Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Comparative Study of US-IDMA and IDMA using Convolutional Code with Prime

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To address the escalating data rates in contemporary communication systems, researchers have explored various multiple access technologies, with US-IDMA (User-Spread Optical Interleave Division Multiple Access Technology) emerging as a prominent solution to meet this demand. This research paper primarily focuses on comparing the performance of US-IDMA and IDMA, employing convolutional codes with a fixed code rate of 1/4 and various constraint lengths (3, 5, and 7). When optical channels are integrated into US-IDMA, it transforms into optical US-IDMA, combining the strengths of CDMA and IDMA. This integration results in enhanced performance and reduced losses. Essentially, optical US-IDMA offers superior efficiency compared to its electrical counterparts, marking a significant advancement in multiple access technologies. In every digital communication system, coding plays a crucial role, particularly in managing errors within the transmitted data. Convolutional codes are commonly employed for correcting burst errors in noisy communication channels. In our study, we utilized convolutional codes with fixed code rates and various constraint lengths, implemented within the MATLAB software environment. The focus of our analysis lies in comparing the performance of optical US-IDMA and IDMA, with the evaluation metric being the Bit Error Rate (BER). To facilitate this comparison, we employed a random interleaver, ensuring minimal optical loss within a window of 1330nm for analysis purposes. This approach allows for a comprehensive assessment of the effectiveness of these multiple access techniques in practical communication scenarios.

Keywords: IDMA, US-IDMA, Prime Interleaver, Code Rate, Constraint Length.

1. Introduction

In contemporary wired communication systems, optical fiber has become increasingly prevalent due to its wide bandwidth and minimal noise characteristics. Maximizing the utilization of available bandwidth is essential in optical fiber systems, as it enables accommodating a larger number of users and facilitates higher data transmission rates. Multiple access schemes play a crucial role in efficiently managing this bandwidth. However, as traffic intensity grows, various challenges emerge in current multiple access techniques, including CDMA, DS-CDMA, TDMA and FDMA. These challenges include issues like inter-symbol interference (ISI), multiple access interference (MAI), near-far issues and multiuser detection [1-2]. Interleavers play a crucial role in distinguishing individual users through turbo-like joint detection methods.

A software-based technique, incorporating APP (A Posteriori Probability) LLR (Log-Likelihood Ratio) calculation by PSE (Probabilistic Symbol Estimation), along with feedback mechanisms for automatic correction, is employed for user discrimination. The primary objective of utilizing interleavers is to distribute burst errors into random errors effectively. In our study, we utilize prime interleavers individually and in combinations of two, selected based on the design parameters of the communication link. We analyze the performance of prime interleavers within US-IDMA systems and compute the bit rate achieved, shedding light on their efficacy in enhancing communication system performance. When optical technology is integrated into IDMA, it becomes more potent, known as OIDMA. Optical technology offers significant advantages such as expansive bandwidth, minimal loss, reduced interference, low cross talk, and minimal bit error rates, making it highly desirable for long-distance transmissions. To address the challenges posed by heavy user traffic, IDMA technology provides a solution by effectively mitigating issues encountered in other multiple access techniques. In communication systems, interleaving serves as a common method to combat correlated channel noise, burst errors, and fading. This technique plays a vital role in enhancing system robustness and reliability, ensuring smoother data transmission in various environmental conditions. Interleaving is a common practice in communication systems, enhancing the performance of forward error correcting codes. Specifically, user-specific interleaving significantly contributes to the efficiency of IDMA systems. Traditional multiple access techniques utilized in 1G/2G/3G systems typically achieve a maximum data rate of around 72 Mbps. However, with the demands of 4G systems requiring higher data rates, alternatives are sought. In IDMA, data streams are segregated using various interleavers, as opposed to different spreading codes employed in DS-CDMA. This approach enables more efficient data transmission, accommodating the increased data rate requirements of 4G systems and beyond [3-5].

Various error correction and detection techniques for convolutional codes include the Viterbi algorithm, low-density parity-check (LDPC) codes, and forward error correction (FEC) codes. Among these, convolutional codes offer distinct advantages over other coding techniques, such as block codes. Convolutional codes are particularly favored for their superior error-correcting capabilities, especially when employing a low rate, which is preferable in Optical Interleave Division Multiple Access (OIDMA) systems. The use of higher code rates enhances the error-correcting capability of OIDMA [6-9].

The rest of the paper is organized as follows: Section 2 provides an introduction to the US-OIDMA system, outlining its key components and operation. Section 3 elaborates on the mechanism of Prime interleaving, explaining its role and implementation within the communication system. Section 4 provides an in-depth description of convolutional encoding, detailing its principles and application in the context of the discussed system. Section 5 presents the simulation results and their corresponding discussion, analyzing the performance and implications of the proposed approach. Finally, the paper concludes by summarizing the findings and providing necessary references for further exploration of the topic.

US-IDMA SYSTEM:

The current IDMA system employed in contemporary communication networks is effectively structured to handle high traffic loads, catering to numerous users while maintaining minimal bit error rates. The US-IDMA system represents an evolution of the IDMA framework, introducing variations in spreading sequences and interleavers tailored to individual users. This adaptation enhances system security and noise immunity by employing distinct PNS sequences for each user, thereby bolstering overall system resilience against external interference and potential security threats. While employing distinct PNS sequences for individual users increases the receiver's design complexity, it substantially reduces the bit error rate compared to the OIDMA system. To generate maximum length sequences (MLS), this paper demonstrates different configurations of shift registers combined with adders. The optimal configurations for producing PNS sequences involve five shift registers with one adder (5, 2), as well as five shift registers with three adders (5, 4, 3, and 2). These configurations are demonstrated to yield efficient PNS sequences in the study [9-11].

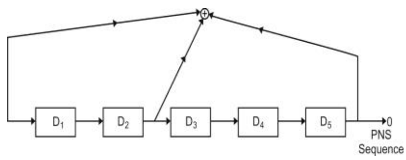

Fig. 1 Feedback Shift Register with a D Flip-Flop and (5, 2) Configuration

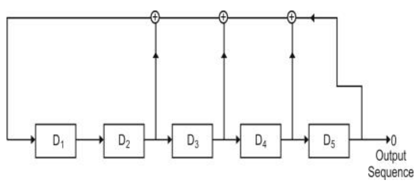

Fig. 2 Feedback Shift Register with a D-flip flop and (5, 4, 3, 2) Configuration

6 ⟶ (6 , 1) (6, 5, 2, 1) (6, 5, 3, 2)

7 ⟶ (7, 1) (7, 3) (7, 3, 2, 1)

(7, 4, 3, 2) (7, 4,3,2)

(7, 6, 4, 2) (7, 6, 3, 1)

(7, 6, 5, 2) (7, 6, 5, 4, 2, 1)

(7, 5, 4, 3, 2, 1)

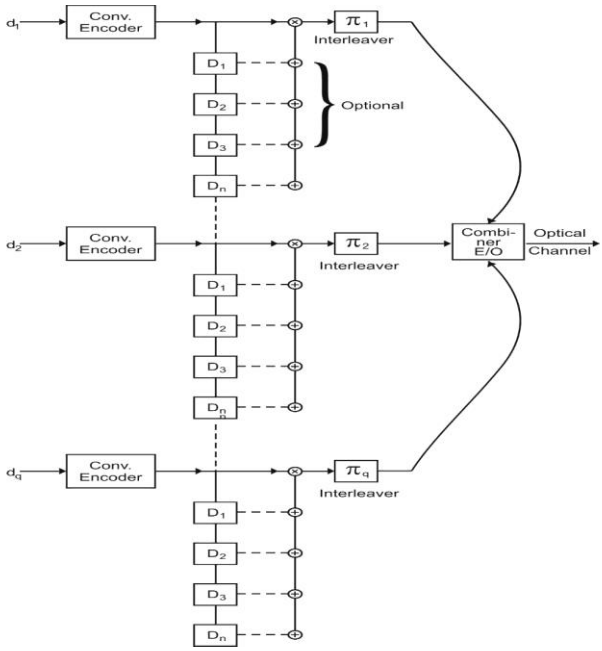

Fig. 3 User-Spread OIDMA Transmitter

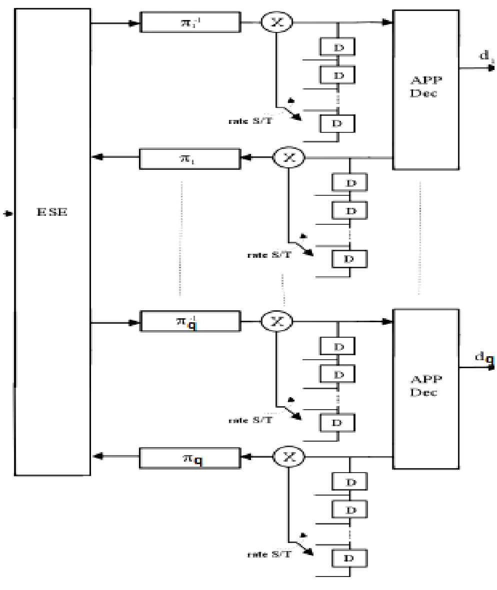

Fig. 4 User-Spread OIDMA Receiver

PRIME INTERLEAVER:

In digital communication and US-IDMA technologies, different types of interleavers are employed. However, this discussion focuses on a particularly significant and widely used interleaver within our US-IDMA system: the prime interleaver. The prime interleaver stands out as it is specifically designed based on prime numbers. Notably, it offers the advantage of minimal complexity, making it an efficient choice. Moreover, the Bit Error Rate (BER) performance of Turbo Block Interleaving (TBI) using the prime interleaver is comparable to Random Interleaving (RI), further highlighting its effectiveness and utility in communication systems. Random interleavers commonly suffer from the drawback of requiring significant memory space. To address this limitation, a specialized type of interleaver is developed, which is exclusively based on prime numbers. This special interleaver is constructed using seed values, where only prime numbers are utilized as seeds. This unique characteristic gives rise to its name, the prime interleaver. It ensures a separation between interleaved bits on a specified length G [N], facilitating efficient interleaving operations with reduced memory requirements [12-14].

CONVOLUTIONAL ENCODING:

Convolutional coding involves combining a fixed number of input data streams. Input data bits are stored in memory elements of fixed length, and Ex-OR gates are used to add them together. This process closely resembles binary convolution, hence the name "convolutional coding. The entire process is depicted using a simple hardware setup illustrated in the circuit diagram [15-17].

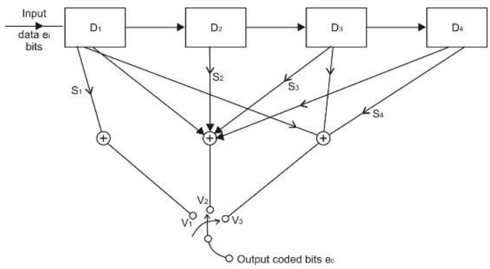

Fig. 5 Convolutional Encoder

A convolutional coder is denoted as (n, k, K), where n represents the number of output bits, k indicates the number of input bits, and K signifies the number of shift registers utilized in the encoder design. In the provided figure, four D flip-flops (FF) are interconnected in a series, with three Ex-OR gates connected at the output. The input bits are denoted as ei, while the output bits are represented as eo, namely V1, V2, and V3, which are derived through the encoder connections [6-8].

$V_1 = S_1$

$V_2 = S_1 \oplus S_2 \oplus S_3 \oplus S_4$

$V_3 = S_1 \oplus S_3 \oplus S_4$

The operation of the convolutional encoder begins with all flip-flops initially in a clear state, where both input and output are set to zero. Each flip-flop has a storage capacity of a single bit, indicating k = 1. Given that each one bit of input is encoded into a three-bit output, we have n = 3, and since four flip-flops are employed, k = 4. Let's consider an input data stream of 1 0 1 1. As the first input bit '1' enters the circuit, the outputs of flip-flops D1, D2, D3, and D4 change accordingly, causing the output bits V1, V2, and V3 to adjust their values based on their respective expressions (111). Subsequently, when the next bit '0' is introduced, the output undergoes further alteration.

The process continues until the last input bit '1' enters the circuit, resulting in an output of '110'. Following the last bit, a series of four zeros ('0000') is transmitted into the circuit to clear the encoder. Overall, the total number of output bits is represented as V(L + K), where V denotes the output bits, L signifies the message length, and K indicates the number of memory elements utilized in the circuit. In the current scenario, L = 4, V = 3, and K = 4, thus yielding a total of 3 × (4 + 4) = 24 bits. Through this process, it becomes evident that each input bit affects K groups of V bits. In this particular example, one input bit influences 12 output bits until it exits the encoder.

2. SIMULATION RESULT AND DISCUSSION:

The US-IDMA system incorporates various interconnected blocks programmed to operate together. Convolutional codes with constraint lengths of 3, 5, and 7, corresponding to 2, 4, and 6 memory elements respectively, are utilized alongside 4 Ex-OR gates. With the fixed number of Ex-OR gates at 4, the resulting code rate is (1, 4), categorized as a high code rate. Input parameters include a spread length of 32, a block length of 100, and a fixed data length of 512. Optical parameters involve a Gaussian pulse of 1mW power, a maximum rate of 1000 Mbps, alongside fixed fiber numerical aperture and dispersion parameters. Optical detection is facilitated by an Avalanche Photodiode (APD) with a gain of 1000, operating at a wavelength of 1553nm. The system's performance is evaluated by varying the number of users from 500 to 640. The observed Bit Error Rate (BER) for constraint lengths (3, 5, and 7) and the code rate (1, 4) is tabulated, and the corresponding graph is plotted.

Table 1, depicted graphically in Figure 6, illustrates the Bit Error Rate (BER) performance of both US-IDMA and IDMA systems utilizing a Code Rate of 1/4 and a Constraint Length of 3. Across all readings, Figure 6 demonstrates a consistent trend: as the number of users increases, the BER also rises. For instance, in the IDMA scenario, the BER climbs from 3.3652×10^{-8} for 500 users to 8.5493×10^{-7} for 640 users. Conversely, in the US-IDMA scenario, the BER remains at 0 for 500 users, increasing only to 8.3610×10^{-8} for 640 users. Similarly, from Table 2 and Figure 7, with the same Code Rate of 1/4 and Constraint Length of 3, the trend persists: the BER for IDMA escalates from 5.8930×10^{-8} for 500 users to 7.8438×10^{-7} for 640 users. Meanwhile, in the US-IDMA case, the BER remains at 0 for 500 users, rising slightly to 8.9821×10^{-8} for 640 users. This pattern holds true for all Constraint Lengths, including L = 5 and L = 7, as depicted in Figure 8. For instance, with L = 7 and a Code Rate of 1/4, the BER starts at 0 for 500 users, reaching 9.6583×10^{-8} for 640 users in the OIDMA scenario. In contrast, in the US-OIDMA setup, the BER remains at 0 for 500 users, increasing to 8.9850×10^{-8} for 640 users.

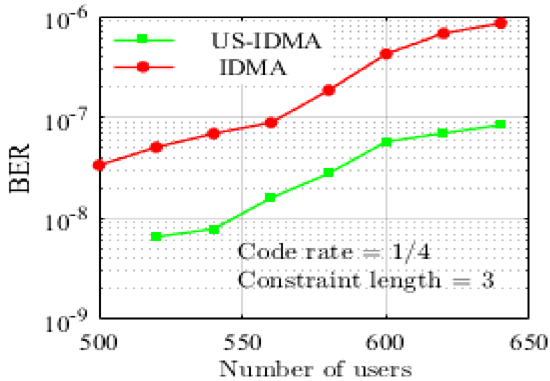

Fig. 6 BER Performance of US-IDMA and IDMA using Code Rate ¼ and Constraint Length 3

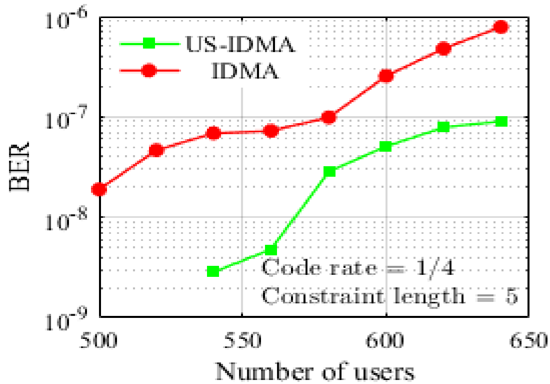

Fig. 7 BER Performance of US-IDMA and IDMA using Code Rate ¼ and Constraint Length 5

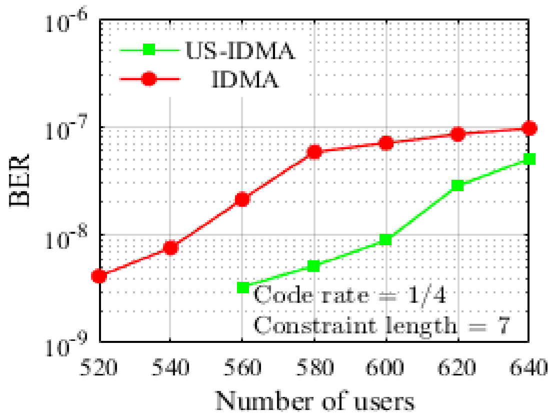

Fig. 8 BER Performance of US-IDMA and IDMA using Code Rate ¼ and Constraint Length 5

Table 1: Variation in BER for US-IDMA and IDMA with different numbers of users, using a code rate of 1/4 and a constraint length of 3 with a prime interleaver

S. No.	No. of Users	Bit Error Rate	
		IDMA	US-IDMA
1	500	3.3652×10^{-8}	NO BER
2	520	5.0597×10^{-8}	6.5837×10^{-9}
3	540	6.9135×10^{-8}	7.8654×10^{-9}
4	560	8.8635×10^{-8}	1.5963×10^{-8}
5	580	1.8587×10^{-7}	2.7932×10^{-8}
6	600	4.2357×10^{-7}	5.7432×10^{-8}
7	620	6.7843×10^{-7}	6.9765×10^{-8}
8	640	8.5493×10^{-7}	8.3610×10^{-8}

Table 2: Variation in BER for US-IDMA and OIDMA with different numbers of users, using a code rate of 1/4and a constraint length of 5 with a prime interleaver

S. No.	No. of Users	Bit Error Rate	
		IDMA	US-IDMA
1	500	5.8930×10^{-8}	NO BER
2	520	7.6387×10^{-8}	NO BER
3	540	8.4816×10^{-8}	2.8431×10^{-9}
4	560	8.9635×10^{-8}	4.7862×10^{-9}
5	580	9.8453×10^{-8}	2.8431×10^{-8}
6	600	2.5436×10^{-7}	5.0627×10^{-8}
7	620	4.7636×10^{-7}	7.8382×10^{-8}
8	640	7.8438×10^{-7}	8.9821×10^{-8}

Table 3: Variation in BER for US-IDMA and IDMA with different numbers of users, using a code rate of 1/4and a constraint length of 7 with a tree interleaver

S. No.	No. of Users	Bit Error Rate	
		IDMA	US-IDMA
1	500	NO BER	NO BER
2	520	4.1528×10^{-9}	NO BER
3	540	6.5869×10^{-9}	NO BER
4	560	7.9884×10^{-9}	8.3054×10^{-9}
5	580	8.3656×10^{-8}	8.9859×10^{-9}
6	600	7.0657×10^{-8}	9.9032×10^{-9}
7	620	8.5430×10^{-8}	6.9739×10^{-8}
8	640	9.6583×10^{-8}	8.9850×10^{-8}

3. CONCLUSION

The results from Tables 1, 2, and 3, along with the corresponding graphical representations in Figures 6, 7, and 8, unmistakably demonstrate the superiority of the US-IDMA system. These findings validate theoretical assertions that increasing constraint lengths leads to the generation of more uncorrelated code words, thereby enhancing the minimum Hamming distance (dmin) and bolstering the error correction capabilities of the code, consequently improving the Bit Error Rate (BER) performance of the US-IDMA system. Moreover, the augmentation of constraint length yields a greater number of uncorrelated code words, exerting a positive impact on the results. Across all simulation outcomes, it's evident that a constraint length of L = 7 yields superior results compared to L = 3 and L = 5. While the potential for further enhancement exists through the incorporation of more shift registers in both the spreading and coding sections, it's essential to consider the trade-off between improved performance and increased system delay. By judiciously selecting the appropriate number of shift registers and adders in both sections, the US-IDMA system emerges as a compelling alternative to existing IDMA systems, offering enhanced performance without compromising system speed.

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