

Article

Design and Analysis of Enhanced IM/DD System with Nonorthogonal Code Shift Keying and Parallel Transmission

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Abstract: Providing Optical Wireless Communications (OWCs) is desirable for high data transmission efficiency. Intensity Modulation and Direct Detection (IM/DD) is widely adopted for its simplicity and practicality. Among various modulation schemes, Code Shift Keying (CSK) has demonstrated superior transmission efficiency compared to On-Off Keying (OOK) and Pulse Position Modulation (PPM). Prior research has shown that CSK performance can be further enhanced through parallel transmission and code concatenation techniques. However, the direct application of concatenated CSK to parallel transmission reduces the number of available code combinations as the concatenation level increases, potentially lowering modulation efficiency. This study proposes an advanced transmission scheme that integrates parallel transmission with a multi-level intensity adjustment mechanism. The proposed method preserves a high number of distinguishable transmission symbols, thereby achieving higher data transmission rates. Analytical derivations for transmission efficiency are provided for single-user scenarios, and numerical simulations validate the effectiveness of the proposed system. The key contributions of this work include mitigating symbol reduction in nonorthogonal CSK with parallel transmission and adjusting the multi-level intensity to enhance overall system performance. The results confirm that the proposed scheme significantly improves the efficiency and scalability of nonorthogonal CSK in OWC applications.

Keywords: optical wireless communication (OWC); intensity modulation and direct detection (IM/DD); code shift keying; parallel transmission



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1. Introduction

The rapid evolution of wireless communication technologies over the past few decades has catalyzed their widespread integration into diverse applications [1–21]. Within this technological surge, Optical Wireless Communication (OWC) systems have emerged as a promising solution for high-speed and energy-efficient data transmission, gaining notable traction in recent years. Among the various implementation techniques, the Intensity Modulation with Direct Detection (IM/DD) approach has become a dominant methodology because of its simplicity and practicality. Unlike radio communication, where the modulating signal is a complex value, IM/DD modulates the optical intensity to encode information. In this scheme, the modulating signal (current) remains real and positive, as the received light intensity is directly detected at the receiver to recover the transmitted data. The IM/DD method, particularly in free-space optics links, is anticipated to support diverse applications due to its minimal deployment and infrastructure requirements. One notable example is LiFi (Light-Fidelity) [22,23], which leverages LED-based

communication. By integrating illumination and data transmission, LiFi enhances energy efficiency. Furthermore, IM/DD has potential applications in underwater optical communication for marine [24], and vehicle-to-vehicle communication [25]. Research has been conducted on the relationship between code length and error rate in IM/DD systems [26], as well as on channel capacity modeling in the IM/DD [27] and modulation techniques [5,11,12,16–18,20,21,28,29].

Modulation schemes for IM/DD-based OWCs can be broadly categorized into On-Off Keying (OOK) [11,12], Pulse Position Modulation (PPM) [5,28], Sequence Inversion Keying (SIK) [16–18], and Code Shift Keying (CSK) [20,21]. Although OOK and SIK achieve a data transmission efficiency of 1 bit per code, PPM provides enhanced bit error rate performance by leveraging orthogonal signal structures. However, PPM's efficiency, $\frac{\log_2 N}{N}$ (bits/code), decreases as the number of slots N increases. In contrast, CSK achieves superior transmission efficiency, $\log_2 M$ (bits/code), where M is the number of distinct codes. Given these advantages, CSK represents a compelling candidate for further exploration. The optical codes are desired to be suitable for the communication quality.

The design criteria for optical codes can be classified into two main categories. The first criterion focuses on avoiding pulse collisions between codes. This approach is commonly applied in optical communications, with examples including optical orthogonal codes and extended prime codes [14,15]. The second criterion allows pulse collisions between codes but ensures that, over the code period, the correlation characteristic remains zero (orthogonal or pseudo-orthogonal). Pseudo-orthogonal M-sequence pairs [19] are a notable example of optical codes designed under this criterion. In this study, we adopt codes based on the latter design criterion.

Previous research on CSK [20,21,30] has established that CSK systems improve transmission efficiency by mapping data to one of M codes, with efficiency scaling as M increases. Additional performance gains have been achieved by employing parallel transmission techniques that leverage the orthogonality or pseudo-orthogonality of pseudo-orthogonal M-sequences [31], as well as concatenated CSK code structures. We have focused on the latter—the concatenated CSK code structures—and demonstrated the effectiveness of this design approach [32–34]. Combining these two performance-enhancing technologies is expected to further improve performance; however, the extent of the improvement remains unclear. Additionally, while conventional CSK with parallel code combination transmission significantly enhances information transfer by expanding the set of available transmission candidates, the proposed nonorthogonal CSK method, which is constructed by concatenating orthogonal or pseudo-orthogonal codes, may experience performance degradation due to a reduced number of code combinations under equal code length conditions. Therefore, further improvements are necessary to achieve the highest possible transmission rate in a parallel transmission environment.

This study proposes an advanced transmission scheme that extends the previous nonorthogonal code construction strategy [34] by introducing a novel parallel transmission mechanism. By intelligently selecting and combining multiple codes from the previously designed code set, our method increases the number of available transmission code combinations, thereby enhancing the overall data transmission rate. Furthermore, to address the limitations of directly applying the previous approach to parallel transmission, we introduce a multi-level intensity adjustment strategy for parallel transmission procedures comparable to those of conventional parallel transmission, thereby achieving higher data transmission rates. Since the nonorthogonal CSK method proposed by the authors is influenced by multiple factors—such as improved noise immunity with an increased optical scale level, increased inter-code interference with a higher number of concatenations, the expansion of the available code set through the use of nonorthogonal CSK codes, and a

decrease in the number of viable transmission combinations—we determine the optimal number of concatenations. Analytical derivations for data transmission efficiency are presented for single-user scenarios, with numerical simulations validating the efficacy of the proposed system under various configurations. This study builds upon the previously proposed nonorthogonal CSK scheme. The key advancements are as follows:

Preventing Symbol Reduction in Parallel Transmission: Applying the previous method to parallel transmission reduces available code combinations as concatenation increases, lowering modulation levels. The proposed method incorporates multi-level intensity adjustment to maintain a high number of available symbols for transmission.

Achieving Higher Data Transmission Rates: While the previous method improves efficiency in single-code transmission, its direct extension to parallel transmission leads to diminishing returns. The proposed method addresses this by combining parallel code combination transmission with multi-level intensity adjustment, enhancing transmission rates.

2. Proposed System Framework

2.1. Design of Nonorthogonal Codes

The proposed method generates nonorthogonal codes by concatenating M_{con} pseudo-orthogonal M-sequences (POMs). The POM set, denoted as OS , consists of M-sequences augmented by an additional chip, as defined below:

$$OS = \begin{pmatrix} OS_1 \\ OS_2 \\ \vdots \\ OS_{M_{pom}} \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & a_3 & \cdots & a_{L_M} & -1 \\ a_2 & a_3 & \cdots & a_{L_M} & a_1 & -1 \\ & & \vdots & & & \\ a_{L_M} & a_1 & a_2 & \cdots & a_{L_M-1} & -1 \end{pmatrix}, \quad (1)$$

where a_i ($i = 1, 2, \dots, L_M$) is a binary value of +1 or −1, and L_M represents the M-sequence length. At the transmitter, all −1 values are replaced with 0 for transmission purposes. In contrast, the receiver uses POMs in their original $\{+1, -1\}$ form.

The cross-correlation between the i -th POM used by the transmitter, OS_{T_i} , and the j -th POM at the receiver, OS_{R_j} , can be expressed as

$$\frac{1}{T} \int_0^T OS_{T_i}(t) OS_{R_j}(t) dt = \begin{cases} \frac{L_M}{2} & \text{if } T_i = R_j, \\ 0 & \text{if } T_i \neq R_j, \end{cases} \quad (2)$$

where T denotes the POM cycle period.

For M_{pom} POMs and M_{con} concatenations, the resulting nonorthogonal code set NS is structured as follows:

$$NS = \begin{pmatrix} NS\ 1 \\ NS\ 2 \\ \vdots \\ NS\ M_{pom} \cdot 2^{M_{con}} \end{pmatrix} = \begin{pmatrix} OS^{(1)} & OS^{(2)} & \cdots & OS^{(M_{con}-1)} & OS^{(M_{con})} \\ OS^{(1)} & OS^{(2)} & \cdots & OS^{(M_{con}-1)} & \overline{OS^{(M_{con})}} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \overline{OS^{(1)}} & \overline{OS^{(2)}} & \cdots & \overline{OS^{(M_{con}-1)}} & \overline{OS^{(M_{con})}} \\ OS^{(1)} & OS^{(2)} & \cdots & OS^{(M_{con}-1)} & OS^{(M_{con})} \end{pmatrix}, \quad (3)$$

where $OS^{(i)}$ represents the i -th sequence, and $\overline{OS^{(i)}}$ is its negation. Since the proposed method constructs nonorthogonal codes in an organized manner, it can be constructed with the same level of complexity as conventional CSK.

In the proposed system, M_{pom} POMs are selected based on $\lfloor \log_2 \left(\frac{M_{pom}}{m} \right) \rfloor$ bits of data. The selected i -th POM is concatenated according to $M_{con}^{(i)}$ bits and the intensity of concatenated code is scaled by $M_a^{(i)}$, representing its modulation level, where the intensity scaling

can be described as a parallel transmission of concatenated part. This structure allows a frame to encode $\left(\lfloor \log_2(M_m^{pom}) \rfloor + m(M_{con} + \log_2 M_a^{(i)})\right)$ bits of information.

2.2. System Architecture

The overall system structure is shown in Figure 1, while Figure 2 provides an example of the transmitted signal format. The transmitter begins by mapping the input data into $\left(\lfloor \log_2(M_m^{pom}) \rfloor + m(M_{con} + \log_2 M_a^{(i)})\right)$ bits. In this paper, we refer to $\lfloor \log_2(M_m^{pom}) \rfloor$ (bits), M_{con} (bits), and $\log_2 M_a^{(i)}$ (bits) as Data 1, Data 2, and Data 3, respectively. Next, m POMs are selected based on the data, and each sequence is concatenated according to its corresponding $M_{con}^{(i)}$ pattern. Light intensity levels of the concatenation pattern are then adjusted using $M_a^{(i)}$, and all -1 chips are converted into 0 before transmission.

At the receiver, shown in Figure 3, $\{+1, -1\}$ -valued POMs are utilized. The received optical signal is converted into an electrical signal by an Avalanche Photo-diode (APD). The receiver calculates correlation values for each POM and identifies the m POMs with the highest absolute correlations. From these, it extracts data encoded in POM selection, concatenation patterns, and light intensity levels.

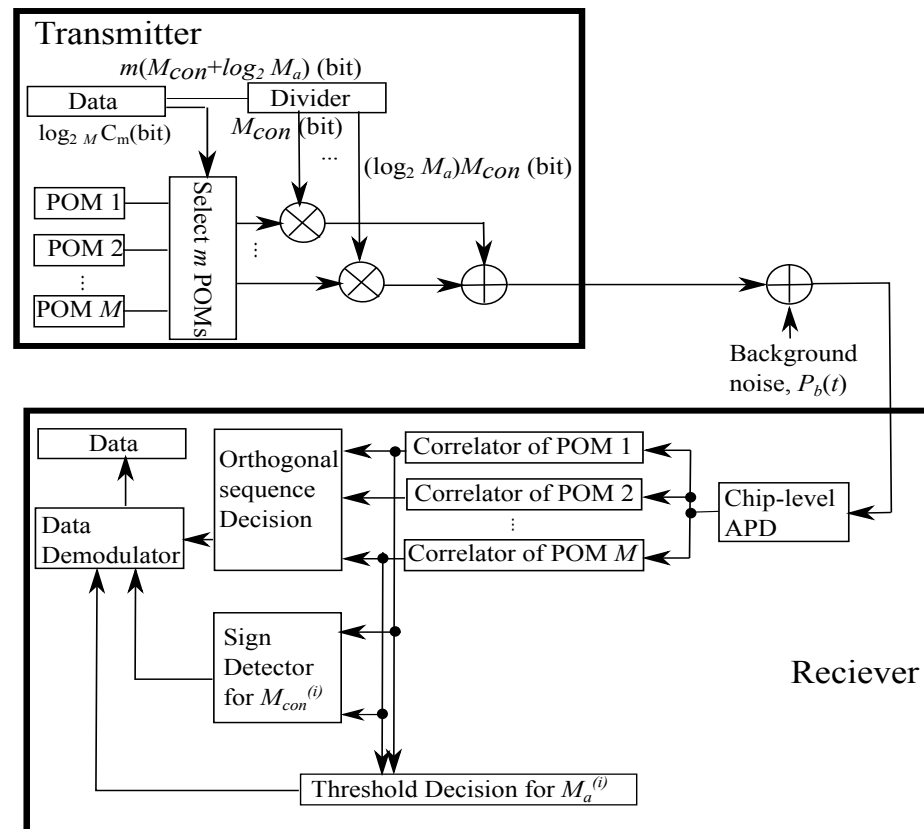


Figure 1. Proposed system architecture.

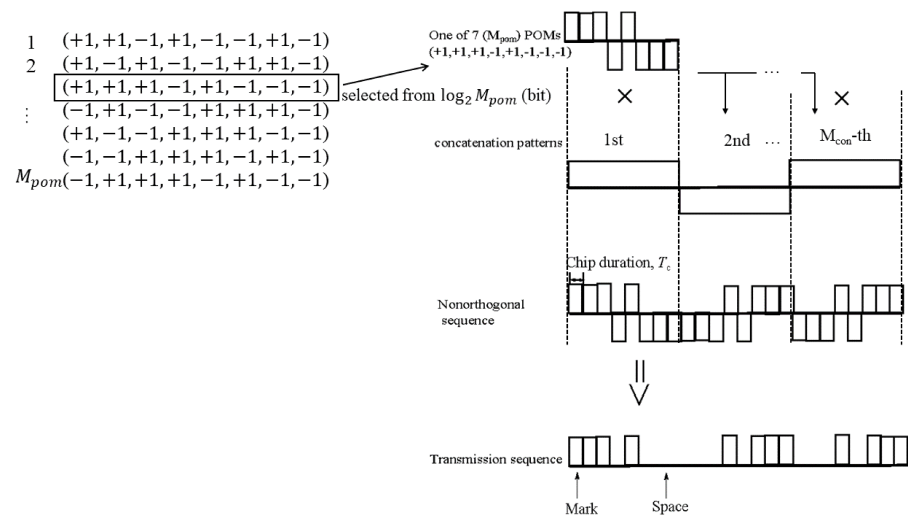


Figure 2. Example of transmitted signal structure.

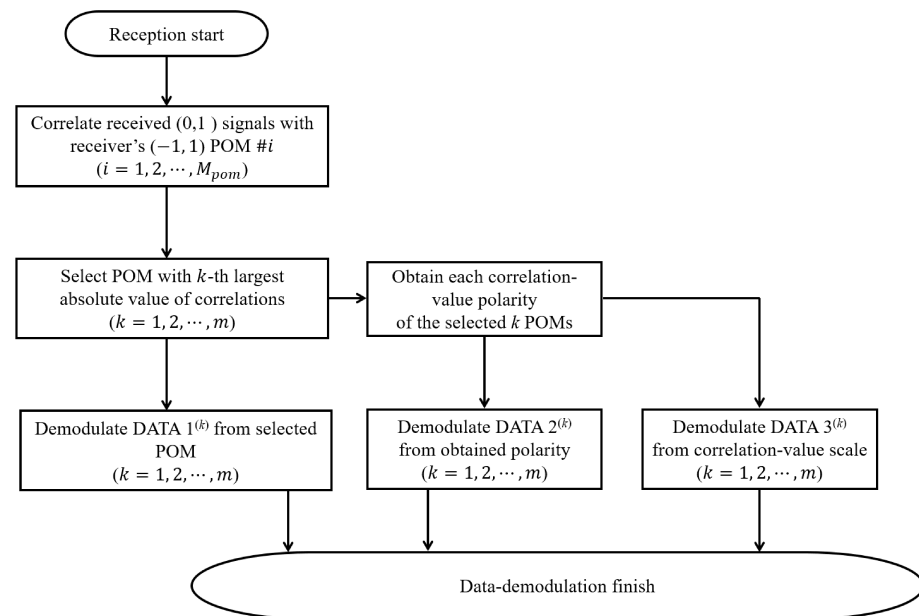


Figure 3. Receiver workflow.

3. Theoretical Analysis

This study evaluates the data transmission efficiency of the proposed system. Following the approach of previous work on IM/DD channel modeling [1,28], this analysis incorporates the effects of background noise and APD noise, where the noise variance depends on signal intensity in the optical communication channel. To extract the fundamental characteristics of the proposed method, the analysis largely follows the framework in [1,28].

In this paper, data transmission efficiency is defined as the total number of correctly transmitted bits from all users per chip duration.

The mean number of photons absorbed during T_c is expressed as

$$\lambda_s = \frac{\eta_A P_w}{hf}, \quad (4)$$

where λ_s denotes the photon absorption rate, h is Planck's constant, η_A is the efficiency of the avalanche photo-diode (APD), and P_w represents the received laser power with-

out accounting for scintillation and background light. The total photon absorption rate λ —accounting for signal, background light, and APD bulk leakage current—is given by

$$\lambda = \begin{cases} \lambda_s + \lambda_b + \frac{I_b}{e}, & \text{for a mark,} \\ \frac{\lambda_s}{Me} + \lambda_b + \frac{I_b}{e}, & \text{for a space,} \end{cases} \quad (5)$$

where I_b is the bulk leakage current of the APD, e is the elementary charge, Me is the modulation extinction ratio of the laser diode between mark and space states, and λ_b represents the photon absorption rate due to background light, which is calculated as $\lambda_b = \frac{\eta_A P_b}{hf}$ when P_b is the background noise per chip duration.

When m represents the number of parallel transmitted POMs, the probability of a frame being correctly demodulated, $P_c(m)$, can be described as

$$P_c(m) = m \left[1 - \frac{1}{M_a} \sum_{i=1}^{M_a} \frac{1}{2} \operatorname{erfc} \left(\frac{Th_i - \mu_a(i)}{\sqrt{2\sigma_m^2(i)}} \right) \right]^{mM_{con}} \cdot (1 - P_{pom}(m)), \quad (6)$$

where $\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-t^2) dt$ is the complementary error function, $\mu_a(i)$ and $\sigma_s(i)$ represent the mean and variance of the largest correlation output, and Th_i is threshold for determining the light intensity levels of the concatenation pattern. $P_{pom}(m)$ is the symbol error rate of POM when the number of parallel transmitted POMs is m . If a concatenated POM code c_1 is sent, $P_{pom}(m)$ is given by

$$P_{pom}(m) = 1 - \int_{-\infty}^{\infty} f(c_1) - \int_{-\infty}^{c_1} f(c_{ii>m}) dc_i M_{pom} - \int_{-\infty}^{c_1} f(c_m) dc_m m - 1 dc_1, \quad (7)$$

where $f(c_j)$ is the PDF of correlation output for the j -th code c_j , which is

$$f(c_j) = g(|q_j^{(1)}|) * \dots * g(|q_j^{(M_{con})}|), \quad (8)$$

$$g(q_j) = \frac{1}{\sqrt{2\pi\sigma_j^2}} \exp \left[-\frac{(q_j - \mu_j(i))^2}{2\sigma_j^2 M_{con}} \right]. \quad (9)$$

Here, $g(|q_j^{(j)}|)$ is the PDF of the absolute value of correlation output for the j -th POM q_j , $*$ represents the convolution integral, and μ_j and σ_j^2 are the mean and variance for the j -th correlation output, given by

$$\mu_1(i) = \dots = \mu_m(i) = GT_c \left(\frac{L_f + 1}{2} i\lambda_s + \frac{L_f - 1}{2} \frac{i\lambda_s}{M_e} + \lambda_b \right), \quad (10)$$

$$\mu_{m+1}(i) = \dots = \mu_{M_{pom}}(i) = GT_c \left(\frac{L_f i\lambda_s}{M_e} + \lambda_b \right), \quad (11)$$

and

$$\sigma_1^2(i) = \dots = \sigma_{M_{pom}}^2(i) = G^2 FT_c \left[m \frac{L_f + 1}{2} i\lambda_s + m \frac{L_f^2 - 1}{2} \frac{i\lambda_s}{M_e} + L_f \lambda_b + \frac{2I_b}{e} \right] + \frac{2I_s T_c}{e} + 2\sigma_{th}^2, \quad (12)$$

respectively. In Equations (10)–(12), F and σ_{th}^2 are

$$F = k_{eff} G + (1 - k_{eff}) \frac{2G - 1}{G}, \quad (13)$$

and

$$\sigma_{th}^2 = \frac{2k_B T_r T_c}{e^2 R_L}, \quad (14)$$

respectively.

When the number of parallel transmitted codes is m , the data transmission efficiency of the proposed system is then given by

$$S_{sys}(m) = \frac{KN_{bit}P_c(m)}{L_f}. \quad (15)$$

4. Numerical Results

This study evaluates the proposed system's performance through analysis and simulation. Figure 4 shows the simulation diagram. This study conducted the simulation by Monte Carlo simulation. In the simulation, first, each transmitter generates data bits and transmits them. Then, the simulation multiplies each light intensity of transmission signals by a random value based on a log-normal distribution (i.e., scintillation). Also, the simulation adds a random value based on a normal distribution to those signals (i.e., noise). In other words, the simulation artificially gives scintillation and noise, similar to the references [1,28]. The simulation calculates the data transmission efficiency from the demodulated signal at the receiver. The simulation trials were conducted 10,000,000 times in order to calculate data transmission efficiency. Table 1 shows the parameters which are used in this paper. This paper uses typical APD parameters [1,28]. Parameters in Table 1 are determined according to the values used in [1,28,35].

Table 1. Parameter settings.

Parameter	Value
Chip duration, T_c	4.0×10^{-4}
APD effective ionization ratio, k_{eff}	0.02
Average APD gain, G	100
Modulation extinction ratio of the laser diode output power in the mark and space states, Me	100
Boltzmann's constant, k_B	1.38^{-23}
Receiver noise temperature, T_r	300 (K)
Receive load resistor, R_L	1030 (Ω)
Elementary charge, e	1.6×10^{-16} (C)
Planck's constant, h	6.626×10^{-34}
APD bulk leakage current, I_b	0.1 (nA)
APD surface leakage current, I_s	10 (nA)
Quantum efficiency, η	0.6
Laser wavelength, λ_l	830 (nm)

Figure 5 illustrates the variation in data transmission efficiency as a function of the parallel level for both the conventional CSK system and the proposed scheme. The parallel level is defined as the product of the number of selected POMs, m , and the light intensity levels of the concatenation pattern, M_a , representing the total intensity levels of the transmission signals. The solid lines represent the analytical results, while the plots correspond to the simulation results obtained using Monte Carlo simulations. This evaluation

assumes an ideal scenario, excluding both background and thermal noise. Under these conditions, the proposed system achieves data transmission efficiencies exceeding 1.0, a performance level unattainable by the conventional CSK system. Notably, the configuration ($M_{oc} = 7, M_{con} = 3$) demonstrates the highest efficiency in this ideal scenario.

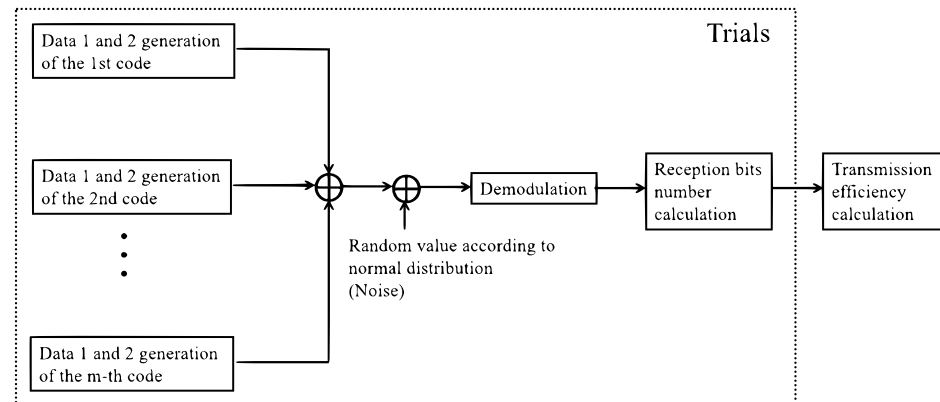


Figure 4. Simulation diagram.

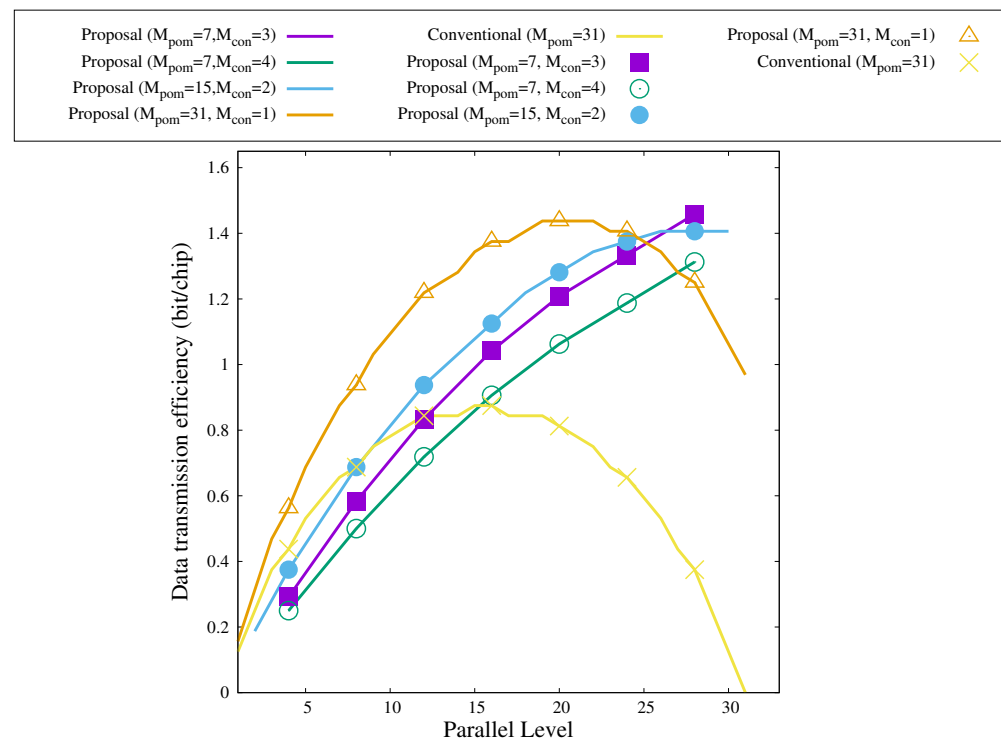


Figure 5. Data transmission efficiency as a function of the parallel level.

Figure 6 illustrates the relationship between data transmission efficiency and the transmit laser power per bit (P_w) for the conventional CSK system and the proposed scheme with light intensity scaling, evaluating the effect of background light noise. Here, the proposed method sets the threshold value Th_i to $\frac{2i+1}{2}P_w$. The evaluation assumes $L_{bit} = 4000$ bits. In the proposed scheme, the combinations of (M_{oc}, M_{con}) are (7,3), (7,4), (15,2), and (31,1). Each method sets the number of selected POMs (m) to the number at which the combined transmission reaches its maximum. The solid lines represent the analytical results, while the plots correspond to the simulation results obtained using Monte Carlo simulations. The analytical results are in qualitative agreement with the simulation results, confirming the validity of the analysis. For the conventional CSK system, the frame length is 31 chips, with the number of POMs also set to 31, and the number of bits per

frame is given by $\left\lfloor \log_2 \left(\frac{M_{oc}}{m} \right) \right\rfloor$. In the proposed system, the frame lengths are 21, 28, 30, and 31 chips for $(M_{oc}, M_{con}) = (7, 3), (7, 4), (15, 2),$ and $(31, 1)$, respectively. As shown in Figure 6, the configuration $(M_{oc} = 7, M_{con} = 3)$ achieves the highest data transmission efficiency.

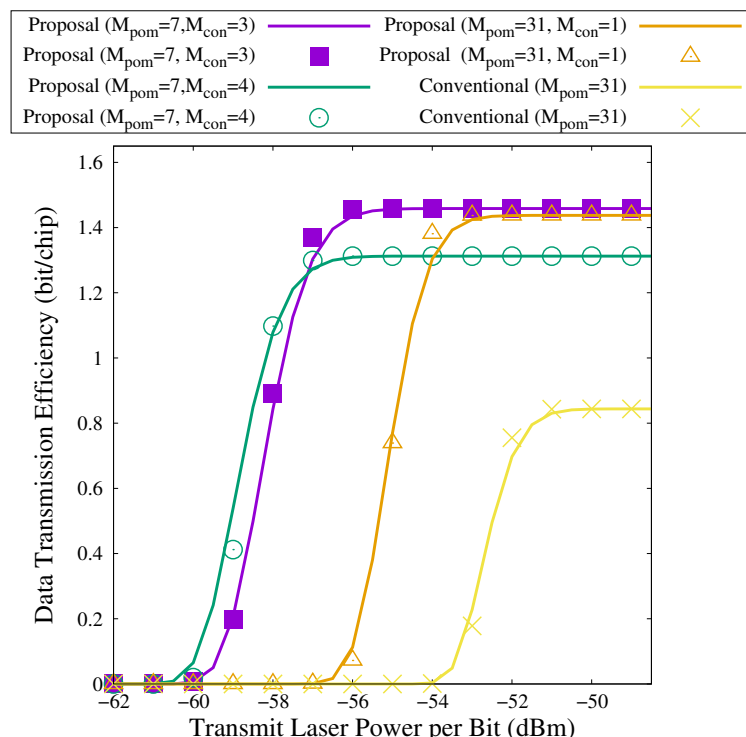


Figure 6. Data transmission efficiency as a function of the transmit laser power per bit.

Figure 7 illustrates the relationship between data transmission efficiency and the APD effective ionization ratio (k_{eff}) for the proposed scheme with light intensity scaling, evaluating the influence of APD shot noise. In the proposed method, the threshold value Th_i is defined as $\frac{2i+1}{2}P_w$, with an evaluation assuming $L_{bit} = 4000$ bits. The proposed scheme considers the parameter combinations (M_{oc}, M_{con}) as $(7, 3), (7, 4), (15, 2),$ and $(31, 1)$. Each method sets m to the value where the combined transmission achieves its peak performance. The solid lines represent analytical results, while the plotted points correspond to Monte Carlo simulation results, showing good agreement and confirming the validity of the analysis. In the proposed system, the frame lengths are 21, 28, 30, and 31 chips for $(M_{oc}, M_{con}) = (7, 3), (7, 4), (15, 2),$ and $(31, 1)$, respectively. The performance of the proposed method is influenced by multiple factors: noise immunity improves with an increased optical scale level, inter-code interference increases with a higher number of concatenations, the use of nonorthogonal CSK codes expands the available code set, and the number of viable transmission combinations decreases. Figure 7 indicates that configurations with fewer concatenations generally achieve higher performance due to a greater number of code combination patterns but are more vulnerable to noise. As shown in Figure 7, the configuration $(M_{oc} = 7, M_{con} = 3)$ achieves the highest data transmission efficiency.

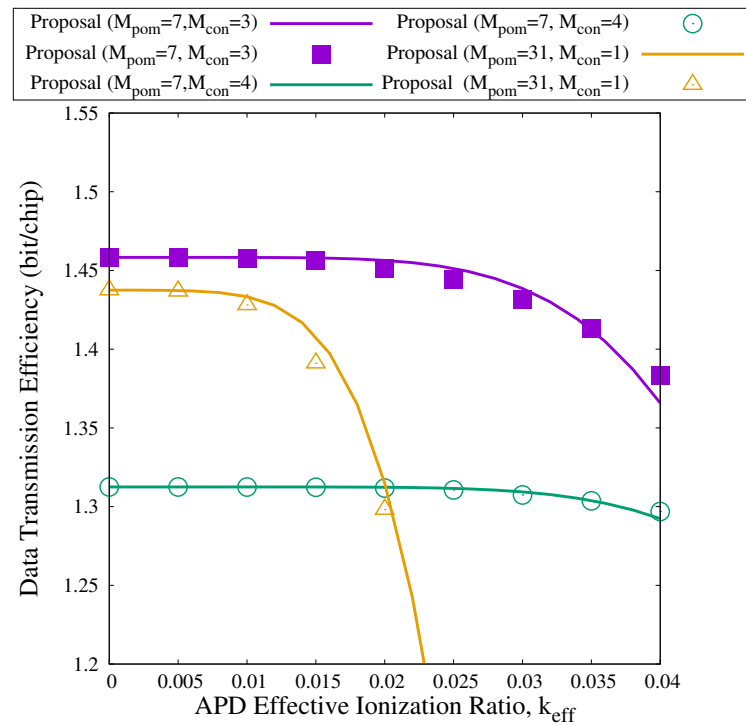


Figure 7. Data transmission efficiency as a function of the APD effective ionization ratio, k_{eff} .

Figure 8 depicts the data transmission efficiency of the proposed and conventional systems. In this figure, the combinations of (M_{pom}, M_{con}) in the proposed system are $(127, 1)$, $(63, 2)$, $(31, 3)$, and $(31, 4)$. The frame lengths for the cases of $(127, 1)$, $(63, 2)$, and $(31, 4)$ are 128, while the frame length for the case of $(31, 3)$ is 96. Additionally, Figure 9 illustrates the relationship between data transmission efficiency and frame length for both the conventional CSK system and the proposed scheme, where the number of bits per frame increases proportionally with the frame length.

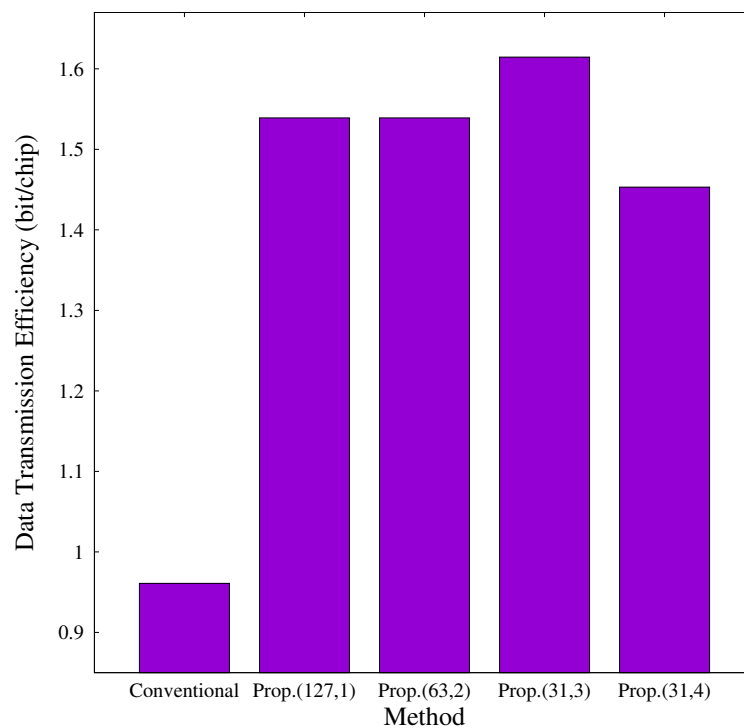


Figure 8. Comparison of data transmission efficiency as the proposed and conventional systems.

As in the evaluations shown in Figure 5, an ideal noise-free scenario is assumed. The results in Figures 8 and 9 reveal that the proposed scheme achieves data transmission efficiencies exceeding 1.0, a performance that is unattainable by the conventional CSK system. Among the evaluated configurations, the case of $M_{con} = 3$ achieves the highest data transmission efficiency, highlighting the effectiveness of combining nonorthogonal CSK with parallel transmission strategies. Furthermore, the findings indicate that the optimal concatenation number, M_{con} , for the proposed system, is 3.

A POM is constructed by extending an M-sequence with one additional chip. In the proposed method, the number of generated POMs is one less than the code length of the POM (i.e., the number of chips comprising the POM). This discrepancy leads to a reduction in data transmission efficiency, particularly when the code length is short, as shown in Figure 9. Furthermore, while the number of additional chips increases as the number of concatenations grows, this effect becomes negligible when the code length of the POM is sufficiently large relative to the number of concatenations.

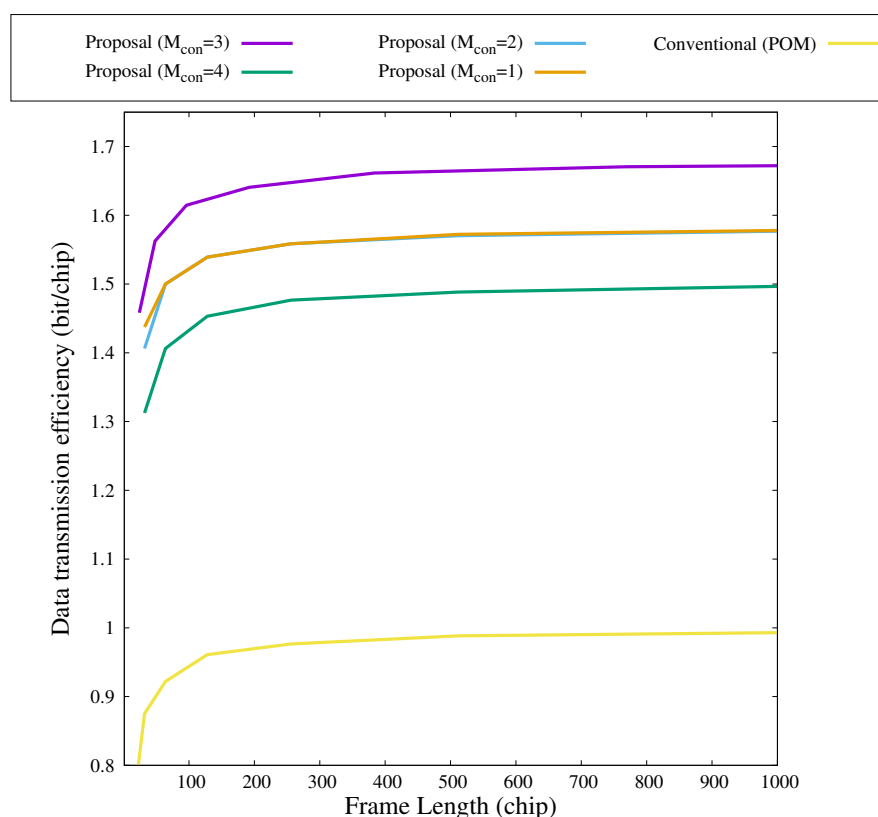


Figure 9. Data transmission efficiency as a function of the frame length.

5. Conclusions

This paper presented a novel strategy to enhance data transmission efficiency in IM/DD-based OWCs and evaluated its effectiveness. The proposed system integrated a parallel OWC structure with a nonorthogonal CSK approach, where CSK codes were generated from concatenated POMs. To assess the fundamental performance of the proposed system, its behavior was analyzed under the influence of background noise. Analytical expressions for data transmission efficiency in a single-user scenario were derived, and numerical results confirmed the improved performance of the proposed framework.

The proposed scheme enhances data transmission efficiency with increasing frame length and the number of parallel codes, demonstrating its adaptability. The optimal concatenation number was identified as $M_{con} = 3$, which provides the best balance between efficiency and performance. The results obtained confirm that the systematically

constructed nonorthogonal code effectively enhances the performance of IM/DD OWCs, offering valuable insights for future research and development in this field.

Since the nonorthogonal CSK method proposed by the authors is influenced by multiple factors—such as improved noise immunity with an increased optical scale level, increased inter-code interference with a higher number of concatenations, an expanded available code set through the use of nonorthogonal CSK codes, and a reduced number of viable transmission combinations—we investigated the effects of the proposed scheme and determined the optimal number of concatenations. The optimal concatenation number was identified as $M_{con} = 3$, providing the best balance between efficiency and performance. The results confirm that the systematically constructed nonorthogonal code effectively enhances the performance of IM/DD OWCs, offering valuable insights for future research and development in this field.

While this study investigated the proposed system in a single-user environment, multiple primitive polynomials can generate an M-sequence, allowing multiple connections to be established by assigning the resulting sequences to different users. This is expected to enable multiple access in the proposed system. Future work includes evaluating the multi-connection performance of the proposed method while considering the effects of atmospheric turbulence, directional errors, turbulence-induced fading, and other factors.

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