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SCM-SM: Superposition Coded Modulation-Aided Spatial Modulation With a Low-Complexity Detector

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***Abstract*—Spatial modulation (SM) is a spatial multiplexing scheme that utilizes both the signal constellation and antenna index to convey information. In the original SM, traditional modulation schemes such as quadrature amplitude modulation (QAM) are employed for constellation mapping. In this paper, we propose a novel scheme where superposition coded modulation (SCM) is employed to modulate the information onto the constellation points. We also develop a low-complexity iterative detector for our proposed SCM-SM system. Analysis and simulations demonstrate that SCM-SM significantly outperforms the original SM system with the same data rate while maintaining the relatively low complexity, particularly in the high data rate scenario.**

***Index Terms*—Iterative detection, multiple-input–multiple-output (MIMO), spatial modulation (SM), superposition coded modulation (SCM).**

I. Introduction

Spatial modulation (SM) is a spatial multiplexing scheme in multiple-input–multiple-output (MIMO) systems [1]–[3]. In SM, the active antenna index is considered as an additional dimension to convey information. The information data are mapped not only to the traditional constellation points but also to the antenna indices in the spatial domain. The spatial multiplexing gain is therefore achieved. Moreover, rather than emitting multiple data streams simultaneously, in SM, only one selected antenna is generally active during the transmission. In the past five years, a lot of work has been done to improve the detection performance of SM. However, the *signal constellation mapping* in all these works is based on traditional schemes such as QPSK or quadrature amplitude modulation (QAM), hence leaving limited space for performance improvement.

More recently, superposition coded modulation (SCM) has been proposed in [4] and [5]. It is a coded-modulation scheme that can support high-rate transmissions, based on the superposition coding concept in information theory. Due to its close relationship to

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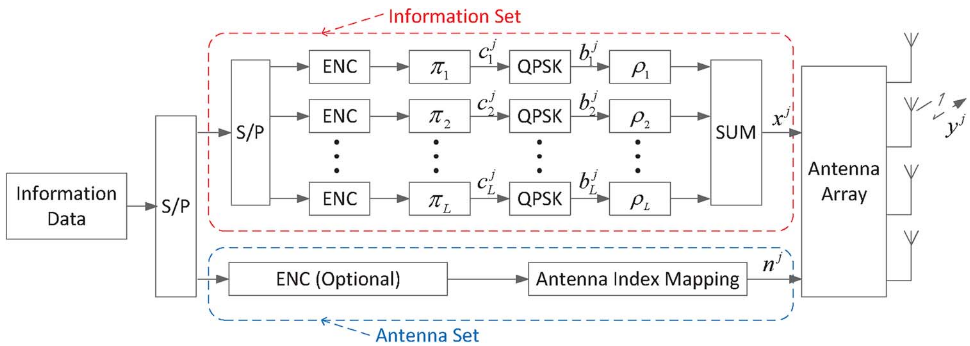

Fig. 1. Transmitter of SCM-SM scheme with four transmit antennas. π_l represents the random interleavers. The encoder is the optional component in the antenna set.

the interleave-division multiple-access (IDMA) technique, the high-performance low-complexity iterative detection algorithm originally developed for IDMA [6] is naturally applicable to SCM. Its multilayer property also makes SCM readily optimizable and suitable for adaptive modulation.

In this paper, we introduce SCM into the original SM to further improve the system performance. In the proposed SCM-SM scheme, SCM is employed in lieu of the traditional modulations in the original SM. Different from the scheme in [7] and [8], where the trellis coded modulation was used for antenna index mapping to combat the channel correlation, our focus in this paper is the application of SCM for constellation mapping in the signal domain, with the purpose of improving the bit-error-rate (BER) performance in the constrained channel condition [1]. Furthermore, for our proposed SCM-SM, we design a low-complexity detector to iteratively decode the information in the signal constellation domain and the antenna index domain. Due to the coding, interleaving, and iterative decoding involved in SCM, the proposed SCM-SM scheme is more robust against the channel estimation error caused by the unreliable initial detection of the antenna index and hence leads to better performance. Furthermore, although we only apply SCM in the signal domain, it also benefits the detection on antenna index with the proposed detector in an iterative manner. The overall performance is therefore enhanced. Analysis shows that the complexity of our proposed detector mainly depends on the number of iterations, whereas a significant performance improvement can be achieved with only a few iterations. Furthermore, the complexity of the SCM-SM detector increases only linearly with the number of layers, which indicates that the proposed SCM-SM is suitable for high-data-rate transmission with large constellation size. Simulation comparisons between our proposed SCM-SM detector and the sphere decoding (SD) detector of the original SM scheme confirm that the former is significantly lower than the latter when the data rate is high.

The remainder of this paper is organized as follows. In Section II, we present the system model of SCM-SM. In Section III, we describe the proposed iterative detector. Complexity analysis is also included in this section. Simulation results are shown in Section IV to evaluate the performance of SCM-SM. Section V provides the concluding remarks.

II. System Model

We consider a wireless MIMO system consisting of N_t transmit antennas and N_r receive antennas. The transmitter of SCM-SM is shown in Fig. 1. The source information bits are partitioned into two sets, namely, the antenna set and the information set. The bits in the antenna set are used to select the active transmit antenna for data transmission, following the approach in [1] and [2]. In the information set, SCM is employed to map the information data onto the constellation points. To generate the SCM symbol, the information bits are further partitioned into L subsequences, each of which forms one layer of the SCM signal. The data on each layer are encoded by the same encoder but followed by different interleavers, resulting in the independently permuted coded bit sequences $\mathbf{c}_l$, $(l = 1, \ldots, L)$. Then, the sequences on each layer are converted into binary antipodal signals as $0 \to 1$ and $1 \to -1$, with every two successive bits mapped onto the real and imaginary parts of one QPSK symbol, respectively. Finally, the QPSK symbols from each layer are linearly superimposed together to yield the output signal as

$$x^j = \sum_{l=1}^{L} \rho_l b_l^j, \quad j = 0, \ldots, J-1 \tag{1}$$

where J is the symbol sequence length within one data block, $b_l^j = (-1)^{c_l^{(2j)}} + i(-1)^{c_l^{(2j+1)}}$ is the jth QPSK symbol on the lth layer, and ρ_l is the corresponding weighting factor. Note that ρ_l is of great importance on the shape of the resultant constellation. For example, one can get the QAM constellation through setting the factor as

$$\rho_l = \frac{2^{l-1}}{\sqrt{\left(2\sum_{l=1}^{L}(2^{l-1})^2\right)}}. \tag{2}$$

Output symbol x^j is emitted to the wireless channel through the selected antenna. The total number of source information bits carried in one symbol is $((2L + \log_2 N_t) \cdot S)$ or $(2LS + \log_2 N_t)$, depending on whether the encoder is adopted in the antenna set or not, where S is the code rate.

Compared with the original SM [1], [2], the only difference from the transmitter of SCM-SM is that SCM is introduced to take the place of the traditional modulation scheme for signal constellation mapping. Instead of directly mapping $\log_2 M$ consecutive coded bits onto the constellation point, we superimpose L layers of weighted QPSK symbols together to form the final constellation, where $M = 2^{(2L)}$ is the constellation size. The additional operations with the SCM-SM transmitter are the serial-to-parallel conversion at the beginning and the weighted summation at the final stage, which involve very minor complexity increases.

We further use $\boldsymbol{H}$ to represent the $N_r \times N_t$ channel matrix and assume that the channel between each transceiver antenna pair experiences quasi-static Rayleigh fading during each data block. The received signal can be expressed as

$$\boldsymbol{y}^j = \boldsymbol{h}_n^j x^j + \boldsymbol{\omega}_0, \quad n \in [1, \ldots, N_t] \tag{3}$$

where $\boldsymbol{y}^j = [y_1^j, \ldots, y_{N_r}^j]$ contains the replicas of the received signal at each receive antenna, $\boldsymbol{h}_n$ is chosen from the nth column of $\boldsymbol{H}$,

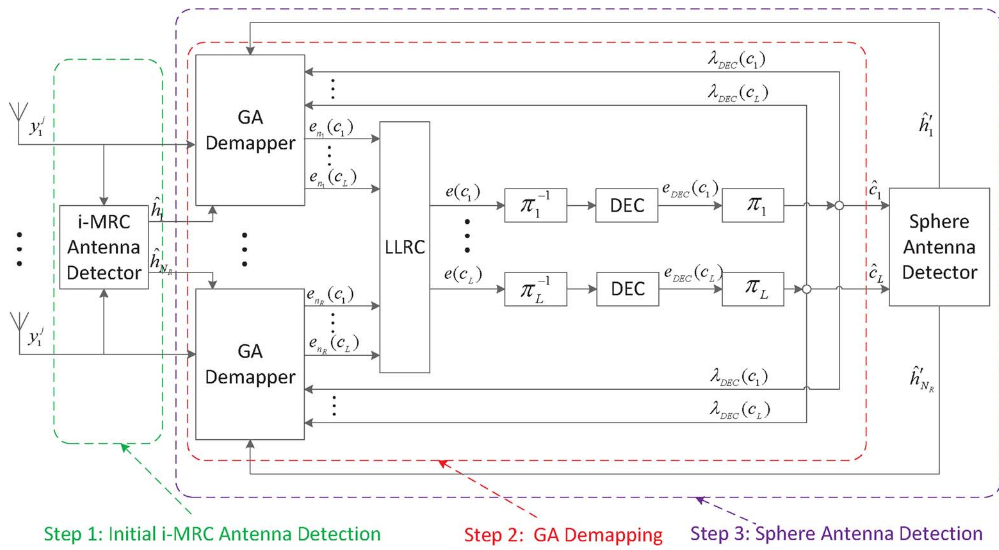

Fig. 2. Iterative detector of the SCM-SM scheme.

according to the decision from the antenna set at time j, and $\boldsymbol{\omega}_0$ is the vector containing additive white Gaussian noise.[1]

III. Proposed Detector and Complexity Analysis

A. Iterative Detector

Here, we describe the proposed detector for SCM-SM. As we focus on the detection process for one particular symbol, time index j is omitted for notational simplicity. To recover the information data, the receiver needs to estimate both the modulated symbols and the transmit antenna indices. As shown in Fig. 2, our proposed iterative detector involves three steps. In the first step, the received signal is fed into the i-Maximum Ratio Combining (i-MRC) antenna detector to get a rough initial estimation of the transmit antenna index [2]

$$\hat{n} = \underset{n\in[1,\ldots,N_t]}{\arg\max} \left\|\boldsymbol{h}_n^H \boldsymbol{y}\right\|_F \tag{4}$$

$$\hat{\boldsymbol{h}} = \boldsymbol{h}_{\hat{n}} = [h_{1,\hat{n}},\ldots,h_{N_r,\hat{n}}]^T \tag{5}$$

where $(\cdot)^H$ denotes the Hermitian transpose, and $\|\cdot\|_F$ is the Frobenius norm.

Based on $\hat{\boldsymbol{h}}$, the Gaussian approximation (GA) detector is employed in the second step to demodulate the received signal in an iterative manner [4]. The GA detector consists of N_r GA de-mappers with each one allocated to one receive antenna, L decoders, and L pairs of interleavers and de-interleavers. It operates as follows. From (3), the received signal at the n_rth receive antenna is represented as

$$y_{n_r} = \hat{h}_{n_r}\sum_{l=1}^{L}\rho_l b_l + N_0 = \hat{h}_{n_r}^l b_l + \xi_l \tag{6}$$

$$\xi_l = \hat{h}_{n_r}^{l'}\sum_{l'\neq l} b_{l'} + N_0 \tag{7}$$

$$\hat{h}_{n_r}^l = \hat{h}_{n_r}\rho_l \tag{8}$$

where ξ_l denotes the interference plus noise part with respect to the demand signal b_l on the lth layer. Note that ξ_l is the sum of $L-1$ independent sequences and the additive noise and can therefore be approximated as the Gaussian variable [4], [5]. $\hat{h}_{n_r}^l$ is the equivalent channel coefficient associated with the weighting factor ρ_l. The log-likelihood ratio (LLR) of the coded bit c_l carried by the real part of b_l is thereby computed as

$$\begin{aligned} e_{n_r}(c_l) &= \log\frac{P(y_{n_r}|c_l=0)}{P(y_{n_r}|c_l=1)} = \log\frac{P\left(y_{n_r}|b_l^{\mathrm{Re}}=+1\right)}{P\left(y_{n_r}|b_l^{\mathrm{Re}}=-1\right)} \\ &= 2\left|\hat{h}_{n_r}^l\right|^2 \frac{\left(\hat{h}_{n_r}^{l*}y_{n_r}\right)^{\mathrm{Re}} - E\left(\left(\hat{h}_{n_r}^{l*}\xi_l\right)^{\mathrm{Re}}\right)}{V\left(\left(\hat{h}_{n_r}^{l*}\xi_l\right)^{\mathrm{Re}}\right)} \end{aligned} \tag{9}$$

where $(\cdot)^{\mathrm{Re}}$ denotes the real part of variable, and $(\cdot)^*$ is the conjugate transpose. $E(\cdot)$ and $V(\cdot)$ are the mean and variance, respectively. The calculation of $E((\hat{h}_{n_r}^{l*}\xi_l)^{\mathrm{Re}})$ and $V((\hat{h}_{n_r}^{l*}\xi_l)^{\mathrm{Re}})$ can be found in [4] and [6]. Note that the LLR of the imaginary part of b_l can be obtained in a similar manner. The LLRs about c_l from each receive antenna are combined together to form the final soft output as

$$e(c_l) = \sum_{n_r=1}^{N_r} e_{n_r}(c_l). \tag{10}$$

The combined LLR $e(c_l)$ is then de-interleaved and sent to the decoders. Based on the inputs and coding rule, the decoders provide the LLR information $e_{\mathrm{DEC}}(c_l)$, which is then interleaved and fed back to the GA de-mappers to update the statistic information on c_l for the next iteration as

$$E(c_l) = \tanh\left(\frac{\lambda_{\mathrm{DEC}}(c_l)}{2}\right), \quad V(c_l) = 1 - E^2(c_l) \tag{11}$$

where $\lambda_{\mathrm{DEC}}(c_l)$ is the interleaved version of $e_{\mathrm{DEC}}(c_l)$. After a certain number of iterations, the decoders provide the hard decision on $\hat{c}_l$.

So far, we have estimated the data from both the antenna and information sets in the first two steps. However, the i-MRC detection in the first step only gives a very rough estimation of transmit antenna indices [9] and may lead to performance degradation of SCM detection in the second step due to the unreliability of $\hat{\boldsymbol{h}}$. To further improve the performance, we employ the antenna sphere decoder in the third step. The key idea of SD is to perform the maximum-likelihood (ML) detection only among the points whose Euclidean distance error is inside the defined radius R [10]–[12]. This can greatly reduce the detection complexity while at the same time maintain similar

[1]Note that in this letter, we considered the constrained channel, i.e., $\|\boldsymbol{h}_n|_F^2 = \mathcal{C}$, $\forall n\in[1,\ldots N_t]$, where $\mathcal{C}$ is a constant value. The reason is due to the i-MRC detector employed in our proposed detection algorithm, which will be introduced in detail in the following section [9].

performance with that of the conventional ML detection. Following the similar idea in [10], we have the antenna sphere detection process of our scheme with radius initialization/updating as follows:

1) Radius Initialization: $R = \sqrt{2\alpha N_r \sigma^2}$;
2) For $n = 1$: N_t
   a) For $r = 1$: N_r
      1) $d(n) += |y_r - h_{r,n}\hat{x}|$;
      2) If $d(n) \geq R$, go to (b) for the next loop;
      3) end
   b) $\widetilde{N}_r(n) = r$;
   c) If $\widetilde{N}_r(n) = N_r$, update the radius as: $R = d(n)$;
   d) end
3) $\hat{n}' = \arg\max_{n\in[1,\ldots,N_t]} d(n)$; $\hat{\boldsymbol{h}}' = \boldsymbol{h}_{\hat{n}'} = [h_{1,\hat{n}'}, \ldots, h_{N_r,\hat{n}'}]^T$.

The initial value of R is chosen as the same in [10] and [11]. $\widetilde{N}_r(n) \in [1, \ldots, N_r]$ is the number of receive antennas actually used to calculate the Euclidean distance of the nth transmit antenna. $\hat{\boldsymbol{h}}'$ is the updated channel information, which would be fed back to the GA de-mapper in the second step to redetect the transmitted signal $\boldsymbol{y}$. This procedure goes on iteratively between the second and third steps. Note that the data from the information set $\hat{x}$ have been already detected in the second step in the proposed algorithm. Therefore, the proposed SD detector is only responsible to recover the data from the antenna set, which is quite different from that in [10].

The final decisions on $\hat{x}^Q$ and $\hat{n}^Q$ are made after the Qth iteration. It is clear that there are two iterative processes in the proposed detector, i.e., the inner iteration involved in the second step and the outer iteration that works between the second and third steps.

We summarize the detection procedure of the proposed iterative detector in three steps.

Step 1) Employ the i-MRC detector in (4) to get the initial channel estimation $\hat{\boldsymbol{h}}$.

Step 2) Based on the received signal and channel estimates, obtain the demodulated data $\hat{c}_l^q$ using the iterative GA detector in (9)–(11).

Step 3) Employ the sphere antenna detector to estimate the transmit antenna index $\hat{n}^q$. If $q < Q_o$, update the channel estimate $\hat{h}^q$ according to $\hat{n}^q$ and return to Step 2. If $q = Q_o$, detection is terminated and $\hat{c}_l^Q$ and $\hat{n}^Q$ are given.

B. Complexity Analysis

Here, we analyze the complexity of SCM-SM. As previously mentioned in Section II, the complexity increase in the SCM-SM transmitter is negligible compared with that in the original SM transmitter. Therefore, our focus is on the complexity of the receiver end. Inspired by [9], we calculate the complexity of the proposed detector in terms of real multiplications. Recall that there are three steps in the proposed detector. In the first step, the complexity of the i-MRC detector is $C_{i-MRC} = N_r N_t$ [2]. The following two steps work in an iterative manner. The complexity of the GA detector and SD antenna detector after the Q_oth outer iteration can be calculated as [6], [11]

$$C_{\mathrm{GA}} = 16LN_rQ_iQ_o, \quad C_{\mathrm{SD}} = 8\sum_{q=1}^{Q_o}\sum_{n=1}^{N_t}\widetilde{N}_r(n,q) \tag{12}$$

where Q_i and Q_o denote the number of inner and outer iterations, respectively. The overall complexity of the proposed detector is

$$C_{\mathrm{SCM-SM}} = N_rN_t + 16LN_rQ_iQ_o + 8\sum_{q=1}^{Q_o}\sum_{n=1}^{N_t}\widetilde{N}_r(n,q). \tag{13}$$

By contrast, to jointly detect the antenna index and symbol, the original SD approach in SM needs to search not only the transmit antenna index but also all M points of the constellation, which has complexity

$$C_{\mathrm{SM-SD}} = 8\sum_{n=1}^{N_t}\sum_{m=1}^{M}\widetilde{N}_r'(n,m). \tag{14}$$

Comparing (13) and (14), we find that the complexity involved in the proposed detector is mainly proportional to the iteration number. Meanwhile, the complexity of the SD detector for traditional SM is mainly due to the constellation size M. We will show later in Section IV that the proposed detector can achieve good performance with only a few iterations. The complexity of the proposed detector turns out to be lower than that of the SM-SD detector as data rate increases and M becomes larger.

C. Advantages of the SCM-SM Scheme

Based on the previous discussion, four advantages of the proposed SCM-SM scheme along with the iterative detector can be obviously concluded.

1) Coding and interleaving involved in SCM make the proposed scheme more robust to the channel estimation error caused by the unreliable detection on antenna index. Furthermore, such advantage can be achieved using the algorithm proposed in [6] with very low complexity.
2) The successful detection in the signal constellation domain can help improve the detection accuracy on the antenna index, whereas the improvement on the latter may again benefit the former during iteration. The overall system performance is therefore enhanced.
3) The complexity of the SCM-SM iterative detector increases only linearly with the number of layers, which indicates its advantage in higher data rate scenario.
4) The proposed SCM-SM scheme also inherits other advantages of SCM such as the multilayer property, which makes itself readily optimizable and suitable for adaptive modulation. These features may be discussed in our future research.

IV. Simulations and Discussions

Here, we provide simulation results to evaluate the performance of the proposed SCM-SM scheme. We consider a MIMO system with $N_r = N_t = 4$. The weighting factor of SCM is $\rho_l = (2^{l-1})/(\sqrt{(2\sum_{l=1}^{L}(2^{l-1})^2)})$ to form the QAM constellation. The number of inner iterations for the proposed SCM-SM detector is $Q_i = 8$. Furthermore, as the i-MRC detector is employed for SCM-SM, we consider the constrained channel model in [1] and [2].

In Fig. 3, we first evaluate the BER performance of the two-layer SCM-SM with different numbers of outer iterations. We apply the 1/4-rate repetition code to both the information and antenna sets. The information data rate is therefore $(2L + \log_2 N_t) \cdot S = 1.5$ bits/symbol. We can see that the performance converges with only two outer iterations, which shows the high efficiency of our proposed detector. Recall that the complexity of the proposed detector depends on the number of iterations. This simulation confirms that the proposed detector comes with relatively low complexity. Based on this result, we set the number of outer iterations as $Q_o = 2$ for all other testing cases.

In Fig. 4, we compare the BER performance of the two-layer SCM-SM scheme with the original SM scheme at comparable data rates. The 1/4-rate repetition code is considered in this simulation. Note

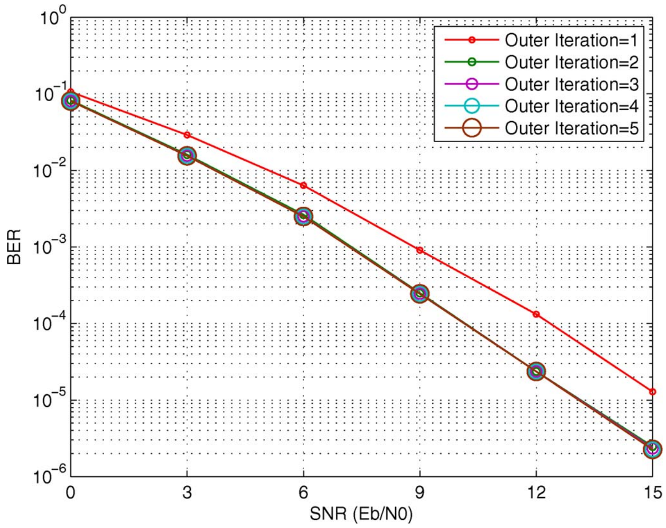

Fig. 3. BER performance of the two-layer SCM-SM with different numbers of outer iterations. The number of inner iterations is eight.

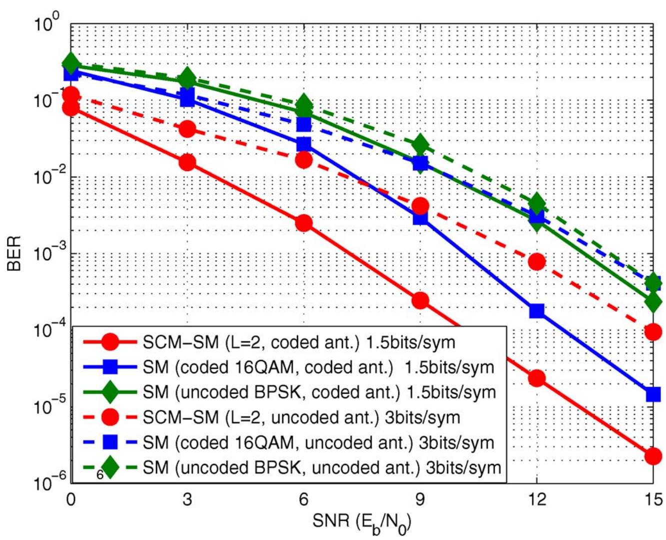

Fig. 4. BER performance comparison between the two-layer SCM-SM scheme and the original SM scheme with the same achievable information data rate.

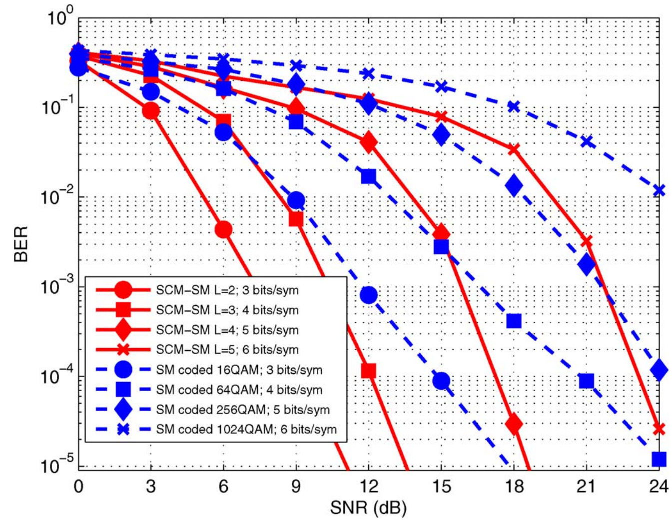

Fig. 5. BER performance of SCM-SM with different layers and SM-SD at comparable data rates. A 1/2-rate $(7, 5)_8$ convolutional code is employed in both antenna and information sets of both schemes.

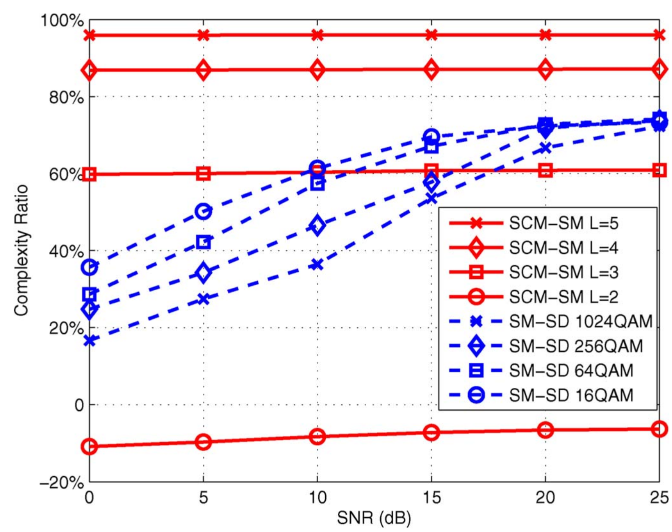

Fig. 6. Complexity comparison between SCM-SM and SM-SD with different data rates. $N_r = N_t = 4$. For SCM-SM, $Q_o = 2$ and $Q_i = 8$.

that, in both SCM-SM and original SM approaches, the source data are divided into two sets, namely, the information set and the antenna set, where the former is SCM or traditional modulated and the latter determines the active antenna. The SCM requires the information set to be coded, whereas the traditional modulated information set in the original SM scheme and the antenna set do not have to be coded. Hence, in terms of the antenna set, we have the coded and uncoded cases, whereas in terms of the information set, we consider three cases with identical data rates, i.e., SCM with $L = 2$, coded 16-ary QAM (16-QAM), and uncoded BPSK. These give rise to the six curves in Fig. 4. Note that for the coded SM scheme, to get the information data, the received signal is first demodulated through the SD detector and then decoded based on standard majority logic decoding. We can see that, in both the coded and uncoded antenna set cases, the proposed SCM-SM scheme provides the best performance, whereas the SM scheme with coded 16-QAM performs better than that with the uncoded BPSK. We also find that coding of the antenna set provides significant benefit to both the original SM scheme and the SCM-SM scheme. However, it is worth noticing that such gain is very small when uncoded BPSK is used. Hence, in the next testing case, we will only consider the original SM with the coded information set.

In Fig. 5, we show the BER performance of the SCM-SM schemes with $L = [2\ 3\ 4\ 5]$, which are matched by the SM-SD schemes with coded M-ary QAM, where $M = [16\ 64\ 256\ 1024]$. The 1/2-rate $(7, 5)_8$ convolutional code is applied to both information and antenna sets of these two schemes. Note that for the coded SM-SD scheme, Viterbi decoding with the track back length equal to four times of the constraint length is employed after demodulation. We can see that the proposed SCM-SM scheme significantly outperforms the original SM-SD scheme at any data rates. However, it is also observed that as L increases, larger SNR is required for the performance of SCM-SM to enter the "water-fall" region.

Furthermore, based on (13) and (14), we compare the complexity of these two schemes in the previous simulation. For better illustration, we plot the amount of complexity reduction of SCM-SM and SM-SD, as compared with that of the traditional ML detector for SM [9], i.e., $\Re_{\mathrm{SCM-SM}} = 1 - (C_{\mathrm{SCM-SM}}/C_{\mathrm{SM-ML}})$ and $\Re_{\mathrm{SM-SD}} = 1 - (C_{\mathrm{SM-SD}}/C_{\mathrm{SM-ML}})$, where $C_{\mathrm{SM-ML}} = 8MN_rN_t$ is the complexity of the ML SM detector. We can find in Fig. 6 that in $L = 2$ case, $\Re_{\mathrm{SCM-SM}}$ is much smaller than $\Re_{\mathrm{SM-SD}}$, indicating that the complexity of SCM-SM is much higher than that of SM-SD. Nevertheless, considering the performance gain provided by SCM-SM, such a cost may be reasonable. For the cases in which $L \geq 3$, the complexity of SCM-SM turns out to be lower than that of SM-SD. The only exception happens in the case where $L = 3$ and SNR > 11 dB, where the complexity of the former turns out to be higher than that of the latter. Such observations once again confirm that the proposed scheme is favorable in the high-data-rate scenario.

V. Concluding Remarks

In this paper, we have proposed a novel SCM-SM scheme where SCM is introduced to form the modulated signal in an SM scheme. An iterative detector with low complexity has been designed for the proposed SCM-SM scheme. We have presented the detailed detection procedure and the complexity analysis. Simulation results have confirmed that, with the proposed detector, SCM-SM performs much better than the original SM scheme with a sphere decoder. Furthermore, the complexity of the proposed scheme turns out to be even lower than that of the latter at high data rates.

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