Paper

Using of Golden Code Orthogonal Super-Symbol in Media-Based Modulation for Single-Input Multiple-Output Schemes

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Abstract—The media-based modulation (MBM) scheme is capable of providing high throughput, increasing spectrum efficiency, and enhancing bit error rate (BER) performance of communication systems. In this paper, an MBM employing radio frequency (RF) mirrors and golden code is investigated in a single-input multiple-output (GC-SIMO) application. The aim is to reduce complexity of the system, maximize linear relationships between RF mirrors and improve spectral efficiency of MBM to in order to obtain a high data rate with the use of less hardware. Orthogonal pairs of the super-symbol in the GC scheme's encoder are employed, transmitted via different RF mirrors at different time slots in order to achieve the full data rate and high diversity. In the results having BER of 10^{-5}, the GC-SIMO, MBM exhibits better performance than GD-SIMO, with the gain of approximately 7 dB and 6.5 dB SNR for 4 b/s/Hz and 6 b/s/Hz, respectively. The derived theoretical average error probability of the proposed scheme is validated with the use of the Monte Carlo simulation.

Keywords—golden code, media-based modulation, radio RF mirrors, SIMO.

1. Introduction

The continuous need for higher throughputs in wireless communications has led to increased popularity of multiple-input multiple-output (MIMO) systems which have shown great promise regarding high transmission capacity and improved link reliability and are considered to offer good prospects for modern wireless communications [1]–[6].

MIMO systems split signals into several separated bit streams for a high data rate, via simultaneous transmissions of information to multiple receivers. A typical example of a MIMO to consider is spatial modulation (SM) [7], a unique MIMO scheme which employs a number of transmit antennas for high data rate communication.

The basic idea of spatial modulation (SM) is to convey information using both amplitude/phase modulation (APM) and the transmit antenna index. For example, a conventional MIMO system with 4 transmit antennas and 4-QAM modulation yields a data rate of 2 b/s/Hz, while the same configuration in an SM system shows a data rate of 4 b/s/Hz. Similarly, the involvement of a single radio frequency (RF) chain in SM improves the eliminates the setbacks experienced in a conventional MIMO system, such as, for example, inter-antenna synchronization (IAS) and inter-channel interference (ICI) [7]–[11]. Improvements to SM schemes are currently receiving much attention in terms of research focusing on MIMO systems [12], [13].

Spatial diversity is a technique to improve link reliability through the channel's frequency, time, and space variations, with numerous copies of data received at the receiver side. An example to consider is space-time block code (STBC) transmit diversity scheme [14]–[16] which employs the precoding technique to send multiple packets of data from to the group of transmit antennas to optimize SNR and transmitting power with a suitable phase and amplitude. Two time slots are required to transmit two symbols – hence, the data rate remains unchanged [14], [15]. There is an improvement in the reliability of the link due to transmitting redundant data packets over an independent channel. Signal space diversity (SSD) [17], [18] is another example that should be mentioned here, as it achieves communication diversity by transmitting the in-phase and quadrature of the rotated multi-dimension signal to the receiver via an independent fading channel. It offers improved link reliability at no additional cost of hardware, bandwidth, and transmit power.

For the next generation of wireless communication systems, energy efficiency, spectrum usage and system complexity are essential for supporting demand related to multimedia services and applications. Such features bring the media-based modulation (MBM) [19]–[21] enhancing transmission data rate.

MBM uses numerous RF mirrors to design complicated fading symbols, even with a single transmit antenna, by positioning a number of RF mirrors near the transmit antenna that broadcasts a tone. The placement of RF mirrors near the transmit antenna is the same technique as the placement of scatterers near the transmitter in the propagation environment. The mirror activation pattern (MAP) can change the radiation properties of each of these scatterers, i.e. RF mirrors. The propagation environment adjacent to the transmitter varies from one MAP to the other. Thanks to minor perturbation in the propagation environment reinforced by many random reflections in a rich scattering environment, an independent channel feature is obtained. By serving as regulated scatterers, RF mirrors produce this type of radio interference, resulting in independent fading characteristics for different MAPs.

2. Related Work

Due to low hardware requirements and performance advantages of MBM, it has recently attracted considerable amounts of research attention [22]–[25] as a promising technique exhibiting greater benefits over the existing index modulation (IM) systems, such as frequency-domain IM (FD-IM) [26], [27], space domain IM (SD-IM), also referred to as spatial modulation (SM) [8], [28], and time-domain IM (TD-IM) [29] [30]. MBM offers better performance also when compared with conventional modulation schemes [14], [21], [23], [31]. Likewise, research focusing on MBM in MIMO and multiuser settings also showed improved performance of MBM [12], [24]. In addition, describing a scenario in which RF mirrors are employed, papers [24], [32]–[34] prove that MBM may further improve link reliability at a lower degree of hardware complexity, compared to other spatial multiplexing techniques. This is due to the linear correlation between spectral efficiency and the number of RF mirrors used, which is achieved by creating different channel fade realizations via the RF mirrors, known as mirror activation patterns (MAPs) [24]. In [33], a SIMO-aided MBM (SIMO-MBM) scheme is used, where the linear correlation between spectral efficiency and the number of RF mirrors m_{rf} reduces the system's complexity. Considering an example of an equivalent SM system, which would require $2^{m_{rf}}$ transmit antennas to achieve the same spectral efficiency as SIMO-MBM, the SIMO-MBM system is more efficient, in terms of data rate and hardware complexity, than SM. In MBM, RF mirrors may be positioned side-by-side, resulting in the received constellation size being independent of the transmit power, while in conventional MIMO schemes, transmit antennas are adequately separated to achieve independent fading. Therefore, a large increase in spectral efficiency is easily realizable in MBM schemes [35], [36].

In papers [37]–[41], golden code (GC) has been introduced as a scheme. It achieves a full rate and full diversity by employing a precoding technique, using different transmit antennas at various time slots based on the idea of space time label diversity. In [38], GC modulation was investigated, with SIMO systems maintaining the same bandwidth efficiency if a pair of super-symbols is transmitted, coupled with an extra diversity gain. Computation complexity (CC) of a GC-SIMO scheme presented in [37] is reduced by transmitting only the orthogonal pairs in the encoder, such that two symbols are transmitted in total. This still achieves an extra diversity gain when compared to the conventional SIMO system.

The MBM technique was also investigated in connection with GC modulation in [42]. The scheme employs four complex symbols to output the super-symbols, called the golden codewords, via the encoder. The super-symbols are transmitted via four independents transmit antennas in different time slots, such that four symbols are transmitted in total, achieving full rate and full diversity. Each pair of these super-symbols is transmitted via multi-active transmit antennas and in a different time slot. However, complexity of the system proposed in [42] is high, which limits its practical application.

When incorporating the MBM technique in the GC-SIMO scheme, only the super-symbol orthogonal pairs are employed, i.e. only two symbols are used in the encoder against four in [42], which allows to achieve a high data rate similar to that from [37], with reduced hardware complexity. This feature serves as our motivation to propose media-based golden codeword modulation for SIMO, referred to as GC-SIMO-MBM.

In this paper, we start by examining RF mirror-based MBM in a GC-SIMO scheme. Next, theoretical considerations of the proposed system are validated by means of Monte Carlo simulation.

Note. Scalar quantities are represented by regular letters, while vectors/matrices are indicated by bold/italic lowercase/uppercase symbols. $\|\cdot\|$ symbolizes the Frobenius norm, $Q(\cdot)$ denotes the Gaussian Q-function, $\underset{w}{\operatorname{argmin}}(\cdot)$ and $\underset{w}{\operatorname{argmax}}(\cdot)$ signify the minimum/maximum rate of an argument with reference to w, the binomial coefficient is represented by $\binom{\cdot}{\cdot}$, i is a complex number and the real component of the complex number is given by $R\{\cdot\}$, $|\cdot|$ signifies the Euclidean norm, $[\cdot]^T$ represent transpose and $\lfloor\cdot\rfloor$ indicates the closest integer to a lesser extent than the input argument.

3. Golden Code

The golden code offers the full rate and full diversity, employing the precoding technique. The golden code encoder employs 4 unique complex symbols to output 4 super-symbols which are transmitted via unique independent transmit antennas in two time slots. The golden codeword matrix is given as [37], [42]:

$$\boldsymbol{X} = \begin{bmatrix} \alpha(x_1+x_2\theta)\frac{1}{\sqrt{5}} & \gamma\overline{\alpha}(x_3+x_4\overline{\theta})\frac{1}{\sqrt{5}} \\ \alpha(x_3+x_4\theta)\frac{1}{\sqrt{5}} & \overline{\alpha}(x_1+x_2\overline{\theta})\frac{1}{\sqrt{5}} \end{bmatrix},$$

where $\theta = \frac{1+\frac{1}{\sqrt{5}}}{2}$, $\overline{\theta} = 1-\theta$, $\alpha = 1+j(1-\overline{\theta})$ and $\gamma = j$.

Four super-symbols:

$$\alpha(x_1+x_2\theta)\frac{1}{\sqrt{5}},\quad \gamma\overline{\alpha}(x_3+x_4\overline{\theta})\frac{1}{\sqrt{5}},\quad \alpha(x_3+x_4\theta)\frac{1}{\sqrt{5}},\quad \text{and}\quad (\overline{\alpha}x_1+x_2\overline{\theta})\frac{1}{\sqrt{5}},$$

are generated and are referred to as the golden codeword. They comprise two pairs of super-symbols:

$$\left\{\alpha(x_1+x_2\theta)\frac{1}{\sqrt{5}}\ ,\ \ \overline{\alpha}(x_1+x_2\overline{\theta})\frac{1}{\sqrt{5}}\right\}$$

and

$$\left\{\alpha(x_3+x_4\theta)\frac{1}{\sqrt{5}}\ ,\ \ \gamma\overline{\alpha}(x_3+x_4\overline{\theta})\frac{1}{\sqrt{5}}\right\}\ .$$

The pair $\left\{\alpha(x_1+x_2\theta)\frac{1}{\sqrt{5}},\ \overline{\alpha}(x_1+x_2\overline{\theta})\frac{1}{\sqrt{5}}\right\}$ is employed for transmission in the proposed system.

4. Proposed GC-SIMO-MBM

The system model of the proposed GC-SIMO-MBM scheme is shown in Fig. 1. Spectral efficiency associated with this scheme is $m=\log_2(M)+m_{rf}$ [b/s/Hz], where M and m_{rf} represents the amplitude/phase modulation (APM) constellation size and the number of RF mirrors at the transmitting unit, respectively.

In the proposed GC-SIMO-MBM, input bit $\log_2(M)$ is fed into mappers Ω_1 and Ω_2 to map $\log_2(M)$ bits onto the constellation points from the signal set of $\alpha(x_1+x_2\theta)\frac{1}{\sqrt{5}}$ – and $\overline{\alpha}(x_1+x_2\overline{\theta})\frac{1}{\sqrt{5}}$ – in the Argand plane, which yields two super-symbols x_q^1 and x_q^2. In addition, m_{rf} bit chooses the RF mirror to be used for transmission. The number of available RF mirrors m_{rf}, yields the mirror activation pattern (MAP), such that $N_m=2^{m_{rf}}$. For example, if $m_{rf}=2$, then $N_m=4$.

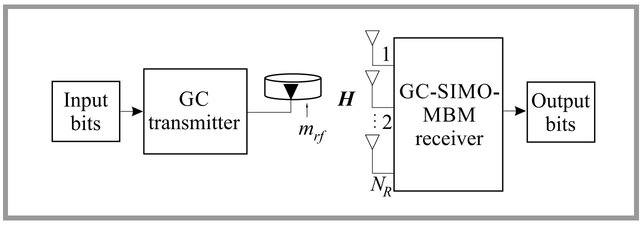

Fig. 1. System model of the proposed GC-SIMO-MBM.

The modulated symbol is conveyed across a channel $\boldsymbol{H}_i$ of magnitude $N_R\times N_m$ in the presence of additive white Gaussian noise (AWGN) $\boldsymbol{n}_i$ of magnitude $N_R\times 1$, e_{ℓ_i} is an $N_m\times 1$ vector. A Rayleigh frequency-flat fading channel is assumed. Therefore, the received signal vector $\boldsymbol{y}_i$ can be written as:

$$\boldsymbol{y}_i=\boldsymbol{H}_i x_q^i \boldsymbol{e}_{\ell_i}+\boldsymbol{n}_i\ , \tag{1}$$

where $i\in[1:2]$, the corresponding transmit antenna employed to transmit the modulated symbol is represented by ℓ_i, while $\boldsymbol{H}_i$ is the i-th column of the channel matrix, which is independent, and identically distributed (i.i.d.) complex Gaussian random variables are distributed as $CN(0,\,1)$.

Using the maximum likelihood (ML) detector at the receiver, the received signal vector $\boldsymbol{y}_i$ is detected optimally, examining the total signal space of M^2 constellation points combined with all possible transmit antenna index. The ML detector can be defined as:

$$\left[\hat{\ell}_1,\,\ldots,\,\hat{\ell}_i,\,x_q^i\right]=\underset{\substack{\ell\in[1:i]\\ x\in\Omega}}{\operatorname{argmin}}\left(\left\|\boldsymbol{y}_i-\boldsymbol{H}_i x_q^i\boldsymbol{e}_{\ell_i}\right\|_F^2\right)\ . \tag{2}$$

5. Performance Analysis

In the performance evaluation of the proposed GC-SIMO-MBM, the BER metric is considered. Similarly to [31], ABEP is defined as:

$$P_e\leq\frac{1}{2N_mM^2m}\sum_{q=1}^{N_mM^2}\sum_{\hat{q}\neq q}^{N_mM^2}N(i,\,\hat{i})P(\boldsymbol{X}_q\rightarrow\boldsymbol{X}_{\hat{q}})\ , \tag{3}$$

where $P(\boldsymbol{X}_q\rightarrow\boldsymbol{X}_{\hat{q}})$ symbolizes the pairwise error probability (PEP) of $\boldsymbol{X}_{\hat{q}}$ detected at the receiver, given that $\boldsymbol{X}_q$ is transmitted, $\boldsymbol{X}_q=(x_q^1,\,x_q^2)$ and $\boldsymbol{X}_{\hat{q}}=(x_{\hat{q}}^1,\,x_{\hat{q}}^2)$, $N(i,\,\hat{i})$ stand for the bit error connected with the PEP event. Similarly to [35], the conditional PEP may be defined as:

$$\begin{aligned}P(\boldsymbol{X}_q\!\rightarrow\!\boldsymbol{X}_{\hat{q}}|\boldsymbol{H}_i)&=P\left(\left\|\boldsymbol{y}_i-\boldsymbol{H}_{\hat{i}}x_q^i\boldsymbol{e}_{\ell_i}\right\|_F^2<\left\|\boldsymbol{y}_i-\boldsymbol{H}_i x_q^i\boldsymbol{e}_{\ell_i}\right\|_F^2|\boldsymbol{H}_i\right)\\&=P\left(\sum_{i=1}^{2}\left\|\boldsymbol{H}_{\hat{i}}x_q^i\boldsymbol{e}_{\ell_i}+\boldsymbol{n}\right\|_F^2<\sum_{i=1}^{2}\left\|\boldsymbol{n}\right\|_F^2\right)\\&=Q\sum_{i=1}^{2}\alpha_i\ ,\end{aligned} \tag{4}$$

where α_i is central chi-squared distribution with $2N_R$ degrees of freedom defined as:

$$\frac{\rho}{2}\left\|\boldsymbol{h}_i\right\|_F^2\left|d_x^i\right|^2=\sum_{k=1}^{2N_R}\alpha_i^2$$

with $N(0,\,\sigma^2)$, $\sigma^2=\frac{\rho}{4}\left|d_x^i\right|^2$.

The probability density function PDF of α_i^2, employing $f_{\alpha_i}(\alpha_i)=\frac{\alpha_i^{N_R-1}e^{\frac{-\alpha_i}{2\sigma^2}}}{(2\sigma^2)^{N_R}(N_R-1)!}$ is similar to the PEP derivation of the GC-SIMO in [37], and is coupled with the trapezoidal approximation of the Q-function given in [17]. Therefore, the PEP for GC-SIMO-MBM can be defined as:

$$\frac{1}{4n}\left(\frac{1}{2}\prod_{i=1}^{2}\left(\frac{\rho}{4}\left|d_x^i\right|^2\right)^{-N_R}+\sum_{k=1}^{2}\left(\frac{\rho}{4}\frac{|d_x^i|^2}{u_k}\right)^{-N_R}\right)\ , \tag{5}$$

where ρ represents the signal-to-noise ratio (SNR), $n>10$ for trapezoidal approximation convergence of the Q-function [17], $i\in[1:2]$, $k\in[1:2N_R]$, $u_k=\sin^2\left(\frac{k\pi}{2n}\right)$ and $\left|d_x^i\right|^2=\left|x_q^i-x_{\hat{q}}^i\right|^2$.

6. Numerical Analysis and Discussion

The results of the simulation obtained for the proposed GC-SIMO-MBM scheme are presented in terms of average BER and SNR parameters. Likewise, the result of the evaluated theoretical ABEP is presented. In all cases, the ML detector is utilized.

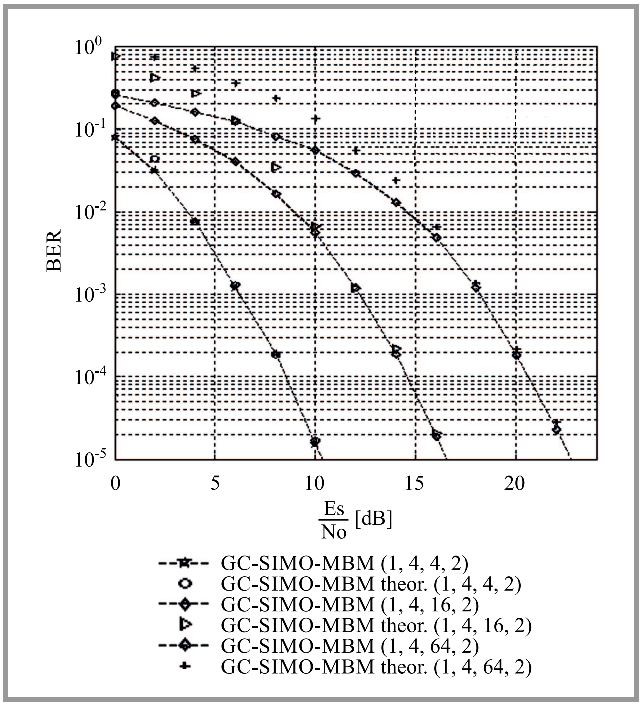

Fig. 2. Performance analysis validation for GC-SIMO-MBM for 4, and 8 b/s/Hz.

In Fig. 2, the GC-SIMO-MBM scheme is shown with a configuration setting of 1×4 4-QAM, 1×4 16-QAM and 1×4 64-QAM with 2 RF mirrors around each transmit antenna ($m_{rf} = 2$). This yields a spectral efficiency of 4, 6, and 8 b/s/Hz, respectively. The results of MC simulation obtained showed a close match with the average theoretical analysis in the high SNR region, validating the proposed scheme.

Figure 3 presents a comparison of performance between the GC modulation of SIMO-MBM [37] and the proposed GC-SIMO-MBM system with the same spectral efficiency of 4 and 6 b/s/Hz, respectively. The simulation results revealed that GC-SIMO-MBM outperforms its counterpart in 4 and 6 b/s/Hz.

One can see from the MC simulation results that using the MBM technique based on RF mirrors improves the system's error performance at a reduced hardware complexity. At a BER of 10^{-5}, GC-SIMO-MBM exhibits a significant performance gain of approximately 7 dB and 6.5 dB SNR for 4 and 6 b/s/Hz, respectively, compared to GC-SIMO from [37]. Similarly, GC-SIMO-MBM outperforms SIMO-MBM by 5 dB and 3.5 dB in 4 and 6 b/s/Hz, respectively.

7. Conclusion

In this paper media-based modulation was examined in a GC-SIMO scheme based on the RF mirrors to improve BER performance and enhance spectral efficiency. The topology based on the GC-SIMO-MBM technique offers

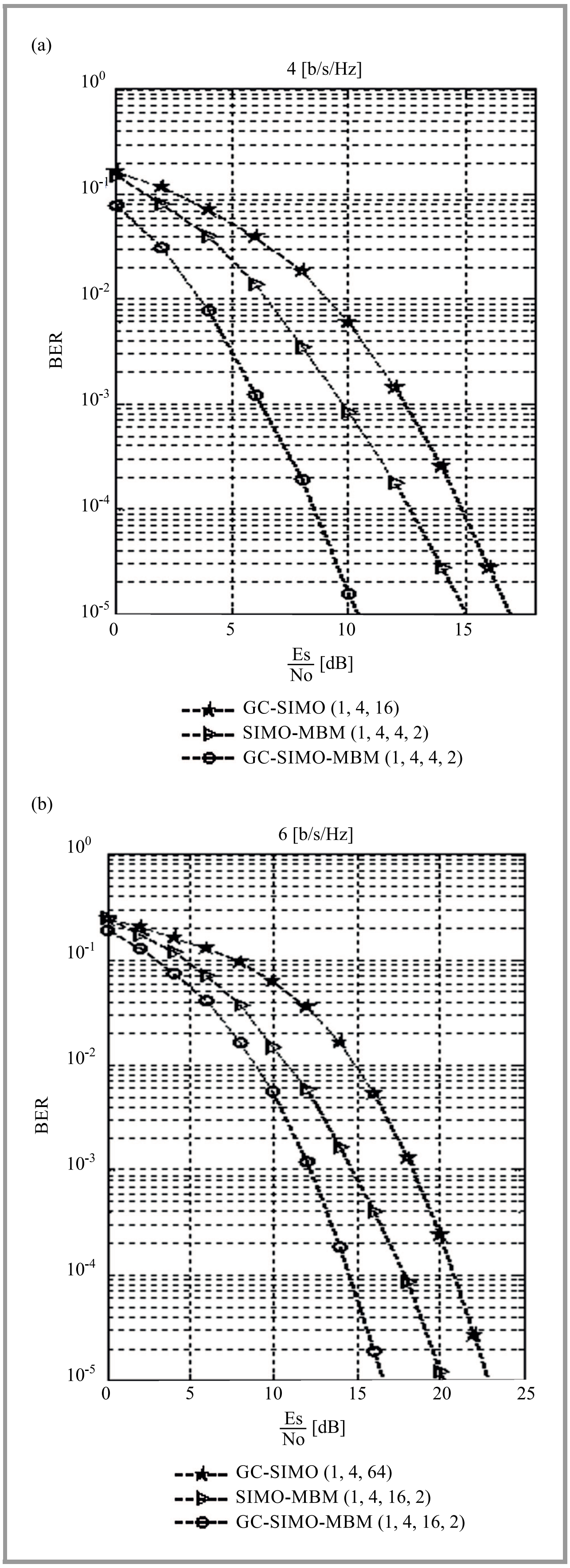

Fig. 3. BER performance comparison of GC-SIMO-MBM, GC-SIMO, and SIMO-MBM for 4 and 6 b/s/Hz.

better BER performance compared to SIMO-MBM and GC-SIMO of the same spectral efficiency. Results of the Monte Carlo simulation indicate that GC-SIMO-MBM shows a significant performance gain of approximately 7 dB and 6.5 dB SNR for 4 and 6 b/s/Hz, respectively, compared to GC-SIMO at a BER of 10^{-5}. The proposed GC-SIMO-MBM system is validated by theoretical and numerical results which show that the scheme is capable of significantly improving the system's hardware complexity, maximizing the linear relationship between RF mirrors and the spectral efficiency in MBM to accomplish a high data rate at a reduced hardware complexity by employing orthogonal pairs of the super-symbol in the GC scheme's encoder, transmitted via different RF mirrors at different time slots to achieve full rate and full diversity.

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