Analog Integr Circ Sig Process (2012) 73:443–450
DOI 10.1007/s10470-012-9945-1

LTE uplink MIMO receiver with low complexity interference cancellation

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Received: 26 February 2012 / Revised: 19 June 2012 / Accepted: 2 August 2012 / Published online: 22 August 2012

Abstract In LTE/LTE-A uplink receiver, frequency domain equalizers (FDE) are adopted to achieve good performance. However, in multi-tap channels, the residual inter-symbol and inter-antenna interference still exist after FDE and degrade the performance. Conventional interference cancellation schemes can minimize this interference by using frequency domain interference cancellation. However, those schemes have high complexity and large feedback latency, especially when adopting a large number of iterations. These result in low throughput and require a large amount of resource in software defined radio implementation. In this paper, we propose a novel low complexity interference cancellation scheme to minimize the residual interference in LTE/LTE-A uplink. Our proposed scheme can bring about 2 dB gains in different channels, but only adds up to 7.2 % complexity to the receiver. The scheme is further implemented on Xilinx FPGA. Compared to other conventional interference cancellation schemes, our scheme has less complexity, less data to store, and shorter feedback latency.

Keywords LTE/LTE-A uplink · Interference cancellation · SC-FDMA · FPGA

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1 Introduction

The long term evolution (LTE) standard adopts OFDM in the downlink and single carrier-FDMA (SC-FDMA) for uplink transmission [1]. With usage of MIMO, the LTE downlink can support up to 300 Mbps transmission rate and uplink can reach 75 Mbps. The advanced version LTE-A can support up to 1 Gbps in downlink and 500 Mbps in uplink. Compared to the OFDM used in downlink, SC-FDMA has lower peak-to-average power ratio for the transmitter. This provides higher power efficiency for the mobile device.

Although, the usage of MIMO increases data rate tremendously, it also introduces inter-antenna interference. Besides this interference, the multi-path fading channels result in inter-symbol interference. With the help of cyclic prefix, the inter-symbol interference between SC-FDMA symbols can be minimized very well. However, the inter-symbol interference between symbols inside the same SC-FDMA symbol still remains significant. Minimum mean square error (MMSE) frequency domain equalizers (FDE) are usually adopted to reduce both inter-antenna and inter-symbol interference [2]. However, in multi-path channels, MMSE-FDE can not remove the interference completely. Both residual inter-symbol interference and inter-antenna interference still exist. They are especially strong in equal tap channels. As a result, they will degrade the receiver performance.

In recent years, several schemes were proposed to perform interference cancellation in LTE downlink [3] and uplink [4–10]. However, few papers exist on low complexity implementation for software defined radio (SDR). For example, in [5], frequency domain interference cancellation was adopted. First, the detected time domain symbols are sent back to the frequency domain. Then, the interference cancellation is performed in the frequency domain. This scheme reduces the residual interference of MMSE-FDE and improves the receiver performance. However, in order to send the data back to the frequency domain, an extra set of DFTs is required for the transformation. This increases the integrated circuit area of the receiver. In order to preform frequency interference cancellation, receivers also need to have enough memory to buffer all the detected signal used by the DFTs. Moreover, because the feedback needs to go through DFTs to the frequency domain and then go back to time domain by IDFTs, this scheme suffers from large feedback latency. Thus, this scheme has many disadvantages for real time implementation. In papers [6–10], the log-likelihood ratios (LLR) from the channel decoder are sent back to the frequency domain to achieve interference cancellation. These schemes are similar to [5], but with an even longer feedback loop, which is from the channel decoder to the FDE. Besides the disadvantages of [5], these schemes have much larger feedback latency. Because the throughput and complexity are key criteria for SDR [11, 12], the above schemes are not suitable for SDR implementation.

In order to perform the interference cancellation in a more efficient way, in this paper, we propose a low complexity and low latency interference cancellation scheme for LTE/LTE-A uplink receivers. Different from other schemes, we reconstruct the residual inter-symbol and inter-antenna interference in the time domain from selected detected symbols. With this selection, we can perform much less computation than using all detected symbols during the interference reconstruction. After interference reconstruction, the receiver removes the regenerated interference from current symbols. Because the interference cancellation is performed in the time domain instead of the frequency domain, the feedback latency is much shorter than other schemes. Compared with other schemes, our scheme neither needs the extra DFTs for the feedback signal nor needs to store all the detected symbols in the same SC-FDMA symbol. Thus, our proposed scheme requires less integrated circuit area for computation, less memory for storage, and less latency for feedback, which make it more suitable for implementation.

From the simulations, we show that our interference cancellation scheme can improve the performance of the MMSE-FDE receiver around 2 dB in different channels. It is also shown that our scheme only adds about 7.2 % additional complexity to the receiver, which makes it easier to implement. Based on this, the scheme is implemented on Xilinx FPGA by using system generator.

Furthermore, it was shown in the literature that a FDE based receiver can be potentially used for supporting both UMTS and LTE standards [13]. Based on this, our interference cancellation scheme can also be extended and applied to improve the performance of that system.

In Sect. 2, the conventional LTE uplink MIMO receiver with MMSE-FDE is described. Section 3 analyzes the interference in the LTE uplink receiver: inter-antenna and inter-symbol interference. In Sect. 4, we propose a low complexity interference cancellation scheme to improve the receiver performance. Simulations are shown in Sect. 5. In Sect. 6, complexity is analyzed. Result of FPGA implementation is shown in Sect. 7 Conclusions are drawn in Sect. 8.

2 System model

We use a spatial multiplexing LTE MIMO uplink system with N_T transmitter antennas and N_R receiver antennas. In an SC-FDMA transmitter [1], shown in Fig. 1, we use $s^i_{n_t}$ ($i = 0,\ldots,N_{DFT} - 1$) to represent the ith symbol on the n_tth antenna, where N_{DFT} is the length of the DFT. For each user, after modulation, an DFT transforms the modulated symbols from time domain to frequency domain as $\{S^i_{n_t}\}(i = 0,\ldots, N_{DFT} - 1)$ at each antenna. Then the frequency domain symbols are mapped to the corresponding frequency subcarriers allocated for the current user on all antennas at subcarrier mapping module. Next, an IDFT at each antenna converts the mapped frequency symbols back to the time domain as $\{x^i_{n_t}\}(i = 0,\ldots, N_{IDFT} - 1)$. After this, a cyclic prefix is added to the time domain signal at each antenna, and then the signal is transmitted to the channel.

The SC-FDMA receiver for the LTE MIMO uplink multi-user system is shown in Fig. 2. The maximum length of the channel is assumed to be L. The $N_R \times 1$ received signal at the sample time m is

$$\mathbf{y}^m = \sum_{n_t=1}^{N_T} \sum_{i=0}^{L-1} \mathbf{h}^i_{n_t} x^{m-i}_{n_t} + \mathbf{n}^m, \qquad (1)$$

where $\mathbf{h}^i_{n_t}$ is the $N_R \times 1$ channel coefficient vector for $x^{m-i}_{n_t}$; $\mathbf{n}^m$ is a $N_R \times 1$ vector of additive white Gaussian noise with zero-mean and variance σ^2.

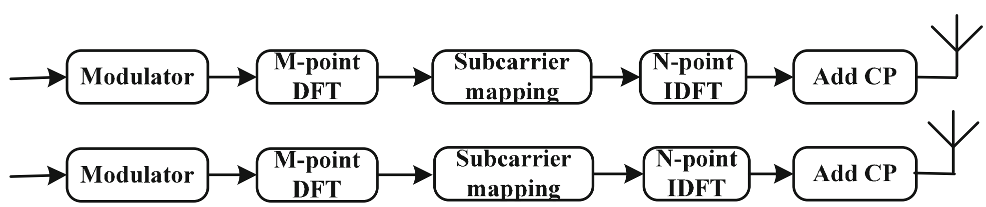

Fig. 1 LTE uplink MIMO transmitter for one user

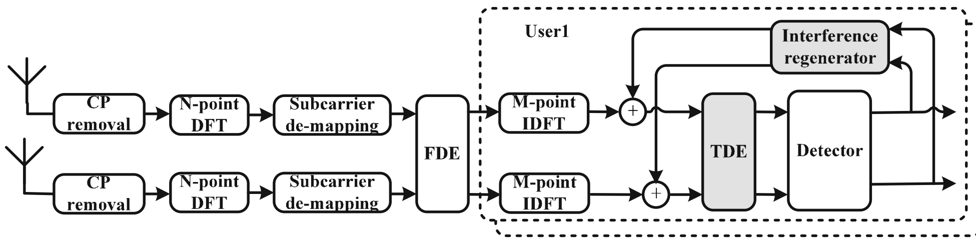

Fig. 2 LTE uplink MIMO multi-user receiver with interference cancellation; *Shaded modules* are for interference cancellation

The cyclic prefix is first removed from the received signal at each antenna. The received signal at each antenna is then transformed into frequency domain by a DFT. The frequency domain signal on all antennas on the mth frequency subcarrier is

$$\mathbf{Y}^m = \mathbf{H}^m\mathbf{X}^m + \mathbf{N}^m, \tag{2}$$

where $\mathbf{Y}^m$ and $\mathbf{X}^m$ are $N_R \times 1$ symbol vectors in the frequency domain; $\mathbf{H}^m$ is a $N_R \times N_T$ frequency domain channel matrix; and $\mathbf{N}^m$ is a $N_R \times 1$ noise vector in the frequency domain.

By assuming that the channel matrix $\mathbf{H}^m$ is known by the receiver, MMSE-FDE is applied to the mth frequency subcarrier as

$$\mathbf{Y}^m_{eq} = \left(\mathbf{H}^{m\mathrm{H}}\mathbf{H}^m + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^{m\mathrm{H}}\mathbf{Y}^m, \tag{3}$$

where $\mathbf{Y}^m_{eq}$ is a $N_R \times 1$ vector of the equalized frequency domain symbol. The $N_R \times N_T$ equalized frequency domain channel matrix on the mth frequency subcarrier can be computed by

$$\mathbf{H}^m_{eq} = \left(\mathbf{H}^{m\mathrm{H}}\mathbf{H}^m + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^{m\mathrm{H}}\mathbf{H}^m. \tag{4}$$

The frequency domain symbols at different subcarriers are then de-mapped to the corresponding user. The IDFT at each antenna and each user converts the equalized frequency domain symbols and equalized frequency domain channel matrix to the time domain. They are represented as $\mathbf{y}_{eq}$ and $\mathbf{h}_{eq}$. After this, without interference cancellation, symbols are directly detected for each user.

3 Inter-antenna and inter-symbol interference

In this section, we analyze the interference in the LTE uplink receiver. Usually, there are inter-subcarrier interference, inter-symbol interference, and inter-antenna interference in the receiver. Because we assume that there is no frequency offset, there is no inter-subcarrier interference in our receiver. The inter-antenna interference comes from the MIMO used in the LTE uplink.

There are two types of inter-symbol interference in the receiver. One type is the inter-symbol interference between SC-FDMA symbols. In the LTE standard, a cyclic prefix is adopted to minimize this type of interference. The cyclic prefix provides enough guard symbols between SC-FDMA symbols, so that this type of interference is very small. The other interference is inter-symbol interference between the sampled symbols inside the same SC-FDMA symbol. Because there are DFT, IDFT, and cyclic prefix, this type of interference is much more complicated. In multi-path channels, for each user, the inter-symbol interference of one symbol is not only from the symbols transmitted before it but also from the symbols transmitted after it. In other words, this type of interference is from all other symbols inside the same SC-FDMA symbol. This type of inter-symbol interference is shown in Fig. 3.

Conventionally, an MMSE-FDE receiver is used for equalizing the channels and suppressing the interference. However, MMSE-FDE can not remove all the above interference completely. The residual interference from both inter-symbol interference and inter-antenna interference still exists. After MMSE-FDE and IDFT, the mth time domain symbol of user u is represented as

$$\mathbf{y}^m_{eq}(u) = \mathbf{h}^0_{eq}(u)\mathbf{s}^m(u) + \sum_{\substack{i=j-M+1\\ i\neq 0}}^{j} \mathbf{h}^i_{eq}(u)\mathbf{s}^{m-i}(u) + \mathbf{n}^m_{eq}(u) \tag{5}$$

where $\mathbf{s}^m(u)$ is the mth $N_T \times 1$ vector of transmitted symbols from user u; j is equal to $(m \bmod M), M$ is the total

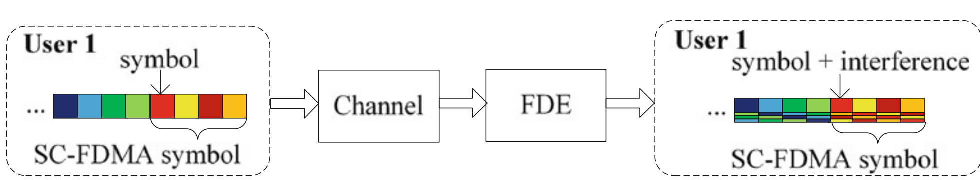

Fig. 3 Inter-symbol interference inside one SC-FDMA symbol

number of symbols of the current user in one SC-FDMA symbol; $\mathbf{h}^{i}_{eq}(u)$ is the ith $N_R \times N_T$ equalized time domain channel matrix of user u, which represents the residual channel after the MMSE-FDE and IDFT, and $\mathbf{h}^{i}_{eq}(u) = \mathbf{h}^{M+i}_{eq}(u)$; $\mathbf{n}^{m}_{eq}(u)$ is the mth $N_R \times 1$ equalized time domain additive white Gaussian noise of user u. The first term in the equation is the desired symbols, while the second term is the inter-symbol and inter-antenna interference from the other $(M-1) \times N_T$ symbols inside the same SC-FDMA symbol. This term degrades the receiver performance, especially in equal tap channels. However, it can be minimized by regenerating the interference from selected detected symbols.

4 Low complexity interference cancellation

Conventional schemes cancel the interference in the frequency domain. This requires extra DFTs to transform the detected symbols back to the frequency domain, which introduces high complexity and latency. In the SDR implementation, high complexity means more resources, and high latency means lower throughput. In order to reduce the complexity and latency, we propose a low complexity interference cancellation scheme. The scheme performs partial inter-symbol and inter-antenna interference cancellation to minimize the residual interference of MMSE-FDE. The blocks are also shown in Fig. 2, which include an interference regenerator and time domain equalization (TDE). The flow is shown below.

4.1 Partial interference cancellation

After detection, the detected symbols are represented as $\hat{\mathbf{s}}^{m}(u)$ for the uth user. By using $\hat{\mathbf{s}}^{m}(u)$ with the equalized time domain channel matrix $\mathbf{h}^{m}_{eq}$, the residual interference can be regenerated in the time domain as

$$\mathbf{y}^{m}_{ri}(u) = \sum_{\substack{i=-L_{FF} \\ i \neq 0}}^{L_{FB}} \mathbf{h}^{i}_{eq}(u)\hat{\mathbf{s}}^{m-i}(u), \tag{6}$$

where L_{FB} and L_{FF} are the number of symbols previously detected and future detected from all antennas, respectively. The future symbols represent the symbols received later than the current symbol. From the implementation perspective, these symbols are received and buffered, but used as future symbols. When $L_{FB} + L_{FF} = M - 1$, the equation means that the residual interference is regenerated from all other symbols inside the same SC-FDMA symbol. This is a full interference regeneration and has performance close to the frequency domain interference cancellation. However, the interference from different symbols is not equally strong. The interference from the neighboring symbols is the strongest one. This means there is no need to regenerate the interference from all symbols. By selecting L_{FB} and L_{FF} to cover only the symbols with the strongest interference, we can achieve almost the same performance as with full regeneration, but with much less computation. Furthermore, because we do not use all the detected symbols, we do not need to save all of them, but only a few neighboring symbols. This reduces the amount of memory for storage.

If the residual interference is perfectly cancelled by subtracting $\mathbf{y}^{m}_{ri}(u)$ from $\mathbf{y}^{m}_{eq}(u)$, Eq. (5) becomes

$$\mathbf{y}^{m}_{ic}(u) = \mathbf{y}^{m}_{eq}(u) - \mathbf{y}^{m}_{ri}(u) = \mathbf{h}^{0}_{eq}(u)\mathbf{s}^{m}(u) + \mathbf{n}^{m}_{eq}(u). \tag{7}$$

Only the desired symbols and noise are in the equation.

4.2 Time domain equalization

In order to minimize the error of $\mathbf{y}^{m}_{ic}(u)$, according to MMSE criterion, Eq. (7) becomes

$$\mathbf{y}^{m}_{mmse}(u) = \mathbf{h}^{0}_{eq}(u)^{\mathrm{H}} \times \left(\mathbf{h}^{0}_{eq}(u)\mathbf{h}^{0}_{eq}(u)^{\mathrm{H}} + \mathbf{C}_{noise}(u)\right)^{-1} \mathbf{y}^{m}_{ic}(u), \tag{8}$$

where $\mathbf{C}_{noise}(u)$ is the $N_T \times N_T$ covariance matrix of the noise $\mathbf{n}^{m}_{eq}(u)$ in Eq. (7). Because the noise is equalized after the MMSE-FDE, the noise covariance is no longer $\sigma^2\mathbf{I}$. If we assume the noise is independent from each antenna before the MMSE-FDE, the noise becomes correlated at each antenna after the MMSE-FDE in Eq. (3). The noise after MMSE-FDE is

$$\mathbf{N}^{m}_{eq} = (\mathbf{H}^{m\mathrm{H}}\mathbf{H}^{m} + \sigma^2\mathbf{I})^{-1}\mathbf{H}^{m\mathrm{H}}\mathbf{N}^{m}, \tag{9}$$

where $\mathbf{N}^{m}_{eq}$ is the frequency domain equalized noise.

The covariance of $\mathbf{N}^{m}_{eq}$ is calculated as follows. First define matrix $\mathbf{A}^{m}$ as

$$\mathbf{A}^{m} = (\mathbf{H}^{m\mathrm{H}}\mathbf{H}^{m} + \sigma^2\mathbf{I})^{-1}\mathbf{H}^{m\mathrm{H}}. \tag{10}$$

Because this is already calculated in Eq. (9), it can be reused to save the computation. The $\mathbf{C}_{noise}(u)$ for the current user u is then calculated by

$$\mathbf{C}_{noise}(u) = \frac{\sigma^2}{M}\sum_{m=1}^{M}\mathbf{A}^{m}\mathbf{H}^{m\mathrm{H}}, \tag{11}$$

where m is the mth frequency subcarrier; M is the total number of the frequency subcarriers of the current user. Because the noise of the current user is only from the noise on the frequency subcarriers allocated to the current user, the $\mathbf{C}_{noise}(u)$ only includes the frequency subcarrier of the current user.

The complexity of the above scheme can be reduced by sharing the MMSE-FDE and MMSE-TDE modules. This can be achieved in LTE uplink receive, since the length of DFT is much larger than the length of the IDFT, which means that the MMSE-FDE will not be performed all the time. In the rest $N_{DFT} - N_{IDFT}$ period of time, the MMSE-FDE can be used as the MMSE-TDE, so there is no need to add an MMSE-TDE module in the system. This reduces the required integrated circuit area.

Moreover, because the cancellation is performed in the time domain instead of the frequency domain, this shortens the feedback loop by not going through the DFT and IDFT. This not only speeds up the system throughput, but also reduces the amount of memory required to store all the data required for DFT. The integrated circuit area for additional DFTs can also be saved.

4.3 Summary

As analyzed above, our partial interference cancellation with TDE can remove the inter-symbol interference and inter-antenna interference. Compared to the full interference cancellation scheme, it has less computation and latency. These are very important for implementation. Furthermore, our interference cancellation scheme not only works for the LTE/LTE-A uplink. Recently, it was shown that a FDE based receiver can be used as a multi-standard receiver for both UMTS and LTE standards. Because our interference cancellation scheme is designed for FDE, it can also be extended for use in a multi-standard receiver.

5 Simulations

In this section, we compare the performance of our scheme with other schemes used for LTE uplink with the assumption of perfect channel estimation. The simulation parameters are chosen to support different configurations in the LTE standard. They are shown in Table 1. The Rayleigh channels we used have four taps with power profile [0 −4.7712 −7.7815 −7.7815] dB. The L_{FF} and L_{FB} can be chosen to balance the performance and the complexity. When $L_{FF} + L_{FB} = 299$, it becomes a full interference cancellation, which has best performance but with highest complexity. If $L_{FF} + L_{FB} = 0$, no interference cancellation is performed. After experimentally checking different equalized channels after MMSE-FDE, we found that beyond two times of L from the current symbol, the residual channel coefficients become ignorable and almost equal. Thus, in the simulation we choose the windows length $L_{FF} + L_{FB}$ around four times of L to cover most of the interference.

Five curves are shown in Figs. 4, 5, and 6.

1. *No IC:* This means there are no interference regenerator and MMSE-TDE in the receiver shown in Fig. 2.

Table 1 Simulation parameters

Parameter	Value
Channels	Rayleigh channels
Length of DFT	512
Length of IDFT	300
Length of CP	36
Modulation order	16-QAM; 64-QAM
Number of antennas	2 × 2; 4 × 4
FDE	MMSE-FDE
TDE	MMSE-TDE
L_{FF}	8
L_{FB}	8

2. *PIC + MMSE-TDE:* This is conventional parallel interference cancellation. All the symbols are first detected and then sent back to interference regenerator. After cancelling the interference, MMSE-TDE is applied to the data.
3. *Full IC + MMSE-TDE:* This is full interference cancellation, where $L_{FB} + L_{FF} = M - 1$. The detection is performed in parallel with interference cancellation. After cancelling the interference, MMSE-TDE is applied to the data.
4. *Partial IC + MMSE-TDE:* This is our proposed scheme. Different from full IC, only the selected detected symbols are sent back to the interference regenerator. After cancelling the interference, MMSE-TDE is applied to the data.
5. *Perfect IC + MMSE-TDE:* This is a best case performance. The symbols sent to the interference regenerator are the accurate transmitted symbols. After cancelling the interference, MMSE-TDE is applied to the data.

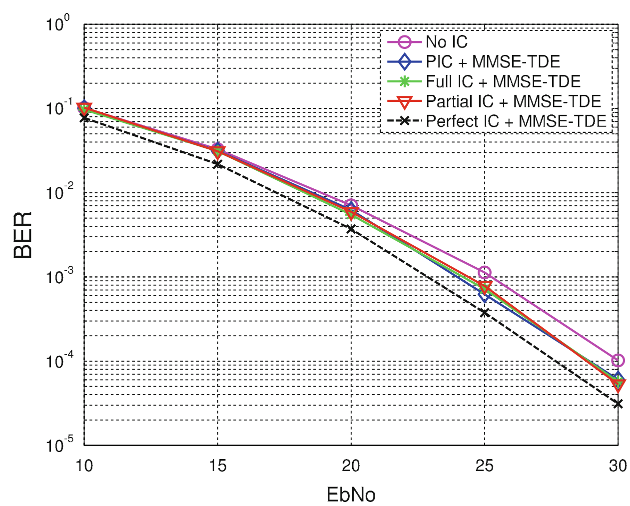

Fig. 4 Performance of 2 × 2 MIMO in Rayleigh channels with 16-QAM

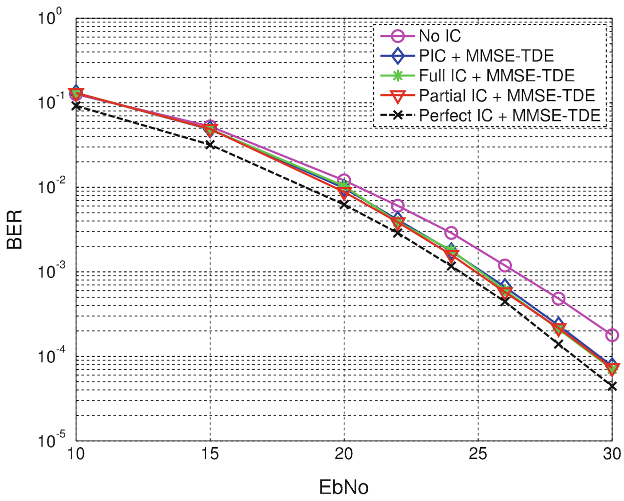

Fig. 5 Performance of 4 × 4 MIMO in Rayleigh channels with 16-QAM

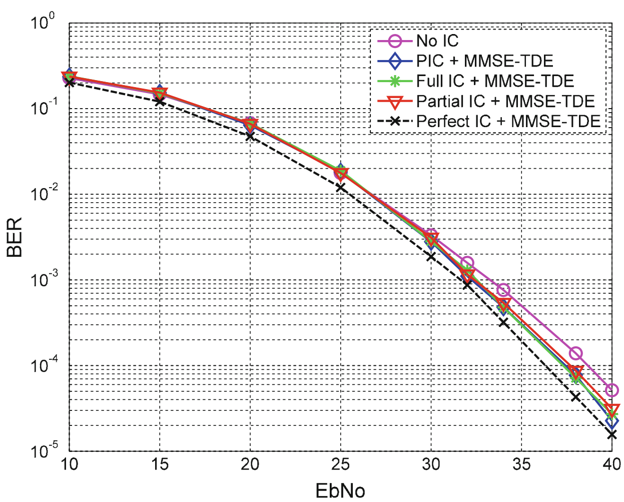

Fig. 6 Performance of 4 × 4 MIMO in Rayleigh channels with 64-QAM

As shown in Figs. 4, 5, and 6, compared to no IC, our scheme can achieve up to 2 dB improvement. It is also shown that our proposed scheme has almost the same performance as full IC + MMSE-TDE and PIC + MMSE-TDE. This means that only cancelling the strongest interference will have negligible affect on the performance. The performance of our proposed scheme is close to the perfect IC + MMSE-TDE. The gap between them mainly comes from the inaccurate detected symbols. This can be improved by using better MIMO detection schemes, such as K-best or sphere detector. Our scheme performs almost as well as the full IC + MMSE-TDE and PIC + MMSE-TDE, and also performs close to the perfect IC + MMSE-TDE.

6 Complexity analysis

Without interference cancellation, the complexity of a LTE receiver mainly comes from DFTs and IDFTs. These modules have complexity $O(NlogN)$. The complexity of the proposed interference cancellation mainly depends on MMSE-TDE and the partial interference regenerator. As mentioned in Sect. 4, because MMSE-TDE can share the same resource with the MMSE-FDE, the partial interference regenerator contributes to the main complexity of the proposed interference cancellation, which is $O(N_T^2(L_{FB} + L_{FF}))$. The noise correlation matrix in the MMSE-TDE also needs to be computed. As mentioned before, part of its computation can be saved by reusing the results computed for MMSE-FDE in the frequency domain. Thus, its complexity is only from the remaining portion of the computation, which is matrix multiplication with complexity $O(N_T^3)$.

In order to compare the complexity, the number of equivalent multiplications needed by each LTE MIMO symbol are counted. This is computed by first summing up all the multiplications required for an SC-FDMA symbol, and then averaging over the number of symbols inside one SC-FDMA symbol. The parameters for comparison are chosen as the ones in Table 1. The results are shown in Table 2.

The R1 is the ratio of full IC + MMSE-TDE to an LTE receiver without interference cancellation. As shown, the full IC + MMSE-TDE is up to 52.7 % of the receiver. The R2 is the ratio of partial IC + MMSE-TDE to an LTE receiver without interference cancellation. As indicated, partial IC + MMSE-TDE is only about 7.2 % of the receiver even at the 4 × 4 MIMO case. Our scheme largely reduces the interference cancellation area.

7 FPGA implementation

To further quantify the complexity, the proposed scheme for a 2 × 2 MIMO LTE uplink receiver is implemented in System Generator. A Xilinx FPGA Virtex-4 is the target

Table 2 Number of equivalent multiplications per LTE MIMO symbol

Module	Number of antennas		
	1 × 1	2 × 2	4 × 4
LTE receiver without IC	9.2	18.4	37.1
Full IC + MMSE-TDE	1.2	4.8	19.6
Partial IC + MMSE-TDE	0.13	0.58	2.7
Noise covariance	0.3	2.3	18.8
R1 = (full IC + MMSE-TDE) / LTE receiver without IC	12.9 %	26.0 %	52.7 %
R2 = (partial IC + MMSE-TDE) / LTE receiver without IC	1.4 %	3.1 %	7.2 %

Table 3 FPGA resource utilization summary of 2 × 2 MIMO receiver on Xilinx Virtex-4 device

Module	FFs	4 input LUTs	DSP48s	Max. freq. (MHz)
DFTs	2,692	2,934	3	346
MMSE-FDE + MMSE-TDE	7,687	9,139	76	84.331
IDFTs	9,746	11,398	16	234
Interference regenerator	256	1,792	48	118.737
Noise covariance	64	412	18	101.174

device. The implementation is not optimized, but a few resource sharing techniques are applied. The first one is the time sharing between the MMSE-FDE and MMSE-TDE. Another one is to share the intermediate results between MMSE-FDE and noise covariance calculation.

The implementation result is summarized in Table 3. The DFT and IDFT modules used in the implementation are from the Xilinx library. The area of IDFT is much larger than the area of DFT. The reason is that DFT is based on radix-2 FFT, while IDFT needs radix-2, radix-3, and radix-5 computation, which increase the area of IDFT.

In order to share resource between MMSE-FDE and MMSE-TDE , Eq. (3) needs to be rewritten in the same format to Eq. (8) as

$$\mathbf{Y}_{eq}^{m} = \mathbf{H}^{m\mathrm{H}}\left(\mathbf{H}^{m}\mathbf{H}^{m\mathrm{H}} + \sigma^{2}\mathbf{I}\right)^{-1}\mathbf{Y}^{m}. \tag{12}$$

The above equation and Eq. (3) can be further rewritten as

$$\mathbf{Y}_{eq}^{m} = \left(\mathbf{H}^{m} + \sigma^{2}\left(\mathbf{H}^{m\mathrm{H}}\right)^{-1}\right)^{-1}\mathbf{Y}^{m}, \tag{13}$$

$$\mathbf{y}_{mmse}^{m}(u) = \left(\mathbf{h}_{eq}^{0}(u) + \mathbf{C}_{noise}(u)\left(\mathbf{h}_{eq}^{0}(u)^{\mathrm{H}}\right)^{-1}\right)^{-1}\mathbf{y}_{ic}^{m}(u). \tag{14}$$

Compared to the original Eqs. (3) and (8), these two equations require less dynamic range for the matrix inversion operation [14].

The interference regenerator is a linear filter, which is implemented by using multipliers and adders. The total area of interference regenerator is linear to its length $L_{FB} + L_{FF}$.

The computation of noise covariance is mainly matrix multiplication. Because the result of Eq. (11) is a Hermitian matrix, only half of the number of the elements need to be computed.

8 Conclusion

In the paper, we propose a novel low complexity and low latency interference cancellation scheme and further implement it on FPGA. The scheme improves the performance of an LTE/LTE-A uplink MIMO receiver by cancelling the inter-symbol interference and inter-antenna interference. Different from other schemes, our scheme uses partial interference cancellation and time domain equalization instead of the frequency domain interference cancellation. This results in less integrated circuit area, less data storage, and shorter feedback latency. As shown in the simulations, our scheme can improve the performance in different channels. The complexity of our scheme is relatively small compared with an LTE receiver. All of these features make our scheme suitable for SDR implementation.

Acknowledgments This work was supported in part by Renesas Mobile, Texas Instruments, Xilinx, Samsung, Huawei, and US National Science Foundation under grants EECS-0925942 and CNS-0923479.

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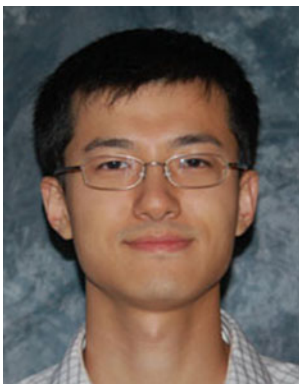

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