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Enhanced generalized space shift keying with search field based iterative MLD for 6G

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ABSTRACT

This paper proposes the novel enhanced generalized space shift keying (EGSSK) to improve the spectral efficiency (SE) and energy efficiency (EE). In conventional GSSK, all of antenna combinations are not used because of power-of-two form. To overcome this problem, we suggest to exploit spare antenna combination for cell-edge users (CEUs). Concurrently, we propose the search field based iterative maximum likelihood detector (SFMLD) to reduce the complexity at the receiver. The simulated and analytical results are shown in terms of SE, average bit error rate (ABER), complexity and EE.

1. Introduction

The advent of wireless technology has increased the expansion from connecting human beings to various things. For social infrastructure and daily lives, wireless communication has become an essential part with advanced technologies such as artificial intelligence (AI), robotics, and automation. This kind of environment leads toward satisfying major requirements such as system capacity, massive connectivity, and energy reduction. For heterogeneous networks, there are three services: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communications (URLLC). With 6G wireless networks, as successors of 5G networks, these services overlap to achieve extreme coverage and reliability according to a key performance indicator (KPI) [1–5]. These KPIs are achieved by improving spectral efficiency (SE), energy efficiency (EE) and reducing complexity with multiple-input multiple-output (MIMO) system. As a physical layer solution for 6G wireless network, the index modulation (IM) is considered as the innovative way to convey extra information.

Following the trend, many researchers have investigated in IM which is a promising technology to meet the SE, EE and low complexity. The main idea for IM is to obtain additional index bits through available transmit entities such radio frequency (RF) mirrors, subcarriers, time slots, and antennas [6–9]. Therefore, the IM schemes have opportunities to save energy by deactivating the main elements for beyond and 5G wireless systems. Additionally, IM comes up with new dimensions to convey index information without increasing the hardware complexity. Owing to the design and implementation of IM, the antenna-based IM is a promising technique that can reduce the associated hardware costs. Additionally, massive MIMO systems [10], where each base station (BS) is equipped with more antennas like 100 or more, come up with IM to provide the high degree of freedom and data rate.

Spatial modulation (SM) [11] is the representative technology of antenna-based IM. Space shift keying (SSK) [12] is proposed based on the conventional SM technique. The recent SM/SSK related literature has introduced in [13] to uncover other promising progresses with emerging wireless communication systems. Contrary to SSK, generalized spatial modulation (GSM) [14] is proposed to increase SE which is extended from generalized space shift keying (GSSK) [15]. In [16], a combination of two-way relaying with SSK is introduced to valid transmit power optimization. Moreover, the SM/SSK scheme was extended into the in-phase/quadrature domain which is called as quadrature SM (QSM) [17] to increase SE of SM/SSK by doubling the length of index bits. More recently, generalized precoding-aided QSM (GPQSM) [18] is proposed employing precoding which require channel state information (CSI) at the transmitter. The generalized quadrature spatial modulation (GQSM) [19] is proposed to increase the SE by collaborating with non-orthogonal multiple access (NOMA).

As described earlier, diverse researches on GSSK have focused on combination of additional information and modulation. However, GSSK has an apparent weakness because of the antenna combination which is indexed by the transmit and active antennas. Unused antenna combination are wasted because antenna

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combinations consist of power-of-two form. The perturbation is arisen to enhance SE by exploiting spare antenna combinations. To the best of our knowledge, a previous paper [20] proposed to exploit spare antenna combinations using error correction code (ECC) to impose redundancy while reducing symbol error rate (SER).

The optimal detector for GSSK which is a maximum likelihood detector (MLD) has extremely high computational complexity because the detector explores all antenna combinations as symbols. Hence, the practical integration of GSSK with MLD requires sub-optimal and low complexity. Several detection schemes have been proposed to reduce the complexity [21–23]. Quadratic programming (QP) detection [24] determines the set of most probable active antennas by using complex data vectors to search over patterns and constellation symbols. The iterative sparse reconstruction (ISR) detection [25] exploits the inherent sparse property of GSSK. This algorithm is based on the strategic adoption and transformation of sparse reconstruction from image processing.

This paper proposes the novel enhanced generalized space shift keying (EGSSK) to improve the SE, EE, and the search field based iterative maximum likelihood detection (SFMLD) reduces the complexity. The major contributions of this paper are the assignment of spare combinations, which is called as efficient bit allocation, for cell-edge users (CEUs) and cell-center users (CCUs) and SFMLD for low complexity. For efficient bit allocation, CCUs have strong channel gains therefore a higher number of bits is allocated vice versa a lower number of bits for CEUs. To reduce the complexity, the search field for active antenna combination is sequentially detected and iterated by decreasing multiplication operations and increasing iteration operations.

The rest of this paper is organized as follows. Section 2 discusses the system model wherein the CCUs and CEUs are distributed in a cell. The details of EGSSK are described separately with efficient bit allocation and SFMLD. In Section 3, the error probability, complexity, and EE are analyzed. The results are shown in Section 4 including the SE, complexity, ABER and EE. The conclusions drawn from this study are presented in Section 5.

Notations: $(\cdot)^T$ denotes the conjugate transpose, $(\cdot)^H$ denotes the Hermitian transpose, and $\|\cdot\|^2$ denotes the L-2 norm distance or Euclidean distance; $|\cdot|$ is used for the absolute value of a vector or scalar; $\det(\cdot)$ is the determinant of a matrix and $\otimes$ is the Kronecker product. I_N is N size of a square matrix of ones; $\lfloor\cdot\rfloor$ denotes the floor function and $C(v,w)$ denotes the combination $v!/\{w!(v-w)!\}$ where $w \le v$.

2. System model

Let us assume that $N+K$ users are homogeneously distributed within a cell. These users are divided into K number of CEUs with low channel gains and N number of CCUs with higher channel gains. For massive connectivity, the BS separates into two groups of users such as K number of CEUs and N number of CCUs. The groups of users are compromised in the order of channel gains, $\sum_{n=1}^{N}|h_n|^2 > \sum_{k=1}^{K}|h_k|^2$. To improve the SE, channel gains are criteria assigning efficient bit allocation for CEUs and CCUs.

The proposed transmitter consists of N_t number of transmit antennas and N_a number of active antennas, as shown in Fig. 1. The antenna combination is generated by combination of transmit and active antennas, $C(N_t, N_a)$. In the detail, a random sequence of independent bit streams b enters into a channel selection, where users are divided according to the channel gains. N number of CCUs and K number of CEUs are grouped from channel selection to comprise CCU-bit $b_{n,N}$ and CEU-bit $b_{k,F}$. These bits are mapped into a constellation vector X, which is called as EGSSK mapping. Multiple number of CCUs and CEUs are supported by EGSSK according to the antenna combination. It is assumed that every user equips N_r number of receive antennas. The MIMO fading channel is considered to be independent and identically distributed (i.i.d), and expressed as $H \in \mathbb{C}^{N_r \times N_t}$.

Table 1
An example of EGSSK mapping.

$b_{1,\mathrm{N}} = [b_1 \; b_2 \; b_3]$	$X = [x_1 \; x_2 \; \cdots \; x_5]^T$
[0 0 0]	$[\frac{1}{\sqrt{2}} \; \frac{1}{\sqrt{2}} \; 0 \; 0 \; 0]$
[0 0 1]	$[\frac{1}{\sqrt{2}} \; 0 \; \frac{1}{\sqrt{2}} \; 0 \; 0]$
[0 1 0]	$[\frac{1}{\sqrt{2}} \; 0 \; 0 \; \frac{1}{\sqrt{2}} \; 0]$
[0 1 1]	$[\frac{1}{\sqrt{2}} \; 0 \; 0 \; 0 \; \frac{1}{\sqrt{2}}]$
[1 0 0]	$[0 \; \frac{1}{\sqrt{2}} \; \frac{1}{\sqrt{2}} \; 0 \; 0]$
[1 0 1]	$[0 \; \frac{1}{\sqrt{2}} \; 0 \; \frac{1}{\sqrt{2}} \; 0]$
[1 1 0]	$[0 \; \frac{1}{\sqrt{2}} \; 0 \; 0 \; \frac{1}{\sqrt{2}}]$
[1 1 1]	$[0 \; 0 \; \frac{1}{\sqrt{2}} \; \frac{1}{\sqrt{2}} \; 0]$
(a) 3-bit allocation for a CCU	
$b_{1,\mathrm{F}} = [b_1]$	$X = [x_1 \; x_2 \; \cdots \; x_5]^T$
[0]	$[0 \; 0 \; \frac{1}{\sqrt{2}} \; 0 \; \frac{1}{\sqrt{2}}]$
[1]	$[0 \; 0 \; 0 \; \frac{1}{\sqrt{2}} \; \frac{1}{\sqrt{2}}]$
(b) 1-bit allocation for a CEU	

2.1. Efficient bit allocation

The main idea of EGSSK is that spare antenna combinations, which are not used in GSSK, are allocated for CEUs to transmit additional bits. The GSSK has a limitation in terms of exploiting all antenna combinations, but EGSSK allows to use spare antenna combination by enhancing SE. The bits for entire and spare antenna combinations are defined as follows

$$\begin{aligned} |C_{\mathrm{entire}}| &= 2^m \\ |C_{\mathrm{spare}}| &= 2^{\lfloor \log_2 (N_c - |C_{\mathrm{entire}}|) \rfloor} \end{aligned} \tag{1}$$

where $m = \lfloor \log_2 N_c \rfloor$ and $N_c = C(N_t, N_a)$. To estimate the antenna indices for the CCUs and CEUs, the defined antenna combinations are used with $|C_{\mathrm{entire}}|$ and $|C_{\mathrm{spare}}|$, respectively. Two examples are considered as form of $C(N_t, N_a)$: $C(5,2) = 10$ and $C(7,2) = 21$. In the first example $C(5,2) = 10$, the BS assigns 8 symbols for a CCU and 2 symbols for a CEU. In this example, all antenna combinations are fully used. Otherwise, the BS assigns 16 symbols for a CCU and 4 symbols for a CEU, which leaves a symbol in the second example $C(7,2) = 21$. It is inevitable to handle all symbols because a symbol is expressed as the power-of-two form. For the detail of instance, the $C(5,2)$ antenna combination with EGSSK mapping is presented in Table 1, where $b_{1,\mathrm{N}}$, $b_{1,\mathrm{F}}$ for a CCU and a CEU are the matrices for bit vectors and X is the matrix of the active antenna vectors. Without loss of generality, it is assumed that there are a CCU with strong channel and a CEU with weak channel, that is, $P_{e,CCU} \le P_{e,CEU}$. The single CCU is assumed to apply entire antenna combination for comparison purpose as well as the single CEU is added with different channel gains to verify practical situation. The sum capacity of the proposed EGSSK is expressed as follows

$$\begin{aligned} C_{CONV} &= (1 - P_{e,CCU}) \lfloor \log_2 |C_{\mathrm{entire}}| \rfloor \\ C_{PROP} &= C_{CONV} + (1 - P_{e,CEU}) \lfloor \log_2 |C_{\mathrm{spare}}| \rfloor \end{aligned} \tag{2}$$

where $P_{e,CCU}$ and $P_{e,CEU}$ are error probability for a CCU and a CEU, respectively.

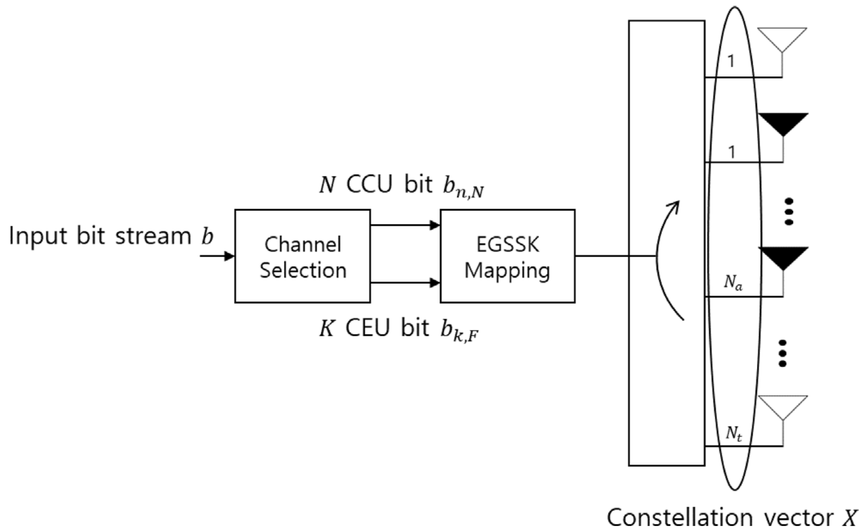

Fig. 1. Proposed transmitter.

2.2. Search field based iterative MLD (SFMLD)

The main idea of SFMLD is to divide the search field which is generated by the entire antenna combination, $|C_{\text{entire}}|$. The search field means that detector explores estimating a received symbol with the mapping table. In GSSK, the mapping table indicates antenna combination. Therefore, the conventional search field consists of $N_r \times N_c$; the proposed search field consists of $N_r \times N_a$. Each active antenna is estimated at every iteration of the detection by reducing the search field. The relationship between the search field and the operations is shown in Fig. 2. For the fair comparison, it is assumed that $N_c = C(N_t, N_a)$ and the number of receive antenna N_r is fixed. For example, in the case of $N_t = 7$ and $N_a = 3$, the conventional search field is calculated as $C(7, 3) = 35$ on every detection. Otherwise, the proposed search field is different compared with conventional search field because it estimates active antenna individually. Therefore, the proposed search field is calculated as $C(7, 1) = 7$ estimating the first active antenna index, $C(6, 1) = 6$ for second estimation, and $C(5, 1) = 5$ for third estimation. Conclusively, the proposed search field is reduced at every iteration. Generally, complex multiplication and addition operations are carried out to calculate the complexity. Therefore, the SFMLD reduces the multiplication operations by reducing the complexity.

In detail, let the selected active antenna candidates be grouped into an array, and denoted as $\hat{l}_k$ which can be expressed as

$$\hat{l}_k = \{\hat{l}_1\ ,\ \hat{l}_2\ ,\ \cdots\ ,\ \hat{l}_a\} \tag{3}$$

where a is the index of active antennas. The antenna combination from active antenna indices can be obtained by ordering the magnitudes of indices in ascending order as

$$|\hat{l}_q|^2 > \cdots > |\hat{l}_p|^2 \text{ subject to } q > p \tag{4}$$

The received signal $Y_i = H_{(i,j)}X_j + N_i$; the channel matrix consists of $H_{(i,j)} = [h_{(1,1)}, h_{(1,2)}, \ldots, h_{(i,1)}, \ldots, h_{(i,j)}]$, where i and j specify the number of the receive and transmit antennas of H, and N_i is additive white Gaussian noise (AWGN). The SFMLD decodes the spatial symbol as follows

$$\begin{aligned}\hat{l} &= \arg\max_j \mathrm{p}_Y(Y_i|X_j, H_{j,\text{prop}}) \\ &= \arg\min_j \|Y_i - \sqrt{\frac{\rho}{N_a}}H_{j,\text{prop}}\|^2\end{aligned} \tag{5}$$

where the active channel matrix consists of $H_{j,\text{prop}} = h_{(i,j)}$ $(j \in \{1, 2, \ldots, N_a\})$, ρ is the total transmit power, and

$$\mathrm{p}_Y(Y_i|X_j, H_{j,\text{prop}}) = \frac{1}{\pi^{N_r}} \exp(-\|Y_i - \sqrt{\frac{\rho}{N_a}}H_{j,\text{prop}}\|^2) \tag{6}$$

is the probability density function (PDF) of Y_i conditional on X_j and $H_{j,\text{prop}}$. Our proposed SFMLD is summarized in Algorithm 1.

Algorithm 1 Search field based iterative MLD (SFMLD)

$\hat{l}_k$: the active antenna candidates
$H_{j,\text{prop}} \in \mathbb{C}^{N_r \times N_t}$: the channel matrix
a: the index of active antenna
L: the estimated index array of active antennas
for $k = 1 : N_t$ **do**
    $\hat{l}_k = \arg\min_j \|Y_i - \sqrt{\frac{\rho}{N_a}}H_{j,\text{prop}}\|^2$
    $|\hat{l}_p|^2 > \cdots > |\hat{l}_q|^2$ subject to $p > q$
end for
$L = [\underbrace{\hat{l}_p\ \cdots\ \hat{l}_q}_{a}]$

3. Performance analysis

3.1. Error probability

To derive the performance of EGSSK with SFMLD, the upper bound for error probability of the conventional MLD is used to estimate the active antenna indices. The channel state information at the transmitter (CSIT) for SFMLD is perfectly generated to detect EGSSK symbols. Thus, the average bit error rate (ABER) can be expressed by [26] (Eq. (4).53) with pairwise error probability (PEP) conditioned as follows

$$\begin{aligned}\text{ABER} &\le E\left[\sum_l \mathbb{A}(j,l)P(x_j \to x_l)\right] \\ &= \sum_j \sum_l \frac{\mathbb{A}(j,l)}{|C_{\text{entire}}|}P(x_j \to x_l)\end{aligned} \tag{7}$$

where $P(x_j \to x_l)$ is the PEP of selecting the estimated signal vector x_l given by x_j, and $\mathbb{A}(j,l)$ is the number of bits error between the transmit antenna index x_j and the estimated antenna index x_l. Furthermore, the PEP conditional on MIMO channel matrix, $H_{j,\text{prop}}$

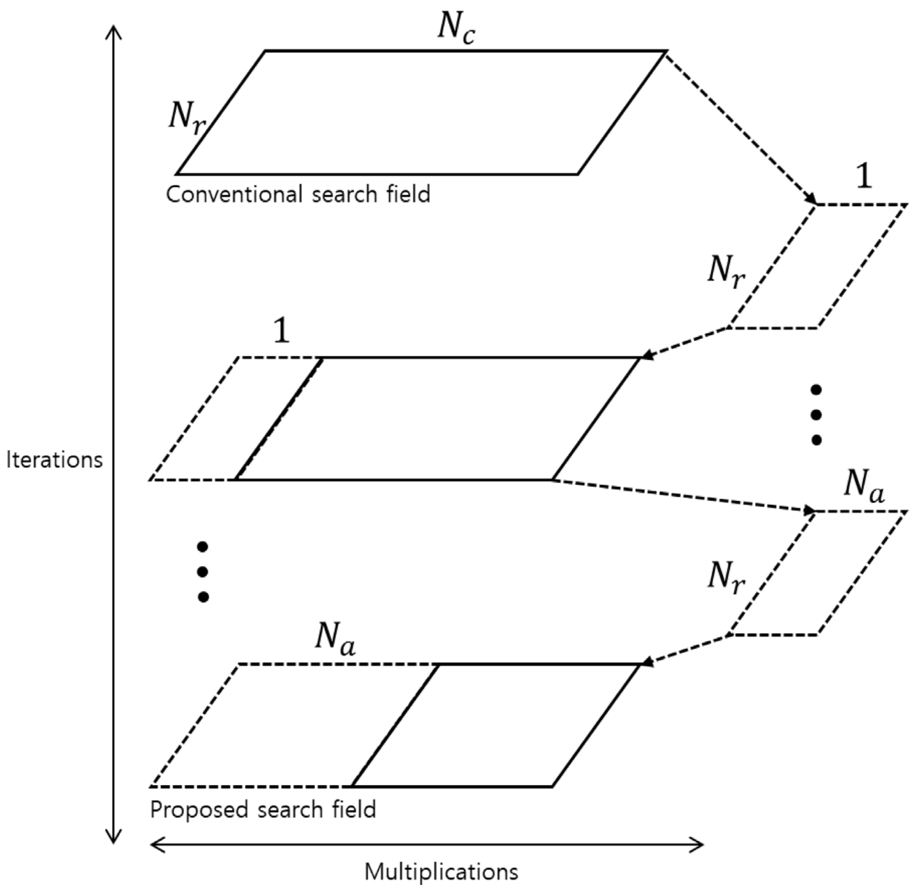

Fig. 2. An example of search field.

is given by [26] (Eq. (4).54)

$$P(x_j \to x_l) = \frac{1}{2}\frac{\exp(-\frac{\gamma}{2}\mu_H^H\sqrt{H_{j,prop}}\left(I_{N_rN_t} + \frac{\gamma}{\sqrt{2}}\right)^{-1}\mu_H)}{\det(I_{N_rN_t} - \frac{\gamma}{\sqrt{2}}\sigma_H^2 H_{j,prop}\Lambda)} \tag{8}$$

where $\Lambda = I_{N_rN_t} \otimes \Psi\Psi^H$, $\gamma = 1/(2\sigma_n^2)$, and $\Psi = (x_l - x_j)$ is the error between vectors x_l and x_j; σ_H and σ_n are the variances of the channel and noise, respectively. μ_H is the mean of the MIMO channel $H_{j,prop}$.

Finally, by using (4) and (5), the analytical error probability of the SFMLD can be calculated as follows

$$\text{ABER} \le \sum_j\sum_l \frac{1}{2}\frac{\mathbb{A}(j,l)}{|C_{\text{entire}}|}\frac{\exp\left(-\frac{\gamma}{2}\mu_H^H\sqrt{H_{j,prop}}\left(I_{N_rN_t} + \frac{\gamma}{\sqrt{2}}\right)^{-1}\mu_H\right)}{\det(I_{N_rN_t} - \frac{\gamma}{\sqrt{2}}\sigma_H^2 H_{j,prop}\Lambda)} \tag{9}$$

For the high SNR($\gamma \to \infty$) approximation where $\exp(x) \approx 1$ for $x \to 0$. By this approximation, the asymptotic analysis can be rewritten as

$$\text{ABER}_{\gamma\to\infty} \le \sum_j\sum_l \frac{1}{2}\frac{\mathbb{A}(j,l)}{|C_{\text{entire}}|}\frac{1}{\det(I_{N_rN_t} - \frac{\gamma}{\sqrt{2}}\sigma_H^2 H_{j,prop}\Lambda)} \tag{10}$$

3.2. Complexity

The previous complexity of QP [24], ISR [25] and MLD [27] are $\mathcal{O}(N_t^3 + N_rN_c)$, $\mathcal{O}(p((2N_r)^2N_t + 2N_t^3))$, and $\mathcal{O}(N_rN_t^{N_a})$, respectively. Here, p is the number of executions required to exceed one. In Section 2.2, a number of complex multiplication and addition operations are described for the proposed SFMLD. The operation of search field is described as $N_t^{N_a}$ in the complexity of MLD. This complexity is analyzed into two parts which are the search field for symbols and the receiver antennas for the diversity. The difference between SFMLD and MLD is $N_t!/(N_a+1)!$ size of the search field. Therefore, the complexity of SFMLD can be described as $\mathcal{O}(N_rN_t!/(N_a+1)!)$.

3.3. Energy efficiency

Generally, the energy efficiency (EE) is expressed with the capacity and total transmit power. For the future wireless network, EE can be another significant performance metric. Thus, we demonstrate EE of the proposed EGSSK and conventional GSSK. The EE expression can be written by

$$\eta_{CONV} = \frac{C_{CONV}}{\sqrt{N_a}}$$
$$\eta_{PROP} = \frac{C_{PROP}}{\sqrt{N_a}} \tag{11}$$

4. Results and discussion

This section presents simulated and analytical results of our proposed EGSSK with SFMLD in terms of SE, ABER, complexity, and EE. It is assumed that the Rayleigh fading channel for the MIMO system and every user is equipped with two receive antennas. The system bandwidth, the radius of the cell and the total transmit power are normalized as 1. Moreover, the normalized distances from the BS are $d_1 = 0.3$ and $d_2 = 0.7$ for the CCU and CEU, respectively. In all simulations, we consider that antenna combination are two types such as $C(5,2)$ and $C(7,2)$.

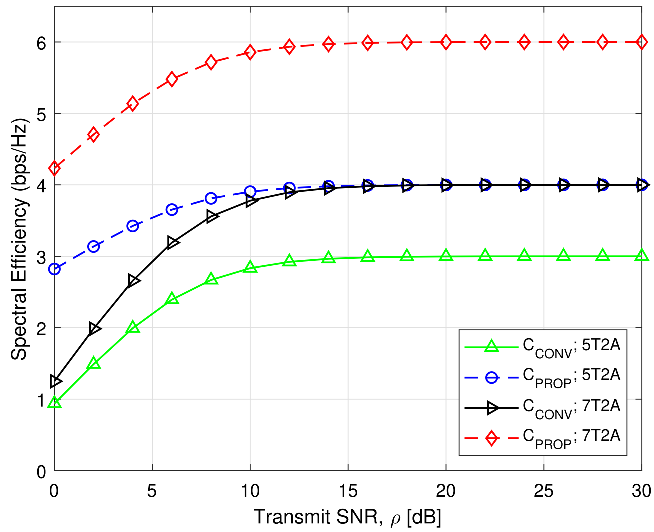

Fig. 3. The SE comparison of conventional and proposed.

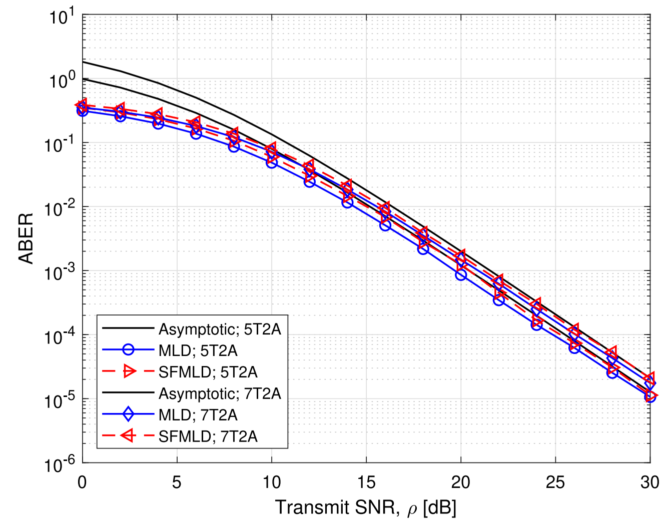

Fig. 5. The ABER comparisons of MLD and SFMLD.

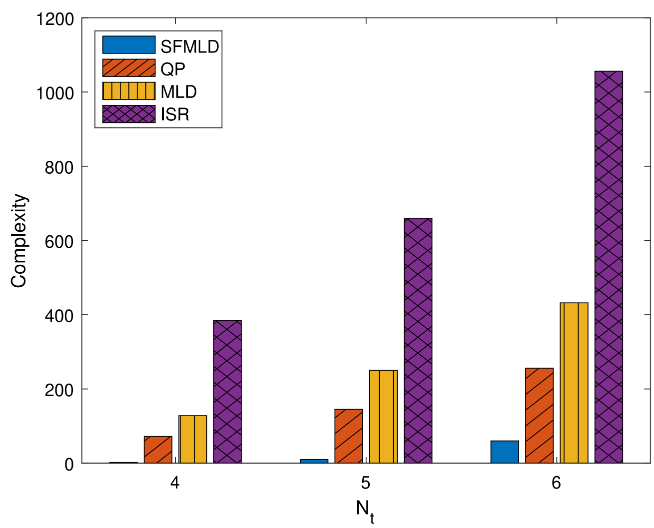

Fig. 4. The complexity comparison of QP, MLD, ISR and SFMLD.

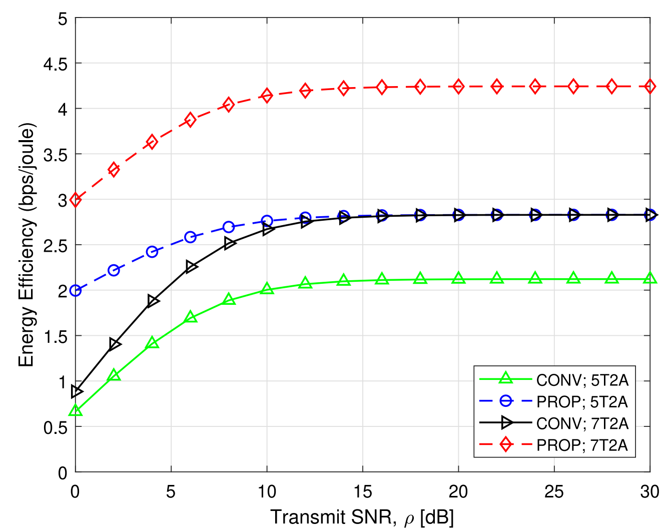

Fig. 6. The EE comparison of conventional and proposed.

Fig. 3 shows the SE of the conventional and proposed schemes when $N_t = 5, 7$ and $N_a = 2$ are fixed. As can be seen, EGSSK outperforms than the conventional GSSK because of efficient bit allocation. Additional indices are assigned for the CEUs. Consequentially, it is also shown that the proposed EGSSK outperforms than the conventional GSSK even if the error probability of a CEU is lower than that of a CCU owing to additional bit acquisition.

In Fig. 4, the complexity of the proposed SFMLD is drew with other detections for the purpose of comparison. The simulation parameters are static as $N_a = 3$ and $p = 2$ with varying the number of transmit antennas, $N_t = 4, 5, 6$. The proposed SFMLD has been less affected compared with other detections such as MLD, QP, and ISR increasing the number of transmit antennas. Moreover, the complexity of other detectors dramatically increases whereas the complexity of SFMLD slowly varies. Following earlier discussion, a number of transmit and active antennas is critical factor to enhance the SE. Thus, the SFMLD has overwhelming low complexity which allows simple implementation.

Fig. 5 shows the ABER comparison between MLD and SFMLD with asymptotic analysis. The asymptotic analysis for ABER is revealed to emphasize the validation on conventional MLD and proposed SFMLD. Overall, the ABER of the SFMLD is slight higher than that of MLD. The estimating probability of antenna in dices for the SFMLD is worse than MLD because the antenna index is detected individually.

Fig. 6 shows EE comparison between conventional GSSK and proposed EGSSK with respect to SNR considering the sum capacity. It is observed that proposed EGSSK shows significantly better performance than conventional GSSK. After tending to specific SNR, EE is saturated because error probability has tiny value which affects to derive SE. As a result, it is presented the SFMLD is sub-optimal and has low complexity compared with other detectors.

5. Conclusion

This paper proposes a novel EGSSK to improve the SE, EE and the SFMLD reduce the complexity. To overcome problem of conventional GSSK, spare antenna combination is used for the CEUs to improve the SE allowing additional bit allocation. In the massive MIMO system, it immensely affects to increase the number of entire antenna combination. The SFMLD uses iterative approach to reduce search field which is important factor for complexity. The feasibility and performance of EGSSK and SFMLD are comprehensively investigated and shown by comparison with simulated and analytical analysis.

CRediT authorship contribution statement

Man Hee Lee: Conceptualization, Methodology, Investigation, Writing – original draft. **Soo Young Shin:** Supervision, Resources, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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