Nonbinary Turbo-Coded Spatial Modulation over PAPR-Limited Channel
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Abstract This paper proposes a novel coded spatial modulation technique with nonbinary signaling based on a nonbinary turbo-coding approach. The aim of this work is to improve the average bit error rate (BER) performance over a peak-to-average power ratio (PAPR)-limited channel. The use of nonbinary signaling such as hexagonal quadrature amplitude modulation (HQAM), has been studied as a technique that can mitigate the PAPR. However, it is not suitable for the transmission of binary information because the number of modulation level cannot be given by a power of two, which leads to translation loss from nonbinary to binary numbers. On the other hand, generalized spatial modulation (GSM) has been proposed as an extended version of spatial modulation (SM) and it can boost the transmission rate. However, the number of modulation levels of GSM cannot be given by a power of two. This work proposes to jointly design coded spatial modulation composed of nonbinary signaling and nonbinary SM i.e., GSM, by using nonbinary turbo coding. Simulation results demonstrate the improved BER the proposed coded SM over a PAPR-limited channel.

Keywords: spatial modulation, nonbinary turbo code, peak-to-average power ratio limited channel

1. Introduction

It is essential for future wireless communications to realize bandwidth, and energy-efficient transmission. As bandwidth-efficient transmission techniques, multiple-input multiple-output (MIMO) techniques such as spatial multiplexing and space-time coding have been intensively studied. However, most MIMO systems have high power consumption due to the necessity of multiple radio frequency (RF) chains. Recently, spatial modulation (SM) has been proposed as a new type of MIMO transmission [1]. Unlike MIMO systems, the transmitter of SM activates only one transmit antenna at a given time corresponding to the transmission of information. As a result, the transmitter can be composed of only one RF chain, which leads to simplification of the transmitter. Meanwhile, the receiver of SM estimates which transmit antenna has been activated and can then decode the transmitted signal. SM can be decomposed into spatial-domain modulation, generally called space-shift keying (SSK) [2], and conventional IQ-domain modulation for example, phase-shift keying (PSK) and quadrature amplitude modulation (QAM). Thus, the transmission rate of SM depends on the number of transmit antennas and the modulation level of the IQ-domain signal. In order to boost the transmission rate with the same number of transmit antennas, generalized space-shift keying (GSSK) has been proposed as an extended version of SM, where the transmitter activates an arbitrary number of transmit antennas [3]. However, GSSK requires the same number of RF chains as activated antennas since the transmitter must activate more than one transmit antenna at a given time. Furthermore, the modulation level of GSSK cannot be a power of two, and thus, some modification is needed to transmit binary information.

To achieve higher bandwidth efficiency of SM, a higher order of modulation in the IQ-domain signal is a reasonable solution. QAM and amplitude phase shift keying (APSK) are suitable for high-order modulation, for example, 16APSK and 64QAM, from the viewpoint of minimum Euclidean distance. Generally, the bit error rate (BER) depends on the minimum Euclidean distance. Thus, square QAM such as 16QAM and 64QAM can achieve a superior BER performance to APSK and PSK signals. However, square QAM has a higher peak-to-average power ratio (PAPR) than PSK and APSK, which leads to the degradation of the power amplifier (PA) efficiency. To avoid the performance degradation caused by the nonlinearity of PA, input power backoff (IBO) is widely utilized. Several types of modulation with a low PAPR and a large Euclidean distance have been proposed, such as star-QAM. It is a well-known fact that hexago-
2. System Model

This section provides the system model of nonbinary coded SM and the PAPR-limited channel. Section 3 proposes two types of nonbinary turbo codes and discusses optimal coding structure. In Sect. 4, we apply nonbinary turbo coding to nonbinary SM and give the performances over PAPR-unlimited and limited channels. Finally, we conclude this paper.

2.1 Nonbinary coded spatial modulation

![Diagram of transmitter and receiver with nonbinary coded spatial modulation]

Fig. 1 Transmitter and receiver with nonbinary coded spatial modulation

We assume that a transmitter and receiver have \( N_t \) and \( N_r \) antennas, respectively, as shown in Fig. 1. SM can be decomposed into spatial-domain modulation called SSK and conventional IQ-domain modulation, for example PSK and QAM, which will be referred to as amplitude phase shift keying (APSK). Thus, APSK in this paper means not only APSK (star-QAM) but also PSK and QAM. The individual modulation levels in the spatial and IQ domains are assumed to be \( M_{\text{SSK}} \) and \( M_{\text{APSK}} \), respectively, and thus the total number of SM levels can be given by \( M_{\text{SM}} = M_{\text{SSK}} \times M_{\text{APSK}} \). At the transmitter, a binary information sequence \( d \in \{0, 1\}^k \) of length \( k \) is fed into the nonbinary encoder and encoded to the nonbinary codeword sequence \( c \in \{0, 1, \ldots, M_{\text{SM}} - 1\}^n \) of length \( n \). Thus, the coding rate can be calculated as \( r = k/n \) [bit/sym]. The nonbinary codeword sequence \( c \) is divided into two parts and then mapped into spatial and IQ-domain signals. In this work, \( M_{\text{SSK}} \) and \( M_{\text{APSK}} \) need not to be restricted to powers of two. Therefore, unlike conventional binary SM, nonbinary coded SM can make full use of its own ability even if the system exploits generalized SSK (GSSK) [3], SSK with nonbinary number of antennas, and/or a nonbinary APSK signal such as TPSK [8] or HQAM [4, 6]. When the transmitter with \( N_t \) antennas utilizes \( M_{\text{APSK}} \)-APSK and GSSK, where it selects two transmit antennas from \( N_t \) transmit antennas\(^1\), the modulation levels of APSK and SSK can be given by \( M_{\text{APSK}} \) and \( M_{\text{SSK}} = N_t C_2 \), respectively. In this case, if the transmitter selects the \( m_{\text{SSK}} \)-th SSK-modulated signal \((0 \leq m_{\text{SSK}} \leq N_t C_2 - 1) \) and the \( m_{\text{APSK}} \)-th APSK modulated signal \((0 \leq m_{\text{APSK}} \leq M_{\text{APSK}}) \), the transmitting symbol matrix \( x_{m_{\text{SSK}},m_{\text{APSK}}} \) \((\in \mathcal{X} \) and \(|\mathcal{X}| = M_{\text{SM}})\), which is an \( N_t \times 1 \) matrix, can be given by

\[
x_{m_{\text{SSK}},m_{\text{APSK}}} = \left[0, \ldots, s_{m_{\text{APSK}}}, \ldots, 0, \ldots, s_{m_{\text{APSK}}}, \ldots, 0\right]^T
\]

where \( s_{m_{\text{APSK}}} \) is the \( m_{\text{APSK}} \)-th APSK modulated signal and \([\cdot]^T\) denotes the transpose operator. In the case of \( N_t C_2 \) GSSK, there are two nonzero components in the transmitting symbol matrix \( x_{m_{\text{SSK}},m_{\text{APSK}}} \) since two transmit antennas are activated. If conventional SSK [1] is applied, only one transmit antenna is activated and thus there is only one nonzero component in the transmitting symbol matrix. The received signal \( y \in \mathbb{C}^{N_r \times 1} \) is expressed as

\[
y = H x_{\text{SM}} + w
\]

where \( H \in \mathbb{C}^{N_r \times N_t} \) is the fading coefficient matrix, where each element is a zero-mean, mutually uncorrelated, and circularly symmetric complex Gaussian random variable with unit variance and \( w \in \mathbb{C}^{N_r \times 1} \) is the

\(^1\)This work focuses only on GSSK with two activated antennas to keep the complexity of the transmitter low, since the transmitter requires the same number of RF chains as activated antennas.
corresponding noise sample sequence comprising a zero-mean Gaussian random variable with variance $\sigma^2$. This work assumes that the fading coefficient matrix is constant within one frame and varies independently from one frame to another. We further assume that the symbol-level synchronization at the receiver is perfect and that the channel state information (CSI) is unknown at the transmitter but is perfectly known at the receiver. At the receiver side, similar to the soft decoding for a nonbinary code [9], an SM demapper calculates a log-likelihood ratio (LLR), which is the logarithmic ratio between the symbol is equal to the codeword symbol $c_{SM}$.

The encoding and decoding for this system will be extrinsic values of the codeword sequence. The details binary there have been many analyses of the CCDF for signals can achieve good PAPR performance. Although efficient transmission power. In contrast, nonsquare QAM and PSK signals such as 18 HQAM and 16 star-APSK signals can achieve good PAPR performance. Although these have been many analyses of the CCDF for binary signals [10, 11], there have been no analysis of the CCDF for nonbinary signals. Thus, this subsection will provide CCDF performances of nonbinary signals.

The complex baseband linear modulation signal whose time scale is normalized the time scale by the symbol period is given by

$$s(\tau) = \sum_{k=-\infty}^{\infty} s_k g(k + \tau)$$

where $\tau$ is the normalized time scale, $s_k$ denotes the $k$th complex baseband signal, and $g(\tau)$ is the impulse response of the square-root raised cosine (SRRC) filter and is expressed as

$$g(\tau) = \begin{cases} 1 - \alpha + \frac{4\alpha}{\pi} \left( \frac{1}{\sqrt{1 - (\frac{4\alpha}{\pi})^2}} \right) - \frac{1}{\sqrt{1 - (\frac{4\alpha}{\pi})^2}} & \tau = 0 \\ \sin \left( \frac{\pi}{\alpha} \left( 1 + \frac{2}{\pi} \right) + (1 - \frac{2}{\pi}) \cos \frac{\pi}{\alpha} \right) + \frac{4\alpha}{\pi} \cos \frac{\pi}{\alpha} (1 + \alpha) \tau & \tau = \pm \frac{1}{2\alpha} \\ \frac{4\alpha}{\pi} \left( 1 - \frac{4\alpha}{\pi} \right) & \text{otherwise} \end{cases}$$

where $\alpha$ denotes the roll-off factor. The probability that the instantaneous power $|s(\tau)|^2$ is below a given level $z$ is given by

$$F(z, \tau) = \Pr[|s(\tau)|^2 < z]$$

In addition, the probability which exceeds the given level is

$$\Gamma(z, \tau) = 1 - F(z, \tau)$$

On the basis of the above equation, Fig. 2 shows the CCDF characteristics of the instantaneous power of the nonbinary signals of 12 PSK, 12 QAM, and 18 HQAM signals. We applied the roll-off factor $\alpha = 0.22$ to the SRRC filter. Moreover, the symbol period $J$ is equal to 18, and then the one-sided symbol length is 32. The 4+12 star-QAM (star-APSK) signal consists of two circles whose ratio between the inner radius and outer radius is given by $\sqrt{2(1 + \sqrt{3})}$ since this ratio can achieve the largest Euclidean distance. From Fig. 2, 16 QAM signal has the highest instantaneous power at CCDF $= 10^{-3}$. Compared to the square 16 QAM, 12 QAM, and 18 HQAM signals, 12 QAM and 18 HQAM signal can achieve better CCDF performances than 16 QAM signal because the constellation points of these modulations are close to the circular shape. Besides, the 4+12 star-QAM signal can further improve the CCDF performance compared to that of 12 QAM, 18 HQAM, and 16 QAM signals. Furthermore, the 12 PSK signal has the best performance since its constellation has a constant amplitude, namely, it is a circular constellation. On the basis of the above analyses, we will discuss the code design of nonbinary SM and the optimal combination of SSK and APSK in Sect. 4.

2.2 Peak-to-average power ratio limited channel

This work focuses on the coded SM over a PAPR-limited channel. Thus, this section provides the complementary cumulative distribution functions (CCDFs) of instantaneous power for several types of APSK signals. Square constellation signals such as 16 QAM signal usually have poor PAPR performance, which results in inefficient transmission power. In contrast, nonsquare QAM and PSK signals such as 18 HQAM and 16 star-APSK signals can achieve good PAPR performance. Although there have been many analyses of the CCDF for binary
This section describes the nonbinary turbo coding for nonbinary SM. For brevity of code design, we focus only on nonbinary numbers that can be decomposed into powers of two and three. For example, 18 can be decomposed as $18 = 3^2 \times 2$. From this constraint of the nonbinary numbers, in order to efficiently encode a binary data sequence to a nonbinary code sequence, the encoder should be composed of encoders with binary and ternary outputs. Thus, our proposed turbo encoder is a combination of ternary-output and binary-output convolutional encoders. Moreover, the design of the proposed nonbinary turbo encoder is based on a serial concatenated convolutional encoder, namely, a serial turbo encoder [12]. Figure 3 shows the proposed nonbinary turbo encoder and decoder.

The decoder calculates LLRs for the ternary and binary codewords $L_{ct}$ and $L_{cb}$ from the received signal using Eq. (3). Individual decoders for the BITO and BIBO encoders calculate the LLRs for the binary symbol. Thus, two soft values can be combined with a parallel-to-serial (P/S) converter to become the LLRs of the interleaved binary codeword. The LLRs are de-interleaved and fed into the BITO (outer) decoder as the input LLR of binary codeword. The BITO outer decoder calculates the soft values for binary codeword and binary information sequences. The LLRs of the binary codeword sequence are interleaved, S/P converted, and fed back to the BITO and BIBO decoders as the a priori probabilities. Thus, the decoder can operate this decoding process iteratively.

We provide two types of nonbinary turbo encoders. The only difference between them is the structure of the BITO encoder, which works as the component encoder in the inner encoder shown in Fig. 3. The BITO encoder is composed of a binary-to-ternary (B/T) converter and a rate 1 recursive ternary-input ternary-output (TTTO) encoder. The B/T converter converts a binary sequence to a ternary sequence in accordance with the conversion rule depicted in Table 1. The mapping rule given by Table 1 is a quasi-Gray mapping. According to this rule, three bits are

\[ x = x_1 x_2 x_3 \]

encoded that consists of BIBO and binary-input ternary-output (BITO) encoders. From [12], the inner and outer encoders of the serial turbo code should be nonrecursive and recursive encoders, respectively. Furthermore, a turbo code with a low-rate outer code can achieve superior performance to one with a high-rate outer code if their overall coding rates are identical.

In a similar fashion, our proposed nonbinary turbo encoder consists of low-rate nonrecursive convolutional outer encoder and high-rate recursive convolutional inner encoder. As seen in Fig. 3, a binary information sequence $d \in \{0, 1\}^k$ is encoded by a nonrecursive BIBO convolutional encoder. Then, the binary codeword sequence is interleaved and divided into two sequences that are respectively fed into the BITO and BIBO encoders. The codeword sequence encoded by the BITO encoder is the ternary sequence $c_t \in \{0, 1, 2\}^{nt}$, while the one encoded by the BIBO encoder is the binary sequence $c_b \in \{0, 1\}^{nb}$. Note that the code length of both codeword depends on the decomposed number of modulation levels of SM. For example, if the number is given by $18 = 3^2 \times 2$, the relationship between $n_t$ and $n_b$ can be expressed as $n_t = 2n_b$ since two ternary codeword symbols and one binary codeword symbol are mapped into the same spatial modulated symbol.

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\[ x = x_1 x_2 x_3 \]
converted to two ternary symbols. Therefore, the coding rate of the BITO encoder composed of the B/T converter and rate-1 TITO encoder can be given by \( r_{\text{BITO}} = 3/2 \), which is more than one. The other BITO encoder is based on a recursive BITO encoder that directly encodes binary information to a ternary codeword and can take advantage of the redundancy caused by B/T conversion. However, to the best of our knowledge, there is no rate 3/2 BITO encoder for the case of a constraint length of less than 4. As a result, we should apply a BITO encoder whose maximum coding rate is limited to less than or equal to 1 by extending the BITO encoder proposed in [8]. Therefore, the coding rate of the outer code depends on the type of BITO encoder.

| Table 1 | BT converter |
|---------|--------------|
| GF(2^2) | GF(3^2) |
| 0 0 0   | 0 0        |
| 0 0 1   | 0 1        |
| 0 1 0   | 1 0        |
| 0 1 1   | 2 0        |
| 1 0 0   | 1 1        |
| 1 0 1   | 1 2        |
| 1 1 0   | 2 1        |
| 1 1 1   | 2 2        |
| /       | 0 2        |

4. System Design over PAPR-Limited Channel

The purpose of this section is to describe our design of nonbinary turbo-coded SM (NTCSM) with good BER performance over a PAPR-limited channel. To achieve this, we will first compare two types of nonbinary turbo code proposed in Sect. 4.1 and evaluate NTCSM over a PAPR-limited channel in Sect. 4.2. In this section, we assume that both the transmitter and the receiver have four antennas and that the transmission rate is 4 bits/symbol. Thus, we exploit three types of signal combination, 4 SSK + 18 HQAM, 4\( C_2 \) SSK + 12 QAM, and 4\( C_2 \) SSK + 12 PSK, where, the individual modulation levels are identical and given by \( M_{\text{SM}} = 72 \). Note that the proposed NTCSM can be extended to cases with more transmit antennas and more receive antennas. However, if the transmitter has more than four antennas, some modification may be required. For example, when the transmitter has five antennas, some binary-pentagonal conversion or a binary-input pentagonal-output encoder is expected to be required in order to make full use of the given ability. The generalization of the modulation level should be carried out as future work.

4.1 Encoder design for nonbinary turbo coded spatial modulation

This subsection discusses which type of nonbinary turbo coding is more suitable for nonbinary SM. Recall that two types of turbo coding were proposed in Sect. 3. One is based on a B/T converter and a rate 1 TITO encoder, which will be referred to as \( \text{NTCSM type I} \). The other is based on a BITO encoder, which will be referred to as \( \text{NTCSM type II} \). A frame is composed of 3 000 pieces of binary information \( (k = 3\ 000) \). In the case where 4 SSK + 18 HQAM is utilized, the modulation levels in the spatial and IQ domains can be given by \( M_{\text{SSK}} = 4 \) and \( M_{\text{APSK}} = 18 \), while in the case where 4\( C_2 \) SSK + 12 QAM is utilized, each level can be given by \( M_{\text{SSK}} = 6 \) and \( M_{\text{APSK}} = 12 \). NTCSM type I consists of a rate 2/3 nonrecursive BIBO convolutional outer encoder and rate 1 TITO and rate 1 BIBO recursive convolutional inner encoders. As mentioned in Sect. 3, we apply a repeat-accumulate (RA) encoder as the inner TITO and BITO encoders in order to efficiently obtain the interleaver gain from the serial turbo code.

The generator matrix of the rate 2/3 BIBO outer encoder is given by \( [1 + D + D^2 + D^3, 1 + D + D^3] \) and is puncturing from rate 1/2 to rate 2/3, which is the greatest nonrecursive convolutional code with constraint length 4 [13]. Also, the generator matrices of the rate 1 recursive TITO and BITO encoders are given by \( [1/(1 + D)] \) in \( \text{GF}(3) \) and \( [1/(1 + D)] \) in \( \text{GF}(2) \), respectively. It is important to note that the rate 1 recursive TITO encoder i.e., the RA encoder in \( \text{GF}(3) \), outputs the ternary symbols with equal occurrence probabilities. Therefore, \( [1/(1 + D)] \) in the \( \text{GF}(3) \) RA code can avoid reducing the entropy of the output. On the other hand, NTCSM type II consists of a rate 4/5 BIBO nonrecursive convolutional outer encoder and rate 1 TITO and BIBO recursive convolutional inner encoders. The generator matrix of the rate 4/5 BIBO outer encoder is the same as that of NTCSM type I but the puncturing pattern is different [13]. As mentioned in Sect. 3, there are no three-bit-input two-ternary-symbol-output (BITO) encoders with a constraint length of less than 4. Thus, we must resort to the conventional BITO encoder. Moreover, from the fact that a recursive convolutional code with a large effective free distance can be made from a nonrecursive convolutional code with a large free distance [14], we utilize the recursive BITO encoder whose generator matrix is given by \( [1/(2 + 2D + D^2)] \) in \( \text{GF}(3) \). Note that a \( [2 + 2D + D^2] \) BITO encoder has a large free distance and good BER performance when ternary PSK is applied [6, 8]. The generator matrix of the BIBO recursive encoder is the same as the one in NTCSM type I. We would like to emphasize that NTCSM type I can

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1We have confirmed this fact by an exhaustive computer search.
Fig. 4 BER performances of NTCSM type I and type II exploit a lower-rate (more powerful) outer encoder than NTCSM type II. In the following evaluations, we utilize a random interleaver.

Fig. 4 shows a comparison of the BER performance between NTCSM type I and type II. In each type, the number of iterative decodings (referred to as “it” in the figures) is five, since the BER performances cannot be improved with more than five iterative decodings. Hereinafter, we will evaluate the BER performance with five iterations. Fig. 4 reveals that NTCSM type I can achieve better performance than NTCSM type II when both 4 SSK+18 HQAM and 4 C2 SSK+12 QAM are utilized, because NTCSM type I can be embedded in a more powerful outer encoder owing to the nature of B/T converter. We conclude that NTCSM should have a low-rate outer code similar to that in the serial turbo code [12].

In the following section, we exploit NTCSM type I as a nonbinary error-correcting code.

4.2 Evaluations over PAPR limited channel

This subsection discusses the performance of NTCSM over a PAPR-limited channel. As described in Sect. 2.2, individual types of APSK signals have different CCDF performances as well as different Euclidean distances, which results in different BER performances depending on the channel model, namely, whether the channel is PAPR unlimited or limited. Hereinafter, we discuss the suitable structure of NTCSMs in the cases of PAPR-limited and -unlimited channels. Firstly, we compare the proposed NTCSMs with 4 SSK+18 HQAM, 4 C2 SSK+12 QAM, and 4 C2 SSK+12 PSK with the bit-interleaved coded SMs (BICSMs) with 4 SSK+16 APSK and 4 SSK+16QAM proposed in [15] over a PAPR-unlimited channel. BICSM consists of a rate 2/3 punctured convolutional code whose generator matrix is given by $[1 + D + D^2 + D^3, 1 + D + D^3]$. It can be seen from Fig. 5 that the conventional BICSMs with 16 APSK and 16 QAM have almost the same BER performances since 16 APSK and 16 QAM have similar BER performances. On the other hand, NTCSM with $C_2$ SSK+12QAM can achieve better BER performance than the NTCSMs with 4 SSK+18 HQAM and $C_2$ SSK+12 PSK because the minimum Euclidean distance of 12 QAM is larger than those of 18 HQAM and 12 PSK. To summarize, the proposed NTCSMs can achieve better performance than BICSM at high SNR region (SNR > 11 dB). In particular NTCSM with $C_2$ SSK+12 PSK can improve the SNR by about 1.5 dB at BER=10^{-5} compared with the conventional BICSMs.

We further evaluate the proposed NTCSM over a PAPR-limited channel. The PA typically exhibits nonlinear characteristics as the signal input power approaches its saturation region. To avoid this nonlinear distortion, the PA should operate with an input power backoff (IBO), which essentially degrades the PA efficiency. In order to evaluate the effect of the incurred IBO, we introduce a soft-envelope limiter as the PA model in the following. Then, the relative IBO gain can be defined as the difference between the instantaneous powers achieving the given value of the CCDF of two different modulation schemes [16]. In the BER evaluations, we defined the hor-
izontal axis as SNR + IBO [dB]. IBO depends on the instantaneous power of the input signal, i.e., the nonlinearity of PA. In this work, the required IBO is defined as the instantaneous power that satisfies CCDF = 10^{-3} from Fig. 2. Fig. 6 reveals that the performance enhancement of the proposed NTCSM against the conventional BICSM is larger than in the case of a PAPR-unlimited channel, since the proposed NTCSM can efficiently exploit nonbinary signals with good CCDF performance. Concretely, the performance of NTCSM with 4C_{2}GSSK and 12 PSK outperforms the conventional BICSM by about 4 dB at BER = 10^{-5}. The proposed NTCSM can moreover improve the BER performance over PAPR limited channel.

5. Conclusions

In this paper, we proposed nonbinary turbo-coded spatial modulation in order to realize power-efficient transmission in terms of the PA. Furthermore, we discussed the suitable structure of nonbinary turbo coding for spatial modulation considering the PAPR. Simulation results revealed that the proposed NTCSM can achieve superior BER performance to the conventional BICSM over both PAPR-unlimited and -limited channels. As a result, our proposed system can realize power-efficient transmission.

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