Per-Tone Equalization for Single Carrier Block Transmission with Cyclic Prefix

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***Abstract*—This paper proposes per-tone equalization methods for single carrier block transmission with cyclic prefix (SC-CP). Minimum mean-square-error (MMSE) based optimum weights of the per-tone equalizers are derived for SISO (single-input single-output), SIMO (single-input multiple-output), and MIMO (multiple-input multiple-output) SC-CP systems. The proposed equalizers have multiple taps for each tone, therefore, they can achieve good performance even when the length of the guard interval (GI) is shorter than channel order. Moreover, by employing sliding discrete Fourier transform (DFT), the proposed equalizers can be efficiently implemented. Computer simulation results show that the proposed equalizers can significantly improve the bit error rate (BER) performance of the SISO, SIMO, and MIMO SC-CP systems with the insufficient GI.

I. Introduction

A block transmission with cyclic prefix (CP), including orthogonal frequency division multiplexing (OFDM)[1],[2] and single carrier block transmission with cyclic prefix (SC-CP)[3],[4], has been drawing much attention as a promising candidate for the 4G (4th generation) mobile communications systems. If all the delayed signals exist within the GI, the insertion of the CP as a guard interval (GI) at the transmitter and the removal of the CP at the receiver eliminates inter-block interference (IBI). Moreover, the insertion and the removal of the CP converts the effect of the channel from a linear convolution into a circular convolution, therefore, the inter-symbol interference (ISI) of the received signal can be effectively equalized by a discrete frequency domain equalizer (FDE) using fast Fourier transform (FFT).

On the other hand, the existence of delayed signals beyond the GI causes residual ISI and IBI after the FDE, and hence deteriorates the performance of the block transmission with the CP. In order to overcome the performance degradation of the OFDM or discrete multitone (DMT)[5] systems due to the insufficient GI, a considerable number of studies have been made on the issue, such as introduction of a temporal equalizer[6]-[8], and per-tone equalization[9],[10]. Although the temporal equalizer can mitigate the IBI and the ISI due to the delayed signals, the per-tone equalizer outperforms the temporal equalizer. This is because per-tone equalizer can use optimum weights at each tone, while a common set of weights have to be used for all the tone in the temporal equalization approach. Furthermore, the per-tone equalizer can be efficiently implemented by using sliding discrete Fourier transform (DFT)[11].

In this paper, we propose per-tone equalization methods for single carrier block transmission with SC-CP systems employing the sliding DFT and minimum mean-square-error (MMSE) based optimum weights of the per-tone equalizers are derived for SISO (single-input single-output), SIMO (single-input multiple-output), and MIMO (multiple-input multiple-output) SC-CP systems. The proposed methods can be regarded as extensions of [9] and [10] into the SC-CP systems, however, we present more simplified and intuitive descriptions of the per-tone equalizers. Also, computer simulations are conducted in order to evaluate the performance of the proposed systems with the insufficient GI. From the simulation results, it can be concluded that the proposed schemes can significantly improve the bit error rate (BER) performance of the SISO, SIMO, and MIMO SC-CP systems with insufficient GI.

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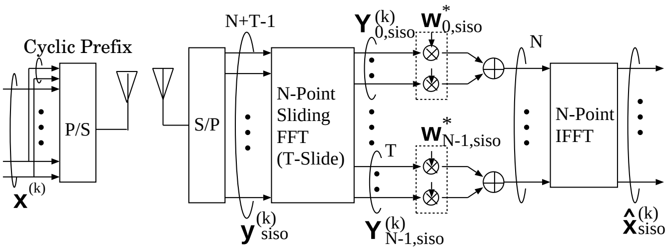

Fig. 1. Configuration of Proposed SISO SC-CP System

II. Proposed Per-Tone Equalization Scheme

In this paper, the following notations are used for describing the proposed systems. K is the length of the GI, N the FFT size, T the number of equalizer taps at each tone, and L is the channel order. An $N \times N$ identity matrix will be denoted as $\mathbf{I}_N$, a zero matrix of size $K \times N$ will be denoted as $\mathbf{0}_{K\times N}$, and a discrete Fourier transform (DFT) matrix of size $N \times N$ as $\mathbf{F}$. We will use $E[\cdot]$ to denote ensemble average, $(\cdot)^T$ for transpose, $(\cdot)^H$ for Hermitian transpose, $tr(\cdot)$ for trace, and $(\cdot)^*$ for complex conjugate.

A. SISO (Single-Input Single-Output) SC-CP System

Fig.1 shows a configuration of the SISO SC-CP system with the proposed per-tone equalizer. If we assume $K + 1 \leq L$, the received signal block, which corresponds to the kth transmitted information signal block $\mathbf{x}^{(k)}$, includes not only $\mathbf{x}^{(k)}$ but also $\mathbf{x}^{(k-1)}$ or $\mathbf{x}^{(k+1)}$, due to the IBI caused by the insufficient GI. Denoting CP insertion matrix as

$$\mathbf{T}_{cp} = \begin{bmatrix} \mathbf{0}_{K\times(N-K)} & \mathbf{I}_K \\ \multicolumn{2}{c}{\mathbf{I}_N} \end{bmatrix}, \quad (1)$$

and a transmitted signal vector including three consecutive information blocks as

$$\mathbf{x} = [\mathbf{x}^{(k-1)T}\ \mathbf{x}^{(k)T}\ \mathbf{x}^{(k+1)T}]^T, \quad (2)$$

the received signal vector $\mathbf{y}_{siso}^{(k)}$ of size $(N+T-1)\times 1$ can be written as

$$\mathbf{y}_{siso}^{(k)} = \mathbf{H}_{siso}\mathbf{x} + \mathbf{n}_{siso}, \tag{3}$$

where $\mathbf{n}_{siso}$ is the white noise vector of variance σ_n^2 and

$$\mathbf{H}_{siso} = \begin{bmatrix} & h_0 & \dots & h_L & & \mathbf{0} & \\ \mathbf{0}_{(1)} & & \ddots & & \ddots & & \mathbf{0}_{(2)} \\ & \mathbf{0} & & h_0 & \dots & h_L & \end{bmatrix}\mathbf{T},$$

$$\mathbf{T} = \begin{bmatrix} \mathbf{T}_{cp} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{T}_{cp} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{T}_{cp} \end{bmatrix}. \tag{4}$$

Here, $\{h_0, \dots, h_L\}$ denotes a channel impulse response, and $\mathbf{0}_{(1)}$ and $\mathbf{0}_{(2)}$ denotes zero matrices, which have $N+T-1$ rows. The number of columns of $\mathbf{0}_{(1)}$ and $\mathbf{0}_{(2)}$ determines the zero reference delay and are adjusted so that the energy of $\mathbf{x}^{(k)}$ in $\mathbf{y}_{siso}^{(k)}$ is maximized.

After the N-point sliding FFT, we have T signals per each tone. Using the signals, a $T\times 1$ vector $\mathbf{Y}_{i,siso}^{(k)}$, which is composed by a sliding FFT output corresponding to the ith tone, can be written as

$$\mathbf{Y}_{i,siso}^{(k)} = \mathbf{F}_i\mathbf{y}_{siso}^{(k)}, \quad \mathbf{F}_i = \begin{bmatrix} \mathbf{f}_i & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{f}_i \end{bmatrix}, \tag{5}$$

where $\mathbf{f}_i$ is the ith row of $\mathbf{F}$. Note that the size of $\mathbf{F}_i$ is $T\times(N+T-1)$ and $\mathbf{F}_i$ denotes the sliding FFT operation on the ith tone.

The per-tone equalizer output signal $\hat{\mathbf{x}}_{siso}^{(k)}$ is given by

$$\hat{\mathbf{x}}_{siso}^{(k)} = \mathbf{F}^H \begin{bmatrix} \mathbf{w}_{0,siso}^H\mathbf{Y}_{0,siso}^{(k)} \\ \vdots \\ \mathbf{w}_{N-1,siso}^H\mathbf{Y}_{N-1,siso}^{(k)} \end{bmatrix}, \tag{6}$$

where the $T\times 1$ vector $\mathbf{w}_{i,siso}$ is a equalizer weight of the ith tone. Here, if we define a $N\times(N+T-1)$ matrix $\mathbf{V}_{siso}^H$, whose ith row is defined as $\mathbf{v}_{i,siso}^H = \mathbf{w}_{i,siso}^H\mathbf{F}_i$, we can rewrite the equalizer output as

$$\hat{\mathbf{x}}_{siso}^{(k)} = \mathbf{F}^H\mathbf{V}_{siso}^H(\mathbf{H}_{siso}\mathbf{x} + \mathbf{n}_{siso}). \tag{7}$$

The optimum weight $\mathbf{w}_{i,siso}^{opt}$ in the MMSE sense is obtained by solving the following minimization problem.

$$\mathbf{w}_{i,siso}^{opt} = \arg\min_{\mathbf{w}_{i,siso}} J, \tag{8}$$

$$J = E\left[tr\{(\hat{\mathbf{x}}_{siso}^{(k)} - \mathbf{x}^{(k)})(\hat{\mathbf{x}}_{siso}^{(k)} - \mathbf{x}^{(k)})^H\}\right]. \tag{9}$$

Assuming the transmitted signals and the channel noise are independent of each other, the cost function J can be calculated as

$$\begin{aligned} J =& tr\{\mathbf{H}_{siso}\mathbf{H}_{siso}^H\mathbf{V}_{siso}\mathbf{V}_{siso}^H + \sigma_n^2\mathbf{V}_{siso}\mathbf{V}_{siso}^H \\ &- \bar{\mathbf{H}}_{siso}\mathbf{F}^H\mathbf{V}_{siso}^H - \mathbf{F}\bar{\mathbf{H}}_{siso}^H\mathbf{V}_{siso}\} \\ =& \sum_{i=0}^{N-1}(tr\{\mathbf{w}_{i,siso}^H\mathbf{F}_i\mathbf{H}_{siso}\mathbf{H}_{siso}^H\mathbf{F}_i^H\mathbf{w}_{i,siso} \\ &+ \sigma_n^2\mathbf{w}_{i,siso}^H\mathbf{F}_i\mathbf{F}_i^H\mathbf{w}_{i,siso} \\ &- \mathbf{w}_{i,siso}^H\mathbf{F}_i\bar{\mathbf{H}}_{siso}\mathbf{f}_i^H - \mathbf{w}_{i,siso}\mathbf{F}_i^H\bar{\mathbf{H}}_{siso}^H\mathbf{f}_i\}), \end{aligned} \tag{10}$$

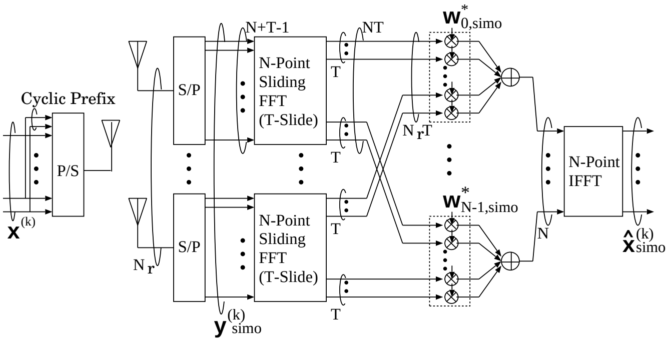

Fig. 2. Configuration of Proposed SIMO SC-CP System

where $\bar{\mathbf{H}}_{siso} = \mathbf{H}_{siso}[\mathbf{0}_{N\times N}\ \ \mathbf{I}_N\ \ \mathbf{0}_{N\times N}]^T$.

The differentiation of J with respect to the equalizer weight of the ith tone $\mathbf{w}_{i,siso}^H$ is given by

$$\begin{aligned} \frac{\partial J}{\partial \mathbf{w}_{i,siso}^H} =& \mathbf{F}_i\mathbf{H}_{siso}\mathbf{H}_{siso}^H\mathbf{F}_i^H\mathbf{w}_{i,siso} \\ &+ \sigma_n^2\mathbf{F}_i\mathbf{F}_i^H\mathbf{w}_{i,siso} - \mathbf{F}_i\bar{\mathbf{H}}_{siso}\mathbf{f}_i^H, \end{aligned} \tag{11}$$

therefore, the optimum equalizer weight of the ith tone is obtained as

$$\mathbf{w}_{i,siso}^{opt} = \left[\mathbf{F}_i\mathbf{H}_{siso}\mathbf{H}_{siso}^H\mathbf{F}_i^H + \sigma_n^2\mathbf{F}_i\mathbf{F}_i^H\right]^{-1}\mathbf{F}_i\bar{\mathbf{H}}_{siso}\mathbf{f}_i^H. \tag{12}$$

B. SIMO (Single-Input Multiple-Output) SC-CP System

Fig.2 shows a configuration of the SIMO SC-CP system with the proposed per-tone equalizer. In the SIMO system, the transmitter structure, and hence the transmitted signal, is the same as that of the SISO SC-CP system.

Denoting the received signal at the jth reception antenna $\mathbf{y}_{j,simo}^{(k)}$, and defining $\mathbf{y}_{simo}^{(k)} = [\mathbf{y}_{0,simo}^{(k)T}, \cdots, \mathbf{y}_{N_r-1,simo}^{(k)T}]^T$, the received signal vector for the SIMO system $\mathbf{y}_{simo}^{(k)}$ can be written as

$$\mathbf{y}_{simo}^{(k)} = \mathbf{H}_{simo}\mathbf{x} + \mathbf{n}_{simo}, \tag{13}$$

where $\mathbf{n}_{simo}$ is the channel noise vector of size $(N+T-1)N_r\times 1$ and

$$\mathbf{H}_{simo} = \begin{bmatrix} & h_0^0 & \dots & h_L^0 & & \mathbf{0} & \\ & & \ddots & & \ddots & & \\ & \mathbf{0} & & h_0^0 & \dots & h_L^0 & \\ \mathbf{0}_{(3)} & & \vdots & & \vdots & & \mathbf{0}_{(4)} \\ & h_0^{N_r-1} & \dots & h_L^{N_r-1} & & \mathbf{0} & \\ & & \ddots & & \ddots & & \\ & \mathbf{0} & & h_0^{N_r-1} & \dots & h_L^{N_r-1} & \end{bmatrix}\mathbf{T}. \tag{14}$$

$\{h_0^j, \dots, h_L^j\}$ denotes a channel impulse response between the transmission antenna and the jth reception antenna. $\mathbf{0}_{(3)}$ and $\mathbf{0}_{(4)}$ denotes zero matrices, which have $(N+T-1)N_r$ rows, and the number of columns of the matrices are determined in the same manner as the SISO system.

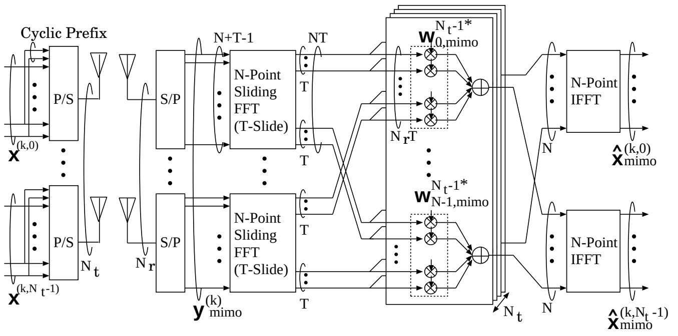

Fig. 3. Configuration of Proposed MIMO SC-CP System

The per-tone equalizer output signal $\hat{\mathbf{x}}^{(k)}_{simo}$ is given by

$$\hat{\mathbf{x}}^{(k)}_{simo} = \mathbf{F}^H \mathbf{V}^H_{simo}(\mathbf{H}_{simo}\mathbf{x} + \mathbf{n}_{simo}), \tag{15}$$

where $\mathbf{V}^H_{simo}$ is a $N \times (N+T-1)N_r$ matrix, whose ith row is defined as

$$\mathbf{v}^H_{i,simo} = \mathbf{w}^H_{i,simo}\bar{\mathbf{F}}_i, \ \ \bar{\mathbf{F}}_i = \begin{bmatrix} \mathbf{F}_i & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{F}_i \end{bmatrix}. \tag{16}$$

$\mathbf{w}_{i,simo}$ $(N_rT \times 1)$ is a equalizer weight vector for the ith tone. By solving a minimization problem,

$$\mathbf{w}^{opt}_{i,simo} = \arg\min_{\mathbf{w}_{i,simo}} E\left[tr\{(\hat{\mathbf{x}}^{(k)}_{simo} - \mathbf{x}^{(k)})(\hat{\mathbf{x}}^{(k)}_{simo} - \mathbf{x}^{(k)})^H\}\right], \tag{17}$$

the optimum weight of the ith tone $\mathbf{w}^{opt}_{i,simo}$ in the MMSE sense is obtained as

$$\mathbf{w}^{opt}_{i,simo} = \left[\bar{\mathbf{F}}_i\mathbf{H}_{simo}\mathbf{H}^H_{simo}\bar{\mathbf{F}}^H_i + \sigma^2_n\bar{\mathbf{F}}_i\bar{\mathbf{F}}^H_i\right]^{-1}\bar{\mathbf{F}}_i\bar{\mathbf{H}}_{simo}\mathbf{f}^H_i, \tag{18}$$

where $\bar{\mathbf{H}}_{simo} = \mathbf{H}_{simo}[\mathbf{0}_{N\times N} \ \ \mathbf{I}_N \ \ \mathbf{0}_{N\times N}]^T$.

C. MIMO (Multiple-Input Multiple-Output) SC-CP System

Fig.3 shows a configuration of the MIMO SC-CP system with the proposed per-tone equalizer. In the MIMO system, N_t and N_r antennas are equipped at the transmitter and the receiver respectively. N_t different signal blocks $\mathbf{x}^{(k,0)}, \ldots, \mathbf{x}^{(k,N_t-1)}$ are simultaneously sent from the transmission antennas, therefore, the MIMO receiver has to not only equalize the received signal distorted by the multipath channel but also cancel the co-channel interference, while the transmission rate of the MIMO system is N_t times the rate of the SISO or the SIMO system.

Denoting the received signal at the jth reception antenna $\mathbf{y}^{(k)}_{j,mimo}$, and defining $\mathbf{y}^{(k)}_{mimo} = [\mathbf{y}^{(k)T}_{0,mimo}, \cdots, \mathbf{y}^{(k)T}_{N_r-1,mimo}]^T$, the received signal vector of the MIMO system $\mathbf{y}^{(k)}_{mimo}$ can be written as

$$\mathbf{y}^{(k)}_{mimo} = \sum_{l=0}^{N_t-1}\mathbf{H}^l_{mimo}\mathbf{x}^l + \mathbf{n}_{mimo}, \tag{19}$$

where $\mathbf{H}^l_{mimo}$ is a channel matrix between the lth transmission antenna and the receiver defined as

$$\mathbf{H}^l_{mimo} = \left[\mathbf{0}_{(5)} \begin{matrix} h_0^{0,l} & \cdots & h_L^{0,l} & & \mathbf{0} \\ & \ddots & & \ddots & \\ \mathbf{0} & & h_0^{0,l} & \cdots & h_L^{0,l} \\ & \vdots & & \vdots & \\ h_0^{N_r-1,l} & \cdots & h_L^{N_r-1,l} & & \mathbf{0} \\ & \ddots & & \ddots & \\ \mathbf{0} & & h_0^{N_r-1,l} & \cdots & h_L^{N_r-1,l} \end{matrix} \mathbf{0}_{(6)}\right]\mathbf{T}. \tag{20}$$

$\{h_0^{j,l}, \ldots, h_L^{j,l}\}$ denotes a channel impulse response between the lth transmission antenna and the jth reception antenna. $\mathbf{0}_{(5)}$ and $\mathbf{0}_{(6)}$ denotes zero matrices, which have $(N+T-1)N_r$ rows, and the number of columns of the matrices are determined in the same manner as the SISO system. Also, $\mathbf{n}_{mimo}$ is the channel noise vector of size $(N+T-1)N_r \times 1$, and $\mathbf{x}^l$ is the transmitted signal block sent from the lth transmission antenna defined as

$$\mathbf{x}^l = [\mathbf{x}^{(k-1,l)T}, \mathbf{x}^{(k,l)T}, \mathbf{x}^{(k+1,l)T}]^T. \tag{21}$$

The output of the per-tone equalizer for the transmitted signal from the l the transmission antenna $\hat{\mathbf{x}}^{(k,l)}_{mimo}$ is given by

$$\hat{\mathbf{x}}^{(k,l)}_{mimo} = \mathbf{F}^H\mathbf{V}^{lH}_{mimo}(\sum_{l=0}^{N_t-1}\mathbf{H}^l_{mimo}\mathbf{x}^l + \mathbf{n}_{mimo}), \tag{22}$$

where $\mathbf{V}^{lH}_{mimo}$ is a $N \times (N+T-1)N_r$ matrix, whose ith row is defined as

$$\mathbf{v}^{lH}_{i,mimo} = \mathbf{w}^{lH}_{i,mimo}\bar{\mathbf{F}}_i, \tag{23}$$

and $\mathbf{w}^l_{i,mimo}$ $(N_rT \times 1)$ is a equalizer weight of the ith tone for the transmitted signal from the l the transmission antenna.

By solving the minimization problem,

$$\mathbf{w}^{l,opt}_{i,mimo} = \arg\min_{\mathbf{w}^l_{i,mimo}} E[tr\{(\hat{\mathbf{x}}^{(k,l)}_{mimo} - \mathbf{x}^{(k,l)}) \cdot(\hat{\mathbf{x}}^{(k,l)}_{mimo} - \mathbf{x}^{(k,l)})^H\}], \tag{24}$$

the optimum weight of the ith tone for the transmitted signal from the l the transmission antenna $\mathbf{w}^{l,opt}_{i,mimo}$ in the MMSE sense is obtained as

$$\mathbf{w}^{l,opt}_{i,mimo} = \left[\bar{\mathbf{F}}_i(\sum_{l=0}^{N_t-1}\mathbf{H}^l_{mimo}\mathbf{H}^{lH}_{mimo})\bar{\mathbf{F}}^H_i + \sigma^2_n\bar{\mathbf{F}}_i\bar{\mathbf{F}}^H_i\right]^{-1} \cdot \bar{\mathbf{F}}_i\bar{\mathbf{H}}^l_{mimo}\mathbf{f}^H_i, \tag{25}$$

where $\bar{\mathbf{H}}^l_{mimo} = \mathbf{H}^l_{mimo}[\mathbf{0}_{N\times N} \ \ \mathbf{I}_N \ \ \mathbf{0}_{N\times N}]^T$.

III. COMPUTER SIMULATION

In order to evaluate the BER performance of the proposed systems, computer simulations are conducted with the following system parameters; modulation/demodulation scheme: QPSK, symbols per block: $M = 64$, GI: $K = 16$, channel order: $L = 20$, channel model: 9-path frequency selective Rayleigh fading channel. Also, perfect channel estimation is assumed in all the simulations.

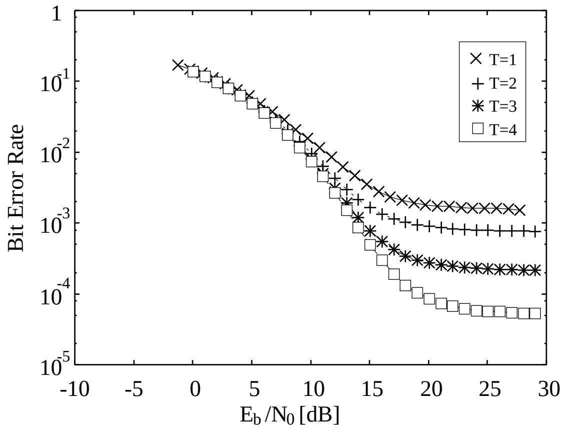

Fig. 4. BER Performance: SISO SC-CP System

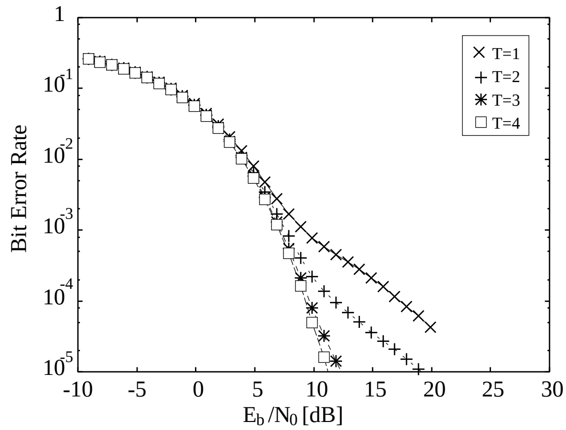

Fig. 5. BER Performance: SIMO SC-CP System

Fig.4 shows the BER performance versus the ratio of the energy per bit to the noise power density (E_b/N_0) of the SISO SC-CP system with the proposed per-tone equalizer for the difference number of taps ($T = 1 - 4$). Note that $T = 1$ corresponds to a conventional 1-tap MMSE DFT domain equalizer. From the figure, we can see that the proposed scheme with $T \geq 2$ can significantly improve the BER performance.

Fig.5 shows the BER performance versus the E_b/N_0 per reception antenna element of the SIMO SC-CP system with the proposed per-tone equalizer for the difference number of taps ($T = 1 - 4$). The number of the reception antenna is set to be $N_r = 2$. In the Figure, $T = 1$ corresponds to a conventional SC-CP system with a post-FFT type adaptive antenna array. Although the conventional adaptive antenna array improves the BER performance compared as the BER performance of $T = 1$ in Fig. 4, the proposed per-tone equalizer with $T \geq 2$ can further improve the performance.

Fig.6 shows the BER performance versus the E_b/N_0 per reception antenna element of the MIMO SC-CP system with the proposed per-tone equalizer for the difference number of taps ($T = 1 - 4$). The number of the transmission and the reception antenna are set to be $N_t = 2$ and $N_r = 2$, therefore, the transmission rate of the MIMO system is twice as that of the SISO or SIMO systems When $T = 1$, the proposed system is the same as the MIMO system proposed in [12]. We can see that the proposed scheme with $T \geq 2$ outperforms the conventional MIMO SC-CP system.

From all the results, it can be concluded that the proposed scheme can significantly improve the BER performance of the SISO, SIMO, and MIMO SC-CP systems with insufficient GI.

IV. Conclusion

We have proposed per-tone equalization methods for the SC-CP systems with the insufficient GI. MMSE based optimum weights of the per-tone equalizers are derived for the SISO, SIMO, and MIMO SC-CP systems. Moreover, computer simulations are conducted in order to evaluate the BER performance of the proposed systems with the insufficient GI. From all the results, it can be concluded that the proposed scheme can significantly improve the BER performance of the SISO, SIMO, and MIMO SC-CP systems with the insufficient GI.

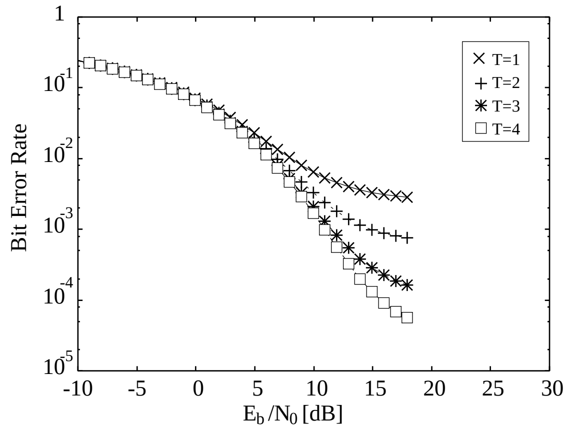

Fig. 6. BER Performance: MIMO SC-CP System

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