Combined Generalized Space Shift Keying and Amplitude/Phase Modulation for High-Rate Data Transmission

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***Abstract*—This paper proposes a novel combined spatial and amplitude-phase modulation (APM) scheme based on the generalize space shift keying (GSSK) system. The so-called GSSK/APM scheme performs two independent modulations using the GSSK and APM constellations. The modulated symbols from the two modulators are multiplied to generate the transmit symbols. With the two different constellations the proposed scheme allows easy control of the spectral efficiency compared to the related multiple antenna systems. In order to detect the transmit symbols, three detectors based on maximum likelihood, linear detection, and correlation are proposed. Theoretical upper bound of the bit error probability (BEP) is also derived and used to validate the simulation results.**

I. INTRODUCTION

The modern wireless communication system has developed very fast in the last decades making it possible for high-rate data transmission over fading channel. Lying behind the success is the invention of multiple antenna transmission techniques. The well-known multiple-input multiple-output (MIMO) system with multiple antennas at both transmitter and receiver has been proved as an effective means to increase spectral efficiency as well as system performance [1]–[4]. MIMO systems can be broadly classified into two types, namely, space-time codes and spatial division multiplexing (SDM). The space-time codes can obtain spatial diversity gain to improve bit error rate performance [3]. A typical SDM system is the vertical Bell-Laboratories layered space-time (V-BLAST) [2] that was demonstrated to increase the spectral efficiency linearly with the number of transmit antennas. The V-BLAST system, however, faces problems of synchronization among signal streams from different transmit antennas and of the cochannel interference (CCI), which possibly degrade the system performance.

In order to avoid these problems, spatial modulation which activates only one antenna at a time, was proposed [5],[6]. The activated antenna in spatial modulation is designed to bear information, thereby increasing the spectral efficiency. As only one antenna is transmitted at a time, the receiver of spatial modulation can use the maximal ratio combining (MRC) to detect the activated antenna and thus requires small complexity. However, despite the aforementioned advantages, spatial modulation suffers from a limitation in constellation size, and thus spectral efficiency, as the number of transmit antennas is constrained. Recently, the generalized space shift keying (GSSK) was proposed as the generalized case of spatial modulation [7]. The GSSK scheme uses only spatial domain, i.e. antenna positions, to convey information bits. The spatial constellation formed by GSSK depends on the combinations of active antennas, and is thus generally spread apart. This feature promises improved BER performance when a maximum likelihood (ML) detector is utilized [7]. It was shown in [7] that in almost cases GSSK provides similar BER performance of the spatial modulation but with lower complexity compared with both the spatial modulation and V-BLAST. This is due to the fact that in a GSSK system, only antennas combinations bear information. Therefore, the problem of signal detection is less complicated. As with spatial modulation, GSSK also faces the problem of spectral efficiency limitation when the number of transmit antennas is restricted.

Motivated by the problem of spatial modulation and GSSK, in this paper we proposed a combined spatial and amplitude-phase modulation scheme based on the generalize space shift keying system. The so-called GSSK/APM scheme contains two independent constellations, one is the spatial and the other the APM. This feature allows us to control the spectral efficiency more flexibly by changing either of the constellations. In order to detect the transmit symbols, we propose an optimal detector based using ML and two sub-optimal detectors based on combinations of linear detection with correlation and ML. We also derive the theoretical upper bound of the bit error probability (BEP) to use as a benchmark for simulations.

The paper is organized as follows. We briefly overview the principle of GSSK in Sect. II. The proposed combined GSSK/APM scheme is described in Sect. III. The upper bound on BEP is derived in Sect.IV. In Sect.V, performance evaluations are presented. Finally, Sect. VI concludes the paper.

$Notation$: throughout the paper we use the following mathematical notations. The bold-italic small/captital letter denotes vector/matrix, respectively. $(.)^T$ is used for transpose while $(.)^H$ for Hermitian operation. $\|.\|_{\mathrm{F}}$ represents the Frobe-

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nius norm of a vector or matrix. $E_{\boldsymbol{x}}\{.\}$ denotes the statistical expectation of $\boldsymbol{x}$. The complex Gaussian distribution with mean a and variance b^2 is denoted by $\mathcal{N}_c(a, b^2)$.

II. Overview of GSSK System

Consider a generalized space-shift keying (GSSK) system working over a MIMO channel with N_t transmit antennas and N_r received antennas as presented in [7]. The transmit data bits are grouped into independent blocks of bits $\boldsymbol{b} = [b_1, b_2, \cdots, b_k]$, where k is the number of bits per transmission symbol. These blocks will be then mapped into a spatial constellation which specifies the utilized transmit-antenna indexes. The modulated signal vector is given by $\boldsymbol{x} = [x_1, x_2, \cdots, x_{N_t}]^T$. The transmit power is normalized such that $E_x\left\{\boldsymbol{x}^H\boldsymbol{x}\right\} = 1$. In the GSSK scheme, only n_t out of N_t transmit antennas are activated during transmission. This means that only n_t elements of $x_j, j = 1, 2, \cdots, N_t$, from $\boldsymbol{x}$ take on non-zero values. These elements are then transmitted over an $N_r \times N_t$ MIMO channel which is represented by the channel matrix $\boldsymbol{H} \in \mathbb{C}^{N_r \times N_t}$. At the receiver, the received signal is affected by the additive white Gaussian noise (AWGN). And given by

$$\boldsymbol{y} = \sqrt{\gamma}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{z}, \tag{1}$$

where $\boldsymbol{z} = [z_1, z_2, \cdots, z_{N_r}]^T$, $\boldsymbol{z} \in \mathbb{C}^{N_r \times 1}$. It is assumed that the fading channel coefficients of $\boldsymbol{H}$ and noise elements of $\boldsymbol{z}$ are independent and identically distributed (iid) with mean zero and unit variance, i.e., $\mathcal{N}_c(0, 1)$. Here γ is defined as the average signal-to-noise power ratio (SNR) at each receiver branch.

A. GSSK Transmitter

In the GSSK scheme, as n_t out of N_t transmit antennas are activated at a given time, there are $M' = \binom{N_t}{n_t}$ possible combinations of transmit antennas. For example we have $M' = 10$ possible antenna combinations for $n_t = 2$ and $N_t = 5$. Since the size of the signal constellation should be in multiple of 2, only $2^3 = 8$ combinations from 10 will be used for signal mapping. The choice of the used combinations may be random or optimized according to a certain criterion [7]. After being mapped to the spatial constellation, the transmit signal vector will be transmitted over the channel $\boldsymbol{H}$. It is worth noting that there are only n_t columns of $\boldsymbol{H}$ are activated depending on the transmit data block. The active antennas form an antenna index vector corresponding to a spatial constellation point. For example, for the case of 3 bits per symbol and with $\boldsymbol{b} = [0,\ 0,\ 1]$, the transmit antenna index vector is given by $\boldsymbol{i} = (1, 3)$ and the transmit signal vector is given by $\boldsymbol{x_i} = \boldsymbol{x}_{(1,3)} = \left[\frac{1}{\sqrt{2}},\ 0,\ \frac{1}{\sqrt{2}},\ 0,\ 0\right]^T$. And for $\boldsymbol{b} = [1,\ 0,\ 1]$, $\boldsymbol{i} = (2,\ 4)$, we have $\boldsymbol{x_i} = \boldsymbol{x}_{(2,4)} = \left[0,\ \frac{1}{\sqrt{2}},\ 0,\ \frac{1}{\sqrt{2}},\ 0\right]^T$. A full list of the signal constellation is given in [7].

B. GSSK Receiver

The GSSK receiver uses a signal detector to estimate the transmit antenna index vector $\boldsymbol{i}$ used for transmission and maps them back to the transmitted bit block $\boldsymbol{b}$. The optimal receiver uses the maximum likelihood (ML) detection to estimate the transmit antenna index vector by minimizing the Euclidean distance given by

$$\hat{\boldsymbol{i}} = \arg\min_{\boldsymbol{i}} \|\boldsymbol{y} - \sqrt{\gamma}\boldsymbol{H}\boldsymbol{x_i}\|_{\mathrm{F}}^2 . \tag{2}$$

This means the ML detector needs to perform $K = 2^k$ trials of $\boldsymbol{x_i}$ to choose a transmit vector index $\boldsymbol{i}$ associated with the transmit vector $\hat{\boldsymbol{x}}_{\boldsymbol{i}}$ which has the minimum Euclidean distance. The ML detector provides optimum performance in terms of BER, however, requires large complexity. As it needs to perform 2^k trials the ML detector requires the complexity order of $\mathcal{O}\left(2^k\right)$. For GSSK, the complexity also increases exponentially with the number of active antennas, i.e., $\mathcal{O}(2^{n_t})$.

III. Proposed Scheme of Combined GSSK and APM

A. GSSK/APM Transmitter

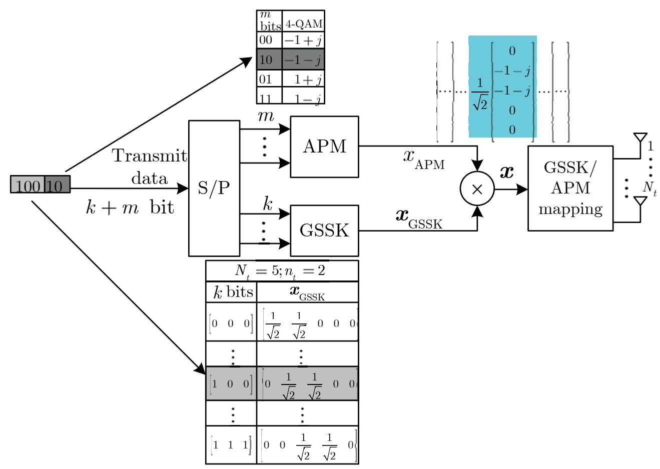

Fig. 1. Block digram of the proposed scheme of combined GSSK and QAM.

The system configuration of the proposed GSSK/APM scheme is illustrated in Fig 1. The transmit data bits are grouped into combinations of $(k+m)$ bits $\boldsymbol{b}$. The first m bits are input to an APM modulator, e.g. M-QAM or M-PSK to have complex modulated symbols x_{APM}. The remaining k bits are mapped into the spatial constellation to obtain the GSSK signal vector $\boldsymbol{x}_{\mathrm{GSSK}}$. Similar to the conventional GSSK system, the GSSK branch activates only n_t from N_t available antennas during transmission. This means that only n_t elements x_{GSSK_j}, $j = 1, 2, ..., N_t$, of $\boldsymbol{x}_{\mathrm{GSSK}}$ have non-zero values as in the example below

$$\boldsymbol{x}_{\mathrm{GSSK}} = \left[\frac{1}{\sqrt{n_t}}, 0, \cdots, 0, \frac{1}{\sqrt{n_t}}, \cdots, 0\right]^T . \tag{3}$$

The output signal vector from the GSSK branch will be then multiplied with the APM modulated symbols. Note that this multiplication changes only the transmit signal energy but not the spatial constellation. As a result, the set of activated antennas at the output of the GSSK/QAM mapping block is still the same with that of the GSSK mapping. The transmit vector

$$\boldsymbol{x} = x_{\mathrm{APM}} \cdot \boldsymbol{x}_{\mathrm{GSSK}}. \tag{4}$$

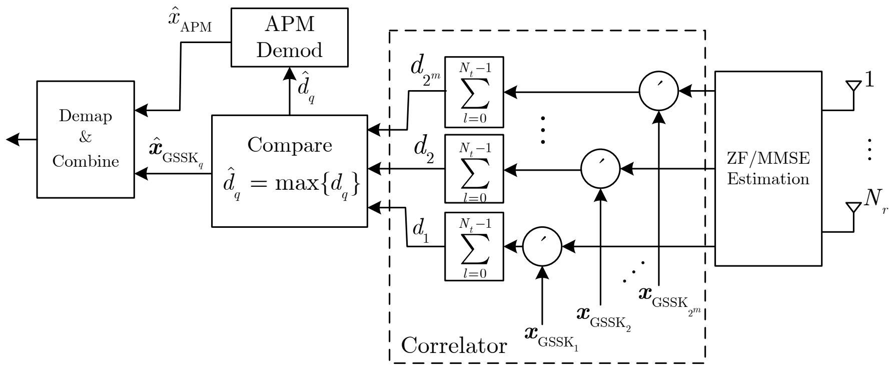

Fig. 2. Proposed configuration of the correlation detector.

is then transmitted over an $N_r \times N_t$ MIMO fading channel. The advantages of the proposed scheme can be explained as follows:

i) In order to increase the spectral efficiency, it is possible to increase either the APM constellation or the spatial constellation. The scheme is thus more flexible than the conventional GSSK [7] and spatial modulation [5], [6].
ii) Compared with the GSSK or spatial modulation system, the proposed GSSK/APM scheme is more advantageous under the case with space constrain. For the GSSK system, in order to increase the spectral efficiency, more transmit antennas need to be used. The proposed GSSK/APM scheme, however, can keep the number of transmit antenna within the limit and increase the APM constellation size.
iii) Inherited from GSSK, the proposed GSSK/APM scheme is superior to the V-BLAST system with the same spectral efficiency since it can reduce the co-channel interference (CCI) due to less number of activated transmit antennas.
iv) The proposed scheme is superior to the conventional single antenna system (SISO) as it has two separate constellations. In the SISO system, increasing the spectral efficiency reduces the Euclidean distance between signal points in the APM constellation, and thus the BER performance. Thanks to having two separate constellations, the proposed GSSK/APM can keep the Euclidean distance at a required level and increase the spatial constellation provided that more antennas are available to use.

B. GSSK/APM Receiver

Similar to the GSSK system, the received signal vector at the receiver can be expressed as

$$\boldsymbol{y} = \sqrt{\gamma}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{z}, \tag{5}$$

where γ is the average SNR at each receive branch. We recall here that as similar to the GSSK system, there are only n_t columns of $\boldsymbol{H}$ are used during transmission. For example, if the transmit index vector is $\boldsymbol{i} = (1, 3)$ then the two active columns are $\boldsymbol{h}_1$ and $\boldsymbol{h}_3$. These columns change according to the transmit data. As the transmit vector $\boldsymbol{x}$ contains both the APM symbol x_{APM} and the spatial symbol $\boldsymbol{x}_{\text{GSSK}}$, the receiver needs to estimate both the symbols. This can be done by detecting them symbol by symbol in a sequence or jointly at the same time.

In this paper we propose three different detectors based on: (a) combined linear detection and correlation, (b) combined linear detection, correlation and ML detection, and (c) ML detection. The first two detectors are sequential while the last one is joint detector. The purpose of the proposals is to find a suitable detector which can balance the BER performance with computational complexity.

1) Correlation Detector: The proposed configuration of the correlation detector shown in Fig. 2 is comprised of three stages. The idea of the detector is to use a linear detector such as zero forcing (ZF) or minimum mean square error (MMSE) to first estimate the transmit vector $\hat{\boldsymbol{x}} = \boldsymbol{W}\boldsymbol{y}$. The combination matrices for the linear MMSE and ZF detectors are respectively given by

$$\boldsymbol{W}^{\text{MMSE}} = \left(\boldsymbol{H}^H\boldsymbol{H} + \tfrac{1}{\gamma}\boldsymbol{I}_{N_t}\right)^{-1}\boldsymbol{H}^H. \tag{6}$$

$$\boldsymbol{W}^{\text{ZF}} = \left(\boldsymbol{H}^H\boldsymbol{H}\right)^{-1}\boldsymbol{H}^H. \tag{7}$$

A correlator is then used to obtain the decision statistic $\hat{d}_q, q = 1, 2, \cdots, 2^m$ and the transmitted spatial vector as follows

$$\hat{q} = \arg\max_q \left\{\boldsymbol{x}^H_{\text{GSSK}_q}\hat{\boldsymbol{x}}\right\} \tag{8}$$

$$\hat{d}_q = d_{\hat{q}} \tag{9}$$

$$\hat{\boldsymbol{x}}_{\text{GSSK}_q} = \boldsymbol{x}_{\text{GSSK}_{\hat{q}}}. \tag{10}$$

The decision static $\hat{d}_q$ is then demodulated to obtain APM symbols

$$\hat{x}_{\text{APM}_j} = \text{apmdemod}\{\hat{d}_q\}. \tag{11}$$

This three-stage sequential detector achieves comparatively good BER performance at low complexity. It is noted that computing the combining weight matrix $\boldsymbol{W}$ requires complexity order $\mathcal{O}(N_r^3)$ and the correlator needs to perform 2^k trials from the antenna combinations. Therefore, the complexity order of the proposed correlation detector is $\mathcal{C}_{\text{corr}} \sim \mathcal{O}\left(\max\left[N_r^3, 2^k\right]\right)$.

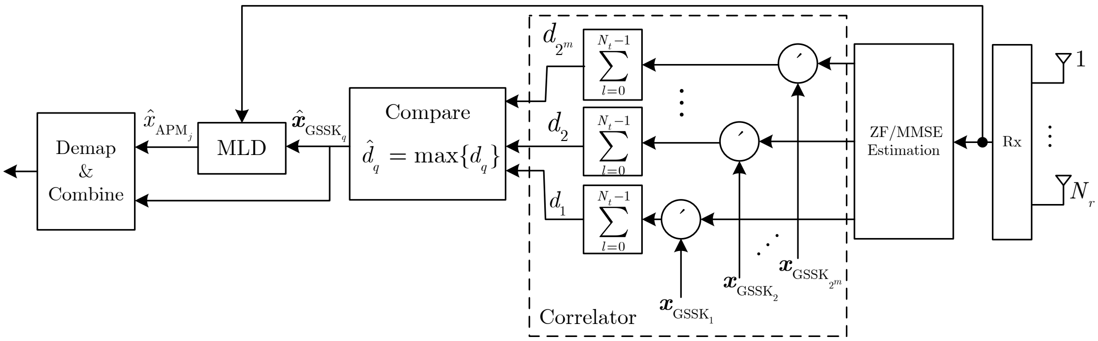

Fig. 3. Configuration of the combined correlation/ML detector.

2) Combined Correlation/Maximum Likelihood Detector: The objective of this proposed detector is to achieve improved BER at small additional complexity compared with the previous correlation detector. The configuration of the proposed detector is shown in Fig. 3. The only difference from the above correlation detector is that after the decision statistic $\hat{\boldsymbol{x}}_{\mathrm{GSSK}_q}$ has been obtained from (10), we use a ML detector rather than the APM demodulator to estimate the transmitted APM symbols $\hat{x}_{\mathrm{APM}_j}$. This operation is expressed as follows

$$\hat{x}_{\mathrm{APM}_j} = \arg\min_j \left\{ \left\| \boldsymbol{y} - \sqrt{\gamma}\boldsymbol{H} \cdot x_{\mathrm{APM}_j} \cdot \hat{\boldsymbol{x}}_{\mathrm{GSSK}_q} \right\|_{\mathrm{F}}^2 \right\}. \tag{12}$$

The use of the ML detector to estimate the APM symbols increases the BER performance of the receiver. However, it requires more computational complexity compared with the conventional APM demodulator. The complexity order of the detector is $\mathcal{C}_{\mathrm{corr/ML}} \sim \mathcal{O}\left(\max\left[N_r^3, 2^k, 2^m\right]\right)$. It can be noted that for low-order APM modulation 2^m is small, and thus the combined correlation/ML detector has the same complexity order with the previous correlation detector.

3) Maximum Likelihood Detector: The proposed ML detector in this case is applied to the joint APM and spatial constellation. This means that the ML detector needs to estimate the desired set of antenna combinations and transmitted APM symbols at the same time. The estimated symbols will be then mapped back to the transmitted bit sequence. Specifically, the ML detector needs to carry out trial tests for all sets of possible combinations of $\boldsymbol{x}$ given by (4) and chooses the vector $\hat{\boldsymbol{x}}$ with the minimum Euclidean distance as the transmitted vector. This operation can be expressed equivalently as follows

$$\left\{\hat{\boldsymbol{x}}_{\mathrm{GSSK}_q}, \hat{x}_{\mathrm{APM}_j}\right\} = \arg\min_{j,q} \left\{ \left\| \boldsymbol{y} - \sqrt{\gamma}\boldsymbol{H} x_{\mathrm{QAM}_j} \boldsymbol{x}_{\mathrm{GSSK}_q} \right\|_{\mathrm{F}}^2 \right\}.$$

The ML detector provides the optimum BER performance, however, requires large computational complexity. Therefore, it is recommended for the system with possible hardware resource. The complexity order of the ML detector is $\mathcal{C} \sim \mathcal{O}\left(2^{k+m}\right)$.

IV. BEP Upper Bound Analysis

In this section, we analyze the bit error probability (BEP) of the proposed GSSK/APM system using the upper bound of the pairwise error probability (PEP). By definition, $P\left(\boldsymbol{x}_m \to \boldsymbol{x}_n\right)$ is the probability that the detector decides the codeword $\boldsymbol{x}_n$ given that the codeword $\boldsymbol{x}_m$ was transmitted. PEP conditioned on the channel $\boldsymbol{H}$ is given by [3],[4]:

$$P\left(\boldsymbol{x}_m \to \boldsymbol{x}_n | \boldsymbol{H}\right) = Q\left(\sqrt{\frac{\gamma}{2} d^2\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right)}\right), \tag{13}$$

where $Q\left(y\right) = \frac{1}{\sqrt{2\pi}} \int_y^\infty e^{-\frac{1}{2}t^2} dt$ and $d^2\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right)$ is the modified Euclidean distance between $\boldsymbol{x}_m$ and $\boldsymbol{x}_n$. Under the assumption that the fading channel is slowly varying, $d^2\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right)$ is given by

$$d^2\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right) = \sum_{k=1}^{N_r} \lambda \left|\beta_k\right|^2, \tag{14}$$

where λ is the eigenvalue of the codeword distance matrix $\boldsymbol{x}_\Delta = \left(\boldsymbol{x}_m - \boldsymbol{x}_n\right)^H \left(\boldsymbol{x}_m - \boldsymbol{x}_n\right)$. It is given by $\lambda = \delta\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right)$ for the proposed GSSK/APM system, where $\delta\left(\cdot\right)$ represents the Euclidean distance; β_k are independent complex Gaussian variables with zero mean and unit variance.

Using the Craig's alternative form of $Q\left(y\right)$, the PEP can be expressed as [4],[8]

$$\begin{aligned} P\left(\boldsymbol{x}_m \to \boldsymbol{x}_n | \boldsymbol{H}\right) &= \frac{1}{\pi} \int_0^{\pi/2} \exp\left[-\frac{\gamma d^2\left(\boldsymbol{x}_m, \boldsymbol{x}_n\right)}{4\sin^2\theta}\right] d\theta \\ &= \frac{1}{\pi} \int_0^{\pi/2} \prod_{k=1}^{N_r} \exp\left[-\frac{\gamma\lambda\left|\beta_k\right|^2}{4\sin^2\theta}\right] d\theta \end{aligned} \tag{15}$$

Since the random variables $\left|\beta_k\right|^2$ has χ^2-distribution, we have the PEP given by [4]

$$\begin{aligned} P\left(\boldsymbol{x}_m \to \boldsymbol{x}_n\right) &= \frac{1}{\pi} \int_0^{\pi/2} \left[1 + \frac{\gamma\lambda}{4\sin^2\theta}\right]^{-N_r} d\theta \\ &= \frac{1}{2}\left[1 - \sqrt{\frac{\gamma\lambda}{4+\gamma\lambda}} \sum_{q=0}^{N_r-1} \binom{2q}{q} \frac{1}{\left(4+\gamma\lambda\right)^q}\right]. \end{aligned} \tag{16}$$

Assume that ℓ data bits are transmitted using one of $L = KM$ GSSK/APM codewords $\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_L$, then using the pairwise probability given in (13), we can obtain the upper bound of the average BEP for the proposed GSSK/APM system as follows [9]

$$P_b \leq \frac{1}{L} \sum_{m=1}^{L} \sum_{n=1}^{L} \frac{P(\boldsymbol{x}_m \rightarrow \boldsymbol{x}_n)\, e_{m,n}}{\ell}, \tag{17}$$

where $e_{n,m}$ is the number of erroneous bits from detecting $\boldsymbol{x}_n$ while $\boldsymbol{x}_m$ was transmitted. In fact, $e_{m,n}$ is the Hamming distance between the two codewords $\boldsymbol{x}_m$ and $\boldsymbol{x}_n$. Using the fact that $P(\boldsymbol{x}_m \rightarrow \boldsymbol{x}_n) = P(\boldsymbol{x}_n \rightarrow \boldsymbol{x}_m)$, $e_{m,n} = e_{n,m}$ and $e_{m,m} = 0$, the upper bound in (15) becomes

$$\begin{aligned} P_b &\leq \tfrac{2}{\ell L} \sum_{m=1}^{L-1} \sum_{n=m}^{L} P(\boldsymbol{x}_m \rightarrow \boldsymbol{x}_n)\, e_{m,n} \\ &= \tfrac{1}{\ell L} \sum_{m=1}^{L-1} \sum_{n=m}^{L} \left[1 - \sqrt{\tfrac{\bar{\gamma}_{m,n}}{4+\bar{\gamma}_{m,n}}} \sum_{q=0}^{N_r-1} \binom{2q}{q} \tfrac{1}{(4+\bar{\gamma}_{m,n})^q} \right] e_{m,n} \end{aligned} \tag{18}$$

where $\bar{\gamma}_{m,n} = \gamma \delta(\mathbf{x}_m, \mathbf{x}_n)$.

V. Performance Evaluation

A. Comparison of Simulation and Analytical Results

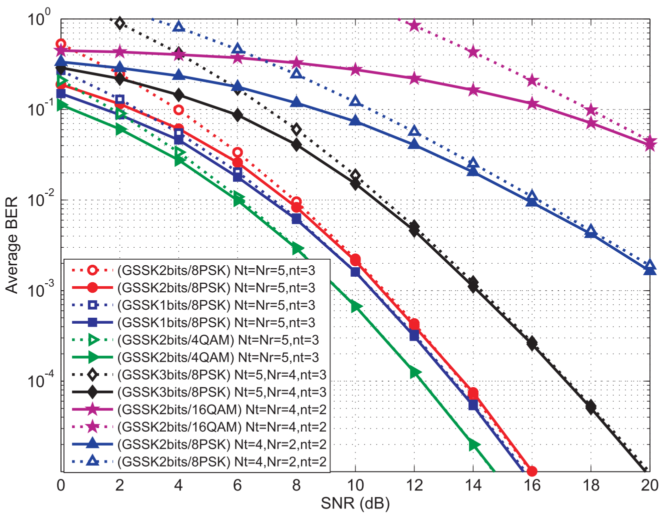

Fig. 4. Simulated BER versus theoretical upper bound of BEP.

In order to validate the upper bound of the BEP in (18), we have used Monte-Carlo simulation to obtain the average BER for the case using ML detector. Figure 4 compares the BER performance with the upper bound for different cases of MIMO configurations over the flat Rayleigh fading channel. It can be clearly seen that the upper bounds agree well with the simulation curves, particularly, at the high SNR region. This means that the upper bound given by (18) can be well suitable for analyzing the bit error performance of the proposed combined GSSK/APM system when SNR is large enough. The comparisons also verify our simulations.

B. BER Comparison of GSSK/APM with Related Systems

In this section we perform BER performance comparison of the proposed GSSK/APM system using the ML detector with

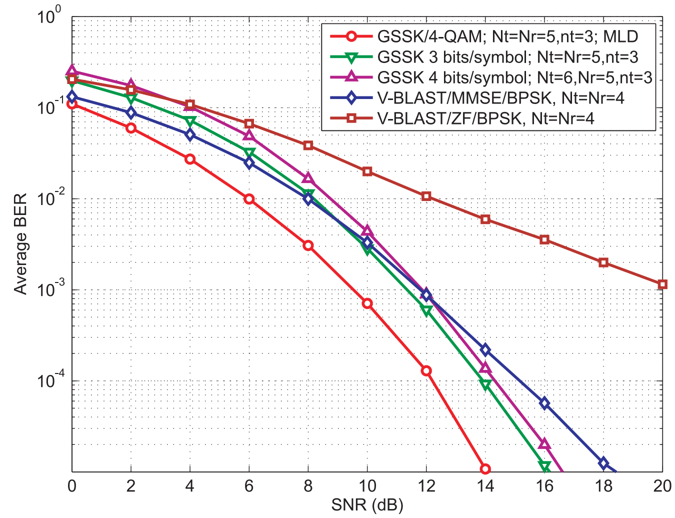

Fig. 5. BER performance of GSSK/APM compared with other related systems.

other popular multiple antenna transmission systems. For convenience, we set the spectral efficiency at 4 bits/symbol. The proposed GSSK/APM system uses the MIMO configuration with $N_t = N_r = 5$, and $n_t = 3$. In order to achieve the required spectral efficiency of 4 bits/symbol, we use $k = 2$ bits for 4-QAM modulation and $m = 2$ bits for GSSK. All simulations are done over the flat Rayleigh fading channel.

Figure 5 compares the BER performance of the proposed GSSK/APM with the conventional GSSK for two different cases, namely, $(N_t = N_r = 5)$ and $(N_t = 6,\ N_r = 5)$. From the antenna configurations we can see that in order to achieve the same spectral efficiency of 4 bits/symbol and 3 activated antennas $(n_t = 3)$, the conventional GSSK system needs one more transmit antenna, i.e., $N_t = 6$. Observing the figure we can also see that at the same spectral efficiency the proposed GSSK/APM outperforms the conventional GSSK system for about 2 dB of SNR. The proposed system is also shown to be much superior to the V-BLAST detectors at the same spectral efficiency.

C. BER Performance of GSSK/APM Under Different Constellations

Figure 6 illustrates BER performance of the proposed GSSK/APM under different signal constellations. Comparing the BER curves with the same spatial configuration $(N_t = N_r = 5,\ n_t = 3)$, we can see that increasing the spectral efficiency by 1 bit/symbol in both the spatial or QAM constellation degrades the BER performance. However, the reduction due to the spatial is much smaller than that due to the QAM constellation. This observation can be used as a guideline for selecting the signal constellation when the spatial configuration is available. However, the figure shows that for a given spectral efficiency (3 bits/symbol) reducing the spatial configuration, e.g. from $(N_t = N_r = 5,\ n_t = 3) \rightarrow (N_t = 4, N_r = 2,\ n_t = 2)$, downgrades the BER performance signif-

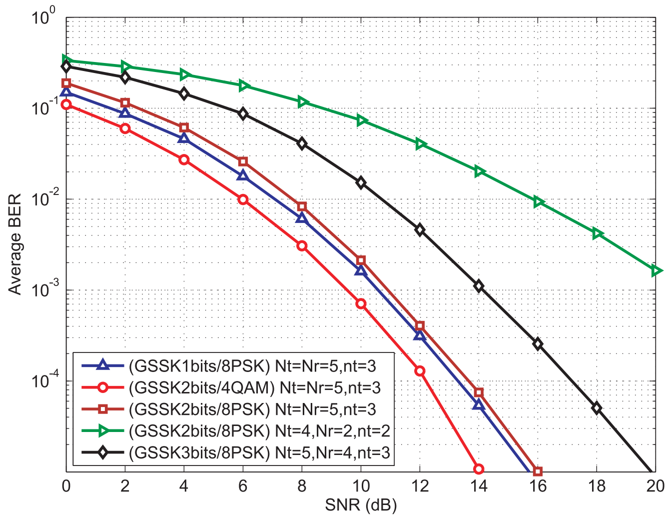

Fig. 6. BER performance of GSSK/APM under different signal constellations.

icantly due to lack of spatial diversity. This can also be seen when increasing the spectral efficiency from 3 bits/symbol to 4 bits/symbol while reducing $N_r = 5 \rightarrow N_r = 4$.

D. BER Performance of the Proposed Detectors

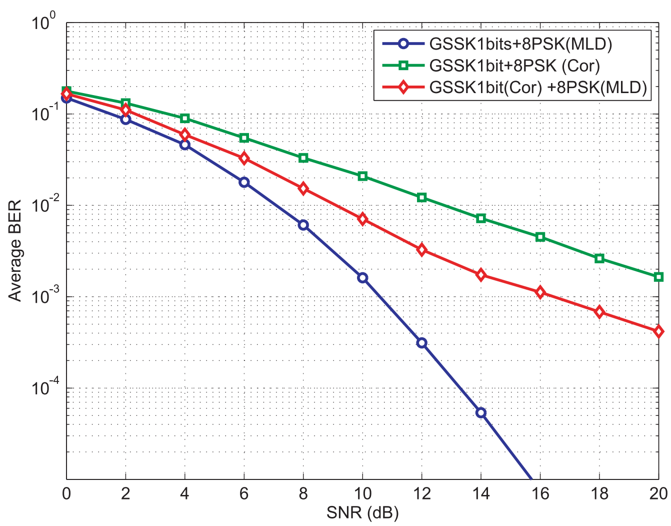

Fig. 7. BER performance of three detectors.

Figure 7 compares the BER performance of the three proposed detectors for the case using 1 bit for GSSK and 3 bits for 8-PSK modulation. It is clearly seen that the ML detector provides the best BER performance due to its optimality. The correlation/ML detector has better BER performance compared with the correlation detector. However, the gap between the correlation/ML detector and the ML detector is still large, especially at the high SNR region. As the ML detector is often prohibitively complex, a detector which can balance better the BER performance with computational complexity is further expected. To this direction, the use of a lattice-reduction aided (LRA) linear detector [10] in place of the conventional linear detector will probably be a good choice.

VI. Conclusions

In this paper, we have proposed a combined GSSK/APM scheme which can provide improved spectral efficiency. Furthermore, at the same spectral efficiency, the proposed scheme achieves better BER performance and also requires less number of active transmit antennas compared with the V-BLAST and GSSK system. We have also proposed three detectors with different capability in minimizing BER and reducing computational complexity. The proposed system thus can be a suitable candidate for high-rate data transmission.

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