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Performance Analysis of Interleave Division Multiple Access (IDMA) using Binary Phase Shift Key (BPSK) and Binary Frequency Shift Key (BFSK) Modulation

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ABSTRACT
Interleave Division Multiple Access (IDMA) is a recently proposed multiple access technique with potential applications in 5G and 6G communication systems. In this study, the wireless communication channel is modeled as an Additive White Gaussian Noise (AWGN) channel, which serves as a widely accepted theoretical framework for evaluating the performance of digital modulation schemes under noise conditions. Phase-Shift Keying (PSK) provides higher bandwidth efficiency and supports higher data rates, whereas Frequency-Shift Keying (FSK) offers superior noise immunity, making it suitable for operation in noisy environments. When integrated with an interleaver, the IDMA system employing both PSK and FSK modulation schemes demonstrates significantly improved performance. In this paper, the performance of the IDMA system has been compared using BPSK and BFSK modulation schemes with both prime and tree interleavers. The Bit Error Rate (BER) is evaluated by varying the Signal-to-Noise Ratio (SNR), and the results are thoroughly analyzed. The complete IDMA system is simulated using MATLAB..

Keywords: *Signal to noise ratio (SNR), Tree Interleaver (TI), Prime Interleaver (PI), Binary frequency-shift keying (BFSK), Binary Phase-shift keying (BPSK) and Interleave Division Multiple Access (IDMA).*
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1. INTRODUCTION:

Wireless communication channels are inherently dynamic and complex, influenced by impairments such as noise, interference, and multipath propagation. Accurate channel modeling is crucial for evaluating system performance and for the design of robust modulation, coding, and error-correction techniques. Rayleigh fading has a significant impact on BER performance, particularly in mobile communication scenarios. To mitigate its effects, various diversity techniques such as spatial diversity and time interleaving are commonly employed [1–2].

User distinction in IDMA systems is achieved through the use of interleavers. An interleaver is a mechanism that rearranges data according to a known deterministic pattern. To enhance transmission quality, several types of interleavers such as random, tree, and helical have been developed. The size and structure of interleavers play a crucial role in determining system performance. In a tree interleaver, two master random interleavers are selected randomly, and all other branches corresponding to different users are generated as combinations of these two master interleavers. Random interleavers require a large amount of memory, which is their main drawback. To overcome this limitation, a special type of interleaver based entirely on prime numbers has been developed. This prime interleaver not only reduces memory requirements but also provides better performance compared to random and tree interleavers [3–5].

Shift keying techniques are widely used in digital modulation schemes, as they offer efficient modulation and data transmission. In these schemes, data is conveyed by altering specific properties of the carrier signal. PSK modulation schemes are generally more efficient than other digital modulation techniques. In BPSK modulation, one bit of data is transmitted per phase shift of the carrier signal, providing strong resistance to noise. On the other hand, FSK systems are commonly used for relatively low-speed data transmission, particularly in scenarios where minimizing receiver cost is important. Applications include early-generation downstream data transmission to addressable set-top boxes, upstream transmission from certain early RF impulse pay-per-view (IPPV) converters, and status monitoring. While spectral efficiency is low, this is relatively unimportant for low-speed applications. The transmission is robust, being resistant to noise and distortion, while the required hardware remains relatively low-cost. Single-chip data receivers have been available for many years [6–7].
In this paper, Section 2 presents the block diagram of Interleave Division Multiple Access (IDMA) using tree and prime interleavers. Sections 3, 4, and 5 detail the processes of BFSK and BPSK modulation, as well as the evaluation of Signal-to-Noise Ratio (SNR). Section 6 presents the simulation results and their discussion, while Section 7 concludes with a summary and outlines future prospects.

2. OVERVIEW OF IDMA SYSTEM-

The architecture of the IDMA system with convolutional coding is shown in Figure 1. In this architecture, the first component is the encoder, which helps reduce errors introduced by the channel in digital communication. Here, the encoder corresponding to the k-th user is used to encode that user's data. After encoding, the data is spread using a PNS sequence by the spreader. This process makes the resulting signal more secure and largely resistant to interference before it is transmitted to the interleaver. The resulting signal is interleaved using the k-th interleaver. The interleaved data is then combined by a combiner and transmitted through an AWGN channel. The received signal is corrupted by noise and is decoded using a chip-matched method for multiuser detection before being passed to the Elementary Signal Estimator (ESE). The ESE, along with the Log-Likelihood Ratio (LLR) and a feedback mechanism, is used to identify the specific users [3–5].

The mechanism of the interleaver is illustrated in Figure 2. A tree interleaver is employed to reduce memory requirements and computational complexity. The tree interleaver consists of two master random interleavers, Π1 and Π2, which are orthogonal to each other. The tree interleaver provides zero cross-correlation and generates user-specific interleavers. The prime interleaver, a specialized type of interleaver based on prime numbers, offers minimal complexity while achieving Bit Error Rate (BER) performance comparable to that of a tree interleaver (TBI), addressing a common drawback of random interleavers. To overcome the large memory requirements of random interleavers, a specialized interleaver based primarily on prime numbers has been developed. This prime interleaver is generated using seeds, with only prime numbers employed as seeds, hence its designation as a prime interleaver [6–10].

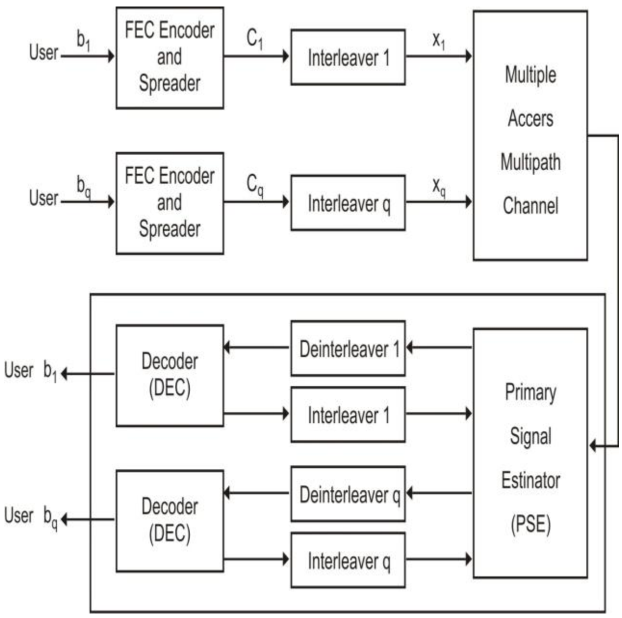

Fig.1. Block Diagram of Optical IDMA System

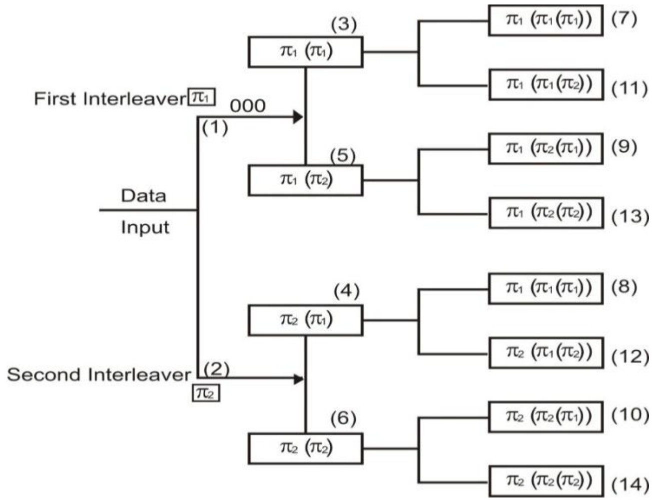

Fig. 2. Tree Based Interleaving Technique

BER FOR BINARY PHASE SHIFT KEYING MODULATION-

In BPSK modulation, two carrier phases are used to transmit the bit stream 0 and 1. A phase of 0° is used to represent bit 1, while a phase of 180° is used to represent bit 0, with the amplitude and frequency of the carrier remaining constant. Thus the signal for sending 1 is $A\ Cos\ Wc(t)$ and for sending 0 we use $A\ Cos\ (Wc(t)+\pi)$ that is $A\ Cos\ Wc(t)$. If we used the data as symbols, then it is termed as M-ARY PSK. For example, when M = 4, N = 2, symbols are 00 01, 10 and 11 and when M = 8, N = 3, symbols are 000, 001……111 [11-12].

The general form of BPSK equation:

$$S_n(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f t + \pi\,(1-n))\ ,n = 0,1 \qquad (1)$$

When the two phases are occurred that is 0 and π. Then the binary data is converted with following equation.

$$S_0(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f t + \pi)\ for\ binary\ \text{"0"} \qquad (2)$$

$$S_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f t)\ for\ binary\ \text{"1"} \qquad (3)$$

Where, f is the frequency of the message signal.

P_e of BPSK in AWGN can be calculated as:

$$P_e = \frac{1}{2}\,erfc\sqrt{\frac{E_b}{N_0}}$$

(4)

BER FOR BINARY FREQUENCY SHIFT KEYING MODULATION-

FSK is a frequency shift keying digital modulation scheme in which the frequency of carrier wave is changed in accordance the instantaneous value of modulating signal (digital data stream). In an FSK system, two sinusoidal carrier waves of the same amplitude but different frequencies use two symbols ''1'' and ''0'' respectively [12-13].

So some number of carrier cycles are transmitted to send ''1'' and other signal is transmitted for binary ''0''. Thus, we have

$$S_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + 2\pi f_d t) \quad \text{for binary "1"} \tag{5}$$

$$S_0(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t - 2\pi f_d t) \quad \text{for binary "0"} \tag{6}$$

Where, E_b is Energy of bit T_b is bit duration and f is the frequency of the message signal.

Probability of Bit Error

$$P_e = \frac{1}{2}\, erfc\sqrt{\frac{E_b}{2N_0}} \tag{7}$$

SIGNAL TO NOISE RATIO-

From Shannon Theory - SNR is used to determine the Data Bit Rate and Error Rate (BER) where SNR is standard mesure for digital communication system performance [11].

E_b/N_0 = Signal-Energy per Bit to Noise-power per Hz .

Now Consider a signal , digital or analog , contains digital data transmitted at a certain bit rate R [bps]. Recalling 1Watt=1 J/s , Energy per Bit is given by $E_b = ST_b$.

Where :

S = Signal Power [watt] & $T_b = 1 / R$

Thus,

$$\frac{E_b}{N_o} = \frac{S/R}{N_O} = \frac{S}{KTR} \tag{8}$$

SIMULATION RESULT AND DISCUSSION-

The whole IDMA system is simulated on MATLAB. A random binary data sequence consisting of 1024 bits was generated as the input for the system. This sequence simulates a typical digital communication scenario. The input bit stream was generated using a uniform random distribution, ensuring that each bit has an equal probability of being 0 or 1. A Prime and Tree Interleaver of length 997 was employed to rearrange the input bit stream. The prime-length interleaver is used to mitigate burst errors and enhance performance over noisy channels. The modulated signals were transmitted through an AWGN channel, which introduces statistically independent Gaussian noise samples to each transmitted symbol. This channel model is widely used to evaluate system performance under standard noise conditions.

Table 1 and Fig. 3 shows the variation of Bit Error Rate (BER) with respect to Signal-to-Noise Ratio (SNR) for BPSK and BFSK modulation schemes using a Prime Interleaver. As the SNR increases from 0 to 6 dB, the BER decreases significantly for both modulation techniques. For all values of SNR, BFSK shows lower BER compared to BPSK. For example, at SNR = 2 dB, the BER for BPSK is approximately 0.0372, whereas for BFSK it is much lower at 0.0024. While BFSK performs better in this setup, BPSK still shows a clear improvement as SNR increases, dropping from a BER of 0.0789 at 0 dB to 0.00024 at 8dB. This suggests that the Prime Interleaver has a more favorable impact on BFSK in this scenario.

From the results Table 2 and Fig. 4, it is observed that as the value of SNR increases, the BER decreases for both BPSK and BFSK. This behaviour is expected because a higher SNR indicates stronger signal power relative to noise, thereby reducing the probability of bit errors. At SNR = 0 dB, the BER is relatively high for both schemes, with BPSK achieving 0.0771 while BFSK shows slightly worse performance at 0.0929. At SNR = 2 dB, the BER reduces to 0.0371 for BPSK and 0.0449 for BFSK, showing that BPSK performs better than BFSK. At SNR = 4 dB, the BER for BPSK decreases significantly to 0.0058 compared to BFSK which remains higher at 0.0161. At SNR = 6 dB, BPSK achieves a much lower BER of 0.0019 compared to BFSK (0.0025). Finally, at SNR = 8 dB, the BER is almost negligible, with BPSK at 0.0005 and BFSK at 0.0003, indicating near error-free transmission. Overall, the analysis shows that BPSK consistently outperforms BFSK at lower and moderate SNR values in terms of BER performance. However, at very high SNR (8 dB), both schemes show almost identical performance with negligible error. The use of a Tree Interleaver helps in further minimizing the impact of burst errors, thereby improving the system reliability. Thus, BPSK with Tree Interleaver is more efficient for communication systems requiring lower BER at moderate SNR, while BFSK converges to similar performance only at higher SNR values.

Table 1: SNR Verses BER for Prime Interleaver

S. No.	SNR	BER	
		BPSK	**BFSK**
1	0	0.0789368	0.0125717
2	2	0.0372116	0.00246134
3	4	0.0121665	0.000179539
4	6	0.00241725	0.00000501505
5	8	0.00024072	0.00000100301

Table 2: SNR Verses BER for Tree Interleaver

S. No.	SNR	BER	
		BPSK	**BFSK**
1	0	0.0771	0.0929
2	2	0.0371	0.0449
3	4	0.0058	0.0161
4	6	0.0019	0.0025
5	8	0.0005	0.0003

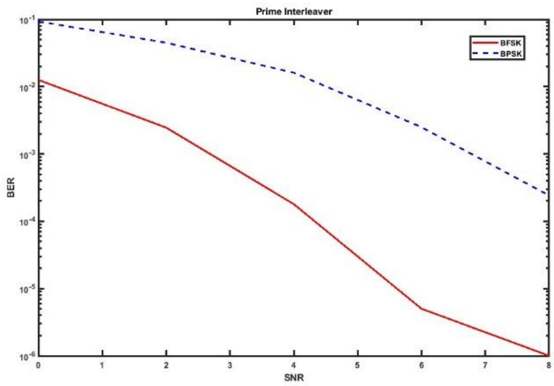

Fig. 3. SNR Verses BER for Prime Interleaver

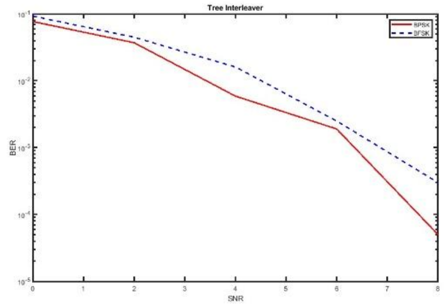

Fig. 4. SNR Verses BER for Tree Interleaver

Simulation results confirm that BER decreases consistently with increasing SNR for both BPSK and BFSK schemes. In the case of Prime Interleaver, BPSK shows superior performance over BFSK, particularly at low to moderate SNR values. In contrast, with Tree Interleaver, BPSK outperforms BFSK across most SNR values. At higher SNR levels (≥ 8 dB), both modulation schemes achieve nearly error-free performance irrespective of the interleaver. Thus, the choice of interleaver significantly affects BER performance, and the optimal scheme depends on the modulation technique and target SNR range..

3. CONCLUSION-

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