Direct Sequence Spread Spectrum Generalized Code Index Modulation Postprint

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Abstract

To address the problem that code index modulation (CIM) consumes substantial pseudo noise (PN) code resources when enhancing information transmission rate by increasing the number of mapping bits, generalized code index modulation (GCIM) is proposed. At the transmitter, information bits are partitioned into mapping bits and modulation bits, which are respectively mapped to PN code group indices and modulation symbols. The in-phase and quadrature components of the modulation symbols then independently select activated PN code groups for spreading. By increasing the number of activated PN codes per transmission time slot, the number of mapping bits can be increased, thereby improving both spectral efficiency and energy efficiency of the system. Simulation results show that at the same spectral efficiency, this scheme incurs a bit error rate performance penalty of approximately 2 dB in Gaussian channels and about 1 dB in Rayleigh fading channels compared to CIM; however, GCIM consumes significantly fewer PN code resources.

Full Text

Preamble

Generalized Code Index Modulation Based on Direct Sequence Spread Spectrum

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Abstract: Code index modulation (CIM) consumes substantial pseudo-noise (PN) code resources when increasing the number of mapping bits to enhance information transmission rate. To address this problem, this paper proposes a novel generalized code index modulation (GCIM) scheme. At the transmitter, information bits are divided into mapping bits and modulation bits, which are mapped to the indices of PN code groups and modulation symbols, respectively. The in-phase and quadrature components of the modulation symbol then select activated PN code groups for spreading. By increasing the number of activated PN codes per transmission slot, the number of mapping bits can be increased, thereby improving the spectral efficiency and energy efficiency of the system. Simulation results demonstrate that at the same spectral efficiency, the proposed GCIM scheme exhibits a bit error rate (BER) performance loss of approximately 2 dB in additive white Gaussian noise (AWGN) channels and about 1 dB in Rayleigh fading channels compared to CIM. Nevertheless, GCIM consumes significantly fewer PN code resources.

Keywords: high data rate; energy efficiency; generalized code index modulation; code index modulation

0 Introduction

Direct sequence spread spectrum (DSSS) technology has been widely applied in personal communication networks, wireless local area networks, satellite communications, third-generation mobile communications, and military communications due to its excellent anti-interference and anti-multipath performance, good concealment, easy code division multiple access (CDMA) implementation, and high direct-sequence communication rates. However, DSSS typically occupies a large bandwidth and suffers from low spectral efficiency. Index modulation techniques address this by mapping partial information bits to specific indices (values) that are implicitly transmitted with the modulation signal, thereby improving efficiency without consuming additional energy.

Building upon DSSS, code index modulation (CIM) adds PN code indices to the transmission scheme. At the transmitter, information bits are partitioned into mapping bits and modulation bits, which are mapped to PN code indices and modulation symbols, respectively. The in-phase and quadrature components of the modulation symbol then select activated PN codes for spreading before transmission. Since mapping bits are implicitly transmitted through the indices of specific PN codes, the spectral efficiency and energy efficiency of spread spectrum communication are effectively enhanced. However, as CIM attempts to further increase the information transmission rate by adding more mapping bits, it consumes a large number of PN code resources.

Multi-level spread spectrum schemes directly map information bits to specific PN codes for transmission. Since information is conveyed solely through mapping bits without modulation bits, both the information transmission rate and bandwidth efficiency are relatively low. Parallel combinatory spread spectrum improves upon multi-level spread spectrum by dividing information bits into two parts: one part maps to a PN code group, while the other maps to the phase information (in-phase or anti-phase) of each PN code within the group. By transmitting multiple PN codes in parallel within one transmission slot and utilizing the phase information of each code, this approach effectively improves PN code utilization and information transmission rate.

This paper introduces the concept of parallel combinatory spread spectrum into code index modulation and proposes generalized code index modulation (GCIM). In a single transmission slot, the mapping bits for either the in-phase or quadrature component can map to a PN code combination rather than a single PN code. With the same total number of PN codes, GCIM can transmit more mapping information bits, thereby improving the system' s information transmission rate and bandwidth utilization. The paper first compares PN code resource usage between GCIM and CIM at the same spectral efficiency, then verifies the BER performance of the proposed scheme through simulation and compares it with CIM.

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1 Transmitter Model

The GCIM transmitter model is illustrated in [Figure 1: see original paper]. The transmitter employs M-ary phase shift keying (MPSK) modulation. Assume the system uses N PN codes, with u codes activated per transmission slot on either the in-phase or quadrature branch, which can generate $\binom{N}{u}$ combinations. According to combinatorial principles, the number of combinations used must be a power of two to completely map all states of the transmitted information bits. Therefore, $c = \lfloor \log_2 \binom{N}{u} \rfloor$, where c represents the number of mapping bits on either the in-phase or quadrature branch. The PN code combinations are denoted as $\mathbf{W}_j = [W_{j,1}, W_{j,2}, \dots, W_{j,L}]^T$, where $j = 1, 2, \dots, L_c$, L_c represents the code length of the PN code group, and T_c is the chip duration.

The number of bits transmitted per slot is $n = c + m$, where m denotes the number of modulation bits and satisfies $m = \log_2 M$. Consequently, the division of the data block $\mathbf{d}_i$ for the i-th transmission slot is as shown in (1):

$$\mathbf{d}_i = [\ \underbrace{d_{I,i}, d_{Q,i}}_{\text{mapping bits}}\ ,\ \underbrace{d_{\text{Mary},i}}_{\text{modulation bits}}\ ]$$

where $d_{I,i}$ and $d_{Q,i}$ represent the in-phase and quadrature PN code mapping blocks, respectively, each of length c; $d_{\text{Mary},i}$ denotes the modulation mapping block of length m, which is baseband-modulated into the modulation symbol x_i as shown in (2):

$$x_i = a_i + jb_i$$

where a_i and b_i represent the real and imaginary parts of the modulation symbol, respectively.

The transmitted signal $y(t)$ can thus be expressed as:

$$y(t) = \sum_{i=0}^{L-1} \sum_{k=1}^{u} \left[a_i W'_{I,k,i} p(t - iLT_c - kT_c) \cos(2\pi f_0 t) + b_i W'_{Q,k,i} p(t - iLT_c - kT_c) \sin(2\pi f_0 t) \right] \tag{3}$$

where $W'_{I,k,i}$ and $W'_{Q,k,i}$ represent the PN code combinations after mapping by $d_{I,i}$ and $d_{Q,i}$, respectively; $d_{I,i}$ and $d_{Q,i}$ denote the index values of the PN code groups; L represents the number of transmission slots; B is the code group length; f_0 is the carrier frequency; $p(t)$ is the rectangular pulse shaping function; and T_c is the chip duration.

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2 PN Code Group Mapping Method

Both the in-phase and quadrature PN code mapping sections in the proposed scheme require index table lookup to select the activated PN code groups. Since the principles are identical for both branches, only the in-phase branch is elaborated here.

Assume the system uses $N = 5$ PN codes, and the in-phase branch activates $u = 2$ PN codes per transmission slot. This configuration can generate $\binom{5}{2} = 10$ combinations. Therefore, the system can map $c = \lfloor \log_2 \binom{5}{2} \rfloor = 3$ information bits. The PN code group index table is shown in .

** PN Code Group Index Table**

In-phase PN Code Mapping Block ($d_{I,i}$)	PN Code Group Index (Number)
000	$w_1 + w_2$
001	$w_1 + w_3$
010	$w_1 + w_4$
011	$w_1 + w_5$
100	$w_2 + w_3$
101	$w_2 + w_4$
110	$w_2 + w_5$
111	$w_3 + w_4$

Since the number of combinations used must be a power of two to completely map all states of the transmitted information bits, $2^c = 8$ combinations are utilized, represented as $\mathbf{W}_j$ for $j = 1, 2, \ldots, 8$, where L_c represents the code length of the PN code group and T_c is the chip duration.

3 Receiver Model

The GCIM receiver model is shown in [Figure 2: see original paper]. Due to the random nature of wireless channels, the transmitted signal may experience fading before reaching the receiver. Therefore, the received signal can be expressed as:

$$r(t) = h(t) * y(t) + n(t)$$

where $h(t)$ represents the channel coefficient; $*$ denotes convolution; and $n(t)$ is additive white Gaussian noise with mean 0 and variance $N_0/2$. The analysis assumes flat Rayleigh fading and ideal channel state information (CSI) available at the receiver.

Since the in-phase and quadrature branches have similar structures at the receiver, only the in-phase branch is analyzed below. After ideal carrier recovery, the baseband signal of the in-phase branch can be expressed as:

$$r_I(t) = \sum_{j=1}^{u} \sum_{i=0}^{L-1} \left[h_i a_i W_{I,k,i} p(t - iLT_c - kT_c) \right] + n_I(t)$$

where $n_I(t)$ represents the additive white Gaussian noise on the in-phase branch.

The signal then undergoes parallel correlation operations with N_c PN code groups, with summation over one symbol period LT_c. Consequently, the output of the j-th branch in the i-th slot of the in-phase branch can be expressed as:

$$R^I_{i,j} = \sum_{k=1}^{L_c} \hat{h}_{i,k} \hat{W}_{j,k} + n^I_{i,j} \tag{6}$$

Equation (6) can be further expressed as:

$$R^I_{i,j} = \begin{cases} \pm\sqrt{E_p} + v_{i,j}, & \hat{W}_j = W'_{I,i} \\ v_{i,j}, & \hat{W}_j \neq W'_{I,i} \end{cases} \tag{7}$$

where $E_p = \sum_{k=1}^{L_c} \hat{h}^2_{i,k}$ represents the energy of the in-phase PN code group; the first term indicates the sum of energies from identical PN codes when the transmitter’ s PN code group contains the same codes as the j-th branch PN code group; $v_{i,j}$ represents noise; and $\hat{h}_i$ denotes the channel coefficient for the i-th transmission slot.

The absolute values of the N_c branch outputs are then compared to identify the maximum:

$$\hat{J}_i^I = \arg \max_{j \in \{1,2,\ldots,N_c\}} |R_{i,j}^I|$$

where $\hat{J}_i^I$ represents the detected index of the PN code group on the in-phase branch. Similarly, the quadrature branch PN code group index $\hat{J}_i^Q$ is detected. The output values corresponding to these indices are despread to obtain the real part $\hat{a}_i$ and imaginary part $\hat{b}_i$ of the modulation symbol. After demodulation, the modulation information bits $d_{\mathrm{Mary},i}$ are obtained. Subsequently, $\hat{J}_i^I$ and $\hat{J}_i^Q$ are used to demap the information bits $d_{I,i}$ and $d_{Q,i}$ through reverse index table lookup. Finally, parallel-to-serial conversion yields the information bits $\hat{d}_i$.

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4 Analysis and Simulation

This section analyzes the index resources of GCIM and validates its performance through Monte Carlo simulation, comparing it with the CIM scheme. The PN codes used are 64-bit Walsh codes. Two channel environments are considered: additive white Gaussian noise (AWGN) channel and flat Rayleigh fading channel. The fading channel has a Doppler shift of 160 Hz and an average channel gain of 0 dB. The signal-to-noise ratio (SNR) in the simulation figures denotes E_b/N_0, where E_b represents the signal energy per modulation bit within a transmitted symbol. The main parameters for each simulation figure are listed in the lower-left corner, representing from left to right: scheme name, baseband modulation order, number of PN codes used in the scheme, and number of PN codes used per slot on the in-phase or quadrature branch.

PN Code Resource Usage Comparison: [Figure 3: see original paper] compares PN code resource usage among GCIM($u = 2$), GCIM($u = 3$), and CIM schemes when transmitting the same number of bits, with all schemes employing 4PSK modulation. At a spectral efficiency of 12 bit/s/Hz, CIM requires 32 PN codes, whereas GCIM($u = 2$) requires only 9 PN codes and GCIM($u = 3$) requires only 7 PN codes. When spectral efficiency increases to 14 bit/s/Hz, CIM requires 64 PN codes, while GCIM($u = 2$) requires 12 PN codes and GCIM($u = 3$) requires 9 PN codes. Therefore, at the same spectral efficiency, GCIM utilizes significantly fewer PN code resources than CIM, and this advantage becomes more pronounced as spectral efficiency increases and the number of PN codes u activated per slot on the in-phase or quadrature branch grows.

BER Performance in AWGN Channel: [Figure 4: see original paper] presents the BER performance of GCIM and CIM in AWGN channels under different parameter configurations. Curves and both achieve a spectral efficiency of 8 bit/s/Hz. GCIM uses 3 fewer PN codes than CIM, but exhibits a performance degradation of approximately 2 dB at a BER of 10^{-5} in AWGN channels. Curves and both achieve a spectral efficiency of 10 bit/s/Hz. GCIM uses 9 fewer PN codes than CIM, but shows a performance loss of about 2 dB at a BER of 10^{-5} in AWGN channels. By increasing the modulation order in both schemes, curves and achieve a spectral efficiency of 9 bit/s/Hz. GCIM uses 3 fewer PN codes than CIM, with a performance degradation of approximately 2 dB in AWGN channels and about 1 dB in Rayleigh fading channels at a BER of 10^{-5}.

BER Performance in Rayleigh Fading Channel: [Figure 5: see original paper] shows the BER performance in flat Rayleigh fading channels. The parameter configurations for curves with identical numbers are the same as in [Figure 4: see original paper], differing only in the simulation environment. The results demonstrate that whether in AWGN or Rayleigh fading channels, GCIM achieves lower BER when increasing spectral efficiency by adding PN codes compared to increasing modulation order. This is because increasing the number of PN codes does not reduce the Euclidean distance between modulation symbols, whereas increasing modulation order significantly decreases this distance.

High Spectral Efficiency Comparison: [Figure 6: see original paper] and [Figure 7: see original paper] compare GCIM($u = 2$) with CIM at a spectral efficiency of 12 bit/s/Hz in AWGN and flat Rayleigh fading channels, respectively. Curves with identical numbers share the same parameter configurations. Curve represents GCIM with two PN codes transmitted in parallel per slot on the in-phase or quadrature branch. Compared with curve (CIM), the performance difference is slightly more than 2 dB at a BER of 10^{-5} in AWGN channels and about 1 dB in Rayleigh fading channels, but GCIM saves 23 PN codes. Curve represents GCIM with three PN codes transmitted in parallel per slot. Comparison between curves and reveals that in AWGN channels, the performance difference is approximately 4 dB at a BER of 10^{-5}, while in Rayleigh fading channels, the difference is about 2 dB at a BER of 10^{-5}, but with a saving of 25 PN codes. Thus, as the number of PN codes u transmitted in parallel per slot on the in-phase or quadrature branch in GCIM increases, the number of required PN codes decreases continuously, albeit with a slight degradation in BER performance.

Furthermore, when GCIM and CIM use the same number of PN codes, GCIM achieves significantly higher spectral efficiency. Assuming the energy transmitted per modulation bit within a modulation symbol is E_b, the average transmission energy consumed per information bit decreases as more information bits are added through PN code mapping. Consequently, the transmission energy efficiency of GCIM is superior to that of CIM. The trade-off, of course, is a slight degradation in BER performance.

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5 Conclusion

This paper proposes generalized code index modulation (GCIM) based on code index modulation combined with parallel combinatory spread spectrum concepts. In a single transmission slot, the mapping bits for either the in-phase or quadrature component can map to a group of PN codes, increasing the number of mapping bits and effectively improving PN code utilization and information transmission rate. Comparative analysis demonstrates that at the same bandwidth efficiency, GCIM uses fewer PN code resources than CIM, with the advantage becoming more significant as bandwidth efficiency increases. Simulation results show that at the same spectral efficiency, GCIM exhibits approximately 2 dB performance degradation compared to CIM in Gaussian channels at a BER of 10^{-5}. Additionally, as the number of activated PN codes u per transmission slot in GCIM increases, the PN code resource savings relative to CIM become more substantial, though accompanied by slight BER performance degradation. Since this study only considers relatively ideal Gaussian and flat Rayleigh fading channels in the simulation process, while actual communication scenarios often involve more complex conditions such as multipath Rayleigh fading and multi-user interference, the analysis of GCIM' s BER performance under these conditions and the improvement of demodulation algorithms will be the focus of future research.

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Note: Figure translations are in progress. See original paper for figures.