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Complex Generalized Quadrature Spatial Modulation for Large Scale MIMO System

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Abstract — Quadrature spatial modulation (QSM) maintains all of the advantages of spatial modulation but further improves upon its spectral efficiency by the logarithm base two of the number of transmit antennas. However, further improvement in terms of system complexity can still be achieved. This led to a generalized quadrature spatial modulation (GQSM) scheme. The proposed scheme is based on employing the transmit antenna combination to create unique groups at every transmission instant. In addition, a unique symbol is transmitted across the transmit antenna groups employed.
GQSM reduced the required number of transmit antennas for high data rate in QSM by employing antenna grouping. Reduction in the imposed complexity for practical implementation of GQSM can still be achieved. Finally, the effects of low-complexity transmit antenna selection for the proposed scheme (CGQSM) is investigated to further reduce the computational complexity (CC) overhead. The selection is based on computing the channel amplitude and antenna correlation to eliminate poor channel(s). Monte Carlo simulation results demonstrate a trade-off between CC and reliability in comparison to the use of optimal antenna selection.

Keywords — Antenna, complex quadrature spatial modulation, generalized quadrature spatial modulation, multiple-input multiple-output, quadrature spatial modulation.

I. INTRODUCTION

A significant promise with respect to potential high capacity coupled with superior system error performance has been shown in multiple-input multiple-output (MIMO) system. This brought about several techniques of MIMO system such as spatial modulation (SM) [1, 2].
SM [1] is an improved MIMO scheme, which employs spatial dimension in an innovative manner to convey additional information via a single radio frequency (RF) chain. The requirement for a single RF chain in SM eliminates the major setback of inter-antenna synchronization (IAS) and inter-channel interference (ICI) experienced in conventional MIMO system. However, SM suffers a criticism of its data rate enhancement, which is proportional to logarithm base-two of the total number of transmit antennas. Unlike other spatial multiplexing techniques such as V-BLAST (Vertical Bell Laboratories Layered Space-Time) [3], the data rate increases linearly with the number of transmit antennas. Similarly, the demand for high data rates in multimedia services requires a scheme with superior error performance and high throughput. However, the computational and hardware complexity (CC) of the system will increase as the spectral efficiency increases, due to the increase in the required number of transmit antennas [4]. This was another setback in the SM system as a high number of transmit antennas are required for high data rates. This led to the investigation of generalized spatial modulation (GSM) [4].
GSM [4], [5] maps its information bits to the index of a transmit antenna combination. Therefore, it employs more than one transmit antenna at every transmission instant, which

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improves the constraint of a large number of transmit antennas in SM. However, the error performance of SM is superior when compared to GSM of the same spectral efficiency.

In addition, the criticism of SM and system performance of GSM led to quadrature spatial modulation (QSM) [6] and SM-based scheme, which extends its spatial constellation into the in-phase and quadrature-phase dimensions. Hence, it enhances the overall spectral efficiency of the system. The in-phase and quadrature-phase components of the QSM system are modulated into the cosine and sine carriers, respectively. The QSM eliminates ICI and IAS in the system and maintains the benefit of SM mentioned earlier. However, the drawback of QSM is that its potential for transmit diversity is not exploited. Hence, it limits the error performance of the system.

In [7], a complex QSM scheme (CQSM), an advanced QSM technique is proposed to achieve a spectral efficiency of 2q+2log_2 (N_T) b/s/Hz, where N_T is the number of transmit antennas. The proposed scheme transmits the real and imaginary parts of a signal constellation symbol in a designated spatial constellation dimension. CQSM transmits two complex signal modulation symbols, drawn from two different modulation sets, at each transmission interval. The first and second symbols are drawn from a conventional phase shift keying/quadrature spatial modulation (PSK/QAM) modulation set and a rotated version of it, respectively. The system exhibits an improved error performance when compared to GQSM and QSM system of the same spectral efficiency. However, the computational complexity (CC) and memory requirement for CQSM are still high for practical implementation, considering the unique symbol employed at every transmission instant coupled with the rotating angle that has to be considered at the receiver, which results in twice the CC of QSM system.

Recently, generalized quadrature spatial modulation (GQSM) [8] is proposed. It employs antenna grouping to achieve a high spectral efficiency. The total number of transmit antennas is divided into small antenna groups, each equipped with two transmit antennas. This can be easily extended to form a group with more than two transmit antennas, and employ the principle of the QSM technique, in which each group transmits a unique M-order quadrature amplitude modulation/phase-shift keying (M-QAM/M-PSK) symbol at every transmission instant. GQSM exhibits an improved error performance when compared to SM and QSM scheme at a cost of high CC.

In this work, we introduce the use of transmit antenna combinations in generalized quadrature spatial modulation to achieve a low CC in a large-scale MIMO scheme, considering the high imposed CC in GQSM. Transmit antenna combinations are employed to transmit a unique decomposed M-QAM complex symbol across each combination as against antenna groups in [8] and without rotating angle to reduce the CC overhead at the receiver. The Monte Carlo simulation results obtained reveal a trade-off in terms of error performance and complexity.

It has been investigated in the literature [9] and [10] that link adaptation can further improve the error performance of any MIMO scheme. For example, in [11], Euclidean distance antenna selection (EDAS), an optimal approach, was incorporated to the SM system to improve the error performance of the scheme based on maximizing the minimum Euclidean distance. The error performance of the scheme is greatly improved at a cost of high CC due to the exhaustive search technique employed by EDAS.

Similarly, in [12], a sub-optimal low-complexity transmit antenna selection approach was investigated in the SM system based on channel amplitude and antenna correlation to further reduce the CC imposed on the system when compared to the exhaustive search technique of EDAS. The overall CC of the system is reduced when compared to the exhaustive search EDAS approach, but the EDAS technique exhibits a superior error performance. Hence, a trade-off in terms of CC and performance exist between both techniques. This motivated us to investigate antenna selection based on channel amplitude and antenna correlation (a sub-optimal technique) in the proposed CGQSM system to further improve the system performance of the scheme.

II. RESEARCH METHOD

A) System model for Complex Generalized Quadrature Spatial Modulation

In the proposed CGQSM, additional transmit antenna index is employed coupled with unique symbols at every active transmit antenna to achieve higher spectral efficiency and further improve system reliability.

The proposed scheme with an array of N_T transmit antennas and M modulation order yields a spectral efficiency of $m = n_b \log_2(M) + \log_2 \binom{N_T}{N_a}$ b/s/Hz. The $n_b \log_2(M)$ bits map the amplitude/phase modulation (APM) symbol; and $\log_2 \binom{N_T}{N_a}$ is mapped to the ℓ_1 and ℓ_2 transmit antennas employed per group, where $\ell \in [1: N_{T_k}]$; N_{T_k} is the number of transmit antennas required per group; N_T is the number of available transmit antennas; N_R is the number of receive antennas; N_a is the number of active transmit antennas per group; and n_b is the number of the unique symbols employed.

The available channel matrix H_ℓ is of dimension $N_R \times N_{T_k}$, which is independent and identically distributed (iid) as $CN(0, 1)$. The channel matrix is employed to transmit the vector x_q in the presence of additive white Gaussian noise (AWGN (n)) of dimension $N_R \times 1$.

Considering an example with the following configuration of 4 × 4, 4-QAM, i.e, 4 transmit antennas and 4 receive antennas, this will yield a spectral efficiency of 6 b/s/Hz. Assuming two active antenna groups at every transmission instant, then, $2\log_2(4) = 4$ b/s/Hz and $\log_2 \left\lfloor \binom{N_T}{2} \right\rfloor = 2$ b/s/Hz, given the set of $N_c = \binom{N_T}{N_a}$ transmit antenna combinations, where N_c is all the antenna combination possible; and N_s is the useable antenna combinations from all the available combination, such that $N_s = 2^{\lfloor \log_2(N_c) \rfloor}$. An example based on the mapping process for the proposed CGQSM is tabulated in Table 1.

TABLE 1
EXAMPLE OF MAPPING PROCESS FOR CGQSM SYSTEM

Settings	**Input bits**	**Antenna bits**	**Symbol bits**
	$n_b(\log_2(M)) + \left\lfloor \log_2 \binom{N_T}{N_a} \right\rfloor$ $N_a = 2$	$\left\lfloor \log_2 \binom{N_T}{N_a} \right\rfloor$ bits	$n_b \log_2 M$ bits
$M = 4$ $N_T = 4$ $N_R = 4$	1 0 1 0 0 0	[1 0] $\ell = 3$	[1 0 0 0] $x_q^1 = 1 + 1i$ $x_q^2 = -1 + 1i$
$M = 16$ $N_T = 4$ $N_R = 4$	1 1 0 1 0 0 0 0 1 0	[1 1] $\ell = 4$	[0 1 0 0 0 0 1 0] $x_q^1 = -1 + 3i$ $x_q^2 = -3 - 3i$

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Table 1 presents an example of the mapping process for the proposed CGQSM scheme. Considering the first configuration settings with input bits (1 0 1 0 0 0) in Table 1, this is divided into two sections. One section chooses the transmit antenna (1 0) based on $\left\lfloor \boldsymbol{log_2}\binom{\boldsymbol{N_T}}{\boldsymbol{N_a}}\right\rfloor$bits. In this case, the third antenna combination from $\binom{\mathbf{4}}{\mathbf{2}}$, which is 1 4 will be active. The first transmit antenna coupled with the fourth transmit antenna will be active for transmission as 1 0 is 3. The second section (1 0 0 0) modulates the APM symbol based on $\boldsymbol{n_b log_2 M}$ bits. Considering $\boldsymbol{n_b}$=2 in this case, the $\boldsymbol{n_b log_2 M}$bits will be sub-divided into two. Hence, 1 0 selects $\mathbf{1+1}\boldsymbol{i}$ APM symbol; and 0 0 selects $-\mathbf{1+1}\boldsymbol{i}$APM symbol, which is further decomposed into real and imaginary components to form the vector $\boldsymbol{x_q}$. The received signal y is expressed as:

$$y = \sqrt{\rho/N_a}\sum_{\ell}^{N_a} H_\ell x_q + n \qquad (1)$$

where $x_q = \left[x_q^{\ell_1} \cdots x_q^{\ell_{N_a}}\right]$; $\ell \in [1{:}N_a]$, $q \in [1{:}M]$, $x_q^{\ell_1} \cdots x_q^{\ell_{N_a}}$ is further decomposed into real and imaginary components; ρ represents the average signal-to-noise ratio (SNR).
Employing (1) coupled with the example explanation given in Table 1, the received signal vector y can be re-written as:

$$y = \sqrt{\rho/N_a}\, H_1 1 + H_4 1i + H_1(-)1 + H_4 1i + n$$

The received signal vector y is detected optimally. It employs the maximum likelihood (ML) by estimating the antenna index and the modulated symbol to recover the transmitted information. Similar to [4], the ML detector evaluation is given as:

$$\left[\ell_{\hat{1},} \cdots \ell_{\hat{N}_a}, x_{\hat{q}}\right] = \mathrm{argmin}_{q\in[1:M]}\left(\left\|y - \sqrt{\rho/N_a}\sum_{\ell}^{N_a} H_\ell x_q\right\|_F^2\right) \qquad (2)$$

Fig. 1 reveals the system model of CGQSM equipped with N_T transmit antennas and N_R receive antennas.

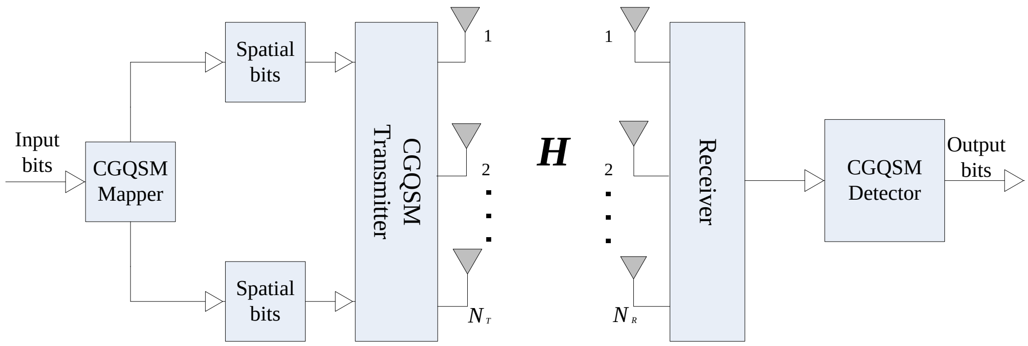

Fig. 1. System model of CGQSM system

B) Average BER Analysis for CGQSM

The conditional pairwise error probability of x_q, which is demodulated correctly, is given as:

$$P\left(x_q \rightarrow x_{\hat{q}} \mid H_\ell\right) = P\left(\left\|y - \sqrt{\frac{\rho}{N_a}}\, h_{\ell_R} x_{q_R}^{\ell} + h_{\ell_I} x_{q_I}^{\ell}\right\|_F > \left\|y - \sqrt{\frac{\rho}{N_a}}\, h_{\ell_{\hat{R}}} x_{q_R}^{\hat{\ell}} + h_{\ell_{\hat{I}}} x_{q_I}^{\hat{\ell}}\right\|\right) \qquad (3)$$

where h_{ℓ_R} and h_{ℓ_I} are the ℓ^{th} column of the channel matrix employed to transmit the real and imaginary component of $x_{q_R}^{\hat{\ell}}$ and $x_{q_I}^{\hat{\ell}}$, repectively. Employing the triangle inequality [13], i.e. $|x| - |y| \leq |x + y| \leq |x| + |y|$ across a combined SNR, we obtain:

$$P\left(x_q \rightarrow x_{\hat{q}} |\, H_\ell\right) = P\left(2 \cdot \|n\|_F > \left\|\sqrt{\frac{\rho}{N_a}} h_{\ell_R} x_{q_R}^{\ell} + h_{\ell_I} x_{q_I}^{\ell} - \sqrt{\frac{\rho}{N_a}} h_{\ell_{\hat{R}}} x_{q_R}^{\hat{\ell}} + h_{\ell_{\hat{I}}} x_{q_I}^{\hat{\ell}}\right\|_F\right) \quad (4)$$

Employing Q-function with some simplification similar to [6], [14] with $CN(0,2\sigma^2)$, the pairwise error probability (PEP) becomes:

$$P\left(x_q \rightarrow x_{\hat{q}} |\, H_\ell\right) = P\left(2\sqrt{2\sigma^2} > \left\|h_{\ell_R} x_{q_R}^{\ell} + h_{\ell_I} x_{q_I}^{\ell} - h_{\ell_{\hat{R}}} x_{q_R}^{\hat{\ell}} + h_{\ell_{\hat{I}}} x_{q_I}^{\hat{\ell}}\right\|_F\right) =$$

$$= Q\left(\frac{\sqrt{\left\|h_{\ell_R} x_{q_R}^{\ell} + h_{\ell_I} x_{q_I}^{\ell} - h_{\ell_{\hat{R}}} x_{q_R}^{\hat{\ell}} + h_{\ell_{\hat{I}}} x_{q_I}^{\hat{\ell}}\right\|_F}}{2\sigma^2}\right) \quad (5)$$

Employing the probability density function of the SNR over Rayleigh fading channel given in [15], and using moment generating function (MGF) for simplification and considering one receive antenna $p_\gamma = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$, we obtain:

$$\mu = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{\gamma+1}}\right) \quad (6)$$

where $\gamma = \frac{\|x_q\|^2}{4\sigma^2}$.

Considering the event across N_R receive antennas,

$$P_\gamma = \sum_{k=1}^{N_R} \gamma_k \;\; k \in [1,2 \ldots . h_{N_T}] \quad (7)$$

Employing substitution method and MGF, the closed-form of (7) is written as [13], [16]:

$$P\left(x_q \rightarrow x_{\hat{q}} |\, H_\ell\right) = \mu^{N_R} \sum_{k=0}^{N_R-1} \binom{N_R - 1 + k}{k} [1 - \mu]^k \quad (8)$$

The union upper bound for average CGQSM can be written as [14], [16]:

$$P_b \leq \frac{1}{2^m} \sum_x \sum_{x \neq \hat{x}} \frac{1}{m} P\left(x_q \rightarrow x_{\hat{q}} |\, H_\ell\right) e_{x,\hat{x}} \quad (9)$$

where $e_{x,\hat{x}}$ is the number of bit error associated with the transmit antennas employed and the estimated transmit antennas.

C) Receiver Computational Complexity

The receiver complexity of the proposed CGQSM system is formulated based on complex multiplications and complex additions similar to [7]. The ML detector searches over the constellation points of 2^m and the transmit antenna combinations. Considering the received signal vector y of dimension $N_R \times 1$ with channel matrix H_ℓ of dimension $N_R \times N_{T_k}$ and the vector x_q of dimension $N_{T_k} \times 1$, $H_\ell x_q$ yields $N_R N_a$ complex multiplications; and $\|\cdot\|_F^2$ yields N_R complex multiplications.

Hence, the receiver complexity of (2) for CGQSM of across N_a with 2^m point is:

$$\varphi = 2^m(N_R(N_a + 1)) \quad (10)$$

D) Transmit Antenna Selection for the Proposed CGQSM

In this section, transmit antenna selection algorithm is introduced for the proposed CGQSM based on channel amplitude and antenna correlation. In both techniques, $\mathrm{N_{all}}$ transmit antennas are considered, where $\mathrm{N_{all}} > \mathrm{N_T}$. An optimal Euclidean distance–based transmit antenna selection will not be considered due to the imposed CC, which is quite high, based on the exhaustive search of the EDAS technique. The number of complex multiplications imposed on the system based on the number of enumerations of selecting $\mathrm{N_T}$ transmit antennas out of the available transmit antennas is not practical. Thus, an optimal based transmit antenna selection is not considered for CGQSM.

E) Channel Amplitude and Antenna Correlation-Based Transmit Antenna Selection

The sub-optimal transmit antenna selection based on channel amplitude and antenna correlation of [12] is investigated in the CGQSM system. This technique demonstrates a low CC when compared to the EDAS technique. This is due to the exhaustive search of the EDAS technique among the transmit antennas combination pairs.

Based on the channel amplitude, the channel vectors are arranged in an ascending. The channel with the highest energy corresponding to each transmit antenna is employed for the next transmission interval as follows:

$$\left\|\mathrm{h}_{\ell_1}\right\|_\mathrm{F}^2 \geq \left\|\mathrm{h}_{\ell_1}\right\|_\mathrm{F}^2 \geq \cdots \geq \left\|\mathrm{h}_{\ell_{\mathrm{N_{all}}}}\right\|_\mathrm{F}^2 \tag{11}$$

Furthermore, transmit antenna correlation, which was investigated in [12], based on discarding transmit antennas, which has high correlation, is used to eliminate the poor channels using the angle of correlation [17], [18] for all possible combinations.

$$\theta = \arccos\left(\frac{\left|\bar{\mathrm{h}}_{\mathrm{k}_1}{}^{\mathrm{H}}\bar{\mathrm{h}}_{\mathrm{k}_2}\right|}{\left\|\bar{\mathrm{h}}_{\mathrm{k}_1}\right\|_\mathrm{F}\left\|\bar{\mathrm{h}}_{\mathrm{k}_2}\right\|_\mathrm{F}}\right) \tag{12}$$

where the number of pairs combination is given by $\binom{\mathrm{N_T}+1}{\mathrm{N_a}}$.The selected channel vector is employed in the next transmission interval.

III. RESULTS AND ANALYSIS

The Monte Carlo simulation results obtained for CGQSM coupled with the analytical result employing a union bound approach is computed in this section to validate the Monte Carlo simulation results obtained. The result presented in Fig. 2a is a $8 \times 4, 4$-QAM system. The analytical result validates the Monte Carlo simulation results in Fig. 2 from low SNR to high SNR region as expected.

Likewise, the result presented in Fig. 2b is equipped with a $7 \times 4, 16$-QAM configuration setting. The theoretical result also validates the Monte Carlo simulation results obtained. At a BER of 10^{-5}, the theoretical result shows a tight bound with the Monte Carlo simulation result, validating the system model of the CGQSM scheme.The gap at the low SNR region is well known with union bound as seen in [6] when compared with the lower bound approach as seen in [13].The notation ($\mathrm{N_T}$, $\mathrm{N_{R,}}$ $M, \mathrm{N_a}$) is employed in all the graph legend.

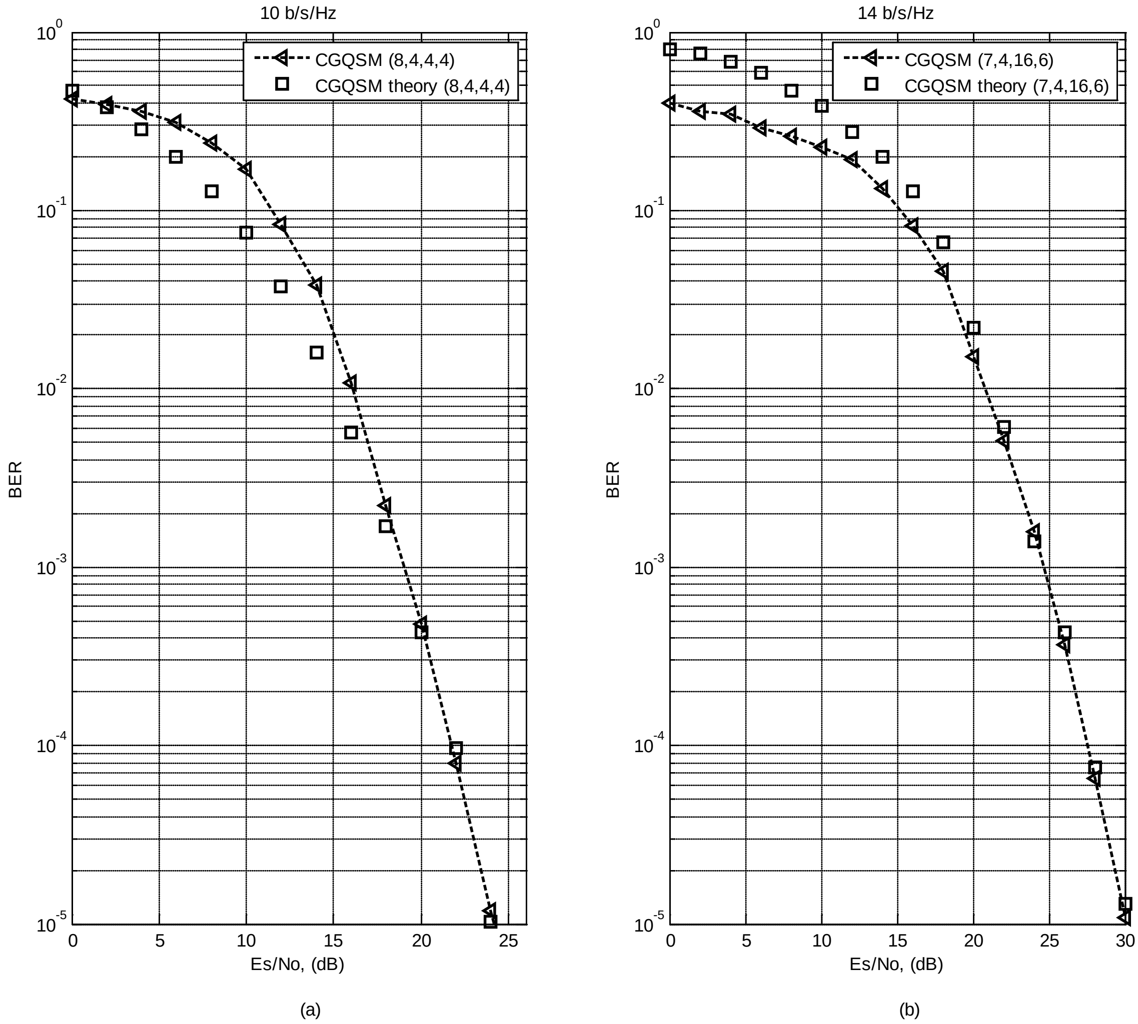

Fig. 2. Validation of CGQSM theoretical analysis with the Monte Carlo simulation result

In Fig. 3, GQSM and CGQSM schemes of the same spectral efficiency are compared to reveal the performance of each system in terms of error performance. It was observed that the error performance of GQSM matches that of CGQSM at a lower CC. Such that at a BER of 10^{-5}, both schemes exhibit the same error performance, while CGQSM exhibits a lower CC.

In Fig. 4, the low-complexity antenna selection was implemented with the proposed CGQSM compared to the error performance with the conventional GQSM and CGQSM schemes; the Monte Carlo simulation result shows that the error performance for CGQSM with transmit antenna selection is improved with a gain of 1 dB at a BER of 10^{-5} as seen in Fig. 4.

The CGQSM with antenna selection shows significant enhancement with a gain of approximately 1 dB at a BER of 10^{-5}over conventional GQSM and CGQSM system with the same spectral efficiency of 10 b/s/Hz.

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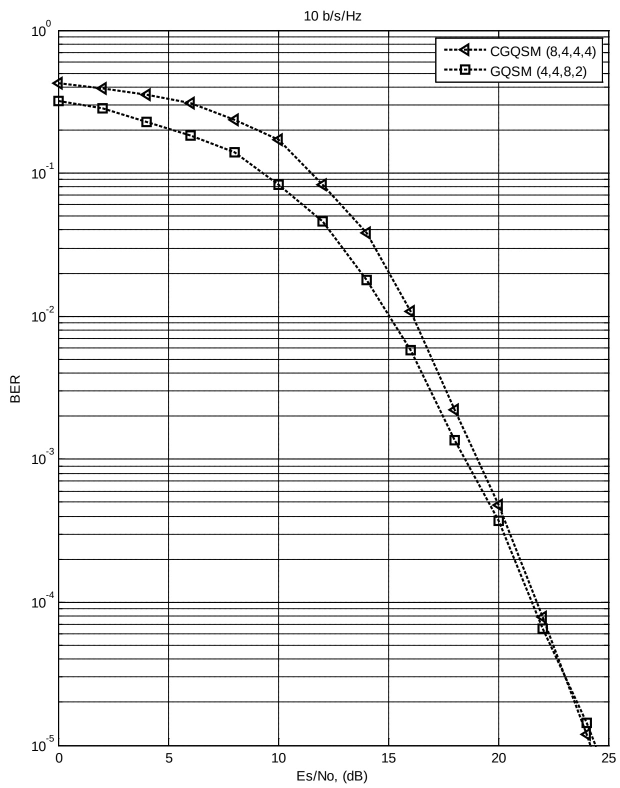

Fig. 3.The Monte Carlo simulation results for GQSM and CGQSM

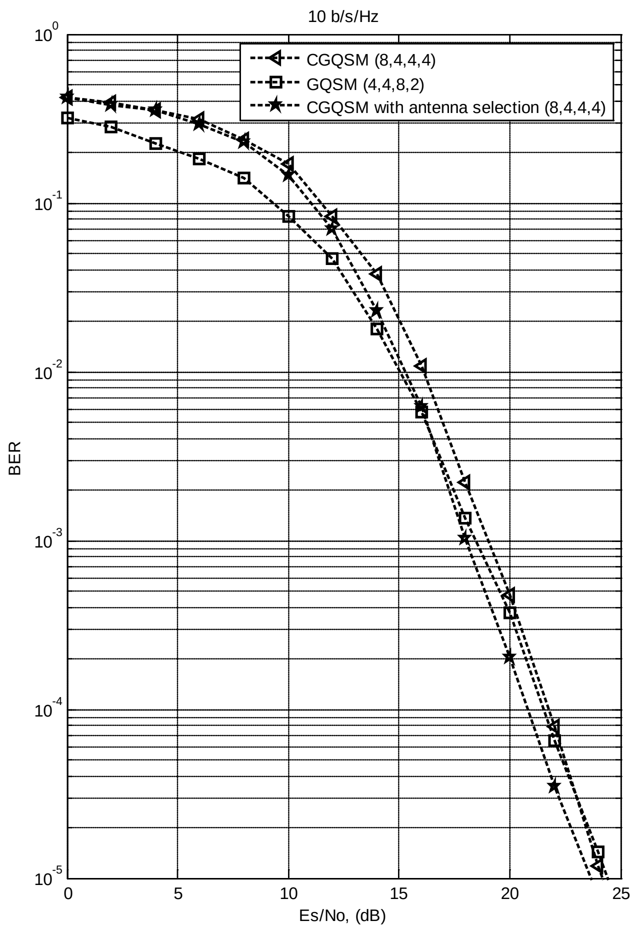

Fig. 4. Monte Carlo simulation results for GQSM, CGQSM and CGQSM with antenna selection

The SNR gain achieved by CGQSM with transmit antenna selection with respect to GQSM and CGQSM schemes is tabulated in Table 2.

TABLE 2
SNR GAIN (DB) ACHIEVED, WITH RESPECT TO THE PROPOSED CGQSM WITH A SPECTRAL EFFICIENCY OF 10 B/S/HZ EQUIPPED TRANSMIT ANTENNA SELECTION

Scheme	SNR gain achieved
GQSM	1 dB
Conventional CGQSM	1dB

Table 2 presents the SNR gain achieved with respect to the proposed system equipped with transmit antenna selection, with the following settings: the 10 b/s/Hz system is equipped with a modulation order of 4-QAM, i.e. $M = 4$ and $N_T = 8$ and four receive antennas. The proposed scheme with transmit antenna selection exhibits a gain of 1 dB over the conventional CGQSM and GQSM in the literature as tabulated in Table 2.

IV. CONCLUSION

In this paper, CGQSM has been investigated in QSM scheme for large scale MIMO system compared to GQSM which is proposed in the literature in terms of error performance. Likewise, transmit antenna selection was introduced to the proposed CGQSM based on the channel amplitude and antenna correlation. The Monte Carlo simulation results obtained exhibit a gain of approximately 1 dB gain over the conventional GQSM and CGQSM system of the same spectral efficiency.

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