A Low-Complexity Detection Scheme for Generalized Spatial Modulation Aided Single Carrier Systems

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***Abstract*—Generalized spatial modulation (GSM), which combines spatial modulation (SM) and vertical Bell Laboratories layered space-time (V-BLAST), is a novel attractive multi-input multi-output (MIMO) technique. In this letter, a low-complexity near-optimal detection scheme is presented for GSM aided single carrier (SC) transmission over dispersive channels. Compared to the conventional partial interference cancellation receiver with successive interference cancellation (PIC-R-SIC), the proposed scheme offers a near maximum likelihood (ML) detection performance while avoiding complicated matrix operations, which allows it to exhibit a lower computational complexity. Simulation results show that the proposed scheme provides a considerable performance improvement compared to PIC-R-SIC, especially in rank-deficient channels scenarios.**

***Index Terms*—Generalized spatial modulation (GSM), single carrier (SC), maximum likelihood (ML) detection, rank-deficient.**

I. Introduction

GENERALIZED spatial modulation (GSM) [1]–[3] is a novel multi-input multi-output (MIMO) transmission technique, which offers a tradeoff between spatial modulation (SM) [4]–[7] and vertical Bell Laboratories layered space-time (V-BLAST). In GSM scheme, parts of the transmit antennas (TAs) are activated as an additional means to convey information. Hence, GSM is capable of achieving a higher spectral efficiency compared to conventional SM associated with a single active TA. Moreover, compared to V-BLAST architecture, GSM needs less radio frequency (RF) chains at the transmitter.

As indicated in [8]–[12], the achieved beneficial bit-error rate (BER) performance of GSM is dominated by the detectors. However, these existing detection algorithms for GSM scheme are conceived for Rayleigh frequency-flat fading channels. Recently the studies in frequency-selective fading channel for SM and its variants, such as space shift keying (SSK), space time shift keying (STSK), and space-time-frequency shift keying (STFSK) schemes were investigated [13]–[16]. Specifically, in [13] OFDM-aided STSK scheme was proposed for combating dispersive channels with high peak-to-average power ratio (PAPR). In [14] STFSK scheme was proposed to exploit the available time-, space- and frequency-diversity over the dispersive channel aided multiple RF chains. Furthermore, the equalizer was utilized for STFSK to eliminate the effect of the dispersive channel, which imposes high complexity. To avoid the high PAPR while reducing the requirement of RF chains, single carrier (SC) aided SM with cyclic prefix (CP) and zero-padded (ZP) schemes were proposed in [15] and [16], respectively, which can be directly applied to GSM scheme. Especially, it was demonstrated in [16] that the ZP-aided SM-SC scheme was preferred over CP-aided SM-SC and SM-OFDM schemes in terms of BER.

The detection of ZP-aided SM-SC is based on the partial interference cancellation receiver with successive interference cancellation (PIC-R-SIC) [16], [17]. This detector relies on a projection matrix, which is orthogonal to sub-channel matrix. On the one hand, the acquisition of this matrix is related to complicated matrix operations. On the other hand, the orthogonality between this projection matrix and sub-channel matrix could be lost in some special MIMO setups leading to inaccurate detection.

Against this background, in this letter, a low-complexity near-ML detection scheme for both GSM and SM aided ZP-SC transmission systems is proposed. Specifically, a low-complexity single-stream ML detection is employed without any complicated matrix operations. Hence the complexity is significantly reduced. The proposed scheme provides a parameter M to balance a tradeoff between the complexity and performance. Furthermore, compared to PIC-R-SIC, the proposed scheme is suitable for arbitrary MIMO configurations in GSM systems.

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II. System Model

A. GSM-SC System Model

We consider a GSM-MIMO system with N_t transmit and N_r receive antennas over a dispersive channel, which has P multipath links between each antenna pair. The receive signal during k^{th} time instant can be written as

$$\mathbf{Y}_k = \sum_{j=0}^{P-1} \mathbf{H}_j \mathbf{x}_{k-j} + \mathbf{n}_k \tag{1}$$

where $\mathbf{x}_k \in \mathbb{C}^{N_t\times 1}$ and $\mathbf{Y}_k \in \mathbb{C}^{N_r\times 1}$ denote transmit and receiver vector. Moreover, $\mathbf{H}_j \in \mathbb{C}^{N_r\times N_t}$ is the channel matrix of the j^{th} path, and $\mathbf{n}_k \in \mathbb{C}^{N_r\times 1}$ denotes the noise vector. The elements of channel matrices and noise vector are assumed to follow the complex Gaussian distribution $\mathcal{CN}(0,1)$ and

$\mathcal{CN}(0, \sigma^2)$, respectively. Assuming that the length of data frame is K and each data frame is prefixed with $(P-1)$ zeros, the receive data frame can be given by (2), shown at the bottom of the page. In GSM system, N_u out of $N_t (N_u < N_t)$ TAs are activated at each time slot and $2^{\lfloor \log_2 (C_{N_t}^{N_u}) \rfloor}$ antenna combinations (ACs) are selected for modulating the information bits, where $C_{N_t}^{N_u}$ denotes the binomial coefficient and $\lfloor \bullet \rfloor$ is the floor operator. For each transmission, $l_1 = \lfloor \log_2 (C_{N_t}^{N_u}) \rfloor$ bits are mapped into the index of ACs and $l_2 = N_u \log_2(L)$ bits are mapped into $L-$ QAM symbols that transmitted by the N_u activated TAs. Hence, the GSM transmit vector is expressed as

$$\mathbf{x}_k = [\ldots, 0, s_1, 0, \ldots, 0, s_2, 0 \ldots, 0, s_{N_u}, 0, \ldots]^T. \tag{3}$$

According to (2), the ML detection is given as

$$\hat{\mathbf{x}}_{ML} = \arg \min_{\mathbf{x} \in \chi} \|\mathbf{Y} - \mathbf{H}\mathbf{x}\|_F^2 \tag{4}$$

where χ is the set of all legitimate transmit vectors with size of $(2^{l_1+l_2})^K$. Hence, the complexity of ML detection increases exponentially with the parameters of K, N_u and N_t.

B. PIC-R-SIC Detection

To reduce the complexity of ML detection, the PIC-R-SIC detector was proposed in [16]. Firstly, (2) is equivalently represented in matrix-form as

$$\mathbf{Y} = \sum_{i=1}^{K} \mathbf{G}_{I_i} \mathbf{x}_i + \mathbf{n} \tag{5}$$

where $\mathbf{G}_{I_i} = (\mathbf{h}_{(i-1)N_t+1}, \ldots, \mathbf{h}_{iN_t})$ is the submatrix with N_t columns of $\mathbf{H}$, and $\mathbf{h}_j$ denotes the j column of $\mathbf{H}$. In the PIC-R-SIC detector, the data $\mathbf{x}_K, \mathbf{x}_{K-1}, \ldots, \mathbf{x}_1$ are estimated in sequence. Specifically, in the detection of $\mathbf{x}_t, t \in (1, K)$, the interference imposed by the detected $\mathbf{x}_{t+1}, \mathbf{x}_{t+2}, \ldots, \mathbf{x}_K$ GSM vectors is removed first. According to (5), the signal $\mathbf{Y}^{(t)}$ without interference is expressed as $\mathbf{Y}^{(t)} = \sum_{i=1}^{t} \mathbf{G}_{I_i} \mathbf{x}_i + \mathbf{n}$. Then, a projection matrix $\mathbf{P}_{I_t} = \mathbf{I}_{N_r(K+P-1)} - \mathbf{Q}_{I_t}$ is multiplied by $\mathbf{Y}^{(t)}$, where $\mathbf{Q}_{I_t} = \mathbf{G}_{I_t}^c ((\mathbf{G}_{I_t}^c)^H \mathbf{G}_{I_t}^c)^{-1} (\mathbf{G}_{I_t}^c)^H$ and $\mathbf{G}_{I_t}^c = [\mathbf{G}_{I_1, \mathbf{G}_{I_2}, \ldots, \mathbf{G}_{I_{t-1}}}]$. Consider $\mathbf{Z}_{I_t} = \mathbf{P}_{I_t} \mathbf{Y}^{(t)}$ given by

$$\begin{aligned} \mathbf{Z}_{I_t} &= \mathbf{P}_{I_t} \mathbf{Y}^{(t)} = \left(\mathbf{I}_{N_r(K+P-1)} - \mathbf{Q}_{I_t}\right) \left(\mathbf{G}_{I_t}^c \mathbf{x}' + \mathbf{G}_{I_t} \mathbf{x}_t + \mathbf{n}\right) \\ &= \mathbf{ISI}_{symbols} + \mathbf{P}_{I_t} \mathbf{G}_{I_t} \mathbf{x}_t + \mathbf{P}_{I_t} \mathbf{n} \end{aligned} \tag{6}$$

where $\mathbf{x}' = [\mathbf{x}_1^T, \mathbf{x}_2^T, \ldots, \mathbf{x}_{t-1}^T]^T$ and $\mathbf{ISI}_{symbols} = \mathbf{G}_{I_t}^c \mathbf{x}' - \mathbf{G}_{I_t}^c ((\mathbf{G}_{I_t}^c)^H \mathbf{G}_{I_t}^c)^{-1} (\mathbf{G}_{I_t}^c)^H \mathbf{G}_{I_t}^c \mathbf{x}'$ denotes the interference imposed by $\mathbf{x}'$. Finally, $\mathbf{x}_t$ was detected as

$$(\hat{\mathbf{x}}_t)_{PIC-R-SIC} = \arg \min_{\mathbf{x}_t \in C_{GSM}} \|\mathbf{Z}_{I_t} - \mathbf{P}_{I_t} \mathbf{G}_{I_t} \mathbf{x}_t\|_F^2 \tag{7}$$

where C_{GSM} is the set of all the legitimate GSM vectors with size of $Q = 2^{l_1+l_2}$.

Note that if the constraint $(K+P-1)N_r > (K-1)N_t$ is satisfied, $\mathbf{G}_{I_t}^c$ is always a column full-rank matrix. Then $\mathbf{ISI}_{symbols}$ is a null matrix in each step. However, if $(K+P-1)N_r \le (K-1)N_t$, $\mathbf{G}_{I_K}^c$ may have all-zero row vectors and hence becomes rank-deficient. As a result, $\mathbf{ISI}_{symbols}$ is not a null matrix, which may provide inaccurate detection result $\mathbf{x}_K$. Hence, the whole detection of $\mathbf{x}$ is inaccurate. Furthermore, the calculation of $\{\mathbf{Q}_{I_t}\}_{t=2}^{t=K}$ needs to compute the matrix inverse operation of $\mathbf{G}_{I_t}^c$ about $K-1$ times, which imposes high complexity.

III. Proposed Scheme for GSM-SC

A. The Proposed Scheme

For reducing the complexity of traditional PIC-R-SIC detector, simplified searching algorithms are desired. However, conventional searching algorithms, such as sphere decoding (SD) [9], [12] and M-algorithm aided QR-decomposition [18] can not be effectively applied into the ZP-aided GSM SC system. For example, the channel matrix of ZP-aided GSM SC system may be rank-deficient, which limits the application of M-algorithm aided QR-decomposition. SD algorithms such as the receiver-centric SD (SD-Rx) and the transmit-centric SD (SD-Tx) can achieve near-ML performance, but it will introduce high complexity especially for a large frame length of K.

In the proposed scheme, the QR-decomposition is avoided and single-stream ML detection is employed. Specifically, the detection consists of $K+1$ steps, and all the M possible combinations $[\mathbf{x}_1^T, \ldots, \mathbf{x}_t^T]^T, t \in (1, K)$ is achieved on t^{th} step utilizing the corresponding receiver signal $[\mathbf{Y}_1^T, \ldots, \mathbf{Y}_t^T]^T$. The final detection result is achieved in the $(K+1)^{th}$ step.

According to (2), the t^{th} term of receiver signal $\hat{\mathbf{Y}}_t$ consisting of tN_r rows of $\mathbf{Y}$ is given by

$$\hat{\mathbf{Y}}_t = \hat{\mathbf{H}}_t \hat{\mathbf{x}}_t + \hat{\mathbf{n}}_t \tag{8}$$

where $\hat{\mathbf{Y}}_t = [\mathbf{Y}_1^T, \mathbf{Y}_2^T, \ldots, \mathbf{Y}_t^T]^T$, $\hat{\mathbf{x}}_t = [\mathbf{x}_1^T, \mathbf{x}_2^T, \ldots, \mathbf{x}_t^T]^T$, $\hat{\mathbf{H}}_t$ is the corresponding submatrix with tN_r rows and tN_t columns of $\mathbf{H}$, and $\hat{\mathbf{n}}_t = [\mathbf{n}_1^T, \mathbf{n}_2^T, \ldots, \mathbf{n}_t^T]^T$.

In the first step of detection, all possible candidate vectors for $\mathbf{x}_1$ are generated. According to (8), the receiver signal at the

$$\underbrace{\begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \\ \vdots \\ \mathbf{Y}_{K+P-1} \end{bmatrix}}_{\mathbf{Y} \text{ of size} (K+P-1)N_r \times 1} = \underbrace{\begin{bmatrix} \mathbf{H}_0 & \mathbf{O} & \ldots & \mathbf{O} & \mathbf{O} \\ \mathbf{H}_1 & \mathbf{H}_0 & \ldots & \mathbf{O} & \mathbf{O} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{H}_{P-1} & \mathbf{H}_{P-2} & \ldots & \mathbf{H}_0 & \mathbf{O} \\ \mathbf{O} & \mathbf{H}_{P-1} & \ldots & \mathbf{H}_1 & \mathbf{H}_0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{O} & \mathbf{O} & \ldots & \mathbf{H}_{P-1} & \mathbf{H}_{P-2} \\ \mathbf{O} & \mathbf{O} & \ldots & \mathbf{O} & \mathbf{H}_{P-1} \end{bmatrix}}_{\mathbf{H} \text{ of size } (K+P-1)N_r \times KN_t} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_K \end{bmatrix}}_{\mathbf{x} \text{ of size } KN_t \times 1} + \underbrace{\begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_{K+P-1} \end{bmatrix}}_{\mathbf{n} \text{ of size } (K+P-1)N_r \times 1} \tag{2}$$

first time slot can be written as

$$\hat{\mathbf{Y}}_1 = \mathbf{Y}_1 = \mathbf{H}_0\mathbf{x}_1 + \mathbf{n}_1 \tag{9}$$

then metrics based on the square Euclidian distances (SED) between $\hat{\mathbf{Y}}_1$ and each candidate vector are computed as

$$\mathbf{e}_1 = ||\hat{\mathbf{Y}}_1 - \mathbf{H}_0\mathbf{x}_1||_F^2, \mathbf{x}_1 \in C_{GSM}. \tag{10}$$

Then, those metrics are sorted in an ascended order and M smallest metrics out of Q are selected. Furthermore, M legitimate GSM vectors $\mathbf{D}_1 = [\mathbf{x}_1^1, \ldots \mathbf{x}_1^m, \ldots, \mathbf{x}_1^M]$ corresponding to the selected metrics $\tilde{\mathbf{e}}_1 = [\tilde{\mathbf{e}}_1^1, \ldots \tilde{\mathbf{e}}_1^m \ldots, \tilde{\mathbf{e}}_1^M]$ are obtained.

In the second step, the second term of receiver signal $\hat{\mathbf{Y}}_2$ is detected with the aid of the estimated $\mathbf{x}_1^m$. From (8), the metrics based on SED between $\hat{\mathbf{Y}}_2$ and each candidate vector are computed as

$$\begin{aligned} \mathbf{e}_2^m &= \left\| \hat{\mathbf{Y}}_2 - \begin{pmatrix} \mathbf{H}_0 & 0 \\ \mathbf{H}_1 & \mathbf{H}_0 \end{pmatrix} \begin{pmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2 \end{pmatrix} \right\|_F^2 \\ &= \tilde{\mathbf{e}}_1^m + \left\| \mathbf{Y}_2 - \begin{pmatrix} \mathbf{H}_1 & \mathbf{H}_0 \end{pmatrix} \begin{pmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2 \end{pmatrix} \right\|_F^2, \mathbf{x}_2 \in C_{GSM}, \end{aligned} \tag{11}$$

where $m \in (1, M)$. According to (11), all the MQ metrics can be calculated as

$$\mathbf{e}_2 = \left[\mathbf{e}_2^1, \ldots, \mathbf{e}_2^m, \ldots, \mathbf{e}_2^M\right]. \tag{12}$$

Then those matrices are sorted in an ascended order and $\hat{M}(\hat{M} < MQ)$ smallest metrics out of MQ metrics are chosen. Hence, the $\hat{M}$ combinations of $\mathbf{x}_1$ and $\mathbf{x}_2$ corresponding to the selected $\hat{M}$ smallest metrics $\tilde{\mathbf{e}}_2 = [\tilde{\mathbf{e}}_2^1, \ldots \tilde{\mathbf{e}}_2^m, \ldots, \tilde{\mathbf{e}}_2^{\hat{M}}]$ can be expressed as

$$\mathbf{D}_2 = \left\{ \left(\left[\mathbf{x}_1^T, \mathbf{x}_2^T\right]^T \right)^1, \ldots, \left(\left[\mathbf{x}_1^T, \mathbf{x}_2^T\right]^T \right)^{\hat{M}} \right\}. \tag{13}$$

The above-mentioned process is repeated until the K^{th} step is completed. And the combinations $[\mathbf{x}_1^T, \ldots, \mathbf{x}_K^T]^T$ achieving from the K^{th} step is given by

$$\mathbf{D}_K = \left[\mathbf{D}_K^1, \ldots, \mathbf{D}_K^m, \ldots, \mathbf{D}_K^{\hat{M}}\right]. \tag{14}$$

According to (2), the final detection is obtained by

$$\hat{\mathbf{x}}_{proposed} = \underset{m \in (1,2,\ldots,\hat{M})}{\arg\min} ||\mathbf{Y} - \mathbf{H}\mathbf{D}_K^m||_F^2. \tag{15}$$

B. Complexity Analysis

In this subsection, the complexity of the proposed scheme with $M = \hat{M}$ is analyzed in terms of the number of real-valued multiplications, which is counted as

$$\begin{aligned} C_P = &(4N_rN_t + 2N_r)Q + \sum_{t=2}^{K} \left((4N_r \times tN_t + 2N_r)Q\right) M \\ &+ (4N_r(P-1)KN_t + 2N_r(P-1))\, M. \end{aligned} \tag{16}$$

For comparative purposes, the complexity operations of the PIC-R-SIC and ML are computed as

$$\begin{aligned} C_{PIC-R-SIC} = &\sum_{t=2}^{K} 8A(B_t)^2 + 2(B_t)^3 + 6(B_t)^2 + 4A^2B_t \\ &+ (4A^2N_t + 4AN_tQ + 2AQ)K \end{aligned} \tag{17}$$

$$C_{ML} = (2A + 4AKN_t)Q^K \tag{18}$$

TABLE I
COMPLEXITY OF DIFFERENT DETECTORS IN TERMS OF THE NUMBER OF REAL-VALUED MULTIPLICATIONS

$N_t=2$, N_r=2, $N_u=1$, $L=2$, $P=3$					
Scheme	ML	PIC-R-SIC	proposed		SD 14-dB
			$M=2$	$M=4$	
K=4	1.0×10^5	1.4×10^4	1.6×10^3	3.1×10^3	SD-Rx 7.2×10^3
K=128	3.1×10^{82}	3.1×10^8	1.1×10^6	2.1×10^6	SD-Tx 3.2×10^8

TABLE II
SIMULATION PARAMETERS

	Fig.1		Fig.2
Scheme	SM-OFDM	ZP aided SM-SC	ZP aided GSM-SC
Antenna ($N_t \times N_r$)	2×1, 2×2		4×2,4×4 $N_u=2$
Modulation	BPSK		QPSK
ZP/CP-length	2		P-1
Frame-length	K=4		K=128
Channel	Rayleigh fading P=3		EVA

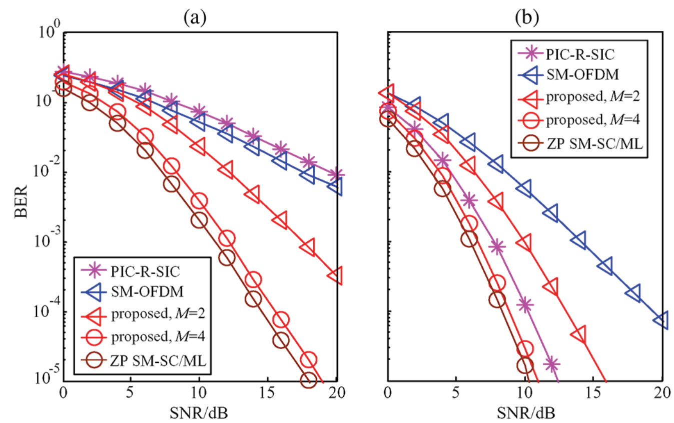

Fig. 1. BER of ZP-aided SM-SC and SM-OFDM with different receiver antennas (a) $N_r = 1$; (b) $N_r = 2$.

where $A = (K+P-1)N_r$, $B_t = (t-1)N_t$. Additionally, the complexity of the proposed scheme, PIC-R-SIC and ML detector is presented in Table I. As benchmarks, the complexity of the SD-Rx and the SD-Tx is also provided. It is shown that although the complexity of the proposed scheme increases as M increases, it still achieves a considerable complexity reduction of 56% compared to SD-Rx [12], 78% compared to PIC-R-SIC and 98% compared to ML detector at $K=4$ and $M=4$. Moreover, for a large value of $K=128$, the size of χ is as large as $|\chi| = 4^{128}$. Hence, the SD-Rx detection [9], [12] becomes impractical and SD-Tx [9] algorithm may be performed in some high SNR, whereas the proposed scheme can achieve more than 99% complexity reduction over PIC-R-SIC and SD-Tx detectors.

IV. SIMULATION RESULTS

In this section, simulations are carried out with ideal channel state information and the simulation parameters are shown in Table II, where EVA channel denotes extended vehicular a model channel. For simplicity, $M = \hat{M}$ is considered for the proposed scheme in all the simulations.

Fig. 1 characterizes the BER performance of ZP-aided SM-SC system and SM-OFDM under 2 bits/s/Hz transmission. It's evident from Fig. 1(a) that the BER of PIC-R-SIC scheme has

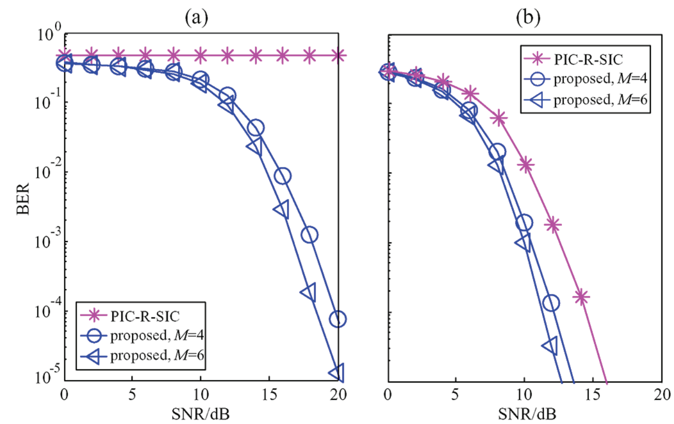

Fig. 2. BER of ZP-aided GSM-SC with different receiver antennas (a) $N_r = 2$; (b) $N_r = 4$.

an error floor at high SNR region in the constraint of $(K + P - 1)N_r \leq (K - 1)N_t$. More importantly, for the condition of $(K + P - 1)N_r > (K - 1)N_t$ in Fig. 1(b), the proposed scheme with $M = 4$ outperforms PIC-R-SIC by around 2-dB at 10^{-4} BER. This can be explained that the noise in (6) is enlarged by multiplying the matrix $\mathbf{P}_{I_t}$. Additionally, it is shown that the proposed scheme with $M = 4$ is capable of approaching ML detection performance and achieving significant performance gain over SM-OFDM based on ML detection in both above-mentioned constrain scenarios.

Fig. 2 shows the BER of ZP-aided GSM-SC system with different receiver antennas at $K = 128$, where ML detection is impractical due to the large K. It is shown in Fig. 2(a) that PIC-R-SIC detector will introduce error-floor in the condition of $(K + P - 1)N_r \leq (K - 1)N_t$. For the condition of $(K + P - 1)N_r > (K - 1)N_t$ in Fig. 2(b), the proposed scheme with $M = 4$ outperforms PIC-R-SIC about 2-dB at 10^{-4} BER. In particular, the higher value of M is, the better the performance of the proposed scheme is. Hence, the proposed scheme is capable of achieving a balanced trade-off between performance and complexity.

V. Conclusion

This Letter proposed a low-complexity detector for GSM SC systems over dispersive channels. In contrast to PIC-R-SIC, the proposed scheme exhibits a better BER performance with reduced complexity. Furthermore, the performance of the proposed scheme is capable of approaching that of the ML detector as M increases, which is quite attractive for GSM SC systems, especially for the rank-deficient channels scenarios.

The impact of the potential bandwidth expansion [19], [20] of ZP-aided GSM-SC system is being considered as a future extension of this work.

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