Antenna-Permutation Channel-Vector Quantization for Finite Rate Feedback in Block-Diagonalizing Beamforming Multiuser MIMO-OFDM Systems

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Abstract: An antenna-permutation (AP) scheme is described for channel vector quantization (CVQ) in block-diagonalizing beamforming (BDBF) multiuser multiple-input and multiple output (MU-MIMO) orthogonal frequency-division multiplexing (OFDM) systems with four receive antennas. The channel vectors for two receive antennas are quantized to a single quantization vector for finite rate feedback by maximum-ratio transmission (MRT). The combinations of two antennas from among the four receive antennas are cyclically permutated for subcarriers. By doing so, BDBF provides severer frequency selectivity. This can be exploited by channel decoding as a larger frequency diversity gain. Simulation results demonstrate that AP-MRT-CVQ with 12-bit quantization achieved average packet error rate performance close to that in the case where perfect channel state information at the transmitter is available.

1. Introduction

Multiuser multiple-input and multiple output (MU-MIMO) systems have recently attracted attention because of their high spectral efficiency. Block-diagonalizing beamforming (BDBF) [1] suppresses inter-user interference at the transmitter side and thus, maximum likelihood detection (MLD) can easily be used for the receiver to detect multiple streams intended for a user.

BDBF, however, requires channel state information at the transmitter. This requires coarsely quantizing the channel vector to accommodate the limited bandwidth of the feedback channel. To maximize the signal-to-noise ratio (SNR) by a transmit beamforming vector and a receive beamforming vector, maximum-ratio transmission channel-vector quantization (MRT-CVQ) [2] and a maximum-ratio combing (MRC) receive beamformer are used for user terminals equipped with multiple receive antennas. When the number of quantization bits is insufficient, however, the transmission performance is degraded by inter-user interference due to quantization errors.

In this paper, to enhance the transmission performance, we propose antenna-permutation- (AP-) CVQ for user terminals equipped with n_R (= 4) receive antennas. The combinations of two antennas from among the four receive antennas for CVQ are cyclically permutated for subcarriers in orthogonal frequency-division multiplexing (OFDM). This permutation results in quantization-channel-vector hopping. The BDBF weight matrices derived through AP-CVQ provide channels with severer frequency selectivity. This selectivity can be exploited by channel decoding as a larger frequency diversity gain as is conventionally used in [3], resulting in better transmission performance.

2. AP-MRT-CVQ

Figures 1 and 2 show the configurations of a transmitter equipped with N_T transmit antennas and a receiver equipped with n_R receive antennas. We define an ($n_R \times N_T$)-dimensional channel matrix $\boldsymbol{H}_j(m)$ at the m-th subcarrier ($1 \le m \le N_S$) for user j ($1 \le j \le J$). For simplicity, we assume that all users have the same number of receive antennas, and that the number of substreams sent to each user is n_T (= $n_R/2$). The channel matrix is assumed to be perfectly estimated at the receiver. It is denoted as $\boldsymbol{H}_j(m) = \left[\boldsymbol{h}_{j,1}^T(m), \boldsymbol{h}_{j,2}^T(m), \cdots, \boldsymbol{h}_{j,n_R}^T(m)\right]^T$, where $\boldsymbol{h}_{j,i_R}(m)$ is an N_T-dimensional channel vector for the i_R-th receive antenna ($1 \le i_R \le n_R$) of user j.

We define the ($n_R \times n_R$)-dimensional antenna permutation matrices as $\boldsymbol{P}(k)$ with $k = \text{mod}(m - 1, N_P) + 1$, where mod(·) is the modulo operation and N_P is the number of cyclic permutation matrices. The index k gives the cyclical antenna permutation for the subcarriers. They are applied to the channel matrix $\boldsymbol{H}_j(m)$ as

$$\begin{aligned}\tilde{\boldsymbol{H}}_j(m) &= \boldsymbol{P}(k)\boldsymbol{H}_j(m) \\ &= \left[\tilde{\boldsymbol{h}}_{j,1}^T(m), \tilde{\boldsymbol{h}}_{j,2}^T(m), \cdots, \tilde{\boldsymbol{h}}_{j,n_R}^T(m)\right]^T \\ &= \left[\boldsymbol{F}_{j,1}(m), \boldsymbol{F}_{j,2}(m), \cdots, \boldsymbol{F}_{j,n_R/2}(m)\right]^T, \end{aligned} \tag{1}$$

where $\boldsymbol{F}_{j,l}(m) = \left[\tilde{\boldsymbol{h}}_{j,2l-1}^T(m), \tilde{\boldsymbol{h}}_{j,2l}^T(m)\right]^T$ and $l = 1, \cdots, n_R/2$. The two channel vectors in $\boldsymbol{F}_{j,l}(m)$ are quantized to a single quantization vector by using a random vector quantization codebook with a size of B bits. The quantization vector for AP-MRT-CVQ is given by

$$\hat{\boldsymbol{h}}_{j,l}(m) = \arg \max_{\boldsymbol{c}=\boldsymbol{c}_1,\cdots,\boldsymbol{c}_{2^B}} \left\| \boldsymbol{F}_{j,l}^*(m)\boldsymbol{c} \right\|^2, \tag{2}$$

where the $\boldsymbol{c}$ are N_T-dimensional unit norm vectors. The codebook indexes for $\left\{\hat{\boldsymbol{h}}_{j,1}(m), \cdots, \hat{\boldsymbol{h}}_{j,n_R/2}(m)\right\}_{m=1}^{N_S}$ are fed back to the transmitter. The quantization vectors are denoted in matrix form as $\hat{\boldsymbol{H}}_j(m) = \left[\hat{\boldsymbol{h}}_{j,1}^T(m), \hat{\boldsymbol{h}}_{j,2}^T(m), \cdots, \hat{\boldsymbol{h}}_{j,n_R/2}^T(m)\right]^T$. If the signals intended for other users are sent to the null space of $\hat{\boldsymbol{H}}_j(m)$,

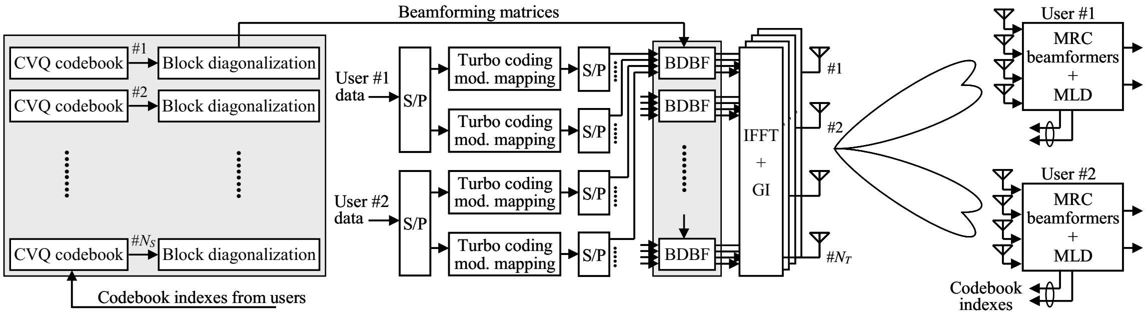

Fig. 1 Transmitter configuration.

user j suffers little inter-user interference if the number of quantization bits is sufficient. The received signal power is maximized by using the MRC weights. The MRC receive beamforming vector is given in normalized form by

$$\boldsymbol{v}_{j,l}(m) = \boldsymbol{F}_{j,l}^{*}(m)\hat{\boldsymbol{h}}_{j,l}(m) \Big/ \left\| \boldsymbol{F}_{j,l}^{*}(m)\hat{\boldsymbol{h}}_{j,l}(m) \right\|. \tag{3}$$

The recieve beamforming vector is used for received signal detection.

3. BDBF

The total number of effective antennas for all active receivers is defined as $N_R = J \cdot n_R/2$. For user j, we define an $\{(N_R - n_R/2) \times N_T\}$-dimensional matrix $\widehat{\boldsymbol{H}}_j(m)$ as $\widehat{\boldsymbol{H}}_j(m) = \left[\widehat{\boldsymbol{H}}_1^T(m), \cdots, \widehat{\boldsymbol{H}}_{j-1}^T(m), \widehat{\boldsymbol{H}}_{j+1}^T(m), \cdots, \widehat{\boldsymbol{H}}_J^T(m)\right]^T$. The zero-interference constraint forces the weight matrix to lie in the null space of $\widehat{\boldsymbol{H}}_j(m)$ as

$$\widehat{\boldsymbol{H}}_j(m) = \hat{\boldsymbol{U}}_j(m)\hat{\boldsymbol{\Sigma}}_j(m)\left[\hat{\boldsymbol{V}}_j^{(1)}(m), \hat{\boldsymbol{V}}_j^{(0)}(m)\right]^H, \tag{4}$$

where $\hat{\boldsymbol{V}}_j^{(0)}(m)$ holds the last $(N_T - N_R + n_R/2)$ right singular vectors. Thus, it forms an orthogonal basis for the null space of $\widehat{\boldsymbol{H}}_j(m)$, and its columns are used as the weight matrix for user j. The downlink weight matrix is then obtained as $\boldsymbol{W}(m) = \left[\hat{\boldsymbol{V}}_1^{(0)}(m), \hat{\boldsymbol{V}}_2^{(0)}(m), \cdots, \hat{\boldsymbol{V}}_J^{(0)}(m)\right]$ and it is also denoted by weight submatrices intended for J users as $\boldsymbol{W}(m) = \left[\boldsymbol{W}_1(m), \boldsymbol{W}_2(m), \cdots, \boldsymbol{W}_J(m)\right]$.

The data to be transmitted are channel coded and mapped onto a modulation constellation. The symbols to be simultaneously transmitted to user j are collected as a transmit symbol vector as $\boldsymbol{s}_j(m)$. The symbol vectors for all the users are defined as $\boldsymbol{s}(m) = \left[\boldsymbol{s}_1^T(m), \boldsymbol{s}_2^T(m), \cdots, \boldsymbol{s}_J^T(m)\right]^T$, which satisfies $E\left[\boldsymbol{s}(m)\boldsymbol{s}^H(m)\right] = \boldsymbol{I}_{N_T}/N_T$, where $E[\cdot]$ is the expectation function and $\boldsymbol{I}_{N_T}$ is an $(N_T \times N_T)$-dimensional identity matrix. The total transmit power is thus constrained to 1. Using the noise variance σ^2 at the receiver, the SNR is thus defined as $1/\sigma^2$. The symbol vector is then multiplexed with the weight matrix as

$$\widetilde{\boldsymbol{s}}(m) = \boldsymbol{W}(m)\boldsymbol{s}(m), \tag{5}$$

where the norm of each weight vector in $\boldsymbol{W}(m)$ is normalized to 1. The beamformed symbol vector in the subcarriers is transformed to a signal vector in the temporal domain by using inverse fast Fourier transforms (IFFTs). When an IFFT is applied, a guard interval (GI) with a length of N_G is inserted to avoid inter-symbol interference.

4. Received Signal Detection

After deleting the GI, the received signal is transformed into signals in the subcarrier by using a fast Fourier transform (FFT). The received subcarrier signal vector at user j is given for the m-th subcarrier by

$$\begin{aligned}\boldsymbol{x}_j(m) &= \boldsymbol{H}_j(m)\widetilde{\boldsymbol{s}}(m) + \boldsymbol{n}_j(m) \\ &= \boldsymbol{H}_j(m)\boldsymbol{W}(m)\boldsymbol{s}(m) + \boldsymbol{n}_j(m),\end{aligned} \tag{6}$$

where $\boldsymbol{n}_j(m)$ is a noise vector at the m-th subcarrier. The entries of the received signal vector are antenna permutated as

$$\begin{aligned}\widetilde{\boldsymbol{x}}_j(m) &= \boldsymbol{P}(k)\boldsymbol{x}_j(m) \\ &= \left[\widetilde{x}_{j,1}(m), \widetilde{x}_{j,2}(m), \cdots, \widetilde{x}_{j,n_R}(m)\right]^T \\ &= \left[\boldsymbol{z}_{j,1}(m), \boldsymbol{z}_{j,2}(m), \cdots, \boldsymbol{z}_{j,n_R/2}(m)\right]^T,\end{aligned} \tag{7}$$

where $\boldsymbol{z}_{j,l}(m) = \left[\widetilde{x}_{j,2l-1}(m), \widetilde{x}_{j,2l}(m)\right]^T$. The beamformer output signal is given by

$$y_{j,l}(m) = \boldsymbol{v}_{j,l}^T \boldsymbol{z}_{j,l}(m). \tag{8}$$

The beamformer output signal vector is then defined as $\boldsymbol{y}_j(m) = \left[y_{j,1}(m), \cdots, y_{j,n_R/2}(m)\right]^T$ and expressed as

$$\boldsymbol{y}_j(m) = \boldsymbol{V}_j(m)\boldsymbol{P}(k)\left[\boldsymbol{H}_j(m)\widetilde{\boldsymbol{s}}(m) + \boldsymbol{n}_j(m)\right], \tag{9}$$

where $\boldsymbol{V}_j(m)$ is a receive beamformer weight matrix given by

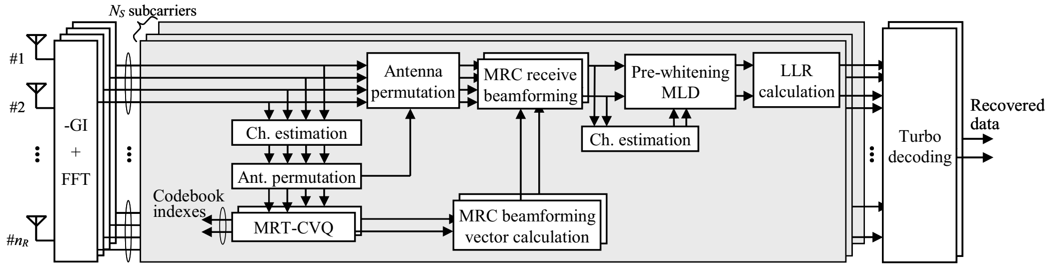

Fig. 2 Receiver configuration.

$$\boldsymbol{V}_j(m) = \begin{bmatrix} \boldsymbol{v}_{j,1}^T(m) & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{v}_{j,2}^T(m) & \ddots & \vdots \\ \vdots & \ddots & \ddots & \boldsymbol{0} \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{v}_{j,n_R/2}^T(m) \end{bmatrix}. \tag{10}$$

The beamformer output signal vector thus becomes

$$\boldsymbol{y}_j(m) = \boldsymbol{G}_{j,j}(m)\boldsymbol{s}_j(m) + \sum_{\substack{i=1 \\ i\neq j}}^{J} \boldsymbol{G}_{j,i}\boldsymbol{s}_i(m) + \boldsymbol{n}'_j(m). \tag{11}$$

where $\boldsymbol{G}_{j,i}(m) = \boldsymbol{V}_j(m)\boldsymbol{P}(k)\boldsymbol{H}_j(m)\boldsymbol{W}_i(m)$ is an ($n_R/2 \times n_T$)-dimensional channel matrix from user i to user j, $\boldsymbol{W}_i(m)$ is a submatrix of $\boldsymbol{W}(m)$ and it consists of n_T column vectors intended for user i, and $\boldsymbol{n}'_j(m) = \boldsymbol{V}_j(m)\boldsymbol{P}(k)\boldsymbol{n}_j(m)$. Using dedicated pilot symbols, the channel matrix $\boldsymbol{G}_{j,i}(m)$ is estimated at user j. From $\boldsymbol{G}_{j,j}(m)$, the maximum likelihood detection is given by

$$\hat{\boldsymbol{s}}_j(m) = \arg\min_{\boldsymbol{s}} \left\| \boldsymbol{y}_j(m) - \boldsymbol{G}_{j,j}(m)\hat{\boldsymbol{s}}_j \right\|^2, \tag{12}$$

where $\hat{\boldsymbol{s}}_j$ is all possible tramsmit symbol vectors for user j. Next, the impairment vector $\boldsymbol{e}_j(m)$ is defined as

$$\boldsymbol{e}_j(m) = \boldsymbol{y}_j(m) - \boldsymbol{G}_{j,j}(m)\hat{\boldsymbol{s}}_j. \tag{13}$$

To mitigate inter-user interference, a pre-whiteninig technique [4] is applied instead of merely calculating (12);

$$\hat{\boldsymbol{s}}_j(m) = \arg\min_{\boldsymbol{s}} \boldsymbol{e}_j^H(m)\boldsymbol{R}_{ee}^{-1}(m)\boldsymbol{e}_j(m), \tag{14}$$

where $\boldsymbol{R}_{ee}(m)$ is the correlation matrix of $\boldsymbol{e}_j(m)$, given by

$$\boldsymbol{R}_{ee}(m) = \frac{1}{N_T}\sum_{\substack{i=1 \\ i\neq j}}^{J} \boldsymbol{G}_{j,i}(m)\boldsymbol{G}_{j,i}^H(m) + \sigma^2\boldsymbol{I}_{n_T}. \tag{15}$$

Based on the detected symbol vector $\hat{\boldsymbol{s}}_j(m)$, the bit-by-bit log-likelihood ratios (LLRs) are calucated and fed into the channel decoders to recover the packet data.

The signal vector for user j is transmitted to the null space of the other users' channel matrix. When the frequency selectivity is not severe, the null space can be in the same direction over several consecutive subcarriers when the antenna permutation is not used. In contrast, when the antenna permutation is applied, the other users' channel matrices are dramatically changed in the adjacent subcarriers. As a result, the beamformed channel takes on the property, $\boldsymbol{G}_{j,j}(m) \neq \boldsymbol{G}_{j,j}(m+1)$, which provides larger frequency diversity.

5. Computer Simulation

The average BER performance and average PER performance were evaluated for BDBF-MU-MIMO-OFDM systems with an MLD receiver. Table 1 lists the simulation parameters while Table 2 lists the antenna permutation matrices. The guard-interval insertion loss was included in the received signal power. Figure 3 shows the average BER performance of various schemes using MLD or pre-whitening MLD for uncoded cases. The average BER performance for single-antenna CVQ was severely degraded from that with perfect channel state information at the transmitter (CSIT), because of inter-user interference due to the quantization errors. The average BER performance for MRT-CVQ was also degraded from that with perfect CSIT in regions with high average E_b/N_0. MRT-CVQ, however, provided average BER performance close to that with perfect CSIT in regions with low average E_b/N_0. Note that AP-MRT-CVQ exhibited the same average BER performance as that of MRT-CVQ in uncoded cases. For the CVQ cases, pre-whitening MLD outperformed MLD in regions with high average E_b/N_0 although the performance improvement was small with an average BER of around 1.0×10^{-2}.

Figure 4 shows the average PER performance of various schemes with or without AP for turbo-coded cases. MLD was used only with perfect CSIT, whereas pre-whitening MLD was used for the other schemes. The average PER performance for single-antenna CVQ was severely degraded from that with perfect CSIT because of inter-user interference. In contrast, AP-MRT-CVQ significantly improved average PER performance over that of MRT-CVQ itself and provided slightly better average PER performance than that for the perfect-CSIT case, because of larger frequency diversity. The required number of quantization bits was, therefore, 12 bits for AP-MRT-CVQ to achieve average PER performance close to that with perfect CSIT in a channel with an r.m.s. delay spread of 0.043 μs. In another simulation (not shown here), AP-MRT-CVQ achieved average PER performance close to that with perfect CSIT for a larger delay spread of up to 0.344 μs.

Table 1 Simulation parameters.

Number of users	$J = 2$
Number of receive antennas per user	n_R = 2 with perfect CSIT and for single-antenna CVQ n_R = 4 for MRT-CVQ and AP-MRT-CVQ
MU-MIMO dimension	$N_R = \{n_R, n_R\}$ and $N_T = 4$
Number of substreams per user	$n_T = 2$
Number of subcarriers	$N_S = 768$
IFFT/FFT size	$N_{FFT} = 1024$
Guard interval length	$N_G = 226$
OFDM symbol duration	T_S = 9.259 μs (GI is included.)
Number of feedback bits / subcarriers / substreams	B = 12 bits
Codebook size	$N_C = 2^B$
Number of antenna permutation matrices	$N_P = 6$
Channel coding / decoding	Turbo coding with a constraint length of 4 / Max-log-MAP decoding
Coding rate	$R = 3/4$
Modulation scheme	QPSK
Path model	12 exponentially decayed paths (Each path is independently Rayleigh faded.)
Path attenuation/path interval	1.0 dB / 2 samples
RMS delay spread	0.0430 μs
Maximum Doppler frequency	0 Hz (quasi-static condition)
Channel estimation	Ideal

Table 2 Antenna permutation matrices.

$\boldsymbol{P}(1) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$,	$\boldsymbol{P}(2) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$,
$\boldsymbol{P}(3) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$,	$\boldsymbol{P}(4) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$,
$\boldsymbol{P}(5) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$,	$\boldsymbol{P}(6) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$.

6. Conclusion

An antenna-permutation approach has been proposed for MRT-CVQ in BDBF-MU-MIMO-OFDM systems with four receive antennas. The channel vectors for two receive antennas are quantized to a single quantization vector within a codebook. The combinations of two antennas from among the four receive antennas are cyclically permutated for subcarriers. This resulted in larger frequency diversity in BDBF-MU-MIMO-OFDM channels. Simulation results demonstrated that AP-MRT-CVQ with 12-bit quantization provided slightly better average PER performance than that with perfect CSIT in a channel with an r.m.s. delay spread of 0.043 μs.

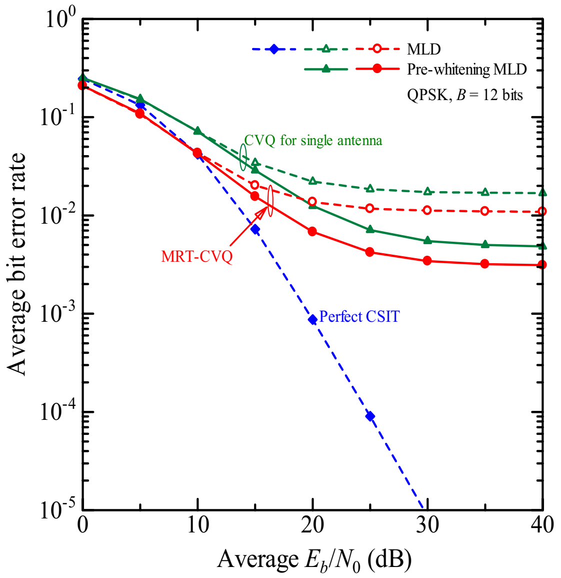

Fig. 3 Average BER performance comparison.

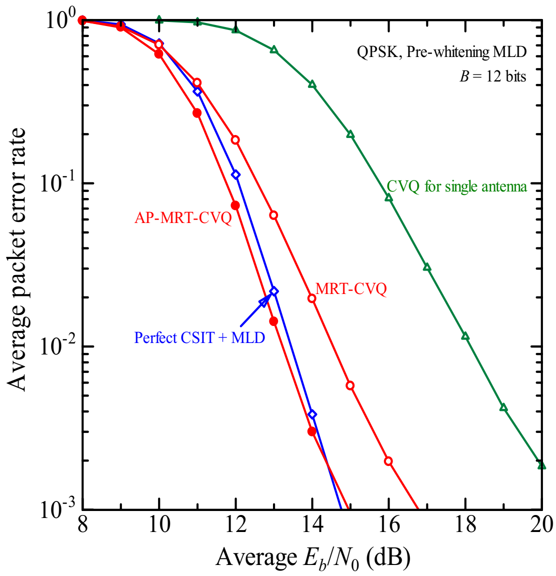

Fig. 4 Average PER performance comparison.

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