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An Enhanced Transceiver Structure for Higher Performances in MIMO-OFDM Systems

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ABSTRACT This paper proposes an enhanced transceiver structure for higher performances in multiple-input multiple-output-orthogonal frequency division multiplexing systems. The proposed scheme has three modes for signal transmission and detection, and decides a scheme adaptively according to the wireless channel environment to efficiently solve main disadvantages for an already-developed path elimination QR decomposition-M algorithm (PEQRD-M). At low SNR, the proposed scheme uses hybrid space-time block code and spatial multiplexing scheme to solve one of the main disadvantages for the PEQRD-M which has poor error and throughput performances at low SNR for obtaining minimum target error performance. Furthermore, the proposed scheme uses hybrid PEQRD-M and lattice reduction-aided zero forcing (LR-aided ZF) to solve one of the main disadvantages for the PEQRD-M which has high complexity at low SNR. At high SNR, the proposed scheme uses the PEQRD-M for optimal signal detection with low complexity. The usage for the hybrid PEQRD-M and LR-aided ZF and the conventional PEQRD-M is decided by comparing normalized received SNR with threshold η per each subcarrier. In simulation results, various performance evaluations are shown for $\eta = 0.3$ and $\eta = 0.7$ using parameters of IEEE 802.11ac. Specifically, the proposed scheme has higher error and throughput performances with lower complexity than the conventional PEQRD-M according to the decreased value of threshold η.

INDEX TERMS LR-aided ZF, MIMO-OFDM, PEQRD-M, STBC.

I. INTRODUCTION

Multiple input multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) system which is widely used in wireless local area network (WLAN) such as IEEE 802.11ac and 4G mobile communication system such as long term evolution (LTE)/LTE-A can increase wireless channel capacity and bandwidth efficiency without additional transmit power [1]–[3]. Simultaneous transmission at all transmit antennas using same frequency band in MIMO-OFDM system can increase channel capacity and lead higher maximum data rate. However, complex signal detection scheme is required at the receiver to separate each transmitted spatial stream because the received signals are mixture form of all distorted transmit signals by wireless channel, interference, and noise. Among several MIMO signal detection schemes, popular linear detection schemes are zero forcing (ZF) and lattice reduction (LR)-aided ZF [4]–[8]. The simple ZF which requires only multiplications of pseudo inverse matrix for the estimated channel matrix nulls interference signals to zero components except for only desired signal. However, the ZF has poor error performance to use in real wireless communication systems due to low post signal-to-noise ratio (SNR) by severe noise amplification. For enhancing the error performance of the ZF, the LR-aided ZF was developed. The LR-aided ZF combines linear ZF with LR which uses complex Lenstra-Lenstra-LovÃąsz (CLLL) algorithm to make existing channel state better conditioned by reducing a condition number for the channel matrix. With simple combination, the LR-aided ZF has very higher error performance than the ZF with slight addition of complex multiplications. As popular nonlinear detection schemes, QR decomposition-M algorithm (QRD-M) was developed [9]–[13]. The QRD-M has optimal error performance with very lower complexity than maximum likelihood (ML). The ML calculates all possible L^{N_t} squared Euclidean distances (SED) and estimates transmit signals by selecting reference set which has minimum SED where L is constellation size and N_t is the number of transmit antennas. Unlike the ML, the QRD-M

calculates only $L + LM(N_t - 1)$ accumulated SED (ASED) where M $(1 \leq M \leq L)$ is the fixed number of selected candidates at each layer in tree structure. However, the QRD-M also has very high complexity in huge MIMO-OFDM systems which use high modulation order and large transmit antennas. To reduce the complexity for the original QRD-M in huge MIMO-OFDM systems, path elimination QRD-M (PEQRD-M) which has very lower complexity than the original QRD-M was developed in [14]. The PEQRD-M eliminates unnecessary survival paths by comparing ASED with an adaptively calculated threshold at each layer. Also, the difference for complexities between the original QRD-M and the conventional PEQRD-M is very large when SNR is high because the PEQRD-M eliminates unnecessary survival paths almost perfectly. However, there are two main disadvantages for the conventional PEQRD-M. One is poor error and throughput performances at low SNR and another is high complexity at low SNR. In the proposed scheme, the authors try to solve these two problems by applying adaptive transceiver structure which has three modes according to channel environments. At low SNR, the proposed scheme uses hybrid space-time block code (STBC) [15] and spatial multiplexing (SM) at the transmitter, and the LR-aided ZF at the receiver to solve one of main disadvantages for the PEQRD-M which has poor error and throughput performances at low SNR for obtaining minimum target error performance. Also, the proposed scheme uses full SM at the transmitter, and the hybrid PEQRD-M and LR-aided ZF at the receiver to solve one of main disadvantages for the PEQRD-M which has high complexity at low SNR. At high SNR, the proposed scheme uses full SM at the transmitter, and the PEQRD-M at the receiver for optimal signal detection with low complexity.

II. MIMO-OFDM SYSTEM MODEL

Fig. 1 shows a MIMO-OFDM system model. In MIMO-OFDM transmitter, input data at each transmit antenna is modulated by OFDM transmitter which includes processor for digital modulation, inverse fast Fourier transform (IFFT), and addition for cyclic prefix (CP). Reversely, in MIMO-OFDM receiver, distorted data at each receive antenna is demodulated by OFDM receiver which includes processor for removal of CP, FFT, MIMO channel equalization, and digital demodulator. In this system model, the number of transmit antennas and receive antennas is N_t and N_r respectively. In MIMO-OFDM receiver, the $N_r \times 1$ received symbols vector $\mathbf{Y} = \left[y_1 \; y_2 \; \cdots \; y_{N_r} \right]^T$ is as follows,

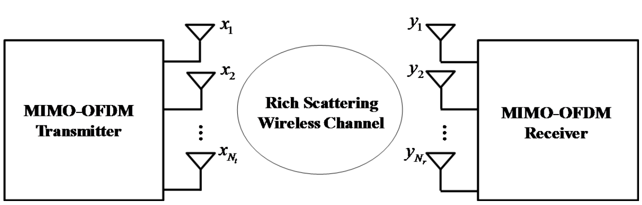

FIGURE 1. The MIMO-OFDM system model.

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N}, \tag{1}$$

where $\mathbf{X} = \left[x_1 \; x_2 \; \cdots \; x_{N_t} \right]^T$ is $N_t \times 1$ transmit symbols vector where its power is normalized to 1 and $\mathbf{N} = \left[n_1 \; n_2 \; \cdots \; n_{N_r} \right]^T$ is $N_r \times 1$ zero-mean complex additive white Gaussian noise (AWGN) vector, and $\mathbf{H}$ is $N_r \times N_t$ rich scattering complex Rayleigh flat fading channel matrix as follows,

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix}, \tag{2}$$

where h_{ij} is channel coefficient from the j-th transmit antenna to the i-th receive antenna.

III. PROPOSED ADAPTIVE TRANSCEIVER

The proposed scheme has three modes according to channel environments: 1) Hybrid STBC and SM, 2) Hybrid PEQRD-M and LR-aided ZF, 3) PEQRD-M. According to channel environments, one of three modes is selected to use its channel environments efficiently. To select a scheme according to channel environments, the proposed scheme decides a value of threshold SNR ρ_{Th} by calculating the required SNR for obtaining target error performance when a receiver uses the hybrid PEQRD-M and LR-aided ZF. Then, the proposed scheme firstly selects a scheme between the hybrid STBC and SM, and the hybrid PEQRD-M and LR-aided ZF by calculating the average SNR ρ for all subcarriers at the transmitter as follows,

$$\rho = \frac{1}{N_S} \sum_{k=1}^{N_S} \frac{P_t \left\| \mathbf{H}(k) \right\|_F^2}{\sigma^2}, \tag{3}$$

where N_S is the number of subcarriers, $\mathbf{H}(k)$ is channel matrix for the k-th subcarrier which is feedback information from the receiver, $\|\cdot\|_F$ is Frobenius norm, P_t is transmit power which is normalized to 1, and σ^2 is noise power. The proposed scheme uses the hybrid STBC and SM at the transmitter and the LR-aided ZF at the receiver when ρ is lower than ρ_{Th} for higher error and throughput performances than the conventional PEQRD-M whereas the proposed scheme uses the full SM at the transmitter, and the hybrid PEQRD-M and LR-aided ZF, and the PEQRD-M adaptively at the receiver when ρ is higher than ρ_{Th} for lower complexity than the conventional PEQRD-M despite of slight loss for the error performance. Also, the proposed scheme secondly selects a scheme between the hybrid PEQRD-M and LR-aided ZF, and the PEQRD-M by calculating normalized SNR $\rho_N(k)$ per each subcarrier at the receiver as follows,

$$\rho_N(k) = \frac{\rho_{\mathrm{Sub}}(k)}{p_{\mathrm{Max}}}, \tag{4}$$

where $\rho_{\mathrm{Sub}}(k)$ is received SNR for the k-th subcarrier and p_{Max} is maximum value of $\rho_{\mathrm{Sub}}(k)$ where $\rho_N(k)$ is less than or equal to 1. For estimating transmit symbols per each subcarrier, $\rho_N(k)$ is compared with η which is set according to requirements of user. The proposed scheme uses the hybrid PEQRD-M and LR-aided ZF when $\rho_N(k)$ is smaller than η because the hybrid PEQRD-M and LR-aided ZF has lower complexity than the PEQRD-M despite of slight loss for the error performance whereas the proposed scheme uses the PEQRD-M when $\rho_N(k)$ is larger than η because the PEQRD-M has optimal error performance with low complexity. For easy notation of the proposed scheme, it is assumed that the number of transmit antennas and receive antennas is the same as N.

A. HYBRID STBC AND SM

One of main disadvantages for the conventional PEQRD-M is poor error and throughput performances at low SNR. To enhance overall performances, both spatial diversity and spatial multiplexing schemes are used although its maximum data rate is decreased compared to simple SM. Among various spatial diversity (SD) schemes, Alamouti code is used for SD at the first and the second transmit antenna, and SM is used at other transmit antennas. The structures of transmit symbols for the hybrid STBC and SM are as follows,

$$\begin{aligned}\mathbf{X}_t &= \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & \cdots & x_N \end{bmatrix}^T, \\ \mathbf{X}_{t+T} &= \begin{bmatrix} -x_2^* & x_1^* & x_3^* & x_4^* & \cdots & x_N^* \end{bmatrix}^T, \end{aligned} \tag{5}$$

where $\mathbf{X}_t$ and $\mathbf{X}_{t+T}$ are transmit vectors at time slot t and $t+T$ respectively. The received vectors at time slot t and $t+T$ with assumption for quasi-static fading channel are as follows,

$$\begin{aligned}\mathbf{Y}_t &= \mathbf{H}\mathbf{X}_t + \mathbf{N}, \\ \mathbf{Y}_{t+T} &= \mathbf{H}\mathbf{X}_{t+T} + \mathbf{N}. \end{aligned} \tag{6}$$

With complex conjugation for $\mathbf{Y}_{t+T}$, composite received symbols vector $\mathbf{Y}_\mathrm{C}$ is as follows,

$$\mathbf{Y}_\mathrm{C} = \begin{bmatrix} \mathbf{Y}_t \\ \mathbf{Y}_{t+T}^* \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H} \\ \bar{\mathbf{H}} \end{bmatrix}}_{\mathbf{H}_\mathrm{C}} \mathbf{X} + \mathbf{N}, \tag{7}$$

where $\bar{\mathbf{H}}$ is modified channel matrix as follows,

$$\bar{\mathbf{H}} = \begin{bmatrix} \mathbf{H}_2^* & -\mathbf{H}_1^* & \mathbf{H}_{3N}^* \end{bmatrix}, \tag{8}$$

where $\mathbf{H}_j$ is the j-th column of $\mathbf{H}$ and $\mathbf{H}_{mn}$ is matrix from the m-th column to the n-th column of $\mathbf{H}$ as follows,

$$\mathbf{H}_{mn} = \begin{bmatrix} h_{1m} & h_{1(m+1)} & \cdots & h_{1n} \\ h_{2m} & h_{2(m+1)} & \cdots & h_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ h_{Nm} & h_{N(m+1)} & \cdots & h_{Nn} \end{bmatrix}. \tag{9}$$

With composite channel matrix $\mathbf{H}_\mathrm{C}$, the LR-aided ZF is applied to (7) for low complexity to solve one of main disadvantages for the PEQRD-M of high complexity at low SNR. By approximating the channel matrix to near-orthogonal state, the LR-aided ZF makes channel matrix more robust for noise amplifications when the inverse channel matrix is multiplied by the received symbols and it improves the post detection SNR. The modified near-orthogonal channel matrix $\tilde{\mathbf{H}}_\mathrm{C}$ which has reduced basis after applying the LR is as follows,

$$\tilde{\mathbf{H}}_\mathrm{C} = \mathbf{H}_\mathrm{C}\mathbf{T}, \tag{10}$$

where $\mathbf{T}$ is unimodular matrix, its elements are integers, and determinant is ± 1 for approximating the channel matrix to near-orthogonal state. Using (10), the received symbols $\mathbf{Y}_\mathrm{C}$ in (7) is rewritten as follows,

$$\mathbf{Y}_\mathrm{C} = \mathbf{H}_\mathrm{C}\mathbf{X} + \mathbf{N} = \mathbf{H}_\mathrm{C}\mathbf{T}\mathbf{T}^{-1}\mathbf{X} + \mathbf{N} = \tilde{\mathbf{H}}_\mathrm{C}\tilde{\mathbf{X}} + \mathbf{N}, \tag{11}$$

where $\tilde{\mathbf{X}} = \mathbf{T}^{-1}\mathbf{X}$ is modified transmit symbols vector in a new domain. In (11), $\mathbf{H}_\mathrm{C}\mathbf{X}$ is the same as $\tilde{\mathbf{H}}_\mathrm{C}\tilde{\mathbf{X}}$, but modified near-orthogonal channel matrix $\tilde{\mathbf{H}}_\mathrm{C}$ is much better conditioned than existing channel matrix $\mathbf{H}_\mathrm{C}$. For estimating $\tilde{\mathbf{X}}$, pseudo inverse matrix for $\tilde{\mathbf{H}}_\mathrm{C}$ is multiplied by $\mathbf{Y}_\mathrm{C}$ in (11) where its noise amplifications are usually low compared to multiplications for existing channel matrix $\mathbf{H}_\mathrm{C}$ by $\mathbf{Y}_\mathrm{C}$.

The estimated transmit symbols vector $\tilde{\mathbf{X}}$ is as follows,

$$\tilde{\mathbf{X}} = \left(\tilde{\mathbf{H}}_\mathrm{C}^H\tilde{\mathbf{H}}_\mathrm{C}\right)^{-1}\tilde{\mathbf{H}}_\mathrm{C}^H\mathbf{Y}_\mathrm{C} = \tilde{\mathbf{X}} + \left(\tilde{\mathbf{H}}_\mathrm{C}^H\tilde{\mathbf{H}}_\mathrm{C}\right)^{-1}\tilde{\mathbf{H}}_\mathrm{C}^H\mathbf{N}. \tag{12}$$

For estimating original transmit symbols vector $\hat{\mathbf{X}}$, $\tilde{\mathbf{X}}$ is quantized and is multiplied by $\mathbf{T}$ after proper scaling as follows,

$$\hat{\mathbf{X}} = \mathbf{T}Q\left\{\tilde{\mathbf{X}}\right\}, \tag{13}$$

where $Q\{\cdot\}$ is quantization function.

The LR-aided ZF has more robust than the simple ZF due to near-orthogonal channel matrix and its error performance is higher than the simple ZF with slightly higher complexity. The hybrid STBC and SM has higher error performance than the simple SM, but its maximum data rate is half of the simple SM. However, the proposed scheme uses the hybrid STBC and SM in poor channel environments for obtaining minimum target error performance at low SNR.

B. HYBRID PEQRD-M AND LR-AIDED ZF

Like section III-A, another main disadvantage for the conventional PEQRD-M is high complexity at low SNR. To reduce the complexity for the conventional PEQRD-M at low SNR, the hybrid PEQRD-M and LR-aided ZF is used. The hybrid PEQRD-M and LR-aided ZF uses PEQRD-M from the N-th layer to the $\lfloor \log_2 N \rfloor$-th layer and estimates transmit symbols initially from $x_{\lfloor \log_2 N \rfloor}$ to x_N where $\lfloor \cdot \rfloor$ is floor operation. Then, the proposed scheme uses successive interference cancellation (SIC) for initially estimated transmit symbols and then, uses the LR-aided ZF for estimating other transmit symbols. For estimating other transmit symbols, the LR-aided ZF is used from the $\lfloor \log_2 N - 1 \rfloor$-th layer to the first layer for lower complexity than the conventional PEQRD-M with slight loss for the error performance. The PEQRD-M starts from QR decomposition for the channel matrix $\mathbf{H}$ as follows,

$$\mathbf{H} = \mathbf{Q}\mathbf{R}, \tag{14}$$

where $\mathbf{Q}$ is $N \times N$ unitary quadrature matrix which is satisfied with $\mathbf{Q}^H\mathbf{Q} = \mathbf{I}_N$ where $\mathbf{I}_N$ is $N \times N$ identity matrix and $\mathbf{R}$ is $N \times N$ upper triangle matrix.

To remove the influence of $\mathbf{Q}$, $\mathbf{Q}^H$ is multiplied by $\mathbf{Y}$ and the resultant received symbols vector $\mathbf{Z} = \left[z_1 \ z_2 \ \cdots \ z_N \right]^T$ is as follows,

$$\begin{aligned}\mathbf{Z} &= \mathbf{Q}^H\mathbf{Y} = \mathbf{R}\mathbf{X} + \bar{\mathbf{N}} \\ &= \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1N} \\ 0 & r_{22} & \cdots & r_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} \bar{n}_1 \\ \bar{n}_2 \\ \vdots \\ \bar{n}_N \end{bmatrix},\end{aligned} \tag{15}$$

where $\bar{\mathbf{N}} = \mathbf{Q}^H\mathbf{N}$ is $N \times 1$ modified noise vector which has the same statistical property as existing noise vector $\mathbf{N}$.

At the N-th layer for $\mathbf{Z}$ (the first row for $\mathbf{Z}$), L times SED between z_N and the k-th modulated reference symbol c_k, i.e. $k = 1, 2, \cdots, L$ is calculated as follows,

$$e_{N,k} = |z_N - r_{NN}c_k|^2. \tag{16}$$

After operation of (16) for all k, $\mathbf{e}_N = \left[e_{N,1} \ e_{N,2} \ \cdots \ e_{N,L} \right]$ is obtained and it is assumed that elements for $\mathbf{e}_N$ are sorted in an ascending order according to all k. Then, the smallest $T = \log_2 L$ elements are selected and its vector $\mathbf{e}_N^{\mathrm{S}}$ is as follows,

$$\mathbf{e}_N^{\mathrm{S}} = \left[e_{N,1} \quad e_{N,2} \quad \cdots \quad e_{N,T} \right]. \tag{17}$$

At the $(N-1)$-th layer of $\mathbf{Z}$, LT times ASED between z_{N-1} and the k-th modulated reference symbol c_k using the p-th element in $\mathbf{e}_N^{\mathrm{S}}$ is calculated as follows,

$$e_{N-1,k}^p = \left| z_{N-1} - \left(r_{N-1N}c_k + r_{NN}\hat{x}_N^p \right) \right|^2 + e_{N,p}, \tag{18}$$

where $\hat{x}_N^p$ is temporarily selected symbol at the N-th layer.

After operation of (18) for all k and p, $\mathbf{e}_{N-1} = \left[\mathbf{e}_{N-1}^1 \ \mathbf{e}_{N-1}^2 \ \cdots \ \mathbf{e}_{N-1}^T \right]$ is obtained where $\mathbf{e}_{N-1}^p = \left[e_{N-1,1}^p \ e_{N-1,2}^p \ \cdots \ e_{N-1,L}^p \right]$ is ASED at the $(N-1)$-th layer for the p-th path of $\mathbf{e}_N^{\mathrm{S}}$ and it is assumed that elements for $\mathbf{e}_{N-1}^p$ are sorted in an ascending order according to all k. Then, the smallest $T = \log_2 L$ elements are selected like the N-th layer and its vector $\mathbf{e}_{N-1}^{\mathrm{S}}$ is as follows,

$$\mathbf{e}_{N-1}^{\mathrm{S}} = \left[e_{N-1,1} \quad e_{N-1,2} \quad \cdots \quad e_{N-1,T} \right]. \tag{19}$$

The calculations and selections for T ASED at each layer are continued until the first layer and the minimum ASED is selected as a threshold η_N at the N-th layer as follows,

$$\eta_N = \min\{\mathbf{e}_1\}. \tag{20}$$

For path eliminations of unnecessary survival paths at the N-th layer, all elements in $\mathbf{e}_N$ are compared with η_N and paths which have larger ASED than η_N are eliminated. When the number of survival paths at the N-th layer is S_N, $S_N L$ paths are extended to the next $(N-1)$-th layer. At the $(N-1)$-th layer, ASED is calculated for $S_N L$ paths and the smallest M paths are selected and the others $(S_N L - M)$ paths are discarded. For calculating threshold η_{N-1} at the $(N-1)$-th layer, (18) to (20) are operated and unnecessary survival paths are eliminated by comparing with η_{N-1} and these calculations are continued until the $\lfloor \log_2 N \rfloor$-th layer. At the $\lfloor \log_2 N \rfloor$-th layer, set for reference symbol corresponding a path which has the smallest ASED is estimated as transmit symbols vector as follows,

$$\hat{\mathbf{X}}_{\lfloor \log_2 N \rfloor N} = \left[x_{\lfloor \log_2 N \rfloor} \quad x_{\lfloor \log_2 N \rfloor + 1} \ \cdots \quad x_N \right]^T, \tag{21}$$

where $\mathbf{X}_{mn}$ is transmit symbols vector from the m-th element to the n-th element of $\mathbf{X}$.

After the PEQRD-M, the SIC and the LR-aided ZF are used for estimating other transmit symbols. After the SIC, the modified received symbols vector $\mathbf{Y}_{\mathrm{SIC}}$ is as follows,

$$\begin{aligned}\mathbf{Y}_{\mathrm{SIC}} &= \mathbf{Y} - \mathbf{H}_{\lfloor \log_2 N \rfloor N}\mathbf{X}_{\lfloor \log_2 N \rfloor N} \\ &= \mathbf{H}_{1\lfloor \log_2 N - 1 \rfloor}\mathbf{X}_{1\lfloor \log_2 N - 1 \rfloor} + \tilde{\mathbf{N}},\end{aligned} \tag{22}$$

where $\mathbf{X}_{1\lfloor \log_2 N - 1 \rfloor} = \left[x_1 \ x_2 \ \cdots \ x_{\lfloor \log_2 N - 1 \rfloor} \right]^T$ is not yet estimated symbols vector and $\tilde{\mathbf{N}}$ is modified noise vector due to SIC and inaccurate estimation for the PEQRD-M from the N-th layer to the $\lfloor \log_2 N \rfloor$-th layer.

For estimating transmit symbols vector $\mathbf{X}_{1\lfloor \log_2 N - 1 \rfloor}$, the LR-aided ZF is used in (22). The complexity for the LR-aided ZF in (22) is very low due to reduced dimension of the channel matrix $\mathbf{H}_{1\lfloor \log_2 N - 1 \rfloor}$. From (14) to (22), all transmit symbols are estimated with very lower complexity than the PEQRD-M.

C. PEQRD-M

At high SNR, the PEQRD-M is used because one of the main advantages for the PEQRD-M is optimal error performance with very low complexity at high SNR. Unlike the hybrid PEQRD-M and LR-aided ZF, the PEQRD-M is used from the N-th layer to the first layer. At high SNR, the complexity for the conventional PEQRD-M is approximated to the complexity for the original QRD-M ($M = 1$) where it calculates only LN_t ASED. Also, its error performance is the same as error performance for the ML. Fig. 2 shows a flow chart for the proposed scheme.

D. COMPLEXITY

To compare complexities for the proposed scheme with conventional schemes, the number of complex multiplications which is dominant indicator of whole complexities is calculated. It is assumed that one complex multiplication between two complex numbers requires four real multiplications. The number of complex multiplications for the conventional LR-aided ZF, QRD-M, PEQRD-M, proposed hybrid STBC and SM, and hybrid PEQRD-M and LR-aided ZF is summarized in TABLE 1.

IV. SIMULATION RESULTS

This section shows simulation results for bit error rate (BER), throughput, and complexity with 7 multi-path Rayleigh fading channel. The used simulation parameters are based on modulation and coding (MCS) index 3 of specification for

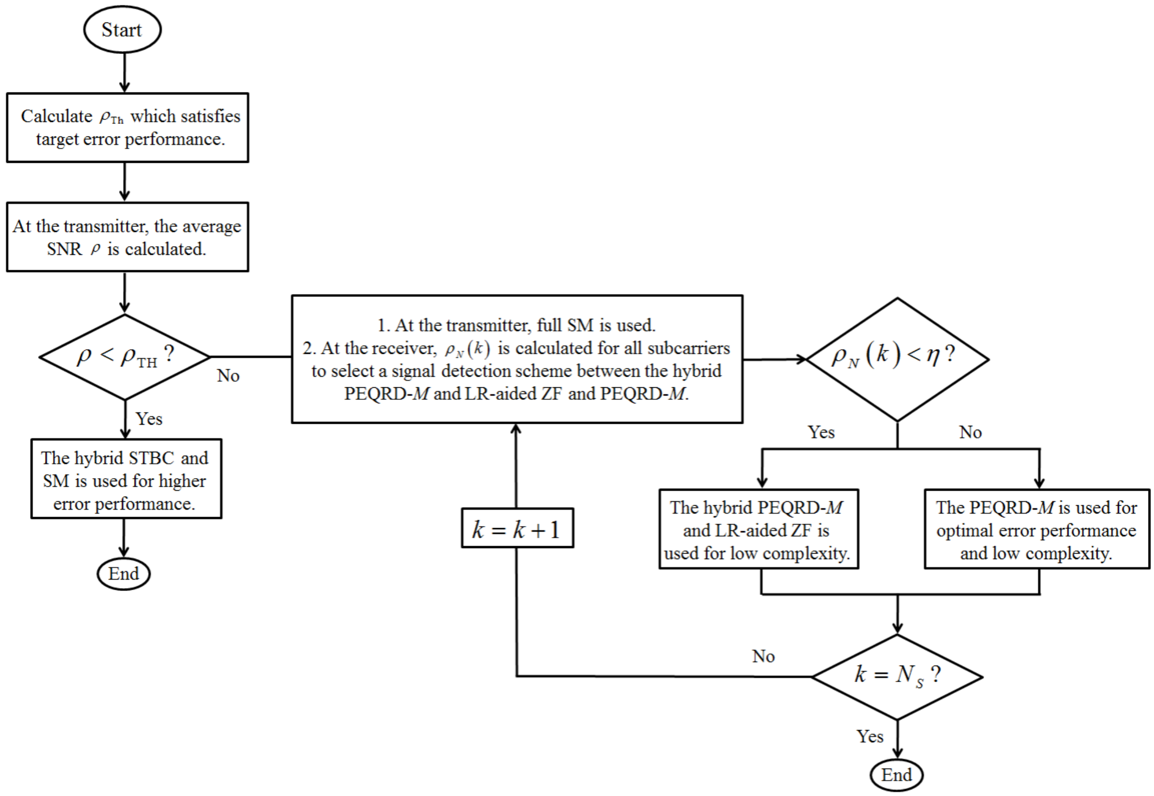

FIGURE 2. The flow chart for the proposed scheme.

TABLE 1. The number of complex multiplications for the conventional LR-aided ZF, QRD-*M*, PEQRD-*M*, proposed hybrid STBC and SM, and hybrid PEQRD-*M* and LR-aided ZF.

Scheme	The number of complex multiplications
LR-aided ZF	$8N^3 + 4N^2 + \mathrm{CLLL}_{N_t,N_r}$ where CLLL_{N_t,N_r} is the number of complex multiplications for CLLL algorithm in $N_t \times N_r$ MIMO-OFDM system.
QRD-M	$12N^3 + 4N^2 + 8L + 4LM \sum_{l=2}^{N} (l+1)$
PEQRD-M	$12N^3 + 4N^2 + 8L + 4L \sum_{l=2}^{N_t} S_l (l+1)$ where S_l is the number of existing survival paths at the l-th layer.
Hybrid STBC and SM	$24N^3 + 8N^2 + \mathrm{CLLL}_{N_t,N_r}$
Hybrid PEQRD-M and LR-aided ZF	$4N^3 + 4N^2 (\lfloor \log_2 N \rfloor + 1) + 4N \lfloor \log_2 N \rfloor (\lfloor \log_2 N \rfloor + 1) + 8L + 4L \sum_{l=2}^{N - \lfloor \log_2 N \rfloor} S_l (l+1)$

IEEE 802.11ac in [16]. The number of used data bits per one OFDM symbol at each spatial stream (N_D) is 216, and the number of used data subcarriers (N_S) is 108. Also, the length of FFT and CP is 512 and 64 respectively. Finally, the used modulation order (O) is 4 for 16-quadrature amplitude modulation (QAM). In our simulation results, only symmetrical

MIMO-OFDM system where the number of transmit antennas is the same as receive antennas is considered. Although the non-symmetrical MIMO-OFDM system where the number of receive antennas is larger than the number of transmit antennas is used, the proposed algorithm is equally applied because the proposed algorithm calculates SNR (ρ) and selects a transmission scheme adaptively.

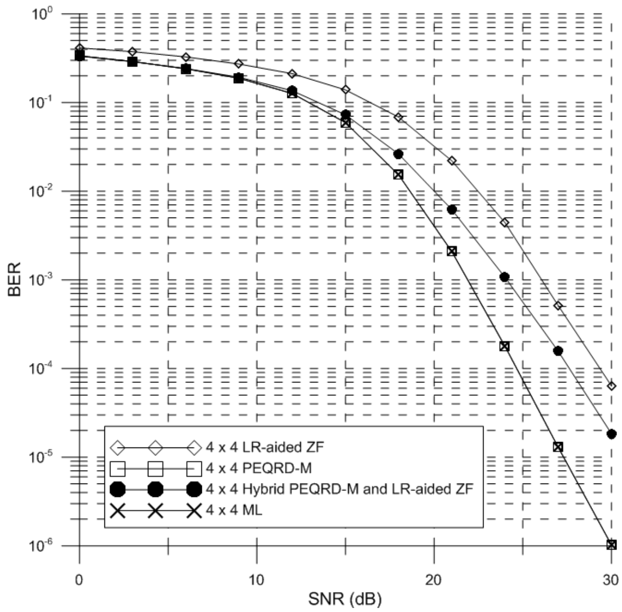

FIGURE 3. **The BER performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed hybrid PEQRD-*M* and LR-aided ZF in 4 × 4 MIMO-OFDM system.**

Fig. 3 shows BER performances for the conventional LR-aided ZF, PEQRD-M, and the proposed hybrid PEQRD-M and LR-aided ZF in 4×4 MIMO-OFDM system. Also, the BER performance for the ML is shown for comparisons. The LR-aided ZF has very lower BER performance than the ML. The difference of required SNR for obtaining BER performance of 10^{-4} between the LR-aided ZF and the ML is about 5dB. However, the PEQRD-M has the same BER performance as ML because it eliminates unnecessary survival paths successfully. Finally, the proposed hybrid PEQRD-M and LR-aided ZF has lower BER performance than the ML because the optimal PEQRD-M is applied from the fourth layer to the second layer, and the LR-aided ZF is applied to the first layer.

Fig. 4 shows BER performances for the conventional LR-aided ZF, PEQRD-M, and the proposed hybrid PEQRD-M and LR-aided ZF in 8×8 MIMO-OFDM system. The BER performance for the LR-aided ZF is decreased compared to 4×4 MIMO-OFDM system because the post detection SNR after channel equalization is poor according to the number of increased transmit antennas due to severe noise amplification. However, the BER performance for the PEQRD-M is improved compared to 4×4 MIMO-OFDM system because diversity gain is more obtained according to the number of increased transmit antennas. Finally, the BER performance

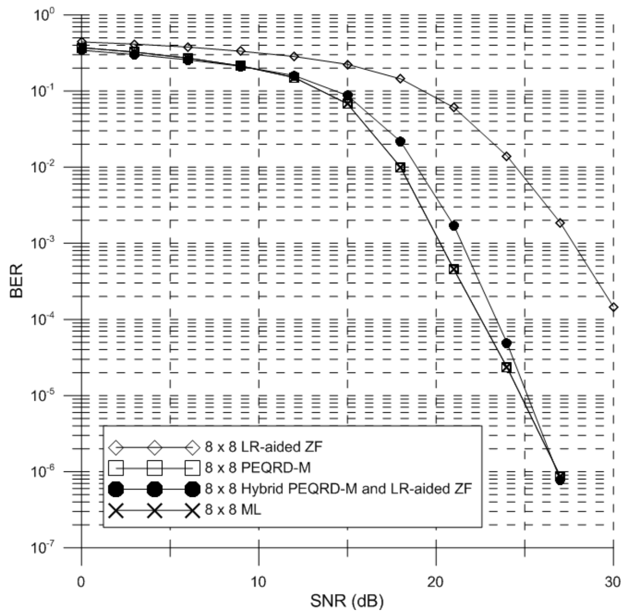

FIGURE 4. **The BER performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed hybrid PEQRD-*M* and LR-aided ZF in 8 × 8 MIMO-OFDM system.**

for the hybrid PEQRD-M and LR-aided ZF is improved compared to 4×4 MIMO-OFDM system because more PEQRD-M is applied and it obtains more diversity gain. Also, it leads improved result where the proposed hybrid PEQRD-M and LR-aided ZF has slightly lower BER performance than the PEQRD-M.

Fig. 5 and Fig. 6 show complexities for the conventional PEQRD-M, and the hybrid PEQRD-M and LR-aided ZF in

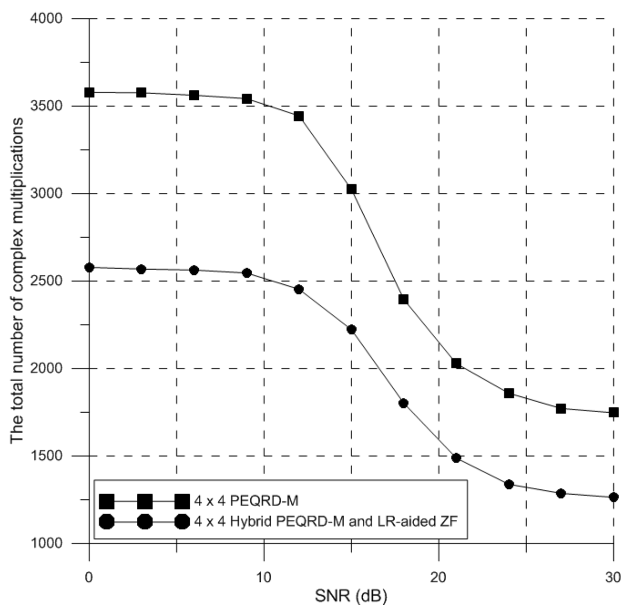

FIGURE 5. **The total number of complex multiplications for the conventional PEQRD-*M*, and the proposed hybrid PEQRD-*M* and LR-aided ZF in 4 × 4 MIMO-OFDM system.**

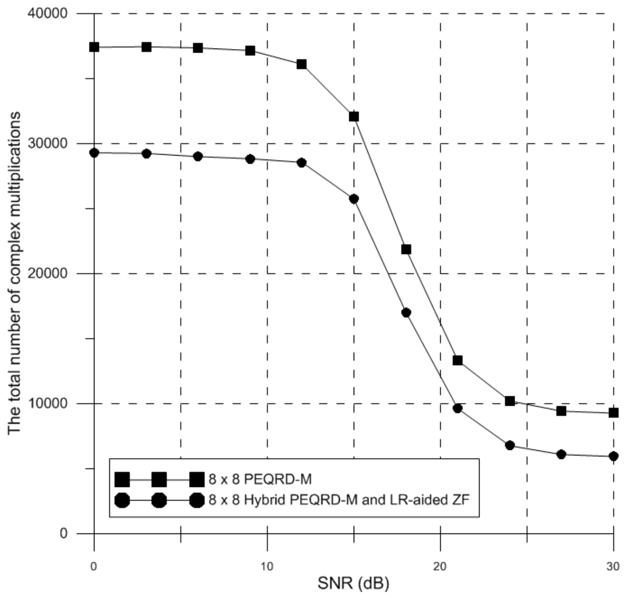

FIGURE 6. **The total number of complex multiplications for the conventional PEQRD-*M*, and the proposed hybrid PEQRD-*M* and LR-aided ZF in 8 × 8 MIMO-OFDM system.**

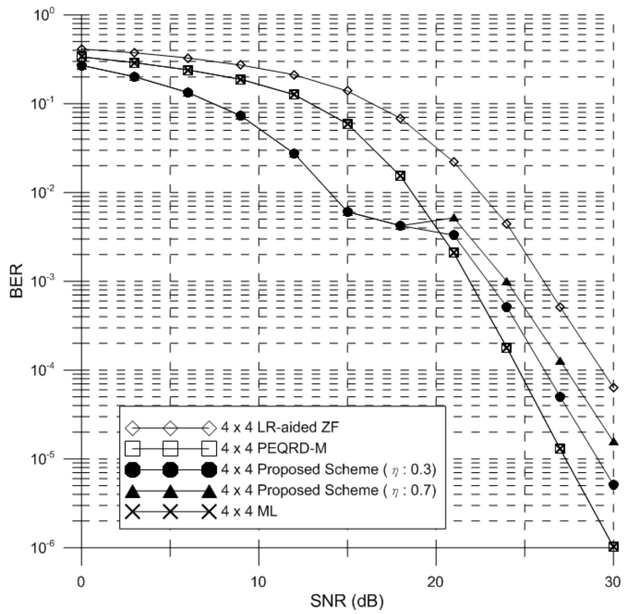

FIGURE 7. **The BER performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed scheme with different η in 4 × 4 MIMO-OFDM system.**

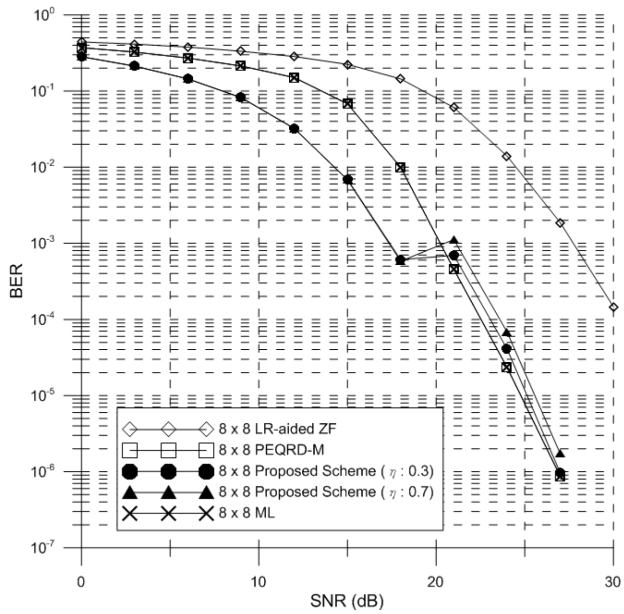

FIGURE 8. **The BER performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed scheme with different η in 8 × 8 MIMO-OFDM system.**

4×4 and 8×8 MIMO-OFDM systems respectively. For comparing the complexity, the total number of complex multiplications is calculated. The main advantage for the PEQRD-M, and the hybrid PEQRD-M and LR-aided ZF is that complexities are decreased according to increased SNR and it has very low complexity at high SNR because the number of eliminated unnecessary survival paths is very large. The total number of complex multiplications for the hybrid PEQRD-M and LR-aided ZF is lower than the conventional PEQRD-M because the complexity for calculating inverse matrix of the LR-aided ZF after the PEQRD-M is very low due to reduced dimension of channel matrix. However, the difference for the complexity between the hybrid PEQRD-M and LR-aided ZF in 8×8 MIMO-OFDM system is lower than 4×4 MIMO-OFDM system because the decrease ratio for the complexity of the hybrid PEQRD-M and LR-aided ZF according to the number of decreased transmit antennas is lower than the conventional PEQRD-M because dimension of inverse matrix for the LR-aided ZF is large according to the number of increased transmit antennas and it causes more high complex multiplications. In the proposed hybrid PEQRD-M and LR-aided ZF, the dimension of inverse matrix after the PEQRD-M is $\lfloor \log_2 N - 1 \rfloor \times N$.

Fig. 7 and Fig. 8 show BER performances for the conventional LR-aided ZF, PEQRD-M, and the proposed scheme in 4×4 and 8×8 MIMO-OFDM systems respectively. For various results of the proposed scheme, threshold η is set to be 0.3 and 0.7. In these simulations, the target error performance for the proposed scheme is set to be lower than 10^{-2} in both 4×4 and 8×8 MIMO-OFDM systems. The proposed scheme uses the hybrid STBC and SM for obtaining the target error performance at low SNR. The proposed scheme with $\eta = 0.3$ has better BER performance than the proposed scheme with $\eta = 0.7$ because the number of used optimal PEQRD-M is larger than the number of used hybrid PEQRD-M and LR-aided ZF in $\eta = 0.7$ compared to $\eta = 0.3$. Also, the BER performances for the proposed scheme for both $\eta = 0.3$ and $\eta = 0.7$ are not smoothly curved at SNR 18 and 21dB in Fig. 7 and at SNR 21dB in Fig. 8 because the calculated SNR ρ is often larger than ρ_{TH} and it leads usage of adaptive hybrid PEQRD-M and LR-aided ZF, and PEQRD-M. Again, it is shown that the hybrid PEQRD-M and LR-aided ZF, and PEQRD-M have better BER performance according to the number of increased transmit antennas in Fig. 3 and Fig. 4.

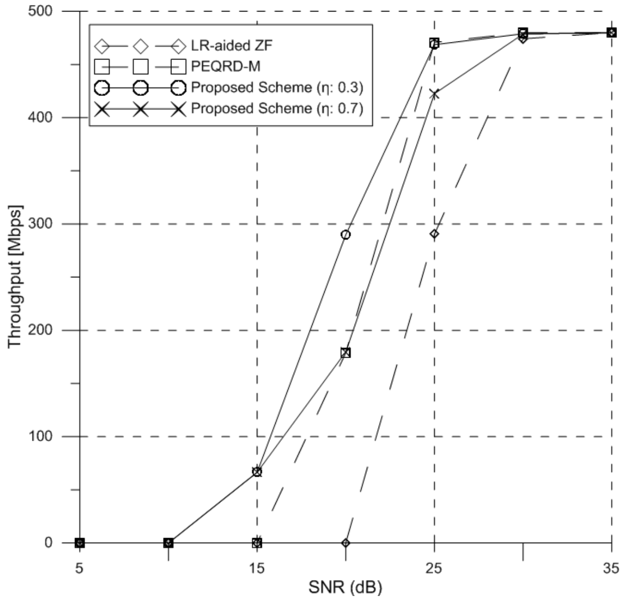

FIGURE 9. **The throughput performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed scheme with different η in 4 × 4 MIMO-OFDM system.**

Fig. 9 and Fig. 10 show throughput performances for the conventional LR-aided ZF, PEQRD-M, and the proposed scheme in 4×4 and 8×8 MIMO-OFDM systems respectively. For accurate comparisons with both Fig. 7 and Fig. 8, η is equally set to be 0.3 and 0.7. The throughput performances for dashed lines are conventional LR-aided ZF and PEQRD-M. The throughput T_H is calculated as follows,

$$T_H = \frac{N_S \times O \times N}{T_S} \times \frac{1}{N_T} \times \sum_{n=1}^{N} (1 - E_n)^{N_D}, \tag{23}$$

where E_n is measured error rate for the n-th spatial stream and N_T is the number of time slots where STBC uses two time slots and SM uses one time slot.

The proposed scheme has higher throughput performance than the conventional LR-aided ZF and PEQRD-M at low SNR in both 4×4 and 8×8 MIMO-OFDM systems. The throughput performances for the conventional LR-aided ZF and PEQRD-M are 0Mbps at 15dB and 20dB SNR respectively because its BER performances are very poor and the number of transmitted data bits is large. Also, the proposed scheme for $\eta = 0.3$ has always higher throughput than the conventional LR-aided ZF and PEQRD-M despite of slightly poorer BER performance than the conventional PEQRD-M. As our simulation results, it is possible that the proposed scheme can approach its maximum data rate for 480Mbps and 960Mbps at SNR 25dB in 4×4 and 8×8 MIMO-OFDM systems respectively.

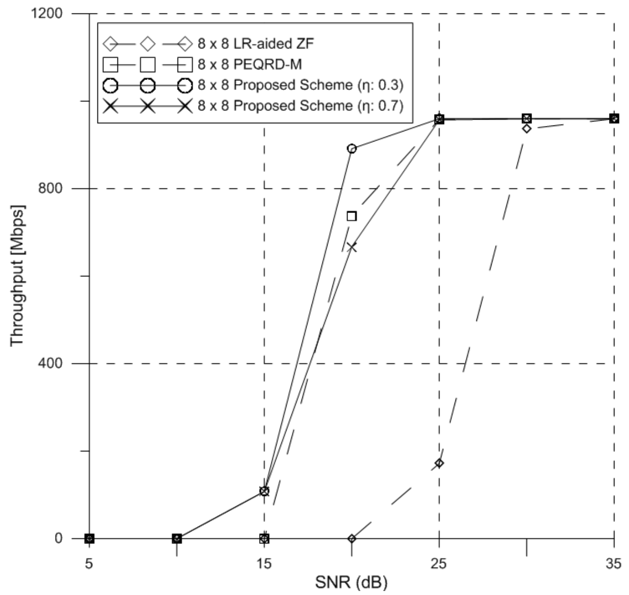

FIGURE 10. **The throughput performances for the conventional LR-aided ZF, PEQRD-*M*, and the proposed scheme with different η in 8 × 8 MIMO-OFDM system.**

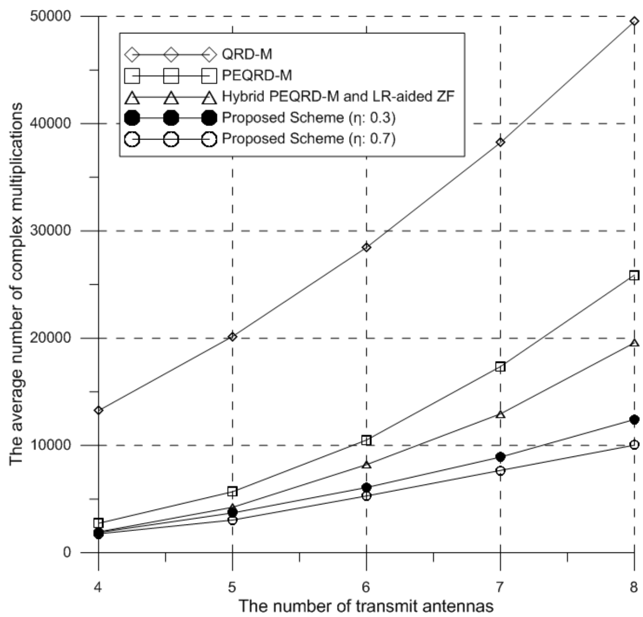

FIGURE 11. **The average number of complex multiplications for the original QRD-*M*, PEQRD-*M*, proposed hybrid PEQRD-*M* and LR-aided ZF, and proposed scheme with respect to the number of transmit antennas.**

Fig. 11 shows complexities for the original QRD-M, PEQRD-M, proposed hybrid PEQRD-M and LR-aided ZF, and proposed scheme with respect to the number of transmit antennas. For comparing the complexity, the average number of complex multiplications with respect to SNR from 0dB to 30dB is calculated. The average number of complex multiplications for the conventional PEQRD-M is very lower than the original QRD-M. However, the conventional PEQRD-M has almost the same increase ratio of the complexity as original QRD-M according to the number of increased transmit antennas. In [14], the complexity for the conventional PEQRD-M is very low at high SNR. So, it can be hard to use in the MIMO-OFDM systems which require high throughput performance at low SNR due to high increase ratio of the complexity. On the other hand, the proposed scheme has lower complexity than the conventional PEQRD-M. Also, its complexity increases linearly compared to the the conventional PEQRD-M according to the number of increased transmit antennas and it has very lower complexity than the conventional PEQRD-M when the number of transmit antennas is large.

V. CONCLUSION

In this paper, an enhanced transceiver structure for higher performances is proposed in MIMO-OFDM systems to solve severe problems for the already developed PEQRD-M which has poor error and throughput performances, and high complexity at low SNR. The proposed scheme has three modes and uses one of three modes which are 1) Hybrid STBC and SM, 2) Hybrid PEQRD-M, and LR-aided ZF, 3) PEQRD-M by comparing the received SNR with threshold for efficient usage of channel state. In simulation results, the proposed scheme for $\eta = 0.3$ has higher throughput and lower complexity than the conventional PEQRD-M with slight loss of the BER performance. Unlike the conventional PEQRD-M, the proposed scheme can be used easily in MIMO-OFDM systems which require very high throughput and low complexity. Also, the proposed scheme can be used well in poor channel environments due to very low complexity. However, the value of threshold η is variable with respect to target performances for users and it is our future task to find an optimal η according to time-varying channel environments using various techniques such as performance analysis and machine learning algorithms.

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