

Lattice-Reduction aided Soft-Output Detector for Spectrally Efficient FDM System

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Abstract—In this paper, we propose the lattice-reduction (LR) aided soft-output detector in conjunction with channel decoder for spectrally efficient frequency division multiplexing (SE-FDM) system. The SE-FDM system can increase spectral efficiency by overlapping the subcarrier closer than the orthogonality condition, but result in inter-carrier-interference (ICI) at receiver. Thus, we utilize the LR-aided detector to achieve near optimum performance by reducing the basis of ICI term in equalization process. In addition, we also study the soft-output LR-aided detector with convolutional coding. Through the Monte Carlo simulation, the LR-aided detector shows good trade-off between complexity and performance for both uncoded and coded SE-FDM system.

Index Terms—Spectrally efficient FDM, lattice reduction, Soft-output.

I. INTRODUCTION

With the explosive demand for high-data rate and multimedia applications, the communication systems are moving toward the new era for 5G systems to cope with the bandwidth scarcity and continuously increasing demand for high-data rate. Orthogonal frequency division multiplexing (OFDM) has long been researched and commercially deployed both in communication and broadcasting systems worldwide, i.e., 3GPP long term evolution (LTE), IEEE 802.11n for wireless local area networks (WLAN), and digital video broadcasting (DVB) systems. However, the spectral efficiency is still far away from the Shannon limit [1]-[3].

One way of increasing the spectral efficiency is to squeeze the bandwidth closer than the orthogonality condition. Thus, the space between adjacent sub-carrier is reduced, but introduces the inter-carrier interference (ICI) which complicate the signal detection at receiver. This transmission scheme is called spectrally efficient frequency division multiplexing (SE-FDM) [1]-[3] and also known as the multi-carrier faster-than-Nyquist (FTN) signaling [4].

With the aided of inverse fractional fourier transform (IFRFT), the SE-FDM signal is relatively easy to generate, but detection is a challenge problem due to the performance deterioration effect causes by ICI. To handel the ICI problem, maximum likelihood (ML) detector can be employed as a optimum detector. However, ML detector is practically infeasible due to high computational complexity. Alternatively, linear detectors, such as zero-forcing (ZF) and minimum mean square error (MMSE) detector and successive interference cancellation (SIC) detector can be used, but this exhibit poor bit-error rate

(BER) performance [5]-[8]. Thus, the sphere decoder (SD) and pruned SD detectors are employed to approach the near ML performance [3], however, SD requires a closest point search for transmitted symbol vector and rather complex in case of large search dimension [5]-[6]. The lattice-reduction aided detectors for non-orthogonal multicarrier systems are proposed in [7], but these techniques have not considered channel coding in the detection process.

In this paper, we propose a lattice-reduction (LR) aided soft-output detector for coded SE-FDM system. LR aided detection is based on transforming the ill-conditioned channel matrix into an equivalent better conditioned channel matrix and also shows a near-ML performance with polynomial time computational complexity. Thus, we employed the basis-reduction to the ICI term in SE-FDE system and MMSE equalization is followed to recover the transmitted symbol appropriately. In addition, we also present bit-interleaved coded modulation (BICM) system employing convolutional code and LR-aided soft-output detector is also presented. Simulation result demonstrate that the proposed scheme performs good trade-off between computational complexity and BER performance.

II. SE-FDM SYSTEM MODEL

We consider a coded SE-FDM transceiver structure described in Fig. 1. The information bits are encoded with a convolutional code, and then randomized by passing through the pseudo random interleaver π . The interleaved bits are mapped onto a complex valued symbol. We assume the channel to be an additive white Gaussian noise (AWGN). The transmitted signal is expressed as:

$$y(t) = s(t) + n(t) \quad (1)$$

where $n(t)$ is Gaussian noise with zero mean and variance of σ^2 , and $s(t)$ is the transmitted FDM symbol that can be expressed as [2]

$$s(t) = \frac{1}{\sqrt{T}} \sum_{n=0}^{N-1} S_n e^{j2\pi n \Delta f t}, \quad (2)$$

where S_n denotes M -ary independent and identically distributed modulating symbols with zero mean and unit variance for $f_{\alpha,n}(t)$ subcarriers. The modulating symbol is transmitted N subcarriers and $\Delta f = \alpha/T$ ($\alpha < 1$) is the frequency separation between each subcarriers [1]. If the frequency separation α is set as $\alpha = 1$, the system model of equation

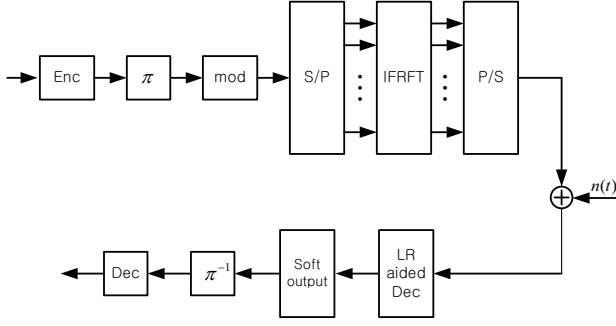


Fig. 1. Block diagram for the SE-FDM system.

(2) can be regarded as a conventional OFDM system. The bandwidth occupied by SE-FDM signal can be reduced by increasing fraction α , but ICI problem will be more severe. The system model (2) can be formulated into matrix form in the following way:

$$\mathbf{y} = \mathbf{F}_\alpha^{-1} \mathbf{s} + \mathbf{n} \quad (3)$$

where $\mathbf{y} = [y_0, \dots, y_{N-1}]^T$ is a vector of N received symbols and $\mathbf{s} = [s_0, \dots, s_{N-1}]^T$ is a vector of N modulating symbol. The SE-FDM signal is generated by using an IFRFT matrix $\mathbf{F}_\alpha^{-1}$ and the l -th low and k -th column element of $\mathbf{F}_\alpha^{-1}$ is calculated by $\mathbf{F}_{\alpha(l,k)}^{-1} = (1/\sqrt{N})\exp[2\pi l k \alpha / N]$ [1].

After having received the transmitted signal, a bank of N correlators $b_n(t)$ is applied to the received symbol $\mathbf{y}$. The correlator $b_n(t)$ is composed of set of orthonormal basis functions that is generated from the FDM carriers using the Gram Schmidt (GS) orthonormalisation method [2]. Thus, the receive filtered signal is given by

$$\mathbf{r} = \mathbf{M} \mathbf{s} + \mathbf{n}. \quad (4)$$

The element of $\mathbf{r}$ and $\mathbf{M}$ are given by

$$r_i = \int_0^T y(t) b_k^*(t), \quad i = 1, \dots, N-1, \quad (5)$$

$$M_{ij} = \int_0^T f_{\alpha,n}(t) b_k^*(t), \quad i, j = 1, \dots, N-1, \quad (6)$$

The matrix $\mathbf{M}$ is upper triangular and the ICI term is still remained at the output of receive filtered signal $\mathbf{r}$. To detect the transmitted information, ML detector can be employed as a optimum detector. The ML decision rule can be expressed as [2]-[3]

$$\hat{\mathbf{s}} = \arg \min \|\mathbf{r} - \mathbf{M} \mathbf{s}\|^2 \quad (7)$$

where $\|\cdot\|$ denotes the Euclidean 2-norm of a vector.

The ML detection problem is not feasible due to its computational complexity. The computational complexity for the ML detection is exponentially increased with the number of subcarriers and the constellation cardinality. Alternatively, the SD can be employed to approach the near ML performance, however, SD requires a closest point search for transmitted symbol vector and rather complex in case of large search dimension.

III. LR AIDED SE-FDM DETECTION

The LR was developed to transform a basis to a nearly orthogonal one, and is applied to a detection problem for a multi-input multi-output (MIMO) systems [5]-[6]. A well-known basis reduction criterion for arbitrary lattice dimensions is Lenstra-Lenstra-Lovász (LLL) algorithm [9]. Note that the LLL algorithm is initially designed with real valued matrix. Thus, the complex valued model (3) can be converted into a real-valued model:

$$\mathbf{y}_r = \mathbf{F}_{r\alpha}^{-1} \mathbf{s}_r + \mathbf{n}_r \quad (8)$$

with the real-valued IFRFT matrix

$$\mathbf{F}_{r\alpha}^{-1} = \begin{bmatrix} \Re(\mathbf{F}_\alpha^{-1}) & -\Im(\mathbf{F}_\alpha^{-1}) \\ \Im(\mathbf{F}_\alpha^{-1}) & \Re(\mathbf{F}_\alpha^{-1}) \end{bmatrix} \in \mathbb{R}^{2N \times 2N} \quad (9)$$

and the real valued vectors

$$\mathbf{y}_r = \begin{bmatrix} \Re(\mathbf{y}) \\ \Im(\mathbf{y}) \end{bmatrix}, \quad \mathbf{s}_r = \begin{bmatrix} \Re(\mathbf{s}) \\ \Im(\mathbf{s}) \end{bmatrix}, \quad \mathbf{n}_r = \begin{bmatrix} \Re(\mathbf{n}) \\ \Im(\mathbf{n}) \end{bmatrix} \quad (10)$$

where $\Re(\cdot)$ and $\Im(\cdot)$ denotes the real and imaginary parts of the argument, respectively. The dimension of the vectors (10) are given by $\mathbf{y}_r \in \mathbb{R}^{2N}$, $\mathbf{s}_r \in \mathbb{R}^{2N}$ and $\mathbf{n}_r \in \mathbb{R}^{2N}$.

A. Lattice Reduction

Before describing the LR-aided detector, we briefly summarize the principle of LR [5]-[6]. Lattices are periodic arrangements of discrete points, and the column vectors of real-valued IFRFT matrix $\mathbf{F}_{r\alpha}^{-1}$ can be interpreted as basis of a lattice. LR is concerned with finding improved representations of a given lattice, which find a basis with short, nearly orthogonal vectors. The reduced matrix can be represented as $\tilde{\mathbf{F}}_{r\alpha}^{-1} = \mathbf{F}_{r\alpha}^{-1} \mathbf{T}$, and the lattice reduced matrix $\tilde{\mathbf{F}}_{r\alpha}^{-1}$ and the original matrix $\mathbf{F}_{r\alpha}^{-1}$ span the same lattice. The matrix $\mathbf{T}$ is a unimodular transformation matrix and its elements only take integer values. The inverse of unimodular matrix $\mathbf{T}^{-1}$ always exists and contains also only integer values. Thus, the real-valued system model (8) can be represented as

$$\mathbf{y}_r = \tilde{\mathbf{F}}_{r\alpha}^{-1} \mathbf{z}_r + \mathbf{n}_r \quad (11)$$

where $\mathbf{z}_r = \mathbf{T}^{-1} \mathbf{s}_r$. The lattice reduced constellation $\mathbf{z}_r$ is differ in original constellation and recovered via $\mathbf{T} \mathbf{z}_r$.

B. Condition Number Reduction

For the LR-aided detection of SE-FDM signal, the condition number of IFRFT matrix is important. The condition number $\kappa(\mathbf{A})$ is defined as the ratio of the maximum and the minimum singular value of matrix $\mathbf{A}$. According to [1], the condition number of Gram matrix $\mathbf{M}$ in (4) is enhanced with decreasing carrier spacing α and increasing the number of carrier N . Likewise, the condition number of lattice reduced matrix $\kappa(\tilde{\mathbf{F}}_{r\alpha}^{-1})$ also depend on the carrier spacing α and the number of carrier N as well as imperfect orthogonalization process of performing LLL algorithm. The matrix singularity is a fundamental limitation for signal detection in SE-FDM system. To reduce the condition number, we apply the the simple matrix normalization method to IFRFT matrix $\tilde{\mathbf{F}}_{r\alpha}^{-1}$.

Let us define the diagonal matrix $\mathbf{G} = \text{diag}\{g_1, \dots, g_{2N}\}$ and i -th diagonal entry take the maximum value of i -th row vector of IFRFT matrix $\tilde{\mathbf{F}}_{r\alpha}^{-1}$, which can be expressed as

$$g_i = \max \left\{ \tilde{\mathbf{F}}_{r\alpha(i,1)}^{-1}, \dots, \tilde{\mathbf{F}}_{r\alpha(i,2N)}^{-1} \right\}, \quad i = 1, \dots, 2N \quad (12)$$

The normalized matrix can be represented as $\mathbf{G}^{-1}\tilde{\mathbf{F}}_{r\alpha}^{-1}$ and the (11) can be rewritten as

$$\begin{aligned} \mathbf{y}_r &= \mathbf{G}^{-1}\tilde{\mathbf{F}}_{r\alpha}^{-1}\mathbf{z}_r + \mathbf{n}_r \\ &= \mathbf{W}_r\mathbf{z}_r + \mathbf{n}_r \end{aligned} \quad (13)$$

C. LR-aided ZF, MMSE Detection

With the aid of LR, the column vector of IFTFT matrix is nearly orthogonal. For an orthogonal matrix, the ZF detection performance is identical to ML detection performance [5]-[6]. Thus, the ZF and MMSE linear detector can be employed to system model in (13), and ICI problem can be handled with relatively easy way. The ZF detection is accomplished by the Moore-Penrose pseudo-inverse of the matrix $\mathbf{W}$ and the LR-aided ZF estimation of the symbol vector can be found as

$$\hat{\mathbf{s}}_{r\text{LR-ZF}} = \mathcal{Q} \left\{ \mathbf{T} \mathcal{Q} \left\{ (\mathbf{W}^T \mathbf{W})^{-1} \mathbf{W}^T \mathbf{y}_r \right\} \right\} \quad (14)$$

where $\mathcal{Q}\{\cdot\}$ stands for the quantization operation over the symbol set.

Likewise, the MMSE detection can be used to improve the performance of SE-FDM system. The MMSE detection take a noise term into account and the extended system model is utilized as follows:

$$\underline{\mathbf{W}}_r = \begin{bmatrix} \mathbf{W}_r \\ \sigma_n \mathbf{I}_{2N} \end{bmatrix} \quad \text{and} \quad \underline{\mathbf{y}}_r = \begin{bmatrix} \mathbf{y}_r \\ \mathbf{0}_{2N} \end{bmatrix} \quad (15)$$

where $\mathbf{I}_M$ and $\mathbf{0}_M$ are an identity matrix of size $M \times M$ and M -dimensional zero vector, respectively. With the extended matrix in (15), the MMSE solution is equal to ZF, which is expressed as

$$\begin{aligned} \hat{\mathbf{s}}_{r\text{LR-MMSE}} &= \mathcal{Q} \left\{ \mathbf{T} \mathcal{Q} \left\{ (\mathbf{W}^T \mathbf{W} + \sigma_n^2 \mathbf{I}_{2N})^{-1} \mathbf{W}^T \mathbf{y}_r \right\} \right\} \\ &= \mathcal{Q} \left\{ \mathbf{T} \mathcal{Q} \left\{ (\underline{\mathbf{W}}^T \underline{\mathbf{W}})^{-1} \underline{\mathbf{W}}^T \underline{\mathbf{y}}_r \right\} \right\} \end{aligned} \quad (16)$$

Although the LR-MMSE detector in (16) can improve the BER performance compared to LR-ZF detector, but the performance gap between LR-MMSE detector and ML detector still remained.

D. LR-aided SIC

The performance of SE-FDM system can be further improved by employing the SIC structure. The ICI affected by other subcarriers can be successively canceled. The SIC is implemented by QR decomposition of matrix $\mathbf{W}_r = \mathbf{Q}\mathbf{R}$, where the $2N \times 2N$ matrix $\mathbf{Q}$ has orthogonal columns with unit norm and the $2N \times 2N$ matrix $\mathbf{R}$ is upper triangular [5]-[8]. Applying QR decomposition to the (14) does not change the noise statistics and yield sufficient statistic,

$$\begin{aligned} \hat{\mathbf{s}}_{r\text{LR-ZF-SIC}} &= \mathbf{Q}^T \mathbf{y}_r = \mathbf{R}\mathbf{z}_r + \mathbf{Q}^T \mathbf{n}_r \\ &= \mathbf{R}\mathbf{z}_r + \eta_r \end{aligned} \quad (17)$$

The matrix $\mathbf{Q}$ and $\mathbf{R}$ can be obtained by performing the LLL algorithm and the upper triangular structure enable that the k -th element of $\hat{\mathbf{s}}_{r\text{LR-ZF-SIC}}$ is free of ICI from adjacent subcarriers

$$\hat{s}_k = r_{k,k}s_k + \sum_{i=k+1}^{2N} r_{k,i}s_i + \eta_k \quad (18)$$

The k -th estimated symbol $\hat{s}_{r\text{LR-ZF-SIC}}$ can be obtained by cancelling the interference from $m+1, \dots, 2N$ subcarriers. If the correct previous decision is assumed, the interference can be perfectly canceled at each step.

The ZF-SIC approach can be easily extended to MMSE criterion and the whole process is same as that of estimating $\hat{\mathbf{s}}_{r\text{LR-ZF-SIC}}$. Let us consider a extended matrix model in (15), the QR decomposition of extended matrix is $\underline{\mathbf{W}}_r = \underline{\mathbf{Q}}\underline{\mathbf{R}}$. Multiplying $\underline{\mathbf{Q}}^T$ to $\underline{\mathbf{y}}_r$ yield

$$\begin{aligned} \hat{\mathbf{s}}_{r\text{LR-MMSE-SIC}} &= \underline{\mathbf{Q}}^T \underline{\mathbf{y}}_r \\ &= \underline{\mathbf{R}}\mathbf{z}_r + \eta_r \end{aligned} \quad (19)$$

The remaining detection procedure is same as LR-aided ZF-SIC. Due do the error propagation, the order of detection influence on the performance of SIC. The sorted QR decomposition (SQRD) is utilized to reorder the columns of matrix $\underline{\mathbf{W}}_r$ [6]. With the aided of ordering process, the BER performance is further enhanced.

E. LR-aided Soft-Output

For a coded system, the log-likelihood ratio (LLR) for k -th information bit of n -th subcarrier $b_{k,n}$ is required. To generate the soft-output of each bit, we employed the hard decision value $\tilde{s}_r$ obtained from previous LR-aided detection procedure, and then produce a initial decision vector [10]. The standard LLR calculation is used to produce the soft-output information:

$$\begin{aligned} L(b_{k,n} | \mathbf{y}_r) &\approx \frac{1}{2} \max_{\tilde{s}_r \in S_{k,n}^1} \left\{ -\frac{1}{\sigma^2} \|\mathbf{y}_r - \mathbf{W}_r \tilde{s}_r\| \right\} \\ &\quad - \frac{1}{2} \max_{\tilde{s}_r \in S_{k,n}^0} \left\{ -\frac{1}{\sigma^2} \|\mathbf{y}_r - \mathbf{W}_r \tilde{s}_r\| \right\} \end{aligned} \quad (20)$$

IV. PERFORMANCE EVALUATIONS

We evaluated the performance of coded SE-FDM system by Monte Carlo simulation. In the simulation, we used 4QAM and the total number of subcarrier is assumed to be $N = 16$ subcarriers. For the comparison purpose, we consider various detection technique to evaluate the performance of LR aided detection schemes.

To varify the effect of condition number normalization approach, we compare the proposed condition number reduction scheme in (13) to the conventional LR-MMSE without normalization in [5]-[6]. As shown in Fig. 2, the normalization method improve the BER performance compared to conventional LR-MMSE system. As mentioned earlier, the condition number is enhanced with decreasing carrier spacing α [2]. Thus, the performance difference between proposed scheme

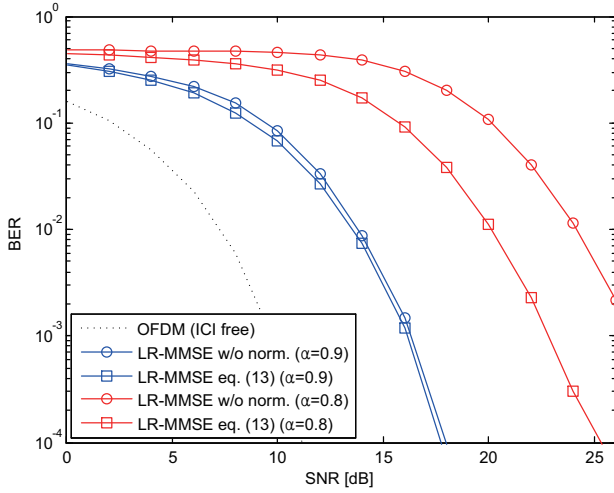


Fig. 2. BER performance comparison between condition number reduction scheme in (13) and conventional scheme.

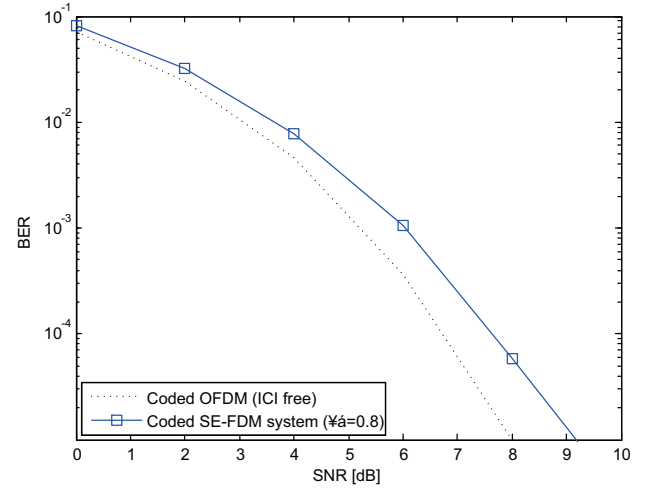


Fig. 4. BER performance for coded SE-FDM system.

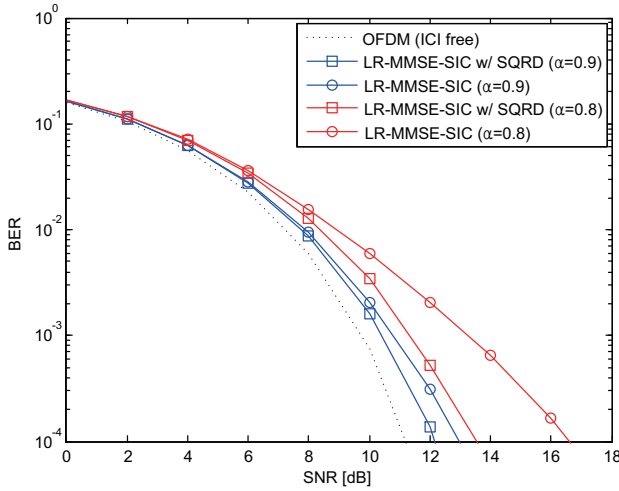


Fig. 3. BER comparison of proposed LR-aided SIC schemes for SE-FDM system.

and conventional scheme is not significant at $\alpha = 0.9$. However, as decreasing the carrier spacing, $\alpha=0.8$, the proposed scheme shows the better performance than conventional one.

Fig. 3 show the BER performance for various detection scheme based on SIC described in (19). As decreasing the subcarrier spacing, the BER performance is slightly degraded compared to ideal ICI free condition. In addition, the ordering process enhance the BER performance and LR-MMSE-SIC with SQRT scheme shows the only about 1dB away from ideal OFDM system at $\alpha = 0.9$.

For the coded SE-FDM system, we employ the convolution code with rate 1/2 and generators $(3, 2)_8$ is used as a outer code. Fig.4 show the BER performance for coded SE-FDM system at $\alpha = 0.8$. The spectral efficiency has gone up by 25%, the BER degradation, however, is only about 1.1dB away from OFDM system.

V. CONCLUSIONS

In this paper, we have proposed a LR-aided detection schemes to mitigate the ICI caused by subcarrier packing for the SE-FDM system. Especially, we consider a matrix condition number and apply the matrix normalization method to the signal detection problem. In addition, we consider soft-output detection scheme for coded SE-FDM system. From the performance evaluation, the proposed LR-aided schemes nearly approaches conventional ICI free transmission system.

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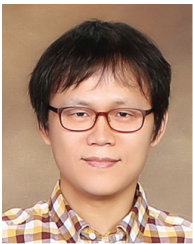
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