Comparative Analysis of Coded and Uncoded OIDMA using Random Inter-leaver with Varying Processing Gain

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Abstract : This article explores how processing gain is an efficient parameter in Direct-sequence spread spectrum communication, and also impacts the comparative performance of coded and uncoded optical IDMA systems. Basically the IDMA's qualities as the sole method for user separation, it adeptly mitigates multiple access interference (MAI), inter-symbol interference (ISI), and other related factors. In assessing the performance of OIDMA systems, interleavers are pivotal. This article introduces random interleavers into both coded and uncoded OIDMA systems one by one, and conducts a qualitative comparison of their impact. In every digital communication system, coding stands as a fundamental constraint. Convolutional codes serve the purpose of correcting burst errors in noisy communication channels. The output of the optical signal received by the O-IDMA system's receiver is a crucial determinant of its performance. In this context, the detection process utilizing Avalanche Photodiode for the O-IDMA system is thoroughly examined and analyzed. This paper utilizes simulations to investigate optical coded and uncoded OIDMA systems employing the minimum loss optical window, specifically at a wavelength of 1553nm, for transmission. The results regarding the probability of bit error are observed using MATLAB. This article explores the variation of processing gain, akin to spread length, and observes the probability of error results for different numbers of users employing random interleavers.

IndexTerms - Optical IDMA (O-IDMA), Convolutional codes, Code Rate, Random Inter-leaver (RI), Direct Sequence Spread Spectrum (DSS), Processing gain (PG).

1. INTRODUCTION

Security has been a persistent concern in wireless networks, primarily because of their broadcast communication nature. The majority of security mechanisms for wireless networks rely on assumptions of intractability and the associated computational complexity. DSSS technology has a channel bandwidth that complicates the decryption or decoding process, as it spreads a narrowband message into a wideband signal. In communication systems, interleaving is widely recognized as a common method to mitigate correlated channel noise, burst errors, and fading. It's a frequently employed technique to enhance the effectiveness of forward error correcting codes. The user-specific interleaver plays a pivotal role in the efficiency of the IDMA system. The existing multiple access techniques employed in 1G/2G/3G systems achieve a maximum data rate of approximately 72 Mbps [1-3].

The CDMA system, commonly employed in wireless communication, faces its own challenges such as multiple access interference (MAI) and intersymbol interference (ISI). Multiuser detection (MUD) further compounds the complexity, particularly in scenarios with a large number of users. To address the challenges encountered in both CDMA and MC-CDMA (multicarrier CDMA), a novel technique meeting the requirements of 4G systems is IDMA. IDMA deviates from CDMA in various aspects, particularly in its emphasis on diversity to combat fading and alleviate the interference from neighboring cell users, even in adverse conditions. It can be viewed as a specialized form of direct sequence code division multiple access (DS-CDMA) [4-6].

In IDMA, data streams are segregated using various interleavers instead of employing different spreading codes as in DS-CDMA. The proposed O-IDMA system introduces a method where interleavers are utilized within the optical channel rather than the wireless channel. Given the superior performance of optical channels in SNR, BER, ISI, and cost-effectiveness, along with their ability to facilitate high data rates reaching thousands of Gbps, the system employs an iterative chip-by-chip multiuser detection algorithm to mitigate the complexity of MUD. This approach enables support for a larger number of users. Interleaving refers to the systematic rearrangement of information bits. The size and design of interleavers significantly influence the quality of a communication system. Numerous interleavers are tailored to achieve specific performance objectives. Random interleavers serve as the fundamental interleaver for analysis purposes. The variation in spreading length, essentially denoting the processing

gain (PG) of the entire system, is examined. The impact of PG variation on the proposed O-IDMA system with random interleavers is observed, providing a notable insight into the improvement of the system's overall bit error rate (BER) [7-10].

A comparison is made between OIDMA employing convolutional codes and uncoded OIDMA, revealing a reduction in Bit Error Rate (BER) to as low as 10^{-8} for a minimum of 80 users. Increasing the coding rate enhances OIDMA's performance even further. Gupta et al. conducted an analysis of PPM-OIDMA technology, suggesting its potential application in 4G networks. The author explores the Free Space Optical (FSO) channel, developing a Pulse Position Modulated Optical IDMA system using MATLAB. The model incorporates factors such as atmospheric turbulence, spatial diversity for free space channel modeling. Additionally, observations include considerations of thermal noise, background noise, and scintillation. The primary emphasis of this paper lies in the spread length, achieved through spreading with the aid of Pseudo Noise Sequence (PNS sequence). The length of the PNS sequence corresponds to the processing gain. The paper delves into various aspects surrounding Pseudo Noise Sequence (PNS) generation, including its generation process, circuit diagram, and components utilized. It also covers topics such as maximum length sequences, detailing their properties such as balance, run, and correlation. Furthermore, the discussion extends to processing gain, elucidating its definition in Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS) scenarios, chip rate, and the consequential impacts on probability of bit error, jamming margin, and Anti-jamming capability [11-15].

This paper begins with Section 2, which presents the block diagram of the Optical Interleave Division Multiple Access (O-IDMA) system and elaborates on the procedures of random interleaving and convolutional coding. In Section 3, the concepts of processing gain are elucidated. Section 4 showcases the simulation results alongside their corresponding discussions. The concluding remarks are provided in Section 5.

2. OIDMA System Overview

Fig. 1 illustrates the architecture of the OIDMA system incorporating convolutional coding. Within the architecture segment, the initial component signifies the encoder. This encoder possesses the capability to minimize errors induced by a channel in digital communication processes. In this context, the kth encoder is employed to encode the kth user's data. Following the encoding process, the encoded data is then spread using a PNS sequence by the spreader. Subsequently, the resulting signal data becomes significantly more secure and nearly immune to interference before being transmitted to the interleaver. The resulting signal undergoes interleaving utilizing kth interleavers. Following this interleaving process, the interleaved data is amalgamated by a combiner and transmitted through an optical source (LASER), ultimately reaching the receiver section [1-4].
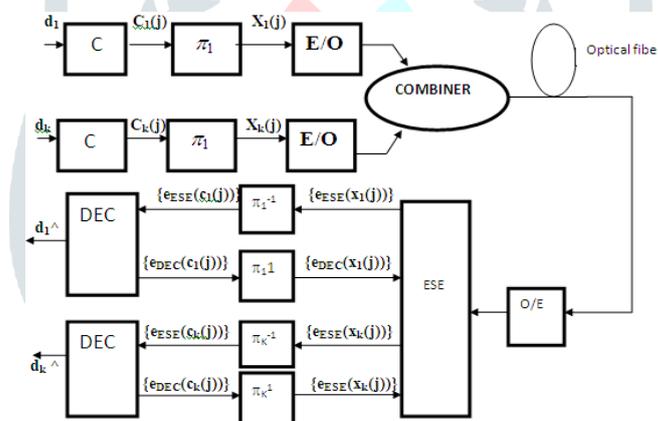

Fig.1. Optical IDMA Transmitter and Receiver Structure

Within the receiver section, the optical data is initially transformed into an electrical signal by the optical detector (APD). As the received signal may contain noise, a chip-matched method is employed for multiuser detection to decode the noisy signal. Subsequently, the decoded signal is forwarded to the elementary signal estimator. Through the utilization of ESE, LLR (Log Likelihood Ratio), and a feedback mechanism, specific users are identified [16-17].

2.1. *Random Interleaver*

Random interleavers operate by interleaving bits in an undetermined, non-periodic fashion. Input bits are organized randomly, and the same arrangement is maintained during the de-interleaving process at the output. Generating random interleavers is a straightforward process but demands larger memory capacity. Manufacturing random interleavers necessitates a greater quantity of hardware components. An illustrative example demonstrating the essence of the random interleaving process is depicted in Figure 2 below.
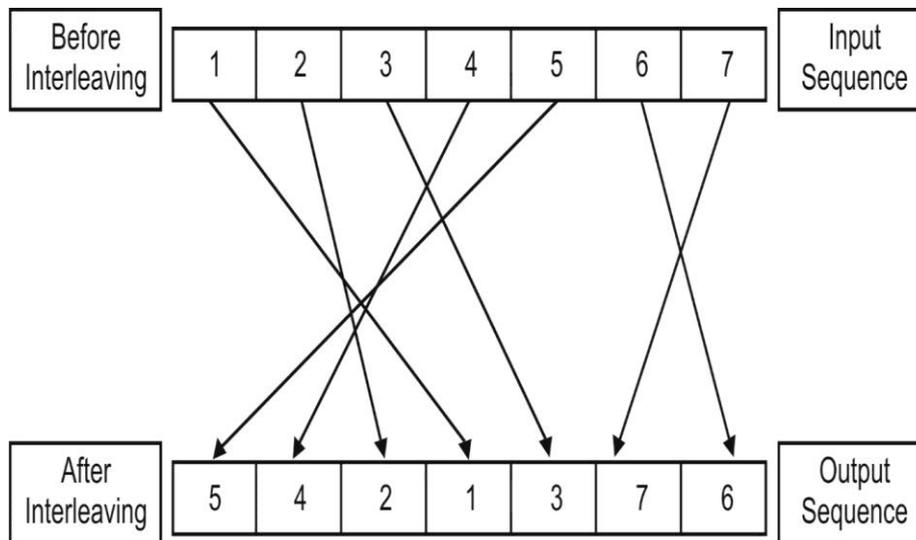
Fig. 2 Procedure for Random Interleaving

2.2 Convolutional Encoder

Convolutional coding is a prevalent technique used in digital communication to rectify errors. It involves D flip-flops and logic gates, with the shifting property of the convolutional encoder often utilized in hardware design for encoding. The D flip-flops serve as the shift register, with the length of the shift register determining the constraint length of the convolutional encoder. Varying the constraint length generates uncorrelated code words. Convolutional encoders are characterized by three parameters: A, B, and C. Here, A represents the number of output bits, B denotes the number of input bits, and C signifies the number of memory elements. The code rate, defined as B/A, quantifies the efficiency of the encoder. As the number of Ex-OR gates increases, the output bits (A) also increase, allowing for the generation of various code rates such as ½, 1/3, and ¼, while maintaining a fixed number of input bits (B) set to 1. The constraint length (L) is determined by m+1, where m represents the number of shift registers in use. Utilizing a higher number of shift registers results in output bits being more heavily influenced by a single bit [17-18].

3. Processing Gain

The unwanted (jamming) signal will possess a bandwidth of at least W. If its power is J watts, its average density, which exhibits uniform characteristics and can be regarded as wideband noise, will have.

$$N_0 = J/W \quad \text{watts/Hz} \tag{1}$$

Assume the desired component of the received signal has power S watts. Consequently, if the data rate is R bits/second, the received energy per bit is

$$E_b = S/R \quad \text{watts/second} \tag{2}$$

It is now widely acknowledged that the performance of bit error rate in digital communication systems correlates directly with the dimensionless ratio Eb/N0. This ratio can be expressed for spread spectrum signals as

$$E_b/N_0 = SW/JR \tag{3}$$

Therefore, the ratio of jamming power to signal power is

$$J/S = WN_0/E_bR \tag{4}$$

This indicates that if Eb/N0 represents the minimum bit energy-to-noise density ratio required to maintain a specific bit error rate, and W/R stands for the spread bandwidth ratio, often termed as the processing gain, then J/S signifies the minimum acceptable jamming power-to-signal power ratio, commonly referred to as the jamming margin [9-10].

We have reached this point without even specifying the characteristics of the spreading signal. In fact, there are two distinct classes of spreading methods. The initial class is known as direct-sequence or pseudo noise (PN) spread spectrum. In this method, spreading occurs through multiplication by a binary pseudorandom sequence, with a symbol rate significantly higher than the binary data bit rate. Occasionally, the symbol rate of the spreading sequence is referred to as the chip rate. Error-correcting coding necessitates redundancy, which expands bandwidth and consequently diminishes the available processing gain within the bandwidth [7-8].

In reality, the situation is quite the opposite. To demonstrate that coding doesn't diminish the effective processing gain, let's reformulate the jamming margin (4) using the symbol rate RS and the symbol energy ES. These quantities are linked to the bit

rate and bit energy via the code rate r, which is defined as the ratio of the number of data bits per transmitted symbol or the reciprocal of the coding expansion factor. (For instance, a rate ½ coded system transmits two code symbols for each data bit). Consequently, it follows that

$$R_S = R/r \quad \text{and} \quad E_S = E_b\, r \tag{5}$$

Now, if we replicate the preceding dimensional analysis, substituting "bits" with "symbols" throughout, we obtain

$$J/S = WN_0/E_b\, R_S \tag{6}$$

However, by substituting the previous definitions for symbol rate and energy, we derive the maximum tolerance ratio of J/S.

$$J/S = W\, N_0/R\, E_b \tag{7}$$

Returning to (4) brings us full circle. While it might appear to be a clever maneuver, it's not. Furthermore, with additional reading, one will come to see that we are actually in a favorable position. In coding, the necessary Eb/N0 for a specific performance level (bit error rate) is effectively lowered. Consequently, coding enhances the jamming margin even more for a given processing gain (W/R).

4. Simulation Result and Discussion

This paper focuses on the optical IDMA system, where specific parameters are meticulously chosen to optimize its performance. The optical channel operates within a narrow window of 1553nm, with a zero dispersion wavelength of 1330nm. Employing an APD in the optical detector, characterized by a responsiveness of 0.85 and a maximum gain of 1000, facilitates a high data rate of up to 1Gbps. Other crucial specifications include an effective area (Aeff) of 0.65, Gaussian-shaped input pulses with an optical power of 1mW, a block length of 100, and a data length (M) of 512. The system operates at a low code rate of ½ with a constraint length of 3. Finally, the performance evaluation, particularly the probability of bit error, is conducted using MATLAB. In this analysis, the processing gain, akin to the spread length (SL), is manipulated at values of 16 and 32. The effects on system performance are then examined across various numbers of users employing random interleaving. For spread length (SL) 16, the number of users is varied from 60 to 160, while for spread length (SL) 32; the range is from 300 to 400 users.

Both Figure 3 and Table 1 illustrate identical findings, showcasing the performance of both coded and uncoded OIDMA systems with a spread length of 16. They exhibit consistent trends where the bit error rate (BER) rises with an increase in the number of users. For example, in the uncoded OIDMA setup, the BER escalates from 3.9562×10^{-6} for 60 users to 7.9847×10^{-5} for 160 users. Conversely, in the coded OIDMA scenario, the BER increases more modestly from 8.8497×10^{-7} for 60 users to 8.9413×10^{-6} for 160 users.

Similarly, both Figure 4 and Table 2 provide consistent insights, illustrating the performance of coded and uncoded OIDMA systems with a spread length of 32. They exhibit analogous trends, wherein the bit error rate (BER) increases with a growing number of users. However, it's notable that in Figure 4 and Table 2, the BER remains zero for both uncoded and coded OIDMA systems before reaching 300 users, attributed to the spread length of 32. For example, in the uncoded OIDMA scenario, the BER rises from 0.9854×10^{-7} for 300 users to 1.6825×10^{-6} for 400 users. In contrast, in the coded OIDMA scenario, the BER remains zero for 300 users and then increases only to 1.8543×10^{-7} for 400 users.
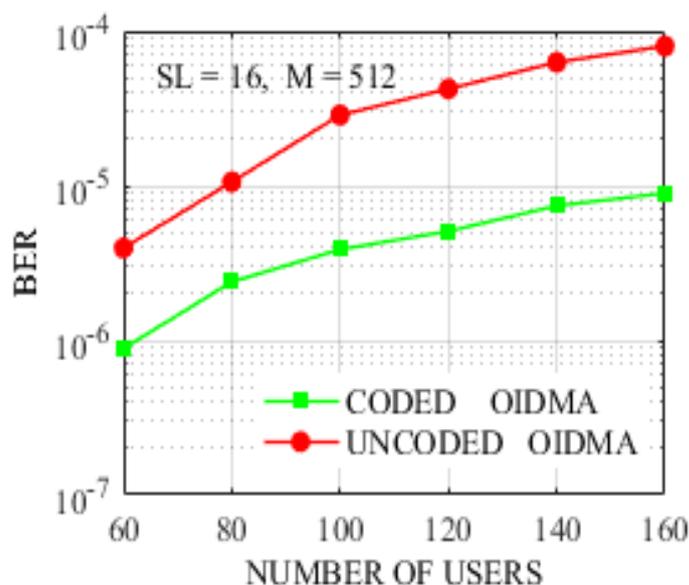

Fig. 3: BER Performance of Coded and Uncoded OIDMA using Spread Length 16 with Random Interleaver
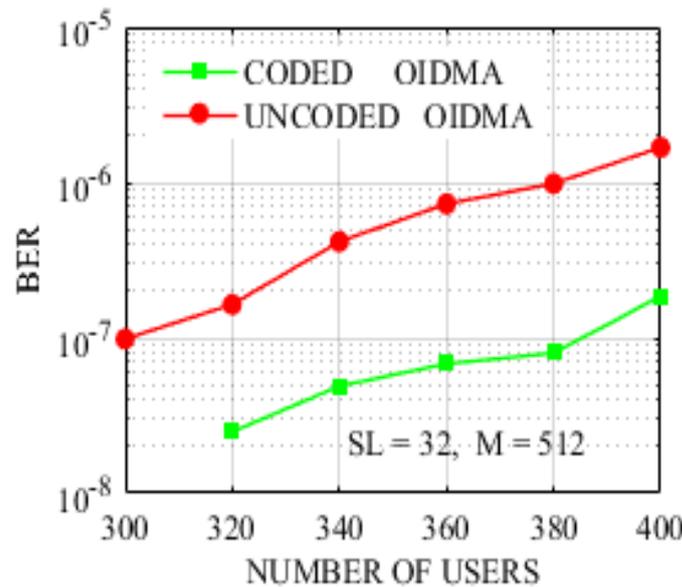
Fig. 4: BER Performance of Coded and Uncoded OIDMA using Spread Length 32 with Random Interleaver

Table 1: BER Performance of Coded and Uncoded OIDMA using Spread Length 16 with Random Interleaver

S. No.	No. of Users	Bit Error Rate	
		Uncoded OIDMA	Coded OIDMA
1	60	3.9562×10^{-6}	8.8497×10^{-7}
2	80	1.0584×10^{-5}	2.3864×10^{-6}
3	100	2.8631×10^{-5}	3.8692×10^{-6}
4	120	4.2649×10^{-5}	5.0732×10^{-6}
5	140	6.2832×10^{-5}	7.4142×10^{-6}
6	160	7.9847×10^{-5}	8.9413×10^{-6}

Table 2: BER Performance of Coded and Uncoded OIDMA using Spread Length 32 with Random Interleaver

S. No.	No. of Users	Bit Error Rate	
		Uncoded OIDMA	Coded OIDMA
1	300	0.9854×10^{-7}	NO BER
2	320	1.6582×10^{-7}	2.4886×10^{-8}
3	340	4.1659×10^{-7}	4.8926×10^{-8}
4	360	7.2843×10^{-7}	6.8183×10^{-8}
5	380	9.8321×10^{-7}	7.6852×10^{-8}
6	400	1.6825×10^{-6}	1.8543×10^{-7}

5. Conclusion

The simulation results affirm that increasing the spread length from 16 to 32 enhances the performance of the OIDMA system. Additionally, when comparing coded OIDMA to uncoded OIDMA, the former exhibits superior performance. Ultimately, it becomes evident that employing coding and processing can notably enhance the performance of the OIDMA system. As we're aware, the spreading length, akin to processing gain, plays a crucial role in direct sequence spread spectrum communication. A higher processing gain enhances the system's anti-jamming capability and security, as it increases the jamming margin and reduces the probability of bit error.

Therefore, it can be inferred that varying the processing gain enhances the performance of the OIDMA system. As the processing gain increases, there is a corresponding improvement in the error probability (Pe). We have opted for a random interleaver for our study due to its simplicity and ease of generation, leading to enhanced results. Ultimately, owing to its reduced multiple access interference, high data rate, low inter-symbol interference (ISI), and cost dependence on the number of users, OIDMA with convolutional coding emerges as a promising tool for future 5G and 6G systems.

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