Simulation and Complexity Analysis of Iterative Interference Cancellation Receivers for LTE/LTE-Advanced

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Abstract

The paper details the simulation of a single user MIMO receiver operating according to the 3GPP/LTE standard applying a Parallel or Successive Interference Cancellation (PIC/SIC) strategy to a multicarrier (OFDMA/SC-FDMA) scheme. The algorithm details are analyzed and the PIC and SIC cancellation strategies are simulated and compared on random MIMO selective fading channels, considering limited complexities. The best PIC and SIC schemes for a given limited complexity (8 turbo decoding iteration per codeword) are compared for different codeblock lengths and spatial correlation scenarios over an EPA channel model. The 2 cycles SIC scheme shows the best performance over the selected scenarios, offering gains over the non-iterative schemes (measured at BLER values of 0.1) ranging from 1 to 4 dB in the considered cases. Larger gains are obtained with higher spatial correlation and shorter codeblock lengths. Better overall performance are obtained with lower spatial correlation and longer codeblock lengths.

1 Introduction

The ever increasing user density in cellular systems coupled with the unitary frequency reuse factor selected for the Long Term Evolution (LTE) standard [1] and the use of MIMO spatial multiplexing have made interference (either inter-stream, inter-cell or intra-cell) the main limiting factor of spectrum efficiency in LTE/LTE-Advanced systems, and Interference Cancellation (IC) one possible solution that needs to be addressed at the receiver.

In this paper we indeed address the problem of inter-stream interference cancellation in MIMO-OFDM LTE/LTE-Advanced systems. Since complexity is an important parameter, iterative receiver structures are analyzed with particular attention, since they allow maximizing performances with a constrained complexity, at the cost of an increased processing delay.

As far as the iterative processing is concerned, given the particular structure of a LTE frame based on sub-frames of duration of 1 ms (denoted as Transmission Time Intervals or TTI), the additional iterative processing delay should not cause problems with the physical layer closed loop procedures, like for example User Equipment (UE) reporting or closed loop power control. In such a case the performance improvement offered by iterative processing comes at practically no cost in terms of delay.

The considered receivers should be able to separate the individual information streams generated by the transmitting antennas, cancelling the mutual interference. Among the available Interference Cancellation (IC) strategies, Sequential Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) strategies are considered, with particular reference to the scheme proposed and discussed in [2,5]. Link level simulations are performed over a MIMO channel with spatial correlation and power delay profiles defined according to the channel models defined in 3GPP [9]. A Down Link (DL) scenario has been considered.

2 Transmitter and MIMO scenario

The considered scenario associated with the useful signal is shown in Figure 1. Multiple antennas are considered at both the UE and the Base Station (BS). The BS is supposed to be equipped with one OFDM transmitter for each antenna. It may use either OFDMA (Orthogonal Frequency Division Multiple Access) or SC-FDMA (Single Carrier Frequency Division Multiple Access, with the addition of appropriate DFT blocks) modulation, as shown in Figure 2.

The channel characteristics are supposed to be completely known by the UE, and the generic two signals received at the UE antennas after OFDM demodulation can be expressed as:

$$y_1 = H_{c11}x_1 + H_{c12}x_2 + n_1$$
$$y_2 = H_{c21}x_1 + H_{c22}x_2 + n_2$$

where n_1 and n_2 are samples of uncorrelated Gaussian processes with mean squared value P_n, and P_x is the mean squared value of the transmitted random variables x_1 and x_2, so that we have, in matrix form,

$$y = H_c x + n$$

where H_c represents the 2x2 channel matrix for the BS1-UE channel associated to the generic *k-th* OFDMA subcarrier. More precisely, the equations above should be rewritten by specifically indicating the subcarrier index, with $k \in [1, N_{SC}]$, where N_{SC} is the number of non-zero OFDM subcarriers

$$y[k] = H_c[k]x[k] + n[k]$$

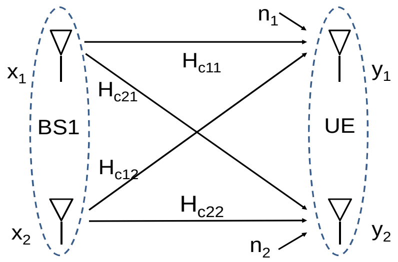

Figure 1 The considered MIMO scenario.

Now, recalling that the transmitted symbols *x[k]* are generated by MIMO encoding of the encoded and modulated symbols *d[k]* according to the equation

$$x[k] = H_{enc}d[k]$$

where H_{enc} is the (unitary) MIMO encoding matrix, we can define the effective channel matrices

$$H[k] = H_c[k]H_{enc}$$

and rewrite the equations above as

$$y[k] = H[k]d[k] + n[k] \tag{1}$$

or, in matrix form

$$y = Hd + n$$

Notice that the mean squared value of sequence x and d coincide, so that $P_x = P_d$.

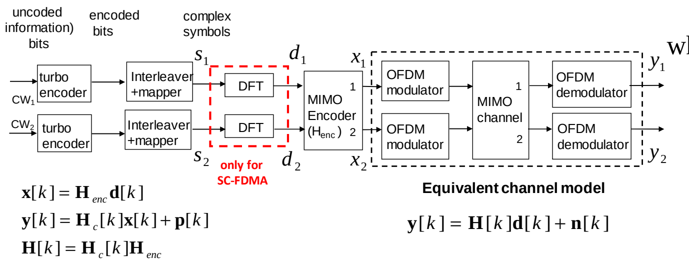

Figure 2 The considered two-codeword OFDMA/SC-FDMA transmitter.

3 The receiver structure

When the two useful codewords x_1 and x_2 carry independent information, they interfere with each other and need to be separated performing spatial de-multiplexing (or cancellation of inter-stream interference). The easiest form of equalization is the so-called Zero Forcing (ZF) equalization, where the transmitted information vector *d* (containing the codewords d_1 and d_2) is estimated as

$$W_{ZF} = H^H(HH^H)^{-1}$$
$$d_{ZF} = W_{ZF}y = H^H(HH^H)^{-1}y$$

when the rows of H are linearly independent (i.e. when the number of receiving antennas N_R smaller or equal than the number of transmitting antennas N_T), or as

$$W_{ZF} = (H^H H)^{-1}H^H$$
$$d_{ZF} = W_{ZF}y = (H^H H)^{-1}H^H y$$

when the columns of H are linearly independent (i.e. when the number of receiving antennas N_R larger or equal than the number of transmitting antennas N_T).

When in presence of strong noise and/or interference (i.e. for low values of signal-over-interference-plus-noise ratio, SINR), the most convenient, and common, form of equalization is the so called Minimum Mean Squared Error (MMSE) spatial de-multiplexing, where the transmitted information vector *d* (containing the codewords d_1 and d_2) is estimated as

$$W_{MMSE} = H^H(HH^H + (P_n/P_x)I)^{-1}$$
$$d_{MMSE} = W_{MMSE}y = H^H(HH^H + (P_n/P_x)I)^{-1}y$$

The actual information codewords CW1 and CW2 can then be derived from d_1 and d_2 performing channel decoding. As previously discussed, better performances can be obtained by using iterative soft processing, and for this reason we will consider iterative MMSE spatial de-multiplexing [2-8]. In order to generate a converging iterative procedure, the MMSE equalization can be slightly modified, adding, at iteration *it*, two weighting matrices Q_1^{it} and Q_2^{it} as described in [2] and iteratively estimating the transmitted sequence with the equations:

$$d_1^{it} = \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix}^H \left(HQ_1^{it}H^H + (P_n/P_x)I\right)^{-1} \hat{y}^{it,1}$$

$$d_2^{it} = \begin{bmatrix} H_{12} \\ H_{22} \end{bmatrix}^H \left(HQ_2^{it}H^H + (P_n/P_x)I\right)^{-1} \hat{y}^{it,2}$$

where

$$\hat{y}^{it,1} = \begin{bmatrix} \hat{y}_1^{it,1} \\ \hat{y}_2^{it,1} \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} - \begin{bmatrix} H_{12} \\ H_{22} \end{bmatrix} \hat{d}_2^{it-1}$$

$$\hat{y}^{it,2} = \begin{bmatrix} \hat{y}_1^{it,2} \\ \hat{y}_2^{it,2} \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} - \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} \hat{d}_1^{it-1}$$

It can be observed that $\hat{y}^{it,1}$ $\hat{y}^{it,2}$ are the estimates of the received vector cleaned from inter-stream interference generated by the two receiver branches. The corresponding receiver architecture is shown in Figure 3.

4 The simulation structure

The system parameters are summarized in Table 1, while Figure 4 shows the structure of one Transport Block (TB), formed by a certain number of codeblocks and transmitted by means of several DFT blocks every TTI. It is apparent how one codeblock is transmitted through multiple DFT blocks, while samples from different codeblocks can be mixed within the same DFT block.

Furthermore, Figure 4 shows that, since in the simulations the channel is considered constant for one entire TB, and each DFT block is associated to one OFDM symbol and transmitted over N_{SC}=600 subcarriers out of the N_{OFDM} = 1024 available subcarriers, the same transfer function must be experienced by all the DFT blocks, and therefore the N_{SC} set of values of the MIMO channel coefficients at the N_{SC} used frequencies must be repeated for all the considered DFT blocks.

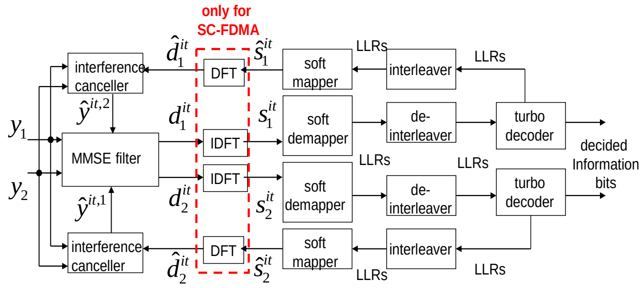

Figure 3 Architecture for iterative MIMO de-multiplexing (inter-stream interference cancellation).

A simplified physical layer simulator has been implemented in Matlab, operating according to the channel model shown in equation (1), where the $N_{OFDM} - N_{SC}$ = 424 guard frequency subcarriers are not simulated, since they carry no data. No rate matching nor hybrid ARQ (Automatic Repeat Request) have been considered.

Description	**Parameter**	**Value**
OFDM FFT size	N_OFDM	1024
Number of used sub-carriers	N_SC	600
Number of OFDM symbols per TB	N_OFDM_TTI	14
Number of codeblocks per TB	Nc_TTI	Variable
Number of information bits per codeblock	Lp	288, 392, 864, 1184
Number of encoded bits per codeblock	Lbcdb	3(Lp+4)
Number of bits per constellation symbol	Nb	2 (QPSK)
Number of complex symbols per codeblock	Lscdb	3(Lp+4)/Nb

Table 1 Description of the main simulation parameters.

The MIMO channel coefficients are generated selecting $N_T \times N_R$ impulse responses according to the EPA 3GPP channel model [9] and then correlating the fading processes according to the Kronecker method the $N_T \times N_R$ coefficients with the same tap index (i.e. with the same delay), thus obtaining $N_T \times N_R$ correlated impulse responses. We then analytically calculate the corresponding $N_T \times N_R$ transfer functions, and sample them in N_{OFDM} points corresponding to the N_{OFDM} subcarriers used by the OFDM modulation, storing only the N_{SC} MIMO channels associated to the non-zero subcarriers.

5 Performance

Simulation performances for both PIC and SIC schemes, with low and high channel spatial correlation, and various codeblock lengths are shown in the figures that follow. The correlation coefficient at the transmitter (α) and receiver (β) are defined as in [9]. In particular for low correlation we have α=β=0 while for high correlation we have α=β=0.9.

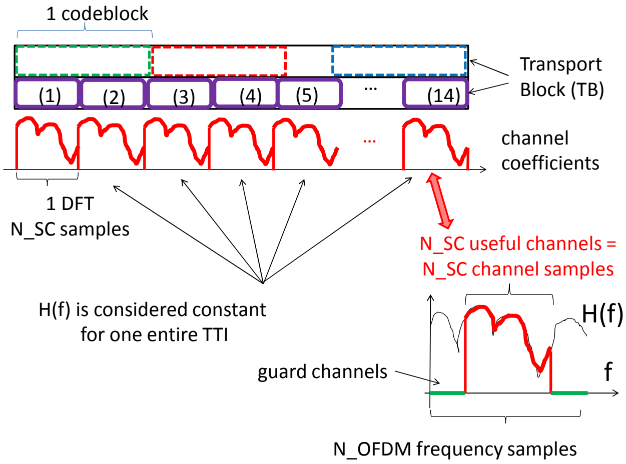

Figure 4 Transmission of one Transport block over a channel that is assumed constant over one TTI.

A maximum number of 8 turbo iterations for each codeword has been considered, generating the set of possibilities shown in Table 2**Errore. L'origine riferimento non è stata trovata.**. We denote as PIC cycle one complete iteration where the two codewords are decoded in parallel, and as SIC cycle a half-iteration where only one codeword is decoded. It follows that in the SIC case one iteration is formed by two consecutive cycles where the two codeword are sequentially decoded.

Number of PIC cycles	# of Turbo iterations per codeword per cycle	Total # of turbo iterations per codeword
1	8	8
2	4	8
4	2	8
8	1	8
Number of SIC cycles	# of Turbo iterations per codeword per cycle	Total # of turbo iterations per codeword
2	8	8
4	4	8
8	2	8
16	1	8

Table 1 Set of combinations tested in the complexity-limited simulations.

In Figure 5 and Figure 6 the BLER performances obtained with the PIC scheme (Figure 5 for L_p=288 and low and high spatial correlation, and Figure 6 for L_p=1184 and low and high spatial correlation) are reported, while Figure 7 and Figure 8 show the BLER performance obtained with a SIC scheme (Figure 7 for L_p=288 and low and high spatial correlation, and Figure 8 for L_p=1184 and low and high spatial correlation).

It can been observed that in the PIC case 2 cancellation iterations are needed for low spatial correlation (the PIC scheme with 1 iteration is actually a non-iterative scheme), and 4 cancellation iterations for high spatial correlation. In the SIC case 1 or 2 cancellation iterations are needed both for low and high spatial correlation, apart from the particular case of high spatial correlation and short codeblock length, in which more cancellation iterations (2 or 4) are needed. Overall for longer codeblock lengths, which is the most common and relevant condition, depending on the spatial correlation, the selection of 2 or 4 cancellation iterations (2 cycles or 4 cycles) in the PIC case seems to be the best choice, while 1 cancellation iteration (2 cycles) in the SIC case seems to be the best choice in all the spatial correlation conditions.

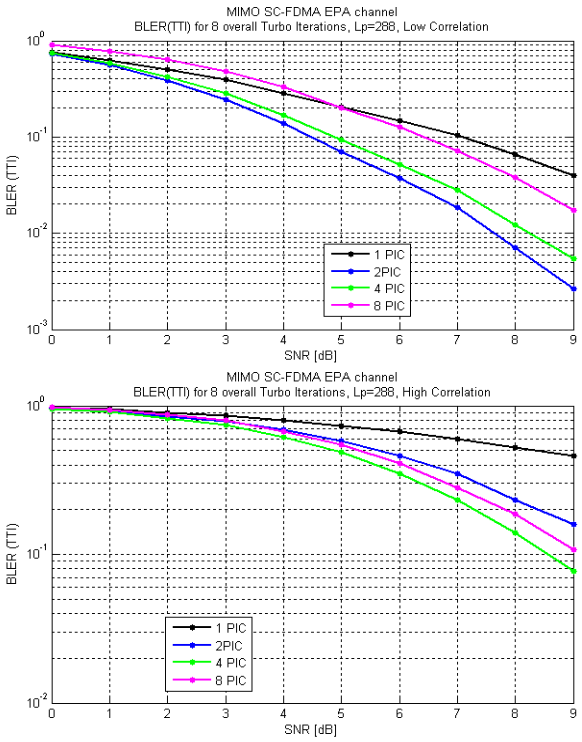

Figure 5 BLER, performance of the iterative parallel interference cancellation scheme (PIC) as a function of the number of PIC iterations, for 8 overall turbo iterations per codeword. Random MIMO channel with low (upper figure) and high (lower figure) spatial correlation, L_p=288.

As a second step, a limited number of cases with reduced complexity have been compared for L_p= 1184 and different spatial correlation values (high and low). In particular, a non-iterative interference cancellation scheme (1 PIC), PIC schemes with 2 and 4 iterations of interference cancellation (2 PIC and 4 PIC) and a SIC scheme with 2 cycles of interference cancellation (2 SIC) have been considered, for 8 overall turbo iterations per codeword, and a random MIMO EPA channel model with low and high spatial correlation (Figure 9).

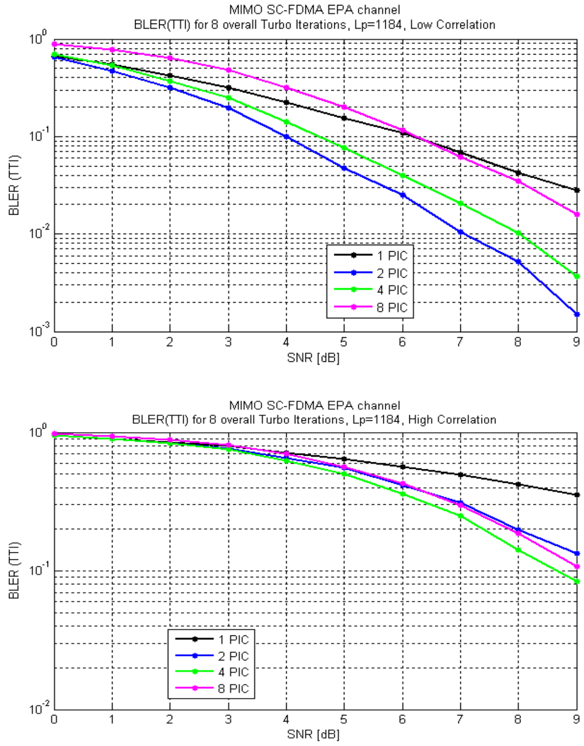

Figure 6 BLER performance of the iterative parallel interference cancellation scheme (PIC) as a function of the number of PIC iterations, for 8 overall turbo iterations per decoder. Random MIMO channel with low (upper figure) and high (lower figure) spatial correlation, L_p=1184.

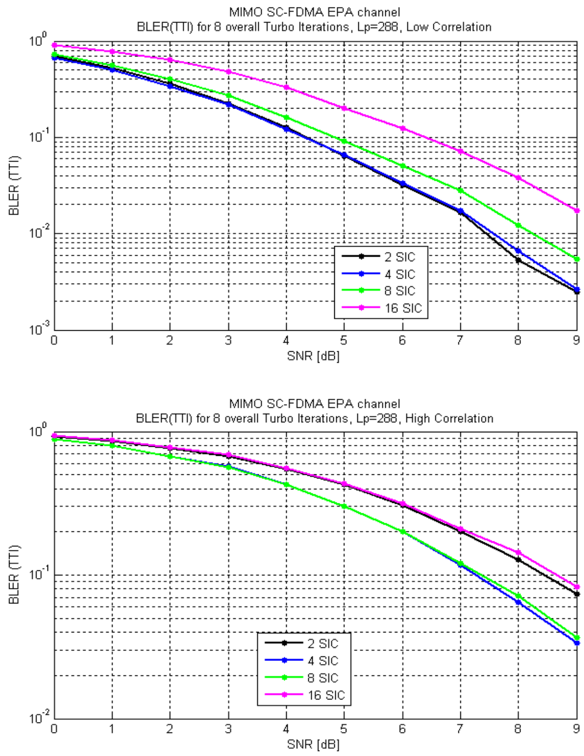

Figure 7 BLER performance of the iterative successive interference cancellation scheme (SIC) as a function of

the number of SIC cycles (2 cycles correspond to 1 iteration), for 8 overall turbo iterations per decoder. Random MIMO channel with low (upper figure) and high (lower figure) spatial correlation, L_p=288.

It can be observed that similar performances are obtained with the considered PIC and SIC schemes in presence of low spatial correlation (with a slight gain of the 2 SIC scheme), while the 2 SIC scheme outperforms the other ones in highly correlate scenarios. In all cases, iterative schemes offer a definite performance advantage over non-iterative ones.

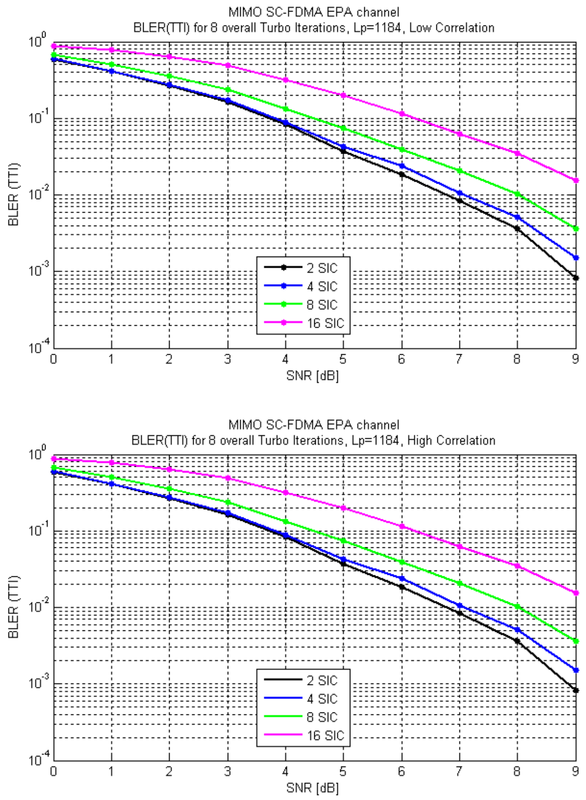

Figure 8 BLER performance of the iterative successive interference cancellation scheme (SIC) as a function of the number of SIC cycles (2 cycles correspond to 1 iteration), for 8 overall turbo iterations per decoder. Random MIMO channel with low (upper figure) and high (lower figure) spatial correlation, L_p=1184.

Finally, Figure 10 compares the BLER values achievable at a given SNR value (5 dB) for different codeblock lengths in a highly spatially correlated scenario.
From this figure it can be observed how the presence of the fading channel makes the final BLER values almost independent on the codeblock length.

The observed gains tend to decrease as the codeblock length increases and increase as the spatial correlation increases. Vice-versa, better overall performances are observed for lower correlation values and larger codeblock lengths, showing that iterative scheme become more relevant in critical conditions. For BLER values of 0.1, gains of almost 3 dB are observed with respect to the non-iterative case for low spatial correlation and L_p=288, but the gains are reduced to 1 dB at L_p=1184. Observing the BLER curves behavior, larger gains can be predicted at lower BLER values.

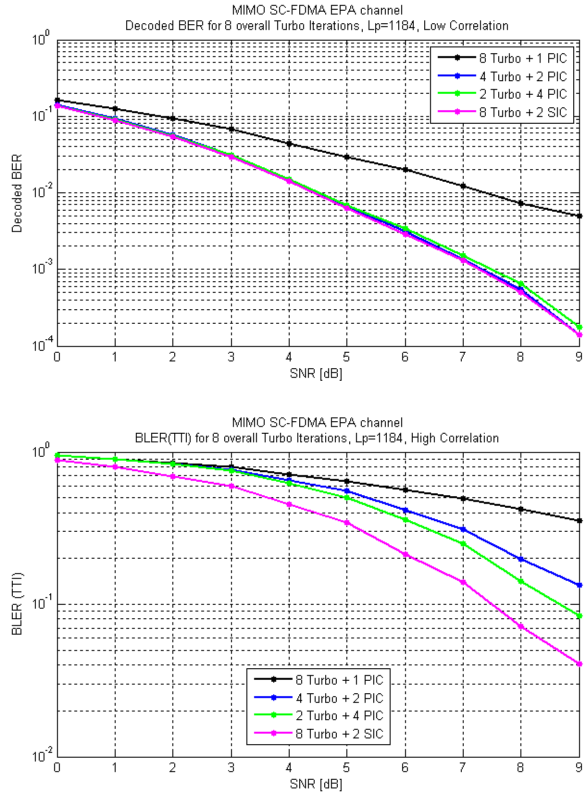

Figure 9 BER performance comparison for codeblock length 1184, between a non-iterative interference cancellation scheme (1 PIC), a PIC scheme with 2 and 4 iterations of IC (2 PIC and 4 PIC) and a SIC scheme with 2 cycles of IC (2 SIC), for 8 overall turbo iterations per decoder. Random MIMO channel with low (upper figure) and high (lower figure) spatial correlation.

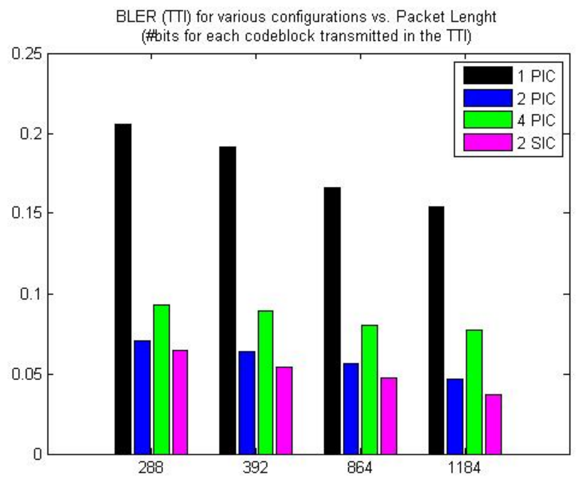

Figure 10 BLER performance comparison for different codeblock lengths and different cancellation schemes at SNR of 5 dB. The following schemes are considered: non-iterative IC (1 PIC), PIC with 2 and 4 iterations of IC (2 PIC and 4 PIC) and SIC with 2 cycles of IC (2 SIC) (random MIMO channel with high spatial correlation).

Finally, Figure 11 shows the throughput performance for L_p=1184 and different cancellation schemes, confirming the superiority of the SIC scheme with 2 cycles of interference cancellation (2 SIC). Since no rate matching nor hybrid ARQ algorithms are present, the considered throughtput values can be used for relative comparisons, and not as absolute values.

6 Conclusions

The paper presents a single user SC-FDMA/OFDMA MIMO receiver operating according to the 3GPP/LTE standard applying a Parallel or Successive Interference Cancellation (PIC/SIC) strategy. The algorithm details are analyzed and the PIC and SIC cancellation strategies are simulated and compared on random MIMO selective fading channels, considering fixed decoding complexity.

The best PIC and SIC strategies are initially selected, and the best PIC and SIC scheme for a given limited complexity (8 turbo iteration per codeword) are compared for different codeblock lengths and spatial correlation scenarios over an EPA channel model.

The 2 cycles SIC scheme shows the best performance over the selected scenarios, offering gains over the non-iterative schemes (measured at BLER values of 0.1) ranging from 1 to 4 dB in the considered cases. Larger gains are obtained with higher spatial correlation and shorter codeblock lengths, while better overall performances are obtained with lower spatial correlation and longer codeblock lengths. This behavior shows that iterative schemes reduce the performance loss incurred in critical conditions.

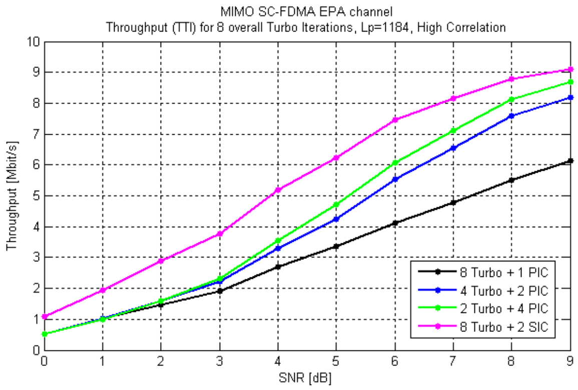

Figure 11 Throughput performance comparison for L_p= 1184 and different cancellation schemes: a non-iterative interference cancellation scheme (1 PIC), a PIC scheme with 2 and 4 cycles of interference cancellation (2 PIC and 4 PIC) and a SIC scheme with 2 cycles of interference cancellation (2 SIC), and random MIMO channel with high spatial correlation. The maximum achievable throughput is 9.47 Mbit/s.

7 Literature

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