논문 15-40-04-04 The Journal of Korean Institute of Communications and Information Sciences '15-04 Vol.40 No.04
http://dx.doi.org/10.7840/kics.2015.40.4.637

8개 송신 안테나에서 쿼터너리 준직교 시퀀스를 이용한 새로운 공간변조 기법

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New Spatial Modulation Scheme based on Quaternary Quasi-Orthogonal Sequence for 8 Transmit Antennas

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ABSTRACT

Recently, a spatial modulation (SM) scheme achieving high throughput based on quaternary quasi-orthogonal sequences (Q-QOSs), referred to as Q-QOS-SM, is presented for $N_t = 2^n (n = 1, 2, \cdots)$ transmit antennas. In this paper, based on the design approach of the conventional Q-QOS-SM, new improved QO-SM (I-QO-SM) schemes are proposed for 8 transmit antennas. The new schemes employ Q-QOSs of length 4 or 2 unlike of 8 in the original one, which guarantees more information bits to be allocated for antenna index parts compared to the conventional Q-QOS-SM. By computer simulation results, the proposed scheme are shown to enjoy much higher throughputs compared to the conventional other SM schemes for all simulation environments. Finally, we also examine and compare analytically the performances of the new and conventional SM schemes by calculating upper-bounds on BER performance.

Key Words : spatial modulation, quaternary quasi-orthogonal sequence, maximum-ratio combining, MIMO, Rayleigh fading

Ⅰ. Introduction

Multiple-input multiple out (MIMO) systems have been attractive in the research field of antenna transmission for many years due to considerable increase in spectral efficiency. Two examples include the space-time block code (STBC)[1-3] and the vertical Bell Labs layered space-time (V-BLAST)[4-5], whereby the former provides diversity gain and the latter achieves a high transmission data rate. However, STBC cannot improve the data rate and the orthogonality is lost in the case where there are more than two transmit antennas. Likewise, although V-BLAST can offer many improvements in spectral efficiency and data rate, the high decoding complexity in the optimal receiver and large inter-channel interference make it restricted in practice.

※ 이 논문은 2014년 교육부와 한국연구재단의 지역혁신창의인력양성사업의 지원을 받아 수행된 연구임(NRF-2014H1C1A1066568)
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논문번호 : KICS2015-02-040, Received February 28, 2015; Revised April 20, 2015; Accepted April 20, 2015

Spatial modulation (SM)[6-11] is proposed to overcome the two disadvantages of V-BLAST. Although SM is not superior to V-BLAST in spectral efficiency and data rate, its low decoding complexity and absence of inter-channel interference make it simple in practice. These advantages are obtained by activating single transmit antenna to transmit the modulation symbol at every symbol duration. It is worth noting that the SM conveys additional information through the spatial dimension by choosing the single active antenna from transmit antenna array. For this reason, the SM achieves a higher throughput than STBC. Meanwhile, the number of transmit antennas in SM must be a power of two.

Generalized spatial modulation (GSM)[12] is proposed to overcome this limitation, and also the GSM conveys more additional information through spatial dimension due to the multiple antennas activated at every symbol duration. Hence, the GSM attains a higher throughput than SM. The GSM provides a direction to improve the throughput of SM, which is increasing the additional information bits allocated to antenna index part.

In [13], quaternary quasi-orthogonal sequence spatial modulation (Q-QOS-SM) was proposed by using a quaternary quasi-orthogonal sequence (Q-QOS)[14,15]. Meanwhile, a concept called spatial modulation matrix (SMM) was also introduced. For SM and GSM, if 0 and 1 denote the states of on-off for every antenna, each candidate of the antenna selection corresponds to the binary sequence. Then, the matrix consisted of these sequences is the so-called SMM. For example, the SMM of SM is an identity matrix. However, for the quaternary sequence, the basic elements 1, -1 and j, -j represent four types of phases, interpreted as four types of weighting values. Due to the large number of sequences, more information bits could be allocated to column index of SMM. Compared to SM and GSM, the throughput of Q-QOS-SM is further enhanced.

In this paper, based on the design approach of conventional Q-QOS‑SM, we propose a new improved quaternary quasi-orthogonal spatial modulation (I-QO-SM) for 8 transmit antennas by employing the Q-QOSs of length 4 and length 2. In the SMM of I-QO-SM, each column is built by Q-QOSs of length 4 or Q-QOSs of length 2. Compared to conventional Q-QOS-SM, the I-QO-SM can allocate 2 bits more to the column index of SMM. The I-QO-SM achieves the higher throughput than conventional Q-QOS-SM.

Organization: Section Ⅱ introduces the conventional SM, GSM and Q-QOS-SM. The proposed scheme is presented in Section Ⅲ. Section Ⅳ describes performance analysis. Finally, the simulation results and conclusion are presented in Section Ⅴ and Section Ⅵ, respectively.

Notation: the bold letter denotes the vectors or matrices, and the non-bold letter denotes the scalar values. C_B^b denotes the b-combination of a set B and $\lfloor \cdot \rfloor$ denotes floor operation. We use the $(\cdot)^H$ for conjugate transpose and $\|\cdot\|_F$ for Frobenius norm. $Re\{\cdot\}$ represents the real part of a complex variable, $E_x[\cdot]$ is the expectation with respect to x and $diag(\boldsymbol{a})$ denotes a diagonal matrix made by vector $\boldsymbol{a}$.

Ⅱ. Conventional SM, GSM and Q-QOS-SM

A generalized $N_r \times N_t$ system block is depicted in Fig. 1, and we can switch it to conventional SM, GSM or Q-QOS-SM by changing the SMM simply. The input information bit vector $\boldsymbol{b}$ is split into two parts, m_s bits are mapped through an M order modulation constellation and m_a bits are mapped into an index of the j-th column vector $\boldsymbol{s}_j$ in SMM $\boldsymbol{S}_{N_t}$ with size $N_t \times N_s$. Generally, if N_s denotes the total number of columns in SMM, the number of information bits transmitted per channel use is given by: $m = m_a + m_s$.

Under the assumption of i.i.d. $N_r \times N_t$ MIMO fading channels $\boldsymbol{H}$, the received signal is given by,

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s}_j x_q + \boldsymbol{n} \tag{1}$$

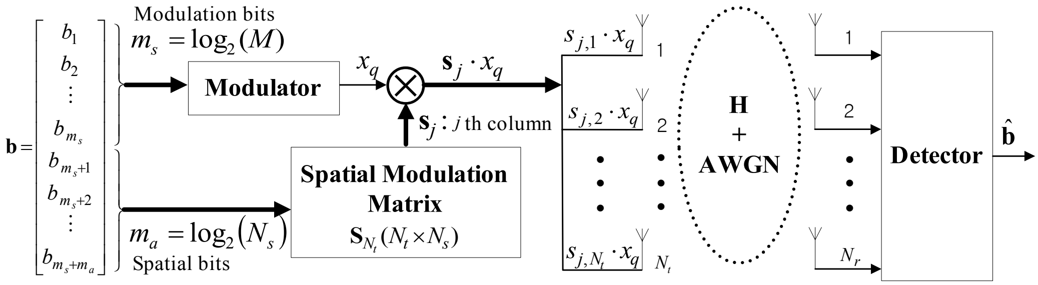

Fig. 1. System structure for conventional SM, GSM and Q-QOS-SM.

where $\boldsymbol{H}$ and n denote $N_r \times N_t$ Rayleigh fading channel matrix and complex Gaussian noise vector of length N_r, respectively.

For decoding, a hard limiting based ML optimal detector (HL-ML) for an SM system was proposed in [11], which can be applied for SM, GSM and Q-QOS-SM as follows.

$$[\hat{j},\hat{q}] = \arg min_{j,q} \parallel \boldsymbol{y} - \boldsymbol{H}\boldsymbol{s}_j x_q \parallel_F^2 \tag{2}$$

$$= \arg min_j \left[\arg min_q \left\| \frac{(\boldsymbol{H}\boldsymbol{s}_j)^H \boldsymbol{y}}{\parallel \boldsymbol{H}\boldsymbol{s}_j \parallel_F^2} - x_q \right\|_F^2 \right]. \tag{3}$$

As shown in Fig. 1, the antenna selection is replaced with column vector selection in SMM for conventional SM[6-11] and the SMM of conventional SM is an $N_t \times N_t$ identity matrix. An example of $N_t = 8$ for conventional SM is given as,

$$\boldsymbol{S}_8^{SM} = \boldsymbol{I}_8 \tag{4}$$

where $\boldsymbol{I}_t$ denotes the $t \times t$ identity matrix.

For GSM[12], since multiple transmit antennas remains active at each symbol epoch, multiple non-zero elements appear in each column of GSM's SMM. Moreover, the size of GSM(N_t, N_u)'s SMM is $N_t \times C_{N_t}^{N_u}$, where N_u is the number of active transmit antennas at each symbol epoch. For instance, the SMM of GSM(8,2) is shown as follows,

$$\boldsymbol{S}_8^{GSM(8,2)}$$

$$= \frac{1}{\sqrt{N_u}} \begin{bmatrix} 1&1&1&1&1&1&1&0&0&0&0&0&0&0&0&0 \\ 1&0&0&0&0&0&0&1&1&1&1&1&1&0&0&0 \\ 0&1&0&0&0&0&0&1&0&0&0&0&0&1&1&1 \\ 0&0&1&0&0&0&0&0&1&0&0&0&0&1&0&0 \\ 0&0&0&1&0&0&0&0&0&1&0&0&0&0&1&0 \\ 0&0&0&0&1&0&0&0&0&0&1&0&0&0&0&1 \\ 0&0&0&0&0&1&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&1&0&0&0 \end{bmatrix}. \tag{5}$$

It can be seen that GSM allocates one bit more to the column index of SMM compared to the conventional SM. Furthermore, the Q-QOS-SM[13] further increases the number of information bits allocated for column index of SMM. The SMM of Q-QOS-SM is an $N_t \times N_t^2$ matrix and is composed of a group of quaternary quasi-orthogonal sequences (Q-QOS)[14,15]. The SMMs of Q-QOS-SM are given by,

$$\boldsymbol{S}_t^{Q-QOS-SM} = \frac{1}{\sqrt{N_t}} [\boldsymbol{Q}_t] \tag{6}$$

$$= \frac{1}{\sqrt{N_t}} [diag(\boldsymbol{m}_1)\boldsymbol{W}_t \quad \cdots \quad diag(\boldsymbol{m}_t)\boldsymbol{W}_t] \tag{7}$$

where $\boldsymbol{Q}_t$ denotes the group of Q-QOSs with length t, $\boldsymbol{m}_i$ is the i-th masking sequence for Q-QOSs and $\boldsymbol{W}_t$ is the Walsh sequence set of length t. The masking sequences for Q-QOSs are given in Table 1.

Table 1. Masking sequences for Q-QOSs.

t	Making sequences of length t
2	$m_1=[1,\ 1]$ $m_2=[1,\ j]$
4	$m_1=[1,\ 1,\ 1,\ 1]$ $m_2=[1,\ -j,\ -1,\ -j]$ $m_3=[1,\ -1,\ -j,\ -j]$ $m_4=[1,\ -j,\ -1,\ -j]$
8	$m_1=[1,\ 1,\ 1,\ 1,\ 1,\ 1,\ 1,\ 1]$ $m_2=[1,\ j,\ -1,\ j,\ -1,\ j,\ -1,\ j]$ $m_3=[1,\ -1,\ j,\ j,\ -1,\ -1,\ -j,\ j]$ $m_4=[1,\ -1,\ -1,\ -1,\ -j,\ j,\ j,\ j]$ $m_5=[1,\ -j,\ -1,\ j,\ j,\ -1,\ j,\ -1]$ $m_6=[1,\ j,\ -j,\ -1,\ j,\ -1,\ -1,\ j]$ $m_7=[1,\ j,\ j,\ -1,\ -1,\ -j,\ j,\ -1]$ $m_8=[1,\ -1,\ j,\ -j,\ j,\ j,\ -1,\ -1]$

The SMM of Q-QOS-SM is extended from N_t columns to N_t^2 columns compared to SM. Hence, the Q-QOS-SM can transmit total $m=\log_2 N_t^2 = 2\log_2 N_t$ bits which is two times more bits than the original SM of $\log_2 N_t$.

Ⅲ. Improved Scheme of Q-QOS-SM

In this section, we will present an extended Q-QOS-SM scheme based on the Q-QOSs of lengths 2 and 4 for 8 transmit antennas, and call it as improved quaternary quasi-orthogonal spatial modulation (I-QO-SM).

Considering highly spectral efficiency and also improved error performance, it is essential to design the SMM that there are as much larger number of column vectors as possible while retaining the small correlation values among these columns. Based on these comments the new SMM can be built as,

$$S_8 = [s_1\ s_2 \cdots\ s_j \cdots\ s_{256}]\ . \tag{8}$$

In I-QO-SM(Q_4), select one 4×1 column from each 4×16 Q_4 and combine the two column vectors into the j-th 8×1 column vector of new SMM.

$$s_j = \frac{1}{\sqrt{N_t}}\begin{bmatrix} q_{4,a_1} \\ q_{4,a_2} \end{bmatrix},\ 1 \le a_1, a_2 \le 16 \tag{9}$$

where $j=16(a_1-1)+a_2$.

In I-QO-SM(Q_4, Q_2), select one 4×1 column from 4×16 Q_4 and one 2×1 column from each 2×4 Q_2, then combine the three column vectors into the j-th 8×1 column vector of new SMM.

$$s_j = \frac{1}{\sqrt{N_t}}\begin{bmatrix} q_{4,a_1} \\ q_{2,a_2} \\ q_{2,a_3} \end{bmatrix},\ \begin{matrix} 1 \le a_1 \le 16 \\ 1 \le a_2,\ a_3 \le 4 \end{matrix} \tag{10}$$

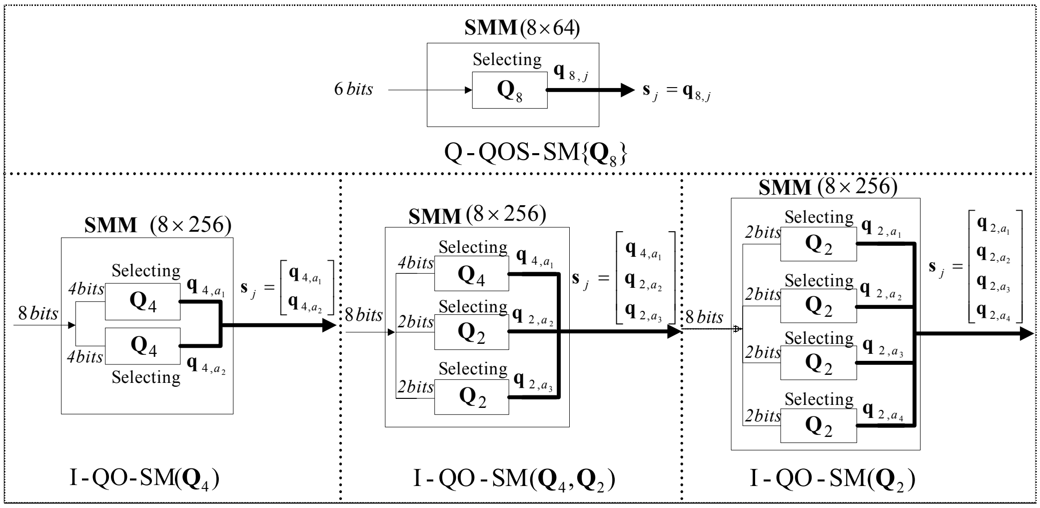

Fig. 2. SMMs of I-QO-SM and Q-QOS-SM for $N_t=8$.

where $j = 16(a_1 - 1) + 4(a_2 - 1) + a_3$.

In I-QO-SM($\boldsymbol{Q}_2$), select one 2×1 column from each 2×4 $\boldsymbol{Q}_2$ and combine the four column vectors into the j-th 8×1 column vector of new SMM.

$$\boldsymbol{s}_j = \frac{1}{\sqrt{N_t}}\begin{bmatrix} \boldsymbol{q}_{2,a_1} \\ \boldsymbol{q}_{2,a_2} \\ \boldsymbol{q}_{2,a_3} \\ \boldsymbol{q}_{2,a_4} \end{bmatrix},\ 1 \le a_1, a_2, a_3, a_4 \le 4 \qquad (11)$$

where $j = 64(a_1 - 1) + 16(a_2 - 1) + 4(a_3 - 1) + a_4$, and $\boldsymbol{q}_{t,i}$ denotes the i-th column of $\boldsymbol{Q}_t$ with size $t\times t^2$.

The I-QO-SM's SMM with size $N_t \times 2^{N_t}$ is established by 2×4 $\boldsymbol{Q}_2$ and 4×16 $\boldsymbol{Q}_4$. Due to 2^2 columns in $\boldsymbol{Q}_2$ and 2^4 columns in $\boldsymbol{Q}_4$, N_t bits are guaranteed to be transmitted through antenna spatial dimension in I-QO-SM. For example, in I-QO-SM ($\boldsymbol{Q}_4$) of Fig. 2, a_1-th column of the first $\boldsymbol{Q}_4$ is selected to be a weighting vector for the first four transmit antennas by the first 4bits, and the second 4bits are allocated to the rest of transmit antennas.

The transmission data rate of SM schemes referred in this paper are listed in Table 2. Compared to other schemes, the I-QO-SM could transmit much more information bits through antenna spatial dimension.

Table 2. Data rate over spatial dimension.

Scheme	Transmission data rate
SM[6-11]	$\log_2 N_t + \log_2 M$
GSM(8, 2)[12]	$\lfloor \log_2 C_{N_t}^{N_u} \rfloor + \log_2 M$
Q-QOS-SM[13]	$2\log_2 N_t + \log_2 M$
Proposed I-QO-SM	$N_t + \log_2 M$

Ⅳ. Performance Analysis

In this section, we generalize the method of performance analysis in [12] to conventional SM, Q-QOS-SM and proposed I-QOS-SM.

Firstly, a well-known union bounding technique[16] is given by,

$$\Pr_{e,bit} \le E_x\Big[\sum_{\hat{j},\hat{q}} \frac{N(x_{j,q}, x_{\hat{j},\hat{q}})\Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}})}{m}\Big] \qquad (12)$$

where $N(x_{j,q}, x_{\hat{j},\hat{q}})$ denotes the number of bits in error between $x_{j,q}$ and $x_{\hat{j},\hat{q}}$. The $\Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}})$ is the probability of detecting signal as $x_{\hat{j},\hat{q}}$ while $x_{j,q}$ is transmitted. Also, it is given by,

$$\begin{aligned}&\Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}}) \\ &= \Pr(\| \boldsymbol{y} - \boldsymbol{H}\boldsymbol{s}_j x_q \|_F^2 > \| \boldsymbol{y} - \boldsymbol{H}\boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2)\end{aligned} \qquad (13)$$

$$= \Pr(\| \boldsymbol{n} \|_F^2 > \| \boldsymbol{H}(\boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}}) + \boldsymbol{n} \|_F^2) \qquad (14)$$

Since the noise and channels are assumed to be independent, the left and right parts of the inequality are chi-square random variables with $2N_r$ degrees of freedom as follows.

$$K_{j,q} = \sum_{i=1}^{N_r} \left| \frac{n_i}{\sigma/\sqrt{2}} \right|^2 \qquad (15)$$

$$K_{\hat{j},\hat{q}} = \sum_{i=1}^{N_r} \left| \frac{\boldsymbol{H}(\boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}}) + n_i}{\hat{\sigma}/\sqrt{2}} \right|^2 \qquad (16)$$

where $\widehat{\sigma^2} = \| \boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2 + \sigma^2$. Inserting (15) and (16) into (14), we obtain

$$\Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}}) = \Pr(K_{\hat{j},\hat{q}}/K_{j,q} < \sigma^2/\widehat{\sigma^2}). \qquad (17)$$

Since $K_{\hat{j},\hat{q}}/K_{j,q}$ follows the F-distribution, by using its cumulative distribution function (CDF), we get

$$\Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}}) = I_{\frac{\sigma^2}{\sigma^2 + \widehat{\sigma^2}}}(N_r, N_r) \qquad (18)$$

where $I_x(a,b)$ is the regularized incomplete beta function, which is given as

$$\begin{aligned} I_x(a,b) &= \frac{B(x;a,b)}{B(a,b)} \\ &= \frac{1}{B(a,b)} \int_0^x t^{a-1}(1-t)^{b-1} dt \end{aligned} \qquad (19)$$

$$B(a,b)=\int_0^1 t^{a-1}(1-t)^{b-1}dt. \quad (20)$$

Substituting (18) in (12), the final expression of the upper bound is shown as

$$\Pr_{e,bit} \le E_x\left[\sum_{\hat{j},\hat{q}} \frac{N(x_{j,q},x_{\hat{j},\hat{q}})I_{\frac{\sigma^2}{\sigma^2+\widehat{\sigma^2}}}(N_r,N_r)}{m}\right]. \quad (21)$$

It can be observed that the performance depends on the value of $\widehat{\sigma^2}=\| \mathbf{s}_j x_q - \mathbf{s}_{\hat{j}} x_{\hat{q}} \|_F^2 + \sigma^2$. A definition is given as

$$d=\| \mathbf{s}_j x_q - \mathbf{s}_{\hat{j}} x_{\hat{q}} \|_F^2 \quad (22)$$

$$=|x_q|^2+|x_{\hat{q}}|^2-2Re\left\{x_q^* x_{\hat{q}} \mathbf{s}_j^H \mathbf{s}_{\hat{j}}\right\} \quad (23)$$

where d denotes the distance between any two signals. Moreover, each signal of the SM schemes contains two types of information: the indices of the selected sequence and the modulated symbol. (17) and (22) indicates that for the larger value of $\widehat{\sigma^2}$ or d, the pairwise error probability (PEP) $\Pr(x_{j,q} \to x_{\hat{j},\hat{q}})$ is small. Hence, if we map the information into a new constellation Φ, the distances between each pair of signal points mapped in the constellation Φ determines the performance of the SM schemes.

From (22), it can be observed that minimum d is related to the maximum column correlation of SMM. As mentioned in section Ⅲ, the SMM of I-QO-SM($\mathcal{Q}_4$) has a smaller maximum column correlation than that of the other two I-QO-SMs. Hence, the I-QO-SM($\mathcal{Q}_4$) is shown to outperform the others at minimum d and BER performance in Table 3 and Fig. 3. Furthermore, the analytical upper bound of (21) is shown to be available to the proposed I-QO-SMs.

As shown in Table 4, the minimum distance of the proposed I-QO-SM(4) is larger than that of SM, GSM, and Q-QOS-SM at the same transmission data rate. This indicates that the proposed scheme achieves a higher spectral efficiency than other schemes. An apparent reason is that the smaller modulation order is used for the proposed scheme.

Table 3. Comparison of minimum value d for proposed I-QO-SMs at $N_t=8$.

Scheme	$m=10$ (4QAM)	$m=11$ (8QAM)
I-QO-SM($\mathcal{Q}_4$)	0.5	0.33
I-QO-SM($\mathcal{Q}_4$, $\mathcal{Q}_2$)	0.33	0.22
I-QO-SM($\mathcal{Q}_2$)	0.25	0.167

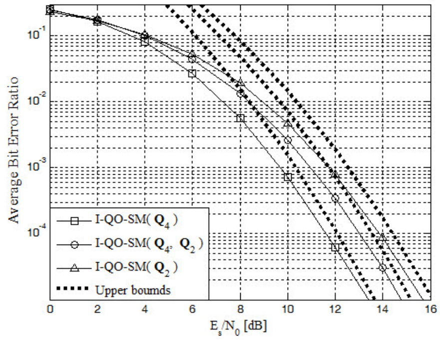

Fig. 3. BERs versus E_s/N_0 [dB] for proposed I-QO-SMs at 10 bits/channel use.

Table 4. Comparison of minimum value d for SM schemes at $N_t=8$.

Scheme	$m=10$	$m=11$
SM	0.049 (128QAM)	0.024 (256QAM)
GSM(8, 2)	0.048 (64QAM)	0.024 (128QAM)
Q-QOS-SM	0.300 (16QAM)	0.150 (32QAM)
I-QO-SM($\mathcal{Q}_4$)	0.500 (4QAM)	0.333 (8QAM)

Ⅴ. Simulation Results

In this section, we present some simulation results to compare the performances of the proposed scheme and other schemes at the same data rate. Moreover, the number of receiving antennas is assumed to be eight for all cases, and the independent single-path Rayleigh fading channel is considered in this paper.

Fig. 4 shows the average BER results when transmission data rate is $m=m_a+m_s=10$ bits per channel use. The modulations used for each SM scheme are: 4QAM in the proposed scheme, 16QAM in Q-QOS-SM, 64QAM in GSM(8,2), and 128QAM in SM. It can be seen that the proposed scheme achieves the best performance compared to other schemes at high signal to noise ratio (SNR). Moreover, the proposed scheme provides about 3 dB SNR gains over Q-QOS-SM, 6 dB SNR gains over GSM(8,2), and 8 dB SNR gains over SM at a BER value of 10^{-4}. The upper bound is tight with simulated BER in high SNR for all SMs that convey a single modulated symbol and have a specific SMM as shown in Fig. 1.

In Fig. 5, the throughput curves with 8 transmit antennas are plotted. Each curve consists of four points, which represent the cases of 4QAM, 16QAM, 64QAM, and 256QAM, respectively. We measure the throughput (per channel use) from the SNR required at BER 10^{-4}. It can easily observed that the proposed scheme can provide at least 2dB SNR gains over Q-QOS-SM, 6 dB SNR gains over GSM(8,2), and 8 dB SNR gains over conventional SM at the same throughput. In throughput, the proposed scheme also provides 1 bit improvement over Q-QOS-SM, 3 bits improvement over GSM(8,2) and 3.5 bits over conventional SM in throughput.

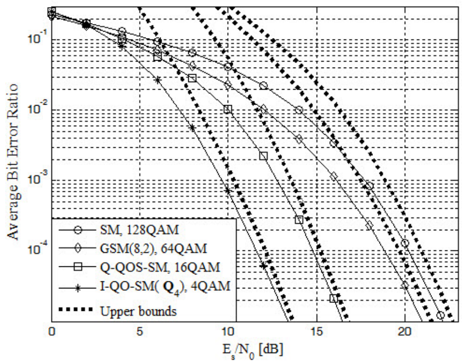

Fig. 4. BERs versus E_s/N_0 [dB] at 10bits/channel use.

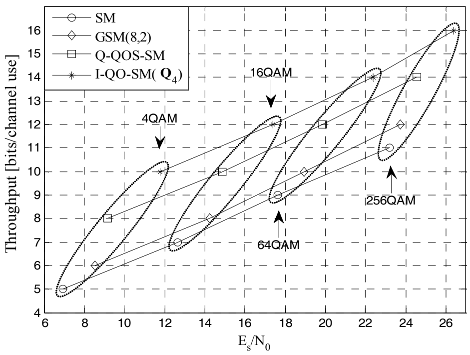

Fig. 5. Throughput (bits/channel use) for $N_t=N_r=8$ (BER=10^{-4}).

In the proposed scheme, we increase the number of bits allocated for column index of SMM by using the Q-QOSs of length 4 and length 2 so that the modulation (M-QAM) order is reduced and the performance of the proposed scheme is superior to that of the other SMs. In other words, extending the number of columns in SMM is a better method for increasing the transmission data rate rather than extending the constellation of modulation for SM system.

Ⅵ. Conclusions

In this paper, we proposed a high-throughput SM scheme, named I-QO-SM, which has some advantages compared to other SMs: (1) the number of bits allocated for column index of SMM is equal to transmit antenna number; (2) it has a higher throughput than other schemes. In detail, the I-QO-SM is proved to obtain at least one bit improvement on throughput compared to other SMs. A generalized upper bound is also shown to be available for all SMs referred to in this paper.

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