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MIMO 공간 다중화 시스템을 위한 효율적인 심볼 검출기의 설계 및 구현

(Design and Implementation of Efficient Symbol Detector for MIMO Spatial Multiplexing Systems)

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요 약

본 논문에서는 다중 입출력 (MIMO) 공간다중화 (spatial multiplelxing, SM) 시스템을 위한 효율적인 심볼 검출 알고리즘이 제안되고, 이의 최적 설계 및 구현 결과가 제시된다. 에러 전파 (error propagation)을 야기하는 첫 검출 심볼의 검출 성능을 개선시킴으로써, 제안된 알고리즘은 기존의 정렬된 QR 분해 (sorted QR decomposition, SQRD) 기반 알고리즘이나 정렬된 순차적 검출 (ordered successive detection, OSD) 알고리즘에 비해 큰 성능 이득을 얻을 수 있다. 4개의 송수신 안테나를 갖는 16QAM MIMO-SM 시스템에 대한 성능 평가 결과, 제안된 알고리즘은 기존 알고리즘에 비해 10^{-3}의 BER에서 약 2.5-13.5 dB의 성능 이득을 얻음을 확인하였다. 제안된 알고리즘은 하드웨어 설계 언어를 이용하여 설계 되었고, 0.18um CMOS 표준 셀 공정 라이브러리를 이용하여 합성 및 구현되었다. 구현결과, 제안된 알고리즘은 하드웨어의 큰 증가없이 구현 가능함을 확인할 수 있었다.

Abstract

In this paper, we propose an efficient symbol detection algorithm for multiple-input multiple-output spatial multiplexing (MIMO-SM) systems and present its design and implementation results. By enhancing the performance of the first detected symbol which causes error propagation, the proposed algorithm achieves a considerable performance gain as compared to the conventional sorted QR decomposition (SQRD) based detection and the ordered successive detection (OSD) algorithms. The bit error rate (BER) performance of the proposed detection algorithm is evaluated by the simulation. In case of 16QAM MIMO-SM system with 4 transmit and 4 receive (4x4) antennas, at BER=10^{-3} the proposed algorithm obtains the gain improvement of about 2.5-13.5 dB over the conventional algorithms. The proposed detection algorithm was designed in a hardware description language (HDL) and synthesized to gate-level circuits using 0.18um 1.8V CMOS standard cell library. The results show that the proposed algorithm can be implemented without increasing the hardware costs significantly.

Keywords : MIMO, ordered successive detection, QR decomposition, spatial multiplexing, symbol detection

Ⅰ. 서 론

Multiple-input multiple-output spatial multiplexing (MIMO-SM) system can achieve very high spectral efficiency in rich multipath environments through exploiting the extra spatial dimension[1]. By taking advantage of the rich multipath environment, it is shown that the spectral efficiency can reach tens of bps/Hz with multiple antennas. By splitting a single user's data stream into multiple sub-streams and transmitting simultaneously the parallel sub-streams in the same frequency band, the effective trans-

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mission rate in MIMO-SM system increases roughly proportional to the number of transmit antennas used and this makes MIMO-SM an attractive technique for realizing very high spectral efficiency in the future wireless communication systems[2~3].

The optimal detection algorithm for MIMO-SM is a maximum likelihood detection (MLD). Since MLD requires exhausitive search for all transmitted symbols, its complexity exponentially increases as the number of transmit antennas and the constellation size increase. Therefore, its real-time implementation is infeasible when a large number of antennas are used together with high constellation size, e.g. 64QAM. As an alternative, the concept of sphere detection (SD) was introduced in [4] and [5] and has further discussed in various publications[6~8]. In order to avoid the exponential complexity of the MLD, the search for the closest lattice point is restricted to include only vector constellation points that fall within a certain search sphere. This approach allows for finding the ML solution with only polynomial complexity for sufficiently high signal-to-noise ratio (SNR)[7]. However, SD has a disadvantage that the computational complexity varies with different signals and channels. Hence, the detection throughput is non-fixed[9], which is not desirable for the real-time hardware implementation. To resolve this problem, the MLD with QR decomposition and M-algorithm (QRM-MLD) was proposed in [10]. At each search layer in QRM-MLD, only the best M candidates are kept for the next level search and therefore, it has the fixed complexity and throughput which is suitable for pipeline hardware implementation. However, its complexity is still exponentially increasing with the number of transmit antennas, which may bring very large computational complexity and power consumption when high spectral efficiencies are required to support higher communication rates[11].

The most commonly considered technique is ordered successive detection (OSD) algorithm. In MIMO-SM system, a data stream is split into n_T uncorrelated sub-streams, each of which is transmitted using one of the n_T transmit antennas. After being perturbed by a channel matrix H (assuming quasi-static), the n_T sub-streams are picked up by the n_R receive antennas. The sub-stream signal with the highest SNR is detected first and this involves the calculation of the Moore-Penrose pseudo-inverse of the channel matrix H using the zero-forcing (ZF) or minimum mean square error (MMSE) algorithm. Then, the detected symbol of this sub-stream is used to re-generate its contributions at the receive antennas which are subtracted from the n_R received signals. Finally, the corresponding column in the channel matrix H is replaced by zeros and this process repeats with the next strongest sub-stream signal among the remaining undetected signals. Thus, this algorithm detects the n_T symbols in n_T iterations and it has been proven in [1] that this detection order is optimal. However, since a series of calculations of pseudo-inverse is required in the above process, its computational complexity is very high and this intensive computation makes it difficult to be implemented in real-time systems.

Recently, many fast and reduced-complexity algorithms have been proposed for the efficient implementation of MIMO-SM symbol detection algorithm[12~16]. Among them, the sorted QR decomposition (SQRD) based algorithm[13~16] can be a good solution for the real-time implementation because it can be implemented without a series of calculation of pseudo-inverse by jointly calculating a detection order and the QR decomposition of the channel matrix H. However, since SQRD based algorithm does not always lead to the optimized detection order as reported in [16], a performance degradation may occur compared to the OSD algorithm. Especially, since the incorrect detection order degrades mostly the error performance of the first detected layer that causes the error propagation, the total system performance may be seriously degraded.

In this paper, an efficient symbol detection algorithm for MIMO-SM system is proposed, and the design and implementation results are presented. By enhancing the error performance of the first detected symbol, the proposed algorithm achieves a considerable performance gain as compared to that of the SQRD based algorithm.

This paper is organized as follows: In Section II, the system model for MIMO-SM is introduced, and the several QRD-based symbol detection algorithms are reviewed in Section III. In Section IV, the proposed detection algorithm is described, and numerical simulation results are depicted in Section V. Hardware design and implementation results for the proposed detection algorithm are presented in Section VI, and finally the Section VII concludes the paper.

II. System Model

Fig. 1 depicts a MIMO-SM system model considered with n_T transmit and n_R receive antennas where $n_T < n_R$.

At the transmitter end, a single data stream is de-multiplexed into n_T sub-streams, and each sub-stream is then mapped into symbols and transmitted over the n_T antennas simultaneously. The wireless channel is assumed to be rich-scattering and quasi-static frequency-flat fading. At the receive end, each receive antenna receives the signals from all n_T transmit antenna. Letting $\mathrm{s} = [s_1, s_2, \cdots, s_{nT}]^T$ denote the $n_T \times 1$ transmit signal vector, where the superscript T denotes the transpose operation, the corresponding $n_R \times 1$ receive signal vector $\mathrm{x} = [x_1, x_2, \cdots, x_{nR}]^T$ can be represented as

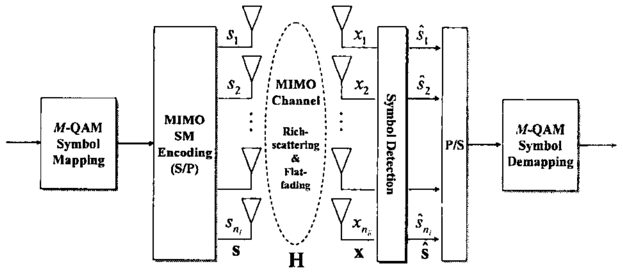

그림 1. n_T개의 송신 안테나와 n_R개의 수신 안테나를 갖는 MIMO-SM 시스템 모델.

Fig. 1. A MIMO-SM system model with n_T transmit and n_R receive antennas.

$$\mathrm{x} = \mathrm{H} \cdot \mathrm{s} + \mathrm{v} \tag{1}$$

where H is the $n_R \times n_T$ complex channel matrix with statistically independent unit-variance entries ($\sigma_c^2=1$). The vector s is assumed to have zero-mean, uncorrelated random variables with variance σ_s^2. The total power of s is assumed to be P. Thus, the covariance matrix of s is given by

$$E(s \cdot s^H) = \sigma_s^2 \cdot \mathrm{I}_{n_T} = \frac{P}{n_T} \cdot \mathrm{I}_{n_T} \tag{2}$$

where the superscript H denotes the conjugate transpose (Hermitian) operation of a vector or matrix and I_{nT} represents the identity matrix with dimension n_T. Note that the total transmitted power does not depend on the number of transmit antennas but is assumed to be fixed at P. The vector $\mathrm{v}=[v_1, v_2, \cdots, v_{nR}]^T$ represents the complex Gaussian noise and is assumed to have zero-mean, uncorrelated random variables with variance σ_v^2 and a covariance matrix $E(\mathrm{v} \cdot \mathrm{v}^H) = \sigma_v^2 \cdot \mathrm{I}_{nR}$. Furthermore, it is assumed that the vectors s and v are independent and thus the following holds: $E(\mathrm{s} \cdot \mathrm{v}^H) = 0$. With the described assumption about the power of the signal and noise, the expected signal-to-noise ratio (SNR) per receive antenna can be found as

$$\rho = \frac{E_s}{N_o} = \frac{n_T \sigma_s^2 \sigma_c^2}{\sigma_v^2} = \frac{P}{\sigma_v^2} \tag{3}$$

where E_s and N_0 denote the signal and noise power per receive antenna, respectively.

III. QRD-Based Detection Algorithms for MIMO-SM Systems

1. Zero-Forcing with Unsorted QRD (ZF-USQRD)

The $n_R \times n_T$ channel matrix H, where $n_T < n_R$, can be decomposed as

$$\mathrm{H} = \mathrm{Q} \cdot \mathrm{R} \tag{4}$$

where Q is an $n_R \times n_T$ unitary matrix and R is an $n_T \times n_T$ upper-triangular matrix, with entries $r_{i,j}=0$, for $i > j$, ($i, j \in \{1, 2, \cdots, n_T\}$), represented as

$$R = \begin{pmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,n_T} \\ 0 & r_{2,2} & \cdots & r_{2,n_T} \\ 0 & 0 & \cdots & r_{3,n_T} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_{n_T n_T} \end{pmatrix} \quad (5)$$

Let us introduce an n_T dimensional column vector y obtained by multiplying from the left the receive signal vector x, given by (1), by the Hermitian matrix of Q

$$y = Q^H x = Q^H(H \cdot s + v) \quad (6)$$

Substituting the QR decomposition of H from (4) into (6), we get for y

$$y = R \cdot s + v' \quad (7)$$

where $v' = Q^H \cdot v$ is an n_T dimensional column vector and its statistical properties remain unchanged because the matrix Q is unitary. As the matrix R is upper-triangular, the ith component in y depends only on the ith and higher layer transmitted symbol, as follows

$$y_i = r_{i,i}s_i + v_i' + \sum_{j=i+1}^{n_T} r_{i,j}s_j \quad (8)$$

Considering s_i as the current desired symbol, (8) shows that y_i contains a lower level of interference than in the received signal x, as the interference from s_l for $l < i$, are suppressed. The third term in (8) represents contributions from other interferers, s_{i+1}, s_{i+2}, $\cdots$, s_{nT}, which are cancelled by using the available decisions assuming that they have been detected. Therefore, the desired symbol is given by

$$\hat{s}_i = Q\left(\frac{y_i - \sum_{j=i+1}^{n_T} r_{i,j}\hat{s}_j}{r_{i,i}}\right), i = 1, 2, \cdots, n_T$$

where $Q(\cdot)$ denotes the slicing functions appropriate to the symbol constellation used.

As mentioned, the order of detection is very crucial for the error probability of the MIMO-SM system due to the risk of error propagation. The sequence of detection is achieved by permuting the components of s and the corresponding columns of H and thereby results in different matrices Q and R. The optimal R maximizes the SNR in each step of the detection process (equals maximizing $|r_{i,i}|$ for $i = n_T, \cdots, 1$) and can be found by performing $O(n_T^2/2)$ QR decompositions of permutations of H[13].

2. Zero-Forcing with Sorted QRD (ZF-SQRD)

The SQRD algorithm is basically an extension of the modified Gram-Schmidt procedure by reordering the columns of H in each orthogonalization step. By applying the Gram-Schmidt algorithm, the QR decomposition computes the matrix R line by line from top to bottom and the matrix $Q = (q_1, \cdots, q_{nT})$ columnwise from left to right. For a given $H = (h_1, \cdots, h_{nT})$, it calculates q_1 of unit length and $r_{1,1} = |h_1|$ to fulfil $h_1 = r_{1,1} \cdot q_1$. In the next step, the components of h_2 in the direction of q_1 are cancelled and q_2 of unit length and $r_{1,2}$ and $r_{2,2}$ are computed to fulfil $h_2 = r_{1,2} \cdot q_1 + r_{2,2} \cdot q_2$. The computation of the next steps is analogous, thus the diagonal elements $r_{i,i}$ represent the length of h_i orthogonal to $q_1, \cdots, q_{i-1}$ and $r_{1,i}, \cdots, r_{i-1,i}$ describe the projection of h_i into the vector space spanned by $q_1, \cdots, q_{i-1}$. Consequently, the diagonal elements are calculated from $r_{1,1}$ to $r_{nT,nT}$. However, as mentioned above, it would be optimal to maximize the $|r_{i,i}|$ in every detection step, that means from $r_{nT,nT}$ to $r_{1,1}$.

The SQRD algorithm finds the permutation of H that minimizes seach $|r_{i,i}|$ for i running from 1 to n_T, leaving all $r_{j,j}$ for $j<k$ unchanged. Therefore, it does not always

표 1. 정렬된 QR 분해 기법.
Table 1. Sorted QR Decomposition.

```
R=0, Q=H, p=(1,⋯,$n_T$)
for $i$ = 1,⋯, $n_T$
    $k_i = \arg\min_{l=i,\dots,n_T} \|\mathbf{q}_l\|^2$
    exchange columns $i$ and $k_i$ in Q, R, and p
    $r_{i,i} = \|\mathbf{q}_i\|$
    $\mathbf{q}_i = \mathbf{q}_i / r_{i,i}$
    for $j$ = $i$+1,⋯,$n_T$
        $r_{i,j} = \mathbf{q}_i^H \cdot \mathbf{q}_j$
        $\mathbf{q}_j = \mathbf{q}_j - r_{i,j} \cdot \mathbf{q}_j$
    end
end
```

표 2. ZF-SQRD 검출 알고리즘.
Table 2. ZF-SQRD Detection Algorithm.

```
(1)  [Q, R, p] = sorted_qrd(H)
(2)  $\mathbf{y} = \mathbf{Q}^H \cdot \mathbf{x}$
(3)  for $i = n_T, \cdots, 1$
(4)      $\tilde{s}_i = y_i / r_{i,i}$
(5)      $\hat{s}_i = Q(\tilde{s}_i)$
(6)      for $j = i, \cdots, n_T$
(7)          $y_{i-1} = y_{i-1} - r_{i-1,j} \cdot \hat{s}_j$
(8)      end
(9)  end
(10) Permute $\hat{\mathbf{s}}$ according to the p
```

lead to the optimal detection order. The only change to the modified Gram-Schmidt algorithm consists of are ordering of the columns of H according to their minimum length orthogonal to the vector space already spanned by $q_1, \cdots, q_{i-1}$. This is performed in lines (4) and (5) of the sorted QR decomposition algorithm shown in Table 1, with the permutation vector p storing the used reordering of H and thereby the order of decoding. With the sorted QR decomposition, the ZF-SQRD detection is summarized in Table 2, where the function *sorted_qrd*(·) denotes the sorted QR decomposition of the channel matrix.

Ⅳ. Proposed Detection Algorithm

Even though SQRD based detection algorithm considerably reduces the complexity by jointly calculating a detection order and QR decomposition, it may show a performance degradation due to a suboptimal detection order. Especially, since the incorrect detection order affects mostly on the first detected symbol that causes the error propagation, the total system performance can be seriously degraded. The proposed algorithm, SQRD based detection with ML test (SQRDML), improves the error performance of the first detected symbol by the following steps:

1) Estimate the decision statistics of the symbol to be first detected via SQRD detection algorithm.

2) Determine the n_C number of candidate symbols, that form an n_C dimensional row vector C_1 around the estimated decision statistics. Since one symbol is not decided immediately and several candidates around it are decided, the error probability of the first detected symbol can be considerably reduced.

3) Cancel the contributions of each candidate symbol in parallel, and determine the n_C number of the second detected symbols. This process is repeated n_T times and the n_T number of row vectors, that form an $n_T \times n_C$ matrix $\hat{c}$, are generated from these processes.

4) Permute the rows of $\hat{c}$ according to the p from SQRD function.

5) Finally, detect the transmitted symbol vector by ML testing over the n_C number of column vectors of $\hat{c}$.

Table 3 summarizes the proposed ZF-SQRDML detection algorithm, where Z is an $n_T \times n_C$ matrix with n_C-times repeated columns, and C is an $n_T \times n_C$ matrix

표 3. ZF-SQRDML 검출 알고리즘.
Table 3. ZF-SQRDML Detection Algorithm.

```
(1)  [Q, R, p] = sorted_qrd(H)
(2)  $\mathbf{y} = \mathbf{Q}^H \cdot \mathbf{x}$
(3)  $\mathbf{Z} = [\overbrace{\mathbf{y} \cdots \mathbf{y}}^{n_C}]$
(4)  for $i = n_T, \cdots, 1$
(5)      $\tilde{\mathbf{C}}_i = \mathbf{Z}_i / r_{i,i}$
(6)      if $i = n_T$
(7)          $\hat{\mathbf{C}}_i = find\_candidate(\tilde{c}_{i,i})$
(8)      else
(9)          $\hat{\mathbf{C}}_i = Q(\tilde{\mathbf{C}}_i)$
(10)     end
(11)     for $j = i, \cdots, n_T$
(12)         $\mathbf{Z}_{i-1} = \mathbf{Z}_{i-1} - r_{i-1,j} \cdot \hat{\mathbf{C}}_j$
(13)     end
(14) end
(15) Permute the rows of C according to the p
(16) $\hat{\mathbf{s}} = \arg\min_{l=1,\ldots,n_C} \|\mathbf{x} - \mathbf{H} \cdot \hat{\mathbf{c}}_l\|^2$
```

with the candidate symbols. The *find_candidate(a)* is the function that finds the candidate symbols around the symbol *a*, which can be simply implemented by look-up table (LUT).

V. Simulation Results

The BER performance of the proposed detection algorithm is evaluated by the simulation. A 16QAM MIMO-SM system with 4 transmit and 4 receive antennas in a slow time varying frequency-flat fading channel is considered.

Fig. 2 shows the BER performance of LD[17], OSD, UQRD, SQRD, and SQRDML (n_C=2 and 4) algorithms with ZF criterion, respectively. It can be observed that at BER=10^{-3} the proposed ZF-SQRDML algorithm with n_C=4 achieves the gain improvement of 11dB over ZF-LD, 9dB over ZF-UQRD, 6dB over ZF-SQRD, and 5dB over ZF-OSD, respectively. For the case of n_C=2, it obtains a gain of 8dB over ZF-LD, 6dB over ZF-UQRD, 3dB over ZF-SQRD, 2dB over ZF-OSD.

The BER performance for MMSE criterion is depicted in Fig. 3. The similar results to the case for ZF criterion are observed. At BER=10^{-3}, the proposed MMSE-SQRDML algorithm with n_C=4 achieves the gain improvement of 13.5dB over MMSE-LD, 12dB over MMSE-UQRD, 7.5dB over MMSE-SQRD, and 5dB over MMSE-OSD, respectively. With n_C=2, it obtains a gain of 11dB over MMSE-LD, 9.5dB over MMSE-UQRD, 5dB over MMSE-SQRD, and 2.5dB over MMSE-OSD, respectively.

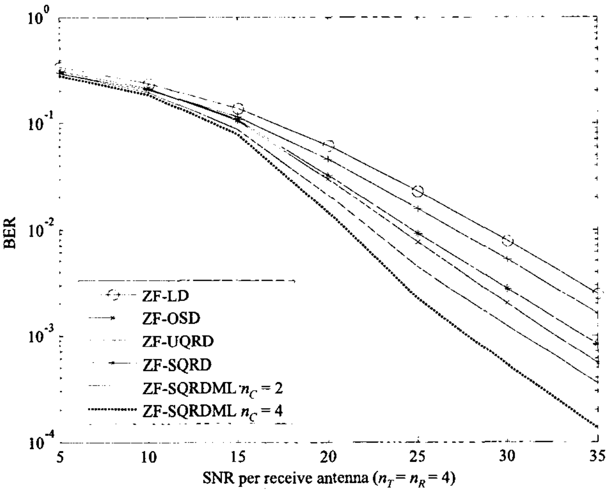

그림 2. ZF-LD, ZF-OSD, ZF-SQRD, ZF-SQRDML (n_C=2), ZF-SQRDML (n_C=4) 알고리즘의 BER 성능.

Fig. 2. BER performance of ZF-LD, ZF-OSD, ZF-SQRD, ZF-SQRDML with n_C=2, and ZF-SQRDML with n_C=4.

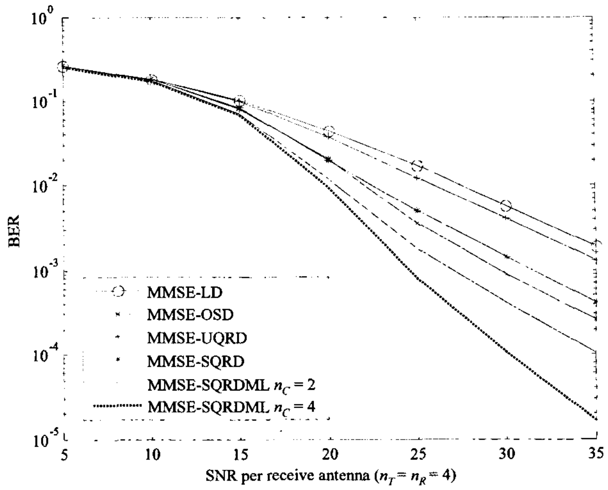

그림 3. MMSE-LD, MMSE-OSD, MMSE-SQRD, MMSE- SQRDML (n_C=2), MMSE-SQRDML (n_C=4) 알고리즘의 BER 성능.

Fig. 3. BER performance of MMSE-LD, MMSE-OSD, MMSE-SQRD, MMSE-SQRDML with n_C=2, and MMSE-SQRDML with n_C=4.

VI. Design and Implementation Results

Fig. 4 depicts the block diagram of the proposed SQRDML detection algorithm. As shown in this figure, the proposed algorithm requires the additional hardware such as ML test block (MLTB), and therefore one may make an issue of the hardware complexity of the proposed algorithm. However, since MLTB is a simple amplitude comparison block, the hardware bit precision can be significantly reduced.

Fig. 5 shows the fixed-point simulation result for

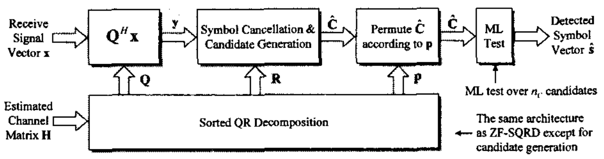

그림 4. 제안된 SQRDML 알고리즘의 블록도.

Fig. 4. Block diagram of the proposed SQRDML detection algorithm.

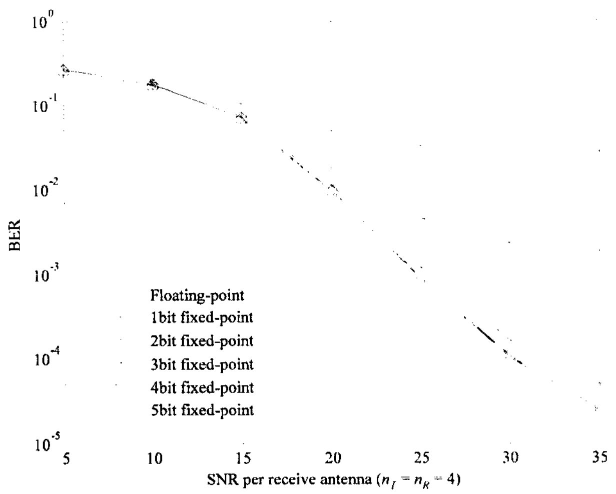

그림 5. MMSE-SQRDML (n_C=4) 알고리즘의 부동 소수점 및 고정 소수점 BER 성능.

Fig. 5. BER performance of MMSE-SQRDML with n_C=4 by floating-point and fixed-point simulation.

MLTB in the proposed SQRDML detection algorithm with MMSE criterion. As shown in this figure, the performance for the four bit precision is nearly the same as that for floating-point case, and therefore the MLTB can be implemented with the four bit precision.

Table 4 depicts the logic synthesis and power analysis results of the proposed ZF-SQRDML detection algorithm with n_C=4 for the MIMO-SM system with 4 transmit and 4 receive antennas. From the results, it is observed that the sorted QR decomposition block (SQRB) is the most dominant block for the complexity. Even though the SQRB is excluded (since it is in a preamble phase), the next dominant block is the $Q^H \cdot x$ calculation block (QxCB) rather than the MLTB or the symbol cancellation & candidate generation block (SCCGB). As shown in Fig. 4, the SQRB and QxCB are a common block for both SQRD and SQRDML detection algorithms. Therefore, it can be found out that the complexity increase of the proposed algorithm is not significant as compare to the SQRD detection algorithm. It is more clearly confirmed by the results shown in Table 5. As shown in this table, in case of $n_T = n_R = 2$, the proposed SQRDML algorithm requires the additional logic gates of 30.4% and power of 30.9%, respectively; in case of n_T=n_R=4, it requires the additional logic gates of 24.3% and power of 23.5%. As the number of transmit and receive antennas increases, it is expected that the rate of the additional gates and power more decreases since the proportion of SQRB and QxCB increases more rapidly as compared to the other blocks such as SCCGB, MLTB, and permutation block (PB). Therefore, with a reasonable complexity overhead and a considerable performance enhancement, the proposed algorithm can be a good solution for MIMO-SM systems.

표 4. 제안된 ZF-SQRDML (n_C=4) 검출 알고리즘의 논리 합성 및 전력 소모량 분석 결과.

Table 4. Logic synthesis and power analysis results of the proposed ZF-SQRDML detection algorithm with n_C=4*.

	Logic Gates		Power Consumption	
	Gate Count	%	Power(mW)	%
SQRB	409K	52.2	63.3	43.8
QxCB	184K	23.5	44.5	30.8
SCCGB	73K	9.4	14.3	9.9
PB	4K	0.4	0.6	0.4
MLTB	113K	14.5	21.8	15.1

* Logic gates and power consumption are analyzed with 0.18um 1.8V CMOS standard cell library.

표 5. 기존의 SQRD 알고리즘과 제안된 SQRDML 알고리즘의 논리 게이트수 및 전력소모량 비교 결과.

Table 5. Comparison results of the SQRD and proposed SQRDML detection algorithm for logic gates and power consumption.

	n_T=n_R=2			n_T=n_R=4		
	SQRD	SQRDML	%	SQRD	SQRDML	%
Gates	148K	193K	30.4	630K	783K	24.3
Power	29.7	38.9	30.9	116.9	144.4	23.5

VII. Conclusion

In this paper, we have reviewed the several detection algorithms and proposed the efficient algorithm for MIMO-SM systems. By improving the error probability of the first detected symbol, the proposed algorithm compensates for the degradation caused by an incorrect detection order and achieves a considerable performance gain. The extensive simulations provided in this paper demonstrate that the proposed algorithm dramatically improves the performance as compared to that of the conventional algorithms such as SQRD and OSD. In case of 16QAM 4×4 MIMO-SM system, it obtains the gain improvement of 2.5-13.5 dB over the conventional algorithms. Through the complexity analysis, it is also observed that the proposed algorithm can be implemented without increasing the hardware costs significantly. Therefore, with a considerable performance improvement and a low computational complexity, the proposed algorithm can be a good solution for MIMO-SM systems.

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