LMS Adaptive Beamforming based on Pre-FFT Combining for Ultra High-Data-Rate OFDM System

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***Abstract*-In this paper, we propose four adaptive beamforming schemes for the ultra high-data-rate orthogonal frequency division multiplexing (OFDM) system which is capable of supporting beyond 100 Mbps data rate. These schemes are based on the least mean square (LMS) algorithm and pre-FFT combining. Their differences result from two factors: One is the pilot arrangement in each OFDM block and the other is either the frequency-domain or time-domain pilot vector is used in the beamforming. These schemes are compared under the condition that the pilot-to-data ratio is the same. The performance investigation shows that the different schemes present different performance in the convergence behavior and estimation accuracy. Provided that enough time is allowed to guarantee the accomplishment of the antenna weights convergence, all proposed adaptive beamforming schemes can decrease the mean square error (MSE) to very low values. Therefore, their BER performances are very similar.**

***Index Terms*-Orthogonal frequency division multiplexing (OFDM), least square mean (LMS), and adaptive beamforming**

I. INTRODUCTION

Due to the good immunity to inter-symbol interference (ISI) and many other advantages, the orthogonal frequency division multiplexing (OFDM) has been regarded as one of most promising techniques to support high-data-rate transmission for the next-generation wireless communications.

The researchers at the National Institute of Information and Communications Technology (NICT, former CRL) of Japan target at an ultra high-data-rate wireless access system based on OFDM which can offer beyond 100Mbps data-rate transmission capabilities. The network architecture is shown by [1], the MAC protocol based on the packet reservation dynamic slot multiple access (PR-DSMA) is introduced in [2], and recently the frame and slot arrangement scheme and PHY layer have been finalized [3].

At the current stage, some new features are planned to be added to the 100Mbps ultra high-data-rate wireless access system. As we know, adaptive antenna array is a very effective technique to improve the performance of wireless systems without requiring additional spectrum or transmit power. Intensive research has been dedicated to applying the adaptive antenna array to CDMA and TDMA systems [4][5][6]. Recently it is investigated to improve the performance of OFDM [7][8][9].

Various adaptive beamforming algorithms [10] have been proposed to control the antenna array weights, among which the least mean square (LMS) algorithm has been intensively investigated [10][11]. In this paper, we investigate the four different adaptive beamforming schemes based on LMS algorithm for the 100Mbps ultra high-data-rate OFDM system.

Due to the consideration of simplicity, all of the beamforming schemes are based on pre-FFT combining, which implies that for every antenna element only one weight is generated and all the frequency-domain components are treated in the same way in the signal combining. Though the pre-FFT combining results in some performance loss compared with the post-FFT combining in which the signal combining is performed at the individual subcarriers, the low-complexity feature makes the pre-FFT combining very attractive in the engineering implementations.

The remainder of this paper is organized as follows. Section II describes the system model. Section III introduces the four adaptive beamforming schemes based LMS algorithm and pre-FFT combining. Section IV shows the simulation results. Finally in Section V, conclusions are given.

II. SYSTEM MODEL

In this section we present the system model. Fig.1 shows the frame construction of the proposed OFDM system which is capable of supporting beyond 100 Mbps data rate [3]. In the downlink, the frame control message slot (FCMS) is used for the control signaling and the message data slot (MDS) is used primarily for the user data; in the uplink, the activation slot (ACTS) is used for the control signaling and MDS is used primarily for the user data.

Each MDS is actually a frequency-time block which is made up of 64 subcarriers and 24 OFDM blocks. The OFDM parameters are shown in TABLE I.

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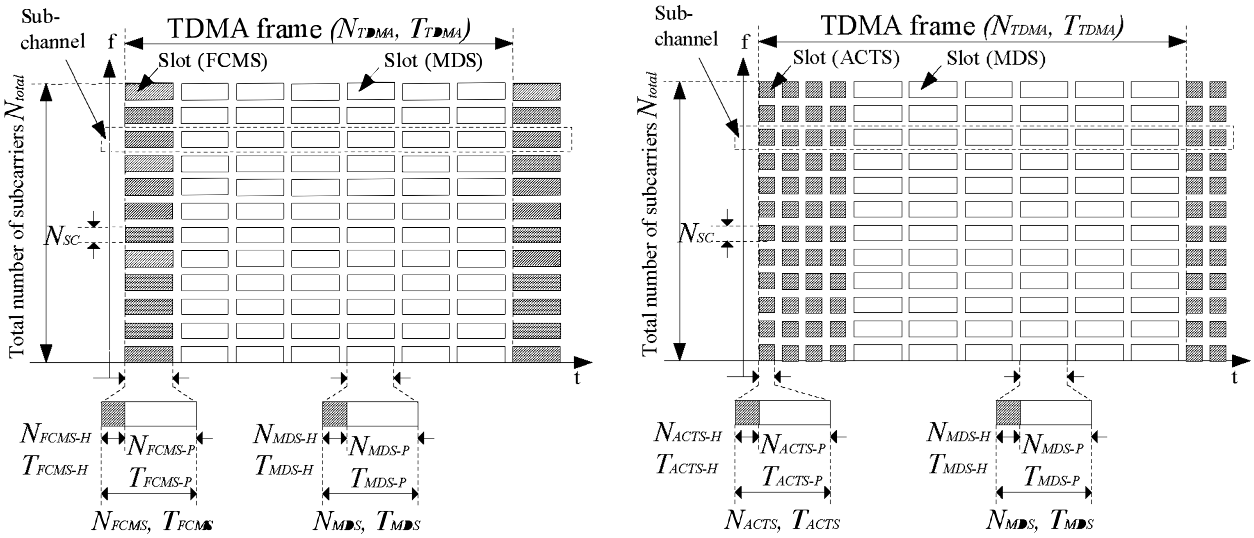

Fig.1. Frame construction of OFDM scheme supporting beyond 100 Mbps data rate (Left: downlink, right: uplink).

TABLE I OFDM PARAMETERS

Length of OFDM symbol (us)	8
Length of guard interval (us)	2
FFT length (point)	1024
Guard interval (point)	256
Total number of subcarriers (N_{total})	768
Number of subcarriers in a subchannel (N_{SC})	64
Number of subchannels	12

III. LMS Beamforming Based on Pre-FFT Combining

We consider LMS algorithm and pre-FFT combining for adaptive beamforming schemes.

A. Pilot Arrangement in OFDM Block

From the frequency-domain point of view, for each OFDM block which carries pilot, the pilot arrangement can be classified into two modes: “AS” and “PS”, as Fig.2 shows. “AS” means “All subcarriers are allocated for pilot or ZERO”, and “PS” means “Partial subcarriers are allocated for pilot or ZERO”. At the ZERO subcarrier, neither pilot or data is allocated. In the “AS” mode, no data is assigned at the subcarriers in the OFDM block; In the “PS” mode, the data and pilot occupy different subcarriers in the OFDM block.

B. Adaptive Beamforming Schemes

For either “AS” or “PS” mode, there are two ways to use the pilot in the beamforming: One way is based on the frequency-domain pilot vector; the other way is based on the time-domain pilot vector. Therefore, we propose four adaptive beamforming schemes.

Fig.3 and Fig.4 show the block diagrams of the adaptive beamforming schemes based on LMS algorithm and pre-FFT combining for “AS” and “PS” mode. The meaning of abbreviations is shown in TABLE II.

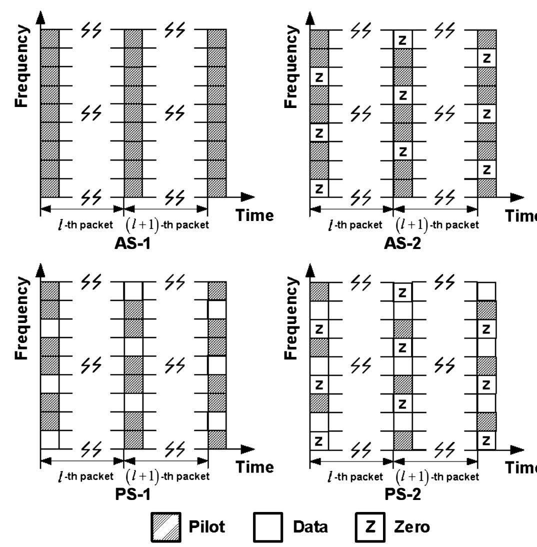

Fig.2. Pilot arrangement in the OFDM block.

TABLE II ABBREVIATIONS

TR-PS	Transmitter, PS mode
TR-AS	Transmitter, AS mode
RE-AS-FP	Receiver, AS mode, frequency-domain pilot vector
RE-AS-TP	Receiver, AS mode, time-domain pilot vector
RE-PS-FP	Receiver, PS mode, frequency-domain pilot vector
RE-PS-TP	Receiver, PS mode, time-domain pilot vector

C. Adaptive Beamforming based on Frequency-Domain Pilot

Among the four beamforming schemes, both ***RE-AS-FP*** and ***RE-PS-FP*** separate the data and pilot in the frequency-domain and use the frequency-domain pilot vector $\vec{\mathbf{x}}_n(l)$ ($n=1,\ldots,N$) and error vector $\vec{\mathbf{e}}(l)$ in the LMS beamforming.

By using the reference pilot, the update of the antenna weights at the $(l+1)$-th OFDM block is expressed as

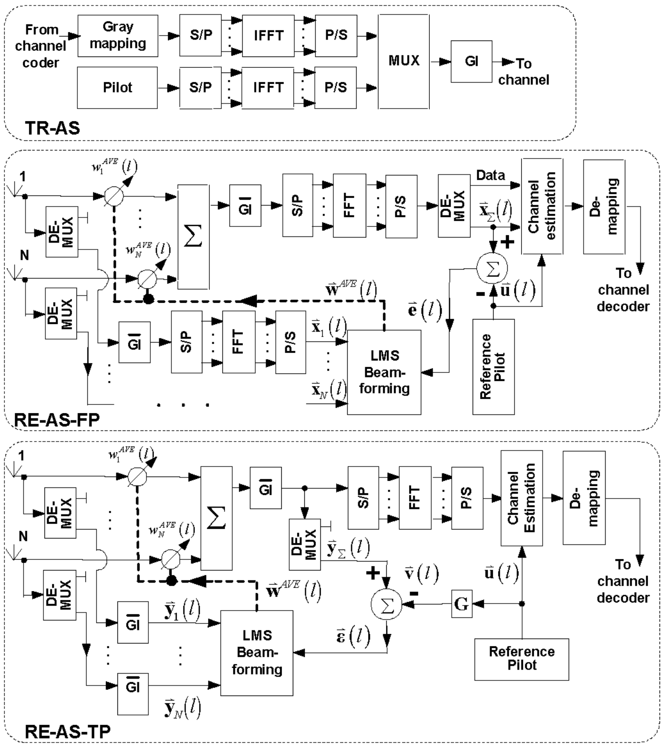

Fig.3. Adaptive beamforming schemes based on LMS algorithm and pre-FFT combining for "AS" mode.

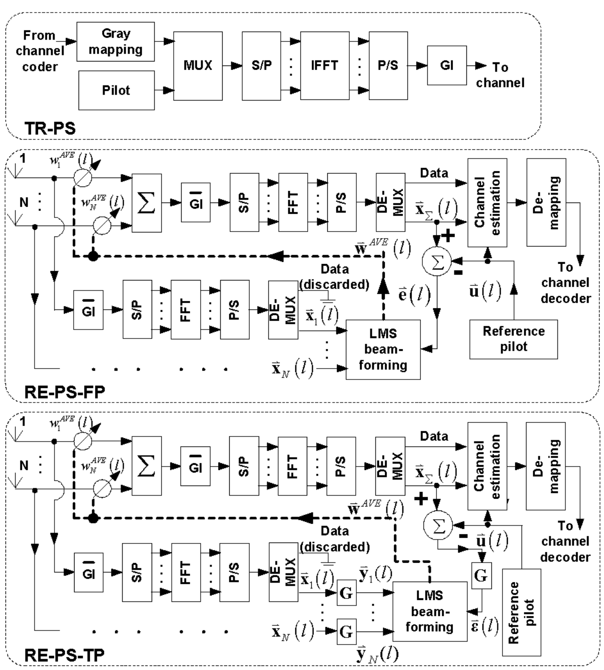

Fig.4. Adaptive beamforming schemes based on LMS algorithm and pre-FFT combining for "PS" mode.

$$\mathbf{W}(l+1)=\mathbf{W}(l)-\mu\mathbf{B}_{\mathrm{NT}}(l), \tag{1}$$

where, μ is a positive scalar (gradient step size) that controls the convergence behavior, $\mathbf{B}_{\mathrm{NT}}(l)$ is the unbiased estimate of the gradient matrix of the MSE with respect to $\mathbf{W}(l)$, $\mathbf{W}(l)$ is a matrix with its elements being the antenna weight

$$\mathbf{W}(l)=\left[\vec{\mathbf{w}}^{(1)}(l),\cdots,\vec{\mathbf{w}}^{(q)}(l),\cdots,\vec{\mathbf{w}}^{(Q)}(l)\right]$$
$$=\begin{bmatrix} w_1^{(1)}(l) & \cdots & w_1^{(q)}(l) & \cdots & w_1^{(Q)}(l) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ w_n^{(1)}(l) & \cdots & w_n^{(q)}(l) & \cdots & w_n^{(Q)}(l) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ w_N^{(1)}(l) & \cdots & w_N^{(q)}(l) & \cdots & w_N^{(Q)}(l) \end{bmatrix}, \tag{2}$$

where, $\vec{\mathbf{w}}^{(q)}(l)$ represents the weight vector for the q-th pilot subcarrier

$$\vec{\mathbf{w}}^{(q)}(l)=\left[w_1^{(q)}(l),\cdots,w_n^{(q)}(l),\cdots,w_N^{(q)}(l)\right]^T, \tag{3}$$

$w_n^{(q)}(l)$ is the weight of the n-th antenna element at the q-th pilot subcarrier.

The gradient matrix can be estimated as

$$\mathbf{B}_{\mathrm{NT}}(l)=2\mathbf{X}(l+1)\vec{\mathbf{e}}(l), \tag{4}$$

where, the subscript 'NT' represents the algorithm without frequency-to-time pilot transform, i.e., $\mathbf{B}_{\mathrm{NT}}(l)$ is calculated by the received and reference pilots symbols in the frequency-domain. $\mathbf{X}(l)$ is a matrix

$$\mathbf{X}(l)=\begin{bmatrix} \vec{\mathbf{x}}_1(l) \\ \vdots \\ \vec{\mathbf{x}}_n(l) \\ \vdots \\ \vec{\mathbf{x}}_N(l) \end{bmatrix}==\begin{bmatrix} x_1^{(1)}(l) & \cdots & x_1^{(q)}(l) & \cdots & x_1^{(Q)}(l) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_n^{(1)}(l) & \cdots & x_n^{(q)}(l) & \cdots & x_n^{(Q)}(l) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_N^{(1)}(l) & \cdots & x_N^{(q)}(l) & \cdots & x_N^{(Q)}(l) \end{bmatrix} \tag{5}$$

with its row vector being

$$\vec{\mathbf{x}}_n(l)=\left[x_n^{(1)}(l),\cdots,x_n^{(q)}(l),\cdots,x_n^{(Q)}(l)\right], \tag{6}$$

and $x_n^{(q)}(l)$ is the received frequency-domain pilot symbol at the q-th pilot subcarrier for the n-th antenna element.

In (4), $\vec{\mathbf{e}}(l)$ is the difference between two vectors

$$\vec{\mathbf{e}}(l)=\vec{\mathbf{x}}_{\Sigma}(l)-\vec{\mathbf{u}}(l), \tag{7}$$

where, the vector $\vec{\mathbf{x}}_{\Sigma}(l)$ represents the frequency-domain pilots symbols after the beamforming operation and signal combination, the vector $\vec{\mathbf{u}}(l)$ represents reference frequency-domain pilots at the l-th ●FDM block.

Based on (1), (2) and (3), the final weight vector controlling the antenna array at the l-th ●FDM block is

$$\vec{\mathbf{w}}^{AVE}(l)=\left(\frac{1}{Q}\sum_{i=1}^{●}\vec{\mathbf{w}}^{(i)}(l)\right)^{H}, \tag{8}$$

which actually is the average of the different weight vectors measured at the Q individual pilot subcarriers.

D. A●aptive Be●mforming b●se● on Time-Dom●in Pilot

In both ***RE-AS-TP*** and ***RE-PS-TP***, we use time-domain pilot vector $\vec{\mathbf{y}}_n(l)$ and time-domain error vector $\vec{\boldsymbol{\varepsilon}}(l)$ in the LMS beamforming. For "AS" mode, $\vec{\mathbf{y}}_n(l)$ can be easily gotten by the removal of guard interval (GI), while for "PS" mode, due to the coexistence of pilot and data in the ●FDM block, we need to use the matrix operation to extract the time-domain pilot components $\vec{\mathbf{y}}_n(l)$.

Similar to (1), the update of the antenna weights at the $(l+1)$-th ●FDM block is expressed as

$$\mathbf{W}(l+1)=\mathbf{W}(l)-\mu\mathbf{B}_{\mathrm{FT}}(l), \tag{●}$$

where, $\mathbf{B}_{\mathrm{FT}}(l)$ is an unbiased estimate of the gradient matrix and its subscript 'FT' represents the algorithm with the frequency-to-time pilot transform. Differing from $\mathbf{B}_{\mathrm{NT}}(l)$ in (4), $\mathbf{B}_{\mathrm{FT}}(l)$ is calculated by the received and reference pilots symbols in the time-domain. ●bviously, the key point is that we need to get the time-domain pilot components.

As we know, in ●FDM the FFT matrix $\mathbf{F}$ can be used to transform the signals from the time-domain into the frequency-domain

$$\mathbf{F}=\begin{bmatrix}1 & 1 & \cdots & 1\\ 1 & e^{-j2\pi(1)(1)/M} & \cdots & e^{-j2\pi(1)(M-1)/M}\\ \vdots & \vdots & \ddots & \vdots\\ 1 & e^{-j2\pi(M-1)(1)/M} & \cdots & e^{-j2\pi(M-1)(M-1)/M}\end{bmatrix} \tag{1●}$$

Similarly, we can define a frequency-to-time transform matrix only for the pilot symbols

$$\mathbf{G}=\begin{bmatrix}1 & 1 & \cdots & 1\\ \vdots & \vdots & \ddots & \vdots\\ e^{j2\pi(k_1-1)(m-1)/M} & e^{j2\pi(k_2-1)(m-1)/M} & \cdots & e^{j2\pi(k_Q-1)(m-1)/M}\\ \vdots & \vdots & \ddots & \vdots\\ e^{j2\pi(k_1-1)(M-1)/M} & e^{j2\pi(k_2-1)(M-1)/M} & \cdots & e^{j2\pi(k_Q-1)(M-1)/M}\end{bmatrix} \tag{11}$$

where k_i is the sequence number of the subcarrier at which the i-th frequency-domain pilot symbol is located.

As shown by ***RE-PS-TP*** in Fig.4, at the l-th ●FDM block and the n-th antenna element, the frequency-to-time pilot transform is

$$\vec{\mathbf{y}}_n(l)=\mathbf{G}\vec{\mathbf{x}}_n(l), \tag{12}$$

where, $\vec{\mathbf{y}}_n(l)$ is the time-domain components of the frequency-domain pilot symbols.

The difference between the received and reference pilot symbols are also transformed into the time-domain

$$\vec{\boldsymbol{\varepsilon}}(l)=\mathbf{G}\left(\vec{\mathbf{x}}_{\Sigma}(l)-\vec{\mathbf{u}}(l)\right). \tag{13}$$

The gradient matrix $\mathbf{B}_{\mathrm{FT}}(l)$ in (●) is calculated by

$$\mathbf{B}_{\mathrm{FT}}(l)=2\mathbf{Y}(l+1)\vec{\boldsymbol{\varepsilon}}(l), \tag{14}$$

where, $\mathbf{Y}(l)$ is a matrix composed of the row vectors representing the time-domain pilot symbols

$$\mathbf{Y}(l)=\begin{bmatrix}\left(\vec{\mathbf{y}}_1(l)\right)^T\\ \vdots\\ \left(\vec{\mathbf{y}}_n(l)\right)^T\\ \vdots\\ \left(\vec{\mathbf{y}}_N(l)\right)^T\end{bmatrix}. \tag{15}$$

V. SMILULATION RESULTS

In this section, we present the simulation results. We focus on the investigation of the uncoded BER performance. The modulation mode is ●PSK.

The adaptive antenna array is a uniform circular array (UCA). The number of antenna element (N) is eight. The distance between the adjacent antenna elements is one-half wavelength ($\lambda/2$). In our simulations, the gradient step scalar μ is ●.●●1 and the initial array weight vector is equal-value-element.

We assume that in each MDS of 64 subcarriers, for "PS" mode, 48 subcarriers are for data, 4 subcarriers are for pilot and the renmants are for ZER●; for "AS" mode, the pilot ●FDM block is inserted in every 12 data ●FDM blocks, in order to guarantee the same pilot-to-data ratio.

Fig.5 shows the convergence behavior of the proposed four adaptive beamforming schemes, when the observation window width is 1●● ●FDM blocks. The Eb/No is 16 dB. "MSE" is the mean square error between the estimated and optimal array weight vector. We can see that under the same conditions, "PS" mode can contribute to more rapid convergence of antenna weights.

Fig.6 shows the convergence behavior when the observation window width is 15●● ●FDM blocks. It is observed that the adaptive beamforming schemes based on time-domain pilot (FP) can give more accurate estimates of the antenna weights in "AS" mode, and "TP" can give more accurate estimates in "PS" mode. "AS" mode can give more accurate estimates compared with "PS" mode under the same conditions.

Therefore, their BER performances are very similar.

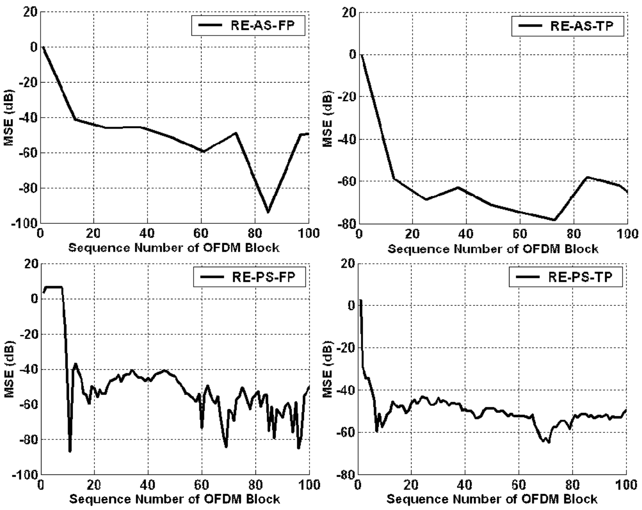

Fig.5. Convergence behavior with 100 OFDM blocks.

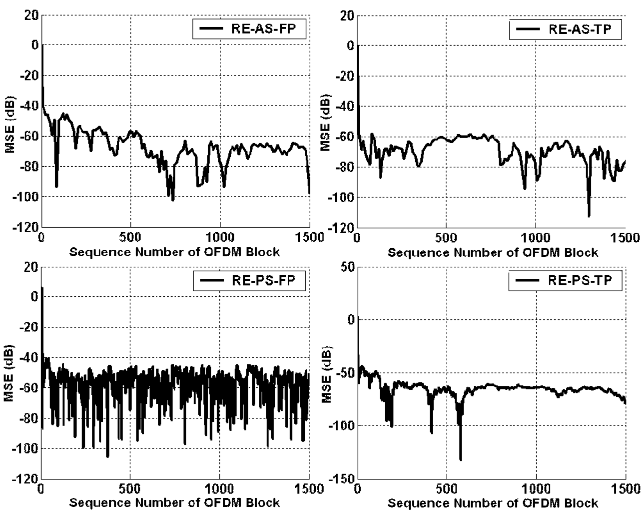

Fig.6. Convergence behavior with 1500 OFDM blocks.

Fig.7 shows the BER performance. It is shown that the four adaptive beamforming schemes can give very similar BER performance. This is because all schemes can lower MSE to very low values once the convergence has been achieved, although "PS" can contribute to more rapid convergence compared with "AS".

Therefore, we prefer "RE-PS-FP" because it requires no frequency-to-time pilot transform and its pilot arrangement is more helpful to the frequency and time synchronization, compared to "AS" mode.

VI. Conclusions

We propose four adaptive beamformings schemes for the ultra high-data-rate OFDM system. Their differences result from the pilot arrangement and the fact that either the frequency-domain or time-domain pilot vector is used in the beamforming. The different schemes present different performance in the convergence behavior and estimation accuracy. If the convergence is achieved, all of the four schemes can decrease MSE to very low values.

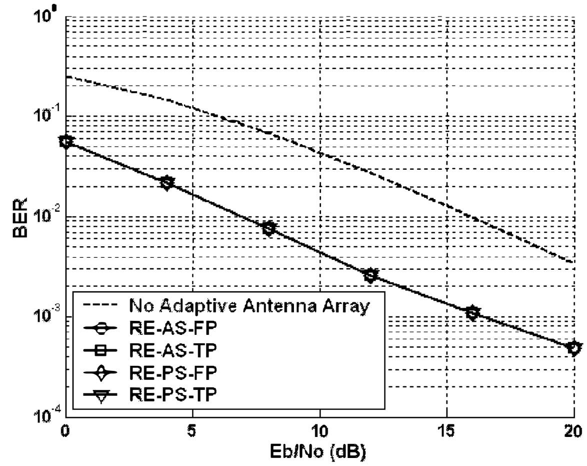

Fig.7. BER performance.

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