Performance Evaluation of Iterative Layered Space Time Receiver in LTE Uplink

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I. Abstract

Layered space time (LST) equalization which employs successive interference cancellation (SIC) and frequency domain equalization (FDE) has been proven to be a promising structure for the receiver of single-carrier (SC) systems with MIMO (Multiple-input Multiple-output) schemes. In this paper, the performance of iterative LST in long term evolution (LTE) uplink system will be presented. The evaluation of the algorithm also considers the algorithm application in practical digital implementation: 1,First, finite word-length of log-likelihood ratio (LLR) for SIC. 2, Second, estimation error of the correlation coefficient between the feedback and ideal symbols. It will demonstrate how much performance degradation will be caused when taking into account the implementation complexity and nonideal conditions of the algorithm.

***Index Terms*— Decision Feedback Equalization (DFE), Frequency Domain Equalization (FDE), Imperfect Decision Feedback, MIMO, Single-carrier FDMA (SC-FDMA)**

II. Introduction

SINGLE carrier frequency division multiple access (SC-FDMA) has been adopted by 3GPP in the uplink of long term evolution (LTE) [1]. It is also called DFT-spread OFDM, because the main difference between SC-FDMA and OFDM in the transmitter structure is an additional DFT operation before the IDFT. By choosing different sizes of IDFT and DFT, the output of SC-FDMA exhibits 'single-carrier' properties, i.e. low peak-to-average power ratio (PAPR) [2]. Because of the inherit similarity in structure, SC-FDMA also has the advantages of OFDM, i.e. flexible bandwidth and frequency domain equalization.

MIMO (Multiple-input Multiple-output) technology has been introduced in LTE to achieve the targeting high data rate. In LTE uplink, multi-user MIMO technology is supported, while the equalization algorithms at the base station need to cope with both the inter symbol interference (ISI) and multi-user interference (MUI) which is a challenging task. Layered space time (LST) receiver has been proven to be a promising structure for the receiver of SC MIMO systems [3]. It is a multistage detection technique which originates from Foschini's work about V-BLAST [4]. At each stage, a block of symbols from one transmitting antenna are detected. The detected symbols serve as the *a priori* knowledge for the following detection stages. By adopting the idea of iterative block decision feedback equalization (IB-DFE), the multiuser interference (MUI) and the residual inter symbol interference (ISI) are mitigated by the interference cancellation (IC) iteratively which gives further improvement of the performance.

The evaluation of ILST is based on the algorithm proposed in [5]. Besides, there are two practical factors which will limit the expected performance gain. One is the word-length of word-length of log-likelihood ratio (LLR) for the decision feedback and the other is the estimation of the reliability of the detection symbols. In this paper, their influence will also be investigated.

In the following text, vectors are marked by bold lowercase, while matrices are marked with bold uppercase. An exception is the frequency domain vector which is also denoted by bold uppercase. $(\cdot)^H$, $(\cdot)^T$ and $(\cdot)^*$ denote Hermitian, transpose and complex conjugate of a vector or a matrix, respectively. $\mathrm{E}[\cdot]$ is the expectation operator.

III. System model and algorithm description

The transmitter structure in LTE uplink is depicted in Fig. 1. The CRC encoder inserts a sequence of parity bits to each transport block, and then the Turbo encoder performs the channel coding. The encoded bits are interleaved to have the statistical independent property. Within the modulation process $d_i, i = 1, ..., Q_m$ interleaved bits are grouped together and mapped to one complex symbol on the constellation map. Then DFT operation is applied to the modulated symbols and the DFT output is mapped to the allocated subcarriers. Finally, an inverse DFT is used and cyclic prefix is inserted as in the OFDMA system.

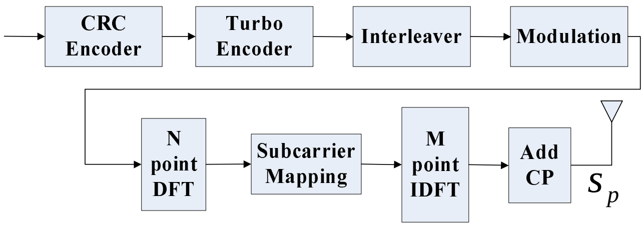

Fig. 1. Transmitter structure of LTE uplink

A multi-user MIMO system with N transmit antennas and P receive antennas is applied. The data streams from different transmit antennas are assumed to be independent and the power of transmitted symbols is normalized to be one. Vector $\mathbf{s}[l] = [s_1[l], s_2[l], ..., s_P[l]]^T, l = 1, ..., M$ is used to represent the transmitted symbols from all transmitting antennas at time instance l, where M is the size of the transmit symbol block. The received symbols are also denoted as a vector $\mathbf{y}[l] = [y_1[l], y_2[l], ..., y_N[l]]^T$. Assuming vector $\mathbf{h}_p[i], i = 0, 1, ..., I$ is the channel impulse response from transmit antenna p to all receive antennas, the received symbols can be obtained from

$$\mathbf{y}[l] = \sum_{p=1}^{P} \sum_{i=0}^{I-1} \mathbf{h}_p[i] s_p[l-i] + \mathbf{n}[l], l = 1, ..., M \quad (1)$$

where $\mathbf{n}[l]$ represents the additive white Gaussian noise vector with zero mean and variance of σ_n^2.

ILST is an iterative multistage detection algorithm which the feedforward and feedback filters are both operated in frequency domain. Fig.2 shows the block diagram of one detection stage. At each stage, a block of symbols from a specific transmitting antenna is detected. The received symbols from all receive antennas are transferred to frequency domain by DFT operations, which gives

$$\mathbf{Y}[m] = \sum_{p=1}^{P} \mathbf{H}_p[m] S_p[m] + \mathbf{N}[m], m = 1, ..., M \quad (2)$$

where $\mathbf{H}_p$ is the corresponding channel frequency response from transmit antenna p to all receive antennas. The frequency domain symbols are multiplied with the feedforward filter coefficients which are designed to suppress the ISI and MUI. The output of the feedforward filter is transferred back to time domain and passes a decision device. The detected symbols are then feeded back to reduce the residual interference which achieves additional performance gain. According to [5], the detected symbols are obtained from the demodulator, however, it can also adopt the idea of Turbo equalization in which the feed back symbols are estimated based on the LLR from the Turbo decoder [6]. In the following sections, the Turbo decision feedback is used because of its superior performance at the price of its higher latency and complexity.

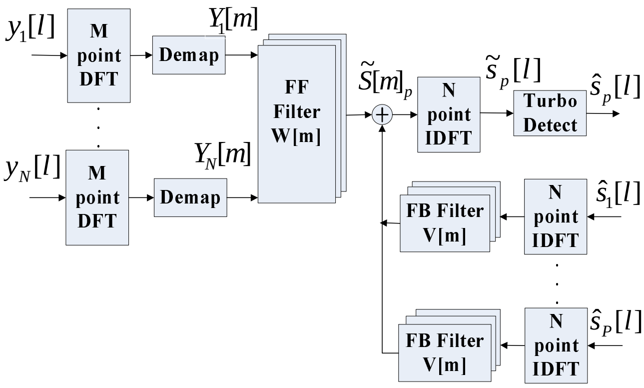

Fig. 2. Block diagram of ILST equalizer

Let $\mathbf{W}_p[m] = [W_{1,p}[m], W_{2,p}[m], ..., W_{N,p}[m]]^T$ and $\mathbf{V}_p[m] = [V_{1,p}[m], V_{2,p}[m], ..., V_{P,p}[m]]^T$ represent the feedforward and feedback filter coefficients for the detecting layer p with respect to frequency component m. The frequency domain output samples of a certain detection stage is given by [5]

$$\tilde{S}_p[m] = \sum_{n=1}^{N} W_{n,p}[m] Y_n[m] - \sum_{p'=1}^{P} V_{p',p}[m] \hat{S}_{p'}[m]$$

In the following sections, frequency index m is omitted for simplicity unless explicitly. Define matrix $\mathbf{F}$ as

$$\mathbf{F} = \begin{pmatrix} H_{1,1}^* & \cdots & H_{1,P}^* \\ \vdots & & \vdots \\ H_{N,1}^* & \cdots & H_{N,P}^* \end{pmatrix} \begin{pmatrix} (1-\rho_1^2) H_{1,1} & \cdots & (1-\rho_1^2) H_{N,1} \\ \vdots & & \vdots \\ (1-\rho_P^2) H_{1,P} & \cdots & (1-\rho_P^2) H_{N,P} \end{pmatrix} \quad (3)$$

$\mathbf{W}_p$ is calculated by

$$(\mathbf{F} + \frac{1}{\text{SNR}}\mathbf{I}_N)\mathbf{W}_p = (1 - \rho_p^2)\mathbf{H}_p^* \tag{4}$$

Given the feedforward filter coefficients, the optimal feedback filter coefficients can be obtained as

$$V_{p,p} = \rho_p \left(\sum_{n=0}^{N-1} W_{n,p} H_{n,p} - \gamma_p \right) \tag{5}$$

$$V_{p',p} = \rho_{p'} \sum_{n=0}^{N-1} W_{n,p} H_{n,p'}, \qquad p' \neq p. \tag{6}$$

with γ_p defined as

$$\gamma_p = \frac{1}{M} \sum_{n=1}^{N} \sum_{m=0}^{M-1} W_{n,p}[m] H_{n,p}[m] \tag{7}$$

IV. Simulation Results

To evaluate the performance of ILST, the simulation is done in LTE uplink environment. Each subcarrier is assumed to have a bandwidth of 15 kHz, while the number of total subcarriers is 2048 with 1200 subcarriers assigned to each user. So the overall bandwidth is 20 MHz. QPSK modulation is applied. A 4 by 4 Rayleigh distributed channel with 6 independent taps is used. Besides, the channel is assumed to be static over one OFDM symbol. Fig.3 shows the performance gain of ILST after 2 iterations compared with MMSE. At BER $= 10^{-3}$, the performance gain is around 5 dB.

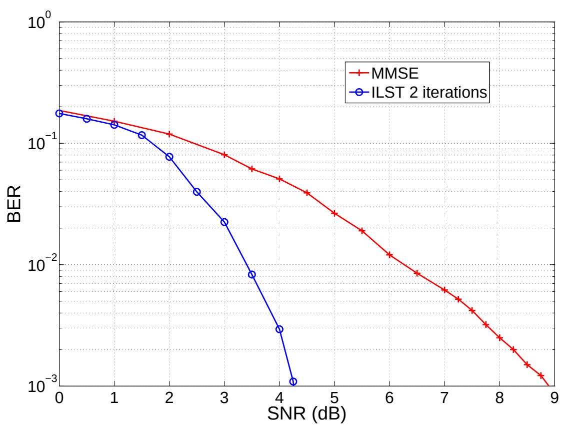

Fig. 3. Performance comparison between MMSE and ILST after 2 iterations

A. Quantization error of LLR

The detected symbols from the other layers or from the current layer of previous iteration are used for decision feedback in ILST algorithm. The feedback symbol takes the reliability of the symbol estimation into consideration, and consequently it has better performance than hard decided symbol. The soft estimated symbols $\hat{s}[l]$ can be computed from the knowledge of the *a priori* LLRs as described in [6]. The conditional mean estimator is defined by

$$\hat{s}[l] = \text{E}\{s[l] \mid \text{L}_a^{dec}\}. \tag{8}$$

where L_a^{dec} is the *a priori* LLR given by the Turbo decoder. Assuming the modulated bits are independent,

$$\hat{s}[l] = \sum_{\ell=0}^{M-1} s^\ell \, \text{Pr}_a\{\mathbf{s}_k^\ell\} \tag{9}$$

The *a priori* probabilities $\text{Pr}_a\{\mathbf{d}_k^\ell\}$ can be computed as

$$\text{Pr}_a\{\mathbf{s}_k^\ell\} = \text{Pr}\{s_k = s^\ell\} = \prod_{\psi=1}^{Q_m} \text{Pr}\{d_{l,\psi} = d_{\ell,\psi}\} \tag{10}$$

where $d_{\ell,\psi}$ is the ψ^{th} bit associated with the constellation point s^ℓ, and $M = 2^{Q_m}$ is the number of different symbols in the I/Q constellation diagram. $\text{Pr}\{b_{l,\psi} = b_{\ell,\psi}\}$ is obtained from the LLRs by definition. In practical digital implementation only finite word-length symbol can be used, thus the quantization error is introduced. The word-length of LLR needs to be carefully chosen to optimize the trade-off between the quantization error and the implementation complexity.

First, the uniform normalization is performed directly on LLR. The simulation results show that 8 bits normalization result in around 0.1 dB performance degradation, while for 6 bits the degradation increases sharply. It is also shown that at low SNR region the impact of the quantization error is not obvious, while at high SNR the requirement is higher. So a dynamic word-length adapted based on the SNR can help to remain the advantage of soft symbol while keeping the complexity low. Second, the theorectical range of LLR is from $\pm\infty$. At high SNR range, when the detection of the received symbols is more reliable, the LLR value tends to be very large. As suggested by [7], the normalization can be performed on $\tanh(\text{LLR})$ with the range from -1 to $+1$. Fig.4 also demonstrates the performance of the second normalization method. It shows that even with only 4 bits, the second method can achieve the similar performance with the first one of 8 bits.

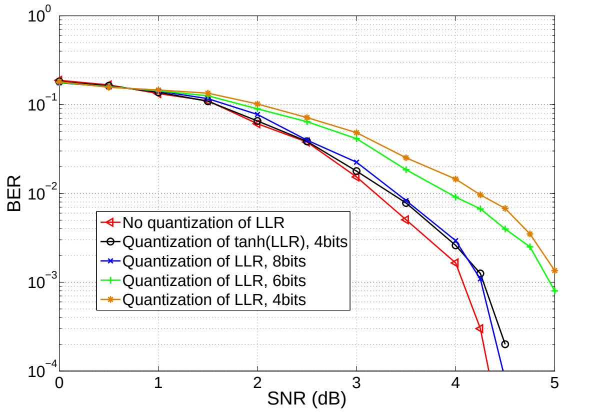

Fig. 4. Performance degradation of the quantization error of LLR

B. Estimation of the reliability of the detected symbols

The reliability of the detected symbols is defined by $\rho = \frac{\mathrm{E}[s_n \hat{s}_n^{i\,*}]}{E_s}$, which is the correlation coefficient between the detected and ideal symbols. When calculating the equalization filter coefficients, ρ is applied to mitigate the error propagation caused by the unreliable detection [8]. The definition of the correlation coefficients requires the knowledge of the ideal transmitted symbols which is obviously impossible at the receiver side. In [9], it provides the method of estimating ρ value of the hard decided symbols. The estimation is based on the SNIR at the equalizer output.

$$\rho = 1 - \frac{1}{M}\sum_{m=0}^{M-1}\left(\frac{1}{1+\exp\left(\frac{D|\tilde{s}_n^I|}{\sigma_\epsilon^2}\right)} + \frac{1}{1+\exp\left(\frac{D|\tilde{s}_n^Q|}{\sigma_\epsilon^2}\right)}\right) \tag{11}$$

where ϵ is the overall noise plus interference of the equalizer output in time domain $\epsilon = \tilde{s}_n - s_n$. It is assumed to be Gaussian distributed. D is the minimum Euclidian distance within the constellation map. There is a second estimation method from [6], which is defined as the variance of the soft symbols. Fig.5 demonstrates the performance degradation caused by the imperfect ρ values. Although the first estimation method is designed for hard decided symbol, it shows negligible performance degradation for soft symbols when compared with perfect ρ case. The second method has relatively worse performance, while the advatange of it is the simplicity.

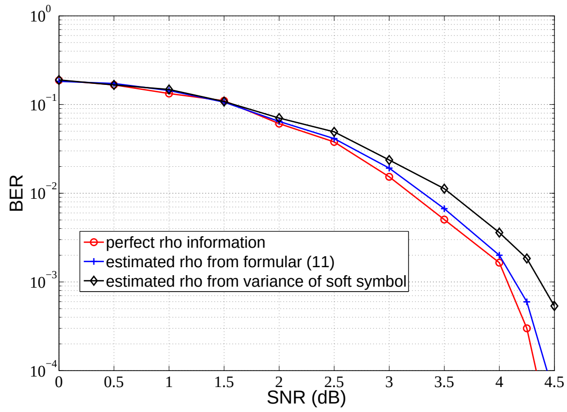

Fig. 5. Performance degradation from the estimation error of rho

V. Conclusions

In this paper, the application of ILST is extended to LTE uplink system. It demonstrates the performance of ILST after the second iterations. Compared to MMSE equalization algorithm, ILST gives around 5 dB performance gain at BER=10^{-3}. However, this performance gain will be reduced by the constraints in practical implementation. The effects of the limited word-length of LLR and the imperfect estimation of reliability coefficient is investigated. ILST still shows considerable performance improvement taking into account these implementation constraints.

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