

Article

A Cyclic-Shift Code Index Modulation Scheme Based on Fast Cyclic-Correlation Detection

Rui Ding, Bo Qian *, Yongxin Feng * and Zichao Chen

School of Information Science and Engineering, Shenyang Ligong University, Shenyang 100159, China; dingrui@stu.sylu.edu.cn (R.D.); 2503620510@stu.sylu.edu.cn (Z.C.)

* Correspondence: qianbo@syu.edu.cn (B.Q.); fengyongxin@syu.edu.cn (Y.F.)

Abstract

Code Index Modulation (CIM) schemes usually rely on large orthogonal spreading codebooks to improve their index-carrying capability, resulting in high codebook resource consumption and a rapidly increasing receiver-side detection complexity. To address this problem, this paper proposes a Cyclic-Shift Code Index Modulation (CSCIM) scheme based on fast cyclic-correlation detection. Unlike conventional CIM, which carries information through the codebook indices of multiple independent spreading codes, CSCIM transforms the index-bearing mechanism from multi-code selection into cyclic-shift state selection of a single spreading code. At the transmitter, index bits control the cyclic-shift offset of a single spreading code to generate candidate index states. A composite frame structure consisting of a Zadoff–Chu (ZC) synchronization header and spread-spectrum data blocks is designed to eliminate code-offset ambiguity during fast correlation acquisition. At the receiver, an FFT-based fast cyclic-correlation mechanism obtains full-shift-domain correlation peaks through a single detection path, and the index information is recovered from the detected peak position. A local spreading code with the corresponding cyclic-shift phase is then generated to complete despreading and symbol decision. The simulation results show that CSCIM exhibits a stable BER reduction trend over both AWGN and flat Rayleigh fading channels, and maintains effective data-detection performance under high-order index configurations. The proposed CSCIM scheme requires only one spreading code sequence to generate all candidate spreading codes, effectively reducing the codebook resource consumption and receiver-side detection complexity while maintaining a competitive BER performance.

Keywords: cyclic-shift Code Index Modulation; Code Index Modulation; correlation peak position detection; spread-spectrum communication; FFT

Received: 6 June 2026

Revised: 6 July 2026

Accepted: 9 July 2026

Published: 9 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

With the rapid development of sixth-generation (6G) mobile communication networks, satellite communications, and the Internet of Things (IoT), wireless communication systems are evolving toward high reliability, low power consumption, and high spectral efficiency [1,2]. In complex electromagnetic environments, interference resistance, reliable transmission, and efficient resource utilization have become key objectives in physical-layer design. Direct-Sequence Spread Spectrum (DSSS) has long played an important role in both civilian and military communications because of its strong anti-jamming capability and low probability of interception, particularly in narrowband-interference and

harsh-channel scenarios [3,4]. However, conventional DSSS schemes generally obtain processing gain at the cost of spectral efficiency, which makes them less suitable for modern high-data-rate communication systems [5].

Index Modulation (IM) provides a new technical approach for overcoming the performance bottlenecks of conventional modulation techniques under fixed bandwidth and power constraints [6,7]. By exploiting the indices of resource units such as spreading codes, active antennae, or subcarriers, IM can carry additional information bits without extra energy consumption or bandwidth expansion [8,9]. Among various IM variants, CIM is naturally compatible with DSSS systems [10]. In CIM, spreading-code sequences are used as index resources. The input bit stream is divided into symbol bits and index bits, where the index bits are mapped to the index of a specific spreading code for transmission, and the symbol bits are modulated and then multiplied by the selected spreading code [11]. This integration preserves the anti-jamming advantage of DSSS while significantly improving spectral efficiency and energy efficiency.

Subsequent studies have extensively investigated the CIM performance and applications. The existing works can be broadly summarized into three directions: code-domain dimension expansion, cross-domain joint modulation, and the optimization of codebook resources and detection complexity. In code-domain dimension expansion, researchers improve spectral efficiency by relaxing the single-code activation constraint [12]. For example, Generalized CIM (GCIM) improves the data rate, throughput, and energy efficiency by generalizing bit partitioning and candidate spreading-code selection [13]. Quadruple CIM (QCIM) further extends the transmission-rate boundary through multi-code index reuse within a single transmission [14]. In cross-domain joint modulation, CIM is combined with Multiple-Input Multiple-Output (MIMO), Spatial Modulation (SM), and related techniques [15]. Through the joint mapping of code indices, antenna indices, and modulation symbols, these schemes further improve the data rate without additional hardware cost. CIM-assisted Quadrature Spatial Modulation (CIM-QSM) greatly expands the signal constellation space by performing index mapping simultaneously in the code and spatial domains [16]. Code Index Modulation-aided Spatial Media-Based Modulation (CIM-SMBM) further introduces the channel-state index used in media modulation [17]. Joint Code Index Modulation-aided Enhanced Spatial Modulation (JCIM-ESM) embeds CIM into an enhanced spatial modulation framework and improves the code utilization and data rate through joint code selection [18]. However, the above schemes usually require large-scale orthogonal codebooks. To address this issue, studies on codebook resource and detection-complexity optimization have been conducted. The multidimensional invisible-data CIM (MID-CIM) scheme reduces the dependence on orthogonal codes by exploiting the polarity and positional features of pseudo-code sequences [19]. Bit-Activated CIM (BA-CIM) selects and superimposes pseudo-codes according to the activation state of the index bits, thereby reducing pseudo-code resource consumption and improving overall performance [20].

In addition, cyclic shifts, code phases, and delay positions have also been widely used in studies related to spread-spectrum modulation and index transmission. Dillard et al. proposed Cyclic Code Shift Keying (CCSK), in which information is carried by the cyclic-shift position of a pseudo-random spreading code to realize low-probability-of-intercept communication [21]. In recent years, CCSK has been further combined with channel coding and high-data-rate GNSS links to improve the data rate, robustness, and implementation efficiency of spread-spectrum communications [22]. In another class of position-index modulation studies, delay-domain or delay-Doppler-domain resource units can also be used to carry index bits, thereby improving the reliability and spectral efficiency of modulation schemes for high-mobility scenarios such as OTFS [23]. Meanwhile, physical-layer anti-jamming studies in complex electromagnetic environments have begun to introduce

intelligent recognition methods. For example, the CGAN-CNN few-shot jamming-signal recognition framework proposed by Ding et al. provides a new technical approach for interference awareness and anti-jamming decision-making [24]. These studies indicate that exploiting the code phase, cyclic shift, delay position, or intelligent sensing mechanisms is valuable for improving spread-spectrum communication and anti-jamming performance. However, these works mainly focus on shift-keying modulation, delay-domain indexing, or interference recognition, and have not yet been investigated within the CIM framework.

Despite these advances, existing CIM schemes and their variants still have several limitations in practical engineering applications. First, to support high data rates while maintaining reliable communication performance, most CIM schemes require a large number of mutually orthogonal or quasi-orthogonal spreading codes, such as Walsh codes, to carry different index information. This requirement is difficult to satisfy under the limited pseudo-code resource allocation in practical systems [25]. Second, a large codebook requires the receiver to perform correlation matching over a large number of candidate spreading codes, which causes the detection complexity to increase with the codebook size and severely limits practical deployment. In addition, most existing low-complexity detection methods are designed for spatial modulation or MIMO scenarios and are difficult to directly transfer to code-domain index detection [26]. Finally, practical communication systems require robust synchronization mechanisms, but most existing CIM studies are conducted under the assumption of ideal synchronization and rarely discuss the effects of timing errors and frame-start offsets [27].

Based on the above discussion, this paper proposes a CSCIM scheme to address the excessive spreading-codebook consumption and high receiver-side detection complexity of CIM. The proposed scheme redefines the representation of index resources in CIM. Conventional CIM maps index bits to the identities of different spreading codes, whereas CSCIM maps index bits to the cyclic-shift states of a single spreading code, thereby transforming multi-code selection into shift-state selection. At the receiver, only one correlation path is required to determine the correlation-peak position and recover the index information. Thus, CSCIM changes the way in which codebook resource consumption and receiver-side detection complexity increase with the index order in conventional CIM. The main contributions of this paper are summarized as follows:

(1) A CSCIM code-index mapping mechanism based on cyclic shifts of a single spreading code is proposed. In this mechanism, index bits are mapped to the cyclic-shift offsets of a single spreading code, so that candidate index states are generated by different cyclic shifts of the same spreading code. CSCIM transforms the code-domain index-bearing mechanism from multi-code selection into single-code shift-state selection, thereby reducing the demand for independent spreading-code resources under high-order index configurations.

(2) A full-shift-domain fast correlation-peak detection method is designed for CSCIM. Instead of configuring parallel correlators for multiple independent spreading codes, the receiver uses FFT/IFFT-based fast cyclic correlation to obtain the full-shift-domain correlation response between the received data and the local reference spreading code in a single operation. The maximum correlation-peak position is then detected within the predefined shift set to recover the index information. This method makes the receiver-side multiplication complexity dominated by FFT/IFFT operations rather than by the size of an independent spreading-codebook.

(3) A composite frame structure suitable for cyclic-shift index recovery is constructed, and the necessity of the synchronization mechanism is verified. Since a receive-window offset is equivalent to a change in the cyclic-shift offset of the spreading code, it may cause index misdetection. Therefore, a ZC synchronization header is introduced to provide a

frame-start reference at the receiver and to avoid the cyclic-shift acquisition ambiguity caused by the misaligned extraction of spread-spectrum data blocks.

The remainder of this paper is organized as follows: Section 2 introduces the principle of CIM. Section 3 presents the system model of the proposed CSCIM scheme, including the frame structure, transmitter mapping rules, and receiver detection mechanism. Section 4 evaluates the BER performance, synchronization effectiveness, robustness under practical channel impairments, computational complexity, effective throughput, and the impact of index order. Section 5 concludes the paper and outlines future research directions.

2. Models of the CIM Communication System

Traditional DSSS employs high-rate pseudo-random (PN) code sequences to spread the transmitted signal. To improve the transmission rate of DSSS without sacrificing the spreading gain, CIM was proposed. CIM preserves the basic DSSS architecture while dividing the transmitter bit stream into modulation bits and index bits. The transceiver structure of a conventional CIM system is shown in Figure 1.

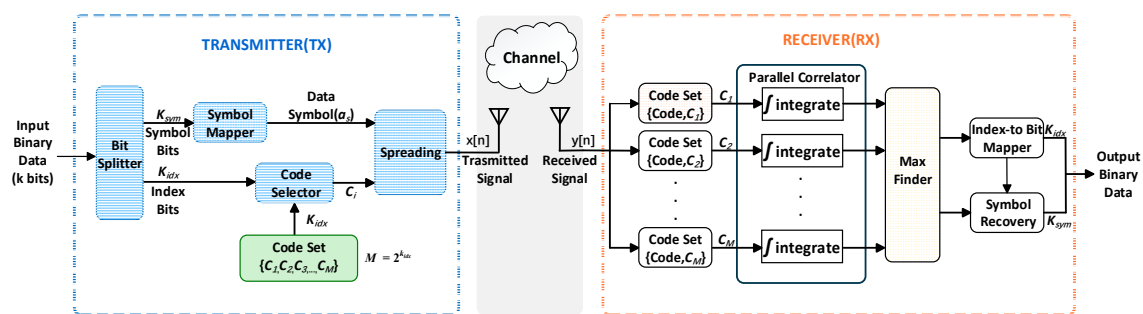


Figure 1. Block diagram of a conventional CIM system.

Assume that the CIM system transmits K_b information bits within one symbol period, among which k_{sym} bits are used as conventional modulation bits and k_{idx} bits are used as index bits, i.e., $K_b = k_{sym} + k_{idx}$. The index bits k_{idx} are used to select one active spreading code $c_q(t)$ from a mutually orthogonal spreading codebook of size $M = 2^{k_{idx}}$, denoted as $\mathcal{C} = \{c_1(t), c_2(t), \dots, c_M(t)\}$. The conventional modulation bits are mapped to a modulation symbol s through modulation schemes such as BPSK or QPSK. The transmitted spread-spectrum signal can then be expressed as

$$x(t) = \sqrt{P_s} \cdot s \cdot c_q(t) \quad (1)$$

where $x(t)$ is the transmitted spread-spectrum signal, P_s is the transmit power, s is the conventional modulation symbol, and $c_q(t)$ is the selected q -th spreading-code sequence.

At the receiver, considering additive white Gaussian noise (AWGN) and channel fading, the received signal can be expressed as

$$y(t) = h(t) \cdot x(t) + n(t) \quad (2)$$

where $y(t)$ is the received signal, $h(t)$ is the channel fading coefficient, and $n(t)$ is the additive white Gaussian noise.

CIM receivers usually employ maximum likelihood detection or correlation detection. To recover the index q , the receiver correlates $y(t)$ with each candidate spreading code in the codebook. The output of the j -th correlator can be expressed as

$$R_j = \int_0^{T_s} y(t) \cdot c_j^*(t) dt, j = 1, 2, \dots, M \quad (3)$$

where R_j is the output of the j -th correlator, T_s is the symbol period, $c_j(t)$ is the j -th local spreading code, and $(\cdot)^*$ denotes complex conjugation. If the spreading code is a real-valued bipolar sequence, then $c_j^*(t) = c_j(t)$.

The active spreading-code index is then estimated by comparing the output energies of all correlators and selecting the index corresponding to the maximum value:

$$\hat{q} = \arg \max |R_j|^2, j \in \{1, \dots, M\} \quad (4)$$

The local spreading-code sequence is determined according to the estimated active-code index $\hat{q}$, and the implicitly transmitted index data are recovered through inverse mapping. Finally, the conventional modulation data are demodulated using the despread signal corresponding to the maximum correlation peak.

Although CIM transmits additional information through pseudo-code indices, in practical communications, such as systems using Walsh codes or m -sequences, the number of strictly orthogonal or quasi-orthogonal sequences is strictly limited by the spreading gain and the sequence length L . As the demand for spectral efficiency increases, orthogonal code resources are rapidly exhausted. However, using code sequences with poor cross-correlation may lead to severe inter-code interference (ICI). Moreover, as the index order increases, the number of parallel correlators at the receiver also increases sharply, resulting in a prohibitive system complexity and computational cost. Therefore, CIM faces an inherent tradeoff between the data rate and receiver-side complexity.

3. CSCIM Scheme Design and Transmission Mechanism

The analysis in Section 2 shows that CIM carries index information by selecting different spreading codes. Although this improves the spectral efficiency, it also introduces codebook resource consumption and increases the complexity of multi-branch correlation detection. To address these problems, this paper proposes the CSCIM scheme, whose schematic diagram is shown in Figure 2.

Unlike CIM, which relies on a large orthogonal codebook for index activation, CSCIM uses different cyclic-shift offsets of a single spreading code to carry additional index information, thereby significantly reducing the codebook resource requirement. Meanwhile, with frequency-domain FFT/IFFT operations, the receiver can simplify the parallel correlator array into a single fast cyclic-correlation detection path. Following the signal-processing flow of the system, this section introduces cyclic-shift codebook generation and transmitter-side signal generation, composite frame structure design, and receiver synchronization and information recovery.

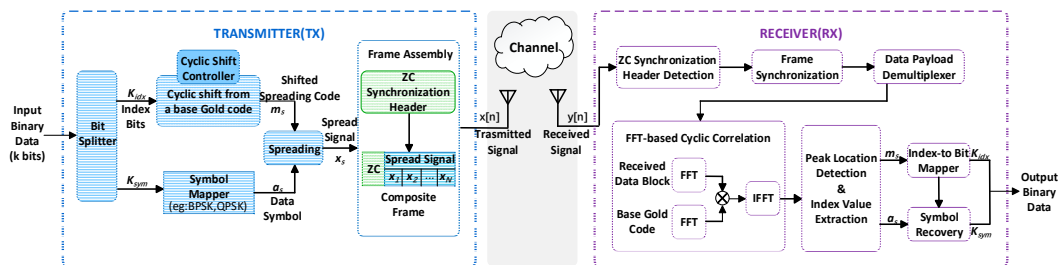


Figure 2. Schematic diagram of the proposed CSCIM scheme.

3.1. Cyclic-Shift Codebook Generation and Transmitter Signal Generation

The main tasks of the CSCIM transmitter include cyclic-shift codebook generation, mapping from index bits to cyclic-shift offsets, and mapping from symbol bits to baseband modulation symbols. Therefore, following the transmitter signal-processing order, this

section introduces cyclic-shift codebook generation, index-bit mapping, symbol mapping, and baseband signal spreading.

3.1.1. Cyclic-Shift Codebook Generation

In CIM, to transmit k_{idx} index bits, the transmitter must store and generate $M = 2^{k_{idx}}$ mutually orthogonal independent spreading codes. In the proposed CSCIM scheme, the transmitter only needs to retain one spreading code with favorable autocorrelation and cyclic-shift properties, such as a Gold code, and then generate candidate spreading codes through cyclic shifts at different offsets. In this way, the index information is transformed from multi-code selection in CIM into shift-offset selection in CSCIM. This preserves the spread-spectrum structure while significantly reducing the codebook size. Once the receiver estimates the relative shift offset, the corresponding index information can be recovered.

Specifically, let a bipolar spreading code of length N_c be expressed as

$$c_0 = [c_0(0), c_0(1), \dots, c_0(N_c - 1)]^T \quad (5)$$

where $c_0(n) \in \{+1, -1\}$, $n = 0, 1, \dots, N_c - 1$. By cyclically shifting the spreading code by an offset m , the spreading code corresponding to the selected index is obtained as follows:

$$c_m = [c_m(0), c_m(1), \dots, c_m(N_c - 1)]^T \quad (6)$$

The n -th chip is defined as

$$c_m(n) = c_0[(n - m) \bmod N_c], n = 0, 1, \dots, N_c - 1 \quad (7)$$

As shown in Equation (7), the shift offset m corresponds one-to-one to the cyclic offset of the spreading code, thereby forming the candidate spreading-code set for CSCIM index modulation.

3.1.2. Index Bit Mapping

Suppose that each spreading block carries k_{idx} index bits. The number of representable index states is $M = 2^{k_{idx}}$. To reduce correlation leakage between adjacent candidate shifts and fully utilize the complete cyclic-shift space provided by the spreading code of length N_c , the M cyclic-shift offsets are approximately uniformly distributed over the complete shift interval $[0, N_c - 1]$. The i -th valid cyclic-shift offset is defined as

$$m_i = \text{round}\left(\frac{i(N_c - 1)}{M - 1}\right), i = 0, 1, \dots, M - 1 \quad (8)$$

Therefore, the predefined cyclic-shift set S is

$$S = \{m_i \mid i = 0, 1, \dots, M - 1\} \quad (9)$$

where $\text{round}(\cdot)$ denotes rounding to the nearest integer. When $M = 1$, the shift set is $S = \{0\}$.

After the predefined cyclic-shift set (S) is obtained, the cyclic spacing between adjacent shift states is defined as

$$d_i = \{m_{i+1} - m_i, i = 0, 1, \dots, M - 2\} \quad (10)$$

The minimum and maximum cyclic spacings are further defined as $d_{\min} = \min_i d_i$, $d_{\max} = \max_i d_i$. According to Equation (8), when $M \leq N_c$, the nominal spacing between adjacent shift points satisfies $\frac{N_c}{M} \geq 1$. Therefore, the rounding operation does not produce duplicate shift positions. When N_c is not divisible by M , the rounding operation makes the minimum cyclic spacing of the shift set satisfy $d_i \in \left\{\left\lfloor \frac{N_c}{M} \right\rfloor, \left\lceil \frac{N_c}{M} \right\rceil\right\}$, where $\lfloor x \rfloor$ and $\lceil x \rceil$ denotes the largest integer not greater than x and the smallest integer not less than x .

This indicates that the constructed shift set can maintain an approximately uniform distribution, and the spacing between adjacent shift states differs by at most one chip. Therefore, under a given code length and index order, the proposed shift-set construction can reduce the correlation-peak confusion between adjacent candidate shifts as much as possible.

The k_{idx} index bits of the s -th spreading block are denoted as

$$b_{idx,s} = [b_{idx,s,1}, b_{idx,s,2}, \dots, b_{idx,s,k_{idx}}]^T \quad (11)$$

The bit sequence is mapped to a decimal index value $v_s \in \{0, 1, \dots, M-1\}$, and the corresponding cyclic-shift offset is then obtained as $m_s = S(v_s + 1)$, i.e., the $(v_s + 1)$ -th element in S . In this way, the one-to-one mapping from index bits to cyclic-shift offsets is completed, and the index information is mapped into the code domain.

3.1.3. Correlation Analysis of Cyclically Shifted Codes

To further explain the distinguishability among cyclic-shift candidate codes, this section analyzes the correlation among different shifted codes. Let the reference spreading code be $c_0(n)$, and let its cyclically shifted code be $c_m(n) = c_0[(n - m) \bmod N_c]$. For any two valid shift offsets $m_i, m_j \in S$, the periodic cross-correlation between the corresponding candidate spreading codes can be expressed as

$$R_{i,j} = \sum_{n=0}^{N_c-1} c_{m_i}(n) c_{m_j}^*(n) \quad (12)$$

Since $c_{m_i}(n)$ and $c_{m_j}(n)$ are both obtained by cyclically shifting the same reference spreading code, the above expression is equivalent to the periodic autocorrelation of the reference spreading code at the relative shift difference $\Delta_{i,j} = (m_j - m_i) \bmod N_c$, i.e., $R_{i,j} = R_c(\Delta_{i,j})$, where

$$R_c(\tau) = \sum_{n=0}^{N_c-1} c_0(n) c_0^*[(n - \tau) \bmod N_c] \quad (13)$$

Therefore, the distinguishability among different candidate shifted codes in CSCIM is mainly determined by the periodic autocorrelation sidelobes of the reference spreading code. To quantify the worst-case correlation leakage, the normalized maximum correlation coefficient is defined as

$$\rho_{\max} = \max_{i \neq j} \frac{|R_c[(m_j - m_i) \bmod N_c]|}{N_c}, \quad i, j \in \{0, 1, \dots, M-1\} \quad (14)$$

A smaller $\rho_{\max}$ value indicates a lower correlation peak at an incorrect candidate shift, making it easier for the receiver to identify the true shift offset from the full-shift-domain correlation response. Conversely, a larger value reduces the decision margin between the correct peak and incorrect peaks, thereby increasing the risk of index misdetection.

As discussed in Section 3.1.2, under the valid index configuration $M \leq N_c$, the minimum cyclic spacing satisfies $d_{\min} \geq \lfloor \frac{N_c}{M} \rfloor$. Therefore, for a fixed code length N_c , a larger index-set size M leads to denser shift states and increases the risk of correlation-peak confusion between incorrect candidate shifts and the true shift. For a fixed M , increasing N_c enlarges the shift spacing and helps improve the index-detection reliability.

Different code families exhibit significantly different periodic autocorrelation properties. When $M = 64$, the maximum normalized periodic autocorrelation sidelobes of a standard m-sequence and a Gold code with length 127 are 0.0079 and 0.1339, respectively, whereas the average value over 16 realizations of random bipolar sequences is 0.2313. Although a Walsh–Hadamard code with length 128 has inter-code orthogonality, its cyclic shifts do not preserve orthogonality, and its maximum sidelobe can reach 1. This indicates

that conventional orthogonal codes are not necessarily suitable for cyclic-shift indexing, whereas pseudo-random sequences with bounded periodic autocorrelation sidelobes are more favorable for distinguishing candidate shift states.

The code length and shift-set construction also affect the resolvability of candidate states. When Gold codes with lengths of 31, 63, and 127 are used under $M = 16$, their maximum normalized sidelobes are 0.2903, 0.2698, and 0.1339, respectively, and the corresponding $d_{\min}$ values are 1, 3, and 7. For $N_c = 127$ and $M = 64$, the rounding-based approximately uniform shift set satisfies $d_{\min} = 1$ and $d_{\max} = 2$, whereas fixed-step mapping produces an uncovered interval with $d_{\max} = 64$. Therefore, this paper adopts a Gold code of length 127 and the rounding-based uniform shift set to balance bounded periodic correlation sidelobes, available code-family size, and implementation complexity.

3.1.4. Symbol Mapping and Baseband Signal Spreading

After the cyclic-shift offset m_s of the s -th spreading block is determined, the system further maps the symbol bits in the same spreading block. The k_{sym} symbol bits $b_{\text{sym},s}$ of the s -th spreading block are mapped to a complex baseband modulation symbol a_s with the unit average energy according to the following rules.

BPSK modulation ($k_{\text{sym}} = 1$):

$$a_s = 1 - 2 \cdot b_{\text{sym},s} \quad (15)$$

QPSK modulation ($k_{\text{sym}} = 2$): $b_{\text{sym},s}$ is divided into the in-phase bit b_0 and the quadrature bit b_1 , and is mapped as

$$a_s = \frac{(1 - 2b_0) + j(1 - 2b_1)}{\sqrt{2}} \quad (16)$$

The above BPSK/QPSK mappings ensure normalized average symbol energy. According to the index-mapping result in Section 3.1.2, the index bits of the s -th spreading block are mapped to the cyclic-shift offset m_s . Therefore, by setting $m = m_s$ in Equation (8), the actual cyclically shifted spreading-code chip $c_{m_s}(n)$ used by the s -th spreading block can be obtained. Then, the complex baseband modulation symbol a_s is multiplied by $c_{m_s}(n)$, thereby jointly embedding the symbol and index information into the same spreading block. The chip sequence of the s -th spreading block can be expressed as

$$x_s(n) = a_s \cdot c_{m_s}(n), n = 0, 1, \dots, N_c - 1 \quad (17)$$

3.2. Composite Frame Structure Design

After the index mapping, symbol mapping, and spreading-block generation are completed, the system concatenates the synchronization sequence and consecutive spread-spectrum data blocks into a complete transmitted frame. In the CSCIM scheme, all spreading codes are generated by cyclically shifting a single spreading code. Although this design effectively reduces pseudo-code resource consumption, it requires an accurate frame-start reference at the receiver. This is because a timing offset in the receive window is mathematically equivalent to a change in the cyclic-shift offset of the spreading code, which may lead to an incorrect correlation-peak decision. As shown in Figure 3, when the receiver incorrectly extracts a spreading block, the subsequent FFT/IFFT-based fast cyclic-correlation process may produce an erroneous peak position, causing index misdetection.

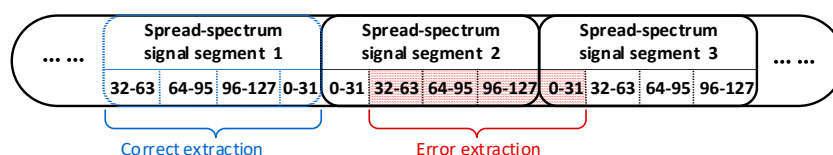


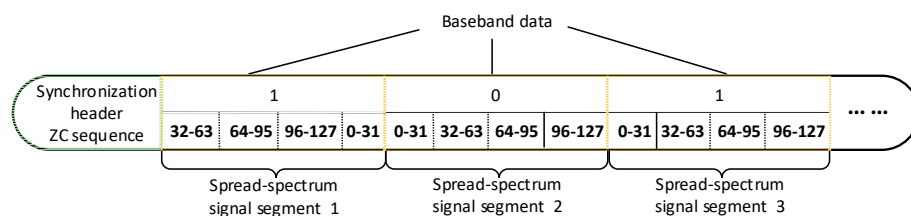
Figure 3. Illustration of decision ambiguity induced by cyclic-shift offset.

To resolve offset ambiguity during fast correlation acquisition, a composite frame structure consisting of a ZC synchronization header followed by consecutive spread-spectrum data blocks is designed. The ZC sequence has the ideal Constant Amplitude Zero Autocorrelation (CAZAC) property. Its autocorrelation peak is extremely sharp and free from sidelobe interference. Moreover, the cross-correlation between the ZC sequence and the spreading sequence used for data spreading is very low, which reduces the mutual interference between the synchronization segment and the data segment. By inserting a fixed-length ZC synchronization header at the beginning of each frame, the receiver can obtain a reliable timing reference before data-block extraction, thereby ensuring the correct alignment of the subsequent cyclically shifted spreading blocks.

Let the chip length of the ZC synchronization header be N_{zc} , the chip length of a single spreading code be N_c , and each frame contain N_s spread-spectrum data blocks. The system oversampling factor is L , and the sampling rate satisfies $f_s = f_c \cdot L$, where f_c is the chip sampling frequency. Each spreading block carries two types of information bits, k_{idx} index bits used to map the cyclic-shift offset of the spreading code, and k_{sym} symbol bits used to map the complex baseband modulation symbol. The total number of transmitted bits per frame is $N_s \cdot (k_{idx} + k_{sym})$, and the composite frame structure is expressed as follows:

$$x_{chip} = [z^T, x_1^T, x_2^T, \dots, x_{N_s}^T]^T \quad (18)$$

where z is the ZC synchronization sequence of length N_{zc} , and x_s is the chip sequence of the s -th spreading block. The composite frame structure of the CSCIM scheme is shown in Figure 4.

**Figure 4.** Composite frame structure of the proposed CSCIM scheme.

As shown in Equation (18), the CSCIM composite frame achieves rapid frame-start acquisition through a fixed-length ZC synchronization header. The subsequent consecutive equal-length spreading blocks carry index and modulation information. Therefore, this frame structure provides a fixed synchronization overhead and a scalable payload length.

According to the above composite frame structure, after the ZC synchronization header and N_s consecutive spreading blocks are concatenated into a complete frame, repeated upsampling is performed through the Kronecker product to obtain the final transmitted sequence:

$$x_{sm} = \text{kron}(x_{chip}, 1_L) \quad (19)$$

where 1_L is an all-one column vector of length L , and $\text{kron}(\cdot)$ denotes the Kronecker product. This operation repeats each chip L times to adapt the transmitted sequence to the physical-channel transmission.

3.3. Receiver Synchronization and Information Recovery Mechanism

At the receiver, signal processing proceeds from time-domain synchronization to frequency-domain despreading and information recovery. It consists of three steps: ZC synchronization acquisition, index information recovery, and despreading with symbol demodulation. First, the receiver uses the ZC synchronization header to determine the frame-start position from the continuous received sequence and extracts the aligned spread-spectrum data blocks. Then, based on FFT/IFFT fast cyclic-correlation detection, the correlation-peak position is detected to recover the cyclic-shift offset and the corresponding index bits. Finally, a local spreading code with the same shifted phase is generated according to the estimated shift offset, and despreading and symbol decision are completed.

3.3.1. ZC Synchronization Acquisition

In the CSCIM system, since the transmitter maps index information through cyclic shifts of a single spreading code, the absence of a frame-start reference causes a receiver-side delay offset to be mathematically equivalent to a change in the cyclic-shift offset of the reference code. As a result, an incorrect correlation-peak position may be extracted during despreading, leading to index misdetection.

During ZC synchronization acquisition, the receiver searches for the synchronization-header position in the continuous received sequence. Therefore, this process is essentially a sliding linear correlation between the received sequence $y_{sm}[n]$ and the local ZC synchronization sequence $z[n]$. Its time-domain expression can be written as

$$R_{zy}(\tau) = \sum_{n=0}^{N_{zc}-1} y_{sm}(\tau+n)z^*(n), \tau=0,1,\dots,N_y-N_{zc} \quad (20)$$

where N_y denotes the length of the received sequence used for the synchronization search, N_{zc} is the length of the ZC synchronization header, τ denotes the candidate timing offset, and $(\cdot)^*$ denotes complex conjugation. To improve the computational efficiency, the linear correlation in Equation (20) can be implemented by FFT-based linear convolution:

$$R_{zy}[\tau] = \text{IFFT}\left(\text{FFT}(y_{sm}) \cdot \text{FFT}(\text{flipud}(z^*))\right)(\tau) \quad (21)$$

where $\text{flipud}(\cdot)$ denotes sequence reversal, and $\text{flipud}(z^*)$ denotes the reversed conjugate form of the local ZC sequence. Owing to the CAZAC property of the ZC sequence, its autocorrelation peak is extremely sharp and free from sidelobe interference. Meanwhile, it causes negligible interference with the spreading code. Therefore, the system can accurately lock the frame-start position by searching for the maximum peak. When the Peak-to-Sidelobe Ratio (PSR) exceeds a preset threshold, synchronization is declared successful. Based on this precise timing reference, the system extracts the aligned complete frame y from the received sequence y_{sm} , and then extracts each data spreading-block sequence for subsequent despreading.

3.3.2. Index Information Recovery

After the timing alignment is completed and the data spreading block $r_s(n)$ is successfully extracted, the receiver further recovers the cyclic-shift offset m_s carried by the block. In the CSCIM scheme, the synchronization module and the index-recovery module are mathematically consistent. To improve resource reuse and reduce the receiver-side processing delay, the index-recovery process directly reuses the FFT-based fast-correlation architecture described in Section 3.3.1.

Let the s -th received spreading block be $r_s(n)$, and let the local reference spreading code be $c_0(n)$. Their frequency-domain representations are $R_s(k) = \text{FFT}[r_s(n)]$, $C_0(k) =$

FFT[$c_0(n)$], and pointwise conjugate multiplication is performed in the frequency domain as

$$X_s(k) = R_s(k)C_0^*(k), \quad k = 0, 1, \dots, N_c - 1 \quad (22)$$

Then, IFFT is applied to obtain the full-shift-domain cyclic-correlation sequence:

$$\text{corr}_s(\tau) = \text{IFFT } X_s(k)[\tau], \tau = 0, 1, \dots, N_c - 1 \quad (23)$$

where $\text{corr}_s[\tau]$ denotes the correlation output between the received spreading block and the local reference spreading code under the cyclic-shift hypothesis τ .

Under ideal noise-free conditions, as shown in Figure 5, the blue curves denote the magnitude of the cyclic-correlation response, the black vertical lines indicate the transmitted cyclic-shift offsets, and the red dashed lines indicate the detected peak positions. The magnitude of the full-delay-domain cyclic-correlation sequence obtained by IFFT has a unique significant peak at the transmitted cyclic-shift offset m_s . Figure 5a–d show the correlation responses for $m_s = 0$, $m_s = 32$, $m_s = 64$, and $m_s = 96$, respectively. In each case, the detected peak position is consistent with the transmitted cyclic-shift offset, indicating that the peak position can be used to recover the index information.

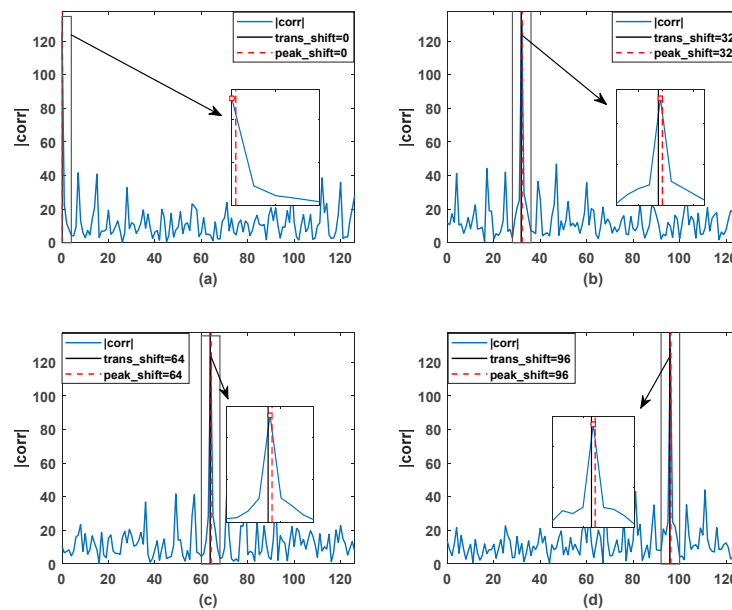


Figure 5. Illustration of full-delay-domain cyclic-correlation peaks under different transmitted cyclic-shift offsets: (a) $m_s = 0$, (b) $m_s = 32$, (c) $m_s = 64$, and (d) $m_s = 96$.

Although fading channels may cause peak-energy distortion and tailing effects, the main-path correlation peak can still be reliably extracted when the spreading code has favorable autocorrelation properties. In the simulations of this paper, a Gold code is used as the spreading code to verify the effectiveness of this mechanism.

After obtaining the cyclic-correlation sequence, the receiver avoids a multi-branch exhaustive search for despreading and index estimation. To reduce false detections and remain consistent with transmitter-side mapping, it searches only within the predefined shift set S and selects the maximum correlation peak as the cyclic-shift estimate:

$$\hat{m}_s = \arg \max | \text{corr}_s(m) |, m \in S \quad (24)$$

Let $S = \{m_0, m_1, \dots, m_{M-1}\}$, where m_i denotes the i -th cyclic-shift offset. According to the transmitter-side index-bit mapping rule, the position of $\hat{m}_s$ in the set S is the recovered decimal index value:

$$\hat{v}_s = \text{index}_S(\hat{m}_s) \quad (25)$$

where $\text{index}_S(\cdot)$ denotes the element index of a shift offset in the predefined set S . Then, $\hat{v}_s$ is converted into a binary sequence of length k_{idx} :

$$\hat{b}_{\text{idx},s} = \text{bin}_{k_{\text{idx}}}(\hat{v}_s) \quad (26)$$

where $\text{bin}_{k_{\text{idx}}}(\cdot)$ denotes a binary representation with output length k_{idx} . Thus, index information recovery is completed.

3.3.3. Despreading and Symbol Demodulation

After the estimated cyclic-shift offset $\hat{m}_s$ of the current spreading block is recovered, the receiver generates the local spreading code $c_{\hat{m}_s}(n)$ with the corresponding shifted phase. The received spreading block $r_s(n)$ is then correlated with $c_{\hat{m}_s}(n)$ for despreading:

$$\hat{a}_s = \frac{1}{N_c} \sum_{n=0}^{N_c-1} r_s(n) \cdot c_{\hat{m}_s}^*(n) \quad (27)$$

where $\hat{a}_s$ is the recovered modulation-symbol estimate. Since the spreading code adopted in this paper is a real-valued bipolar sequence, when $c_{\hat{m}_s}(n) \in \{+1, -1\}$, $c_{\hat{m}_s}^*(n) = c_{\hat{m}_s}(n)$.

Since the full-delay-domain cyclic-correlation sequence in Equation (23) already contains the correlation-despreading results for all candidate shifts, the receiver directly extracts the complex correlation value at the maximum-peak position and normalizes it by N_c :

$$\hat{a}_s = \frac{\text{corr}_s[\hat{m}_s]}{N_c} \quad (28)$$

Finally, using the symbol estimate $\hat{a}_s$ obtained through despreading, the system recovers k_{sym} symbol bits according to the BPSK or QPSK decision region in which $\hat{a}_s$ falls. Thus, the recovery of both index bits and symbol bits from the received signal is completed.

3.4. Complexity Analysis

To ensure comparability among different receiver structures, this section adopts the number of real multiplications (RMs) required at the receiver per frame as the unified complexity metric. Only multiplication operations in the payload-detection stage are counted as the main comparison metric among different schemes. The ZC synchronization acquisition overhead required by CSCIM is counted separately in its end-to-end receiver complexity. Offline operations, such as local spreading-code generation, codebook storage, and the FFT precomputation of the local reference code, are not included in online RMs because they are not repeated for each transmitted frame. Comparisons, table lookups, modulo operations, square-root operations, divisions, and hard decisions are not converted into equivalent RMs, but are reported as separate operation types. According to the commonly used complex-arithmetic model, one complex multiplication is equivalent to four real multiplications, and an FFT or IFFT of length N_c approximately requires $(N_c/2)\log_2 N_c$ complex multiplications.

For the CSCIM scheme, index recovery for one spreading block consists of three parts: the FFT of the received block, pointwise conjugate multiplication in the frequency domain, and IFFT. Since the FFT results of both the local reference spreading code and the

ZC template can be precomputed and stored, let the FFT length used for synchronization correlation be N_F . During synchronization and online detection, only the FFT of the received block, N_F or N_c point complex multiplication, and one IFFT need to be computed. Therefore, the multiplication complexity of synchronization acquisition is $4N_F \log_2 N_F + 4N_F$, the receiver-side multiplication complexity of one spreading block is $4N_c \log_2 N_c + 4N_c$, and the per-frame receiver-side multiplication complexity of CSCIM with N_s spreading blocks is $4N_F \log_2 N_F + 4N_F + N_s(4N_c \log_2 N_c + 4N_c)$.

Unlike conventional CIM and its variants, the CSCIM scheme obtains the full-shift-domain correlation response through one FFT/IFFT-based fast cyclic-correlation operation. The subsequent peak search only involves a magnitude comparison and introduces no additional multiplication overhead. Therefore, under the RM-counting criterion adopted in this paper, the receiver-side multiplication complexity of CSCIM does not increase with the index order. Let the number of candidate delays in the synchronization search range be N_τ , and let the number of sidelobe samples outside the PSR guard region be N_{sl} . The synchronization module requires $N_\tau - 1$ main-peak comparisons, $N_{sl} - 1$ sidelobe comparisons, and one PSR threshold decision. The data-detection module performs $M - 1$ shift-peak comparisons for each spreading block and $k_{\text{sym}} = 2$ times hard decisions in the QPSK symbol domain. Therefore, the total number of comparisons and decisions per frame is $(N_\tau - 1) + (N_{sl} - 1) + 1 + N_s(M - 1) + N_s k_{\text{sym}}$. These operations are not included in RMs, but are reported as independent hardware operation types. The one-time precomputation complexity of the two template FFTs is $2N_F \log_2 N_F + 2N_c \log_2 N_c$. Since the ZC synchronization header does not carry payload information, its frame-level chip overhead is

$$\eta_{\text{ZC}} = \frac{N_{\text{zc}}}{N_{\text{zc}} + N_s N_c} \quad (29)$$

This overhead is not part of the computational complexity, but it is deducted when calculating the effective throughput.

The converted per-frame RM expressions of CIM and its related variants are listed in Table 1. Table 1 compares the online RMs of the payload detectors of different schemes, rather than the complete hardware cost including synchronization, storage, and frame-header overhead. This criterion remains consistent with the complexity formulae of the benchmark schemes under the assumption of ideal synchronization in their original papers, where N_r and N_t denote the numbers of receive and transmit antennae, respectively, and M_{mod} denotes the modulation order. It can be seen that the complexity of CIM and its variants usually increases rapidly with the codebook size, the number of candidate code combinations, or the joint detection search space, whereas CSCIM maintains a low and stable receiver-side multiplication complexity under high-order index configurations.

Table 1. Complexity comparison.

Scheme	RMs per Frame
BA_CIM	$N_s[2N_c \log_2(N_c) + ((k_{\text{idx}}/2) + 1)(2N_c \log_2(N_c) + 4N_c)]$
CSCIM	$N_s[4N_c \log_2(N_c) + 4N_c]$
CIM	$4N_s \times 2^{k_{\text{idx}}} N_c$
GCIM	$N_s N_c (2^{k_{\text{idx}/2} + 2^{k_{\text{idx}}/2})$
CIM_ESM	$N_s[16N_c(2^{k_{\text{idx}/2} + 2^{k_{\text{idx}}/2})(N_r + 1) + 8N_r N_t^2 M_{\text{mod}}]$
CIM_QSM	$N_s[16N_c(2^{k_{\text{idx}/2} + 2^{k_{\text{idx}}/2})(N_r + 1) + 8N_r N_t^2 M_{\text{mod}}]$

4. System Performance Evaluation and Simulation Analysis

Monte Carlo simulations were conducted to evaluate the BER performance, ZC synchronization effectiveness, codebook resource consumption, receiver-side computational

complexity, and effective throughput of the proposed CSCIM scheme. Under unified simulation conditions, CSCIM was compared with representative CIM schemes, including BA-CIM, CIM, GCIM, CIM-ESM, and CIM-QSM.

The simulations considered the AWGN channel and the flat Rayleigh fading channel with AWGN. In the simulations, the CSCIM scheme adopted a Gold code as the spreading code. Unless otherwise specified, the independent CSCIM link, the ZC synchronization ablation experiment, and the practical channel-impairment experiments adopt $N_c = N_{zc} = 127$, $N_s = 9$, and an oversampling factor of $L = 1$. To unify the frame resources across different index orders and different benchmark schemes, the comparative experiments in Section 4.4 set the target frame resource to approximately 4096 chips, which gives $N_s = 31$. These two configurations are used for mechanism verification and unified-resource comparison, respectively, and the corresponding parameters are specified separately in the relevant subsections. The ZC sequence length is kept consistent with the spreading-code length. The ZC sequence length is consistent with the spreading-code length, which facilitates the reuse of the FFT/IFFT operation module at the receiver. Setting $N_c = 127$ provides a reasonable balance between the spreading processing gain and system bandwidth overhead. The simulations assumed that the carrier phase had been ideally compensated. Therefore, the equivalent fading coefficient was $a = |h|$. The receiver was assumed to have perfect amplitude-gain information, and one-tap equalization was performed before ZC synchronization and data detection as $y_{eq} = y/a$. Therefore, the results correspond to ideal-phase-tracking and perfect-amplitude CSI, without involving pilot-aided channel estimation or noncoherent QPSK detection. The AWGN variance was referenced to the transmit signal power before fading.

4.1. Impact of Index Order on System Performance

In the CSCIM scheme, the number of index bits k_{idx} determines the index-set size $M = 2^{k_{idx}}$. Increasing M can improve the amount of index information carried by each spreading block. However, it also makes the legal cyclic-shift states denser, reducing the spacing between adjacent candidate shifts and increasing the difficulty of the correlation-peak position decision. Therefore, the index order reflects a tradeoff between spectral efficiency and detection reliability.

Figure 6 shows the BER performance of CSCIM under different index-set sizes over AWGN and the flat Rayleigh fading channels. To isolate the effect of the index-set size on cyclic-shift detection, all M configurations adopt the same chip-level signal-to-noise ratio. Suppose that each frame contains N_s spread-spectrum data blocks, and each block carries $k_{idx} + k_{sym}$ payload bits. Then, for the configuration $M = 2^{k_{idx}}$, the frame-level payload rate is given by

$$R_M = \frac{N_s (k_{idx} + k_{sym})}{N_{zc} + N_s N_c} \quad (30)$$

The relationship between the chip-level SNR γ_c and the actual E_b/N_0 of this configuration is

$$\left(\frac{E_b}{N_0} \right)_M = \frac{\gamma_c}{R_M} \quad (31)$$

In dB form, it can be expressed as

$$\left(\frac{E_b}{N_0} \right)_{M, \text{dB}} = \gamma_{c, \text{dB}} - 10 \log_{10} R_M \quad (32)$$

In Figure 6, the payload rate of $M_{\text{ref}} = 4$ is used as the unified reference. Therefore, the horizontal axis is defined as the reference-equivalent E_b/N_0 :

$$\left(\frac{E_b}{N_0} \right)_{\text{ref,dB}} = \gamma_{c,\text{dB}} - 10 \log_{10} R_{M=4} \quad (33)$$

This horizontal axis represents the reference-equivalent E_b/N_0 . This treatment ensures that different M configurations are evaluated under the same chip-level signal and noise conditions, thereby avoiding the additional SNR gain that would otherwise be introduced for the high-order index configuration when the actual E_b/N_0 normalization is used.

The results show that, as M increases, the BER curves shift rightward in the low-to-medium SNR region, indicating that denser shift states increase the difficulty of the index decision. Meanwhile, the BER curves of all configurations continue to decrease with the reference-equivalent E_b/N_0 . This indicates that the single-code cyclic-shift structure in CSCIM can still support reliable data transmission under high-order index configurations.

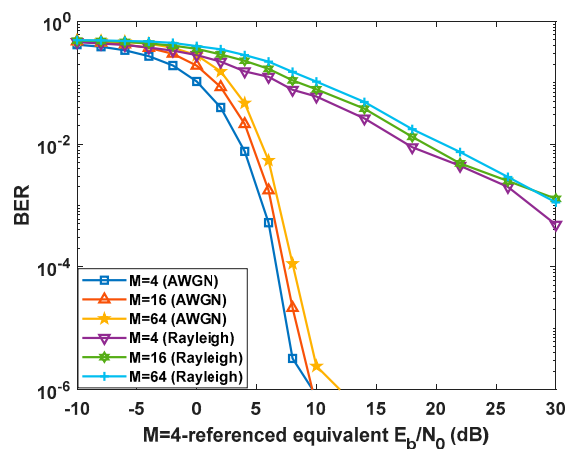


Figure 6. BER performance of the CSCIM system under different index orders.

The above results verify the influence of the index order on the BER performance of CSCIM. Since index recovery in CSCIM relies on the location of the cyclic-correlation peak, the accuracy of the receiver-side frame-start position directly affects the index decision. Therefore, the next subsection further verifies the role of the ZC synchronization header under random timing offsets.

4.2. Verification of ZC Synchronization Effectiveness Under Random Timing Offsets

To verify the ability of the ZC synchronization header in the proposed composite frame structure to suppress the cyclic-shift acquisition ambiguity, a comparative experiment on the ZC synchronization effectiveness was conducted by introducing random timing offsets at the receiver. A random time offset was inserted before each received frame, so that the receiver cannot directly obtain the correct start position of the data block without synchronization. Three receiving modes were compared: ZC-assisted data-block extraction, direct extraction without synchronization compensation, and ideal extraction using the true frame start. To further distinguish between different synchronization outcomes and the ideal timing reference based on the true frame start, the ZC acquisition events are classified into three categories. If the correlation peak passes the PSR threshold and the estimated frame-start position is correct, the event is regarded as a correct timing acquisition. If the correlation peak does not pass the PSR threshold, the event is regarded as a missed acquisition. If the correlation peak passes the PSR threshold but the estimated timing position is incorrect, the event is regarded as a false timing acquisition. The corre-

sponding probabilities are denoted by P_C , P_M , and P_F , respectively, and satisfy $P_C + P_M + P_F = 1$.

Because cyclic-shift states are denser under high-order configurations, $M = 64$ was selected to evaluate the influence of synchronization on index-recovery reliability.

Figure 7 shows the index error rates of the three receiving modes under random timing offsets. Without ZC synchronization, the receiver always extracts the data block from the default position. Therefore, its IER remains on a high error floor close to 1. This is because the index information of the CSCIM scheme is carried by the cyclic-shift position. Without synchronization, the random frame-start offset at the receiver destroys the correct extraction of the spread-spectrum data block, causing the subsequent index decision based on the cyclic-correlation peak position to fail. In contrast, after ZC synchronization is adopted, the receiver first estimates the frame-start position and then extracts the spread-spectrum data block. As E_b/N_0 increases, the IER decreases rapidly and gradually approaches the ideal result obtained with the known true timing reference. For example, when $E_b/N_0 = 6$ dB, the IERs of the ZC synchronization, no-synchronization, and known-timing modes are approximately 1.11×10^{-4} , 9.79×10^{-1} , and 1.11×10^{-4} , respectively. This result indicates that the ZC synchronization header can effectively suppress the cyclic-shift acquisition ambiguity caused by random timing offsets.

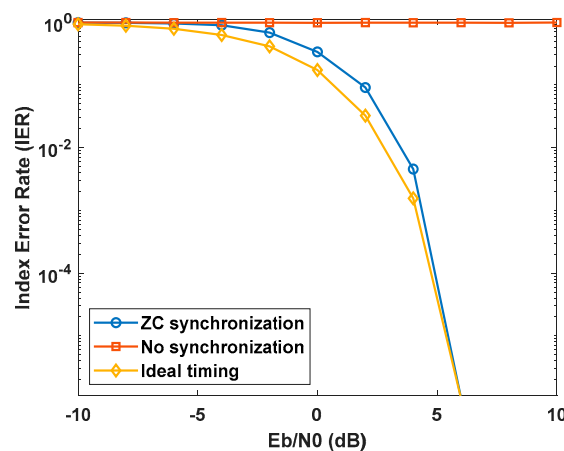


Figure 7. Index error rate comparison of ZC synchronization under random timing offsets ($M = 64$).

4.3. Robustness Evaluation Under Practical Channel Impairments

To evaluate the reliability of CSCIM under non-ideal propagation conditions, this section investigates the effects of the carrier frequency offset (CFO), multipath delay spread, and Doppler effect on index recovery and ZC synchronization acquisition. The simulations adopt $M = 64$, $N_c = N_{zc} = 127$, QPSK modulation, and $E_b/N_0 = 14$ dB. The normalized CFO and Doppler frequency are denoted by $\Delta f T_s$ and $f_D T_s$, where Δf , f_D , and T_s denote the carrier frequency offset, the maximum Doppler frequency, and the sampling interval, respectively. A two-path quasi-static Rayleigh channel is used for the multipath model, where the average power of the second path is 6 dB lower than that of the first path, and its delay is uniformly selected from 1 to $D_{\max}$ chips.

The IER performance under typical channel perturbations is shown in Figure 8, where Figure 8a, Figure 8b, and Figure 8c correspond to the carrier frequency offset, multipath delay spread, and Doppler effect, respectively. It can be observed that uncompensated CFO destroys the coherent accumulation of both the synchronization header and the spreading code, causing the IER to increase significantly with the normalized CFO. After ZC-assisted frequency-offset estimation and compensation are adopted, the perfor-

mance degradation is substantially suppressed. Multipath components generate delayed peaks in the correlation domain and may compete with the predefined cyclic-shift positions. Since the correlation sidelobes depend on the specific relative delay, the IER exhibits locally non-monotonic variations with the multipath delay. The known timing reference in the figure is used only to separate timing acquisition errors from post-synchronization multipath interference. This result further indicates that, even when the frame start is perfectly known, multipath-induced correlation side peaks may still lead to cyclic-shift index misdetection. As the Doppler effect increases, the intra-frame channel variation weakens the stability of ZC acquisition and cyclic-correlation detection, and, therefore, the IER gradually increases.

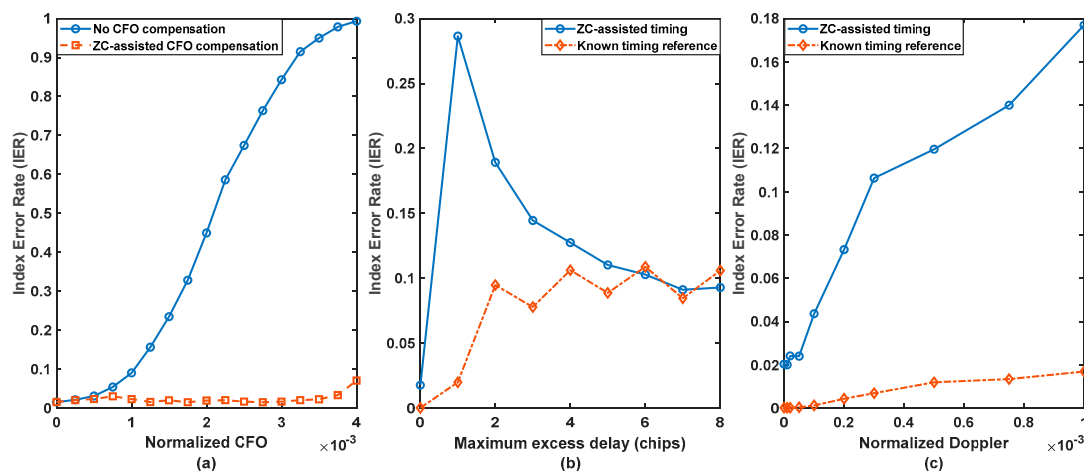


Figure 8. Index error rate of CSCIM under representative channel impairments: (a) carrier frequency offset. (b) multipath delay spread. and (c) Doppler effect.

Figure 9a–c show the ZC synchronization acquisition results under CFO, multipath delay spread, and Doppler conditions, respectively. Figure 9 shows that uncompensated CFO mainly causes a rapid decrease in the probability of correct timing acquisition, whereas ZC-assisted frequency-offset compensation maintains a high acquisition probability within the investigated range. Under multipath conditions, both missed acquisition and false acquisition occur, indicating that delayed correlation peaks not only reduce the decision margin of the main peak, but may also cause the receiver to lock onto a non-first-path position. For the investigated Doppler range, the false-acquisition probability is close to zero, whereas the missed-acquisition probability increases with Doppler, indicating that Doppler mainly prevents the synchronization peak from passing the decision threshold by reducing the PSR. The synchronization results further show that the CFO, multipath delay spread, and Doppler effect increase the probabilities of missed acquisition or false timing acquisition by reducing the distinguishability of the ZC correlation peak. For example, when the normalized CFO is 4×10^{-3} , after ZC-assisted frequency-offset compensation, the correct timing acquisition rate, missed acquisition rate, and false timing acquisition rate are 92.9%, 4.13%, and 2.97%, respectively, and the corresponding IER is approximately 7.07%. When the maximum multipath delay is eight chips, the correct timing acquisition rate, missed acquisition rate, and false timing acquisition rate are 73.77%, 8.10%, and 18.13%, respectively, and the corresponding IER is approximately 9.29%. Overall, ZC synchronization and frequency-offset compensation can effectively improve the index-recovery reliability of CSCIM, but multipath equalization and time-varying channel tracking remain key issues for practical implementation.

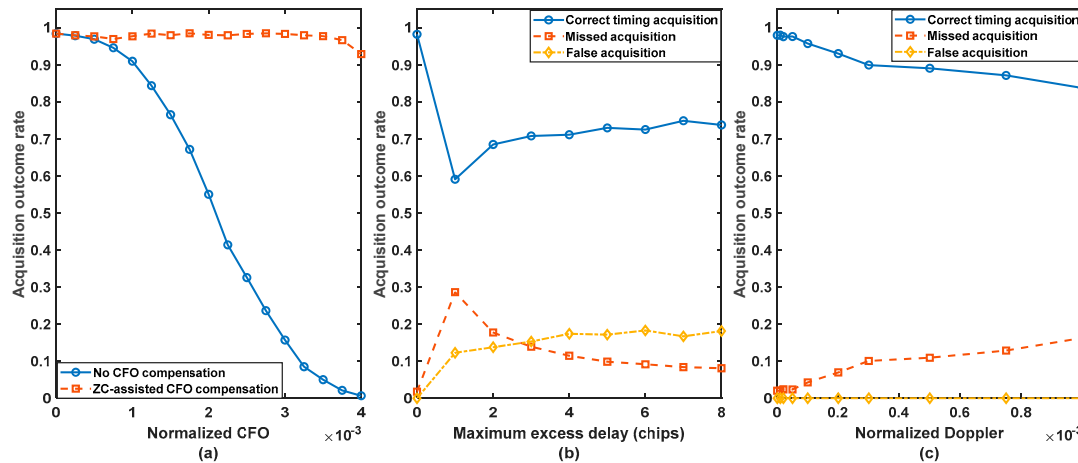


Figure 9. Acquisition performance of ZC-based frame synchronization under representative channel impairments: (a) carrier frequency offset, (b) multipath delay spread, and (c) Doppler effect.

4.4. Performance Comparison Under Unified Constraints

Under unified frame-resource and target-spectral-efficiency constraints, this subsection presents a comparison of the CSCIM scheme with five CIM schemes, namely, BA-CIM, CIM, CIM-ESM, CIM-QSM, and GCIM. The comparison is conducted from four aspects: BER performance, codebook resource consumption, computational complexity, and effective throughput.

To ensure a fair comparison, the performance evaluation is divided into two parts: matched-payload comparison and high-order scalability analysis.

All schemes adopt a ZC synchronization header of length 127 and 31 spread-spectrum data blocks, and the horizontal axis E_b/N_0 is normalized according to the actual payload rate of each scheme. Due to the structural constraints of the code families, the lengths of the Gold code and Walsh code are set to 127 and 128, respectively, corresponding to frame lengths of 4064 and 4095 chips. CSCIM ($M = 4$) and CIM both carry 4 bits/block and are used for a low-order matched-payload comparison. CSCIM ($M = 64$) carries 8 bits/block and is used for a comparison under a high-payload configuration, so as to demonstrate the scalability of the proposed cyclic-shift construction under high-order indexing. The remaining schemes are used as reference configurations for different CIM structures, and their modulation and index structures follow those defined in their original papers. Since different schemes adopt different receiver models, the CSI usage follows the implementation setting of each detector. For CSCIM, the ZC synchronization header is included as the frame-level overhead when the effective throughput is calculated. Table 2 lists the key parameters of all schemes.

Table 2. Scheme parameters.

Scheme	M	N_T	N_R	Code Type	Code Length
BA_CIM	4	1	1	Gold	127
CSCIM ($M = 4$)	4	1	1	Gold	127
CSCIM ($M = 64$)	64	1	1	Gold	127
CIM	4	1	1	Walsh	128
GCIM	4	1	1	Walsh	128
CIM_ESM	4	4	1	Walsh	128
CIM_QSM	4	4	1	Walsh	128

4.4.1. Bit Error Rate Performance Comparison

Figure 10 shows the BER comparison of different schemes over flat Rayleigh fading with AWGN, which is used to evaluate the overall noise performance of different schemes in fading channels. Representative schemes were selected in Figure 11 to compare their BER curves under the AWGN channel and the flat Rayleigh fading channel with AWGN, so as to analyze the influence of channel fading on system error performance.

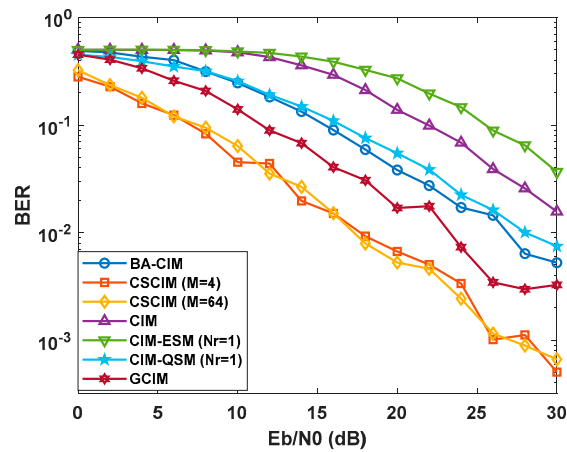


Figure 10. BER comparison of different schemes over flat Rayleigh fading with AWGN.

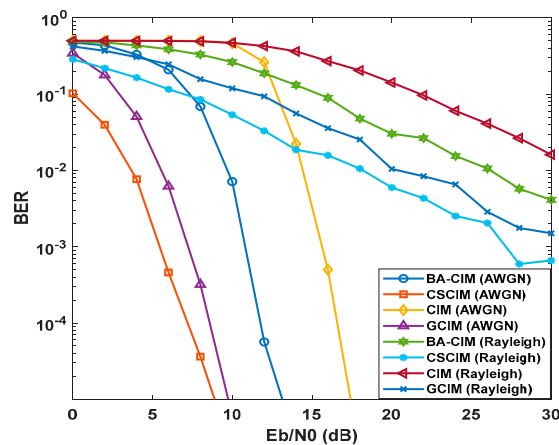


Figure 11. BER comparison of representative schemes under different channel conditions.

For each E_b/N_0 point, the simulations recorded the actual number of frames, the number of transmitted payload bits, and the number of bit-error events. The two-sided Clopper–Pearson method was used to calculate the 95% confidence intervals. Each data point in Figure 10 contains 500–5000 frames and $6.2 \times 10^4 - 1.24 \times 10^6$ payload bits, whereas each data point in Figure 11 contains 800–5000 frames and $9.92 \times 10^4 - 1.24 \times 10^6$ payload bits. For the flat Rayleigh fading branch of CSCIM, an independent fading coefficient $h \sim \mathcal{CN}(0,0.5)$ was generated for each frame and remained unchanged within the frame.

As shown in Figure 10, under flat Rayleigh fading with AWGN, CSCIM ($M = 4$) achieves a better BER performance than low-order CIM-type schemes such as BA-CIM, CIM, and GCIM. For the high-order configuration, although the index-carrying capability is higher and the detection difficulty increases accordingly, its BER curve still decreases steadily in the high-SNR region. Even under the high-order index configuration of $M =$

64, the BER performance of CSCIM can still outperform several CIM and CIM-variant schemes, indicating that it remains effective under high-order index configurations.

Figure 11 shows that, compared with the AWGN channel, flat Rayleigh fading with AWGN shifts the BER curves of all schemes rightward, indicating that fading increases the difficulty of index detection and symbol decision. However, the CSCIM scheme maintains a rapid BER decrease under both channel conditions. Under the same channel condition, CSCIM achieves a better BER performance than BA-CIM, GCIM, and conventional CIM. This is because CIM and its variants rely on the orthogonality among multiple different spreading codes to carry index information and are therefore vulnerable to inter-code cross-correlation interference in fading channels. In contrast, CSCIM constructs candidate spreading codes by cyclically shifting the same spreading code. The distinguishability among candidate states mainly depends on the autocorrelation property of the reference code. When a Gold code with favorable autocorrelation is used as the spreading code, CSCIM can maintain a high index-recognition accuracy.

4.4.2. Comparison of Codebook Resources and Computational Complexity

Figure 12 shows the relationship between the required number of spreading codes and the number of index bits for different schemes. Figure 13 further compares the receiver-side computational complexity of these schemes.

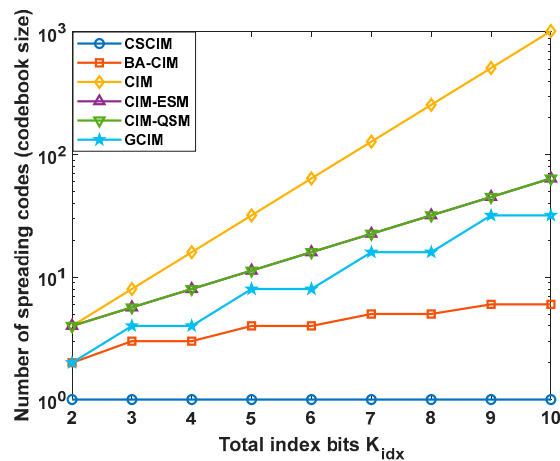


Figure 12. Required number of spreading codes versus the number of index bits.

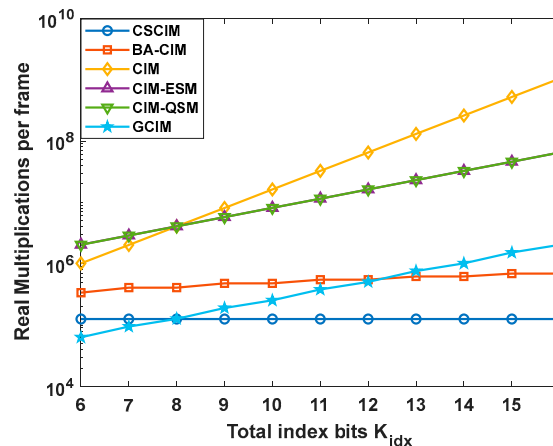


Figure 13. Receiver-side computational complexity versus the number of index bits.

As shown in Figure 12, as the number of index bits carried by each spreading block increases, CIM and its variants usually require more candidate spreading codes or code combinations, and the codebook size increases accordingly. In contrast, CSCIM requires only one Gold code in the simulations, and different index states are generated by cyclic shifts of this spreading code. Therefore, its spreading-code resource requirement does not increase with the number of index bits, giving it a lower codebook resource overhead under high index orders.

As shown in Figure 13, CIM-type schemes usually require parallel matching or correlation detection over all candidate spreading codes. Therefore, their receiver-side computational complexity increases rapidly with the codebook size and the number of index bits. The CSCIM scheme obtains the full-shift-domain correlation response at once through FFT/IFFT. The subsequent correlation-peak search only involves a magnitude comparison and does not introduce additional multiplication overhead. Therefore, under the RM-counting criterion, the receiver-side multiplication complexity of CSCIM does not increase with the index order. It can maintain a low and stable computational cost under high-order index configurations, and its complexity advantage becomes more evident as the index order increases.

4.4.3. Comparison of Effective Throughput

To uniformly evaluate the effective transmission capability of different schemes under the joint effects of the frame overhead and detection errors, the normalized effective throughput is defined as the number of information bits correctly recovered at the receiver per chip. This metric jointly reflects the effects of spectral efficiency and BER. For each frame containing N_s spread-spectrum data blocks, the number of effective information bits is

$$B_{\text{payload}} = N_s (k_{\text{idx}} + k_{\text{sym}}) \quad (34)$$

The frame length including the synchronization header and guard interval is expressed as

$$N_{\text{frame}} = N_{\text{zc}} + N_s N_c + N_{\text{guard}} \quad (35)$$

In the simulations of this paper, the frame consists of a ZC synchronization header and consecutive spread-spectrum data blocks without an additional guard interval. Therefore, $N_{\text{guard}} = 0$. If synchronization fails, or if either the index bits or modulation bits are recovered incorrectly, the frame is regarded as an erroneous frame. Therefore, the normalized effective throughput is defined as

$$\eta_{\text{eff}} = \frac{B_{\text{payload}}}{N_{\text{frame}}} (1 - \text{FER}) \quad (36)$$

This definition deducts the ZC synchronization-header overhead and the frame loss caused by synchronization failure. BER and IER are used to characterize the bit recovery and index recovery performance, respectively, whereas FER is directly obtained from simulations without assuming independent bit errors. Since chip-level normalization is adopted in this paper, the oversampling factor (L) is not included in the denominator. If normalization is performed with respect to sampling points, the effective throughput should be further divided by (L). In this experiment, ($L = 1$).

Figure 14 shows the normalized effective throughput of different schemes as E_b/N_0 varies. The effective throughput is calculated as the number of correctly recovered payload bits per frame chip, where the ZC synchronization header is included in the frame length. Therefore, the results reflect the joint effects of the synchronization overhead and frame-detection reliability.

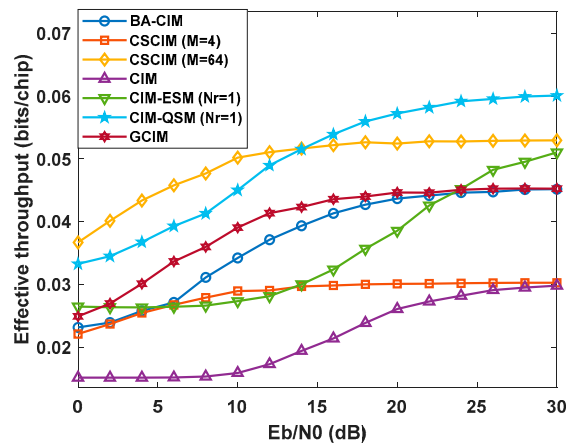


Figure 14. Normalized effective throughput comparison of different schemes versus E_b/N_0 .

Under the parameter setting of this paper, CSCIM ($M = 4$) carries 4 bits/block and is used for a low-order performance comparison, whereas CSCIM ($M = 64$) carries 8 bits/block and is used for a comparison under a high-payload configuration. As E_b/N_0 increases, the frame error rate of each scheme gradually decreases, and the effective throughput correspondingly approaches its peak spectral efficiency. CSCIM ($M = 4$) maintains an effective throughput comparable to that of conventional CIM under the low-order configuration. The higher throughput of CSCIM ($M = 64$) mainly comes from the fact that it carries more index bits. This result indicates that CSCIM can be extended to higher-payload configurations while keeping the number of independent spreading codes equal to one and while maintaining a receiver-side complexity that is almost independent of the index order. Meanwhile, its effective throughput increases steadily with E_b/N_0 , demonstrating that the proposed cyclic-shift index structure still provides a usable transmission reliability under high-order configurations.

5. Conclusions

This paper proposes a CSCIM scheme to address the dependence of CIM on large orthogonal codebooks and the rapidly increasing receiver-side detection complexity under high-order index mapping. The proposed scheme uses different cyclic-shift states of a single spreading code to carry index information and transforms multi-code selection mapping into single-code cyclic-shift mapping. In this way, codebook resource consumption is reduced while the spread-spectrum transmission framework is preserved. Meanwhile, a composite frame structure consisting of a ZC synchronization header and spread-spectrum data blocks is designed to establish a reliable frame-start reference and resolve the cyclic-shift acquisition ambiguity.

At the receiver, an FFT/IFFT-based fast cyclic-correlation detection method is adopted to obtain the full-shift-domain correlation response through a single processing path, and recovers the index information according to the correlation-peak position. The simulation results show that the proposed CSCIM scheme achieves a competitive overall performance in terms of BER, codebook resource consumption, receiver-side computational complexity, and effective throughput. Its codebook and complexity advantages are particularly evident under high-order index configurations. The additional results further reveal the sensitivity of CSCIM to the carrier frequency offset, multipath delay spread, and Doppler effects. Future work will focus on enhanced frequency-offset compensation, multipath equalization, time-varying channel tracking, multiuser access, non-ideal channel estimation, and hardware-oriented system validation.

Author Contributions: Conceptualization, methodology, and writing—original draft: R.D.; formal analysis: Z.C.; writing—review and editing: B.Q. and Y.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Liaoning Province, grant number 2024-MS-113; the Liaoning Provincial Department of Education Science and Technology Innovation Team Project, grant number LJ222510144001; and Xingliao Talents Plan, grant number XLYC2202013.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

References

1. Tera, S.P.; Chinthajinjala, R.; Pau, G.; Kim, T.H. Toward 6G: An Overview of the Next Generation of Intelligent Network Connectivity. *IEEE Access* **2025**, *13*, 925–961. <https://doi.org/10.1109/ACCESS.2024.3523327>.
2. Sheraz, M.; Chuah, T.C.; Tareen, W.U.K.; Al-Habashna, A.; Saeed, S.I.; Ahmed, M.; Lee, I.E.; Guizani, M. A Comprehensive Survey on GenAI-Enabled 6G: Technologies, Challenges, and Future Research Avenues. *IEEE Open J. Commun. Soc.* **2025**, *6*, 4563–4590. <https://doi.org/10.1109/OJCOMS.2025.3568496>.
3. Han, C.; An, K.; Lin, Z.; Chatzinotas, S.; Wang, J. Endogenous Anti-Jamming Communications for SAGIN: A Network Perspective. *IEEE Netw.* **2025**, early access. <https://doi.org/10.1109/MNET.2025.3551248>.
4. Zhu, J.; Wang, A.; Wu, W.; Zhao, Z.; Xu, Y.; Lei, R.; Yue, K. Deep-Learning-Based Recovery of Frequency-Hopping Sequences for Anti-Jamming Applications. *Electronics* **2023**, *12*, 496. <https://doi.org/10.3390/electronics12030496>.
5. Shamasundar, B.; Nosratinia, A. On the Capacity of Index Modulation. *IEEE Trans. Wirel. Commun.* **2022**, *21*, 9114–9126. <https://doi.org/10.1109/TWC.2022.3173207>.
6. Pihtili, M.E.; Ilter, M.C.; Basar, E.; Wichman, R.; Hämäläinen, J. Index Modulation-Based Information Harvesting for Far-Field RF Power Transfer. *IEEE Trans. Wirel. Commun.* **2024**, *23*, 14895–14909. <https://doi.org/10.1109/TWC.2024.3420073>.
7. Rou, H.S.; de Abreu, G.T.F.; Takahashi, T.; González G., D.; Gonsa, O. Enabling Massive Index Modulation Systems via Combinatorics-Free Detection. *IEEE Trans. Wirel. Commun.* **2025**, *24*, 8025–8039. <https://doi.org/10.1109/TWC.2025.3564159>.
8. Ozden, B.A.; Aydin, E.; Aslandogan, E.; Ilhan, H.; Basar, E.; Wen, M.; Di Renzo, M. A New OTFS-Based Index Modulation System for 6G and Beyond: OTFS-Based Code Index Modulation. In Proceedings of the 2025 IEEE 36th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Istanbul, Türkiye, 1–4 September 2025; pp. 1–6. <https://doi.org/10.1109/PIMRC62392.2025.11274686>.
9. Dogukan, A.T.; Basar, E. Reconfigurable Intelligent Surface Code Index Modulation With Quadrature Receive Spatial Modulation. *IEEE Trans. Green Commun. Netw.* **2026**, *10*, 522–532. <https://doi.org/10.1109/TGCN.2025.3587881>.
10. Shi, Y.; Lu, X.; He, Z.; Li, Y.; An, K.; Chatzinotas, S. Efficient Jamming Detection for Index Modulation Based Frequency Hopping Spread Spectrum. In Proceedings of the 2025 IEEE 36th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Istanbul, Türkiye, 1–4 September 2025; pp. 1–7. <https://doi.org/10.1109/PIMRC62392.2025.11275466>.
11. Kaddoum, G.; Ahmed, M.F.A.; Nijsure, Y. Code Index Modulation: A High Data Rate and Energy Efficient Communication System. *IEEE Commun. Lett.* **2015**, *19*, 175–178. <https://doi.org/10.1109/LCOMM.2014.2385054>.
12. Huang, B.; Xu, J.; Alouini, M.-S. Generalized Code-Frequency-Space Index Modulation: A Next-Generation Green Communication Solution. *IEEE Trans. Wirel. Commun.* **2025**, *24*, 5990–6005. <https://doi.org/10.1109/TWC.2025.3550446>.
13. Kaddoum, G.; Nijsure, Y.; Tran, H. Generalized Code Index Modulation Technique for High-Data-Rate Communication Systems. *IEEE Trans. Veh. Technol.* **2016**, *65*, 7000–7009. <https://doi.org/10.1109/TVT.2015.2498040>.
14. Cai, X.; Xie, Z.; Chen, P.; Fang, Y.; Basar, E.; Yuen, C. Quadruple Code Index Modulation. *IEEE Trans. Cogn. Commun. Netw.* **2025**, *11*, 2327–2339. <https://doi.org/10.1109/TCCN.2024.3516050>.
15. Zhang, K.; Hai, H.; Wen, M.; Jiang, X.-Q.; Qiu, R. Generalized Space-Code Index Modulation for High Rate and Energy-Efficient MIMO Transmission. *IEEE Trans. Veh. Technol.* **2021**, *70*, 12812–12820. <https://doi.org/10.1109/TVT.2021.3120291>.

16. Aydin, E.; Cogen, F.; Basar, E. Code-Index Modulation Aided Quadrature Spatial Modulation for High-Rate MIMO Systems. *IEEE Trans. Veh. Technol.* **2019**, *68*, 10257–10261. <https://doi.org/10.1109/TVT.2019.2928378>.
17. Ozden, B.A.; Aydin, E.; Cogen, F. Code Index Modulation-Aided Spatial Media-Based Modulation System for Future Wireless Networks. *IEEE Syst. J.* **2023**, *17*, 3762–3770. <https://doi.org/10.1109/JSYST.2022.3230775>.
18. Zhang, G.; Jiang, X.-Q.; Hai, H.; Wen, M.; Shang, P.; Wei, S. Joint Code Index Modulation Aided Enhanced Spatial Modulation for High-Rate MIMO Systems. *IEEE Trans. Green Commun. Netw.* **2023**, *7*, 1383–1393. <https://doi.org/10.1109/TGCN.2023.3237710>.
19. Liu, F.; Zheng, Y.; Lu, H.; Feng, Y. Code Index Modulation Method with Multidimensional Invisible Data Mapping. *IET Signal Process.* **2022**, *16*, 1144–1154. <https://doi.org/10.1049/sil2.12159>.
20. Liu, F.; Zheng, Y.; Feng, Y. High Performance Bit-Activation Code Index Modulation Method. *IET Signal Process.* **2023**, *17*, 481–491. <https://doi.org/10.1049/sil2.12202>.
21. Dillard, G.M.; Reuter, M.; Zeidler, J.; Zeidler, B. Cyclic Code Shift Keying: A Low Probability of Intercept Communication Technique. *IEEE Trans. Aerosp. Electron. Syst.* **2003**, *39*, 786–798. <https://doi.org/10.1109/TAES.2003.1238736>.
22. Chauvat, R.; Garcia-Pena, A.; Paonni, M. Efficient LDPC-Coded CCSK Links for Robust High Data Rates GNSS. *IEEE Trans. Aerosp. Electron. Syst.* **2023**, *59*, 404–417. <https://doi.org/10.1109/TAES.2022.3190819>.
23. Tek, Y.I.; Basar, E. Joint Delay-Doppler Index Modulation for Orthogonal Time Frequency Space Modulation. *IEEE Trans. Commun.* **2024**, *72*, 3985–3993. <https://doi.org/10.1109/TCOMM.2024.3370827>.
24. Ding, X.; Lu, Q.; Zhang, Y.; Li, G.; Gao, X.; Ye, N.; Niyato, D.; Yang, K. Few-Shot Recognition and Classification Framework for Jamming Signal: A CGAN-Based Fusion CNN Approach. *IEEE Trans. Veh. Technol.* **2026**, early access. <https://doi.org/10.1109/TVT.2026.3678290>.
25. Li, M.; Xu, W.; Hong, S.; Sun, H. A Block Index Modulation Aided Multiple Sequences Spread-Spectrum System for Underwater Acoustic Communication. In Proceedings of the 2024 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), Bali, Indonesia, 19–24 August 2024; pp. 1–6. <https://doi.org/10.1109/ICSPCC62635.2024.10770398>.
26. Zhang, P.; Jin, X.; Wan, C.; Xing, S.; Huang, C.; Wen, M.; Yao, Y. Rectangular Differential Reflecting Spatial Modulation: A Noncoherent Joint Index-Modulation of RIS-Assisted MIMO System. *IEEE Trans. Commun.* **2024**, *72*, 7387–7400. <https://doi.org/10.1109/TCOMM.2024.3409538>.
27. Elbir, A.M.; Celik, A.; Eltawil, A.M.; Amin, M.G. Index Modulation for Integrated Sensing and Communications: A Signal Processing Perspective. *IEEE Signal Process. Mag.* **2024**, *41*, 44–55. <https://doi.org/10.1109/MSP.2024.3444195>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.