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Spectral-Centroid-Based Non-Coherent Detection for Chaos Shift Keying

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Abstract

Classical coherent chaos shift keying (CSK) provides certain physical-layer advantages by exploiting chaotic waveforms, but it relies on fragile chaos synchronization, which is difficult to maintain in multipath fading channels. To overcome this limitation, we propose a novel non-coherent CSK detector based on the spectral centroid (SC)—the center of mass of the power spectral density. We demonstrate that the SC is an intrinsic invariant of a chaotic map, enabling a fixed-threshold detection scheme that requires no synchronization, no reference sequence, and no channel estimation. Simulation results over multipath Rayleigh fading channels show that the proposed system significantly outperforms conventional CSK pairs. Unlike coherent CSK, which suffers from an error floor under frequency-selective fading, the proposed SC-CSK system benefits from frequency diversity and achieves robust performance. Moreover, while conventional differential chaos shift keying (DCSK) degrades severely under high-mobility scenarios, the proposed system maintains a stable BER across a wide range of Doppler shifts. The receiver is lightweight, interpretable, and well-suited for resource-constrained applications such as Internet of Things (IoT) devices.

Keywords: chaos shift keying (CSK); multipath Rayleigh fading; spectral centroid; non-coherent detection

1. Introduction

The fifth-generation (5G) and next-generation wireless networks, including the envisioned sixth-generation (6G), are designed to support enhanced physical-layer security, massive connectivity, and low-complexity device design. Among various physical-layer techniques, chaotic modulation has attracted considerable attention due to its inherent wideband, noise-like, and deterministic but unpredictable properties, which are favorable for low-probability-of-intercept (LPI) and anti-jamming communications [1,2].

Chaos-based digital communications uniquely combine information transmission with inherent secrecy. This concept was articulated in seminal theoretical works on chaos-based digital communications [3], and has been further validated by recent advances, including chaotic information metasurfaces for direct physical-layer secure communication [4] and chaotic optical communication for secure free-space links under adverse weather conditions [5]. Collectively, these efforts demonstrate that chaotic signals can simultaneously carry information and provide security without relying on conventional encryption. Among various chaotic modulation schemes, chaos shift keying (CSK) is the most fundamental [6]. In CSK, information bits are mapped to different chaotic basis functions, each generated by a distinct chaotic map. Despite its conceptual simplicity and excellent security, classical CSK requires the receiver to regenerate the same chaotic sequence as the



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transmitter—a process known as chaos synchronization [7]. Although chaos synchronization has been theoretically proven in additive white Gaussian noise (AWGN) channels, it becomes extremely challenging to maintain in multipath fading channels [3]. Consequently, the practical implementation of coherent CSK faces significant difficulties.

To circumvent the synchronization requirement, differential chaos shift keying (DCSK) was introduced by Kolumbán et al. [8]. In DCSK, each symbol consists of a reference sequence followed by an information-bearing sequence delayed by half the duration of the symbol. The receiver performs a delayed correlation to recover the bit, eliminating the need for chaotic synchronization. This elegant design has been extended to various application scenarios, including vehicular communications [9], terrestrial–satellite hybrid free-space optical/Radio Frequency (FSO/RF) links [10], and covert wireless communications [11].

In recent years, numerous DCSK variants have been proposed to overcome its inherent limitations. Early efforts exploited index modulation (IM) techniques, which use the indices of carriers, time slots, codes, or permutations to convey additional information bits with little or no extra energy. Representative works include carrier index DCSK (CI-DCSK) [12], time slot index DCSK [13], code index DCSK (CIM-DCSK) [14], and permutation index DCSK (PI-DCSK) [15]. To further enhance data rate and spectral efficiency, subsequent works generalized the concept to multi-dimensional IM, where two or more indices are jointly exploited, such as Carrier-Time-Code Index Modulation Differential Chaos Shift Keying (CTCIM-DCSK) [16] and Hybrid Carrier-Code and Reference Index Modulation in DCSK System With Time-Frequency Resources (HCCRIM-TF-DCSK) [17]. These index-based schemes have significantly improved the data rate and spectral efficiency while maintaining favorable BER performance.

Parallel to IM, another line of research has focused on waveform and physical-layer structure improvements. Representative designs include three-dimensional non-constant-envelope constellation-assisted DCSK [18], generalized multilevel code-shifted DCSK [19], low-peak-to-average power ratio (low-PAPR) orthogonal frequency division multiplexing differential chaos shift keying (OFDM-DCSK) for integrated sensing and communication (ISAC) [20], and matrix-index assisted multi-carrier DCSK for physical-layer security [21]. Orthogonal time-frequency space modulation with differential chaos shift keying (OTFS-DCSK) with alternating direction method of multipliers (ADMM)-based detection for high-mobility scenarios [9] has also been proposed. Moreover, polar-coded and space-time-block-coded DCSK schemes have been developed to further enhance transmission reliability and diversity gain [22,23].

Despite these advances, most DCSK schemes still require a reference sequence per symbol, which not only reduces spectral efficiency but, more critically, creates a fundamental security vulnerability. This predictable anchor point makes the system particularly susceptible to malicious attacks, such as pulse jamming, where the known signal structure can be exploited to significantly degrade performance [24].

To mitigate these vulnerabilities, various security enhancement mechanisms have been integrated into DCSK designs. Examples include an reconfigurable intelligent surface (RIS)-enabled M-ary DCSK system with block interleaving, where a chaotic merging sort algorithm is used to encrypt interleaving patterns, and security metrics such as information leakage and probability of secrecy outage are analyzed [25]. A permutation-index-based OFDM-DCSK system has been developed with physical-layer secrecy analysis, derived from secrecy capacity and secrecy outage probability to quantify the performance disparity between legitimate and eavesdropping receivers [26]. More recently, a reference-modulated DCSK (RM-DCSK) system employing a 2D memristor-coupled Chebyshev map has been proposed for power line communication, where a stream cipher with SHA-512 hashing is used to encrypt data prior to modulation, reinforcing security against both eavesdropping

and differential attacks [27]. However, these approaches either incur increased system complexity, rely on reference signal transmission, or require channel state information at the transmitter, limiting their practicality in certain scenarios.

Recently, deep learning (DL)-based architectures have emerged that shift the focus back to CSK while eliminating the need for chaotic synchronization. By learning chaotic signal characteristics during offline training, these receivers remove the requirement for reference signals [28–30]. Nevertheless, these approaches face inherent limitations: they require extensive offline training, are sensitive to channel variations, and fail to fully exploit the distinct properties of chaotic signals.

To address this, recent works have incorporated spectral features into DL-based receivers. For example, the PSD-DLCSK scheme uses the power spectral density (PSD) as a deep neural network (DNN) input [31], and a dual-domain DL-non-orthogonal multiple access-CSK (DL-NOMA-CSK) system jointly processes time- and frequency-domain information [32]. Both demonstrate that the PSD is an effective discriminant. However, they still suffer from the aforementioned DL limitations: high complexity, lack of interpretability, and dependence on offline training.

This observation motivates our work. Instead of relying on data-hungry black-box neural networks, we propose extracting a simple yet informative physical feature—the spectral centroid, defined as the center of mass of the PSD. This single scalar captures the essence of the PSD shape and serves as a natural discriminant for different chaotic maps. Our approach requires no offline training, no chaotic synchronization, and no reference signal transmission, offering a lightweight, interpretable, and computationally efficient alternative to existing DL-based solutions that also exploit PSD features. The main contributions of this paper are summarized as follows.

- We establish that the spectral centroid (SC) is an intrinsic invariant of a chaotic map, independent of the initial condition, and provide SC values for 11 commonly used chaotic maps. Based on this invariance, we develop a non-coherent CSK detector with a fixed threshold determined solely by the map pair.
- With a proper selection of chaotic map pairs, extensive simulations over multipath Rayleigh fading channels demonstrate that the proposed scheme achieves significantly better BER performance than conventional CSK, while requiring no synchronization, no reference sequence, and no channel estimation.
- The robustness of the proposed scheme is further validated under various multipath configurations and under high-mobility scenarios with large Doppler shifts, where conventional DCSK suffers from severe performance degradation.

The remainder of this paper is organized as follows. Section 2 describes the system model, including the chaotic maps, the multipath Rayleigh fading channel, and the definition of the spectral centroid. Section 3 presents the theoretical analysis, covering the invariance of the spectral centroid, the derivation of the decision threshold, and the separability criterion for map pair selection. Section 4 provides simulation results to evaluate the BER performance of the proposed scheme under various channel conditions. Section 5 concludes the paper.

2. Novel System Model

In this section, we present the complete system model of the proposed spectral-centroid-based CSK (SC-CSK) scheme. The block diagram of the proposed system is shown in Figure 1.

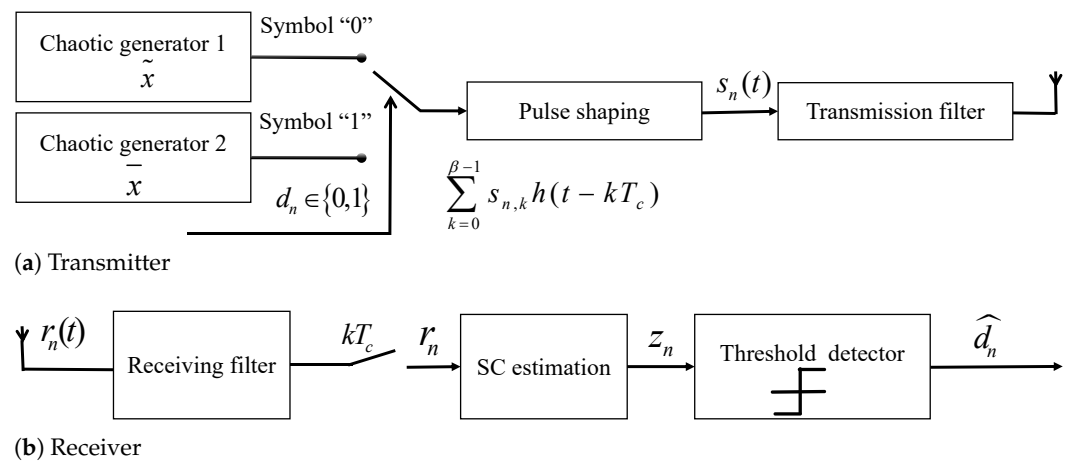


Figure 1. Block diagram of the proposed SC-CSK system.

2.1. CSK Transmitter

In classical CSK, information bits are mapped to different chaotic basis functions. Let the preprocessed output vectors generated by chaotic generator 1 and chaotic generator 2 in Figure 1 be denoted as $\tilde{\mathbf{x}} = [\tilde{x}_1, \tilde{x}_2, \dots, \tilde{x}_\beta]^T$ and $\bar{\mathbf{x}} = [\bar{x}_1, \bar{x}_2, \dots, \bar{x}_\beta]^T$, respectively. Let $d_n \in \{0, 1\}$ represent the n -th transmitted binary symbol. During the n -th symbol transmission over the channel, the continuous-time transmitted signal $s_n(t)$ is given by

$$s_n(t) = \sum_{k=0}^{\beta-1} s_{n,k} g(t - kT_c), \quad 0 \leq t \leq T_b \quad (1)$$

where $g(t)$ is the pulse shaping filter, and $s_{n,k}$ is the k -th chip of the n -th transmitted symbol, given by

$$s_{n,k} = \begin{cases} \tilde{x}_k, & \text{if } d_n = 0, \\ \bar{x}_k, & \text{if } d_n = 1. \end{cases} \quad (2)$$

The proposed system follows the conventional CSK transmission framework, which is inherently a spread-spectrum communication scheme. The spreading factor β represents the number of chaotic chips used to transmit one information bit. Specifically, each information bit with duration T_b is spread into a chaotic sequence containing β chips, where the duration of each chaotic chip is given by $T_c = T_b / \beta$.

In practical CSK systems, β is a configurable parameter that determines the trade-off among detection performance, computational complexity, and transmission efficiency. A small β may result in insufficient chaotic samples for exploiting the statistical characteristics of the chaotic sequence, whereas a large β increases the number of chaotic samples processed for each transmitted bit and thus increases the computational cost. Therefore, appropriate values of β are selected in the simulation study according to different evaluation scenarios.

2.2. Spectral-Centroid-Based Receiver

At the receiver side, the transmitted signal is subject to channel fading and additive noise. For multipath Rayleigh fading channels, the channel impulse response is given by

$$h(t) = \sum_{l=1}^L \lambda_l \delta(t - \tau_l), \quad (3)$$

where L denotes the number of multipath components. Here, λ_l denotes the complex-valued fading coefficient, whereas τ_l represents the real-valued propagation delay of the l -th path. For each path l , the fading coefficient is modeled as

$$\lambda_l = a_l + jb_l, \quad (4)$$

where a_l and b_l are independent zero-mean Gaussian random variables with variance σ_l^2 , following the conventional Rayleigh fading channel model [33]. The independence of the real and imaginary components results from the circularly symmetric complex Gaussian assumption widely adopted in wireless channel modeling. The additive noise term represents the receiver thermal noise and is modeled as AWGN. The channel power is normalized such that $\sum_{l=1}^L \mathbb{E}[|\lambda_l|^2] = 1$.

Consequently, the received signal for the n -th symbol can be expressed as

$$r_n(t) = h(t) \otimes s_n(t) + w_n(t), \quad 0 \leq t \leq T_b, \quad (5)$$

where $\otimes$ denotes convolution, $s_n(t)$ is the transmitted signal defined in (1), and $w_n(t)$ is the additive white Gaussian noise (AWGN) with zero mean and power spectral density $N_0/2$.

Although the transmitted waveform is formulated in the continuous-time domain, the receiver performs all subsequent signal processing in the discrete-time domain after matched filtering and sampling. The receiver is assumed to have prior knowledge of the selected chaotic map pair and the corresponding threshold γ , which are determined during system initialization and shared between the transmitter and receiver. During data detection, no reference sequence or local chaotic synchronization is required. Specifically, the received continuous-time signal $r_n(t)$ is first passed through a matched filter and sampled at the sampling interval T_c in Figure 1b, yielding the discrete-time sequence

$$r_{n,k} = r_n(t)|_{t=kT_c}, \quad k = 0, 1, \dots, \beta - 1.$$

The spectral centroid is then calculated based on the discrete-time sequence $\mathbf{r}_n = [r_{n,0}, r_{n,1}, \dots, r_{n,\beta-1}]^T$ through FFT and power spectrum estimation. Finally, the obtained SC value is compared with a predetermined threshold γ to recover the transmitted bit $\hat{d}_n$. The threshold γ is obtained offline according to the spectral centroid characteristics of the selected chaotic basis pair and is assumed to be available at the receiver before communication. Since the proposed detector only exploits the spectral centroid of the received sequence, the receiver does not require knowledge of the chaotic map pair or the generation of local chaotic reference sequences during detection. Specifically, the decision variable Z_n (the spectral centroid) is computed from $\mathbf{r}_n$ through the following four steps.

Step 1 (DFT): Compute the β -point discrete Fourier transform of the received sequence $\mathbf{r}_n = [r_{n,0}, r_{n,1}, \dots, r_{n,\beta-1}]^T$:

$$R(k) = \sum_{i=0}^{\beta-1} r_{n,i} e^{-j2\pi ki/\beta}, \quad k = 0, 1, \dots, \beta - 1. \quad (6)$$

Step 2 (Power spectrum): Retain only the first half of the spectrum:

$$P(k) = |R(k)|^2, \quad k = 0, 1, \dots, \left\lfloor \frac{\beta}{2} \right\rfloor - 1. \quad (7)$$

Step 3 (Normalized frequencies): Define the normalized frequencies:

$$f_k = \frac{k}{\beta}, \quad k = 0, 1, \dots, \left\lfloor \frac{\beta}{2} \right\rfloor - 1. \quad (8)$$

Step 4 (Spectral centroid): Compute the decision variable Z_n as the spectral centroid:

$$Z_n = \frac{\sum_{k=0}^{\lfloor \beta/2 \rfloor - 1} f_k P(k)}{\sum_{k=0}^{\lfloor \beta/2 \rfloor - 1} P(k)}. \quad (9)$$

The spectral centroid is the center of mass of the PSD. Physically, a small Z_n indicates that the signal energy is concentrated at low frequencies, while a large Z_n indicates concentration at high frequencies. For a perfectly flat spectrum, $Z_n = 0.25$ (the midpoint of the frequency range $[0, 0.5]$). The decision threshold γ is determined offline according to the SC distributions of the selected chaotic map pair and is assumed to be available at the receiver before communication.

Decision rule: The detected bit $\hat{d}_n$ is obtained by comparing Z_n with a fixed threshold γ :

$$\hat{d}_n = \begin{cases} 0, & \text{if } Z_n > \gamma, \\ 1, & \text{if } Z_n \leq \gamma. \end{cases} \quad (10)$$

By convention, the chaotic map with the higher Z_n mean is used for bit 0, and the one with the lower Z_n mean is used for bit 1. The threshold γ is predetermined as the arithmetic mean of the two SC means and remains constant for all operating conditions.

The entire receiver processing consists of one β -point FFT, $O(\beta)$ operations to compute the weighted sum and sum of powers, and one comparison. These operations are standard and well-supported by efficient hardware implementations (e.g., FFT processors, multiply-accumulate units), making the proposed receiver practical for real-time applications.

For practical deployment, the system operates as follows: (i) select a map pair with large SC separation; (ii) precompute the SC means of the two maps offline and set γ to their midpoint; (iii) the threshold γ is hard-coded in the receiver and never updated. Per symbol, the receiver merely performs an FFT, computes the SC, and compares it with γ . No chaos synchronization circuit, delay line, reference sequence storage, channel estimation module, or adaptive threshold logic is required. This low hardware complexity makes the proposed scheme particularly attractive for resource-constrained IoT and sensor nodes.

3. Theoretical Analysis

This section establishes the theoretical foundation for the proposed spectral-centroid-based detection scheme. The logic proceeds as follows: (i) different chaotic maps have distinct power spectral densities (PSDs); (ii) distinct PSDs yield different spectral centroids (SCs); (iii) the SC is a map invariant independent of initial conditions; (iv) channel fading and additive noise do not change the mean SC. Therefore, the SC can serve as a decision statistic with a fixed, predetermined threshold.

3.1. Spectral Centroid as a Map Invariant

For a general chaotic map, due to the ergodicity of chaotic systems, the SC can be accurately estimated numerically using long-sequence averaging. Table 1 lists the SC values for 11 commonly used chaotic maps, including asymptotic values (as $\beta \rightarrow \infty$), practical values at the operating length $\beta = 180$, and standard deviations.

Table 1. Spectral centroid (SC) values for the chaotic maps used in simulations.

Map	Parameters	$\overline{SC} (\beta \rightarrow \infty)$	$\overline{SC} (\beta = 180)$	σ_{SC}
Logistic	$r = 3.7$	0.408	0.408	0.009
Logistic	$r = 3.9$	0.344	0.344	0.006
PiecewiseLogistic	$r = 3.99$	0.308	0.308	0.0187
ICMIC	$a = 2.0$	0.155	0.155	0.008
Bernoulli	$r = 1.5$	0.176	0.176	0.010
Bernoulli	$r = 1.8$	0.187	0.187	0.010
Chebyshev	$k = 4$	0.250	0.250	0.006
PWLCM	$p = 0.4$	0.250	0.250	0.005
Sine	$r = 0.9$	0.409	0.409	0.009
SkewTent	$p = 0.15$	0.398	0.398	0.0147
SkewTent	$p = 0.10$	0.423	0.423	0.0140
Cubic	$a = 4.0$	0.250	0.250	0.007

Note: $\overline{SC}$ values are averaged over 10^5 independent realizations. σ_{SC} denotes the standard deviation at $\beta = 180$.

Several important observations can be drawn from Table 1. First, different chaotic maps exhibit distinct mean spectral centroid (SC) values, which can be broadly classified into three categories: (i) maps with relatively high SC values, such as the Logistic map ($r = 3.7$, $\overline{SC} \approx 0.41$), the Piecewise Logistic map ($r = 3.99$, $\overline{SC} \approx 0.34$), the Sine map, and the Skew Tent map; (ii) maps with intermediate SC values, including the Cubic, Chebyshev, and PWLCM maps, whose mean SC values are around 0.25; and (iii) maps with relatively low SC values, such as the ICMIC map ($a = 2.0$, $\overline{SC} \approx 0.15$) and the Bernoulli map ($r = 1.8$, $\overline{SC} \approx 0.19$). Second, even within the same chaotic map family, different control parameters may produce significantly different SC values. This is because the control parameter changes the dynamical behavior of the chaotic map, thereby affecting the temporal correlation properties of the generated sequence, its power spectral density (PSD), and consequently the resulting SC. More generally, the observed SC differences originate from the distinct dynamical characteristics of the chaotic maps, which result in different autocorrelation structures and consequently different spectral distributions.

Figure 2a shows the PSDs of four representative chaotic maps under ideal (channel-free) conditions. Skew Tent ($p = 0.15$) and Logistic ($r = 3.9$) exhibit dominant high-frequency components, with their spectral energy concentrated around $f = 0.48$ and $f = 0.38$, respectively. In contrast, ICMIC ($a = 2.0$) exhibits a pronounced low-frequency concentration around $f = 0.05$, while the Bernoulli map ($r = 1.8$) is also dominated by low-frequency components with a more gradually decaying spectrum. These distinct PSD characteristics give rise to the differences in spectral centroid (SC) values among the chaotic maps. Figure 2b illustrates the corresponding PSDs after transmission through a multipath Rayleigh fading channel at an SNR of 30 dB. Although frequency-selective fading introduces random fluctuations into the PSD, the overall spectral centroid of each chaotic map remains largely unchanged. This observation provides the physical basis for the proposed SC-based non-coherent detector and will be analyzed quantitatively in the following subsections.

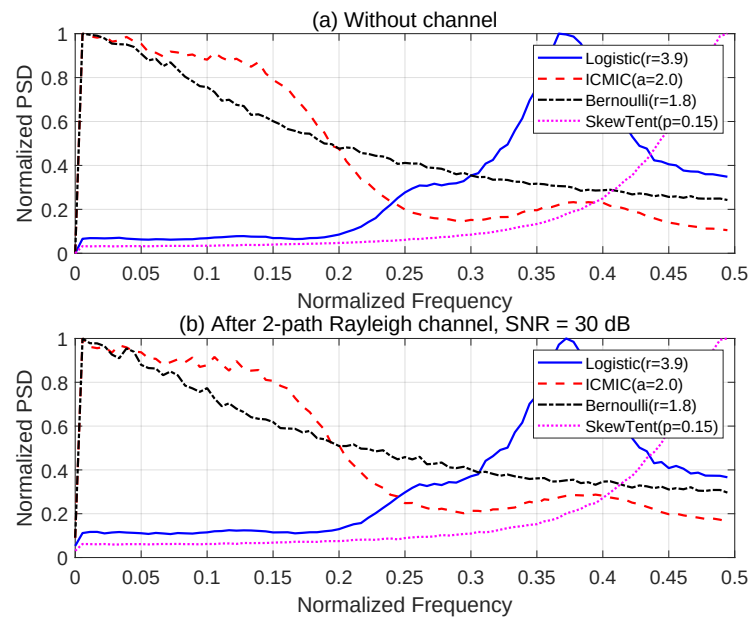


Figure 2. PSD of four representative chaotic maps: (a) ideal (no channel); (b) after multipath Rayleigh channel at SNR = 30 dB.

3.2. Effect of AWGN on Spectral Centroid

Consider first a pure AWGN channel (no multipath), where the received signal is $r(n) = s(n) + w(n)$. Since the signal and noise are uncorrelated, the power spectrum of the received signal is

$$P_r(k) = \mathbb{E}[|R(k)|^2] = |S(k)|^2 + \sigma_w^2 = P_s(k) + \sigma_w^2, \quad (11)$$

where $P_s(k)$ is the power spectrum of the transmitted signal. AWGN appears as a uniform noise floor elevation in the power spectrum.

Substituting (11) into the definition of the spectral centroid yields

$$Z_n = \frac{\sum_{k=0}^{M-1} f_k (P_s(k) + \sigma_w^2)}{\sum_{k=0}^{M-1} (P_s(k) + \sigma_w^2)}, \quad (12)$$

where $M = \lfloor \beta/2 \rfloor$, $f_k = k/\beta$, and σ_w^2 is the noise variance.

Let $E_P = \sum_{k=0}^{M-1} P_s(k) = \beta$ (since the signal energy is normalized to one per sample), and define the signal spectral centroid as $\overline{SC}(s) = \frac{1}{E_P} \sum_{k=0}^{M-1} f_k P_s(k)$. The sums of the frequency weights are

$$\sum_{k=0}^{M-1} f_k = \frac{1}{\beta} \cdot \frac{M(M-1)}{2}, \quad \sum_{k=0}^{M-1} 1 = M. \quad (13)$$

For large β , we have $M \approx \beta/2$ and $\sum_k f_k \approx \beta/8$. Substituting these approximations into (12) gives the following simplified expression that reveals the asymptotic behavior:

$$Z_n \approx \frac{\overline{SC}(s) \cdot \text{SNR} + 1/8}{\text{SNR} + 1/2}, \quad (14)$$

where $\text{SNR} = 1/\sigma_w^2$. As $\text{SNR} \rightarrow \infty$, $Z_n \rightarrow \overline{SC}(s)$; as $\text{SNR} \rightarrow 0$, $Z_n \rightarrow 1/4$.

For exact calculations at finite β , one should use the precise expression

$$Z_n = \frac{\overline{SC}(s) \cdot \beta + \sigma_w^2 \cdot \frac{M(M-1)}{2\beta}}{\beta + \sigma_w^2 M}, \quad M = \lfloor \beta/2 \rfloor. \quad (15)$$

Remark 1. Equation (14) reveals that AWGN causes the SC to contract toward $1/4$. However, this contraction is symmetric for both maps: if $\overline{\text{SC}}(s_0) > 1/4$ and $\overline{\text{SC}}(s_1) < 1/4$, then $Z_n^{(0)} > 1/4 > Z_n^{(1)}$ for any SNR. More generally, if the two SC means are symmetric about some point, that point remains the optimal threshold for all SNRs.

3.3. Effect of Multipath Fading on Spectral Centroid

In a multipath channel, the frequency-domain representation of the received signal is

$$R(k) = H(k)S(k) + W(k), \quad (16)$$

$$H(k) = \sum_{l=1}^L \lambda_l e^{-j2\pi k \tau_l / \beta}, \quad (17)$$

where $H(k)$ is the channel frequency response, and λ_l and τ_l are the complex fading coefficient and delay of the l -th path as defined in (3). The power spectrum becomes

$$P_r(k) = |H(k)|^2 P_s(k) + \sigma_w^2. \quad (18)$$

Compared with pure AWGN, the multipath configuration introduces frequency-selective multiplicative distortion $|H(k)|^2$.

Taking the expectation over channel realizations and using the channel power normalization $\mathbb{E}[|H(k)|^2] = \sum_{l=1}^L \mathbb{E}[|\lambda_l|^2] = \sum_{l=1}^L P_l = 1$, where $P_l = \mathbb{E}[|\lambda_l|^2]$ denotes the average power of the l -th path, satisfying $\sum_{l=1}^L P_l = 1$, we obtain

$$\mathbb{E}_h[P_r(k)] = P_s(k) + \sigma_w^2. \quad (19)$$

This is identical to the pure AWGN case. Consequently, the expected SC under multipath fading is

$$\mathbb{E}_h[Z_n] \approx \frac{\overline{\text{SC}}(s) \cdot \text{SNR} + 1/8}{\text{SNR} + 1/2}, \quad (20)$$

which is the same as (14).

Remark 2. Multipath fading does not bias the SC estimate; it only increases its variance. The variance $\text{Var}_h[Z_n]$ depends on the frequency selectivity of the channel. A larger delay spread (e.g., larger τ_l) causes $|H(k)|^2$ to fluctuate more rapidly across frequency bins, and these fluctuations are averaged out in the summations of the SC calculation, resulting in smaller variance—a frequency diversity effect. Conversely, a very small delay spread makes $|H(k)|^2$ nearly flat, and a deep fade can affect the entire signal band, leading to larger variance. This explains the counter-intuitive observation that increasing the second-path delay improves BER performance (to be verified in Section 4).

Importantly, multipath increases the variance of the decision statistic but introduces no bias. This is the fundamental reason why a fixed threshold remains feasible under multipath fading, in contrast to DCSK, where the reference sequence itself is distorted by the channel, causing both bias and increased variance in the correlation output.

As the delay spread increases, $|H(k)|^2$ fluctuates more rapidly across frequency bins, leading to a reduction in the estimation variance $\sigma_{\text{ch}}^2(\tau)$. This effect, which we term frequency diversity, is characterized by the channel-induced variance

$$\sigma_{\text{ch}}^2(\tau) = \mathbb{E}[(Z_n - \mathbb{E}[Z_n])^2], \quad (21)$$

which is empirically observed to decrease with τ .

Consider a two-path multipath channel with delay τ . The channel frequency response is $H(f) = 1 + e^{-j2\pi f\tau}$, and its power transfer function is $|H(f)|^2 = 4\cos^2(\pi f\tau)$. The spectral nulls occur at frequencies $f = (2n + 1)/(2\tau)$.

When τ is small (e.g., $\tau = 1$), the first null is located at $f = 0.5$. This null may fall within the signal's energy-concentrated band, causing severe distortion that affects the entire signal spectrum. Consequently, the SC estimate exhibits large variance.

When τ is sufficiently large (e.g., $\tau = 50$), the first null shifts to a very low frequency ($f = 0.01$), far from the signal's energy-concentrated band. In this case, $|H(f)|^2$ fluctuates rapidly across the signal band, creating multiple independent fading realizations. The summation operations in the SC calculation average over these independent fluctuations, effectively reducing the estimation variance.

As τ increases, the coherence bandwidth $B_c \approx 1/\tau$ decreases, and the number of effectively independent frequency bins within the signal band increases. This frequency diversity reduces $\sigma_{\text{ch}}^2(\tau)$, leading to improved BER performance. In the limit of very large τ , $|H(k)|^2$ becomes uncorrelated across frequencies, and $\sigma_{\text{ch}}^2(\tau)$ tends to zero. This analysis reveals a fundamental advantage of the proposed SC-CSK scheme: unlike conventional DCSK, which suffers from severe inter-symbol interference (ISI) as delay increases, the SC-CSK detector exploits large delay spreads to achieve frequency diversity, thereby improving performance.

The overall variance of the SC estimator can be decomposed into three independent contributions:

$$\text{Var}[Z_n] = \underbrace{\frac{\sigma_0^2}{\beta}}_{\text{intrinsic}} + \underbrace{\frac{N_0}{24\beta}}_{\text{noise}} + \underbrace{\sigma_{\text{ch}}^2}_{\text{channel}}, \quad (22)$$

where σ_0^2 is the single-sample SC variance of the chaotic map, $N_0/2$ is the noise power spectral density, and σ_{ch}^2 is the channel-induced variance analyzed in (21). The first two terms decay as $1/\beta$, indicating that increasing the spreading factor β reduces the estimation variance and improves detection reliability.

3.4. Threshold Determination and Map Pair Selection

From the analyses above, the conditional expectations of Z_n under the two hypotheses are

$$\mathbb{E}[Z_n | H_i] = \frac{\overline{\text{SC}}_i \cdot \text{SNR} + 1/8}{\text{SNR} + 1/2}, \quad i = 0, 1. \quad (23)$$

Under equal prior probabilities and assuming approximately equal variances, the optimal threshold that minimizes the BER is the midpoint of the two conditional means:

$$\gamma_{\text{opt}}(\text{SNR}) = \frac{\mathbb{E}[Z_n | H_0] + \mathbb{E}[Z_n | H_1]}{2} = \frac{(\overline{\text{SC}}_0 + \overline{\text{SC}}_1) \cdot \text{SNR}/2 + 1/8}{\text{SNR} + 1/2}. \quad (24)$$

For high SNR ($\text{SNR} \gg 1$), $\gamma_{\text{opt}} \rightarrow (\overline{\text{SC}}_0 + \overline{\text{SC}}_1)/2$. For low SNR, the threshold shifts toward $1/4$, but due to the symmetric contraction of both conditional means, the midpoint remains near-optimal. Therefore, the fixed threshold

$$\gamma = \frac{\overline{\text{SC}}_A + \overline{\text{SC}}_B}{2} \quad (25)$$

is robust across the entire SNR range.

Not all map pairs are equally suitable for SC-based detection. To quantitatively evaluate map pairs, we define the separability index

$$\rho = \frac{|\overline{SC}_A - \overline{SC}_B|}{\sqrt{\sigma_A^2 + \sigma_B^2}}. \quad (26)$$

A larger ρ indicates smaller overlap between the two SC distributions and, hence, better detection performance.

Table 2 lists the candidate chaotic map pairs together with the decision threshold γ , mean SC separation $\Delta\overline{SC}$, standard deviations σ_A and σ_B , and separability index ρ . Among all the evaluated combinations, the pairs consisting of Logistic ($r = 3.9$) versus ICMIC ($a = 2.0$) and Sine ($r = 0.9$) versus ICMIC ($a = 2.0$) achieve high separability indices of $\rho = 18.82$ and $\rho = 20.58$, respectively. These two map pairs exhibit several desirable characteristics: (i) relatively large separations between the mean SC values ($\Delta\overline{SC} = 0.19$ and 0.16 , respectively); (ii) small SC standard deviations ($\sigma_{\text{Logistic}} = 0.006$, $\sigma_{\text{Sine}} = 0.009$, and $\sigma_{\text{ICMIC}} = 0.008$); and (iii) sufficiently distinguishable SC distributions with limited overlap, which facilitate reliable threshold-based detection.

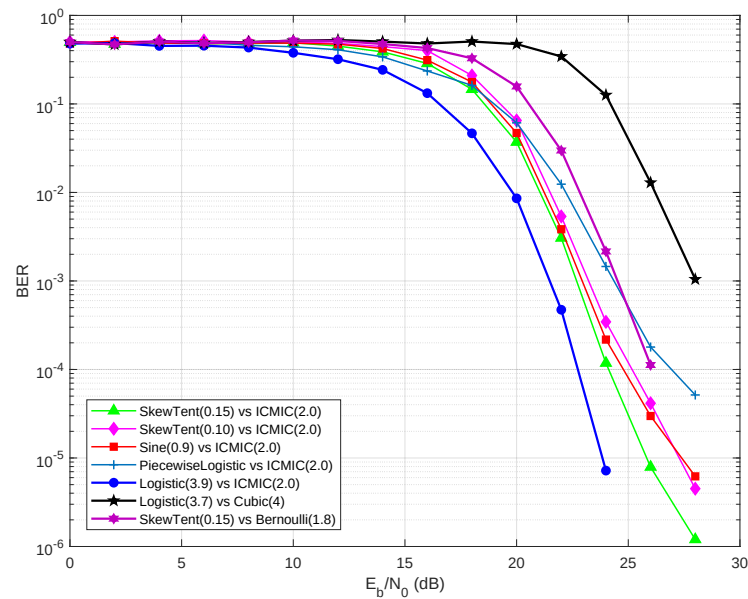
Table 2. Spectral-centroid separability analysis of different chaotic map pairs.

Chaotic Map Pair	γ	$ \Delta\overline{SC} $	σ_A	σ_B	ρ
Logistic (3.9) vs. ICMIC (2.0)	0.2495	0.1899	0.0056	0.0084	18.82
Logistic (3.7) vs. Cubic (4.0)	0.3292	0.1577	0.0089	0.0155	8.81
Sine (0.9) vs. ICMIC (2.0)	0.2820	0.2550	0.0091	0.0084	20.58
Piecewise Logistic vs. ICMIC (2.0)	0.2314	0.1539	0.0187	0.0084	7.50
Skew Tent (0.10) vs. ICMIC (2.0)	0.2891	0.2693	0.0140	0.0084	16.53
SkewTent (0.15) vs. ICMIC (2.0)	0.2763	0.2435	0.0147	0.0084	14.40
SkewTent (0.15) vs. Bernoulli (1.8)	0.2924	0.2436	0.0147	0.0137	10.53

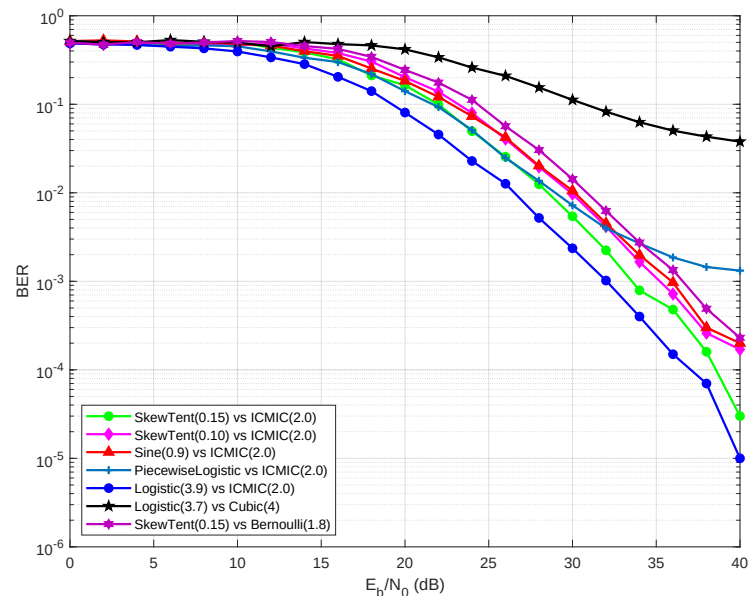
Although the Sine–ICMIC pair achieves a slightly higher separability index ($\rho = 20.58$) than the Logistic–ICMIC pair ($\rho = 18.82$), the Sine map exhibits a larger SC standard deviation, resulting in a relatively wider SC distribution. This increased dispersion may affect the detection performance under practical channel conditions, as observed in the simulation results presented in Figure 3. Therefore, while the separability index ρ provides an effective measure of the statistical distinguishability between two chaotic basis sequences, the final detection performance is also influenced by the detailed distribution characteristics of the SC values.

For comparison, the conventional chaotic map pairs, namely Logistic ($r = 3.7$) versus Cubic ($a = 4.0$) and Piecewise Logistic versus ICMIC ($a = 2.0$), achieve separability indices of only $\rho = 8.81$ and $\rho = 7.50$, respectively, which are significantly lower than those of the selected map pairs. These results demonstrate that chaotic map pairs with larger SC separability provide more suitable basis sequences for the proposed SC-based non-coherent detection scheme.

It should be noted that classical discrete chaotic maps, such as the Logistic map, have known limitations, including non-uniform invariant distributions and periodic behaviors under finite-precision implementations. These issues are particularly important in cryptographic applications, where randomness and unpredictability are the primary requirements. However, the objective of this work is not to design a cryptographically secure chaotic generator, but to investigate a non-coherent detection framework based on the spectral characteristics of chaotic sequences. The results in Table 2 and Figure 3 demonstrate that the proposed detector is applicable to a broad class of discrete chaotic maps with suitable spectral separability, rather than being tailored to a specific chaotic generator.



(a) AWGN channel



(b) Multipath Rayleigh channel

Figure 3. BER performance of the proposed SC-CSK scheme with different map pair selection under (a) AWGN and (b) multipath Rayleigh fading channels.

4. Simulation Analysis

4.1. Simulation Setup

This section presents a comprehensive performance evaluation of the proposed SC-CSK scheme. Specifically, we describe the simulation setup and parameter configuration, investigate the selection criteria for optimal chaotic map pairs, analyze the impact of spreading factor β on system performance, compare the BER performance against coherent CSK and theoretical lower bounds, and evaluate the system's robustness under various multipath channel conditions.

4.2. Selection of Map Pairs

Figure 3 illustrates the BER performance comparison of different chaotic map pairs over AWGN and 2-path Rayleigh fading channels with a spreading factor $\beta = 180$. For the

multipath Rayleigh channel, the path delays and normalized average powers are set as $\tau = [0, 5T_c]$ and equal power distribution (e.g., $[1/2, 1/2]$), respectively. As shown in the figure, under both AWGN and multipath Rayleigh fading channels, chaotic map pairs with relatively large separability indices ρ generally achieve reliable communication performance, with BER decreasing rapidly as E_b/N_0 increases. These pairs include SkewTent (0.15) vs. ICMIC (2.0), SkewTent (0.10) vs. ICMIC (2.0), Sine (0.9) vs. ICMIC (2.0), Logistic (3.9) vs. ICMIC (2.0), and SkewTent (0.15) vs. Bernoulli (1.8). In contrast, the Piecewise Logistic vs. ICMIC (2.0) and Logistic (3.7) vs. Cubic (4.0) pair exhibits significantly degraded performance. In particular, under the multipath Rayleigh fading channel, BER remains above 10^{-2} even when E_b/N_0 reaches 40 dB for the Logistic (3.7) vs. Cubic (4.0) pair.

By jointly analyzing the BER results in Figure 3 and the separability analysis in Table 2, it can be observed that chaotic map pairs with larger separability indices generally provide better detection performance. For example, the Logistic (3.9) vs. ICMIC (2.0) pair achieves a relatively high separability index ($\rho = 18.82$) and exhibits excellent BER performance under both AWGN and multipath fading channels. Conversely, the Logistic (3.7) vs. Cubic (4.0) pair has a much lower separability index ($\rho = 8.81$), corresponding to poor SC distinguishability and significantly degraded BER performance. These results indicate that the separability index ρ can serve as an effective auxiliary criterion for selecting suitable chaotic map pairs in SC-based CSK systems.

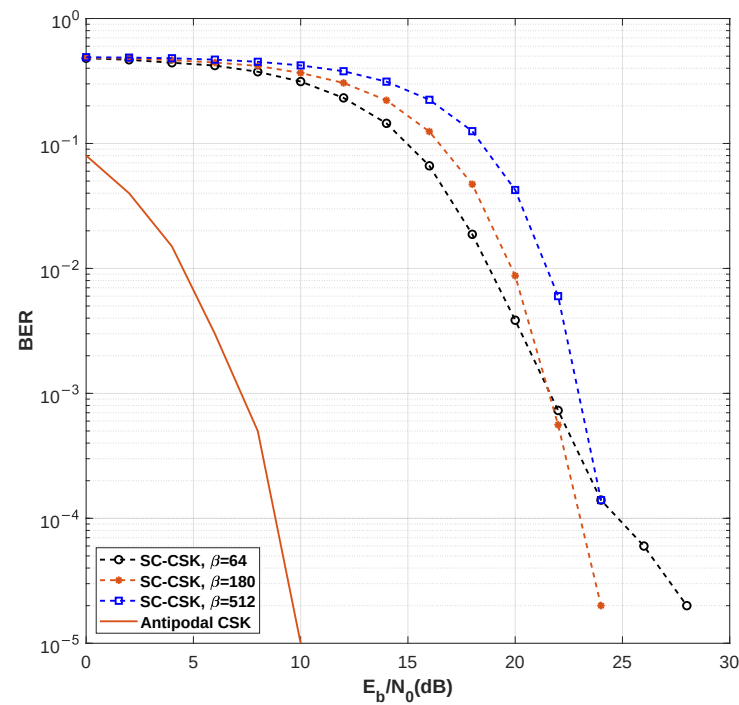
It is worth noting that ρ alone does not completely determine the final detection performance. Although the Sine (0.9) vs. ICMIC (2.0) pair achieves a higher separability index than the Logistic (3.9) vs. ICMIC (2.0) pair, its BER performance is slightly inferior under both AWGN and multipath Rayleigh fading channels. This phenomenon can be attributed to the larger SC standard deviation of the Sine map, which results in a wider SC distribution and increases the overlap probability between the decision regions. Therefore, in addition to the separability index, the statistical distribution characteristics of SC values should also be considered when selecting chaotic map pairs.

Based on the above comparison, the Logistic ($r = 3.9$) and ICMIC ($a = 2.0$) pair is adopted in the following simulations due to its favorable BER performance under both AWGN and multipath Rayleigh fading channels.

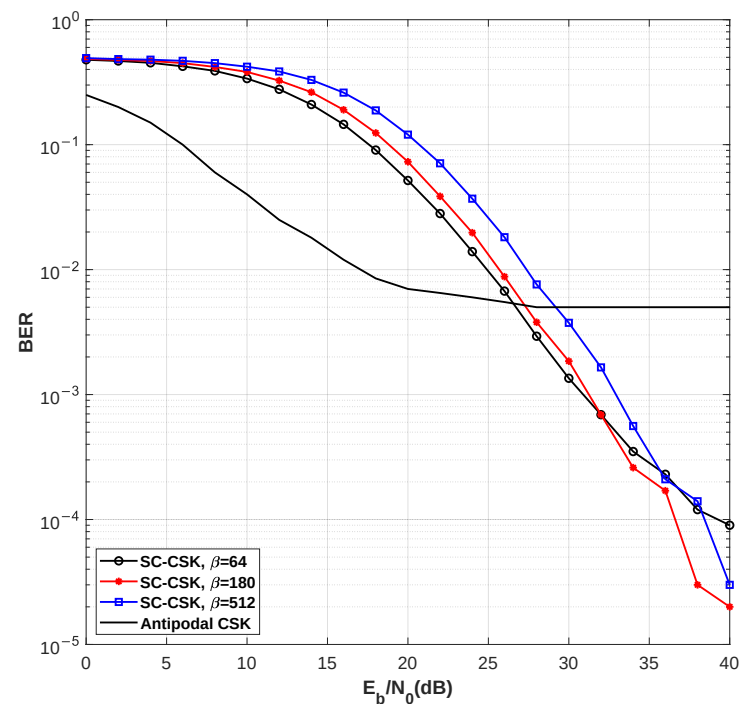
4.3. Impact of Sequence Length on Estimation Variance

Figure 4 depicts the BER performance of the SC-CSK scheme under AWGN and two-path Rayleigh fading channels (with delay $\tau = [0, 5T_c]$) for spreading factors $\beta = 64, 180$, and 512. As observed from the figure, the BER performance deteriorates as β increases under both channel conditions. This behavior can be explained by the chip-level signal-to-noise ratio (SNR). Under a fixed total bit energy E_b , the energy per chip is $E_{\text{chip}} = E_b/\beta$, leading to a chip-level SNR of $\text{SNR}_{\text{chip}} = E_b/(\beta\sigma^2)$. As β increases, the chip-level SNR decreases, resulting in higher BER.

According to the variance analysis in Equation (22), the estimation variance of the spectral centroid consists of three terms: intrinsic variance σ_0^2/β , noise variance $N_0/(24\beta)$, and channel-induced variance σ_{ch}^2 . For a small spreading factor (e.g., $\beta = 64$), the intrinsic and noise variance terms are relatively large, limiting the estimation accuracy. Consequently, as E_b/N_0 increases, the BER quickly reaches an error floor because further reduction in the noise variance cannot compensate for the large estimation variance due to insufficient statistical averaging. In contrast, for a large spreading factor (e.g., $\beta = 512$), the $1/\beta$ terms are sufficiently small, allowing the BER to continue decreasing with increasing E_b/N_0 without an early floor. This explains why smaller β achieves lower BER at low SNR but suffers from an error floor at high SNR, while larger β exhibits higher BER at low SNR but maintains a steady performance improvement across the entire SNR range.



(a) AWGN channel



(b) Multipath Rayleigh channel

Figure 4. BER versus E_b/N_0 for different spreading factors $\beta = 64, 180, 512$ under AWGN and two-path Rayleigh fading channels.

In the AWGN channel, the proposed SC-CSK system exhibits a noticeable performance gap compared to the coherent CSK benchmark [34]. This is because the AWGN channel is frequency-flat, offering no frequency diversity. The coherent CSK detector, benefiting from perfect synchronization and channel knowledge, achieves the optimal matched filter bound.

In contrast, under the two-path Rayleigh fading channel, the proposed SC-CSK system demonstrates a clear advantage over the coherent CSK benchmark [34], particularly

when $E_b/N_0 > 25$ dB. The coherent CSK benchmark suffers from an error floor, with its BER stagnating between 10^{-2} and 10^{-3} , failing to improve further with increasing SNR. This is because coherent CSK requires accurate channel estimation and synchronization, which become unreliable under frequency-selective fading. In contrast, the SC-CSK system continues to achieve lower BER as E_b/N_0 increases. This advantage stems from the frequency diversity effect analyzed in Section 3. As derived in Equation (21) and discussed therein, a frequency-selective channel with delay spread τ introduces independent fading across different frequency bins. The summation operations in the SC calculation average over these independent fluctuations, effectively reducing the channel-induced variance $\sigma_{\text{ch}}^2(\tau)$. Consequently, the SC-CSK system not only avoids the error floor but also benefits from the multipath channel, making it particularly suitable for frequency-selective fading environments.

To identify the optimal spreading factor for the proposed system, we evaluate the system performance over a range of spreading factors from $\beta = 10$ to 1000 on the two-path Rayleigh channel with delay $\tau = [0, 5T_c]$. As illustrated in Figure 5, the optimal spreading factor is consistently located around $\beta \approx 100$ for all tested SNR levels, i.e., $E_b/N_0 = 24, 28$, and 32 dB. Moreover, it can be observed that the optimal spreading factor increases with E_b/N_0 .

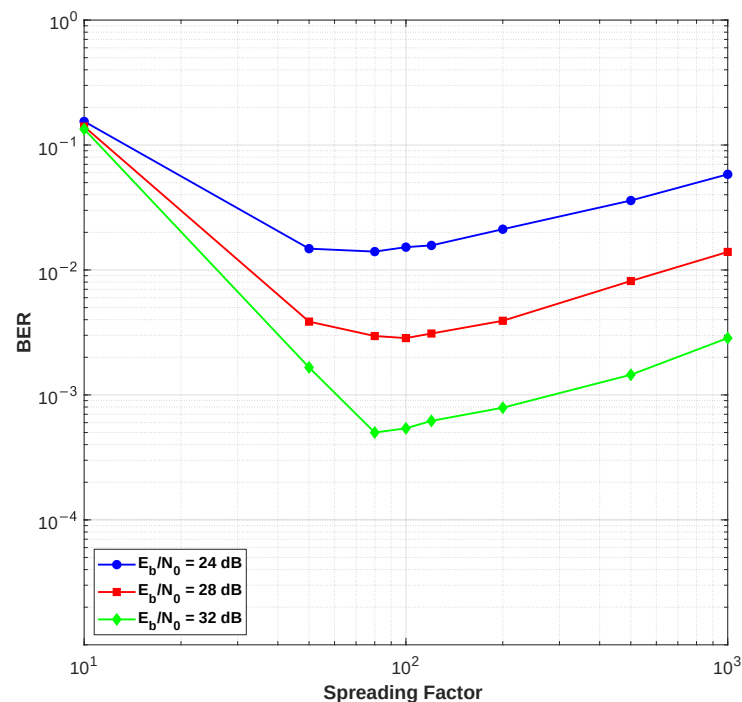


Figure 5. BER versus spreading factor β under a two-path Rayleigh fading channel.

4.4. Various Multipath Configurations

We first investigate the effect of power allocation on the BER performance of the proposed SC-CSK scheme under a two-path Rayleigh fading channel with delay $\tau = [0, 10T_c]$. The spreading factor is set to $\beta = 256$. As shown in Figure 6, the system performance remains almost identical regardless of whether the two paths have equal power distribution (e.g., $[1/2, 1/2]$) or unequal power distribution (e.g., $[1/3, 2/3]$). It can be clearly observed that the power allocation ratio between the two paths has a negligible impact on the overall system performance.

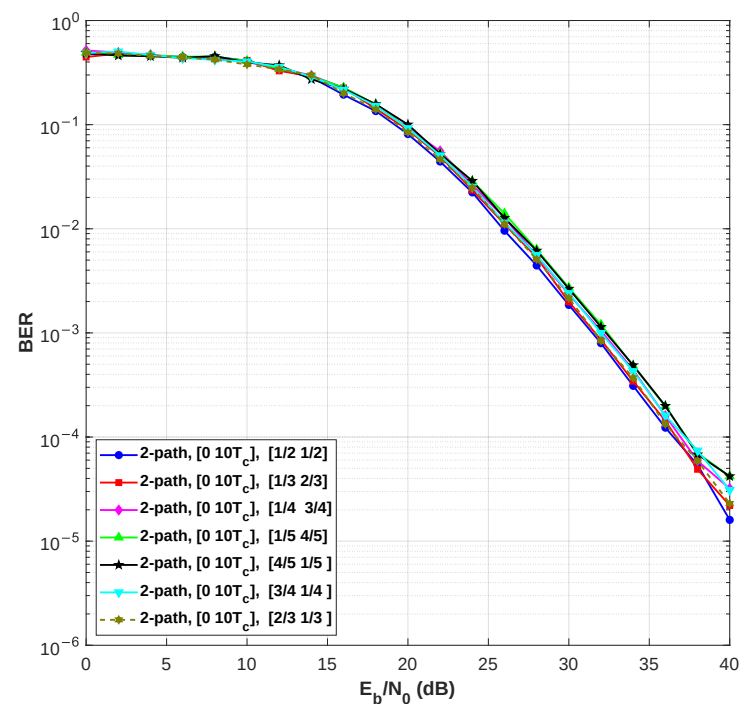


Figure 6. BER performance comparison under different power allocation ratios for a two-path Rayleigh fading channel with delay $\tau = [0, 10T_c]$.

This observation can be explained as follows. The spectral centroid is a global frequency-domain feature that primarily depends on the overall shape of the power spectral density rather than the detailed power distribution among individual multipath components. As long as the delay spread is sufficiently large to induce frequency-selective fading, the inherent averaging effect of the spectral centroid calculation mitigates the influence of specific power ratios. Consequently, the proposed SC-CSK scheme exhibits robust performance against variations in path power allocation, which significantly simplifies system design in practical multipath environments.

We further investigate the effect of channel delay spread on the performance of the proposed SC-CSK scheme with spreading factor $\beta = 180$. A two-path Rayleigh fading channel with equal power allocation is considered, where the path delay is increased from $[0, T_c]$ to $[0, 50T_c]$.

As shown in Figure 7, an interesting observation is that larger path delays lead to better BER performance. This counter-intuitive phenomenon is consistent with the frequency diversity analysis presented in Section 3. Specifically, as derived in Equation (21), a larger delay spread τ reduces the coherence bandwidth $B_c \approx 1/\tau$, increasing the number of independent frequency bins within the signal band. The summation operations in the SC calculation average over these independent fluctuations, effectively reducing the estimation variance $\sigma_{\text{ch}}^2(\tau)$ and leading to improved BER performance.

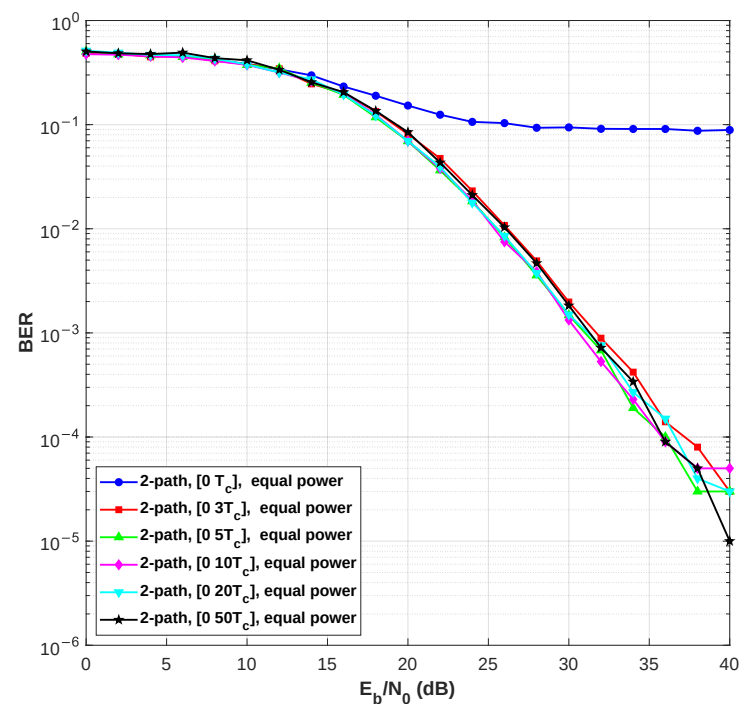


Figure 7. BER performance of the proposed SC-CSK scheme under a two-path Rayleigh fading channel with different delay spreads.

4.5. Comparison with Others

The core principle of the proposed system is to distinguish different chaotic maps based on their spectral centroids. This idea aligns with the PSD-DLCSK scheme [31], which also exploits the power spectral density (PSD) of chaotic signals for detection. However, the key difference lies in the receiver design: the proposed system employs a simple statistical feature—the spectral centroid—while PSD-DLCSK relies on a deep neural network to learn the distribution of the PSD.

Figure 8 compares the BER performance of the two schemes under multipath Rayleigh fading channels with $L = 2, 3$, and 4 paths. The spreading factor is $\beta = 256$, the delay spacing between consecutive paths is $15T_c$, and both equal and unequal power allocations are considered.

Several key observations can be made. First, regardless of the power allocation or multipath configuration, the PSD-DLCSK scheme exhibits an error floor after $E_b/N_0 = 30$ dB, indicating that its performance cannot be improved further by increasing SNR. Second, the diversity gain of the PSD-DLCSK scheme is marginal, as the BER curves for different numbers of paths remain close to each other.

In sharp contrast, the proposed SC-CSK scheme does not exhibit any error floor up to $E_b/N_0 = 40$ dB and achieves a significant diversity gain—the BER decreases substantially as the number of paths increases. Notably, under the four-path channel at a BER of 10^{-4} , the proposed scheme achieves a performance gain of 10 dB over the PSD-DLCSK scheme. In addition, a significant diversity gain is observed in SC-CSK system. Specifically, the system performance improves consistently as the number of paths increases. This is because a larger number of paths introduces more independent fading realizations across the frequency domain, which are effectively averaged out by the spectral centroid calculation. Consequently, the estimation variance decreases, leading to improved BER performance. This result demonstrates that the proposed SC-CSK scheme can effectively exploit multipath diversity to enhance detection reliability without requiring complex channel estimation or equalization techniques. These results demonstrate that the proposed

spectral-centroid-based approach not only avoids the complexity of deep learning but also achieves superior performance, particularly in rich multipath environments.

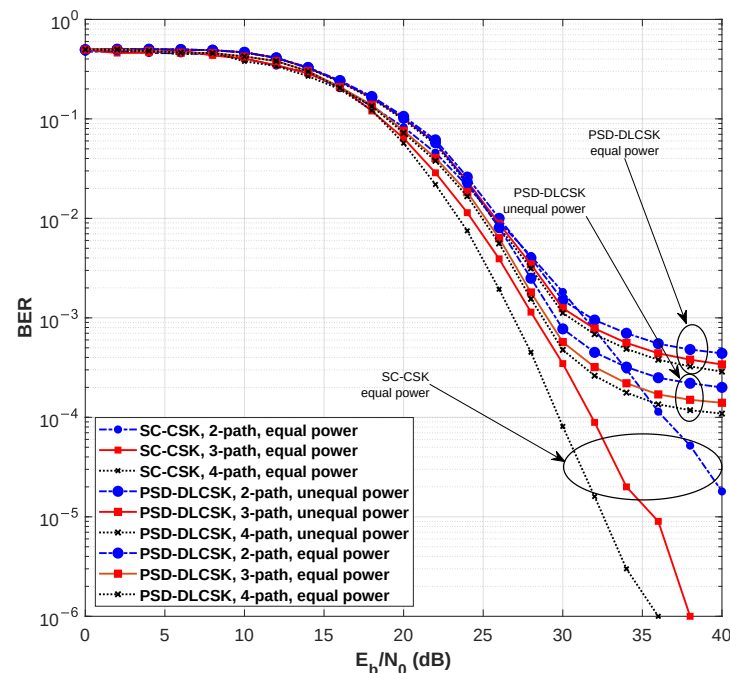


Figure 8. BER performance comparison between the proposed SC-CSK scheme and the PSD-DLCSK scheme [31] under multipath Rayleigh fading channels.

Figure 9 presents the BER performance comparison between the proposed SC-CSK system and the conventional DCSK system under a four-path Rayleigh fading channel, where the delay spacing between consecutive paths is $15T_c$. The spreading factor of the SC-CSK system is set to $\beta = 180$, so the DCSK system uses $2\beta = 360$ to transmit one bit. Three normalized Doppler shift scenarios are considered: $f_d/f_s = 0.0001$, 0.001 , and 0.01 , corresponding to slow, moderate, and fast fading conditions, respectively.

As observed from Figure 9, under slow fading ($f_d/f_s = 0.0001$), the conventional DCSK system exhibits better BER performance than the proposed SC-CSK. However, when the normalized Doppler shift increases to $f_d/f_s = 0.001$ and 0.01 , the performance of DCSK deteriorates dramatically. This degradation is attributed to the fact that DCSK relies on the correlation between the reference and data signals, which is severely compromised by rapid channel variations.

In contrast, the proposed SC-CSK system demonstrates robust performance across all three Doppler scenarios. Even at $f_d/f_s = 0.01$ (fast fading), the SC-CSK system maintains satisfactory BER performance. This advantage stems from its non-coherent detection mechanism, which does not depend on the temporal correlation between reference and data signals but rather exploits the spectral characteristics of chaotic signals for reliable detection.

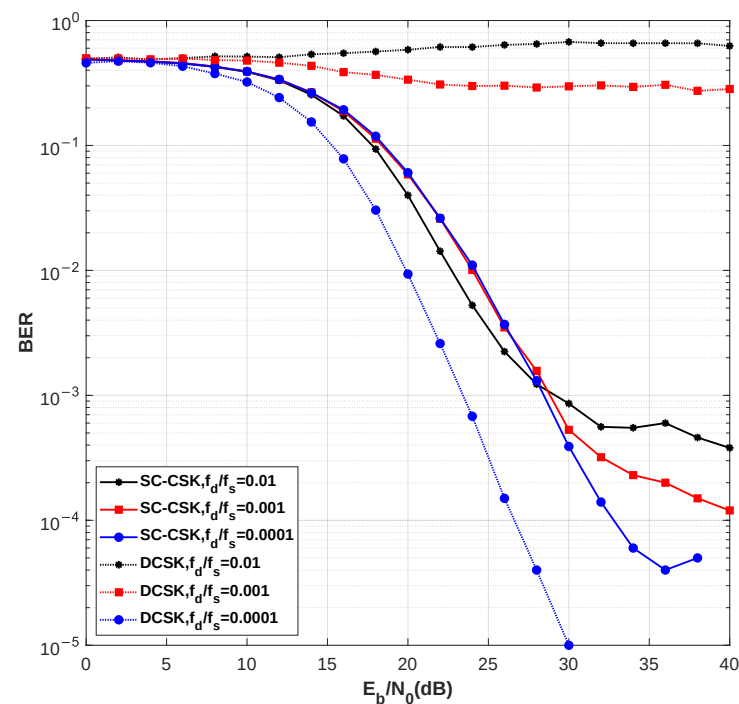


Figure 9. BER performance comparison between SC-CSK system and conventional DCSK under Rayleigh multipath fading channels with different normalized Doppler shifts ($f_d/f_s = 0.0001, 0.001, 0.01$).

5. Conclusions

In this paper, we have proposed a spectral-centroid-based non-coherent CSK detector that eliminates the need for chaos synchronization, reference sequence transmission, and channel estimation. We have demonstrated that the spectral centroid provides a characteristic spectral feature of chaotic maps, enabling a fixed-threshold detection scheme that is both lightweight and interpretable. Extensive simulations over multipath Rayleigh fading channels have shown that the proposed SC-CSK system significantly outperforms conventional CSK schemes. In contrast to coherent CSK, which suffers from an error floor under frequency-selective fading (with BER stagnating between 10^{-2} and 10^{-3} at high SNR), the proposed system continues to achieve lower BER as E_b/N_0 increases, benefiting from the statistical robustness of the spectral-centroid-based decision feature. Furthermore, the proposed system exhibits robust performance under high-mobility scenarios. While conventional DCSK suffers from severe performance degradation as the normalized Doppler shift increases, the SC-CSK system maintains stable BER across a wide range of Doppler frequencies. This advantage stems from its spectral-feature-based detection, which does not rely on the temporal correlation between reference and data signals.

Although the proposed detector is robust against channel fading and Doppler effects, intentional spectral-domain interference, such as narrowband interference or spectral-shaping interference, may influence the estimated spectral centroid and consequently affect the detection performance. Therefore, developing interference-resilient SC-based detection strategies represents an important direction for future research.

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References

1. Abel, A.; Schwarz, W. Chaos Communications-Principles, Schemes, and System Analysis. *Proc. IEEE* **2002**, *90*, 691–710.
2. Kolumbán, G.; Kennedy, M.P.; Jako, Z.; Kis, G. Chaotic Communications with Correlator Receivers: Theory and Performance Limits. *Proc. IEEE* **2002**, *90*, 711–732.
3. Kennedy, M.P.; Kolumbán, G. Digital Communication Using Chaos. In *Controlling Chaos and Bifurcation in Engineering Systems*; Chen, G., Ed.; CRC Press: Boca Raton, FL, USA, 2000; pp. 477–500.
4. Xu, J.W.; Wei, M.; Zhang, L.; Galdi, V.; Li, L.; Cui, T.J. Chaotic Information Metasurface for Direct Physical-Layer Secure Communication. *Nat. Commun.* **2025**, *16*, 5853.
5. Zaminga, S.; Martinez, A.; Huang, H.; Rontani, D.; Morichetti, F.; Melloni, A.; Grillot, F. Optical Chaotic Signal Recovery in Turbulent Environments Using a Programmable Optical Processor. *Light Sci. Appl.* **2025**, *14*, 131.
6. Dedieu, H.; Kennedy, M.P.; Hasler, M. Chaos Shift Keying: Modulation and Demodulation of a Chaotic Carrier Using Self-Synchronizing Chua's Circuits. *IEEE Trans. Circuits Syst. II Analog Digit. Signal Process.* **1993**, *40*, 634–642.
7. Pecora, L.M.; Carroll, T.L. Synchronization in Chaotic Systems. *Phys. Rev. Lett.* **1990**, *64*, 821–824.
8. Kolumbán, G.; Vizvári, B.; Schwarz, W.; Abel, A. Differential Chaos Shift Keying: A Robust Coding for Chaos Communication. In Proceedings of the International Workshop on Nonlinear Dynamics of Electronic Systems (NDES), Seville, Spain, 27–28 June 1996; Volume 96, pp. 87–92.
9. Liu, Z.; Wang, Z.Y.; So, H.C.; Chen, Z.; Zhang, L.; Chan, T.T. Reliable ADMM-Based Signal Detection for OTFS-DCSK Under High-Mobility Scenarios. *IEEE Trans. Wirel. Commun.* **2026**, *25*, 3991–4005.
10. Li, Z.; Yang, Y.; Yan, D.; Wang, Y. An Adaptive Combining Hybrid FSO/RF Terrestrial-Satellite Links Communication System Based on DCSK. *IEEE Photonics Technol. Lett.* **2026**, *38*, 1058–1061.
11. Mu, Y.; Zhang, L.; Chen, Z.; Zheng, J.; Wu, Z. Design of a Dual Index PPM-DCSK Transceiver for Covert Wireless Communications. *IEEE Trans. Commun.* **2025**, *73*, 8228–8242.
12. Cheng, G.; Chen, X.; Liu, W.; Xiao, W. GCI-DCSK: Generalized Carrier Index Differential Chaos Shift Keying Modulation. *IEEE Commun. Lett.* **2019**, *23*, 2012–2016.
13. He, L.; Xue, Y.; Wu, X. Multiple Time Slot Index and Code Index Applied to DCSK Systems—More Full Utilization of Time Slot Index. *IEEE Wirel. Commun. Lett.* **2026**, *15*, 1115–1119.
14. Yang, R.; Fang, Y.; Chen, P.; Ma, H. Design of a New CIM-DCSK-Based Ambient Backscatter Communication System. *IEEE Trans. Veh. Technol.* **2024**, *73*, 19832–19837.
15. Wang, B.; Piao, X.; Guo, Q.; Xie, Z.; Chen, P. Permutation Index Aided Multicarrier Differential Chaos Shift Keying Modulation. *IEEE Internet Things J.* **2025**, *12*, 36370–36379.
16. He, L.; Xue, Y.; Wu, X.; Zhang, K. Analysis of DCSK System Based on Code Indexing, Timeslot Indexing and Carrier Indexing. *IEEE Trans. Veh. Technol.* **2026**, *75*, 2672–2685.
17. Zhang, G.; Chen, X.; Hu, Y.; Luo, Z. Hybrid Carrier-Code and Reference Index Modulation in DCSK System With Time-Frequency Resources. *IEEE Trans. Veh. Technol.* **2025**, *74*, 4148–4162.
18. Tan, Y.; Tao, Y.; Fang, Y.; Han, G.; Duan, C. A Three-Dimensional Non-Constant-Envelope Constellation-Assisted DCSK System With Cyclic Shift Correlator. *IEEE Trans. Veh. Technol.* **2025**, *74*, 16636–16641.
19. Li, S.Y.; Yang, H.; Jiang, G.P. Generalized Multilevel Code-Shifted Differential Chaos Shift Keying Modulation System. *IEEE Trans. Circuits Syst. I Regul. Pap.* **2025**, *72*, 7225–7237.
20. Peng, C.; Tan, Y.; Ma, D.; Yang, Z.; Zhang, C.; Fang, Y. A Novel Design of Low-PAPR OFDM-DCSK Waveform With Riemann Matrix-Based G-SLM for ISAC. *IEEE Commun. Lett.* **2026**, *30*, 1533–1537.
21. Duan, C.; Tao, Y.; Fang, Y.; Han, G.; Guizani, M. Multi-Carrier DCSK Scheme With Matrix Index Technique: A New Transmission Scheme for Physical Layer Security. *IEEE J. Sel. Areas Commun.* **2026**, *44*, 3798–3811.
22. Zhou, Y.; Lv, L.; Ma, D.; Li, Y.; Fang, Y. Design of a Dual-Level Polar-Coded Scheme for GCI-DCSK Systems. *IEEE Commun. Lett.* **2025**, *29*, 804–808.
23. Chen, F.; Huang, J.; Chen, H.; Xie, Z.; Chen, P. M-ary Space-Time-Block-Code Shift Index Modulation for High-Data-Rate Chaotic Communications. *IEEE Trans. Veh. Technol.* **2025**, *74*, 10524–10535.

24. Vuong, D.P.; Le, D.K.; Nguyen, K.K.; Van Nguyen, B. Correlation Receiver With Nonlinearity Blanking for DCSK Systems Under Pulse Jamming Attack. *IEEE Access* **2019**, *7*, 25037–25045.
25. Cai, X.; Yuen, C.; Huang, C.; Xu, W.; Wang, L. Toward Chaotic Secure Communications: An RIS Enabled M-Ary Differential Chaos Shift Keying System With Block Interleaving. *IEEE Trans. Commun.* **2023**, *71*, 3541–3558.
26. Hameed, D.H.; Hasan, F.S. Physical Layer Secrecy Analysis Using Permutation Index-Based OFDM-DCSK System. In Proceedings of the 2023 3rd International Scientific Conference of Engineering Sciences (ISCES), Diyala, Iraq, 3–4 May 2023; pp. 31–36.
27. Maxwell, C.L.; Yu, D.; Yu, S.S. A Memristor-Based Encryption for Power and Data Synchronous Transmission. *Int. J. Bifurc. Chaos* **2026**, *36*, 2650024.
28. Zhang, L.; Zhang, H.; Jiang, Y.; Wu, Z. Intelligent and Reliable Deep Learning LSTM Neural Networks-Based OFDM-DCSK Demodulation Design. *IEEE Trans. Veh. Technol.* **2020**, *69*, 16163–16167.
29. Zhang, H.; Zhang, L.; Jiang, Y.; Wu, Z. Reliable and Secure Deep Learning-Based OFDM-DCSK Transceiver Design Without Delivery of Reference Chaotic Sequences. *IEEE Trans. Veh. Technol.* **2022**, *71*, 8059–8074.
30. Mobini, M.; Kaddoum, G.; Herceg, M. Design of a SIMO Deep Learning-Based Chaos Shift Keying (DLCSK) Communication System. *Sensors* **2022**, *22*, 333.
31. Chen, J.; Huang, T.; Zeng, H.; Cai, G.; Zhou, H.; Shen, Z.; Kaddoum, G. A Novel Deep Learning-Based Receiver for Non-Coherent Chaotic Communication Systems With Temporal Dependencies and Spectral Properties of Chaotic Signals. *IEEE Trans. Commun.* **2025**, *73*, 11403–11417.
32. Huang, T.; Chen, J.; Zeng, H.; Cai, G.; Kaddoum, G. Dual-Domain Deep Learning-Assisted NOMA-CSK Systems for Secure and Efficient Vehicular Communications. *IEEE Trans. Commun.* **2026**, *74*, 7480–7493.
33. Simon, M.K.; Alouini, M.S. *Digital Communication over Fading Channels*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2005.
34. Xia, Y.; Tse, C.K.; Lau, F.C.M. Some Benchmark Multipath Performance Data of Coherent CSK Digital Communication Systems. In Proceedings of the RISP International Workshop on Nonlinear Circuit and Signal Processing (NCSP'04), Honolulu, HI, USA, 5–7 March 2004; pp. 261–264.

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