bits plus the CRC bits. The resulting CW is transmitted to the Rx.

If the Rx can correctly decode the data (detected by a positive CRC), the Rx sends an acknowledge (ACK) message to the Tx, and the Tx can continue the transmission with a new TB. If the Rx cannot

correctly decode the data (detected by a negative CRC), a retransmission is initiated by sending a not-acknowledge (NAK) message to the Tx. Then after retransmission, at the Rx the retransmitted data is combined with the originally transmitted data in a HARQ buffer and a new channel decoding attempt is performed on the data stored in this HARQ buffer. The data in the HARQ buffer is stored in the form of LLRs, so that data from retransmissions can be simply added to the data already in the HARQ buffer.

In this paper we consider a HARQ scheme with incremental redundancy (IR). The CW in each transmission is different. However, it is derived from the same TB. This is achieved by having a mother code (3GPP LTE rate-1/3 turbo code [4]) for channel encoding, and applying different puncturing patterns on the turbo encoder output resulting in so-called different redundancy versions. Of course the puncturing patterns per transmission must be known to both the BS and MS.

The procedure of retransmissions is continued either until the data is correctly decoded or some maximum number of transmissions has been reached, in which case the TB is discarded at the Tx and a retransmission must be initiated by higher layers.

As there are delays in generating and signaling ACK/NAK messages, and in order not to leave the radio resources unused while waiting for the ACK/NAK messages at the Tx, a number of so-called HARQ processes is used. The transmitter can continuously transmit data by serving a number of HARQ processes. A TB is associated to a HARQ process until the TB is successfully received or the maximum number of transmissions is reached. Normally, we have one HARQ buffer per HARQ process. For example, while waiting for a ACK/NAK for the TB associated with HARQ process 1, the Tx can continue to transmit other TBs on HARQ processes 2, 3, ... As soon as it gets the ACK/NAK for HARQ process 1, it can come back to either initiate a retransmission for the TB in HARQ process 1, or use HARQ process 1 for a new TB.

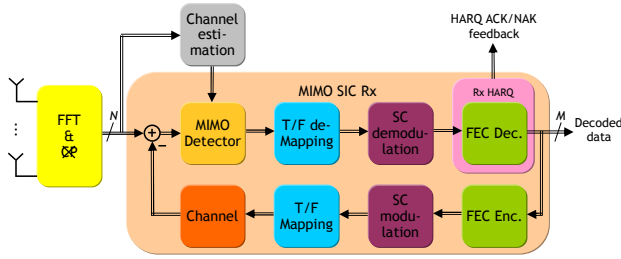


Fig. 2. Block diagram of type-0 SIC receiver

C. SIC RX WITH CHANNEL DECODING

Fig. 2 shows the block diagram of a SIC Rx, which in a first step is not optimized for HARQ operation. In order to distinguish it from other SIC Rx options, we call this a type-0 SIC Rx. First, detection for one particular data stream j is performed by multiplying the j -th rows of the weight matrices $\mathbf{W}_{k,l}$ to the received signal vectors $\mathbf{r}_{k,l} = [r_{1,k,l} \ r_{2,k,l} \ \dots \ r_{N,k,l}]^T = \mathbf{H}_{k,l} \cdot \mathbf{s}_{k,l} + \mathbf{n}_{k,l}$. $\mathbf{H}_{k,l}$ are the $N \times M$ channel matrices, and $\mathbf{n}_{k,l}$ are N -element column vectors representing noise and interference. The matrices $\mathbf{W}_{k,l}$ are calculated based on the estimated channel matrices either according to the zero-forcing (ZF) or the minimum mean squared error (MMSE) criterion [3]. We perform T/F demapping and single-carrier demodulation (SCD) for data stream j and write the resulting LLRs into the HARQ buffer for channel decoding. If the CW for data stream j cannot be correctly decoded, we try to detect and decode one of the other M data streams. If the CW for data stream j can be correctly decoded, we cancel the signal part belonging to data stream j from the received signal vectors $\mathbf{r}_{k,l}$. For that, we reconstruct the transmit signal $s_{j,k,l}$ for data stream j by re-encoding and remodulation. This can be achieved perfectly as we have error-free versions of the information bits because of the positive CRC. We reconstruct the received signal part belonging to data stream j and remove it from the received signal, i.e. we get a new effective received signal vector $\mathbf{r}_{k,l}^{\{j\}} = \mathbf{r}_{k,l} - \mathbf{H}_{k,l} \cdot [0 \ \dots \ 0 \ s_{j,k,l} \ 0 \ \dots \ 0]^T$. The superscript indicates the set of cancelled data streams. In all subsequent cancellation steps, the effective received signal vectors with previously cancelled data streams are used. After a data stream has been cancelled, we continue to try to detect and decode one of the remaining data streams. This process is continued until no further data streams can be correctly decoded.

For all the data streams that have been correctly decoded, the Rx HARQ functionality sends an ACK message to the Tx, whereas it sends a NAK

message for all incorrectly decoded data streams.

In this SIC process, it may happen that decoding attempts for a certain CW are performed before and after the cancellation of other data streams. Therefore, there are different LLRs available in the various decoding attempts. If LLRs are simply added to the HARQ buffers in each decoding attempt, the HARQ buffers may contain the superposition of “interference-containing” and “interference-free” LLRs. As this may degrade the decoding performance, we will look at SIC Rx overcoming this drawback in the next subsection II.D.

D. SIC RX OPTIMIZED FOR HARQ

D.1 Cancellation in current TTI (Type-1 SIC)

In this subsection we look at a modified SIC Rx optimized for HARQ operation. This type-1 SIC Rx is closely related to the type-0 SIC Rx from subsection II.C, however in addition to the HARQ buffers containing LLRs accumulated over previous TTIs it further comprises additional LLR buffers. Here, the idea is to add LLRs to the HARQ buffers only after all possible data streams have been cancelled, i.e. after all useful decoding attempts have been performed in the current TTI. In this way, only the “best possible” LLRs are added to the HARQ buffers for decoding attempts in the following TTIs. “Best possible” LLRs means that they are derived from the effective received signal with as many cancelled data streams as possible, i.e. the effective received signal with the lowest remaining interference. Thus, the HARQ buffers will not contain the superposition of LLRs from various decoding attempts in the SIC process in the current TTI. For intermediate decoding attempts in the current TTI, the LLRs are written to the additional LLR buffers (which are flushed every time before writing to them), and decoding is performed on the sum of the LLRs from the HARQ buffers and the LLRs from the additional LLR buffers. See Fig. 3 for an example with two data streams.

D.2 Cancellation in current and previous TTIs (Type-2 SIC)

In a further modified SIC Rx, we now allow cancellation in the current and previous TTIs. If the TB on a certain HARQ process of a certain data stream is correctly decoded, the interference is cancelled from the received signal in the current TTI. Furthermore, it is checked if there are remaining undecoded TBs of other data streams in previous

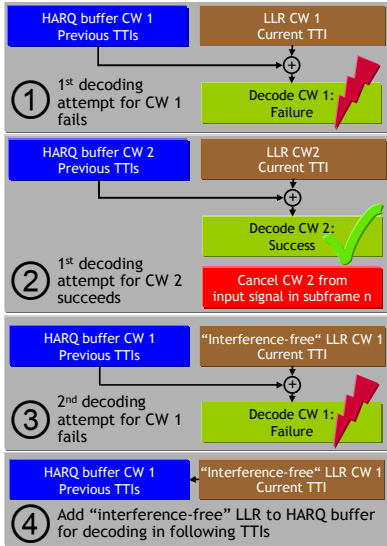


Fig. 3. Type-1 SIC Rx example with 2 data streams

TTIs, where there have been HARQ transmissions of the now correctly decoded TB. If so, the interference from the correctly decoded TB is cancelled in the received signal in the corresponding previous TTIs. The LLRs of the undecoded TBs in the TTIs in which the cancellation has been performed are recomputed and can be used for any upcoming decoding attempts in the current or following TTIs. In order to always use the LLRs after as many cancellations as possible, i.e. “containing” the lowest interference, there must be LLR buffers for each possible HARQ transmission number for all HARQ processes. The LLR values that are actually used in a decoding attempt are the sum of the LLRs in the HARQ buffers per HARQ transmission. See Fig. 4 for an example with 2 data streams.

III. SIMULATION RESULTS

Figs. 5(a) and (b) first compare type-0 SIC Rx to linear Rx using ZF or MMSE weight matrices with ideal and real CE, respectively, in a 2x2 MIMO SM

system. The envelope throughput (TP) curves are derived from TP curves for the following modulation and coding schemes (MCS): QPSK with code rates (CR) 1/6, 1/3, 1/2, 2/3, 16-QAM with CRs 1/2, 2/3, 4/5, and 64-QAM with CRs 2/3, 4/5.

For ideal CE we observe, that the SIC Rx outperforms the linear Rx both for ZF and MMSE. The best performance is always achieved with MMSE SIC. In the low signal-to-noise ratio (SNR) region, linear MMSE is still better than ZF SIC. In the high SNR region, however, both MMSE SIC and ZF SIC are better than linear MMSE and also linear ZF. This has to be expected as the ZF criterion is the same as the MMSE criterion for infinite SNR [3]. For real CE we qualitatively make the same observations as for ideal CE. However, we note that in the high SNR region we can only achieve the full TP with the SIC Rx. Thus, degradations from real CE can be partly compensated by the SIC Rx.

For quantifying the SIC gain, we determine the gain at 90% of the max. TP of each individual MCS for ideal and real CE. In both cases, we find a SIC gain of approx. 2 dB across the MCS for ZF, and of approx. 3 dB across the MCS for MMSE. Thus, using a SIC Rx instead of a linear Rx in MIMO SM systems leads to significant performance gains.

In Fig. 6 we now study the benefits of the SIC Rx optimization for HARQ operation from subsection II.D. Fig. 6(a) shows the TP for 2x2 MIMO SM with ideal CE and QPSK with CR 2/3. We observe that in the high SNR/high TP region, there is no performance difference between the different SIC Rx types. In this region, the HARQ scheme has a low average number of transmissions close to 1, so the benefits of adding only “interference-free” LLR values to the HARQ buffer (type-1) or of performing interference cancellation in previous TTIs (type-2) cannot be leveraged, the latter simply because there are no previous TTIs where cancella-

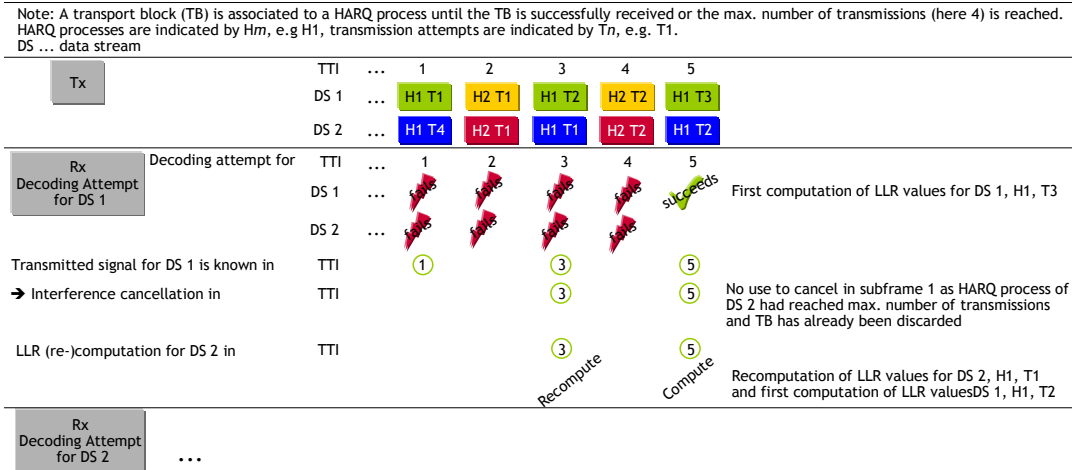


Fig. 4. Type-2 SIC Rx example with 2 data streams

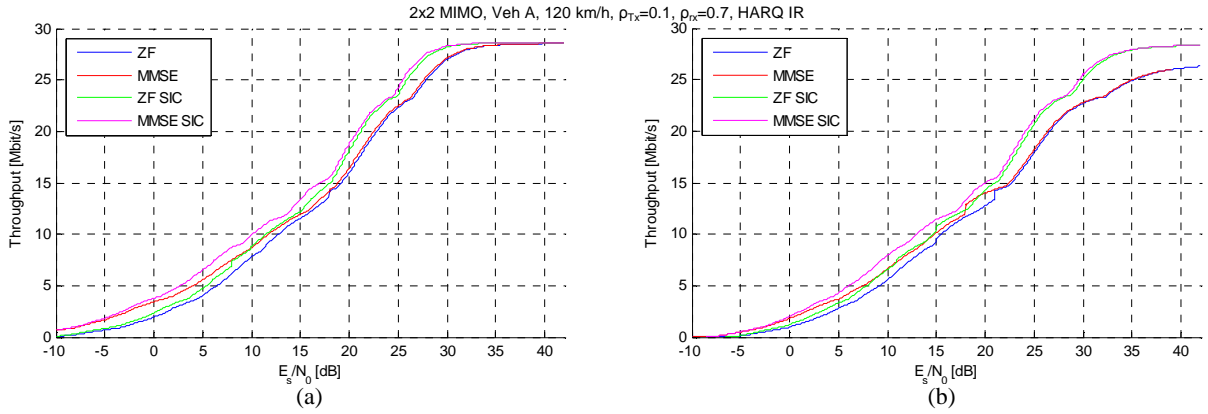


Fig. 5. Comparison of throughput envelopes of linear and type-0 SIC Rx: (a) ideal and (b) real CE

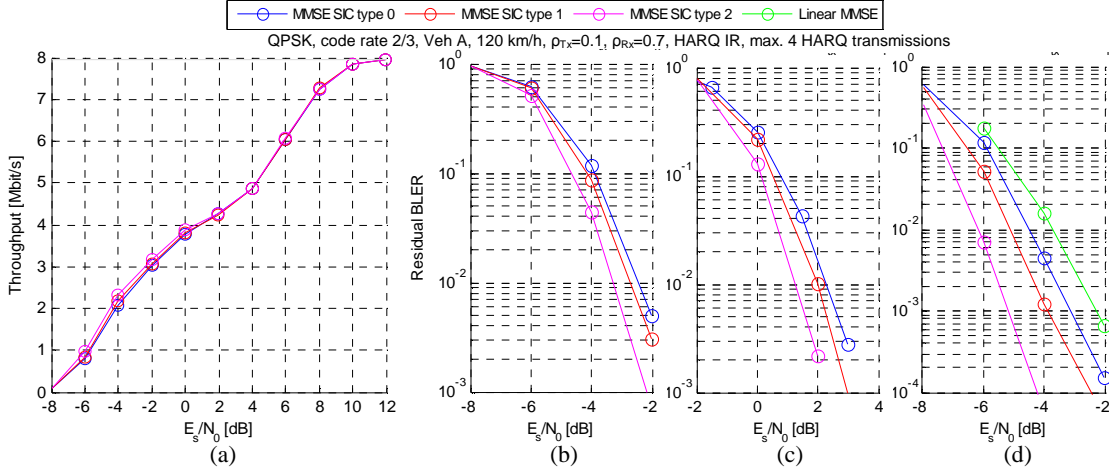


Fig. 6. Comparison of SIC Rx types: (a) Throughput for 2x2 MIMO with ideal CE and residual BLER of (a) 2x2 MIMO with ideal CE, (b) 2x2 MIMO with real CE, and (c) 4x4 MIMO with ideal CE

tion must be performed. In the low SNR/ low TP region, however, where the average number of transmissions is close to the maximum number of transmissions, we observe the best performance for the type-2 SIC Rx followed by the type-1 SIC Rx. Obviously, the more transmissions are performed for a certain TB, the higher the benefits of having higher-quality LLRs for transmissions in previous TTIs. But we also notice that the gains of type-2 and type-1 SIC Rx over the type-0 SIC Rx are small compared to the additional complexity.

However, in Figs. 6(b) to (d) we now look at the more complex SIC Rx from a reliability perspective. We plot the residual block error ratios (BLER) for the three SIC Rx types. A residual block error is made if a TB cannot be correctly decoded after the maximum number of transmissions. In the 2x2 case with ideal CE in Fig. 6(b) we observe a 0.9-dB (0.3-dB) advantage for the type-2 (type-1) over the type-0 SIC Rx at a residual BLER of 0.01. For the same configuration but with real CE in Fig. 6(c) these gains are 1.1 dB and 0.3 dB, respectively. These gains are more pronounced in the 4x4 case in Fig. 6(d), as there are more data streams that can benefit from the type-2 and type-1 concepts. Now,

we observe a 1.7-dB (0.6-dB) advantage for the type-2 (type-1) over the type-0 SIC Rx. The more stringent the residual BLER requirement, the higher the gain. Therefore, in a MIMO SM application where low residual BLER is required, the usage of the more complex SIC Rx can be beneficial.

IV. CONCLUSION

Our simulations show significant performance gains of SIC Rx over linear Rx, if the SIC process includes the channel de-/encoding. Furthermore, the SIC Rx can be optimized for HARQ, which shows to be especially beneficial in 4x4 MIMO SM systems when low residual BLER is required.

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