Precoder and Combiner Design for Generalized Spatial Modulation based Multiuser MIMO Systems

Bernardo Brogueira[1,2], João Pedro Pavia[1,2], Nuno Souto[1,2] and Américo Correia[1,2]
[1] Department of Information Science and Technology, ISCTE-University Institute of Lisbon, 1649-026 Lisboa, Portugal.
[2] Instituto de Telecomunicações, 1049 - 001 Lisboa, Portugal.
Correspondence should be addressed to Bernardo Brogueira: bernardo_brogueira@iscte-iul.pt

Abstract – **Multiple input multiple output (MIMO) schemes based on generalized spatial modulations (GSM) have been widely considered as potential candidate techniques for next-generation wireless networks, as they can improve both spectral and energy efficiency. In this paper we propose a multi-user MIMO system, where a base station transmits precoded GSM symbols to several receivers. In the adopted GSM approach, multiple antennas transmit different high-level QAM symbols simultaneously. The precoder is designed in order to remove interference between users while an iterative algorithm is applied at the receiver to accomplish single-user GSM detection. Simulation results show that the presented GSM MU-MIMO approach is capable to effectively exploit a large number of transmit antennas deployed at the transmitter and also provide performance gains over conventional MU-MIMO schemes with identical spectral efficiencies.**

Keywords—B5G, generalised spatial modulation (GSM), Precoder design, multiple input multiple output (MIMO), quadrature amplitude modulation (QAM) constellations.

I. INTRODUCTION

Future beyond fifth generation (B5G) wireless communications are expected to bring innovation and a solid system with high spectrum efficiency and high energy efficiency. To meet the challenging requirements of B5G, new emerging techniques have appeared as potential candidates such as index modulation (IM), which has been obtaining a significant attention due to the its capability to activate a subset of certain elements of communication resources, namely antennas, subcarriers and time-slots[1], [2]. One specific case of IM suitable for large scale MIMO antenna schemes is based on generalized spatial modulations (GSM) which have recently emerged as an attractive technique for achieving greater energy efficiency (EE) with ease of implementation [3-5]. Considering that the information is encoded in the combination of active antennas and, also in the modulated symbols transmitted in the active antennas, GSM can achieve a greater spectral efficiency (SE) than single antenna communications. Moreover, GSM can be considered as a compromise between conventional MIMO and simple radio frequency (RF) transmissions, since only a subset of the available transmission antennas is active for a certain period of time, thus reducing the number of RF chains required.

Several detectors have been proposed in the GSM literature for single user. For example, in [6] the authors proposed a minimal average square block error detector (OB-MMSE) that achieves an almost optimal performance, while its required complexity is much lower compared to other detectors. It starts with an algorithm that sorts the possible transmit antenna combinations (TAC), followed by the detection in sequence of the possible signal vector for each TAC using block minimum mean square error (MMSE). To reduce the number of tested TACs, a termination threshold is applied. This detector is able to achieve near-optimal performance but can incur in substantial complexity in large scenarios. In [7] a different GSM iterative detector is proposed, which is based on dividing the problem of the maximum likelihood detection (MLD) into a sequence of simpler steps: minimizing the unrestricted Euclidean distance, projection of the elements onto the signal constellation and a projection onto the set of valid active antenna combinations. This allows a substantial complexity reduction when compared with the optimal MLD while still achieving near-optimal performance.

While GSM can be directly applied to uplink multi-user (MU) scenarios [8, 9], only a few works have extended the use of GSM to downlink MU [10, 11]. In [2], despite describing a system for scalable video broadcast communications, the proposed scheme also considered the use of GSM for multiple users. However, the removal of inter-user interference is made at the receiver which demands a large number of antennas at the users. On the other hand, inter-user interference can be removed at the transmitter through a precoder. An example of this is presented in [12] for conventional MU-MIMO, where the authors proposed a precoder called block diagonalization (BD), which guarantees zero inter-user interference and can be thought of as a generalization of channel inversion. A few precoded schemes have been introduced for spatial modulations (SM). In [13] a new precoder scheme for the downlink of MU-SM systems was proposed. This precoder, exploits the channel status information (CSI) at the base station (BS), where a precoding matrix is computed which allows the MU downlink system to be broken down into several independent single user SM systems. Another precoded scheme was developed in [14], in this case for multi-user GSM systems, with the aim of eliminating all inter-user interference while maintaining the antenna selection features of GSM, which means that only some of the antennas are active, while the rest are silenced. It should be noted that in [13], the scheme was only defined for SM while in [14] it was designed specifically for a version of GSM where the *M*-QAM

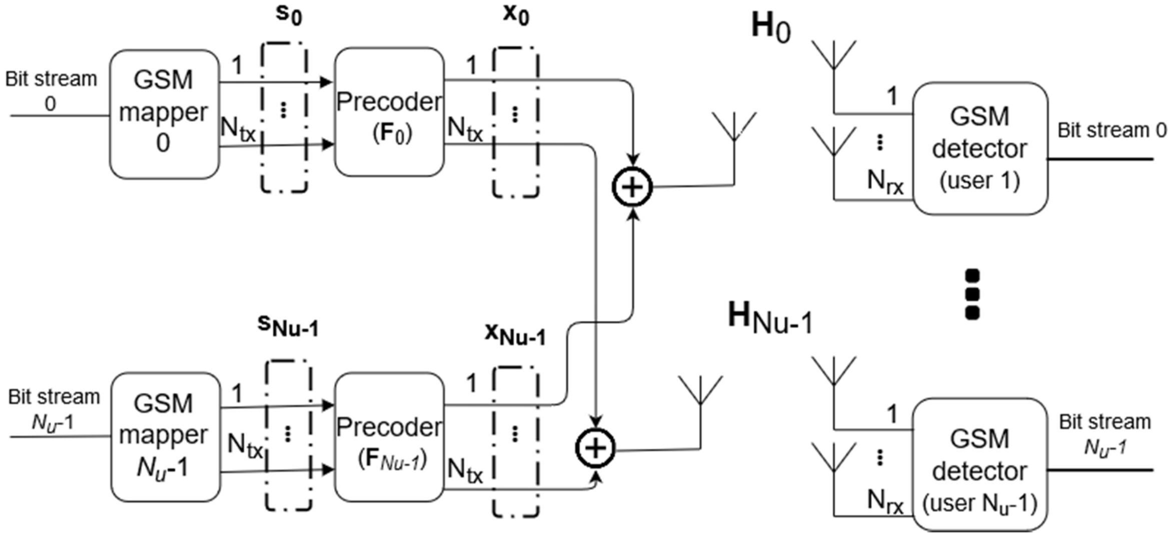

Figure 1. Transmitter and receiver scheme.

symbols are the same in all active antennas. Considering this, it can be concluded that both cases are limited in terms of spectral efficiency.

In this paper we will study a MU-MIMO system, where GSM symbols are transmitted simultaneously to multiple users. To increase the SE of the transmission, different symbols are sent on different (virtual) antennas and high-order *M*-QAM will be considered with the constellation size reaching M=1024 symbols. To remove inter-user interference, a BD precoder is applied at the BS while a modified version of the low-complexity SU GSM detector presented in [7] is used at the receiver. Simulation results show that the presented GSM MU-MIMO approach can provide better performance gains over conventional MU-MIMO. The paper is organized as follows: section II presents the model for the MU GSM system, section III presents the transmitter and receiver structure followed by the performance results obtained in section IV. Finally, the conclusions are outlined in section V.

Notation: Matrices and vectors are denoted by uppercase and lowercase boldface letters, respectively, $(\cdot)^{T}$ and $(\cdot)^{H}$ denote the transpose and conjugate transpose, $\lfloor\cdot\rfloor$ is the floor function, $\binom{N}{k}$ denotes the number of combinations of N symbols taken k at a time and $\mathrm{supp}(\mathbf{x})$ returns the set of indices of nonzero elements in **x** (i.e., the support of **x**).

II. System Model

In this study we consider a downlink MU-MIMO system with a BS and N_u users. The BS is equipped with N_{tx} antennas and each user has N_{rx} antennas, how we can see in Figure 1. The signal is represented as $s=\left[s_0^{T}\dots s_{N_{u-1}}{}^{T}\right]^{T}$, where $s_k\in\mathbb{C}^{N_s\times 1}$ contains the information transmitted to user k and $N_s\le N_{tx}/N_u$. Considering that GSM is being used, only N_a positions of $\boldsymbol{s}_k$ can be nonzero. These correspond to active indexes and carry modulated symbols. The signal vector of each user can be written as

$$\boldsymbol{s}_k=\left[\dots,0,s_k{}^{0},0,\dots,0,s_k{}^{N_a-1},0,\dots\right]^{T} \tag{1}$$

where $s_k^{j}\in\mathcal{A}\quad(j=0,\dots,N_a-1)$ with $\mathcal{A}$ denoting an M-QAM complex valued constellation set. Through this model, the information will be divided in such a way that part of the data will be used to select an active index (AI) from a total $N_{comb}=2^{\left\lfloor\log_2\binom{N_s}{N_a}\right\rfloor}$ AI combinations (AICs) that are available per user. The remaining data will be mapped onto N_a complex-valued M-QAM symbols. The resulting SE is then

$$\boldsymbol{N}_{bits}=N_u\left\lfloor\log_2\binom{N_s}{N_a}\right\rfloor+N_uN_a\log_2 M \tag{2}$$

bits per channel use (bpcu).

III. Transmitter and Receiver Structure

A. Transmitter Design

The channel state information at the transmitter (CSIT) will be used to pre-process the symbols by using a linear precoder $\mathbf{F}=\left[\mathbf{F}_0\dots\mathbf{F}_{N_u-1}\right]$, where $\mathbf{F}_k\in\mathbb{C}^{N_{tx}\times N_s}$. The effective transmitted signal, which will be propagated through a flat fading channel, can be written as

$$\mathbf{x}=\sum_{k=0}^{N_u-1}\mathbf{x}_k=\sum_{k=0}^{N_u-1}\mathbf{F}_k\mathbf{s}_k\,. \tag{3}$$

The baseband signal received by user k can be expressed as

$$\mathbf{y}_k=\mathbf{H}_k\mathbf{x}_k+\mathbf{H}_k\sum_{\substack{j=0\\ j\neq k}}^{N_u-1}\mathbf{x}_j+\mathbf{n}_k \tag{4}$$

where $\mathbf{H}_k \in \mathbb{C}^{N_{rx} \times N_{tx}}$ is the channel matrix for the link between the BS and user k and $\mathbf{n}_k \in \mathbb{C}^{N_{rx} \times 1}$ is the noise vector with samples taken according to a zero-mean circularly symmetric Gaussian distribution with covariance $2\sigma^2 \mathbf{I}_{N_{rx}}$. The first term of this expression is related to the desired signal and the second one is the interference caused by the other users' signals. The multiuser interference can be eliminated by using a BD method as proposed in [12], where the equivalent overall channel matrix $\mathbf{HF}$, with $\mathbf{H} = \left[\mathbf{H}_0{}^T \dots \mathbf{H}_{N_u-1}{}^T\right]^T$, becomes block diagonal. In this paper we assume a simple BD precoder without any power loading optimization, where we design each precoder matrix $\mathbf{F}_k$ so as to enforce that $\mathbf{H}_i \mathbf{F}_k = 0$ for all $i \neq k$. This condition can be satisfied from the null space of $\tilde{\mathbf{H}}_k$ which is defined as

$$\tilde{\mathbf{H}}_k = \left[\mathbf{H}_0{}^T \dots \mathbf{H}_{k-1}{}^T \mathbf{H}_{k+1}{}^T \dots \mathbf{H}_{N_u-1}{}^T\right]^T \tag{5}$$

In order to find an orthonormal basis for the null space of $\tilde{\mathbf{H}}_k$, we can compute its singular value decomposition (SVD) as

$$\tilde{\mathbf{H}}_k = \tilde{\mathbf{U}}_k \tilde{\mathbf{\Lambda}}_k \left[\tilde{\mathbf{V}}_k^{(1)} \ \tilde{\mathbf{V}}_k^{(0)}\right]^H \tag{6}$$

where $\tilde{\mathbf{U}}_k$ is the matrix with the left-singular vectors and $\tilde{\mathbf{\Lambda}}_k$ is a rectangular diagonal matrix containing the nonzero singular values. $\tilde{\mathbf{V}}_k^{(1)}$ and $\tilde{\mathbf{V}}_k^{(0)}$ contain the right singular vectors corresponding to the nonzero singular values and the null singular values, respectively. In this case, the received signal at each receiver reduces to

$$\mathbf{y}_k = \hat{\mathbf{H}}_k \mathbf{s}_k + \mathbf{n}_k, \tag{7}$$

where $\hat{\mathbf{H}}_k = \mathbf{H}_k \mathbf{F}_k$ is the equivalent single user channel seen by the receiver.

B. Receiver Design

Considering the system model combined with the use of a BD precoder, as described in the previous sections, each receiver will have to perform a simpler single user GSM detection. Therefore, we can formulate the MLD problem related to receiver k as

$$\min_{\mathbf{s}} f(\mathbf{s}_k) \triangleq \left\|\mathbf{y}_k - \hat{\mathbf{H}}_k \mathbf{s}_k\right\|_2^2, \tag{8}$$

$$\text{subject to } \mathbf{s}_k \in \mathcal{A}_0^{N_s}, \tag{9}$$

$$\operatorname{supp}(\mathbf{s}_k) \in \mathrm{S}, \tag{10}$$

where $\mathcal{A}_0 \overset{def}{=} \mathcal{A} \cup \{0\}$ and S denotes the set of valid AICs, which has a size of N_{comb}. In this paper, to solve this non-convex problem we adopt the same approach that we applied in [7] which is based on the alternating direction method of the multipliers (ADMM). However, heuristic based approaches can be considered to reach a faster solution even though it may not be the optimal one. Using ADMM as an heuristic, we can split a complex problem into a sequence of smaller subproblems with simpler solutions as addressed in [15]. Based on the derivation provided in [7], Table I shows the general iterative design algorithm to be used for the GSM-MU receiver.

TABLE I

GENERAL ITERATIVE DESIGN ALGORITHM FOR EACH USER k

Input: $\mathbf{u}^0$, $\mathbf{w}^0$, $\mathbf{x}^0$, $\mathbf{z}^0$, $\hat{\mathbf{H}}_k$, $\mathbf{y}_k$, ρ_x, ρ_z, Q
$f_{best} = \infty$.
$\mathbf{\Phi} \leftarrow \left(\hat{\mathbf{H}}_k{}^H \hat{\mathbf{H}}_k + (\rho_x + \rho_z)\mathbf{I}_{N_s}\right)^{-1}$.
for t=0, 1, …Q-1 **do**
$\mathbf{s}_k{}^{(t+1)} \leftarrow \mathbf{\Phi}\left(\hat{\mathbf{H}}_k{}^H \mathbf{y}_k + \rho_x(\mathbf{x}^{(t)} - \mathbf{u}^{(t)}) + \rho_z(\mathbf{z}^{(t)} - \mathbf{w}^{(t)})\right)$.
$\mathbf{x}^{(t+1)} \leftarrow \prod_D \left(\mathbf{s}_k{}^{(t+1)}\right)$
$\mathbf{z}^{(t+1)} \leftarrow \prod_{\mathcal{A}_0^{N_s}} \left(\mathbf{s}_k{}^{(t+1)} + \mathbf{w}^{(t)}\right)$..
$I \leftarrow \operatorname{supp}\left(\mathbf{x}^{(t+1)}\right)$.
$\hat{\mathbf{s}}_{\bar{I}}^{candidate} \leftarrow 0, \hat{\mathbf{s}}_I^{candidate} \leftarrow \prod_{\mathcal{A}^{N_a}} \left(\mathbf{s}_I{}^{(t+1)}\right)$.
if $f(\hat{\mathbf{s}}^{candidate}) < f_{best}$ **then**
$\hat{\mathbf{s}}_{k,\bar{I}} \leftarrow 0, \hat{\mathbf{s}}_{k,I} \leftarrow \hat{\mathbf{s}}_I^{candidate}$.
$f_{best} = f(\hat{\mathbf{s}}^{candidate})$.
end if
$\mathbf{u}^{(t+1)} \leftarrow \mathbf{u}^{(t)} + \mathbf{s}_k{}^{(t+1)} - \mathbf{x}^{(t+1)}$.
$\mathbf{w}^{(t+1)} \leftarrow \mathbf{w}^{(t)} + \mathbf{s}_k{}^{(t+1)} - \mathbf{u}^{(t+1)}$.
end for.
Output: $\hat{\mathbf{s}}_k$

In this table, $\mathbf{x}, \mathbf{u}, \mathbf{w} \in \mathbb{C}^{N_u N_t \times 1}$ are scaled dual variables and ρ_x, ρ_z are penalty parameters to assure that the algorithm reaches a good performance during its execution. In the algorithm, Q is the maximum number of iterations, $\prod_D(.)$ denotes the projection onto set $D = \{\boldsymbol{s} : \operatorname{supp}(\boldsymbol{s}) \in S\}$ and $\prod_{\mathcal{A}_0{}^{N_s}}(.)$ is the projection over $\mathcal{A}_0{}^{N_s}$.

The initial values $\mathbf{u}^0$, $\mathbf{w}^0$, $\mathbf{x}^{u(0)}$, $\mathbf{z}^0$ required by the algorithm can be obtained using a random start or other strategies as described by [7]. Due to the heurist nature of the proposed algorithm, it is not guaranteed that it will converge to the optimal solution of the original MLD problem (which is nonconvex). To increase the chances of finding an optimal solution and improve the performance of the GSM detector, in this paper we propose the adoption of several different strategies. A simple one consists in restarting the algorithm

TABLE III

SOLUTION REFINEMENT ALGORITHM BASED ON A CLOSEST NEIGHBOR SEARCH FOR USER k

Input: $\hat{\mathbf{H}}_k$, $\mathbf{y}_k$, $\hat{\mathbf{s}}$, $\mathbf{s}_k^{(Q)}$, f_{best}, P

$\bar{D}_0 = D$, $I \leftarrow \mathrm{supp}(\hat{\mathbf{s}})$

for p=1, …P **do**

$\bar{D}_p = \bar{D}_{p-1} \setminus \{\mathbf{s} : \mathrm{supp}(\mathbf{s}) = I\}$.

$\mathbf{x} \leftarrow \prod_{\bar{D}_p}\left(\mathbf{s}_k^{(Q)}\right)$

$I \leftarrow \mathrm{supp}(\mathbf{x})$.

$\hat{\mathbf{s}}_{\bar{I}}^{candidate} \leftarrow 0, \hat{\mathbf{s}}_I^{candidate} \leftarrow \prod_{\mathcal{A}^{N_a}}\left(\mathbf{s}_I^{(Q)}\right)$.

if $f(\hat{\mathbf{s}}^{candidate}) < f_{best}$ **then**

$\hat{\mathbf{s}}_{k,\bar{I}} \leftarrow 0, \hat{\mathbf{s}}_{k,I} \leftarrow \hat{\mathbf{s}}_I^{candidate}$.

$f_{best} = f(\hat{\mathbf{s}}^{candidate})$.

end if

end for.

Output: $\hat{\mathbf{s}}_k$

multiple times by using different initializations [15]. Another improvement approach may be accomplished by checking at the end of the algorithm if any of P neighboring candidates results in an improvement of $f(\hat{\mathbf{s}}^{candidate})$. These P neighbors can be selected amongst those with the closest supports using the algorithm presented in Table II.

A third possible refinement method consists in re-solving the MLD problem with the support set fixed according to the candidate point $\hat{\mathbf{s}}_k$ generated by the main algorithm. In this case, the resulting formulation becomes a conventional MIMO detection problem which can also be approximated by a simple projected MMSE estimate, i.e., as

$$\hat{\mathbf{s}}_I^{candidate} = \prod_{\mathcal{A}^{N_a}}\left(\left(\hat{\mathbf{H}}_{k,I}{}^H\hat{\mathbf{H}}_{k,I} + 2\sigma^2\mathbf{I}_{N_a}\right)^{-1}\hat{\mathbf{H}}_{k,I}{}^H\mathbf{y}_k\right). \quad (11)$$

We refer to this third approach as the polishing step. It is important to note that these three strategies can be applied together, as we will show in the next section.

IV. NUMERICAL RESULTS

In this section, the results of Monte Carlo simulations are presented, in order to illustrate the BER performance versus the signal to noise ratio (SNR) in dB of the proposed MU GSM system.

In the first scenarios, the objective is to evaluate the impact of the different configuration parameters of the receiver, namely, the number of iterations, the number of initializations, the polishing steps and the number of neighbours. Two different high-order modulations were considered: 256-QAM and 1024-QAM. Figure 2 and 3, present the results for N_{tx} = 170, N_{rx}= 10, N_u = 15, N_s= 17 and N_a = 2, which corresponds to a spectral efficiency of 23 bps/user/channel use for 256-QAM and 27 bps/user/channel

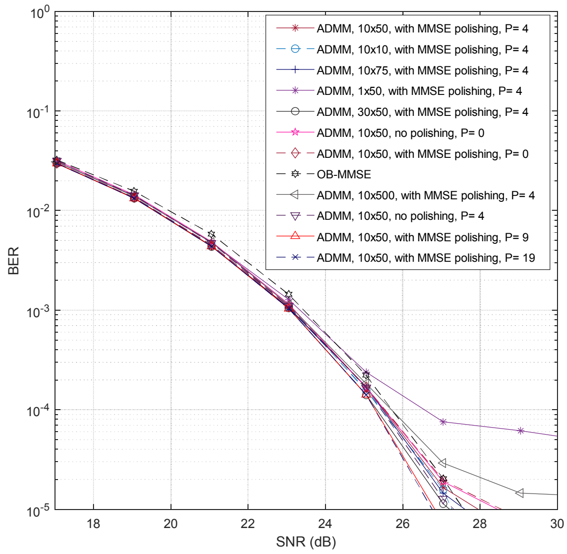

Figure 2. BER performance of ADMM in a MU-MIMO scenario with N_{tx}=170, N_{rx}= 10, N_u= 15, N_s=17 and N_a = 2, 256-QAM (23bps/user/channel use).

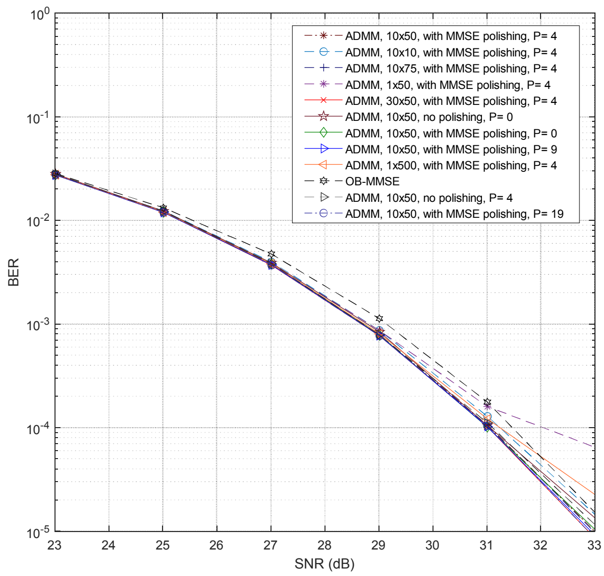

Figure 3. BER performance of ADMM in a MU-MIMO scenario with N_{tx}=170, N_{rx}=10, N_u=15, N_s=17 and N_a=2, 1024-QAM (27bps/user/channel use).

In the legend of both figures $n_1 \times n_2$ denotes that the receiver algorithm was ran with n_1 restarts and n_2 iterations. The type of polishing step applied as well as the number of neighbours is also shown. Besides the expected improvement when using more iterations, it can be observed that by increasing the number of algorithm restarts, we can have a better system performance. This is clear when considering the 1x500 and 10x50 cases which have the same total number of iterations, with the best results being achieved by the case with more restarts (10x50).

By comparing the scenarios, where MMSE polishing is not used and those where it is used, one can observe that those

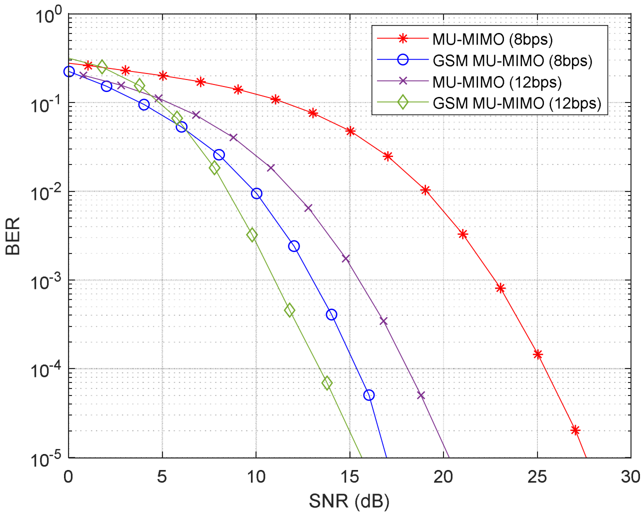

Figure 4. BER performance of a precoder based on GSM MU-MIMO and a precoder based on conventional MU-MIMO.

where polishing is applied have better performance.

Considering the use of neighbour based refinement, we studied the impact of changing the number of neighbours on the performance of the algorithm and we concluded that the greater the number of neighbours, the better the performance will be (see the cases where P=1, 4, 9 and 19). Finally, the combination of the 3 proposed improvement strategies for the ADMM receiver lead to a better performance than the usage of the individual approaches. Globally, the performance of the proposed ADMM algorithm leads to better results when compared to the case where OB-MMSE receivers (which we included as benchmark) are used [6], except when no restarts are applied.

In the second set of simulations, the objective was to provide a comparison between a conventional BD precoded MU-MIMO from [12] and the proposed GSM MU-MIMO. Figure 4 shows the results for two different configurations.

The first case concerns a comparison between the precoded GSM MU-MIMO with N_{tx}=160, N_{rx}= 6, N_u = 10, N_s = 16, N_a = 1, 16-QAM and the conventional BD precoded MU-MIMO with N_{tx}=60, N_{rx}= 6, N_u = 10, N_s=1 and 256-QAM, both with a spectral efficiency of 8 bps/user/channel. In the second case, we present a comparison between the precoder based on GSM MU-MIMO with N_{tx} = 90, N_{rx}= 8, N_u = 10, N_s = 9, N_a = 3, QPSK and the precoder based on conventional MU-MIMO with N_{tx} = 80, N_{rx} = 8, N_u = 10, N_s = 3 and 16-QAM, both with a spectral efficiency of 12 bps/user/channel. In general, it can be observed that the performance of the GSM MU-MIMO precoder is better than the conventional MU-MIMO precoder, achieving better performances and better results. When we look at the curves in Figure 4, focusing at their behaviour for a 10^{-4} BER for the 8 bps/user/channel scenario, the GSM MU-MIMO shows a gain of about 10 dB over the conventional MU-MIMO. Moving on to the 12 bps/user/channel scenario and maintaining the BER at 10^{-4}, the GSM MU-MIMO has a gain of about 5 dB over the conventional MU-MIMO. Through these results, it can be concluded that GSM MU-MIMO can be a potential alternative to increase the SE of the system when compared with the adoption of higher-level modulations in conventional MU-MIMO.

V. Conclusions

In this paper a novel multi-user MIMO system where GSM symbols are transmitted simultaneously to multiple users has been described. By combining large antenna settings at the BS with high-order *M*-QAM constellations, the proposed approach is capable of improving the SE and energy efficiency. A precoder is applied at the BS to completely remove inter-user interference while an iterative SU GSM detector is implemented at each receiver. Simulation results show that the proposed approach can achieve a very competitive and very promising performance compared to conventional MU-MIMO systems with identical SE.

Acknowledgment

This work was partially supported by the ISCTE-University Institute of Lisbon under the grant ISTA-BM-PDCTI-2019 and by the FCT/MCTES through national funds and when applicable co-funded by EU funds under the project UIDB/50008/2020.

References

[1] X. Cheng, M. Zhang, M. Wen, and L. Yang, "Index modulation for 5G: Striving to do more with less," *IEEE Wirel. Commun.*, vol. 25, no. 2, pp. 126–132, 2018.

[2] A. M. C. Correia, N. M. B. Souto, P. Sebastião, D. Gomez-Barquero, and M. Fuentes, "Broadcasting Scalable Video with Generalized Spatial Modulation in Cellular Networks," *IEEE Access*, vol. 8, pp. 22136–22144, 2020.

[3] T. Datta, H. S. Eshwaraiah, and A. Chockalingam, "Generalized Space-and-Frequency Index Modulation," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 4911–4924, 2016.

[4] P. Yang, Y. Xiao, M. Xiao, and Z. Ma, "NOMA-Aided Precoded Spatial Modulation for Downlink MIMO Transmissions," *IEEE J. Sel. Top. Signal Process.*, vol. 13, no. 3, pp. 729–738, 2019.

[5] R. Rajashekar, K. V. S. Hari, and L. Hanzo, "Reduced-complexity ML detection and capacity-optimized training for spatial modulation systems," *IEEE Trans. Commun.*, vol. 62, no. 1, pp. 112–125, 2014.

[6] Y. Jiang, Y. Xu, Y. Xie, S. Hong, and X. Wu, "Low-complexity detection scheme for generalized spatial modulation," *J. Commun.*, vol. 11, no. 8, pp. 726–732, 2016.

[7] H. Lopes and N. Souto, "Iterative Signal Detection for Large-Scale GSM-MIMO Systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7734–7738, 2018.

[8] N. Souto and A. Correia, "Frequency Domain Equalization for Single and Multiuser Generalized Spatial Modulation Systems in Time Dispersive Channels," *IEEE Wirel. Commun. Lett.*, vol. 9, no. 3, pp. 316–320, 2020.

[9] T. L. Narasimhan, P. Raviteja, and A. Chockalingam, "Generalized Spatial Modulation in Large-Scale Multiuser MIMO Systems," *IEEE Trans. Wirel. Commun.*, vol. 14, no. 7, pp. 3764–3779, 2015.

[10] C. Liu, L. L. Yang, W. Wang, and F. Wang, "Joint transmitter-receiver spatial modulation," *IEEE Access*, vol. 6, no. c, pp. 6411–6423, 2018.

[11] F. R. Castillo-Soria, J. Sánchez-García, M. Maciel-Barboza, and J. Flores-Troncoso, "Multiuser MIMO Downlink Transmission using Block Diagonalization and Generalized Spatial Modulation Techniques," *AEU - Int. J. Electron. Commun.*, vol. 70, no. 9, pp. 1228–1234, 2016.

[12] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, 2004.

[13] X. Li, Y. Zhang, L. Xiao, X. Xu, and J. Wang, "A novel precoding scheme for downlink multi-user spatial modulation system," *IEEE*

Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC, pp. 1361–1365, 2013.

[14] H. Zhang, M. Ma, and Z. Shao, "Multi-User Linear Precoding for Downlink Generalized Spatial Modulation Systems," *IEEE Commun. Lett.*, vol. 24, no. 1, pp. 212–216, 2020.

[15] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," *Found. Trends Mach. Learn.*, vol. 3, no. 1, pp. 1–122, 2010.