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Reduced Complexity Detection Algorithm for Spatial Modulation

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ABSTRACT

In this paper, we propose a novel detection algorithm for SM (Spatial Modulation) system to reduce the receiver complexity while achieving a near maximum likelihood (ML) performance. ML detection is known to achieve an optimal performance for SM system. However, the high computational complexity still remains as a problem to be solved in case of using the large number of antennas or high modulation order. The proposed detection algorithm reduces the number of possible candidates for ML detection to avoid exhaustive works. We compare the proposed algorithm and conventional algorithms both in terms of bit error rate (BER) and computational complexity. Simulation results show that the proposed detection algorithm substantially reduce computational complexity and achieves the better BER performance than the conventional algorithms even though the number of candidates is decreased.

KEYWORDS: Multiple-input-multiple-output (MIMO), Spatial Modulation (SM), Maximum-likelihood detection (ML), Receiver complexities

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1. Introduction

Wireless communications have experienced an explosive growth with the demand for higher data rates to accommodate new multimedia services growing rapidly. Therefore, to satisfy the technical demand several approaches such as increasing modulation order or employing multiple antennas at both transmitter and receiver have been studied to enhance the spectral efficiency [1]. Multiple

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input multiple output (MIMO) communication has been recognized as a promising technology to improve the quality of service and to achieve high data rate for wireless communication systems. The MIMO systems can be categorized into two types. One is spatial multiplexing, which is also known as the vertical Bell Laboratories layered space-time (V-BLAST) architecture. Spatial multiplexing is a method to increase the data rate by transmitting independent data streams in parallel through multiple antennas [2]. The other is spatial diversity to overcome the deep fades due to multipath by combining multiple uncorrelated signals Space-time block codes, which reduces the bit error probability for the same spectral efficiency is the example of exploiting spatial diversity [3].

However, several problems are encountered in MIMO systems. Due to inter-channel interference (ICI) caused by coupling multiple symbols in time and space, a receiver requires a complex algorithm which increases the overall system complexity. The complexity of the system will be increased exponentially according to the number of transmit antennas and inter-antenna synchronization (IAS) is essential due to simultaneous transmissions. Furthermore, the main limitation of using multiple antenna architecture is the high cost of the hardware in the radio frequency (RF) chains. RF elements are expensive and it is not simple to implement [4].

Spatial modulation (SM), introduced by Mesleh et al. in [5], is recently proposed to remove the aforementioned problems. In SM, only one transmit antenna is active at any one time instant so that ICI and IAS in conventional MIMO systems are efficiently avoided. In addition, SM employs the antenna index as an additional source of information to enhance the spectral efficiency. The basic detection algorithm, called iterative-maximal ratio combining (i-MRC) is introduced in [5]. However, it can only work under some constrained conditions. Normalized-maximal ratio combining (N-MRC) algorithm is proposed in [6], which works normally under the constrained channel condition. But it cannot achieve the optimal performance in terms of BER. Maximum Likelihood (ML) detection [7], which makes an exhaustive search over the signal modulation constellation is known to achieve an optimal performance for SM. However, the high computational complexity still remains a problem in case of using the large number of antennas or high modulation order [9]-[10]. Recently, a distance-based ordered detection (DBD) algorithm which achieves near optimum performance is proposed in [11]. However, DBD algorithm calculates the distance of whole candidates for ML detection. So, the complexity is high when the number of transmit antenna is increasing since it requires to calculate over all transmit antennas.

In this paper, we propose a novel detection algorithm for SM systems in order to reduce the computational complexity. Proposed algorithm searches the valid candidates for ML detection algorithm and it is computationally efficient compared with the conventional algorithm. In addition, it is shown by computer simulations that the proposed detection algorithm has significant performance advantages over the conventional

DBD algorithm when the number of candidates is decreased.

The remainder of this paper is organized as follows. Section 2 introduces the SM system model with optimum ML detection algorithm. In Section 3, the proposed detection algorithm for SM is presented. Simulation results are presented in Section 4. Finally, Chapter 5 includes the conclusion of the paper.

2. System Model

SM system model with four transmit antennas and quadrature phase shift keying (QPSK) symbols is depicted in <Figure 1>.

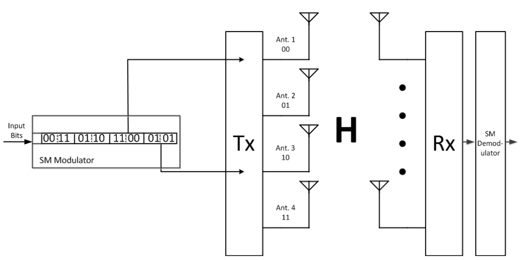

그림 1. 공간 변조 시스템 모델

Figure 1. Spatial modulation system model

In general, the number of bits that can be transmitted using spatial modulation is given as

$$m = \log_2(N_t) + \log_2(M), \qquad (1)$$

where M and N_t represent the constellation and the number of transmit antenna, respectively. As shown in <Figure 1> the input bits are divided into blocks, which containing m bits each. Then, each block is separated into two sub-blocks of $\log_2(N_t)$ and $\log_2(M)$ bits each. The first sub-block is used to select the transmit antenna number and second sub-block is used to choose a symbol in the constellation. As shown in <Figure 1> in the first time instance, the third transmit antenna will be active and in the second time instance, all transmit antennas are off except the first antenna. Each antenna will be transmitting the QPSK symbol, which is chosen in the constellation using the second sub-block. SM system with N_t transmit antennas and N_r receive antennas, a random sequence of independent bits enters the SM mapper, which groups m bits and maps them to a constellation vector $\mathrm{x} = [\, x_1 \; x_2 \cdots x_{N_t}]^T$, with a power constraint of unity (i.e. $E_{\mathrm{x}}[\mathrm{x}^H \mathrm{x}] = 1$), where $(\cdot)^{\mathrm{H}}$ represents Hermitian operation which means conjugate transpose. In SM, only one transmit antenna remains active during the transmission and hence, only one of the x_j in x is nonzero. Then, the transmit vector combined with antenna index is given by

$$x_{j,q} \triangleq [0 \;\cdots\; 0 \;\; \underset{\substack{\uparrow \\ j^{th}\ position}}{x_q} \;\; 0 \cdots 0]^T, \qquad (2)$$

where $j = 1, \cdots, N_t$ represents the activated antenna, and x_q is the q^{th} symbol from the M-ary constellation.

Let the signal is transmitted over an $N_r \times N_t$ wireless channel H, whose elements are assumed to be complex Gaussian random variables with zero mean and unit variance, so the $N_r \times 1$ received signal is given by

$$\mathrm{y} = \mathrm{H} x_{j,q} + \mathrm{n}, \qquad (3)$$

where $\mathrm{n} = [n_1 \ n_2 \ \cdots \ n_{N_t}]^T$ is additive white Gaussian noise (AWGN) which has independent and identically distributed (i.i.d) entries with zero mean and variance of σ^2. Using the equation (3), the output of the channel when x_q is transmitted from the j^{th} antenna is simply expressed as

$$\mathrm{y} = \mathrm{H}_j x_q + \mathrm{n}, \qquad (4)$$

where h_j denotes the j^{th} column of H.

An optimal maximum likelihood (ML) detection algorithm for SM system is proposed in [7]. According to the ML detection algorithm, all transmit antennas and modulated symbols are searched. Then, the group with minimum Euclidean distance (MED) is selected from the received vector as output. We assume that the channel state information (CSI) is perfectly known at receiver. ML detection algorithm can be described as

$$(\hat{j}, \hat{x_q}) = \arg\min_{j,q} \| \mathrm{y} - \mathrm{h}_j \mathrm{x_q} \|_{\mathrm{F}}^2, \qquad (5)$$

where $j = 1,2,\cdots,N_t$, $q = 1,2,\cdots,M$, and $\| \cdot \|_F^2$ represents the Frobenius norm of the vector/matrix. The ML detection algorithm achieves optimal performance for SM systems, however, its computational complexity is high because it requires to exhaustive search of all transmit antennas and modulated symbols.

3. Proposed Detection Algorithm

The conventional DBD detection algorithm proposed in [11] calculates the distance of whole candidates for ML detection. So, the complexity is high when the number of transmit antenna is increasing since it requires to calculate over all transmit antennas. Through the preprocessing and selection of transmit antenna candidates, we can efficiently reduce the number of repetitive computations. In proposed detection method, the receiver first normalizes the every column of the channel H. Here we assume the channel H is assumed to be known at the receiver.

Antenna index estimation based maximum ratio combining (MRC) is proposed in [8]; however, the algorithm can only work under following conditions.

$$|\mathrm{h}_i^H \mathrm{h}_i| = \| \mathrm{h}_i \|^2 \geq |\mathrm{h}_j^H \mathrm{h}_i|, \qquad (6)$$

where $j = 1,2,\cdots,N_t$, h_i is the $N_t \times 1$ vector, and k^{th} column vector of H .

At the same time, if we want to obtain the correct demodulated symbols the diagonal elements of $\mathrm{H}^H\mathrm{H}$ must be 1, which means

$$E[\mathrm{h}_i^H \mathrm{h}_j] = \delta_{i,j}, \qquad (7)$$

where $\delta_{i,j}$ is Kronecker delta function. If a channel matrix meets the requirement of (6) and (7), we call the channel constrained channel. If channel is unconstrained channel, the original detection algorithm cannot work normally. So, every column of the channel matrix should be normalized by its norm through preprocessing, called as normalized MRC (NMRC) [6]. Then, above conditions can be satisfied, and MRC-based algorithm can be applied. The normalized channel can be represented as

$$\overline{\mathrm{h}_j} = \mathrm{h}_j / \| \mathrm{h}_j \| , \quad (8)$$

where $j = 1,2,\cdots,N_t$. Using the preprocessed channel $\overline{\mathrm{h}_j}$, the receiver estimates the transmit antenna candidate vector $\boldsymbol{\alpha}$ by using

$$\overline{\mathrm{g}_j} = \overline{\mathrm{h}_j}^H \mathrm{y} , \quad (j = 1,2,\cdots,N_t) \quad (9)$$

$$\boldsymbol{\alpha} = \arg\max_j \left\{ v\left(\left[\overline{\mathrm{g}_j} \right]_{j=1,2,\cdots,N_t}, L \right) \right\}, \quad (10)$$

where $1 < L < N_t$ and $\boldsymbol{\alpha}$ is obtained by calculating $\arg\max\{v(\overline{\mathrm{g}}, L)\}$, which is chosen as L transmit antenna candidates of a vector $\overline{\mathrm{g}}$ that consists of N_t elements calculated in (9) and is represented as a rearranged vector in order of highest – value - first.

$$\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \cdots, \alpha_l, \cdots, \alpha_L] \; . \quad (11)$$

For symbol estimation, equation (4) is required to be left multiplied by $\mathrm{h}^{\dagger}$ to get the estimation of symbol r, where $(\cdot)^{\dagger}$ represents pseudo inverse of a matrix. In general, NMRC process is $\mathrm{h}^{\dagger} = (\mathrm{h}^H \mathrm{h})^{-1} \mathrm{h}^H / \| \mathrm{h} \|^2$, $\mathrm{r}_{\alpha_l} = \mathrm{h}_{\alpha_l}^H \mathrm{y} / \| \mathrm{h}_{\alpha_l} \|^2$ [6]. Therefore, symbols corresponding to each selected antenna index in (11) are estimated as

$$\mathrm{r}_{\alpha_l} = \mathrm{h}_{\alpha_l}^H \mathrm{y} / \| \mathrm{h}_{\alpha_l} \|^2 = \overline{\mathrm{g}_{\alpha_l}} / \| \mathrm{h}_{\alpha_l} \| , \quad (12)$$

$$\widehat{r_{\alpha_l}} = Q(r_{\alpha_l}) , \quad (13)$$

where $l = 1, 2, \cdots, L$, Q(.) is the constellation quantization function and all the vectors, and matrices are shown without subscription l to avoid complicated expression, so we denote the notation α includes notation with subscription α_l, which means that we abbreviated for clarity as $\alpha = \alpha_l$.

When we calculate the distance between $\widehat{r_\alpha}$ and r_α

$$d_\alpha = \| \mathrm{h}_\alpha \| \left| \widehat{r_\alpha} - r_\alpha \right| . \quad (14)$$

In (14), the distance must be multiplied by $\| \mathrm{h}_\alpha \|$ to return to unscaled form (before normalized scale) because the calculated distance is expressed on the actual scale. So, we need to calculate the actual distance on the transmitted constellation.

Here we introduce a parameter $P(1 \le P \le L)$ which means the number of preselected antenna indices and represents a trade-off between performance and complexity likewise the DBD algorithm [8].

표 1. 제안된 SM 시스템을 위한 검출 알고리듬
Table 1. The proposed detection algorithm for SM system

Output: estimated transmit antenna index $\hat{j}$, estimated symbol $\hat{x}_q$
Step 1. Initialization: channel matrix $H=[h_1, h_2, \cdots, h_{N_t}]$;   # of candidates P;   # of candidates L; # of transmit antenna N_t;   # of receive antenna N_r Step 2. Preprocess the channel and estimate the transmit antenna index   *for* $j=1:N_t$ compute the norm $\Vert h_j \Vert$ for $j=1,2,\ldots N_t$ $\overline{h_j}=h_j/\Vert h_j \Vert$ *// column n vector of the channel matrix,* h_j*, is normalized by its norm* $\Vert h_j \Vert$ $\overline{g_j}=h_j^H y$ *// the value* $\overline{g_j}$ *is computed form different transmit antennas*   *end*   *set L* $L \ge P$, $\alpha=\arg\max_j \left\{ v\left([\overline{g_j}]_{j=1,2,\cdots,N_t}, L \right) \right\}$, $(1<L<N_t)$ antenna sequence : $\alpha=[\alpha_1, \alpha_2, \cdots, \alpha_l, \cdots, \alpha_L]$ Step 3. Symbol estimation according to the estimated antenna index   *for* $\alpha_l=1:L$ $r_{\alpha_l}=h_{\alpha_l}^H y/\Vert h_{\alpha_l} \Vert^2=\overline{g_{\alpha_l}}/\Vert h_{\alpha_l} \Vert$ *end* $\hat{r}_{\alpha_l}=Q(r_{\alpha_l})$ Step 4. Obtain the preselected antenna index sequence in order of smallest-value-first: *for* $\alpha_l=1:L$ $d_{\alpha_l}=\Vert h_{\alpha_l} \Vert \left\vert \hat{r}_{\alpha_l}-r_{\alpha_l} \right\vert$ *// calculate the distance between* $\overline{g_{\alpha_l}}$ *and* g_{α_l} *end*   Step 5. Select the transmit antenna index and symbol $\zeta=\arg\min_{\beta\in\boldsymbol{\beta}} \Vert y-h_\beta \hat{r}_\beta \Vert^2$ *// select the estimated antenna index* $\hat{x}_q=\hat{r}_\zeta$ *// select the estimated symbol* $\hat{x}_q$ *through the antenna index* ζ

The preselected antenna indices are chosen by distance calculated in (14) in order of smallest-value-first. Then, an ordered antenna index sequence could be represented as β $=[\beta_1, \beta_2, \cdots, \beta_p, \cdots, \beta_P]$, where β_1 and β_P denote the antenna index with minimal and maximal distance, respectively. In order to obtain the finally estimated antenna index we calculate the minimum Euclidean distance (MED) among the symbol group $\hat{r}_{\beta_p}=[\hat{r}_{\beta_1}, \hat{r}_{\beta_2}, \ldots, \hat{r}_{\beta_p}, \ldots, \hat{r}_{\beta_P}]$ as followed equation (15); therefore, we can obtain the finally the estimated antenna index $\hat{\beta}$ for the activated antenna j in (2). Here we wrote as $\beta=\beta_p$ for clarity and easy expression.

$$\hat{\beta}=\arg\min_{\beta\in\boldsymbol{\beta}} \Vert y-h_\beta \hat{r}_\beta \Vert^2. \tag{15}$$

The finally estimated symbol $\hat{x}_q$ among the symbol group $\hat{r}_\beta$ can be obtained using the result of (15) as

$$\hat{x}_q=\hat{r}_\zeta. \tag{16}$$

Therefore, the estimated antenna index ζ and the corresponding modulated symbol $\hat{x}_q$ are obtained. The proposed algorithm is summarized in <Table 1>.

As aforementioned, both parameter L and P represent a trade-off between performance and complexity. For proposed algorithm, computational complexity is reduced by selecting P antenna indices of L selected antenna indices through NMRC. If L and N_t are the same, the complexity is same as that of conventional DBD algorithm [11].

표 2. SM 검출 알고리듬의 계산 복잡도 비교
Table 2. Computational complexity Comparison of SM detection algorithms

detection algorithm	Complexity (# of multiplication operation)
i-MRC	$4N_rN_t$
N-MRC	$4N_t(2N_r+1)+2$
ML	$8N_rN_tM$
DBD	$2N_r(5N_t+4P)+7N_t$
Proposed	$8N_r(N_t+P)+4N_t+6L$

The computational complexity of the proposed algorithm is represented with the other SM detection algorithms in Table 2. Suppose the size of the constellation is M, and the computational complexity is evaluated by the number of multiplication operations. And the complexity of $(\cdot)^H$ and $Q(\cdot)$ is neglected since they do not require additional operation.

4. Simulation Results

4.1 BER Performance

In this section, we compare the performance of the proposed SM detection algorithm to the conventional algorithms. Simulations are performed for SM system with spectral efficiency of 4 bits/s/Hz and 5 bits/s/Hz. In the simulation, a flat Rayleigh fading channel is assumed with additive white Gaussian noise (AWGN) and the receiver has the perfect channel state information (CSI). <Figure 2> shows the bit error rate (BER) performance of the proposed algorithm in comparison with ML detection algorithm.

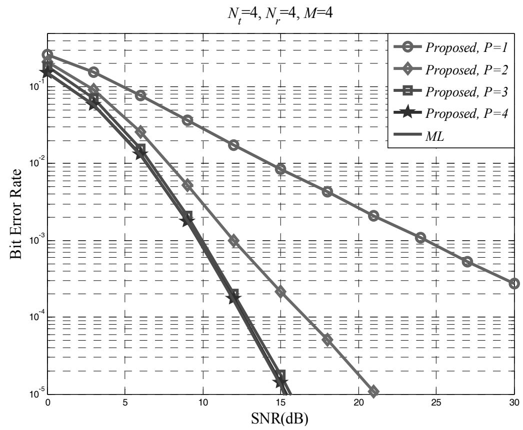

그림 2. 제안 알고리듬의 BER 성능
Figure 2. BER performance of the proposed algorithm

It is shown that the BER performance improves with the increasing of P, which is the number of candidates for final decision in proposed algorithm. For $P=4$, the proposed algorithm approaches ML detection algorithm which achieves optimal performance in SM system. There is a trade-off between the BER performance and computational complexity. That is, increasing the size of P can provide an improvement in BER performance at the cost of increased computational complexity. Therefore, P should be selected carefully to make a good trade-off. As shown in Fig. 2, in the case of $P=3$ and $P=2$, it shows 0.1 dB and 3.5 dB worse performance than $P=4$ at the BER of 10^{-4}. From the complexity point of view, however, $P=3$ could be a good choice for SM systems. <Figure 3>. shows the BER comparison of the proposed algorithm and DBD algorithm which achieves near-ML performance when P is increasing.

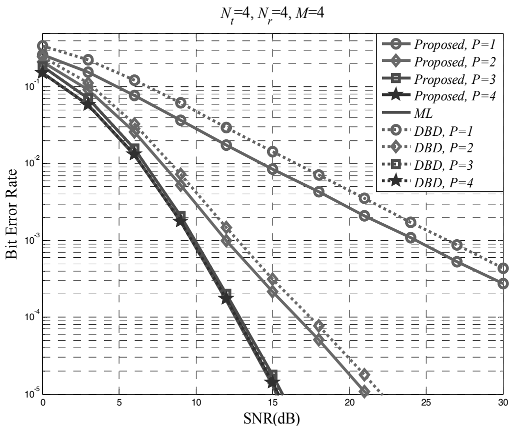

그림 3. DBD와 제안 알고리듬의 BER 성능 비교

Figure 3. BER performance comparison of the DBD and proposed algorithm

Proposed and DBD algorithm are represented as dotted line and solid line, respectively. BER performance of both algorithms improves with the increasing of P . In case of $P=4$, proposed and DBD algorithm approach ML detection and $P=3$ for, there is 0.1 dB penalty of SNR for both algorithms at the BER of 10^{-4}. For $P=1$ and $P=2$, proposed algorithm achieves 1 dB and 3 dB better performance than DBD algorithm at the BER of 10^{-3}. That is, proposed algorithm performs nearly the same as the conventional DBD algorithm when the number of candidates is increasing. However, proposed algorithm achieves better BER performance when P is decreasing.

4.2 Comparison of the Computational Complexity

In this section, we investigate the computational complexity of the proposed and conventional SM detection algorithms. More specifically, we compare the computational complexity of each detection algorithm in terms of modulation order and the number of antennas.

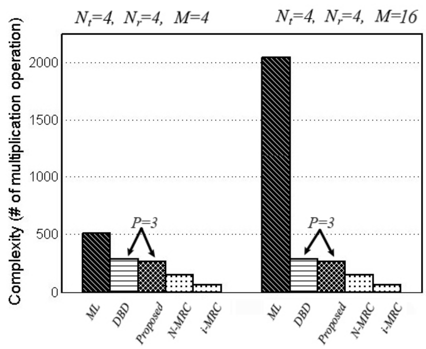

그림 4. SM 알고리듬들 간의 복잡도 비교

(4 bits/s/Hz, 6 bits/s/Hz)

Figure 4. Complexity comparison of SM detection algorithms

(4 bits/s/Hz, 6 bits/s/Hz)

<Figure 4> shows the comparison of the computation complexity of SM detection algorithms according to the modulation order. In this case, a fixed number of antennas are considered. It is shown that the computational complexity of all detection algorithms is not changing except for ML detection. The complexity of ML detection grows exponentially because it requires to exhaustive search of all modulated symbols. i-MRC algorithm has the lowest complexity among the rest of four detection algorithms for both comparisons. However, it works only in the constrained channel. DBD and proposed algorithm with $P=3$ have substantial complex advantages compared to ML detection in the case of high order modulation. N-MRC achieves lower complexity than DBD and proposed algorithms

but it cannot achieve near-ML performance in terms of BER. Therefore, proposed algorithm with can achieve near optimum performance in this case. The complexity comparison of SM detection algorithms according to the number of antennas is represented in Fig. 5.

In <Figure 5>, it is shown that the complexity of SM detection algorithms is increasing with the number of antennas. For SM system, spectral efficiency is increasing with the number of transmit antenna. That is, in case of the fixed modulation order of $M=4$, the number of transmit antenna $N_t=8$ and $N_t=4$ represent spectral efficiency of 5 bits/s/Hz and 4 bits/s/Hz, respectively.

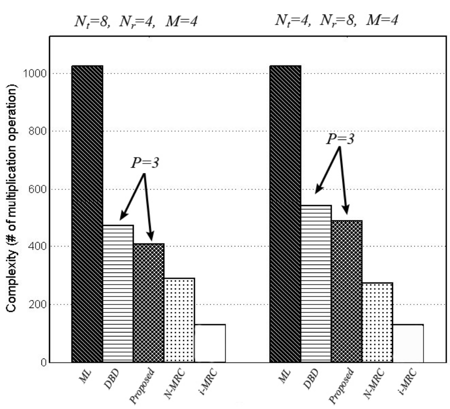

그림 5. SM 알고리듬들 간의 복잡도 비교
(5 bits/s/Hz, 4 bits/s/Hz)
Figure 5. Complexity comparison of SM detection algorithms
(5 bits/s/Hz, 4 bits/s/Hz)

5. Conclusions

In this paper, a novel detection algorithm for SM system has been proposed. We compare the proposed algorithm with the conventional detection algorithms from BER and computational complexity performances point of view. In addition, we confirm that there is a trade-off between the BER performance and computational complexity. As a result, the proposed algorithm achieves near-ML performance in terms of BER and the computational complexity is much lower than ML detection algorithm. Furthermore, in comparison to the conventional algorithm, which also achieves near-ML performance with low complexity at the same time, proposed algorithm outperforms conventional algorithm in terms of complexity achieving the same BER performance. Also, if the number of candidates is decreasing, proposed algorithm achieves better BER performance than conventional algorithm.

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SM 변조된 신호의 검출을 위한 간소화 알고리듬

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요 약

본 논문에서는 공간 변조(SM) 시스템에서 수신기의 성능이 ML 성능에 근접하면서 복잡도를 줄일 수 있는 검출 알고리듬을 제안하다. ML 검출은 SM 시스템에서 최적 성능을 제공한다고 알려져 있다. 그러나 안테나의 수가 많거나 또는 고차 변조를 사용하는 경우 복잡도는 풀어야 할 문제로 남아 있다. 제안한 검출 알고리듬은 ML에서 소모적인 일을 피하기 위하여 ML 검출 가능성이 높은 후보를 줄이는 방식이다. 제안한 방식과 기존 방식을 비트오율(BER)과 계산 복잡도를 비교한다. 시뮬레이션 결과들은 후보군을 줄이더라도 제안한 알고리듬이 기존 방식들에 비하여 성능이 좋을 뿐더러 계산 복잡도가 줄어듦을 보인다.

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