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Generalized Quaternary Quasi-Orthogonal Sequences Spatial Modulation

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ABSTRACT

So called quaternary quasi-orthogonal sequence spatial modulation (Q-QOS-SM) has been presented with an advantage of improved throughputs compared to the conventional SM and generalized spatial modulation (GSM) by virtue of a larger set size of QOSs and its minimized correlation value between these QOSs. However the Q-QOS-SM has been originally invented for limited transmit antennas of only powers of two. In this paper, by extending the Q-QOS-SM to any number of transmit antennas, we propose a generalized Q-QOS-SM, referred as G-QO-SM. Unlike the conventional Q-QOS-SM using the Q-QOSs of length of any power of two, the proposed G-QO-SM is constructed based on the Q-QOSs of only the lengths of 2 and 4. The proposed scheme guarantees the transmission of the total N_t spatial bits with N_t transmit antennas, and thus achieves greatly higher throughputs than the other existing schemes including the SM, GSM, Q-QOS-SM, Quadrature-SM, and Enhanced-SM. The performance improvements of the proposed G-QO-SM is justified by comparing the analytically derived BER upper bounds and also the exact Monte Carlo simulation results.

Key Words : multiple-input multiple-output, spatial modulation, quaternary quasi-orthogonal sequence, maximum likelihood decoder, Rayleigh fading channel.

Ⅰ. Introduction

Multiple-input multiple-output (MIMO) systems are now widely used for wireless communication due to improvements regarding the spectral efficiency and data throughput of systems such as the space-time block code (STBC)[1-3] and Vertical Bell Labs layered space-time (V-BLAST)[4,5]. The STBC provides a diversity gain for the attainment of a higher spectral efficiency, but loses orthogonality in the presence of more than two transmit antennas. V-BLAST achieves a high data throughput by simultaneously transmitting multiple independent data streams through multiple antennas. But the high decoding complexity of the optimal receiver and a large inter-channel interference (ICI) restrict its practical application.

From these reasons, so called spatial modulation (SM)[6-8] has been proposed with the advantages of its low decoding complexity and the avoidance of

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ICI. In the SM, only one modulated symbol is transmitted through a single selected transmit antenna per each symbol duration. It is worth noting that in the SM, extra information bits, called as spatial bits, are simultaneously transmitted through the spatial dimension by selecting one of the transmit antennas. However the single antenna transmission may cause limited data throughput or spectral efficiency with the given antennas, and also the available number of antennas in the SM is constrained to powers of two.

A number of ideas have therefore been presented in order to improve a limited throughput of the original SM. Generalized spatial modulation (GSM)[9] overcomes partly the limitation of the number of transmit antennas by selecting or activating multiple antennas unlike the original SM. Also by using the quaternary quasi-orthogonal sequence (Q-QOS)[11,12], so called Q-QOS-SM[10] achieves the data throughput higher than those of the SM and GSM, while the number of transmit antennas is restricted to a power of two. In the Q-QOS-SM, a spatial modulation matrix (SMM)[11,12] is introduced as a group of weighting vectors, and the spatial bits are mapped into one column vector of the SMM per symbol duration. The improved Q-QOS-SM (I-QO-SM)[13] has been then reported to further improve the data throughput of the Q-QOS-SM, but it is only designed for eight transmit antennas.

Another class of extended SM schemes contains quadrature SM (QSM)[14] and the enhanced SM (ESM)[15] that are constructed by combining the conventional V-BLAST and the original SM schemes. In the QSM, the modulated symbol is divided into in-phase and quadrature components, and each component independently selects activated transmit antenna for the sending of itself and therefore, transmits twice as many spatial bits as the original SM. In the ESM, for the case of one activated transmit antenna, a single symbol with modulation order M is transmitted, and also for the case of two activated transmit antennas, either two independent symbols with modulation order $\sqrt{M}$ or two rotated independent symbols with modulation order $\sqrt{M}$ are transmitted. Apparently, the QSM and ESM enjoy improved data throughputs compared to the SM, but have much higher decoding complexity due to the transmission of independent symbols like the V-BLAST. This means that the simplified maximum likelihood (ML) decoder[8] used in the SM, GSM, and Q-QOS-SM, cannot be available anymore at a receiver for these schemes.

In this paper, we present a new SM scheme based on the design of Q-QOS-SM, named generalized quaternary quasi-orthogonal sequences SM (G-QO-SM), which can be applied for any number of transmit antennas. The G-QO-SM is basically constructed by using Q-QOSs with the lengths of 2 and 4, unlike the Q-QOS-SM using the Q-QOSs with lengths of $N_t = 2^n$. The design of the new scheme resolves the limitation of transmit antennas, and also ensures a much higher data rate at a given number of transmit antennas. In detail, the G-QO-SM could transmit total N_t spatial bits over N_t transmit antennas, which is much larger than the $2\log_2(N_t)$ in Q-QOS-SM except the trivial case of $N_t = 4$. Furthermore, the total transmit power can be equally distributed to all transmit antennas in the G-QO-SM, and hence the G-QO-SM achieves a lower peak-to-average power ratio (PAPR)[16].

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

Ⅱ. Conventional Q-QOS-SM

In this chapter, the conventional Q-QOS-SM is briefly reviewed, and a generalized transmitter structure, which could apply to the SM, GSM, or Q-QOS-SM, is presented in Fig 1.

The input information bit vector b is split into two parts, m_m modulation bits and m_s spatial bits. The modulation bits are modulated as the M-QAM

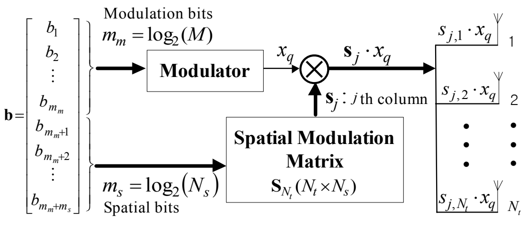

Fig. 1. Generalized transmitter structure for SMs.

symbol, and the spatial bits are mapped into the $j-th$ column vector $\boldsymbol{s}_j$ in the SMM S_{N_t} with a size of $N_t \times N_s$. In addition, the selected column vector $\boldsymbol{s}_j$ weights the signals transmitted by the N_t transmit antennas. In general, the number of information bits transmitted per channel use is given by: $m = \log_2(M) + \log_2(N_s)$.

Under the assumption of i. i. d. $N_r \times N_t$ Rayleigh fading channels H matrix and an average unit transmit power, the received signal is given by the following formula:

$$\boldsymbol{y} = \frac{1}{\sqrt{\| \boldsymbol{s}_j \|_F^2}} \mathrm{H} \boldsymbol{s}_j x_q + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{n}$ is the $N_r - \dim$ additive white Gaussian noise (AWGN) with zero mean and variance σ^2, and every element of H is an independent, complex Gaussian random variable with zero mean and unit variance. The $\| \bullet \|_F$ denotes the Frobenius norm of a vector or matrix.

The Q-QOS-SM[10] adopts the quaternary quasi-orthogonal sequences(Q-QOSs)[10,11] with lengths of $N_t = 2^n$, therefore, the number of transmit antennas must be 2^n and the size of SMM is $N_t \times N_t^2$. The examples of the SMMs in Q-QOS-SM are represented by the following formulas:

$$\mathrm{S}_2 = \mathrm{Q}_2 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & j & -j \end{bmatrix}, \tag{2}$$

$$\mathrm{S}_4 = \mathrm{Q}_4 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -j & j & -j & j & -1 & 1 & -1 & 1 & -j & j & -j & j \\ 1 & 1 & -1 & -1 & 1 & -1 & 1 & 1 & -j & -j & j & j & -j & -j & j & j \\ 1 & -1 & -1 & 1 & j & j & j & -j & -j & j & j & -j & -1 & 1 & 1 & -1 \end{bmatrix} \tag{3}$$

where Q_{N_t} denotes quaternary quasi-orthogonal matrix that made by the Q-QOSs with length N_t.

Compared to the $N_t \times N_t$ identity matrix of the original SM[6-8], the SMM of the Q-QOS-SM comprises many more columns, enabling twice as many spatial bits as the original SM; therefore, if the original SM maintains the identical spectral efficiency with Q-QOS-SM, N_t^2 transmit antennas must be equipped or the modulation order must be MN_t. In GSM[9], because N_u transmit antennas are selected for activation, the number of N_u-combinations from a given set of N_t elements, $C(N_t, N_u)$, is the row size (number of columns) of the SMM. Apparently, the number of combinations increases rapidly with the number of active antennas N_u, but the correlation between the pair of column vectors in the SMM increases more rapidly, and this could causes a considerable performance loss.

For decoding, the hard limiting maximum likelihood (ML) detector (HL-ML) that was proposed for the SM system in [8] can be applied for the above three schemes. In terms of HL-ML detector, the decoding complexity does not grow with the modulation order M under the assumption of uniform quadrature amplitude modulation (QAM).

$$[\hat{j}, \hat{q}] = \arg min_{j,q} \| \boldsymbol{y} - \mathrm{H} \boldsymbol{s}_j x_q \|_F^2 \tag{4}$$

$$= \arg min_j \left[\min_q \| \boldsymbol{z}_j - x_q \|_F^2 - \boldsymbol{z}_j \right] \tag{5}$$

where $\boldsymbol{z}_j = \frac{(\mathrm{H}\boldsymbol{s}_j)^H \boldsymbol{y}}{\| \mathrm{H}\boldsymbol{s}_j \|_F^2}$.

Ⅲ. Proposed G-QO-SM

In this Chapter, we present the new SM scheme, G-QO-SM, that achieves an even greater data throughput than that of the conventional Q-QOS-SM, and the number of transmit antennas is no longer limited. It is known that the number of spatial bits in Q-QOS-SM satisfies $m_s = 2\log_2(N_t) = N_t$ in the case of $N_t = 2,4$.

Based on the quaternary quasi-orthogonal matrices $\mathbf{Q}_2$ and $\mathbf{Q}_4$, the G-QO-SM is designed to guarantee $m_s = N_t$ for an arbitrary N_t. The transmitter diagram of the G-QO-SM is identical to that of Fig 1 with the exception of the corresponding SMM. For G-QO-SM, the SMM is constructed by $\mathbf{Q}_2$ and $\mathbf{Q}_4$, and classified into the following two groups with respect to the number of transmit antennas N_t: even number of transmit antennas and odd number of transmit antennas.

$$N_t = \begin{cases} 2N & \begin{cases} 4n, & N=2n, \quad n=1,2,3,\cdots \\ 4n+2, & N=2n+1, n=0,1,2,\cdots \end{cases} \\ 2N+1 & \begin{cases} 4n+1, & N=2n, \quad n=1,2,3,\cdots \\ 4n+3, & N=2n+1, n=0,1,2,\cdots \end{cases} \end{cases}. \quad (6)$$

3.1 Even number: $N_t = 2N$

For the special case of $N_t = 2,4$, the $\mathbf{Q}_2$ and $\mathbf{Q}_4$ shown in (2) and (3) respectively, are used for the SMM of G-QO-SM. Based on the $\mathbf{S}_4 = \mathbf{Q}_4$, the SMMs are iteratively constructed for $N_t = 4n$, and subsequently the SMMs of $N_t = 4n+2$ can be constructed by the SMMs of $N_t = 4n$ and $\mathbf{S}_2 = \mathbf{Q}_2$.

$N_t = 4n, n = 1, 2, 3, \cdots$

The design of SMM of $N_t = 4n$ is an iteratively construction that is based on $\mathbf{S}_4 = \mathbf{Q}_4$ with size of 4×16. As mentioned before, the $\mathbf{Q}_4$ is the SMM of $N_t = 4$, and the SMM of $N_t = 8$ can therefore be generated by $\mathbf{S}_4$ and the columns of $\mathbf{S}_4$.

$$\mathbf{S}_8 = \underbrace{\overbrace{\left[\begin{array}{c|c|c|c} \overbrace{q_{4,1}\, q_{4,1} \cdots q_{4,1}}^{16} & \overbrace{q_{4,2}\, q_{4,2} \cdots q_{4,2}}^{16} & \cdots & \overbrace{q_{4,16}\, q_{4,16} \cdots q_{4,16}}^{16} \\ \mathbf{S}_4 & \mathbf{S}_4 & & \mathbf{S}_4 \end{array}\right]}^{16}}_{16\times 16 = 2^8} \Big\} 8 \quad (7)$$

where $q_{a,b}$ denotes the $b-th$ column of $\mathbf{Q}_a$ and the $\mathbf{S}_8$ is constructed by the $\mathbf{Q}_4$ and $q_{4,b}$ where $1 \le b \le 16$. In detail, each column of $\mathbf{S}_8$ consists of two columns of $\mathbf{Q}_4$, and the two columns can be the same. There are 16 choices to select one column from $\mathbf{Q}_4$, and it is therefore possible to construct $16 \times 16 = 2^8$ different columns, each with length 8, to form the $\mathbf{S}_8$ with a size of 8×2^8.

Next, the SMM $\mathbf{S}_{12}$ is constructed by the $\mathbf{S}_8$ with a size of 8×256 and the $\mathbf{S}_4$ with a size of 4×16.

$$\mathbf{S}_{12} = \underbrace{\overbrace{\left[\begin{array}{c|c|c|c} \overbrace{q_{4,1}\, q_{4,1} \cdots q_{4,1}}^{256} & \overbrace{q_{4,2}\, q_{4,2} \cdots q_{4,2}}^{256} & \cdots & \overbrace{q_{4,16}\, q_{4,16} \cdots q_{4,16}}^{256} \\ \mathbf{S}_8 & \mathbf{S}_8 & & \mathbf{S}_8 \end{array}\right]}^{16}}_{16\times 256 = 2^{12}} \Big\} 12 \quad (8)$$

Similar to $\mathbf{S}_8$, each column of $\mathbf{S}_{12}$ consists of one column from $\mathbf{S}_4$ and one column from $\mathbf{S}_8$; therefore, 4096 different combinations forming 4096 different columns, each with a length of 12, constitute the $\mathbf{S}_{12}$.

According to this analogy, the SMM of the G-QO-SM for $N_t = 4n$ can be iteratively constructed by the $\mathbf{S}_{4n-4}$ with a size of $(4n-4) \times 2^{4n-4}$ and the $\mathbf{S}_4$ with a size of 4×16, as follows:

$$\mathbf{S}_{4n} = \begin{cases} \mathbf{Q}_4, \; n=1 \\ \overbrace{\left[\begin{array}{c|c|c|c} \overbrace{q_{4,1}\, q_{4,1} \cdots q_{4,1}}^{2^{4n-4}} & \overbrace{q_{4,2}\, q_{4,2} \cdots q_{4,2}}^{2^{4n-4}} & \cdots & \overbrace{q_{4,16}\, q_{4,16} \cdots q_{4,16}}^{2^{4n-4}} \\ \mathbf{S}_{4n-4} & \mathbf{S}_{4n-4} & & \mathbf{S}_{4n-4} \end{array}\right]}^{16}, n \ge 2 \end{cases} \quad (9)$$

where the $\mathbf{S}_{N_t}$ with a size of $N_t \times 2^{N_t}$ is constructed based on the $\mathbf{S}_{N_t-4}$ with a size of $(N_t-4) \times 2^{N_t-4}$ and the $\mathbf{S}_4$ with a size of 4×2^4. One column is selected from $\mathbf{S}_4$ and $\mathbf{S}_{N_t-4}$, respectively, and the two selected columns are then combined into one column with a size of $N_t \times 1$, which is one of the columns in $\mathbf{S}_{N_t}$. In a similar manner, $2^4 \times 2^{N_t-4} = 2^{N_t}$ different columns with a size of $N_t \times 1$ can be made to form the $\mathbf{S}_{N_t}$ with a size of $N_t \times 2^{N_t}$.

$N_t = 4n+2, n = 0, 1, 2, \cdots$

Firstly, $S_2 = Q_2$ is defined, followed by the construction of the SMM of $N_t = 4n+2$ that is based on S_2 and S_{4n} as shown in (9). For example, the S_6 is constructed by the S_2 with a size of 2×4 and the S_4 with a size of 4×16, as follows:

$$S_6 = \underbrace{\overbrace{\left[\overbrace{\begin{matrix} q_{2,1}\, q_{2,1} \cdots q_{2,1} \\ S_4 \end{matrix}}^{16} \left| \overbrace{\begin{matrix} q_{2,2}\, q_{4,2} \cdots q_{2,2} \\ S_4 \end{matrix}}^{16} \right| \cdots \left| \overbrace{\begin{matrix} q_{2,4}\, q_{2,4} \cdots q_{2,4} \\ S_4 \end{matrix}}^{16} \right.\right]}^{4}}_{4\times 16 = 2^6} \Big\} 6\,. \quad (10)$$

For $N_t = 10$, the SMM is constructed based on the $S_2 = Q_2$ and the S_8.

$$S_{10} = \underbrace{\overbrace{\left[\overbrace{\begin{matrix} q_{2,1}\, q_{2,1} \cdots q_{2,1} \\ S_8 \end{matrix}}^{256} \left| \overbrace{\begin{matrix} q_{2,2}\, q_{4,2} \cdots q_{2,2} \\ S_8 \end{matrix}}^{256} \right| \cdots \left| \overbrace{\begin{matrix} q_{2,4}\, q_{2,4} \cdots q_{2,4} \\ S_8 \end{matrix}}^{256} \right.\right]}^{4}}_{4\times 256 = 2^{10}} \Big\} 10\,. \quad (11)$$

For S_6, each column consists of one column from the S_4 and one column from S_2, and $2^2\times 2^4 = 64$ different columns can be made. For S_{10}, each column consists of one column from the S_8 and one column from the S_2, while $2^2\times 2^8 = 1024$ different columns can be made. Similarly, the SMM of $N_t = 4n+2$ can be constructed by the $S_2 = Q_2$ with a size 2×4 and the S_{4n} shown in (9).

$$S_{4n+2} = \begin{cases} Q_2,\ n = 0 \\ \underbrace{\overbrace{\left[\overbrace{\begin{matrix} q_{2,1}\, q_{2,1} \cdots q_{2,1} \\ S_{4n} \end{matrix}}^{2^{4n}} \left| \overbrace{\begin{matrix} q_{2,2}\, q_{2,2} \cdots q_{2,2} \\ S_{4n} \end{matrix}}^{2^{4n}} \right| \cdots \left| \overbrace{\begin{matrix} q_{2,4}\, q_{2,4} \cdots q_{2,4} \\ S_{4n} \end{matrix}}^{2^{4n}} \right.\right]}^{4}}_{2^2\times 2^{4n} = 2^{4n+2}},\ n \geq 1 \end{cases} . \quad (12)$$

Combining the (9) and (12), the SMM of $N_t = 2N$ is shown as follow:

$$S_{2N} = \begin{cases} Q_2,\ N = 1 \\ \left[\begin{matrix} q_{2,1} q_{2,1} \cdots q_{2,1} \\ S_{4n} \end{matrix} \left| \begin{matrix} q_{2,1} q_{2,1} \cdots q_{2,1} \\ S_{4n} \end{matrix} \right| \cdots \left| \begin{matrix} q_{2,4}\, q_{2,4} \cdots q_{2,4} \\ S_{4n} \end{matrix}\right.\right],\ N = 2n+1 \\ Q_4,\ N = 2 \\ \left[\begin{matrix} q_{4,1}\, q_{4,1} \cdots q_{4,1} \\ S_{4n-4} \end{matrix} \left| \begin{matrix} q_{4,2}\, q_{4,2} \cdots q_{4,2} \\ S_{4n-4} \end{matrix} \right| \cdots \left| \begin{matrix} q_{4,16}\, q_{4,16} \cdots q_{4,16} \\ S_{4n-4} \end{matrix}\right.\right],\ N = 2n \end{cases} . \quad (13)$$

3.2 Odd number: $N_t = 2N+1$

In the case of the odd transmit antennas, the SMM can be generated by the S_{2N} in (13) and $Q_1 = [1\ -1]$. For example, the SMMs of $N_t = 3,5,7$ are shown as the following formulas:

$$\begin{aligned} S_3 &= \left[\begin{matrix} 1\ \ 1\ \ 1\ \ 1 \\ Q_2 \end{matrix} \left| \begin{matrix} -1\ -1\ -1\ -1 \\ Q_2 \end{matrix} \right.\right] \\ &= \begin{bmatrix} 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & j & -j & 1 & -1 & j & -j \end{bmatrix} \end{aligned} \quad (14)$$

$$S_5 = \underbrace{\left[\overbrace{\begin{matrix} 1\ \ 1 \cdots\ 1 \\ S_4 \end{matrix}}^{16} \left| \overbrace{\begin{matrix} -1\ -1 \cdots -1 \\ S_4 \end{matrix}}^{16} \right.\right]}_{2\times 16 = 2^5} \Big\} 5 \quad (15)$$

$$S_7 = \underbrace{\left[\overbrace{\begin{matrix} 1\ \ 1 \cdots\ 1 \\ S_6 \end{matrix}}^{64} \left| \overbrace{\begin{matrix} -1\ -1 \cdots -1 \\ S_6 \end{matrix}}^{64} \right.\right]}_{2\times 64 = 2^5} \Big\} 7\,. \quad (16)$$

The design of the odd case is almost identical to that of even case, as long as the S_2 or S_4 is replaced by $Q_1 = [1\ -1]$. Since the size of Q_1 also satisfies the $N_t \times 2^{N_t}$, where N_t denotes the column length of the Q_{N_t}, the size of S_{2N+1} is $(2N+1)\times 2^{2N+1}$. As shown in (14) to (16), the S_3, S_5 and S_7 are generated by Q_1 and S_2, Q_1 and S_4, Q_1 and S_6, respectively. S_{2N+1} is therefore constructed by the S_{2N} in (13) and $Q_1 = [1\ -1]$,

$$\mathbf{S}_{2N+1} = \underbrace{\left[\begin{array}{c|c} \overbrace{1 \quad 1 \ \cdots \ 1}^{2^{2n}} & \overbrace{-1 \ -1 \ \cdots \ -1}^{2^{2n}} \\ \mathbf{S}_{2N} & \mathbf{S}_{2N} \end{array}\right]}_{2 \times 2^{2N} = 2^{2N+1}}, N = 1, 2, 3, \cdots \quad (17)$$

The SMM of G-QO-SM for the arbitrary number of transmit antennas is given in (13) and (17), and the size of SMM is designed as $N_t \times 2^{N_t}$, thereby guaranteeing that the G-QO-SM transmits N_t spatial bits over N_t transmit antennas.

3.3 Comparisons of data rates with other SM schemes

The SMMs of the odd and even antennas are presented in (13) and (17), respectively. From the (7)-(17), it can be observed that the SMM of G-QO-SM is designed to guarantee the size of $N_t \times 2^{N_t}$, whereby N_t spatial bits are mapped into the N_t dimension spatial constellation with the 2^{N_t} modulation order. Unlike the conventional Q-QOS-SM for which the Q-QOSs with a length $N_t = 2^n$ are used, the SMM of the G-QO-SM is constructed by using the quaternary quasi-orthogonal matrix $\mathbf{Q}_2$, $\mathbf{Q}_4$ and an extra $\mathbf{Q}_1$ is not quaternary quasi-orthogonal. Therefore N_t spatial bits can be transmitted over N_t transmit antennas and a full antenna design flexibility is achieved.

The comparison of transmission data rate per channel use is presented in Table 1. The comparison results show that the G-QO-SM achieves the highest transmission data rate among the SM schemes in the case of N_t transmit antenna and M-QAM. At a given m and N_t, the modulation order of G-QO-SM is the smallest of all of the compared SM schemes, since the G-QO-SM could transmit more spatial bits over the same number of transmit antennas. The proposed G-QO-SM can therefore obtain an SNR gain over the other SM schemes, and this will be further proved in the Chapter Ⅳ performance analysis and Chapter Ⅴ simulation results.

In original SM[6-8], conventional Q-QOS-SM[10], QSM[14] and ESM[15], the number of transmit antennas must be $N_t = 2^n$, and the number of spatial bits $m_s = \log_2 N_t$ or $m_s = 2\log_2 N_t$ can not linearly increase with the number of transmit antennas. Therefore, ever-increasing costs are required with the continual updating of the system. For example, if the number of transmit antennas is 128, 128 additional transmit antennas are needed to improve the 1-bit data rate in spatial domain for the original SM. Furthermore, 128 additional transmit antennas are required to improve the 2-bits data rate in spatial domain for conventional Q-QOS-SM, QSM and ESM. However, when t additional antennas are equipped, the G-QO-SM can transmit t spatial bits more. The GSM activates N_u antennas from the total N_t antennas at each symbol epoch, so that the number of spatial bits can be very large in the case of a large N_u. Nonetheless, the large N_u results in a large number of spatial bits, while it also generates a much larger correlation between some pairs of column vectors in SMM, which can cause a large performance loss.

Table 1. Comparison of transmission data rate.

Scheme	Data rate m
SM [6-8]	$\log_2 N_t + \log_2(M)$
GSM(N_t, N_u) [9]	$\lfloor \log_2 C(N_t, N_u) \rfloor + \log_2(M)$
Q-QOS-SM [10]	$2\log_2 N_t + \log_2(M)$
QSM [14]	$2\log_2 N_t + \log_2(M)$
ESM [15]	$2\log_2 N_t + \log_2(M)$
G-QO-SM	$N_t + \log_2(M)$

Ⅳ. Performance Analysis

In this chapter, the method in [9] is used as a reference to derive a bit error rate (BER) upper bound for the original SM, GSM, conventional Q-QOS-SM, and proposed G-QO-SM.

First, a well-known union bounding technique[17] is given as follows:

$$BER \leq E_x \left[\sum_{\hat{j}, \hat{q}} \frac{N(x_{j,q}, x_{\hat{j},\hat{q}}) Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}})}{m} \right] \quad (18)$$

where $N(x_{j,q}, x_{\hat{j},\hat{q}})$ denotes the number of bits in error between $x_{j,q}$ and $x_{\hat{j},\hat{q}}$ and E_x refers to the expectation with respect to x. The $Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}})$ is the pair-wise error probability (PEP) between $x_{\hat{j},\hat{q}}$ and $x_{j,q}$. With the ML equation of (4) serving as a basis, the PEP is expressed by the following equations:

$$Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}})$$
$$= Pr(\| \boldsymbol{y} - \mathrm{H}\boldsymbol{s}_j x_q \|_F^2 > \| \boldsymbol{y} - \mathrm{H}\boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2) \quad (19)$$

$$= Pr(\| \boldsymbol{n} \|_F^2 > \| \mathrm{H}(\boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}}) + \boldsymbol{n} \|_F^2). \quad (20)$$

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

$$K_{j,q} = \sum_{i=1}^{N_r} \left| \frac{n_i}{\sigma/\sqrt{2}} \right|^2 , \quad (21)$$

$$K_{\hat{j},\hat{q}} = \sum_{i=1}^{N_r} \left| \frac{\mathrm{H}(\boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}}) + n_i}{\hat{\sigma}/\sqrt{2}} \right|^2 \quad (22)$$

where $\hat{\sigma}^2 = \| \boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2 + \sigma^2$ and σ^2 is the variance of n_i.

Inserting (21) and (22) into (20), the following equation is obtained,

$$Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}}) = Pr(K_{\hat{j},\hat{q}} / K_{j,q} < \sigma^2 / \hat{\sigma}^2). \quad (23)$$

Since $K_{\hat{j},\hat{q}} / K_{j,q}$ follows the F-distribution, The following equation can be obtained by using the cumulative distribution function (CDF) of F-distribution,

$$Pr(x_{j,q} \rightarrow x_{\hat{j},\hat{q}}) = I_{\frac{\sigma^2}{\sigma^2 + \hat{\sigma}^2}}(N_r, N_r) \quad (24)$$

where $I_x(a,b)$ is the regularized incomplete beta function[9], By substituting (24) in (18), the upper bound is obtained as,

Table 2. Comparison of minimum Euclidean distance.

Scheme	$N_t=5$ $m=7$	$N_t=6$ $m=8$	$N_t=7$ $m=9$	$N_t=8$ $m=10$
SM[6-8]	-	-	-	0.049 M=128
GSM(N_t, 2)[9]	0.2 M=16	0.1 M=32	0.1 M=32	0.048 M=64
Q-QOS-SM[10]	-	-	-	0.3 M=16
QSM[14]	-	-	-	0.2 M=16
ESM[15]	-	-	-	0.4879 M=16
G-QOS-SM	0.5 M=4	0.5 M=4	0.33 M=4	0.5 M=4

$$BER \le E_x \left[\sum_{\hat{j},\hat{q}} \frac{N(x_{j,q}, x_{\hat{j},\hat{q}}) I_{\frac{\sigma^2}{\sigma^2+\hat{\sigma}^2}}(N_r, N_r)}{m} \right]. \quad (25)$$

The (23) and (25) show that the BER performance of SM system greatly depends on $\hat{\sigma}^2 = \| \boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2 + \sigma^2$, and especially depends on the Euclidean distance as follows.

$$d = \| \boldsymbol{s}_j x_q - \boldsymbol{s}_{\hat{j}} x_{\hat{q}} \|_F^2 \quad (26)$$

$$= \| x_q \|_F^2 + \| x_{\hat{q}} \|_F^2 - 2Re\{ (\boldsymbol{s}_j x_q)^H x_{\hat{q}} \boldsymbol{s}_{\hat{j}} \}. \quad (27)$$

It is well-known that a large minimum Euclidean distance signifies an excellent BER performance in the high SNR region. Accordingly, the comparison of minimum Euclidean distance is presented in Table 2. As shown in Table 2, the G-QO-SM has more design flexibility than those of the other SM schemes with the exception of GSM, since the number of transmit antennas is limited to be a power of two in other SM schemes. Moreover, the minimum distance of the proposed G-QO-SM is larger than those of GSM for all of the cases, and is also the largest among all of the SM scheme in the case of $N_t = 8$. These results indicates that the BER performance of proposed G-QO-SM is more favorable than those of the other SM schemes at high SNR. In fact, regarding the G-QO-SM, most of information bits are transmitted through the spatial dimension, resulting in few modulation bits and a

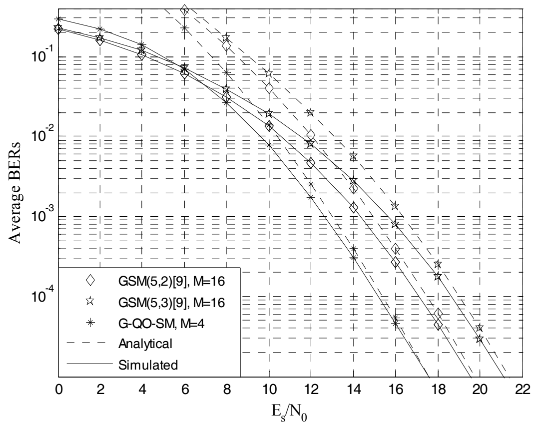

Fig. 2. Average BERs for $N_t = 5$ and $m = 7$.

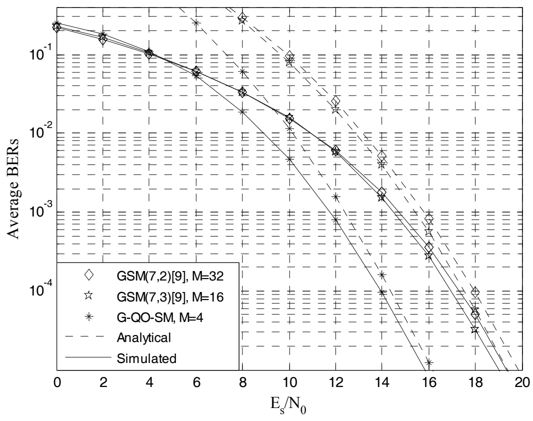

Fig. 4. Average BERs for $N_t = 7$ and $m = 9$.

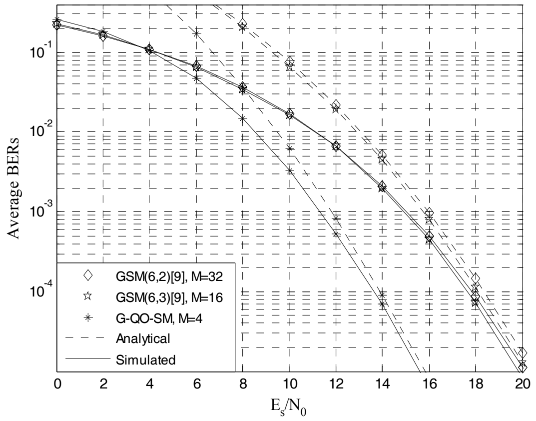

Fig. 3. Average BERs for $N_t = 6$ and $m = 8$.

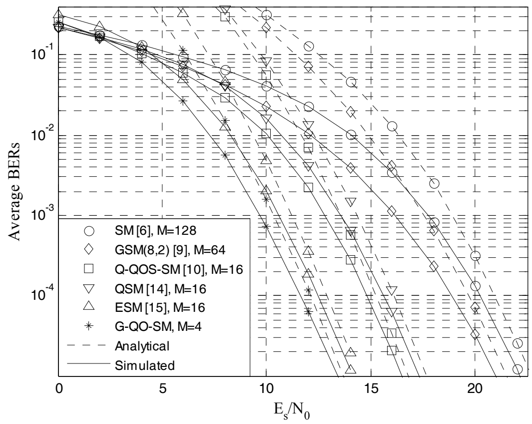

Fig. 5. Average BERs for $N_t = 8$ and $m = 10$.

low modulation order. Furthermore, the spatial dimension consists of N_t sub-dimensions so that the transmission capacity is greater than that of the traditional modulation dimension, the complex plane.

V. Simulation Results

In this chapter, the simulation results of the BER performances and data throughput in the case of Rayleigh fading channel are presented. Moreover, it was assumed that the number of receive antennas is equal to the number of transmit antennas for all of the cases.

The BER curves of $N_t = 5$ and $m = 7$ are presented in Fig 2. The proposed Q-QOS-SM provides about 2 dB SNR gains over GSM(5, 2) and 3 dB SNR gains over GSM(5, 3) at BER value of 10^{-4}. This simulation result agrees with the prediction as previously mentioned. The analytical upper bound in (18) is tight with simulated BER in high SNR as shown in figure.

In Fig 3, the BER curves with $N_t = 6$ at 8 bits per channel use are shown. The G-QO-SM provides about 4 dB SNR gains over GSM at BER value 10^{-4}. In the case of $N_t = 7$ and $m = 9$, as shown in Fig 4, the G-QO-SM also outperforms the two case of GSM with about 3dB SNR gains. Since the number of the transmit antennas of SM, Q-QOS-SM, QSM and ESM must be $N_t = 2^n$, only the BER performance of GSM and the proposed G-QO-SM are presented in Fig 2 to Fig 4.

The Fig 5 presents the BER curves at $N_t = 8$ and $m = 10$ for all referred SM schemes. The G-QO-SM could provide about 1 dB SNR gains

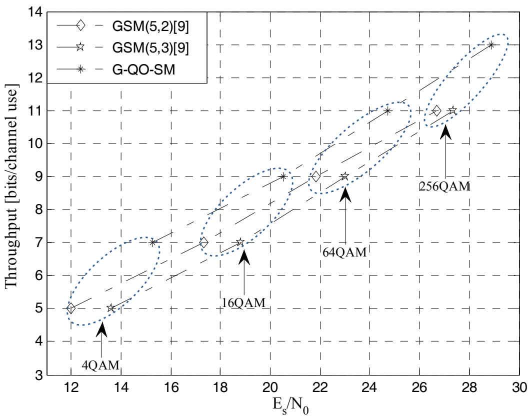

Fig. 6. Data throughput for $N_t=5$.

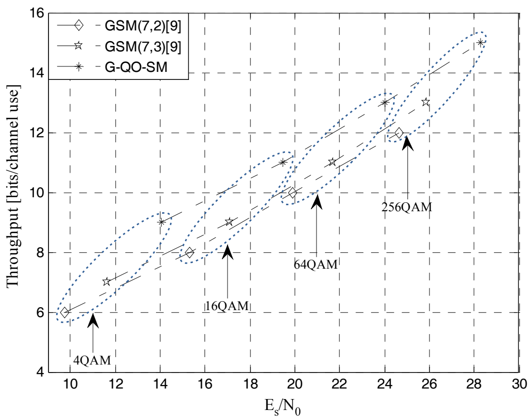

Fig. 8. Data throughput for $N_t=7$.

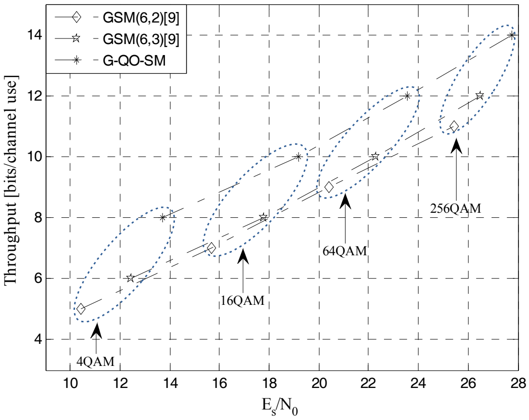

Fig. 7. Data throughput for $N_t=6$.

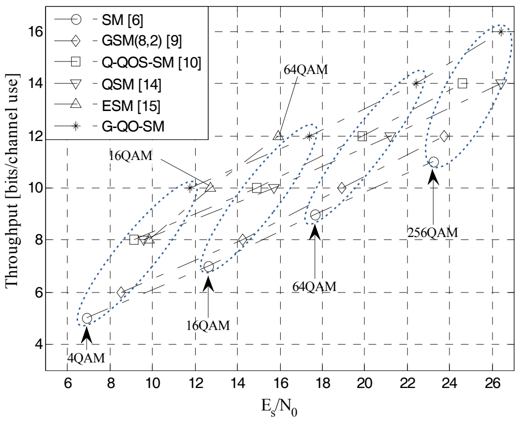

Fig. 9. Data throughput for $N_t=8$.

over ESM, 3 dB SNR gains over Q-QO-SM, 4 dB SNR gain over QSM, 7 dB SNR gains over GSM(8, 2) and 8 dB SNR gains over original SM at the BER value 10^{-4}. Furthermore, the analytical upper bounds for all of the SM schemes are given by using (18) in Chapter Ⅳ, which is very tight to the simulated BER at a high SNR as shown in figure. It can be observed that the modulation order of G-QO-SM is always less than those of the other SM schemes due to the larger number of spatial bits, and thus G-QO-SM achieves a high spectral efficiency at a given m and N_t. This finding confirms that the use of a large size SMM is more efficient the use of a large modulation order in the SM systems.

In the Fig 6 to Fig 9, the data throughput curves are plotted for the case of $N_t=5$, $N_t=6$, $N_t=7$ and $N_t=8$. Each curve consists of 4 points that represents the cases of 4QAM, 16QAM, 64QAM and 256QAM, respectively. The throughput is measured by the SNR required at a BER value of 10^{-4}.

The Fig 6 shows that the proposed G-QO-SM provides a throughput gain of approximately 0.5 bits per channel use (bpcu) over GSM(5, 2) and 1 bpcu over GSM(5, 3). For the case of $N_t=6$ that is shown in Fig 7, the G-QO-SM provides about 1.5 bpcu throughput gains over the best case of GSM. In the Figure 8, the data throughput of G-QO-SM is higher than that of the best case of GSM, with approximately 1 bpcu more than GSM.

In the Fig 9, the data throughput curves with $N_t=8$ are presented for all referred SM schemes. Regarding the ESM[15], only 4QAM, 16QAM and 64QAM have been designed in the paper, and thus the throughput curve of ESM in Fig 9 consists of only three points, from 4QAM to 64QAM. Fig 9 show that the G-QO-SM provides 1 bpcu throughput gains over conventional Q-QOS-SM, 1.5 bpcu over QSM, 3 bpcu over GSM(8,2) and 3.5 bpcu over original SM. For the ESM, only the case of 64QAM is slightly more favorable in the comparison with the proposed G-QO-SM. However, as mentioned in the Chapter I, the HL-ML detector[8] as shown in (5) is not applicable to the ESM, and thus the decoding complexity of ESM is much higher than G-QO-SM in a case where a high-order modulation is used. Further, while ESM is designed only for 4QAM, 16QAM and 64QAM, and the G-QO-SM can use any type of modulation with any modulation order.

Ⅵ. Conclusions

In this paper, a new SM scheme named G-QO-SM, which avoids the transmit-antenna limitation that exists in the original SM, conventional Q-QOS-SM, QSM, and ESM, is proposed, and a further-improved performance is achieved. Compared to the referred SM schemes, the G-QO-SM could transmit N_t spatial bits over N_t transmit antennas, and this is greater than those of the other SM schemes. The large number of spatial bits results in a low modulation order so that the G-QO-SM achieves a higher spectral efficiency than the other SM schemes. The analytical BER upper bound under the assumption of the Rayleigh fading channel is also presented for all of the referred SM schemes in this paper.

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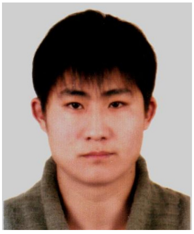

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