Enhanced Bit-Loading Techniques for Adaptive MIMO Bit-Interleaved Coded OFDM Systems

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***Abstract*— When channel state information (CSI) is available at the transmitter, the system throughput can be enhanced by adaptive transmissions and opportunistic multiuser scheduling. In this paper, we consider multi-input multi-output (MIMO) systems employing bit-interleaved coded orthogonal frequency division multiplexing (BIC-OFDM). We first propose a bit-loading algorithm based on the Levin-Campello algorithm for the BIC-OFDM. Then we will apply this algorithm to the MIMO system with a finite set of constellations, by reassigning residual power on each stream. Simulation results show that proposed bit-loading scheme which takes the residual power into account improves the system performance especially at high signal-to-noise ratio (SNR) range.**

I. Introduction

The increased demand for wireless packet services is fueling the need for higher capacity and data rates. To achieve higher data rates, data transmission over wireless channels needs to overcome channel fadings. In such cases, a promising technology is to use multiple-input multiple-output (MIMO) antenna systems and orthogonal frequency division multiplexing (OFDM). It has been shown that the capacity of the MIMO system increases linearly with the number of transmit antennas by providing multiple independent parallel channels [1]. Also, by employing the OFDM, the frequency selective channel is converted into several frequency flat subchannels. The frequency selectivity of wideband wireless channels can be further mitigated by bit-interleaved coded OFDM (BIC-OFDM), which combines the OFDM with bit-interleaved coded modulation (BICM) [2]. Therefore, the BIC-OFDM techniques in MIMO systems are expected to be deployed in future wireless communication systems.

In typical indoor wireless transmissions, user mobility is small. In such low mobility environments, adaptive modulation and coding (AMC) technique is an effective method to achieve the high spectral efficiency. The use of AMC technique allows a wireless system to choose the modulation level, the code rate, and/or other signal transmission parameters dynamically depending on the channel state information (CSI) [3].

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When the CSI is perfectly known at the transmitter, the MIMO channel on each subcarrier can be decomposed into independent parallel channels by applying singular value decomposition (SVD) [4]. Theoretically, bit loading on each subcarrier combined with the spatial domain power loading through the water-filling (WF) technique [5] maximizes the system throughput in the MIMO system [6]. However, this ideal solution requires infinite-length codebook as well as continuous modulation order and continuous power level. Thus this may not be possible to use directly in practical situations. For single antenna systems, a bit-loading algorithm for the BIC-OFDM has been proposed in [7] based on the Levin-Campello (LC) algorithm [8]. To apply the LC algorithm in the BIC-OFDM, the asymptotic coding gain [9] was utilized with a rather loose bit error rate (BER) constraint.

In the MIMO BIC-OFDM, if we consider spatial domain power allocation on each subcarrier, the complexity may be too high [6]. Without the spatial domain power allocation, which means uniform power loading for each transmit antenna, the performance improvement is limited when the maximum level of modulation size is fixed. This limitation is caused by residual power at higher eigenmodes even after the maximum possible number of bits are loaded on all subcarriers.

In this paper, we propose an AMC scheme for the MIMO BIC-OFDM system which adopts a bit-loading algorithm on each decomposed stream by the SVD operation. In this scheme, we efficiently handle the residual power of each layer without any explicit spatial domain power loading scheme. The proposed scheme reassigns the residual power to the next stream after the bit-loading procedure for the current stream is completed. To perform the bit-loading algorithm for each stream, we generalize the scheme in [7] by utilizing the variable channel gap measured through the bit error rate (BER) performance on an additive white Gaussian noise (AWGN) channel. We also compare the performance of the proposed AMC scheme for MIMO BIC-OFDM systems with the throughput of the minimum mean square error (MMSE) receiver structure in the multiuser case [10].

The paper is organized as follows: In section II, the system model for the adaptive MIMO BIC-OFDM is presented. The general bit-loading scheme for the BIC-OFDM utilizing the variable channel gap is proposed in section III-A. In section III-B, we propose a bit loading scheme for BIC-OFDM

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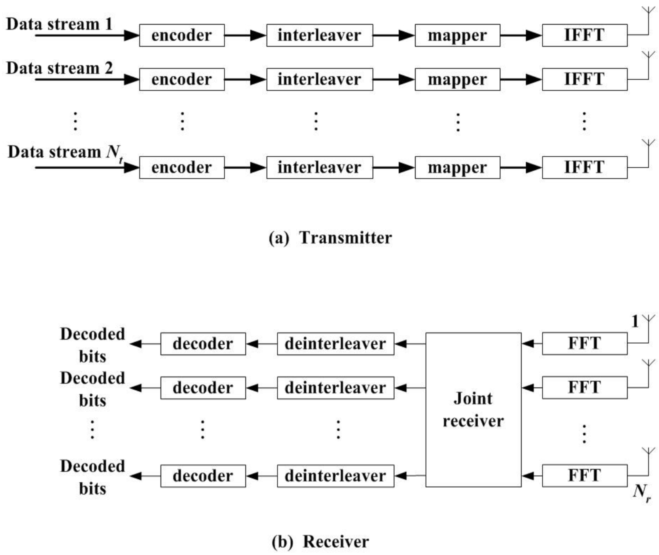

Fig. 1. System model for adaptive MIMO BIC-OFDM

systems based on SVD technique in the practical closed loop system. Finally, the simulation results and a conclusion are presented in sections IV and V, respectively.

II. System Model

A generic adaptive MIMO BIC-OFDM system model with N_t transmit and N_r receive antennas is shown in Fig. 1. Basically, we assume that all the streams come from one user in spatial-division multiplexing (SDM) systems. Depending on the system design strategy, however, we may employ space-division multiple access (SDMA) systems, which assign individual users to each stream. For each stream, an OFDM system with N_c subcarriers is applied by transmitting information sequences modulated by BICM. The BICM achieves diversity gain in the frequency domain through channel codings in frequency selective channels. The BIC-OFDM is constructed by concatenating a binary convolutional encoder with a memoryless mapper through a bit-level interleaver. After a binary label mapping, symbols are then serial-to-parallel converted and are modulated by the inverse fast Fourier transform (IFFT).

As shown in Fig. 1, the transmission rates and power levels are controlled based on the feedback information from the receiver. At each packet transmission, the input bit stream for the ith antenna ($1 \leq i \leq N_t$) is encoded using one of V different binary linear codes, $\{\zeta_v\}_{v=1}^{V}$, and the nth subcarrier delivers $b_n^i \in \{m_1, \cdots, m_{\max}\}$ bits for $n = 1, \cdots, N_c$. Here, we assume that the number of channel codes and the maximum constellation size for the AMC transmission are fixed to V and $2^{m_{\max}}$, respectively. Denoting the bit distribution vector $\mathbf{b}_i$ as $[b_1^i, \cdots, b_{N_c}^i]$, the spectral efficiency for the ith stream $R_T(\mathbf{b}_i; \zeta_v)$ can be written as

$$R_T(\mathbf{b}_i; \zeta_v) = R_c(\zeta_v) \frac{1}{N_c} \sum_{n=1}^{N_c} b_n^i \tag{1}$$

where $R_c(\zeta_v)$ denotes the code rate of the chosen channel encoder ζ_v. Both the channel encoder ζ_v and the number of bits for the nth subcarrier b_n^i are determined by the AMC strategy.

With a fast Fourier transform (FFT) and the cyclic prefix (CP) processing at the receiver, the channel output at the nth subcarrier can be written as

$$\begin{aligned}\mathbf{r}_n &= \begin{bmatrix} r_1^n \\ \vdots \\ r_{N_r}^n \end{bmatrix} = \mathbf{H}_n \mathbf{x}_n + \mathbf{z}_n \\ &= \begin{bmatrix} H_{11}^n & \cdots & H_{N_t 1}^n \\ \vdots & \ddots & \vdots \\ H_{1N_r}^n & \cdots & H_{N_t N_r}^n \end{bmatrix} \begin{bmatrix} x_1^n \\ \vdots \\ x_{N_t}^n \end{bmatrix} + \begin{bmatrix} z_1^n \\ \vdots \\ z_{N_r}^n \end{bmatrix}\end{aligned}$$

where H_{ij}^n represents the equivalent channel frequency response of the link between the ith transmit and the jth receive antenna at the nth subcarrier, z_j^n denotes independent and identically distributed (i.i.d) complex additive Gaussian noise with variance σ_z^2 per complex dimension and x_i^n stands for the transmitted symbol at the ith transmit antenna with energy σ_x^2. The total power of $\mathbf{x}_n$ is assumed to be $P = N_t \cdot \sigma_x^2$.

Assuming that the first and second order statistics of the channel impulse response are time invariant, the equivalent channel frequency response for the received signal can be expressed by $H_{i,j}^n = \sum_{l=1}^{L} \bar{h}_{i,j}(l) \exp(-j2\pi nl/N_c)$, where $\bar{h}_{i,j}(l)$ denotes the time domain channel impulse response at the lth tap of the link from the ith transmit antenna to the jth receive antenna, which is independent complex Gaussian with unit variance.

III. Adaptive transmission strategy on the MIMO BIC-OFDM

In this section, we consider a bit-loading algorithm for the adaptive transmission in the MIMO BIC-OFDM system. We first generalize the discrete LC algorithm in [7], which is suitable for coded modulations over fading channels. And then, we introduce an optimal bit loading scheme in the closed loop MIMO-OFDM and illustrate a simple algorithm which guarantees the enhanced throughput of the SVD scheme in practical MIMO BIC-OFDM systems.

A. Generalized bit-loading algorithm

In this subsection, we generalize the LC algorithm for single antenna systems which can be applied to coded bit streams.

The LC algorithm is one of the most popular discrete bit loading scheme. By updating a bit distribution with another distribution that is closer to more efficient in each step, finally an efficient bit distribution is produced. Here, efficiency means that there is no movement of a bit from one subchannel to another that reduces the symbol energy. The LC algorithm consists of two stages: "Efficientizing (EF)" and "E-tightening (ET)"[5]. The EF algorithm produces an efficient bit distribution by replacing a bit distribution with another distribution. In contrast, the ET algorithm makes the bit distribution to be tighten so that no additional bit can be carried without violation of the total energy constraint [5].

In the LC algorithm, the energy function $\mathcal{E}_n(b_n)$ for M-QAM with $\mathbf{h} = [h_1, \cdots, h_{N_c}]$ can be computed via the gap approximation [5] as

$$\mathcal{E}_n(b_n) = (2^{b_n} - 1)\frac{\sigma_n^2}{|h_n|^2}\Gamma \tag{2}$$

where h_n denotes the nth OFDM subchannel and Γ indicates the channel gap [5].

For an uncoded transmission, the gap can be assumed to be constant [5]. However, with channel coding, the gap actually varies according to the characteristics of the employed channel code. Also the number of bits loaded on the nth subcarrier does not account for information bits since a channel coding is applied to the stream. Therefore, the channel gap in (2) for the given channel code ζ_v should be replaced by the "coding offset" which is defined as

$$\boldsymbol{\gamma}_v(m) = \boldsymbol{\Psi}(m, R_c(\zeta_v)) - 10\log_{10}(2^m - 1) \text{ (dB)} \tag{3}$$

where $\boldsymbol{\Psi}(m, R_c(\zeta_v))$ represents the signal-to-noise ratio (SNR) required to achieve a desired BER and the second term in (3) denotes the SNR required to achieve the maximum date rate of m bps/Hz. The first term can be obtained from the Monte Carlo simulations. The coding offset compensates for the channel gap parameter in (2) by considering SNR difference to transmit m coded bits compared with uncoded case. Thus the energy function in (2) is rewritten as

$$\mathcal{E}_n(b_n; \zeta_v) = (2^{b_n} - 1)\frac{\sigma_n^2}{|h_n|^2} \cdot \boldsymbol{\gamma}_v(b_n). \tag{4}$$

In contrast to (4), $\boldsymbol{\gamma}_v(\cdot)$ is approximated as $\Gamma/d_{min,v}$ in [7] where $d_{min,v}$ denotes the free Hamming distance of the code ζ_v. Consequently, the resulting BER loosely satisfies the required constraint as it cannot reflect the characteristics of the selected code set such as the rate-compatible punctured convolutional (RCPC) code [11].

In Table I, we compute the coding offsets in (3) for various codes and constellations to achieve a BER of 10^{-4}. Although these values can be evaluated numerically by various approximation methods such as in [12], the most accurate results are obtained through simulations. Note that since the table contents are invariant during the bit-loading process, this table needs to be constructed only once at the beginning.

R_c	BPSK	4QAM	8PSK	16QAM	32QAM	64QAM
1	8.40	6.62	7.98	6.33	6.32	6.30
5/6	4.5	2.86	3.98	2.40	2.31	2.06
4/5	4.15	2.43	3.53	2.01	1.89	1.65
3/4	2.97	1.40	2.25	0.94	1.00	0.37
2/3	2.09	0.42	1.00	-0.29	-0.46	-1.09
1/2	0.37	-1.34	-1.35	-2.61	-2.61	-3.98

TABLE I

CODING OFFSETS $\boldsymbol{\gamma}_v(\cdot)$ (dB) REQUIRED TO ACHIEVE A BER OF 10^{-4}

Now, we generalize the LC algorithm by employing the coding offsets. For each code ζ_v, the generalized LC algorithm (GLC) finds the optimal coded bit distribution for one OFDM symbol when a stream is encoded by the code ζ_v. The GLC performs iterative searches to find the best discrete bit distribution. Initially, the bit distribution vector $\mathbf{b}$ is chosen arbitrarily. Then, the EF algorithm and the ET algorithm are performed successively to obtain the optimal bit distribution with the modified incremental energy which is defined as

$$e_n(b_n; \zeta_v) = \mathcal{E}_n(b_n; \zeta_v) - \mathcal{E}_n(b_n - 1; \zeta_v) \ . \tag{5}$$

Finally, the optimal bit distribution considering all available channel codes is obtained by a greedy search which provides the maximum spectral efficiency. Define $\mathbf{b}_i^v$ as the bit distribution obtained from the GLC with the channel code ζ_v for the ith stream. For all $\mathbf{b}_i^v$ ($v = 1, \cdots, V$), the channel code chosen for the transmission $\mathcal{C}$ and the bit distribution $\mathbf{b}$ are determined from

$$\mathcal{C} = \arg \max_{1 \le v \le V} R_T(\mathbf{b}_i^v; \zeta_v).$$

B. Adaptive transmission with SVD technique

In the preceding subsection, we present a generalized bit loading algorithm for single antenna cases. Now we will extend to the MIMO system.

Prior to performing rate adaptations, separating the MIMO channel into equivalent multiple parallel independent channels by the SVD allows us to eliminate the spatial interferences among multiple streams. Here, each of the decomposed channels is called as an eigenmode. With the SVD operation, the channel $\mathbf{H}_n$ can be rewritten as $\mathbf{H}_n = \mathbf{V}_n \boldsymbol{\Sigma}_n \mathbf{U}_n^*$, where $\mathbf{V}_n$ and $\mathbf{U}_n$ are unitary matrices, $(\cdot)^*$ represents Hermitian transpose of a matrix, and $\boldsymbol{\Sigma}_n$ denotes a real valued diagonal matrix diag$(\lambda_{n,1}, \cdots, \lambda_{n,r})$. Here we assume $\lambda_{n,1} \ge \lambda_{n,2} \ge \cdots \lambda_{n,r}$ and r is the rank of $\mathbf{H}_n$. Based on the SVD process, the MIMO channel can be diagonalized by pre-filtering with $\mathbf{U}_n$ and post-filtering with $\mathbf{V}_n^*$. The equivalent signal model at the input of the demapper can be expressed as

$$\begin{aligned} \mathbf{y}_n &= \mathbf{V}_n^*(\mathbf{H}_n \mathbf{U}_n \mathbf{x}_n + \mathbf{z}_n) \\ &= \boldsymbol{\Sigma}_n \mathbf{x}_n + \mathbf{V}_n^* \mathbf{z}_n \ . \end{aligned} \tag{6}$$

There are two methods in processing $\mathbf{x}_n$ in (6). First, power loading with respect to eigenmodes is one common approach [13], which makes the received SNR equal for all receive antennas by allocating more powers to antennas with weaker eigenmodes and vice versa. Furthermore, no power is allocated to an eigenmode, if its gain is less than a certain threshold, i.e., the weakest eigenmodes are dropped. Therefore the optimal power allocation can be obtained by the iterative water-filling procedure in the spatial domain. The second method is the bit-loading scheme which assigns more bits on antennas with larger eigenmodes. Since the power loading requires an iterative procedure and very higher computational complexity, in this paper, we focus on the bit-loading scheme instead of the power loading to maximize the throughput of the system.

Ideally, the spatio-temporal vector coding (STVC) proposed in [6] can achieve the optimal performance in terms of capacity. However, the STVC also requires high complexity to compute the SVD of a matrix of size $N_r N_c \times N_t N_c$. Instead, it was shown in [6] that the overall complexity can be reduced by isolating N_t independent parallel streams with N_c SVD operations of size $N_r \times N_t$, and the performance approaches the optimal case as N_c increases. Thus we employ a similar structure with the reduced complexity scheme in [6]. In this structure, N_c SVD operations for a $N_r \times N_t$ matrix should be carried out for the MIMO BIC-OFDM channels.

From the SVD operation of the channel matrix $\mathbf{H}_n$, we obtain the eigenmode $\lambda_{n,1}, \lambda_{n,2}, \cdots, \lambda_{n,r}$. Then the eigenmodes for all subchannels at the ith transmit antenna are defined as $\hat{\mathbf{H}}_i = [\lambda_{1,i}, \lambda_{2,i}, \cdots, \lambda_{N_c,i}]$. Then bit loadings are independently performed over each antenna based on $\hat{\mathbf{H}}_i$. Denoting $\mathcal{C}^i$ as the channel code adopted for the ith stream, the rate maximization of the parallel streams can be formulated as

$$\begin{aligned} \text{maximize :} \quad & \sum_{i=1}^{N_t} R_c(\mathcal{C}^i) \sum_{n=1}^{N_c} b_{n,i} \\ \text{subject to :} \quad & \sum_{i=1}^{N_t} \sum_{n=1}^{N_c} \mathcal{E}_{n,i} = N_t N_c \sigma_x^2, \\ & P_b \le P_e \end{aligned} \tag{7}$$

where P_b and P_e denote the average received BER and the specified BER constraint, respectively, and $\mathcal{E}_{n,i}$ represents the energy required to transmit $b_{n,i}$ bits through the equivalent channel with eigenmode $\lambda_{n,i}$. Since the bit-loading for each stream can be carried out in parallel in the frequency domain, we also assume that the channel code is fixed for each stream for simplicity.

When employing the GLC algorithm with a uniform power allocation, it is straightforward to obtain the bit-distribution vector $\mathbf{b}_i$ and the code index $\mathcal{C}_i$ for each antenna if the constellation size is not limited. However, as the maximum supportable constellation size is fixed in practice, the overall throughput is mainly limited especially at high SNR for the MIMO system. Since the singular values are placed in a descending order on the diagonal matrix $\mathbf{\Sigma}_n$ in the SVD operation, higher modulations will be assigned to the first eigenmode. As a result, there can be residual power at higher eigenmodes even though the maximum number of bits are assigned for all subcarriers. To avoid this, a water-filling procedure for power loading is normally performed in the spatial domain at each subcarrier to allocate transmission power differently for each antenna. However, this also requires an iterative search again to find the optimal power distribution [6]. Therefore, we propose a simple power distribution method without any explicit power loading which is suitable for the layered structure in Fig 1.

With the layered structure, the LC algorithm will be performed with the constraint of $N_c \mathcal{E}_x$ for each layer. For high SNR values, the required energy to transmit $m_{\max}$ bits can be less than $\mathcal{E}_x$. Consequently, there exist left-over powers as $\sum_{n=1}^{N_c} \mathcal{E}_{n,i}$ can still be less than $N_c \mathcal{E}_x$ even though the maximum number of bits are allocated for all subcarriers. This yields the residual power $N_c \mathcal{E}_x - \sum_{n=1}^{N_c} \mathcal{E}_{n,i}$. In contrast, the layers with lower eigenmodes are able to accept more bits if additional power is supplied. Thus we can improve the system throughput by diversing the residual power of the current stream to the next stream utilized by the LC algorithm. To this end, we introduce a parameter $\hat{\mathcal{E}}_i$ which represents the new power constraint for the ith layer. Initially, it is set to be the same as σ_x^2. Then it will be updated as

$$\hat{\mathcal{E}}_{i+1} = \left(\hat{\mathcal{E}}_i - \frac{1}{N_c} \sum_{n=1}^{N_c} \mathcal{E}_{n,i} \right)_+ + \sigma_x^2 \tag{8}$$

where $(x)_+$ indicates $\max(x, 0)$. By applying this power diversion in (8) to both the EF and the ET algorithm, we can improve the throughput by assigning more bits to the streams with lower singular values. The above bit loading algorithm is summarized as follows:

1) Obtain $\mathbf{\Sigma}_n = \mathbf{V}_n^* \mathbf{H}_n \mathbf{U}_n$ for $n = 1, \cdots, N_c$
2) Set $\hat{\mathcal{E}}_1$ as σ_x^2
3) FOR $1 \le i \le N_t$
   a) $\hat{\mathbf{H}} \leftarrow [\lambda_{1,i}, \cdots, \lambda_{N_c,i}]$
   b) Obtain $\mathbf{b}_i$ and $\mathcal{C}_i$ by performing the LC algorithm with the constraint $N_c \hat{\mathcal{E}}_i$
   c) $\hat{\mathcal{E}}_{i+1} = \left(\hat{\mathcal{E}}_i - \frac{1}{N_c} \sum_{n=1}^{N_c} \mathcal{E}_{n,i} \right)_+ + \sigma_x^2$

Note that the new power constraint in c) can be directly obtained from the ET algorithm without any additional computation. From now on, we refer to this bit loading algorithm for MIMO BIC-OFDM system as the residual power diversion (RPD) algorithm between the streams.

IV. Simulation Results

In this section, we present simulation results for the proposed schemes. We consider an OFDM system with $N_c = 64$ subcarriers and the cyclic prefix length is set to 16 samples. A 5 tap exponentially decaying channel profile is assumed for all users. The AMC table used for simulations is listed in Table II, where R_c denotes the code rate. We use 64 state RCPC codes in [11]. The simulation is performed with a target frame error rate (FER) of 1%; the corresponding BER constraint is around 10^{-4} as in [7]. In evaluating the throughput of each AMC scheme, we adopt the "goodput" [14] to measure the system throughput by counting information bits in decoded frames with correct cyclic redundancy check (CRC) in the automatic repeat request (ARQ) mechanism.

Fig. 2 exhibits the throughput of MIMO BIC-OFDM systems with $N_t = N_r = 4$. The bottom curve shows the performance of the SVD technique with the constant channel gap Γ and uniform power allocation. When we compare both the RPD and the GLC to the conventional SVD scheme, the performance improvement is about 4dB at the spectral efficiency of 18 bps/Hz. As the maximum constellation size is in the single user SDM SVD case, the eigenmodes with higher singular values still have residual power after the maximum bits are allocated for each subcarrier in high SNR. Thus

R_T	R_c	Modulation
0.75bps/Hz	3/4	BPSK
1bps/Hz	1/2	QPSK
1.5bps/Hz	3/4	QPSK
2bps/Hz	1/2	16-QAM
2.5bps/Hz	5/8	16-QAM
3bps/Hz	3/4	16-QAM
3.5bps/Hz	7/12	64-QAM
4bps/Hz	2/3	64-QAM
4.5bps/Hz	3/4	64-QAM
5bps/Hz	5/6	64-QAM

TABLE II

AMC TABLE FOR SIMULATIONS

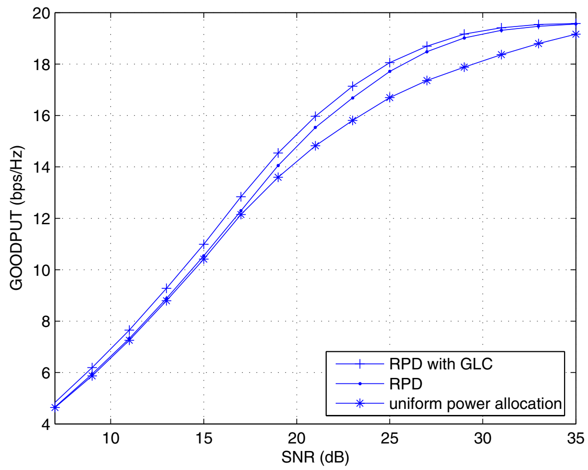

Fig. 2. Average goodput of the SVD techniques in MIMO BIC-OFDM

the performance enhancement of the SVD scheme with RPD becomes greater as the SNR increases.

In Fig. 3, we compare the proposed SVD scheme with the MMSE receiver system [10]. There is about 5dB SNR gap between the MMSE receiver and the enhanced SVD scheme in the single user case. For comparing in practical environments, we also show the throughput of the MMSE receiver in the multiuser situation. by applying the greedy scheduling when the number of users (K) grows to 40, the performance gap between the single user SVD and the multiuser MMSE system reduces to 1dB at the spectral efficiency of 16 bps/Hz.

V. CONCLUSION

In this paper, we have proposed a bit-loading scheme for the MIMO BIC-OFDM system by considering the residual power problem. When performing the bit-loading algorithm, we utilize an adequate channel gap, according to the chosen code rate. The proposed scheme does not require an iterative power loading procedure on the spatial domain. Instead, bit-loading and power allocation for each antenna are performed concurrently using the proposed RPD algorithm. As shown in the simulation section, the performance enhancement is significant at high SNR. Also, the proposed scheme is compared with a linear receiver structure in the multiuser environment.

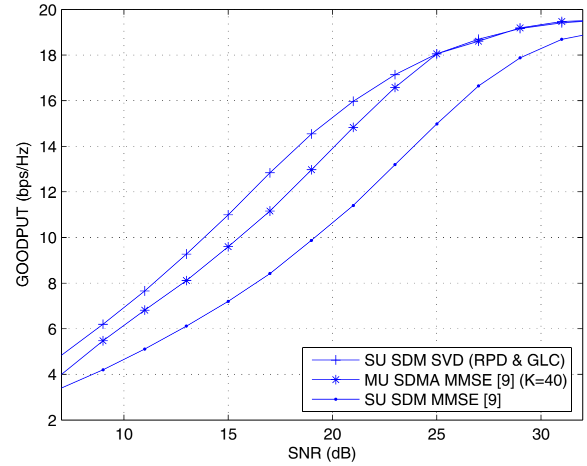

Fig. 3. Performance comparison between the MMSE receiver and the proposed SVD

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