Low complexity MMSE interference cancellation for LTE uplink MIMO receiver

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***Abstract*—In this paper, we propose a novel low complexity minimum mean square error (MMSE) interference cancellation (IC) to minimize the residual inter-symbol and inter-antenna interference in LTE/LTE-Advanced uplink. In the LTE/LTE-Advanced base station, frequency domain equalizers (FDEs) are adopted to achieve good performance. However, in multi-tap channels, the residual interference of FDE still degrades the performance. Conventional IC schemes can minimize this interference, but have high complexity and large feedback latency. These result in low throughput and require a large amount of resource in software defined radio (SDR) implementation. We show that our scheme can bring up to 8 dB gains in different channels, but only adds up to 7.2% complexity to the receiver. Compared to conventional IC, our scheme has fewer multiplications, less data to store, and shorter feedback latency.**

I. INTRODUCTION

The long term evolution (LTE) standard adopts single carrier FDMA (SC-FDMA) for uplink transmission [1]. Compared to OFDM, SC-FDMA has lower peak-to-average power ratio (PAPR) for the transmitter. This provides higher power efficiency for the mobile device. Furthermore, LTE can support up to 50 Mbps in the uplink transmission with MIMO support.

On the other hand, the usage of MIMO introduces inter-antenna interference. At the same time, due to the multi-path fading, there is inter-symbol interference. Because of the usage of cyclic prefix in the LTE standard, the inter-symbol interference between SC-FDMA symbols is minimized very well. Only inter-symbol interference between symbols inside each SC-FDMA symbol remains significant. Frequency domain equalizer (FDE) [2] can be applied to reduce both interference. However, in a multi-path channel, the residual inter-symbol and inter-antenna interference still exists after the minimum mean square error-FDE (MMSE-FDE). This residual interference is especially strong in the equal tap channels. As a result, this interference degrades the system performance.

In recent years, several schemes were proposed to solve this problem in LTE downlink [3]. There is few work for the uplink [4]–[6], especially for low complexity software defined radio (SDR) implementation. In [5], 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 after MMSE-FDE and improves the receiver performance. However, in order to send the data back to the frequency domain, extra DFTs are required for transformation. This increases the area and also requires more memory to buffer the data. Moreover, because the feedback needs to go through DFTs to the frequency domain and then go back to time domain by IDFTs, this scheme has large feedback latency. Thus, this scheme has many disadvantages for real time implementation. In [6], the decoded log-likelihood ratios are sent back to the frequency domain to achieve the interference cancellation. The system is similar to [5], but with an even longer feedback loop, which is from the channel decoder. This results in much longer feedback latency, and also more memory is required to store the data. As discussed in [7], [8], the throughput and complexity are key criteria for SDR. Thus, 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 interference cancellation scheme based on the MMSE criterion to improve the performance of LTE/LTE-Advanced uplink receiver. Different from other schemes, our inter-symbol and inter-antenna interference after MMSE-FDE are reconstructed in the time domain from the selected detected symbols. With this selection, we can perform much less computation during the reconstruction than using all detected symbols. After this reconstruction, the receiver removes the regenerated interference from the current symbols. Because the interference cancellation is performed in the time domain instead of the frequency domain, the feedback latency is much shorter than previous 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 has less latency, less area, and less memory for storage, which make it more suitable for implementation. From the simulations, we show that our scheme can improve the performance of the MMSE-FDE receiver up to 8 dB in different channels. It is also shown that our scheme only adds about 7.2% additional complexity to the receiver, which makes it easy to implement.

Furthermore, it was shown in the literature that a FDE based receiver can be potentially used to support both UMTS and LTE standards [9]. Based on this, our interference cancellation scheme can also be applied to improve the performance of that system.

In section II, the conventional LTE uplink MIMO receiver with MMSE-FDE is described. Section III analyzes the inter-antenna and inter-symbol interference. In section IV, we propose the low complexity MMSE interference cancellation

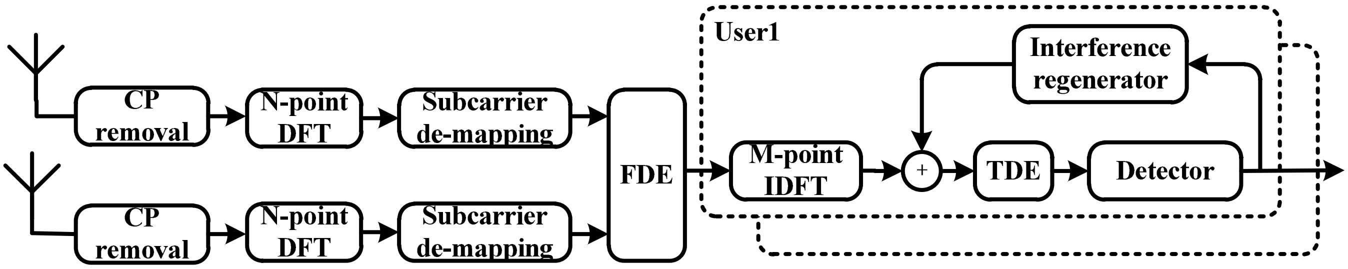

Fig. 1. LTE uplink MIMO receiver with interference cancellation

scheme to improve the performance. Simulations are shown in section V, and complexity is analyzed in section VI. Conclusions are drawn in section VII.

II. System model

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

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

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

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.

The cyclic prefix is first removed from the received data at each antenna. Then, at each antenna, the received signal is transformed to the frequency domain by a DFT. The frequency domain data on all antennas on the m^{th} frequency subcarrier is

$$\mathbf{Y}^m = \mathbf{H}^m \mathbf{X}^m + \mathbf{N}^m, \quad (2)$$

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 m^{th} frequency subcarrier as

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

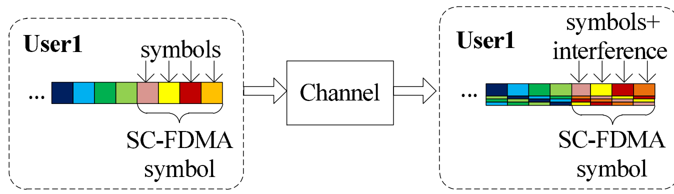

Fig. 2. Inter-symbol interference in LTE uplink

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 m^{th} frequency subcarrier can be computed by

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

The frequency domain symbols are then de-mapped to each user. The IDFT at each antenna and each user converts the equalized frequency domain symbols and channel matrix to the time domain. They are represented as $\mathbf{y}_{eq}$ and $\mathbf{h}_{eq}$. After this, the symbols are detected for each user.

III. Inter-antenna and Inter-symbol Interference

In this section, we analyze the interference in the LTE uplink. Usually, there are inter-subcarrier interference, inter-symbol interference and inter-antenna interference in the receiver. As we assume there is no frequency offset, there is no inter-subcarrier interference in the receiver. There are two kinds of inter-symbol interference in the LTE uplink. One is inter-symbol interference between SC-FDMA symbols. The other is the inter-symbol interference between the sampled symbols. LTE uses cyclic prefix to minimize the inter-symbol interference between SC-FDMA symbols. This provides enough guard symbols between SC-FDMA symbols to suppress this kind of interference. Thus, this interference is very small. Because there are DFT, IDFT, and the cyclic prefix in the LTE uplink, the inter-symbol interference between symbols is much more complicated. In multi-path channels, for one user, the inter-symbol interference to one symbol is not only from the symbols transmitted before it but also from the symbol transmitted after it. In other words, the interference is from all other symbols inside the same SC-FDMA symbol for one user. This inter-symbol interference is shown in Fig. 2. The inter-antenna interference comes from the MIMO used in the LTE uplink.

Conventionally, a MMSE-FDE receiver is used to equalize the channel and eliminate the interference. However, MMSE-FDE can not remove all the above interference completely. There is residual interference from both inter-symbol interference and inter-antenna interference. For the m^{th} time domain symbol after MMSE-FDE of user u, this is represented as

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

where $\mathbf{s}^{m}(u)$ is the m^{th} $N_R\times 1$ vector of transmitted symbols from user u; j is equal to $(m \mod M)$, M is the total number of symbols of the current user in one SC-FDMA symbol; $\mathbf{h}_{eq}^{i}(u)$ is the i^{th} $N_R\times N_T$ equalized time domain channel matrix of user u and $\mathbf{h}_{eq}^{i}(u)=\mathbf{h}_{eq}^{M+i}(u)$; $\mathbf{n}_{eq}^{m}(u)$ is the m^{th} $N_R\times 1$ equalized time domain additive white Gaussian noise of user u. The first term has 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. It can be minimized by regenerating the interference from the selected detected symbols.

IV. Low Complexity Interference Cancellation

Conventional schemes solve this problem in 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 after MMSE-FDE. The blocks are also shown in Fig. 1, which include an interference regenerator and time domain equalization (TDE). The flow is shown below.

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

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

where L_{FB} and L_{FF} are the number of symbols previously detected and future detected, respectively. From the implementation perspective, the future symbols are not the symbols received in the future. These symbols are received and buffered, but used as the symbols received in the future. 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. However, not all interference are 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 only cover the symbols with the strongest interference, we can get almost the same performance as with full regeneration, but with much less computation. And 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 $\mathbf{y}_{ri}^{m}(u)$ from $\mathbf{y}_{eq}^{m}(u)$, Eq. (5) becomes:

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

Then the desired symbols and the noise are left. This cancellation is performed in the time domain instead of the frequency domain. This scheme shortens the feedback loop by not going through the DFT and IDFT, which not only speeds up the system throughput but also saves the memory for storage. Furthermore, the area for additional DFTs can be saved.

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

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

where $\mathbf{C}_{noise}(u)$ is the $N_T\times N_T$ covariance matrix of the noise $\mathbf{n}_{eq}^{m}(u)$ 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. The noise in Eq. (3) is

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

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

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

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

which is already calculated in Eq. (9). This can be reused to save the computation. Then $\mathbf{C}_{noise}(u)$ is calculated by

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

where m is the m^{th} 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. These matrix multiplications can share the multipliers with MMSE-FDE. Because there is feedback latency from the detector to the interference cancellation, and MMSE-FDE can not output any new data before the interference cancellation happens, the noise covariance can be calculated by using the same multipliers from MMSE-FDE during this time. This greatly reduces the area required.

As analyzed above, our partial interference cancellation with TDE can remove the inter-symbol and inter-antenna interference with less computation and latency compared to full interference regeneration scheme. These are very important

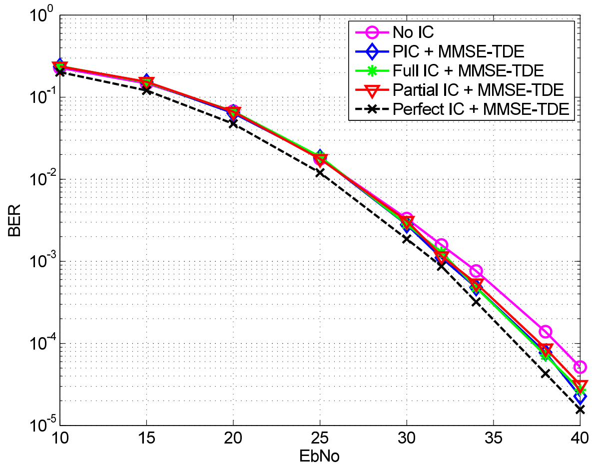

Fig. 3. Performance of 4x4 MIMO in Rayleigh channels with 64-QAM

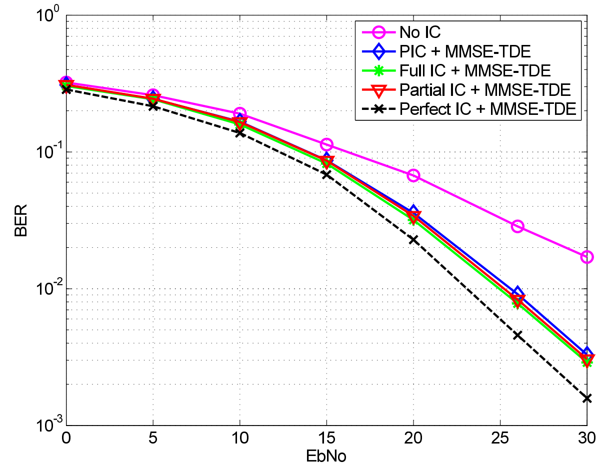

Fig. 4. Performance of 4x4 MIMO in Winner C1 channels with 64-QAM

for real time 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, this means that our scheme can also be used in the multi-standard receiver.

V. Simulations

In this section, we compare the performance of our scheme with other schemes used for LTE uplink. The simulation parameters are chosen to support the maximum rate in the LTE uplink standard. They are shown in Table I. The Rayleigh channel we used has four taps with power profile [0 -4.7712 -7.7815 -7.7815] dB. We also simulated the scheme in the Winner C1 (suburban macro-cell) channel. From the specification, we can see that this channel results in more severe inter-symbol interference. The L_{FF} and L_{FB} are chosen to balance the performance and the area.

TABLE I
Simulation parameters

Parameter	Value
Channel	Rayleigh channels; Winner channels
Length of DFT	512
Length of IDFT	300
Length of CP	36
Modulation order	64-QAM
Number of antennas	4×4
FDE	MMSE-FDE
TDE	MMSE-TDE
L_{FF}	15
L_{FB}	15

Three curves are shown in Fig. 3 and Fig. 4:

1) **No IC:**
This means there are no interference regenerator and TDE in the system shown in Fig. 1.
2) **PIC + MMSE-TDE:**
This is the conventional parallel interference cancellation. All the symbols are first detected and then sent back to the interference regenerator. After cancelling the interference, MMSE-TDE is applied to the data.
3) **Full IC + MMSE-TDE:**
This is the 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 signal.

As shown in Fig. 3, 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 the full IC + MMSE-TDE and PIC + MMSE-TDE. This means that only cancelling the strongest interference will not affect 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 detection schemes, such as sphere detector. In the more severe Winner C1 channels with 64-QAM, as shown in Fig. 4, there is an 8 dB improvement with our scheme. 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.

VI. Complexity analysis

The complexity of LTE receivers without IC mainly depends on DFT and IDFT, which are $O(NlogN)$. The interference cancellation mainly depends on the interference regenerator, which is $O(N_T^2(L_{FB}+L_{FF}))$. The noise correlation matrix needs to be prepared before applying the MMSE-TDE after the interference cancellation. The complexity of this mainly depends on the matrix multiplication, which is $O(N_T^3)$. The parameters for comparison are chosen as shown in Table I. The comparison results are shown in Table II. The complexity in the table indicates the number of equivalent multiplications needed by each LTE MIMO symbol. This is computed by first summing up all the multiplications needed for a SC-FDMA symbol, and then averaging over the number of symbols inside one SC-FDMA symbol.

TABLE II
Number of equivalent multiplications per LTE MIMO symbol

Module	**Number of antennas**		
	1×1	**2×2**	**4×4**
Full IC or PIC + MMSE-TDE	1.2	4.8	19.6
Partial IC + MMSE-TDE	0.13	0.58	2.7
LTE receiver without IC	9.2	18.4	37.1
R1: Full IC + MMSE-TDE/LTE receiver	12.9%	26.0%	52.7%
R2: Partial IC + MMSE-TDE/LTE receiver	1.4%	3.1%	7.2%
Noise covariance	0.3	2.3	18.8
Noise covariance/LTE receiver	3.2%	12.7%	50.5%

The R1 is the ratio of full IC + MMSE-TDE to LTE receiver without IC. As shown, the full IC + MMSE-TDE is 52.7% of the receiver. This means a large amount of area to the receiver. The R2 is the ratio of partial IC + MMSE-TDE to LTE receiver without IC. As indicated, partial IC + MMSE-TDE is only about 7.2% of the receiver even at 4×4 MIMO case. Our scheme largely saves the area from the full IC and PIC schemes. Another computation comes from the calculation of the noise covariance matrix, which is up to 50.5% of a LTE receiver without IC. As we analyzed, this part of computation can share the multipliers in MMSE-FDE, which will reduce huge area.

VII. Conclusion

In the paper, we propose a novel low complexity interference cancellation scheme. The scheme improves the performance of the LTE/LTE-Advanced uplink MIMO receiver by cancelling the inter-symbol and inter-antenna interference. Different from other schemes, our scheme uses partial interference cancellation, and time domain interference cancellation instead of the frequency domain interference cancellation. This results in less 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 very small compared with a LTE receiver. All of these features make our scheme suitable for SDR implementation.

References

[1] H. G. Myung, J. Lim, and D. J. Goodman, "Single Carrier FDMA for Uplink Wireless Transmission," in *IEEE Vehicular Tech. Mag.*, vol. 1, Sept. 2006, pp. 30–38.

[2] D. Falconer, S. Ariyavisitakul, A. Benyamin-Seeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," *IEEE Communications Magazine*, vol. 40, no. 4, pp. 58 –66, Apr. 2002.

[3] C. Manchon, L. Deneire, P. Mogensen, and T. Sorensen, "On the Design of a MIMO-SIC Receiver for LTE Downlink," in *IEEE 68th Vehicular Technology Conference Fall (VTC 2008-Fall)*, Sept. 2008, pp. 1–5.

[4] K. Raghunath and A. Chockalingam, "SC-FDMA Versus OFDMA: Sensitivity to Large Carrier Frequency and Timing Offsets on the Uplink," in *IEEE Global Telecommunications Conference, 2009. GLOBECOM 2009.*, Dec. 2009, pp. 1 –6.

[5] S. Okuyama, K. Takeda, and F. Adachi, "Frequency-Domain Iterative MUI Cancellation for Uplink SC-FDMA Using Frequency-Domain Filtering," in *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*, Sept. 2010, pp. 1 –5.

[6] M. Jiang, N. Prasad, and X. Wang, "Design of high performance MIMO receivers for LTE/LTE-A uplink," in *Conference Record of the Forty Fourth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), 2010*, Nov. 2010, pp. 1493 –1497.

[7] M. Li, R. Appeltans, A. Amin, R. Torrea, H. Cappelle, M. Hartmann, H. Yomo, K. Kobayashi, A. Dejonghe, and L. Van Der Perre, "Overview of a Software Defined Downlink Inner Receiver for Category-E LTE-Advanced UE," in *IEEE International Conference on Communications (ICC), 2011*, June 2011, pp. 1 –5.

[8] Y. Li, J. Zhang, J. Fang, Q. Cui, K. Tan, and X. Tao, "Soft-LTE: A Software Radio Implementation of 3GPP Long Term Evolution Based on Sora Platform," *Demo in ACM MobiCom 2009*, 2009.

[9] L. Martoyo, T. Weiss, F. Capar, and F. Jondral, "Low complexity CDMA downlink receiver based on frequency domain equalization," in *IEEE 58th Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003*, vol. 2, Oct. 2003, pp. 987 – 991 Vol.2.