RF Mirror Media-based Modulation for Golden Codes

N. Pillay, H. Xu
School of Engineering, University of KwaZulu-Natal, Durban, South Africa, 4041
pillayn@ukzn.ac.za

***Abstract*—The application of radio frequency (RF) mirror media-based modulation (MbM) for the Golden code (GcMbM) is investigated. GcMbM improves upon the achievable spectral efficiency/error performance of the conventional Golden code. The analytical error performance of the conventional Golden code has not been presented in the literature; hence, the analytical average bit error probability (ABEP) based on the union bound is presented and validates Monte Carlo simulation results at high signal-to-noise ratios (SNRs). The ABEP analysis is extended to GcMbM and validates simulation results at high SNRs.**

***Index Terms*—Golden Codes; Media-Based Modulation; RF Mirror; Space-Time Block Codes; Space-Time Channel Modulation.**

I. Introduction

The evolution of wireless communication systems demands higher data rates and improved reliability while conserving bandwidth and power. To this end, multiple-input-multiple-output (MIMO) systems have shown significant benefits. However, the practicability of MIMO systems remains a bottleneck to unleashing its full benefits. The Alamouti space-time block code (ASTBC) [1] exploits some of the benefits of MIMO. For instance, the scheme achieves full-diversity, while employing a simple maximum-likelihood (ML) detector in quasi-static frequency-flat Rayleigh fading channels. The Golden code [2, 3] improves upon the spectral efficiency of ASTBC, additionally achieving both full-diversity and full-rate. Furthermore, the Golden code has been included in the 802.16e WiMAX standard. In [3], a detector for the Golden code, which reduces the detection complexity from $O(M^4)$ to $O(M^2)$ was presented.

Recently, media-based modulation (MbM) [4]-[8] has been investigated in the literature. The key idea behind MbM is to employ techniques that vary the RF properties (permittivity, permeability and resistivity) of the air medium in the vicinity of the transmitter. Hence, in a rich-scattering environment, multiple independent end-to-end channels may be realised, which may be exploited for the embedding of information. Numerous advantages and disadvantages of MbM have been discussed in detail in [4]-[6]. Amongst these, MbM is capable of achieving very high spectral and energy efficiencies.

In [6]-[7], MbM based on the use of radio frequency (RF) mirrors was investigated and showed very promising results. In [8], space-time channel modulation (STCM) was proposed and investigates the application of RF mirror MbM to ASTBC. A substantial improvement in performance is demonstrated.

Based on the above background, in this paper, we are motivated to investigate RF mirror MbM for the Golden code (GcMbM). Since the Golden code employs a similar transmission structure to ASTBC, the schemes investigated for STCM [8], are also considered for GcMbM. Three schemes are investigated for GcMbM. Each scheme uses a particular configuration for activation of the RF mirrors [8].

Additionally, the analytical average bit error probability (ABEP) based on the union bound is formulated for the conventional Golden code and extended to GcMbM.

The remainder of the paper is organised as follows: In Section II, the analytical ABEP for the Golden code is presented. Section III presents the system model of the proposed GcMbM. In Section IV, the analytical ABEP for the Golden code is extended to GcMbM. Numerical results are presented in Section V. Finally; conclusions are drawn in Section VI.

Notation: $(\cdot)^H$, $|\cdot|$ and $\|\cdot\|_F$ represents Hermitian, Euclidean norm and Frobenius norm, respectively. $Q(\cdot)$ represents the Gaussian Q-function, $E\{\cdot\}$ is the expectation operator. $\underset{w}{\operatorname{argmin}}(\cdot)$ represents the minimum value of an argument with respect to w, $Re\{\cdot\}$ is the real part of a complex argument and j represents a complex number.

II. Union Bound on ABEP for the Golden Code

Assume a Golden code transmits four amplitude and/or phase modulation (APM) symbols, s_i, where $i \in [1, 2, \cdots, 4]$ and $s_i \in \mathbf{S}$, $|\mathbf{S}| = M$, in two time-slots using a transmission matrix, defined as [2]:

$$\mathbf{X} = \frac{1}{\sqrt{5}}\begin{bmatrix} \alpha(s_1 + s_2\theta) & \alpha(s_3 + s_4\theta) \\ \gamma\bar{\alpha}(s_3 + s_4\bar{\theta}) & \bar{\alpha}(s_1 + s_2\bar{\theta}) \end{bmatrix} \tag{1}$$

where $\theta = \frac{1+\sqrt{5}}{2}$ is the Golden number, $\bar{\theta} = 1 - \theta$, $\alpha = 1 + j\bar{\theta}$, $\bar{\alpha} = 1 + j\theta$ and $\gamma = j$.

Based on Equation (1), considering a frequency-flat Rayleigh fading channel, where the channel gains remain constant during a time-slot but assume independent values from one time-slot to another, the received signal vector (employing N_R receive antennas) over two time-slots may be defined as:

$$\begin{aligned} \mathbf{y}_1 &= \sqrt{\rho/_{10}}\begin{pmatrix} \mathbf{h}_1\alpha(s_1 + s_2\theta) + \\ \mathbf{h}_2\alpha(s_3 + s_4\theta) \end{pmatrix} + \boldsymbol{\eta}_1 \\ \mathbf{y}_2 &= \sqrt{\rho/_{10}}\begin{pmatrix} \mathbf{h}_3\gamma\bar{\alpha}(s_3 + s_4\bar{\theta}) + \\ \mathbf{h}_4\bar{\alpha}(s_1 + s_2\bar{\theta}) \end{pmatrix} + \boldsymbol{\eta}_2 \end{aligned} \tag{2}$$

where $\mathbf{y}_1$ and $\mathbf{y}_2$ are the $N_R \times 1$ received signal vectors in time-slot 1 and 2, respectively. The factor ${\rho}/{10}$ is the average signal-to-noise ratio (SNR) at each receive antenna. The $N_R \times 1$ channel gain vectors are defined as $\mathbf{h}_i$, $i \in [1, 2, \cdots, 4]$. The $N_R \times 1$ vectors $\boldsymbol{\eta}_1$ and $\boldsymbol{\eta}_2$ represent additive Gaussian noise. The entries of $\mathbf{h}_i$, $\boldsymbol{\eta}_1$ and $\boldsymbol{\eta}_2$ are complex Gaussian independent and identically distributed (i.i.d.) random variables (RVs) with zero mean and unit variance.

The ABEP based on the union bound approach [1],[9] may be formulated accordingly as:

$$P_e \leq \frac{1}{M^4} \sum_{\mathbf{X}} \sum_{\widehat{\mathbf{X}}} \frac{N(\mathbf{X}, \widehat{\mathbf{X}}) P(\mathbf{X} \to \widehat{\mathbf{X}})}{4 \log_2 M} \tag{3}$$

where $\widehat{\mathbf{X}} = \frac{1}{\sqrt{5}} \begin{bmatrix} \alpha(\hat{s}_1 + \hat{s}_2\theta) & \alpha(\hat{s}_3 + \hat{s}_4\theta) \\ \gamma\bar{\alpha}(\hat{s}_3 + \hat{s}_4\bar{\theta}) & \bar{\alpha}(\hat{s}_1 + \hat{s}_2\bar{\theta}) \end{bmatrix} = \begin{bmatrix} \hat{x}_1 & \hat{x}_2 \\ \hat{x}_3 & \hat{x}_4 \end{bmatrix}$ is the erroneously detected transmission matrix given $\mathbf{X} = \begin{bmatrix} x_1 & x_2 \\ x_3 & x_4 \end{bmatrix}$ (refer (1)) was transmitted, $N(\mathbf{X}, \widehat{\mathbf{X}})$ is the number of bit errors associated with the pairwise error probability (PEP) event $P(\mathbf{X} \to \widehat{\mathbf{X}})$.

The conditional PEP $P(\mathbf{X} \to \widehat{\mathbf{X}}|\mathbf{H})$ may be formulated as:

$$\begin{aligned} P(\mathbf{X} \to \widehat{\mathbf{X}}|\mathbf{H}) = P\Bigg(\left\| \mathbf{y}_1 - \sqrt{{\rho}/{2}}\, (\mathbf{h}_1\hat{x}_1 + \mathbf{h}_2\hat{x}_2) \right\|_F^2 \\ + \left\| \mathbf{y}_2 - \sqrt{{\rho}/{2}}\, (\mathbf{h}_3\hat{x}_3 + \mathbf{h}_4\hat{x}_4) \right\|_F^2 \\ < \|\boldsymbol{\eta}_1\|_F^2 + \|\boldsymbol{\eta}_2\|_F^2 \Bigg) \end{aligned} \tag{4}$$

Simplifying similar to [9], the conditional PEP may be validated as:

$$\begin{aligned} P(\mathbf{X} \to \widehat{\mathbf{X}}|\mathbf{H}) = \\ Q\left(\sqrt{\frac{\rho}{8} \left(\left\| \mathbf{H}_{12} \begin{bmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \end{bmatrix} \right\|_F^2 + \left\| \mathbf{H}_{34} \begin{bmatrix} x_3 - \hat{x}_3 \\ x_4 - \hat{x}_4 \end{bmatrix} \right\|_F^2 \right)} \right) \end{aligned} \tag{5}$$

where $\mathbf{H}_{12} = [\mathbf{h}_1 \quad \mathbf{h}_2]$ and $\mathbf{H}_{34} = [\mathbf{h}_3 \quad \mathbf{h}_4]$.

Employing the moment generating function, similar to [9] (refer to Equations (6) - (9) in [9]), and solving, we arrive at the unconditional PEP:

$$\begin{aligned} &P(\mathbf{X} \to \widehat{\mathbf{X}}) \\ &= \frac{1}{2n} \left[\begin{array}{c} \frac{1}{2} M_1\left(\frac{1}{2}\right) M_2\left(\frac{1}{2}\right) + \\ \sum_{k=1}^{n-1} M_1\left(\frac{1}{2\sin^2\left(\frac{k\pi}{2n}\right)} \right) M_2\left(\frac{1}{2\sin^2\left(\frac{k\pi}{2n}\right)} \right) \end{array} \right] \end{aligned} \tag{6}$$

where $M_i(s) = \left(\frac{1}{1 + 2\sigma_{\alpha_i}^2 s} \right)^{N_R}$, $i \in [1:2]$ and $\sigma_{\alpha_1}^2 = \frac{\rho}{8} \left\| \begin{bmatrix} x_1 - \hat{x}_1 \\ x_2 - \hat{x}_2 \end{bmatrix} \right\|_F^2$, $\sigma_{\alpha_2}^2 = \frac{\rho}{8} \left\| \begin{bmatrix} x_3 - \hat{x}_3 \\ x_4 - \hat{x}_4 \end{bmatrix} \right\|_F^2$ and $n \geq 10$ is chosen for convergence of the trapezoidal approximation [9], used to arrive at Equation (6).

III. System Model of GcMbM

Consider a MIMO configuration with $N_T = 2$ transmit antennas and N_R receive antennas as illustrated in Figure 1.

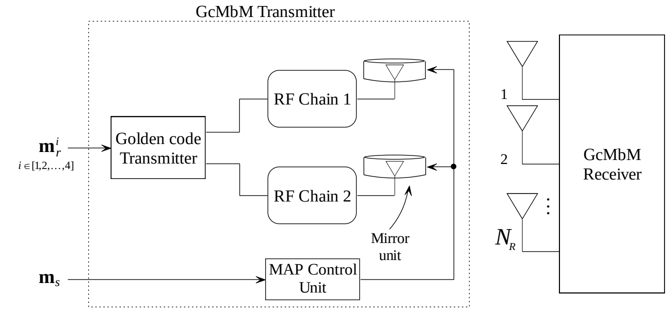

Figure 1: System Model of GcMbM.

Each transmit antenna is surrounded by a set of m_{RF} RF mirrors in a mirror unit [7]. We refer to the antenna and the associated mirror unit as an MbM transmit unit (MbM-TU). The individual mirrors of the MbM-TU are activated or deactivated by switching them ON/OFF via a mirror activation control interface. Hence, m_{RF} mirrors create $N_m = 2^{m_{RF}}$ distinct permutations or mirror activation patterns (MAPs).

GcMbM employs two consecutive time slots to transmit four APM symbols. Given $r = \log_2 M$ and $s = M_{RF}$, where M_{RF} is the number of MAP bits, a $(4r + s)$-tuple message is partitioned into four r-tuple vectors $\mathbf{m}_r^i = [m_{1,i} \quad m_{2,i} \quad \cdots \quad m_{r,i}]$, $i \in [1, 2, \cdots, 4]$ and an s-tuple vector $\mathbf{m}_s = [m_1 \quad m_2 \quad \cdots \quad m_s]$. The vectors $\mathbf{m}_r^i$, $i \in [1, 2, \cdots, 4]$ are then mapped onto M-ary quadrature amplitude modulation (MQAM) (we consider MQAM but this may be easily extended to MPSK) Gray-coded symbol constellation points s_i, $i \in [1, 2, \cdots, 4]$, $s_i \in \mathbf{S}$, $|\mathbf{S}| = M$ and $E\{|s_i|^2\} = 1$. As assumed earlier,

$$\mathbf{X} = \frac{1}{\sqrt{5}} \begin{bmatrix} \alpha(s_1 + s_2\theta) & \alpha(s_3 + s_4\theta) \\ \gamma\bar{\alpha}(s_3 + s_4\bar{\theta}) & \bar{\alpha}(s_1 + s_2\bar{\theta}) \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ x_3 & x_4 \end{bmatrix}.$$

GcMbM is essentially the extension of RF mirror MbM to the Golden code, and since the transmit antenna usage of the Golden code is identical to the Alamouti STBC, we may employ the transmit antenna usage of STCM [8]. Hence, given N_m distinct MAPs at each transmit antenna, the vector $\mathbf{m}_s$ is used to select indices j_k, j_ℓ and j_m, j_n, $j \in [1: N_m]$ at the first and second transmit antennas, in time-slot 1 and 2, respectively. The activation of these MAPs at each transmit antenna may be performed as follows [8]: a) Scheme 1: $M_{RF} = 2m_{RF}, j_k = j_m,\ j_\ell = j_n$, Scheme 2: $M_{RF} = m_{RF}, j_k = j_\ell = j_m = j_n$ and Scheme 3: $M_{RF} = 2m_{RF}, j_k = j_n,\ j_\ell = j_m$.

Hence, the $N_R \times 1$ received signal vectors for GcMbM, over two time slots, may be formulated as:

$$\begin{aligned} \mathbf{y}_1 &= \sqrt{{\rho}/{2}}\, (\mathbf{H}_1 x_1 \mathbf{e}_{j_k} + \mathbf{H}_2 x_2 \mathbf{e}_{j_\ell}) + \boldsymbol{\eta}_1 \\ \mathbf{y}_2 &= \sqrt{{\rho}/{2}}\, (\mathbf{H}_3 x_3 \mathbf{e}_{j_m} + \mathbf{H}_4 x_4 \mathbf{e}_{j_n}) + \boldsymbol{\eta}_2 \end{aligned} \tag{7}$$

where ${\rho}/{2}$ is the average SNR, $\mathbf{H}_i$, $i \in [1, 2, \cdots, 4]$ is the $N_R \times N_m$ frequency-flat Rayleigh fading channel gain matrix, as assumed earlier. The vectors $\mathbf{e}_{j_k}$, $\mathbf{e}_{j_\ell}$, $\mathbf{e}_{j_m}$ and $\mathbf{e}_{j_n}$ are of dimension $N_m \times 1$ with a single non-zero unit entry at location j_k, j_ℓ, j_m and j_n. $\boldsymbol{\eta}_i,\ i \in [1:2]$, represents the $N_R \times 1$ additive Gaussian noise vector. Note, the entries of $\mathbf{H}_i,\ i \in [1, 2, \cdots, 4]$ and $\boldsymbol{\eta}_i,\ i \in [1:2]$ are i.i.d. according to $\mathcal{CN}(0,1)$.

Given complete knowledge of the channel at the receiver, the ML detector may be formulated as:

$$[\hat{x}_1, \hat{x}_2, \hat{x}_3, \hat{x}_4, \hat{j}_k, \hat{j}_\ell] = \underset{\substack{s_i \in \mathbf{S} \\ j \in [1,2,\cdots,N_m]}}{\operatorname{argmin}} \left\{ \begin{array}{l} \left\| \mathbf{y}_1 - \sqrt{\rho/2}\left(\mathbf{H}_1 x_1 \mathbf{e}_{j_k} + \mathbf{H}_2 x_2 \mathbf{e}_{j_\ell}\right) \right\|_F^2 + \\ \left\| \mathbf{y}_2 - \sqrt{\rho/2}\left(\mathbf{H}_3 x_3 \mathbf{e}_{j_m} + \mathbf{H}_4 x_4 \mathbf{e}_{j_n}\right) \right\|_F^2 \end{array} \right\} \tag{8}$$

Given $\mathbf{H}_1 \mathbf{e}_{j_k} = \mathbf{h}^1_{j_k}$, $\mathbf{H}_2 \mathbf{e}_{j_\ell} = \mathbf{h}^2_{j_\ell}$, $\mathbf{H}_3 \mathbf{e}_{j_m} = \mathbf{h}^3_{j_m}$ and $\mathbf{H}_4 \mathbf{e}_{j_n} = \mathbf{h}^4_{j_n}$, it may be further validated that the first and second norm terms in Equation (8), may be simplified as follows:

$$\begin{aligned} \epsilon_1 &= \sqrt{\frac{\rho}{2}} \left\| \mathbf{g}^1_{j_k} \right\| + \sqrt{\frac{\rho}{2}} \left\| \mathbf{g}^2_{j_\ell} \right\| - 2Re\left\{ \mathbf{y}_1^H \mathbf{g}^1_{j_k} \right\} \\ &\quad - 2Re\left\{ \mathbf{y}_1^H \mathbf{g}^2_{j_\ell} \right\} \\ &\quad + \sqrt{2\rho} Re\left\{ {\mathbf{g}^1_{j_k}}^H \mathbf{g}^2_{j_\ell} \right\} \\ \epsilon_2 &= \sqrt{\frac{\rho}{2}} \left\| \mathbf{g}^3_{j_m} \right\| + \sqrt{\frac{\rho}{2}} \left\| \mathbf{g}^4_{j_n} \right\| - 2Re\left\{ \mathbf{y}_1^H \mathbf{g}^3_{j_m} \right\} \\ &\quad - 2Re\left\{ \mathbf{y}_1^H \mathbf{g}^4_{j_n} \right\} \\ &\quad + \sqrt{2\rho} Re\left\{ {\mathbf{g}^3_{j_m}}^H \mathbf{g}^4_{j_n} \right\} \end{aligned} \tag{9}$$

where $\mathbf{g}^1_{j_k} = \mathbf{h}^1_{j_k} x_1$, $\mathbf{g}^2_{j_\ell} = \mathbf{h}^2_{j_\ell} x_2$, $\mathbf{g}^3_{j_m} = \mathbf{h}^3_{j_m} x_3$ and $\mathbf{g}^4_{j_n} = \mathbf{h}^4_{j_n} x_4$.

In terms of computational complexity, Equation (8) requires $M^4 N_m^2$ metric calculations [8] for Scheme 1, 3 and $M^4 N_m$ metric calculations for Scheme 2.

IV. Union Bound on ABEP for GcMbM

Given that the matrix $\mathbf{X}_e = \begin{bmatrix} x_1 \mathbf{e}_{j_k} & x_2 \mathbf{e}_{j_\ell} \\ x_3 \mathbf{e}_{j_m} & x_4 \mathbf{e}_{j_n} \end{bmatrix}$ was transmitted and the matrix $\hat{\mathbf{X}}_e = \begin{bmatrix} \hat{x}_1 \mathbf{e}_{\hat{j}_k} & \hat{x}_2 \mathbf{e}_{\hat{j}_\ell} \\ \hat{x}_3 \mathbf{e}_{\hat{j}_m} & \hat{x}_4 \mathbf{e}_{\hat{j}_n} \end{bmatrix}$ was erroneously received, the ABEP for GcMbM may be formulated as:

$$P_e \leq \frac{1}{2^{M_{RF}} M^4} \sum_{\mathbf{X}_e} \sum_{\hat{\mathbf{X}}_e} \frac{N\left(\mathbf{X}_e, \hat{\mathbf{X}}_e\right) P\left(\mathbf{X}_e \to \hat{\mathbf{X}}_e\right)}{4 \log_2 M + M_{RF}} \tag{10}$$

Based on Equation (7), the conditional PEP may be defined as:

$$\begin{aligned} &P\left(\mathbf{X}_e \to \hat{\mathbf{X}}_e | \mathbf{H}\right) = \\ &P\left(\left\| \mathbf{y}_1 - \sqrt{\rho/2} \begin{pmatrix} \mathbf{H}_1 \hat{x}_1 \mathbf{e}_{\hat{j}_k} + \\ \mathbf{H}_2 \hat{x}_2 \mathbf{e}_{\hat{j}_\ell} \end{pmatrix} \right\|_F^2 \right. \\ &\qquad + \left\| \mathbf{y}_2 - \sqrt{\rho/2} \begin{pmatrix} \mathbf{H}_3 \hat{x}_3 \mathbf{e}_{\hat{j}_m} + \\ \mathbf{H}_4 \hat{x}_4 \mathbf{e}_{\hat{j}_n} \end{pmatrix} \right\|_F^2 \\ &\qquad \left. < \left\| \boldsymbol{\eta}_1 \right\|_F^2 + \left\| \boldsymbol{\eta}_2 \right\|_F^2 \right) \end{aligned} \tag{11}$$

As earlier (refer to [9]), simplifying Equation (11), it may be validated that $P\left(\mathbf{X}_e \to \hat{\mathbf{X}}_e | \mathbf{H}\right)$ is given by:

$$\begin{aligned} &P\left(\mathbf{X}_e \to \hat{\mathbf{X}}_e | \mathbf{H}\right) \\ &= Q\left(\sqrt{\frac{\rho}{8} \left(\left\| \mathbf{H}_{12} \mathbf{S}_{k\ell} \right\|_F^2 + \left\| \mathbf{H}_{34} \mathbf{S}_{mn} \right\|_F^2 \right)} \right) \end{aligned} \tag{12}$$

where $\mathbf{S}_{k\ell} = \begin{bmatrix} x_1 \mathbf{e}_{j_k} - \hat{x}_1 \mathbf{e}_{\hat{j}_k} \\ x_2 \mathbf{e}_{j_\ell} - \hat{x}_2 \mathbf{e}_{\hat{j}_\ell} \end{bmatrix}$, $\mathbf{S}_{mn} = \begin{bmatrix} x_3 \mathbf{e}_{j_m} - \hat{x}_3 \mathbf{e}_{\hat{j}_m} \\ x_4 \mathbf{e}_{j_n} - \hat{x}_4 \mathbf{e}_{\hat{j}_n} \end{bmatrix}$, $\mathbf{H}_{12} = [\mathbf{H}_1 \quad \mathbf{H}_2]$ and $\mathbf{H}_{34} = [\mathbf{H}_3 \quad \mathbf{H}_4]$.

The unconditional PEP may then be evaluated using Equation (6), where $\sigma^2_{\alpha_1} = \frac{\rho}{8} \left\| \mathbf{S}_{k\ell} \right\|_F^2$ and $\sigma^2_{\alpha_2} = \frac{\rho}{8} \left\| \mathbf{S}_{mn} \right\|_F^2$.

V. Numerical Results

In this section, we first validate the simulation results of the Golden code using the bound given by Equation (3). We assume complete channel knowledge and an ML detector for the Golden code [3]. We have considered both MPSK and MQAM. The notation employed is (N_R, M). In both cases (refer to Figure 2), it may be seen that the theoretical results agree closely with the simulation results, especially at high SNRs for $M = 4, 8$ and 16. Next, we present the error performance results for GcMbM (refer to Figure 3). Comparisons are drawn with ASTBC, the conventional Golden code and STCM (Schemes 1-3). The notation employed for ASTBC and the Golden code is (N_R, M), while the notation (N_R, M, m_{RF}) is employed for STCM and GcMbM. In all instances, complete channel knowledge is assumed. A spectral efficiency of 6 bits per channel use (bpcu) is considered.

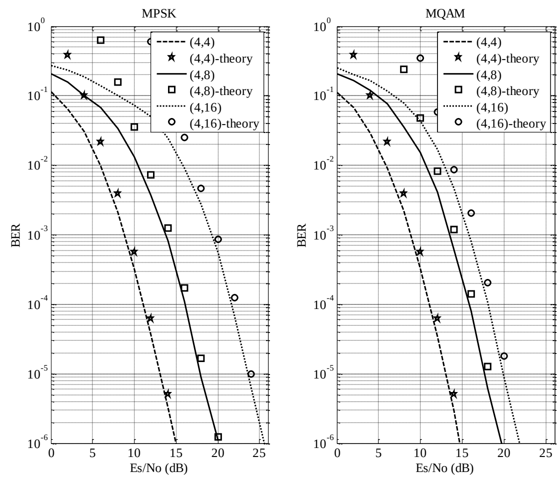

Figure 2: Validation of Monte Carlo simulation results for the Golden code with MPSK and MQAM.

It is evident that GcMbM-1 loses transmit diversity [8]; hence, performing more poorly than STCM-1, while GcMbM-2 and GcMbM-3 retain full-diversity and yield significant SNR gain. For example, at a BER of 10^{-6}, GcMbM-2 yields an SNR gain of approximately 2.9 dB compared to STCM-2, while GcMbM-3 yields a gain of 3 dB over STCM-3. Furthermore, GcMbM-1, 2 and 3 yield SNR gains of 1 dB, 4.8 dB and 4.2 dB, respectively, compared to the Golden code, and 5.3 dB, 9.3 dB and 8.5 dB, respectively, compared to ASTBC.

In all cases, it is evident that the theoretical ABEP given by Equation (10), agrees well with simulation results at high SNR, hence validating the error performance of the proposed GcMbM.

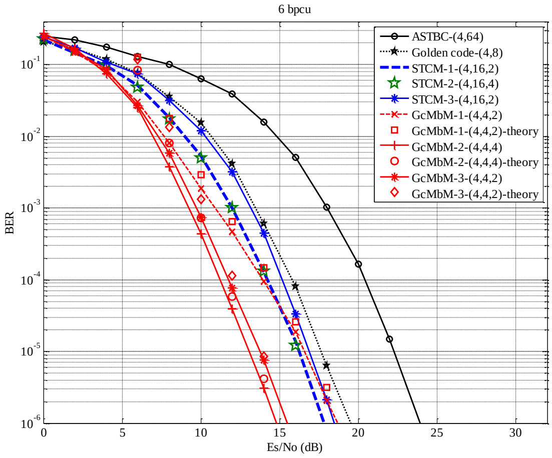

Figure 3: Comparison of numerical results for GcMbM at a spectral efficiency of 6 bpcu.

VI. CONCLUSION

An analytical ABEP (union bound) expression for the Golden code was formulated and validates simulation results at high SNRs. GcMbM was then proposed and exhibits an improved spectral efficiency/error performance. The analytical ABEP of the Golden code was extended to GcMbM and validated simulation results at high SNRs. Possible future work is the investigation of low-complexity detection schemes for GcMbM.

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