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# SINGLE-CARRIER TRANSMISSION USING QRM-MLD WITH ANTENNA DIVERSITY

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## ABSTRACT

The frequency-domain received single-carrier (SC) signal can be expressed using the matrix representation similar to the multiple-input multiple-output (MIMO) multiplexing. The signal detection schemes developed for MIMO multiplexing can be applied to the SC transmissions. In this paper, we apply maximum likelihood detection employing QR decomposition and M-algorithm (QRM-MLD) to the SC signal detection with antenna diversity reception. We show that by using antenna diversity reception, the number of surviving symbol candidates can be reduced. We evaluate, by the computer simulation, the bit error rate (BER) performance achievable by QRM-MLD and compare it with that achievable by the Vertical-Bell Laboratories Layered space-time architecture (V-BLAST) detection.

## I. INTRODUCTION

In next generation mobile communication systems, broadband data services are demanded. Since the mobile wireless channel is composed of many propagation paths with different time delays, the channel becomes severely frequency-selective. One-tap frequency-domain equalization based on the minimum mean square error criterion (MMSE-FDE) can significantly improve the bit error rate (BER) performance of single-carrier (SC) transmission in a frequency-selective fading channel [1, 2]. However, a big performance gap from the theoretical lower bound still exists due to the presence of residual inter-symbol interference (ISI) after FDE [3].

Recently, we pointed out [4] that the frequency-domain received SC signal is expressed using the matrix representation similar to the multiple-input multiple-output (MIMO) multiplexing, and therefore, signal detection schemes developed for MIMO multiplexing can be applied to the SC transmissions. Then, we proposed a new signal detection scheme, which combines FDE with MIMO signal detection, for the reception of SC signals (we call this frequency-domain block signal detection). We showed that the frequency-domain block signal detection combined with Vertical-Bell Laboratories layered space-time architecture (V-BLAST) detection [5] and iterative V-BLAST detection can significantly improve the BER performance of SC transmission.

The optimum detection method for MIMO multiplexing is maximum likelihood detection (MLD) [6, 7]. However, MLD requires a prohibitively high computational complexity. Recently, MLD employing QR decomposition and M-algorithm (QRM-MLD) was proposed in [8], where the performance is near the performance of MLD but with quite reduced complexity comparing to the MLD. In Ref. [9], QRM-MLD is applied to single carrier frequency division multiple access (SC-FDMA).

Frequency-domain block signal detection combined with QRM-MLD can achieve the BER performance close to the theoretical lower bound by increasing the number of surviving symbol candidates. However, increase in the number of surviving symbol candidates increases computational complexity.

The joint use of frequency-domain block signal detection and antenna diversity reception can further improve the BER performance [10]. By using antenna diversity reception, the probability of removing correct symbol candidates at early stages in QRM-MLD can be reduced and therefore, antenna receive diversity have a potential to reduce of the number of surviving symbol candidates, thereby reducing the computational complexity.

In this paper, we extend the frequency-domain block signal detection combined with QRM-MLD to include antenna diversity reception and evaluate, by computer simulation, the BER performance of SC transmissions. We compare the BER performance achievable by QRM-MLD and V-BLAST detection.

The remainder of this paper is organized as follows. Sect. II presents SC signal representation. In Sect. III, QRM-MLD with antenna diversity reception is developed. In Sect. IV, iterative V-BLAST detection is presented. In Sect. V, the BER performances achievable by QRM-MLD and iterative V-BLAST both with antenna diversity reception in a frequency-selective fading channel are evaluated by computer simulation. Sect. VI offers the conclusion.

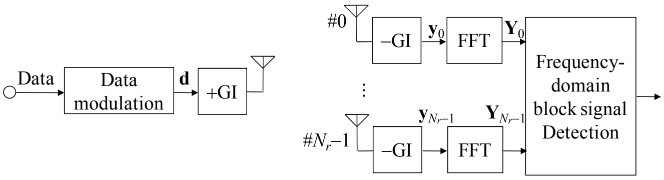

Figure 1: SC transmission system model.

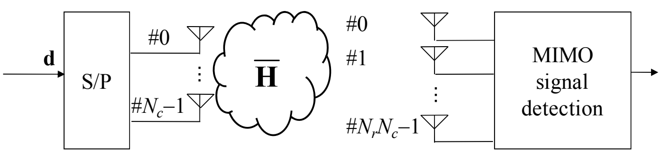

Figure 2: Equivalent system model.

## II. SC SIGNAL REPRESENTATION

The SC transmission model using $N_r$-antenna diversity reception is illustrated in Fig. 1. At the transmitter, a binary information sequence is data-modulated and then, the data-modulated symbol sequence is divided into a sequence of signal blocks of $N_c$ symbols each, where $N_c$ is the size of fast Fourier transform (FFT). The data symbol block can be expressed using the vector form as $\mathbf{d}=[d(0),\ldots,d(N_c-1)]^T$. The last $N_g$ symbols of each block are copied as a cyclic prefix and inserted into the guard interval (GI) placed at the beginning of each block and a sequence of signal blocks is transmitted.

Each transmitted signal block goes through a symbol-spaced frequency-selective fading channel composed of $L$ distinct paths. The channel impulse response $h_m(\tau)$ between the transmitter and the $m$th receive antenna ($m$=0~$N_r$–1) is given by

$$h_m(\tau)=\sum_{l=0}^{L-1}h_{m,l}\delta(\tau-\tau_{m,l}), \tag{1}$$

where $h_{m,l}$ and $\tau_{m,l}$ are respectively the complex-valued path gain with $E[\sum_{l=0}^{L-1}\left|h_{m,l}\right|^2]=1$ and the time delay of the $l$th path. The GI-removed received signal block $\mathbf{y}_m=[y_m(0),\ldots,y_m(N_c-1)]^T$ can be expressed using the matrix form as

$$\mathbf{y}_m=\sqrt{2E_s/T_s}\,\mathbf{h}_m\mathbf{d}+\mathbf{n}_m, \tag{2}$$

where $E_s$ and $T_s$ are respectively the symbol energy and the symbol duration, $\mathbf{h}_m$ is the $N_c\times N_c$ channel impulse response matrix given as

$$\mathbf{h}_m=\begin{bmatrix}
h_{m,0} & & & & h_{m,L-1} & & \\
\vdots & h_{m,0} & & & & \ddots & \\
 & \vdots & h_{m,0} & \mathbf{0} & & & h_{m,L-1} \\
h_{m,L-1} & & \vdots & \ddots & & & \\
 & h_{m,L-1} & & & h_{m,0} & & \\
 & & h_{m,L-1} & & \vdots & \ddots & \\
\mathbf{0} & & & \ddots & & & h_{m,0}
\end{bmatrix}, \tag{3}$$

and $\mathbf{n}_m=[n_m(0),\ldots,n_m(N_c-1)]^T$ is the noise vector. The $t$th element, $n_m(t)$, of $\mathbf{n}_m$ is the zero-mean additive white Gaussian noise (AWGN) having variance $2N_0/T_s$ with $N_0$ being the one-sided noise power spectrum density.

At the receiver, $N_c$-point FFT is applied to transform the received signal block into the frequency-domain signal vector $\mathbf{Y}_m=[Y_m(0),\ldots,Y_m(N_c-1)]^T$. Since $\mathbf{F}\mathbf{h}_m\mathbf{F}^H=diag[H_m(0),\ldots,H_m(N_c-1)]\equiv\mathbf{H}_m$ [11], where $(.)^H$ is the Hermitian transpose operation and $H_m(k)=\sum_{l=0}^{L-1}h_{m,l}\exp(-j2\pi k\tau_{m,l}/N_c)$, $\mathbf{Y}_m$ is expressed as

$$\mathbf{Y}_m=\mathbf{F}\mathbf{y}_m=\sqrt{2E_s/T_s}\,\mathbf{H}_m\mathbf{F}\mathbf{d}+\mathbf{N}_m=\sqrt{2E_s/T_s}\,\overline{\mathbf{H}}_m\mathbf{d}+\mathbf{N}_m, \tag{4}$$

where $\mathbf{F}$ is the FFT matrix of size $N_c\times N_c$, given by

$$\mathbf{F}=\frac{1}{\sqrt{N_c}}\begin{bmatrix}
e^{-j2\pi\frac{0\times0}{N_c}} & e^{-j2\pi\frac{0\times1}{N_c}} & \cdots & e^{-j2\pi\frac{0\times(N_c-1)}{N_c}} \\
e^{-j2\pi\frac{1\times0}{N_c}} & e^{-j2\pi\frac{1\times1}{N_c}} & \cdots & e^{-j2\pi\frac{1\times(N_c-1)}{N_c}} \\
\vdots & \vdots & \ddots & \vdots \\
e^{-j2\pi\frac{(N_c-1)\times0}{N_c}} & e^{-j2\pi\frac{(N_c-1)\times1}{N_c}} & \cdots & e^{-j2\pi\frac{(N_c-1)\times(N_c-1)}{N_c}}
\end{bmatrix}. \tag{5}$$

$\overline{\mathbf{H}}_m=\mathbf{H}_m\mathbf{F}$ and $\mathbf{N}_m=[N_m(0),\ldots,N_m(N_c-1)]^T$ are respectively the equivalent channel matrix and the frequency-domain noise vector. The frequency-domain signals at all receive antennas can be expressed collectively as

$$\begin{aligned}\mathbf{Y}=\begin{bmatrix}\mathbf{Y}_0\\ \vdots\\ \mathbf{Y}_{N_r-1}\end{bmatrix}&=\sqrt{2E_s/T_s}\begin{bmatrix}\overline{\mathbf{H}}_0\\ \vdots\\ \overline{\mathbf{H}}_{N_r-1}\end{bmatrix}\mathbf{d}+\begin{bmatrix}\mathbf{N}_0\\ \vdots\\ \mathbf{N}_{N_r-1}\end{bmatrix},\\ &=\sqrt{2E_s/T_s}\,\overline{\mathbf{H}}\mathbf{d}+\mathbf{N}\end{aligned} \tag{6}$$

where $\mathbf{Y}$ is the $N_rN_c\times1$ vector, $\overline{\mathbf{H}}$ and $\mathbf{N}$ are respectively an $N_rN_c\times N_c$ extended equivalent channel matrix and an $N_rN_c\times1$ extended frequency-domain noise vector. From Eq. (6), it can be understood that the frequency-domain received SC signal using antenna diversity reception can be treated as a received signal in MIMO multiplexing using $N_c$ transmit antennas and $N_rN_c$ receive antennas with the channel matrix $\overline{\mathbf{H}}$ (see Fig.2). According to this understanding, a new frequency-domain block signal detection scheme, which combines FDE and MIMO signal detection, can be developed for the reception of the SC signals.

## III. QRM-MLD WITH ANTENNA DIVERSITY RECEPTION

### A. QRM-MLD

In the case of SC transmissions, all symbols have the same signal-to-interference plus noise power ratio (SINR) and hence, no ordering is necessary. First, using the QR decomposition, $\overline{\mathbf{H}}$ can be expressed as

$$\overline{\mathbf{H}}=\mathbf{Q}\mathbf{R}, \tag{7}$$

where $\mathbf{Q}$ is an $N_rN_c\times N_c$ matrix satisfying $\mathbf{Q}^H\mathbf{Q}$=$\mathbf{I}$ ($\mathbf{I}$ is the identity matrix) and $\mathbf{R}$ is an $N_c\times N_c$ upper triangular matrix given by

$$\mathbf{R}=\mathbf{Q}^H\overline{\mathbf{H}}=\begin{bmatrix}
R_{0,0} & R_{0,1} & \cdots & R_{0,N_c-1}\\
 & R_{1,1} & \cdots & R_{1,N_c-1}\\
 & & \ddots & \vdots\\
\mathbf{0} & & & R_{N_c-1,N_c-1}
\end{bmatrix}. \tag{8}$$

The transformed frequency-domain received signal $\hat{\mathbf{Y}}=[\hat{Y}(0),\ldots,\hat{Y}(N_c-1)]^T$ is obtained as

$$\hat{\mathbf{Y}}=\mathbf{Q}^H\mathbf{Y}=\sqrt{2E_s/T_s}\,\mathbf{R}\mathbf{d}+\mathbf{Q}^H\mathbf{N}. \tag{9}$$

The M-algorithm [12] is composed of $N_c$ stages, each corresponding to each symbol in a block. In each stage, the reliability is calculated using $\hat{\mathbf{Y}}$, **R** and symbol candidates. Then, the symbol candidates with low reliability are successively discarded based on the M-algorithm.

In the first stage, all possible symbol candidates for the last symbol $d(N_c-1)$ are generated. The metric based on the squared Euclidian distance between $\hat{Y}(N_c-1)$ and each symbol candidate is calculated as

$$e_0 = \left|\hat{Y}(N_c-1) - \sqrt{2E_s/T_s}\,R_{N_c-1,N_c-1}\bar{d}(N_c-1)\right|^2, \qquad (10)$$

where $\bar{d}(n)$ is the symbol candidates for $d(n)$. Then, $M$ ($M \leq X$) symbol candidates having the smallest metrics are selected as surviving symbol candidates, where $X$ is the modulation level. These surviving symbol candidates are transferred to the second stage. In the second stage, there are a total of $X$ symbol candidates of $d(N_c-2)$ leaving from each of surviving symbol candidate of $d(N_c-1)$. Therefore, there are a total of $MX$ combinations of $d(N_c-1)$ and $d(N_c-2)$. The branch metrics are calculated for all possible $MX$ combinations. The metric is calculated as

$$e_1 = \sum_{n=0}^{1}\left|\hat{Y}(N_c-1-n) - \sqrt{\frac{2E_s}{T_s}}\sum_{i=0}^{n} R_{N_c-1-n,N_c-1-i}\bar{d}(N_c-1-i)\right|^2 . \qquad (11)$$

Similar to the first stage, $M$ surviving symbol candidates are selected from $MX$ combinations of $d(N_c-1)$ and $d(N_c-2)$. The process is repeated until the last stage. Signal detection is carried out using the symbol replica with the smallest accumulated branch metric at the last stage.

In QRM-MLD, the number of squared Euclidian distance calculations is reduced to $X\{1+M(N_c-1)\}$.

### *B. Antenna Diversity in QRM-MLD*

The received signal power associated with the $n$th symbol $d(n)$ is the squared norm of the $n$th column vector of **R** [9]. Since **Q** satisfy $\mathbf{Q}^H\mathbf{Q}=\mathbf{I}$, the norm of the $n$th column vector of **R** is equal to the norm of the $n$th column vector of $\overline{\mathbf{H}}$. We have

$$\begin{aligned}
\|(\mathbf{R})_n\|^2 = \|(\overline{\mathbf{H}})_n\|^2 &= \sum_{m=0}^{N_r-1}\|(\overline{\mathbf{H}}_m)_n\|^2 = \sum_{m=0}^{N_r-1}\sum_{k=0}^{N_c-1}\left|\overline{H}_m^{k,n}\right|^2 \\
&= \frac{1}{N_c}\sum_{m=0}^{N_r-1}\sum_{k=0}^{N_c-1}\left|H_m(k)\exp\left(-j2\pi\frac{k\times n}{N_c}\right)\right|^2 , \qquad (12)\\
&= \frac{1}{N_c}\sum_{m=0}^{N_r-1}\sum_{k=0}^{N_c-1}\left|H_m(k)\right|^2 = \sum_{m=0}^{N_r-1}\sum_{l=0}^{L-1}\left|h_{m,l}\right|^2
\end{aligned}$$

where $(\mathbf{A})_n$ is an $n$th column vector of **A**. Eq. (12) clearly shows that the $(N_r \times L)$th order diversity can be achieved. When a small $M$ is used, the probability of removing the correct symbol candidates at early stages increases. The reason for this is given below. The received signal power associated with the symbol $d(N_c-1-n)$ to be detected at the $n'$th stage ($n' \geq n$, $n=0 \sim N_c-1$) is the sum of the squared values of the $(N_c-1-n')$ to $(N_c-1)$th elements of the $(N_c-1-n)$th column of **R**. When antenna diversity reception is used, the signal power is increases and therefore, the probability of removing the correct symbol candidates at early stage can be reduced. This suggests that a smaller $M$ can be used, thereby reducing the computational complexity of QRM-MLD.

## IV. ITERATIVE V-BLAST[4]

Frequency-domain block signal detection combined with iterative V-BLAST detection is illustrated in Fig.3. V-BLAST uses interference cancellation and is composed of i) ordering, ii) interference cancellation, and iii) signal detection. However, in the case of SC transmission, since the SINR is the same for all symbols, signal detection can be carried out simply from the first symbol (i.e., $d(0)$). Then, the replica of the symbol, which has been just detected, is generated and is subtracted from **Y**. A new MMSE weight matrix for the undetected symbols is computed again and one of these symbols is detected.

The above symbol detection and interference cancellation is repeated until all of the transmitted symbols are detected. However, the V-BLAST detection cannot suppress the ISI sufficiently, in particular for those symbols which have been detected earlier. To further improve the performance, the use of iterative approach is effective [13]. After all of transmitted symbols are detected, V-BLAST detection is carried out again. This is repeated a sufficient number of times.

Two types of iterative V-BLAST detection are considered. The first (called the hard decision iterative V-BLAST in this paper) uses the hard symbol replica which is obtained from the hard decision result. The second (called the soft decision iterative V-BLAST in this paper) uses the soft symbol replica which is generated based on the log-likelihood ratio (LLR). The equalization weight for the signal detection is derived with the residual ISI taken into account.

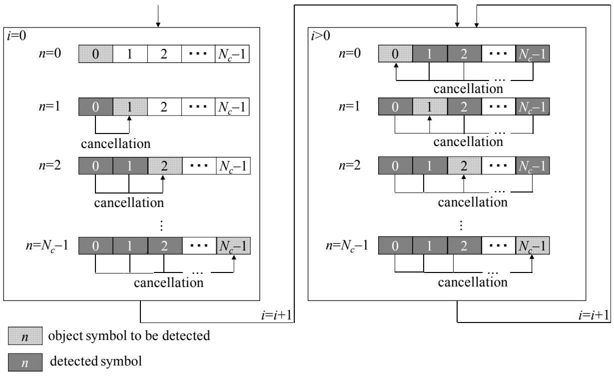

Figure 3: Frequency-domain block signal detection combined with iterative V-BLAST detection.

## V. COMPUTER SIMULATION

The condition for the computer simulation is shown in Table 1. We assume an FFT block size of $N_c$=64 symbols and a GI of $N_g$=16 symbols. The channel is assumed to be a symbol-spaced $L$=16-path frequency-selective block Rayleigh fading channel having uniform power delay profile (i.e., $E[|h_{m,l}|^2]=1/L$). Ideal channel estimation is assumed.

Table 1: Computer simulation condition.

| | | |
|---|---|---|
| Transmitter | Modulation | 16QAM |
| | Block size | $N_c$=64 |
| | GI | $N_g$=16 |
| Channel | Fading type | Frequency-selective block Rayleigh |
| | Power delay profile | $L$=16-path uniform power delay profile |
| | Time delay | $\tau_{m,l}=l$<br>($l$=0~$L$−1, $m$=0~$N_r$−1) |
| Receiver | Channel estimation | Ideal |

### A. Effect of Antenna diversity in QRM-MLD

The average BER performance using QRM-MLD with antenna diversity reception is plotted in Fig. 3 as a function of average received bit energy-to-noise power spectrum density ratio $E_b/N_0(=(E_s/N_0)(1+N_g/N_c)/4)$. Also plotted are the BER performances achievable by the one-tap MMSE-FDE and full MLD. When $N_r$=1(no diversity), the number $M$ of surviving symbol candidates needs to be 256 to achieve the BER performance close to the full MLD. However, by using antenna diversity reception, the achievable BER performance becomes close to the full MLD case when $M$=4. This is because the received signal power increases and hence, the probability of removing the correct symbol candidates at early stages can be reduced.

### B. Comparison of QRM-MLD and iterative V-BLAST

The average BER performances using QRM-MLD and hard decision iterative V-BLAST with antenna diversity reception are plotted in Fig. 4 as a function of average received $E_b/N_0$. Also plotted are the BER performances achievable by the one-tap MMSE-FDE and the full MLD. The number of surviving symbol replica candidates of QRM-MLD is set to $M$=4 when $N_r$>1 and $M$=256 when $N_r$=1. The number of iterations for hard decision iterative V-BLAST is set to $i$=1, which provides sufficiently improved BER performance. In hard decision iterative V-BLAST, error propagation occurs and the ISI still remains. Therefore, when $N_r$=1, the BER performance improvement is smaller than QRM-MLD. On the other hand, by using antenna diversity reception, the achievable BER performance becomes close to the full MLD since the residual ISI is suppressed by antenna diversity reception. When $N_r$=4, hard decision iterative V-BLAST can achieve the same BER performance as the full MLD.

The average BER performances of using QRM-MLD and soft decision iterative V-BLAST with antenna diversity reception are plotted in Fig. 5 as a function of average received $E_b/N_0$. The number of surviving symbol replica candidates in QRM-MLD is set to $M$=4 when $N_r$>1 and $M$=256 when $N_r$=1. The number of iterations for soft decision iterative V-BLAST is set to $i$=1, which provides sufficiently improved BER performance. Since the residual ISI is sufficiently reduced by using the MMSE weight and furthermore, since the influence of error propagation can be reduced by using soft replica, soft decision iterative V-BLAST can achieve almost the same BER performance as the full MLD when $N_r$=2.

### C. Computational complexity

First, we discuss the computational complexity reduction of QRM-MLD by using antenna diversity reception. The complexity here is defined as the number of complex multiply operations. The use of antenna diversity reception can reduce the number of surviving symbol candidates. Therefore, the number of squared Euclidian distance calculations is reduced compared to the single antenna case. When 16QAM is used, the computational complexity of QRM-MLD with $M$=4 and $N_r$=2(4)-branch antenna diversity is about 7.5(13) % of that of QRM-MLD with $M$=256 and $N_r$=1 (single) antenna.

It can be seen from Figs. 4 and 5 that iterative V-BLAST and QRM-MLD can achieve almost the same BER performance. However, their computational complexities are different. Below, we compare their computational complexities. In V-BLAST detection, most of the required computational complexity is due to the calculation of the MMSE weight (matrix inversion). The soft decision iterative V-BLAST requires $(i+1)\times N_c$ times the matrix inversion of size $N_c\times N_c$ and the total number of multiply operations is $(i+1)N_c^4$. Hard decision iterative V-BLAST requires $(N_c-n)\times(N_c-n)$ times the matrix inversion in the $n$th layer of first iteration stage only. Therefore, the number of multiply operations required for the matrix inversion is $(1/2N_c(N_c+1))^2-1$. On the other hand, in QRM-MLD, most of the required computational complexity is due to the QR decomposition and the calculation of the squared Euclidian distance. The number of multiply operations required for the QR decomposition and the calculation of the squared Euclidian distance are respectively $N_rN_c^3$ and $X\{1+(M/2)(N_c+4)(N_c-1)\}$. When $N_r$=2(4), QRM-MLD with $M$=4 and soft (hard) decision iterative V-BLAST using one iteration provide almost same BER performance, but the computational complexity of QRM-MLD is about 0.7(2.4)% of soft (hard) decision iterative V-BLAST when 16QAM is used.

## VI. CONCLUSION

In this paper, we extended the frequency-domain block signal detection combined with QRM-MLD to include antenna diversity reception and evaluated, by computer simulation, the BER performance of SC transmissions. We showed that the use of antenna diversity reception can reduce the number of surviving symbol candidates. We compared the BER performances achievable by QRM-MLD and iterative V-BLAST detection to show that QRM-MLD provides almost same BER performance as the V-BLAST detection with lower computational complexity.

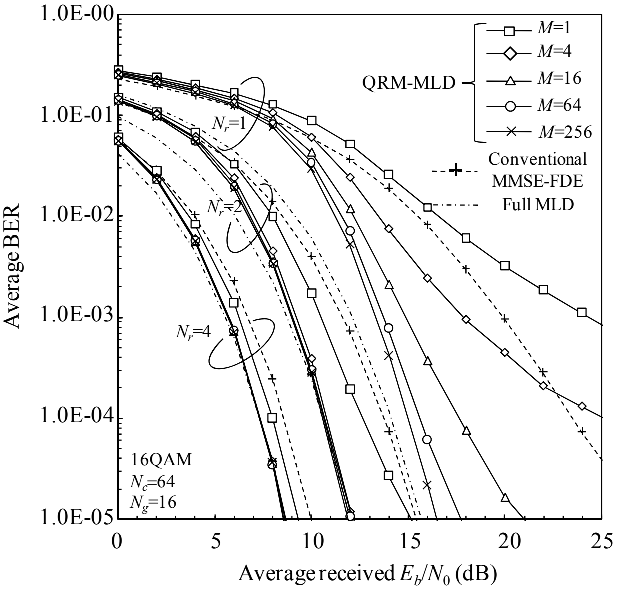

Figure 3: Average BER performances of SC transmission using antenna receive diversity and QRM-MLD.

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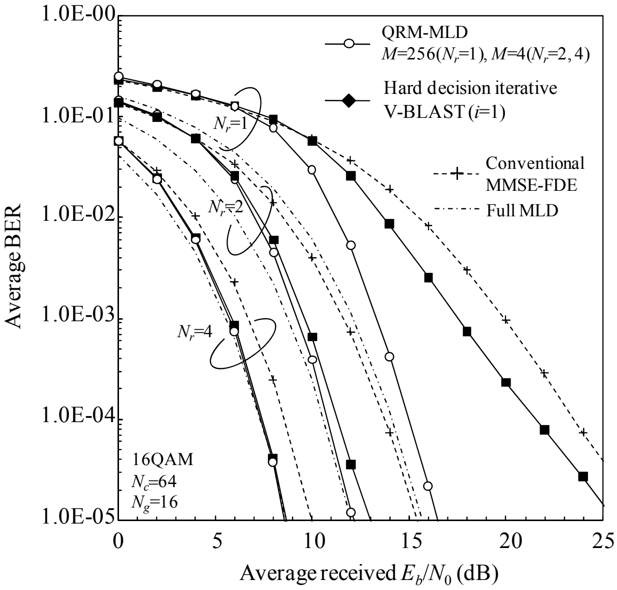

Figure 4: Comparison of QRM-MLD and hard decision iterative V-BLAST.

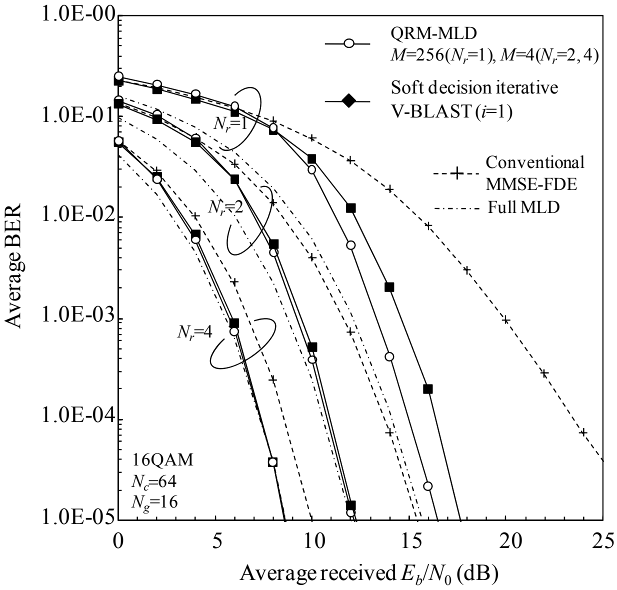

Figure 5: Comparison of QRM-MLD and soft decision iterative V-BLAST.

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