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# Generalized Spatial Modulation in Highly Correlated Channels

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***Abstract*—Generalized spatial modulation (GSM) is a promising technique that can highly increase the spectral efficiency for ultra-high data rate systems. However, its performance degrades in highly correlated channels such as those in the millimeter wave (mmWave) and sub-Terahertz (sub-THz) bands. GSM conveys information by the index of the activated transmit antenna combination (TAC) and by the M-ary symbols. In conventional GSM, the legitimate TACs are randomly selected, where their number should be a power of 2. In this paper, a simplified EGSM (S-EGSM) based on TAC selection but without channel side information (CSI) is proposed for highly correlated channels. Moreover, an efficient Index-to-Bit mapping for spatial bits based on Gray coding is proposed to reduce the spatial bit-error rate (BER) instead of using the normal binary mapping as in conventional GSM. Simulation results show that the proposed TAC selection without CSI (S-EGSM) outperforms the existing method by $1.4$ dB in highly correlated channels. In addition, the proposed S-EGSM when compared to TAC selection with CSI can be considered as a good trade-off between performance and complexity since it does not consider any feedback from the channel when updating the TAC selection, which are, in the proposed approach, determined offline. Finally, simulation results of gray coding for spatial bits show a performance gain of the order of $1$ dB in highly correlated channels, and which becomes less significant in case of low spatially correlated channels.**

***Index Terms*—Beyond 5G, millimeter wave (mmWave), Terahertz systems (THz), multiple-input multiple-output (MIMO), generalized spatial modulation (GSM), index modulation, correlated channels, spatial correlation.**

## I. INTRODUCTION

The high demand for a wireless ultra-high data rate requires a high system spectral efficiency and a large bandwidth that is available in the mmWave and sub-THz bands. In the last decade, Index modulation with advanced MIMO schemes such as GSM [1] has attracted tremendous attention due to their ability to increase the system spectral efficiency. In addition, the proposed methodology for ultra-high data rates in [2] shows that a low power Terabits system can be achieved using GSM with power efficient single carrier modulations. However, the GSM performance is degraded in correlated channels as shown in [2].

In conventional GSM, the cardinality of the legitimate TAC set is a power of 2 ($2^{\lfloor log_2(C_{N_t}^{N_a}))\rfloor}$, where the TACs are randomly selected among the possible TACs, whose number is equal to $C_{N_t}^{N_a}$, where $N_t$ and $N_a$ are the number of transmit antenna (TA) and active TA respectively. In addition, the spatial bits mapping was just a binary coding for the index of activated TAC.

In this paper, we focus on the performance enhancement of GSM systems in highly correlated channels by proposing an efficient TAC selection and Index-to-Bit mapping. In this context, we designed a TAC selection method based only on the transmit spatial correlation, which is well known for a specific transmitter, and without any CSI feedback form the receiver. The aim of the TAC selection is to reduce the errors in TAC detection because this error will propagate to M-ary symbols. In such a case, the erroneous detection of $M$-ary symbols is due to the fact that the receiver is trying to detect the symbols on the non-activated antennas since the TAC is wrongly detected. Moreover, we proposed a spatial bit mapping based on Gray coding in order to reduce the spatial BER. This mapping is trying to reduce the number of different bits between the neighbor TACs that are most susceptible to be interchanged in highly correlated channels.

This paper is organized as follows. In section II, the GSM system and the channel model are presented, whereas in section III a simplified TAC selection method without CSI is proposed for highly correlated channels. Section IV describes the proposed Index-to-bit mapping for spatial bits in GSM. Section V illustrates the results of the proposed methods and discusses the opportunity to reduce the BER in a highly correlated channels. Finally, concluding remarks are given in Section VI.

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The notations used in this paper are as follows. Bold $\mathbf{X}$ represents matrices. $\lfloor . \rfloor$ represents the floor function. $\|.\|$ stands for the Frobenius norm and $|.|$ is for the absolute value. $\mathbf{I}_{N\times M}$ and $\mathbf{0}_{N\times M}$ denotes the identity and zero matrices respectively of size $N\times M$. $\left(C_y^x\right)$ represents the binomial coefficient. $\mathcal{CN}(\mu,\,\sigma^2)$ denotes the complex normal distribution of a random variable having mean $\mu$ and variance $\sigma^2$.

## II. SYSTEM MODEL

### A. GSM Model

The GSM system model consists of $N_t$ transmit antennas (TAs) and $N_r$ receiver antennas (RAs). In this system not all transmit antennas are activated at the same time as shown in Fig. 1, only $N_a$ TAs are activated. Thus, the possible number of TAC is then listed as a combination $N_{all} = C_{Nt}^{Na}$. Therefore, in addition to the $M$-ary Amplitude-Phase Modulated (APM) symbols transmitted on each activated TA [1], more information bits (spatial bits) can be deduced when the receiver detects the index of activated TAC. As a result the number of bits per transmitted GSM symbol is given by:

$$n = \lfloor log_2\left(C_{Nt}^{Na}\right)\rfloor + N_a log_2 M \qquad (1)$$

Note that only $\mathcal{L} = 2^{\lfloor \log_2(N_{all})\rfloor}$ TACs are used to keep the spatial bits length an integer number and the other possibilities are marked as illegal TACs. In addition, the legitimate TACs should be carefully selected from the $N_{all}$ possibilities to minimize the total bit error rate by minimizing the interference and the effect of spatial correlation between antennas.

At the receiver end, the received signal is represented as

$$y = \mathbf{H}x + n, \qquad (2)$$

where $\mathbf{H}$ represents the $N_r$ x $N_t$ channel matrix, $x$ is the GSM transmitted symbol that contains $N_a$ APM symbols at the indices of active transmit antennas, $n$ is $N_r\times 1$ channel noise vector composed of $N_r$ independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) samples with zero mean and variance $\sigma_n^2$, i.e, $\mathcal{CN}(0,\,\sigma_n^2)$ for $r = 1,\ldots,N_r$.

The maximum-likelihood (ML) detector is able to jointly detect both the activated TAC and the transmitted APM symbols, but it suffers from a high complexity. The ML detection can be expressed as follows:

$$\widehat{x} = argmin_{x\in X}\left\|y - \mathbf{H}x\right\|^2. \qquad (3)$$

However, GSM symbol detection could be also performed using the lower complexity ordered block minimum mean-squared error (OB-MMSE) detector which in turn achieves a near-ML performance [3].

Note that one of the greatest limitations of GSM systems is its performance degradation in highly correlated channels [2], where the wrong detection of activated TAC will consequently lead to an error in the symbols detection and as a result the total BER will increase tremendously. In this regard, the following sections will introduce an efficient TAC selection method as well as a spatial mapper (Index-to-Bit mapping) for the spatial bits to minimize the BER in highly correlated channels.

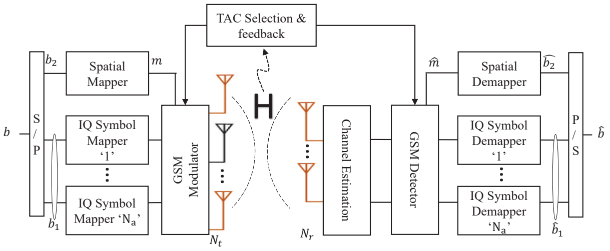

Fig. 1. System model of GSM with TAC selection

### B. Channel Model

In this paper, the Kronecker channel model is used to represent the spatial correlation between antennas. Thus, the Rayleigh and Rician MIMO channels with/without spatial correlation are represented as follows:

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{LoS} + \sqrt{\frac{1}{K+1}}\mathbf{\Sigma}_r^{\frac{1}{2}}\mathbf{H}_{NLoS}\mathbf{\Sigma}_t^{\frac{1}{2}T}, \qquad (4)$$

where K represents the Rician factor, $H_{LoS}$ and $H_{NLoS}$ are the line of sight (LOS) and non-line of sight (NLoS) channel matrices respectively. The $\mathbf{H}_{NLoS}$ can be considered as a Rayleigh channel matrix whose elements satisfies $\mathcal{CN}(0,\,1)$. In addition, the Kronecker model assumes that the spatial correlations at the transmitter $\Sigma_t$ and the receiver $\Sigma_r$ are separable.

## III. TRANSMIT ANTENNA COMBINATION SELECTION

The GSM system has $N_a$ TAs activated out of $N_t$ TAs, and only $N = 2^{\lfloor log_2 N_{all}\rfloor}$ TACs among $N_{all}$ possible TACs will be used to encode the spatial bits. Firstly, the conventional GSM system was used with random selection of $N$ TACs out of $N_{all}$, then TAC selections with/without CSI were introduced in [4]. The objective of TAC selection is to select the optimal legitimate TAC set that permits to reduce the TAC detection errors.

In this section, we will propose a TAC selection method without CSI for highly correlated channels, where a comparative study with the existing methods will be provided.

### A. GSM System Relying on Channel State Information (EGSM)

The Enhanced GSM system (EGSM) is an adaptive technique proposed in [4] where it uses the channel side information as shown in Fig. 1 to select the optimal legitimate TAC set instead of random TAC selection.

This selection is updated continuously on real time to take into consideration the channel variation, then the transmitter and the receiver share between them the legitimate TAC set through a feedback channel. This method is based on computing the Euclidian Distance (ED) matrix $w$ between the $N_{all}$ TACs $(I_1, ..., I_N)$ with all possible $M$-ary APM symbols according to Eq. 5, then eliminating $N_{re} = N_{all} - N$ TACs having the minimum ED.

$$w_{m,n} = \min_{\forall s_m, s_n} \left\| \mathbf{H}_{Im} s_m - \mathbf{H}_{I_n} s_n \right\|_F^2 , \qquad (5)$$

where $I_m$ and $I_n$ are the TACs of index $m$ and $n$ respectively and they contain the indices of the activated TAs within a TAC, $\mathbf{H}_{Im}$ is the $N_r \times N_a$ sub-matrix of $\mathbf{H}$ that contains $N_a$ columns of $\mathbf{H}$ at the indices of activated TAs, and $s$ represents the $M$-ary symbol vector of $N_a$ elements with $M^{N_a}$ possibilities.

The number of ED estimations to generate the matrix $\mathbf{W}$ can be reduced from $N_{all}^2(M^{N_a})^2$ to $N_{all}\frac{(N_{all}+1)}{2}.(M^{N_a}\frac{(M^{N_a}+1)}{2})$ by removing the repeated estimations due to symmetry in each $w_{m,n}$ and $\mathbf{W}$.

Despite the optimal TAC selection of this method, it still have a large complexity for real time estimation of these EDs especially with large values $M$-ary and $N_{all}$. In addition, the useful data rate will be highly reduced in fast time variant channel due to the overhead of the feedback channel.

### *B. Simplified GSM System without Channel State Information (S-EGSM)*

In this method, we are targeting the mmWave and sub-THz bands where the antenna size and separation are very small which leads to a high spatial correlation. Thus, the spatial correlation matrices in Eq. 4 are the dominant terms that will highly affect the detection of the activated TAC. For this reason, we propose a simplified EGSM (S-EGSM) that considers only the transmitter spatial correlation matrix instead of the complete channel matrix $\mathbf{H}$, where there is a larger number of antennas compared to the receiver side. In addition, the transmitter spatial correlation matrix is constant for a specific transmitter because it depends on the antenna characteristics, separation and array geometry. Therefore, S-EGSM is a TAC selection method without CSI, where the feedback channel is no more required as in EGSM because the transceivers agree on the TAC set only once at the setup phase. The S-EGSM system can be described as shown in Fig. 1 but without using the CSI feedback ($\mathbf{H}$).

The algorithm can be summarized as follows:

**Step 1:** Generate all possible TACs according to $N_t$ and $N_a$

**Step 2:** Using only the transmit spatial correlation, compute the lower or upper part of ED matrix **W'** since by symmetry $w'_{m,n} = w'_{n,m}$:

$$w'_{m,n} = \min_{\forall s_m, s_n} \left\| \hat{\mathbf{H}}_{Im} s_m - \hat{\mathbf{H}}_{I_n} s_n \right\|_F^2 , \qquad (6)$$

where $\hat{\mathbf{H}}$ is calculated according to Eq.4 with $\mathbf{H}_{LoS} = 0_{Nr \times Nt}$, $\mathbf{H}_{NLoS} = I_{Nr \times Nt}$, and $\Sigma_r = I_{Nr \times Nr}$ and any values of the $K$ factor since it will not affect the results of this method.

**Step 3:** Sort the ED values in ascending order

$$[v_1, v_2, ...] = \text{sort}(w', \text{'ascend'}) \qquad (7)$$

**Step 4:** Obtain the TAC set by removing $N_{re}$ TAC starting with those that generate the smallest EDs $(v_1, v_2, ...)$.

Note that another TAC selection method without CSI was proposed in [4]. In the following, we will compare our proposed method (S-EGSM) to the methods proposed in [4].

## IV. INDEX-TO-BIT MAPPING: SPATIAL MAPPING

After reducing the TAC error probabilities in the TAC selection methods, an efficient spatial mapping (Index-to-Bit Mapping) is proposed to further reduce the spatial BER and thus the total BER. In conventional GSM, the spatial mapping was simply the normal binary representation of the index $(m-1)$ of the TAC $I_m$, i.e the spatial bits for $I_1$ to $I_4$ were coded as $00, 01, 10, 11$ respectively.

In this section, we propose a spatial mapping method that takes into consideration the effect of spatial correlation. Note that the spatial correlation will leads to high similarity between the channels of neighbor TACs, so when the receiver miss-detects the activated TAC, it will most probably be confusing by one of its neighbors.

Therefore, a Gray coding for spatial bits among each group of neighbor TACs can reduce the total BER. The spatial correlation is the highest between the adjacent antennas, so the order of correlation between any pair of TACs can be deduced from the Hamming distance between their antenna indices in a uniform linear antenna array. The algorithm for the proposed mapping is summarized in the following:

**Step 1:** Compute the Hamming Distance (HD) matrix using the indices of activated antennas between the $N$ possible legitimate TACs according to the following equation:

$$\text{HD}_{m,n} = \sum_{i=1}^{N_a} |m_i - n_i|, \qquad (8)$$

where $I_m = \{m_1, ...m_{N_a}\}$ and $I_n = \{n_1, ...n_{N_a}\}$ and the activated antennas indices $m_i$ and $n_i$ on each TAC are sorted in ascending order. In addition, the number of $\text{HD}_{m,n}$ can be reduced from $N^2$ to $(N-1)\frac{N}{2}$ by benefiting from the symmetry (HD$_{m,n}$ = HD$_{n,m}$) and skipping the distance calculation between the same TACs.

**Step** 2: Compute the frequency of HD = 1 for all TACs $\lambda_m^{HD=1} : \lambda_1^1, ..., \lambda_N^1$ that represents the number of nearest neighbors for each TAC.

**Step** 3: Sort the $N$ TACs in descending order according to their $\lambda_m^1$

$$[p_1, p_2, ...p_N] = \text{sort}(\lambda_m^1, \text{`descend'}) \tag{9}$$

**Step** 4: Start the Gray coding by assigning an unused bit mapping for the TAC that have the highest number of nearest neighbors $(p_1, p_2, ..)$. If this TAC has a previously assigned bit mapping skip this step.

**Step** 5: Generate the Gray code set for this TAC where any bit mapping in the set differs only by a single bit.

**Step** 6: Get the allowed Gray set for this TAC by removing the used bit mapping.

**Step** 7: Assign a bit mapping from its allowed Gray set to its neighbor TACs ($HD = 1$) if it is not previously assigned.

**Step** 8: Repeat from Step 4 until a bit mapping is assigned for all TACs.

In the following, we will illustrate an example for Gray coded spatial mapping with $N_t = 5$ and $N_a = 2$. Thus, the legitimate TACs $(I_1, ..., I_8)$ shown in Table I are obtained from the TAC selection, and each TAC index will be mapped to $log_2(8) = 3$ spatial bits.

The HDs between indices of activated antenna are generated using Eq. 8, i.e. HD$_{1,2} = |1-1| + |4-5| = 1$. Note that the HD matrix for these TACs and the $\lambda_m^1$ are represented in Table I (Step 1, 2). Firstly, the Gray coding algorithm starts with the TAC $I_3$ that has the highest number ($\lambda_3^1 = 4$) of nearest neighbors $(I_1, I_4, I_5, I_7)$ as shown in Table I. Then according to Step 3 to 6, $I_3$ is initialized with $'000'$, then its Gray Set is generated $\{001, 100, 010\}$ and nothing is removed because all bit mapping are not used yet. Then, the bit mapping for $I_1, I_4, I_5$ are assigned respectively from its Gray set and $I_7$ is left for future assignment by another TAC. Next, the neighbors for $I_1 = 001$ (previously assigned) with $\lambda_3^1 = 3$ will be assigned from its allowed Gray set $\{101, 011, \cancel{000}\}$. Finally, these steps are continuously repeated until a bit mapping is assigned for all TACs.

This best effort Gray coding for spatial bits is trying to reduce the effect of spatial correlation that causes a confusion in the detector at the receiver between neighbor TACs. Therefore, this method should enhance the spatial BER because it is trying to limit the number of different bits between neighbors TAC to one whenever it is possible.

TABLE I

HD MATRIX FOR SPATIAL MAPPING EXAMPLE WITH $N_t = 5$ AND $N_a = 2$

| $I_m \setminus I_n$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $I_6$ | $I_7$ | $I_8$ |
|---|---|---|---|---|---|---|---|---|
| $I_1 = \{1,4\}$ | 0 | 1 | 1 | 2 | 2 | 1 | 2 | 3 |
| $I_2 = \{1,5\}$ | 1 | 0 | 2 | 1 | 3 | 2 | 3 | 2 |
| $I_3 = \{2,4\}$ | 1 | 2 | 0 | 1 | 1 | 2 | 1 | 2 |
| $I_4 = \{2,5\}$ | 2 | 1 | 1 | 0 | 2 | 3 | 2 | 1 |
| $I_5 = \{2,3\}$ | 2 | 3 | 1 | 2 | 0 | 1 | 2 | 3 |
| $I_6 = \{1,3\}$ | 1 | 2 | 2 | 3 | 1 | 0 | 3 | 4 |
| $I_7 = \{3,4\}$ | 2 | 3 | 1 | 2 | 2 | 3 | 0 | 1 |
| $I_8 = \{3,5\}$ | 3 | 2 | 2 | 1 | 3 | 4 | 1 | 0 |
| $\lambda_m^1$ | 3 | 2 | 4 | 3 | 2 | 2 | 2 | 2 |

## V. SIMULATION RESULTS & DISCUSSION

In this section, firstly we compare our proposed technique for TAC selection S-EGSM to the existing methods EGSM and No CSI method in [4]. Note that both methods without CSI (S-EGSM and No CSI from [4]) estimate offline the best legitimate TAC set once in the setup phase and they will keep using this set all the time while the transmitter configuration ($N_t$ and $N_a$) and antenna array characteristics are unchanged. However, the EGSM method is an adaptive TAC selection that keeps tracking the channel variation and updates the TAC set accordingly. Hence, this method requires a feedback channel to share the selected TAC set between the transceiver. For a fair comparison, we set the same GSM configuration with the same channels and transmitted bit-stream for all TAC selection methods. These TAC selection methods are compared under different transmit correlation factor to highlight the importance of the proposed methods S-EGSM in highly correlated channel.

The correlation matrices in the Kronecker model are formed according to the exponential model of [5] where the elements of the transmit $\mathbf{\Sigma}_t$ and the receive $\mathbf{\Sigma}_r$ correlation matrices are affected by a fixed correlation factor $\beta$: $[\mathbf{\Sigma}_t]_{i,j} = \beta_t^{|i-j|}$ which is well known for a specific transmitter. We used $\mathbf{\Sigma}_r = I_{N_r}$ to concentrate on the impact of correlation at the transmitter side where a larger antenna array is used to convey the data in the spatial domain of index modulation.

The following parameters are adopted with all TAC selection methods: $GSM(N_t, N_a, M) = GSM(6, 2, 2), Nr = 4, \beta_t = \{0, 0.4, 0.8\}$, the number of GSM symbols is $10^4$ simulated under $100$ channel realizations. In addition, S-EGSM takes into consideration only the transmit spatial correlation matrix which is the dominant term in highly correlated channels. For this reason, Rician channel is used with $K = 5$ to prove that the S-EGSM will not be affected by the LoS component and the Rician $K$ factor that were neglected in Step 2 of the S-EGSM algorithm. Moreover, the adopted GSM detector in these systems is OB-MMSE that is able to detect the TAC and the APM constellations with a balanced trade-off between

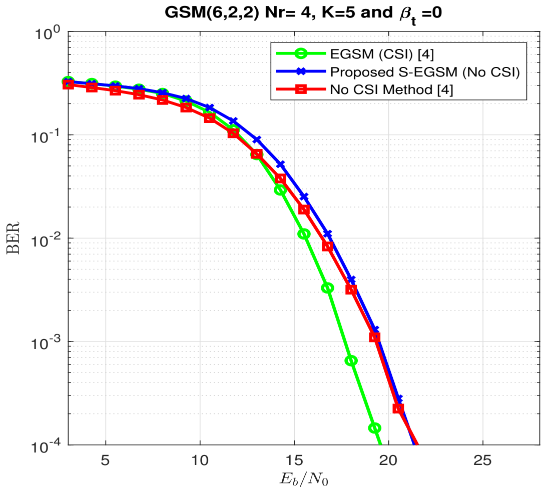

Fig. 2. BER vs $E_b/N_0$ for various TAC selection with $\beta_t = 0$

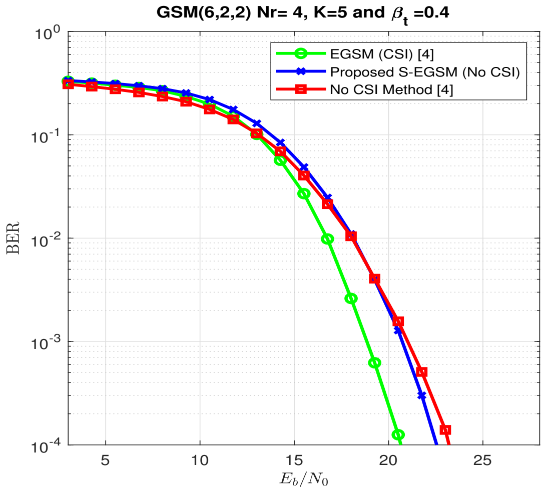

Fig. 3. BER vs $E_b/N_0$ for various TAC selection with $\beta_t = 0.4$

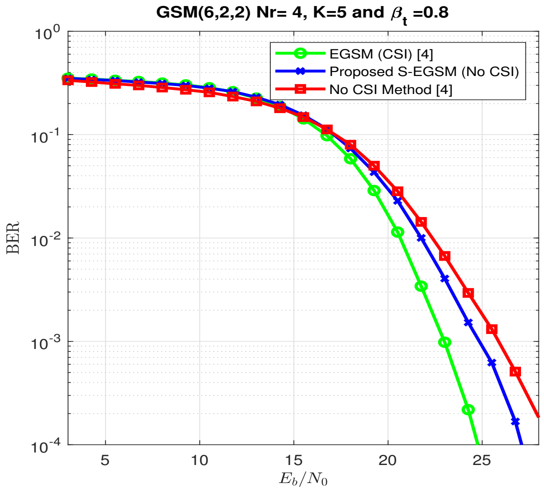

Fig. 4. BER vs $E_b/N_0$ for various TAC selection with $\beta_t = 0.8$

system performance and complexity.

The results in Fig. (2 to 4) show that adaptive method EGSM with CSI has the best performance in all correlation levels because it keeps updating the legitimate TAC set according to channel variations. However, we notice in Fig. 2 to 4 that the No CSI method from [4] has a slightly better performance at low SNR compared to S-EGSM, but as transmit correlation level increases the S-EGSM performance at high SNR becomes the best TAC selection without CSI. Moreover, the advantage of No CSI method [4] at low SNR disappears in highly correlated channel $\beta_t = 0.8$ and the performance of proposed S-EGSM becomes better by $1.4$ dB at BER=$10^{-4}$ compared to the other method without CSI.

Therefore, the S-EGSM is an efficient TAC selection method without CSI in highly correlated channel which is the case in mmWave and THz bands where the correlation factor is in order of $\beta_t = 0.8$ according to [6]. However, the TAC selection with CSI EGSM can be used in slow time variant channel (small Doppler) to achieve the optimal performance, while in fast variant channels TAC selection methods without CSI is preferred to avoid the increased complexity due to real time TAC selection and to limit the overhead of the feedback channel. Finally, the usage of S-EGSM technique in fast variant channel environment depends on the correlation level where it will be highly recommended for highly correlated channels.

In the following, the spatial mapping with binary and gray coding is compared under the same conditions with different correlation levels. For this comparison, we used $GSM(7,4,2)$ where we have $\lfloor log_2(C_7^4)\rfloor = 5$ spatial bits. As shown in Fig. 5, as the correlation factor increases, the gain of Gray coding increases from $0.15$ dB to $0.4dB$.

Note that the gray coding gain appears when the detector at the receiver is confused between the activated TAC and one of its neighbor TACs (HD=1). This misdetection of the activated TAC can cause a single bit error only if this TAC and its neighbors are Gray coded. Thus, the gray coding advantages appear more in highly correlated channel as shown in Fig. 5 where the neighbor TACs cannot be distinguishable at the receiver side in order to correctly detect the activated TAC. Note that the gray coding gain is limited because the TAC selection has already eliminated the neighbors TACs to the maximum in order to enhance the TAC error probabilities.

Moreover, this gain does not appear always because the gray coding for spatial bits is a best effort algorithm where we try to reduce the number of bits difference between neighbor TACs. However, the gray coding for all neighbor TACs is not always guaranteed, so this

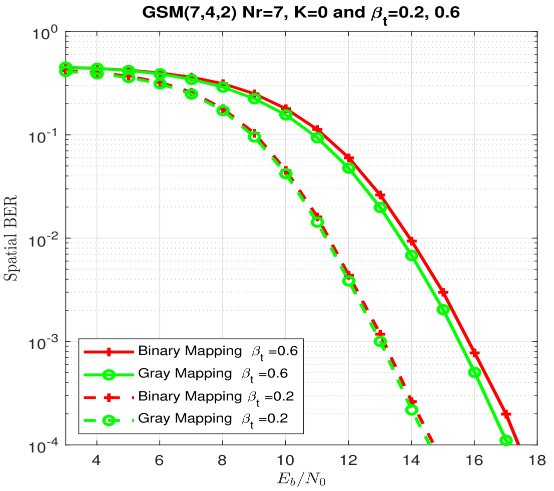

Fig. 5. BER vs $E_b/N_0$ for different TAC spatial mapping with $\beta_t = \{0.2, 0.6\}$

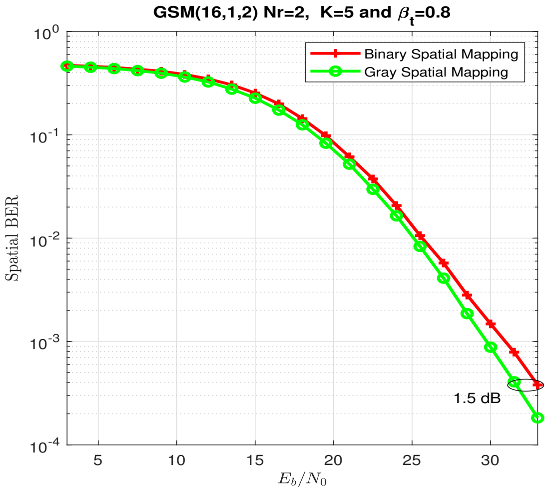

Fig. 6. Spatial BER vs $E_b/N_0$ for binary and gray coding for spatial bits

gain in some cases can vanishes and the performances for both the gray and normal binary coding become similar. Note that the Gray coding for spatial bits is prepared offline once for a given GSM configuration. Therefore, the gray coding should be used in spatial mapping because in all cases it will have some gain or nothing but it will never have a loss compared to normal binary coding for spatial bits.

In the following, we show that the gray coding gain is larger when all the neighbor TACs are gray coded. For example, the gray coding for all neighbors can be satisfied when we take into consideration the Spatial Modulation (SM) that has a single active antenna instead of $N_a$ $(SM(N_t, M) = GSM(N_t, 1, M))$. The gray coding gain increases with SNR for $SM(16, 2)$ and $N_r = 2$ in a highly correlated Rician channel ($K = 5$) as shown in Fig. 6 where it reaches $1.5$ dB at BER=$5.10^{-4}$.

## VI. CONCLUSION

The channels at mmWave and THz bands suffers from a high spatial correlation due to the small distance between the antennas (order of the wavelength). In addition, GSM is a promising technique for ultra-high data rate systems but its performance degrades in highly correlated channels. In order to enhance the BER performance of GSM in these channels, this paper focused on two aspects: the legitimate TAC selection and the spatial bit mapping that was ignored in conventional GSM.

Firstly, we proposed a TAC selection method without CSI (S-EGSM) for highly correlated channel. In this method, we consider only the dominant term in the channel which is the transmit spatial correlation (well known for a specific transmitter). The simulation results show that S-EGSM outperforms the other no CSI-based methods [4] in highly correlated channel by $1.4$ dB. This gain is less significant when the correlation factor becomes low. Note that the TAC selection without CSI is suitable for fast time varying channels since it permits to avoid the overhead of the feedback channel and the increased complexity in real time TAC selection. However, the adaptive TAC selection with CSI (EGSM) can be adopted in slow-time varying channels to get the optimal performance.

Next, we proposed the Gray coding for spatial bits in GSM that tries to limit the number of different bits between neighbor TACs to one bit. Note that the gray coding between all neighbors is not always guaranteed. Simulation results show that the Gray-based mapping method outperforms the normal binary spatial mapping by $1.5$ dB in highly correlated channels.

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