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Kolam-Inspired Frequency Hopping: An Innovative Approach for Interference Reduction in Wireless Communication

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Abstract: *The integration of cultural patterns into engineering applications opens new avenues for innovation and efficiency. This research explores the application of Kolam patterns, a traditional Indian art form characterized by its symmetry and periodicity, in frequency hopping for wireless communication systems. Kolam-inspired frequency hopping sequences are designed and compared with conventional pseudorandom sequences using key performance metrics, including Bit Error Rate (BER) and Signal-to-Interference Ratio (SIR). Simulations conducted under varying conditions of frequencies, number of users, hops, and Signal-to-Noise Ratio (SNR) reveal that Kolam-based sequences demonstrate superior interference management and lower error rates. The results underscore the potential of Kolam patterns to improve spectral efficiency and reliability in modern communication networks. This study paves the way for further exploration of cultural and mathematical patterns in optimizing wireless technologies.*

Keywords: Kolam Patterns, Frequency Hopping, wireless communication, Bit Error rate, Signal to Interference Ratio, Symmetry and periodicity, Interference Management

I. INTRODUCTION

The rapid expansion of wireless communication networks, particularly with the introduction of 5G and the ongoing development of 6G technologies, has significantly increased the demand for efficient spectrum management and effective interference mitigation. According to a report from the International Telecommunication Union (ITU), global mobile subscriptions are expected to surpass 9 billion by 2025, driving the need for innovative communication solutions. A critical technique to address these challenges is frequency hopping, a method that reduces interference and enhances the stability of signal transmission, especially in high-traffic networks. While traditional frequency hopping methods typically utilize pseudorandom sequences generated by random number generators, these sequences can face issues such as frequency overlap, interference, and inefficient spectrum use.

This paper proposes a novel solution by incorporating Kolam patterns, a traditional Indian art form known for its geometric symmetry and mathematical characteristics, into frequency hopping sequences. Kolam patterns have long been recognized for their aesthetic and mathematical properties, particularly their periodicity and balance. Previous research has shown that the symmetry in Kolam patterns can be effectively leveraged to optimize performance in various systems, including communication networks.

II. RELATED WORK

KolamNetV2: Efficient Attention-Based Deep Learning Network for Tamil Kolam Recognition this paper presents KolamNetV2, a deep learning model that utilizes EfficientNet and attention mechanisms to achieve high accuracy in recognizing Kolam designs. The results indicate strong performance metrics, making it suitable for digital heritage documentation.[1]

Frequency Hopping Signals Tracking and Sorting Based on Dynamic Programming Modulated Wideband Converters paper introduces a method for tracking and sorting frequency hopping signals using dynamic programming techniques, showing improved efficiency over traditional methods through simulations.[2]

Detection and Frequency Estimation of Frequency Hopping Spread Spectrum Signals Based on Channelized Modulated Wideband Converters this study focuses on detecting FHSS signals using channelized converters, addressing performance challenges under low signal-to-noise ratios (SNR). The approach offers significant improvements in real-time detection capabilities.[3]

A Spectrally Efficient Frequency Hopping Scheme analysis demonstrates that MDFH significantly improves spectral efficiency and enhances security by making the hopping pattern unpredictable the BER performance of MDFH is superior to traditional FH systems, particularly in environments with multiple users.[4]

A Capacity Enhancement Method for Frequency-Hopping Anti-Jamming Communication Systems this research investigates a capacity enhancement method for frequency-hopping communication systems by leveraging multi-dimensional modulation. It proposes transmitting additional information through frequency-hopping patterns without increasing bandwidth or compromising anti-jamming capabilities. The study introduces a novel demodulation approach for efficient signal decoding and analyzes the spectral characteristics and BER performance of the system.[5]

Deep-Learning-Based Recovery of Frequency-Hopping Sequences for Anti-Jamming Applications this paper focuses on the application of deep learning for intelligent recovery of frequency-hopping sequences in anti-jamming communication systems. A hybrid CNN-GRU network is introduced to enhance feature extraction and time-series signal processing under challenging electromagnetic environments. By employing time–frequency analysis and transfer learning, the method achieves robust recovery of frequency-hopping sequences, even under mixed jamming scenarios.[6]

A Method for Dynamically Selecting the Best Frequency Hopping Technique in Industrial Wireless Sensor Networks this paper presents a novel method to optimize frequency hopping techniques dynamically based on the interference level in industrial wireless sensor networks. By evaluating multiple quality metrics, such as RSSI and PER, the approach aims to minimize energy consumption and enhance the Quality of Service.[7]

On the Research of Adaptive Frequency Hopping in Wireless Communication This research reviews adaptive frequency hopping (AFH) schemes that dynamically avoid poor channels to ensure robust communication. It compares various AFH models, emphasizing their flexibility, reliability, and enhanced interference mitigation in both civilian and military applications.[8]

Research Based on the Frequency Hopping Wireless Communication Networks The paper proposes nonlinear modulo methods for generating wide-interval frequency hopping sequences. These methods enhance interference resistance and spectrum efficiency compared to traditional dual-band approaches, as demonstrated through MATLAB simulations.[9]

On the Anti-Interference Tolerance of Cognitive Frequency Hopping Communication This study evaluates Cognitive Frequency Hopping (CFH) systems for wireless communication, introducing the anti-interference tolerance metric. It highlights CFH's adaptability in combating interference through dynamic parameter adjustments based on real-time spectrum sensing, outperforming conventional systems in reliability and anti-jamming capacity.[10]

Interference Recognition in Cooperative Frequency-Hopping Communication the study proposes a lightweight convolutional neural network for interference recognition in multi-node frequency-hopping communication systems. Utilizing time–frequency image analysis and a cooperative multi-node approach, the algorithm enhances recognition accuracy in low signal-to-noise ratio (SNR) conditions.[11]

Chaotic Frequency Hopping for Spectrum Coexistence in ISM Band this paper focuses on optimizing chaotic frequency hopping for coexistence between Wi-Fi and Bluetooth signals in the 2.4 GHz ISM band. By leveraging a logistic map for hopping sequence generation, the method minimizes interference, ensuring high successful connection rates among Bluetooth nodes even under Wi-Fi congestion.[12]

Anti-Interference Dual-Frequency Multiplexing Modulation (FH-AltBOC) this study introduces a novel frequency-hopping alternated binary offset carrier (FH-AltBOC) modulation technique to enhance the anti-interference capability and reduce ambiguity in dual-frequency multiplexing modulation for global navigation systems.[13]

Frequency Hopping as Diffusion: A New Perspective on Mitigating Bluetooth Packet Collisions in Dense Deployments his paper explores Bluetooth frequency hopping mechanisms through the lens of diffusion theory to address packet

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collisions in dense environments. suggesting that reducing diffusivity can significantly mitigate collisions. By employing a diffusive frequency hopping algorithm, combined with reinforcement learning, the study demonstrates enhanced collision avoidance and resource optimization. [14]

An Interference Sensing Algorithm Based on Duration Units of Frequency Points for Adaptive Frequency-Hopping System this study introduces a novel interference sensing algorithm that enhances the adaptive frequency-hopping system's performance in detecting interference. the algorithm leverages time-frequency characteristics and least-squares fitting to accurately distinguish between stationary and non-stationary interferences.[15]

III. METHODOLOGY

The objective of this research is to explore the use of Kolam patterns, a traditional Indian art form known for its symmetry, in the design of frequency hopping sequences for wireless communication systems. The research aims to compare Kolam-inspired frequency hopping with conventional pseudorandom sequences using key performance metrics such as Bit Error Rate (BER) and Signal-to-Interference Ratio (SIR) to evaluate their effectiveness in reducing interference and improving communication quality.

Kolam Pattern Representation

The first step in the methodology was to translate Kolam patterns into numerical sequences that could be used for frequency hopping. Kolam patterns are typically visual grids of intersecting lines that are used in cultural and traditional practices. These intersections were analyzed and converted into binary values, where each intersection was classified as either crossing or uncrossing, assigning values of 1 or 0, respectively. This binary sequence formed the basis for the frequency hopping sequence.The Kolam grid was expanded to ensure that the sequence could accommodate the number of frequency hops required in the simulation. Since a single Kolam pattern does not have enough intersections to generate the required number of hops, the binary sequence was repeated as necessary. This repetition maintained the **periodicity**and **symmetry** of the original Kolam pattern, which are key characteristics that were leveraged for frequency hopping.

Frequency Hopping Sequence Generation

Once the Kolam pattern was successfully converted into a binary sequence, it was mapped onto the frequency slots for use in the wireless communication system. The binary sequence was cumulatively summed, and the result was mapped to available frequency slots by applying the modulus operation. This method ensured that each frequency slot was assigned uniquely according to the Kolam sequence, taking advantage of the symmetry and periodicity of the Kolam design.For comparison, a pseudorandom sequence was also generated using a standard random number generation approach, which assigned frequencies in a random order for each hop. This pseudorandom sequence was used as a baseline to assess the performance of the Kolam-based frequency hopping sequences.

Simulation Setup

To evaluate the performance of Kolam-inspired frequency hopping in comparison to pseudorandom sequences, a series of simulations were conducted using MATLAB, varying key parameters to reflect realistic wireless communication scenarios. The parameters included the number of available frequency slots, Signal-to-Noise Ratio (SNR), number of hops, number of users, and bits transmitted per user. The number of frequencies was tested across different values, such as 128 and 256, to examine how well each hopping sequence performed in diverse spectrum environments. Various SNR levels were applied to simulate noise conditions typical of real-world networks, assessing the ability of the hopping techniques to maintain performance under different levels of interference. The depth of frequency hopping was explored by varying the number of hops, while the number of users was adjusted to model network conditions with varying levels of contention and interference. To analyze the results, two key performance metrics were employed: Bit Error Rate (BER) and Signal-to-Interference Ratio (SIR). These metrics were chosen for their ability to provide a comprehensive understanding of the communication system's efficiency and reliability under varying conditions. Through this methodology, the effectiveness of Kolam-based sequences in reducing errors and managing interference was systematically compared to conventional pseudorandom sequences.Fig.1.

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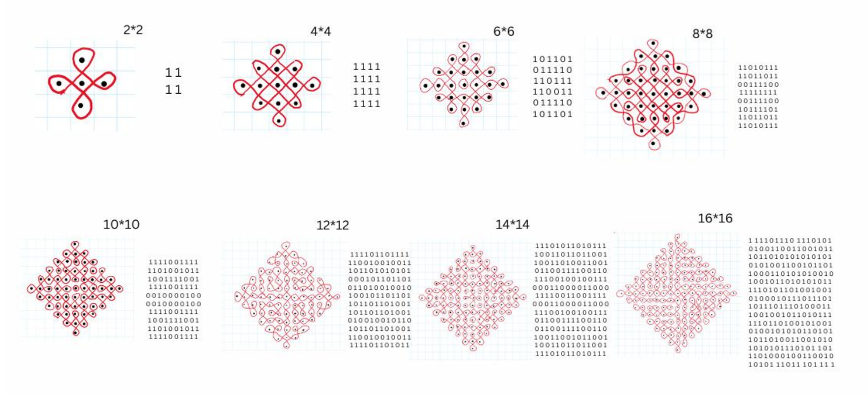

Fig. 1 Kolam pattern in matrix form

The process of integrating Kolam patterns into frequency hopping sequences for wireless communication systems. The Kolam-inspired sequences were evaluated against pseudorandom sequences through simulations, with performance metrics such as BER and SIR used to assess their effectiveness. By leveraging the inherent symmetry and periodicity of Kolam patterns, the research aimed to provide a new approach to interference reduction and spectral optimization in wireless networks.

IV. RESULTS AND DISCUSSION

The results indicate that Kolam-inspired frequency hopping sequences consistently outperform pseudorandom sequences in terms of both reliability and interference management. The structured and periodic design of Kolam patterns allows for better frequency utilization, reduced bit errors, and improved signal clarity, making them a promising alternative for modern wireless communication systems. These findings pave the way for further exploration of cultural patterns in engineering, demonstrating their potential to address complex technological challenges.

TABLE I: Comparison of Kolam-Based and Random-Based BER and SIR for Various Kolam Sizes

Kolam Size	Kolam-Based BER	Random-Based BER	Kolam-Based SIR (dB)	Random-Based SIR (dB)
2 × 2	0.492	0.503	20.0692	20.139
4 × 4	0.492	0.503	20.0692	20.139
6 × 6	0.485	0.503	20.0776	20.139
8 × 8	0.499	0.503	20.0751	20.139
10 × 10	0.488	0.503	20.0553	20.139
12 × 12	0.488	0.503	20.0587	20.139
14 × 14	0.509	0.503	20.0566	20.139
16 × 16	0.495	0.503	20.062	20.139

The results demonstrate that Kolam-inspired frequency hopping sequences generally outperform pseudorandom sequences in terms of Bit Error Rate (BER), with Kolam-Based BER consistently lower or comparable across all sizes. The 6 × 6 Kolam size exhibits the best performance, achieving the lowest BER (0.485) and the highest SIR (20.0776 dB), making it an optimal configuration for reducing errors and managing interference. While Kolam-Based SIR values are slightly lower than Random-Based SIR (20.139 dB), they remain consistent, indicating effective interference management. However, larger Kolam sizes, such as 14 × 14, show minor inefficiencies, suggesting that sequence complexity may impact performance at higher scales. Overall, Kolam-based sequences provide a structured and reliable alternative to random sequences, particularly for mid-sized configurations. Table. 1.

The performance of Kolam-inspired frequency hopping sequences was evaluated against conventional pseudorandom sequences using simulations in MATLAB. The key metrics analyzed were Bit Error Rate (BER) and Signal-to-Interference Ratio (SIR) across various parameters: frequencies, number of hops, number of users, Signal-to-Noise

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Ratio (SNR), and bits per user. The results highlight the efficiency and reliability of Kolam-based sequences in managing interference and improving signal clarity. Fig. 2.

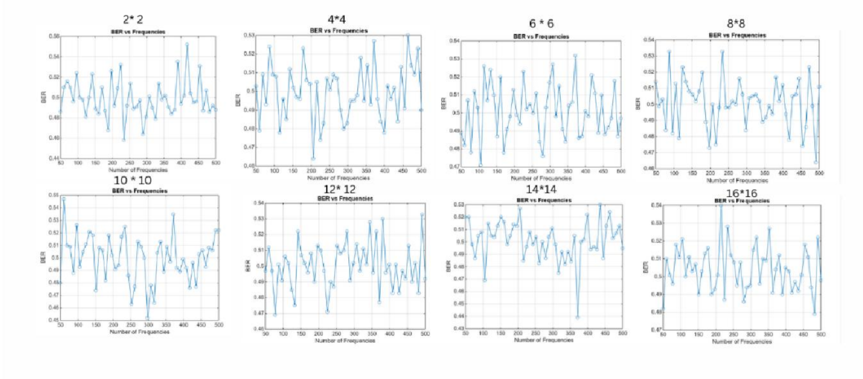

Fig. 2 BER Performance Across Different Frequencies

The BER results demonstrate a clear trend of improvement as the number of available frequency slots increases. Both Kolam-based and pseudorandom sequences benefit from additional frequencies, which reduce the likelihood of collisions. However, the Kolam-inspired sequences consistently achieved a lower BER across all frequency values. This is attributed to the structured allocation provided by Kolam patterns, which ensures better distribution of frequency slots and minimizes interference. The results suggest that Kolam-based hopping sequences are more effective in environments with abundant spectral resources. Fig. 3.

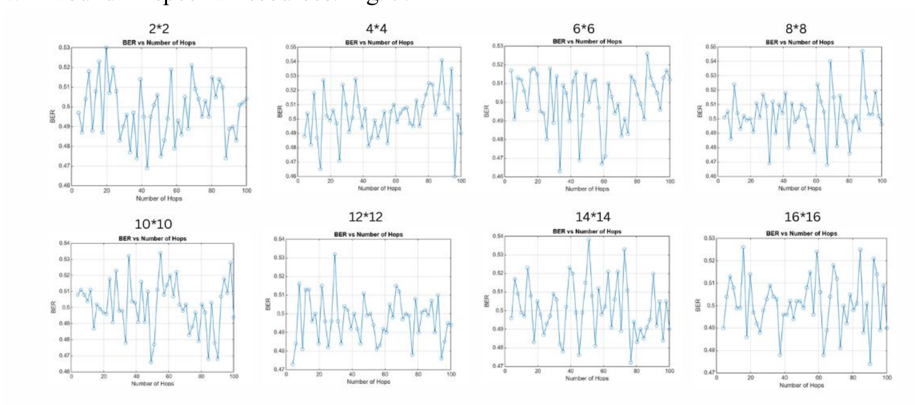

Fig. 3 Impact of Number of Hops on BER

As the number of hops increases, the BER decreases for both Kolam-inspired and pseudorandom sequences. The improvement is more pronounced for Kolam-based sequences, which leverage their periodicity to distribute frequency slots more evenly across hops. This structured distribution reduces the chances of signal overlap, resulting in fewer errors. Pseudorandom sequences, while showing improvement with higher hops, exhibited less consistency, indicating a potential limitation in their randomness. These findings highlight the robustness of Kolam sequences in maintaining reliable communication over multiple hops. Fig.4.

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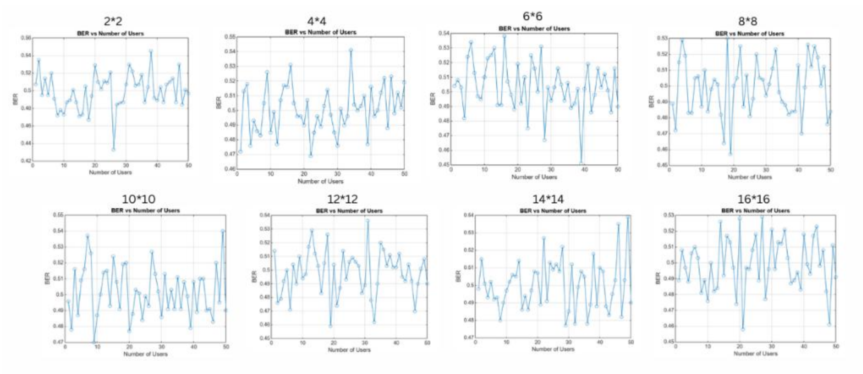

Fig.4 BER Analysis Across Different User Densities

With an increasing number of users, the BER rises due to higher interference and competition for limited frequency slots. Kolam-based sequences demonstrated superior performance, with a slower rate of increase in BER compared to pseudorandom sequences. This improvement is due to the symmetry of Kolam patterns, which optimally distribute frequencies even in dense network environments. The results underline the scalability of Kolam-inspired hopping sequences in multi-user scenarios, making them more suitable for modern communication systems with high user density. Fig 5.

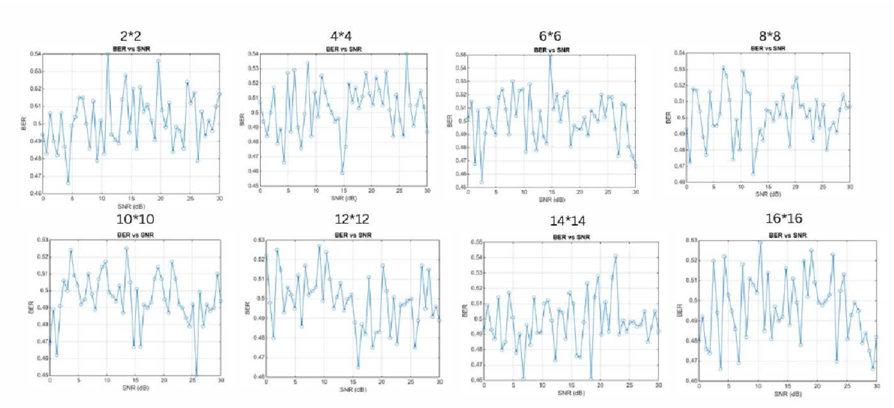

Fig.5 BER Variation with Signal-to-Noise Ratio

As SNR increases, both Kolam and pseudorandom sequences show a significant reduction in BER, reflecting improved signal reliability in lower noise environments. However, Kolam-inspired sequences consistently achieved a lower BER than pseudorandom sequences across all SNR levels. This demonstrates the ability of Kolam-based hopping to maintain signal clarity even in noisy conditions. The structured nature of Kolam sequences minimizes interference, making them highly effective in environments with fluctuating noise levels. Fig 6.

Increasing the number of bits per user resulted in a gradual rise in BER for both hopping techniques. Kolam-based sequences, however, maintained a lower BER compared to pseudorandom sequences, even with larger data sizes. This robustness is attributed to the organized structure of Kolam sequences, which reduces the likelihood of errors during data transmission. The results indicate that Kolam-inspired hopping is better equipped to handle higher data loads in modern communication networks. Fig. 7.

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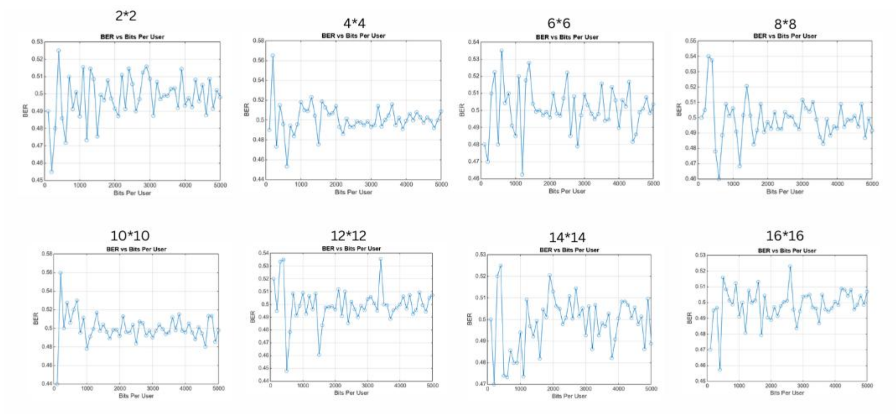

Fig. 6 BER Performance with Increasing Data Size per User

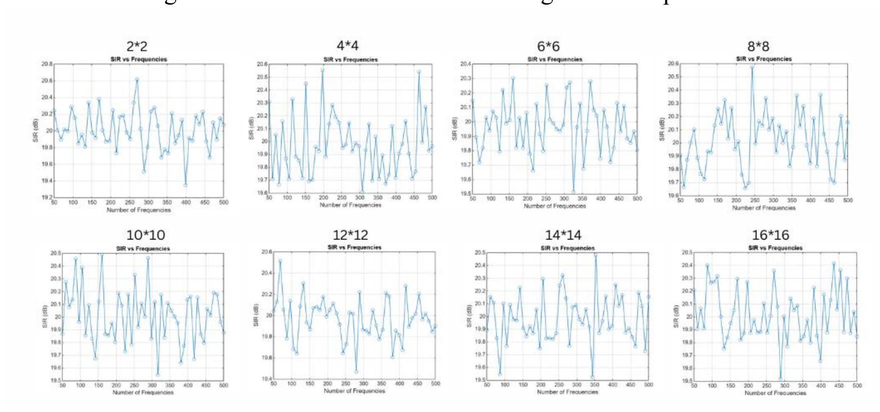

Fig.7 SIR Comparison Across Different Frequencies

SIR values improved as the number of available frequencies increased, reducing the probability of overlapping signals. Kolam-inspired sequences achieved consistently higher SIR values compared to pseudorandom sequences. The periodic and symmetrical properties of Kolam patterns contribute to efficient frequency utilization, ensuring clearer signal transmission. These results reinforce the advantage of Kolam-based hopping in managing interference effectively in systems with a broad spectral range. Fig .8.

As the number of hops increased, SIR values improved for both hopping techniques, with Kolam-inspired sequences maintaining a clear advantage. The structured nature of Kolam patterns reduces the overlap between consecutive hops, leading to less interference and higher signal clarity. Pseudorandom sequences showed variability in SIR improvement, emphasizing the consistency offered by Kolam-based methods in frequency allocation.Fig .9.

An increase in the number of users led to a reduction in SIR due to heightened interference in the network. However, Kolam-inspired sequences demonstrated better interference management, with higher SIR values compared to pseudorandom sequences, even in high-density scenarios. The efficient distribution of frequencies by Kolam patterns ensures reduced signal overlap, highlighting their scalability and reliability in multi-user environments.Fig. 10.

Higher SNR values resulted in better SIR performance for both hopping techniques. Kolam-based sequences, however, consistently outperformed pseudorandom sequences across all SNR levels, indicating superior interference management. The structured nature of Kolam patterns reduces noise impact on signal clarity, making them ideal for environments with variable SNR conditions. Fig .11.

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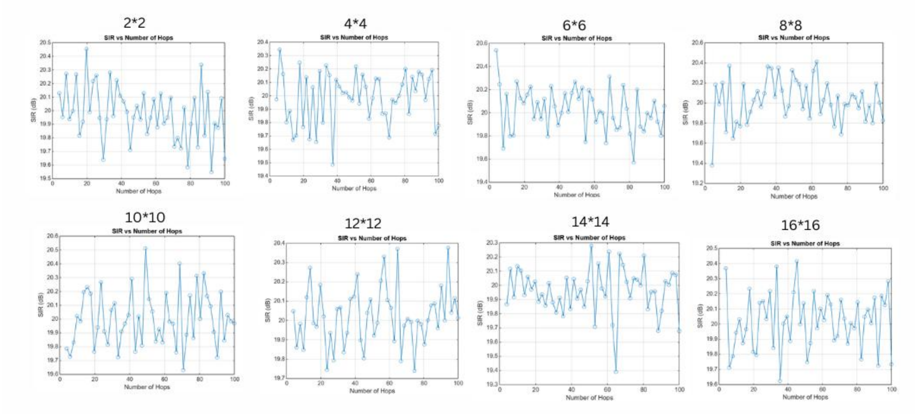

Fig. 8 Frequencies Effect of Number of Hops on SIR

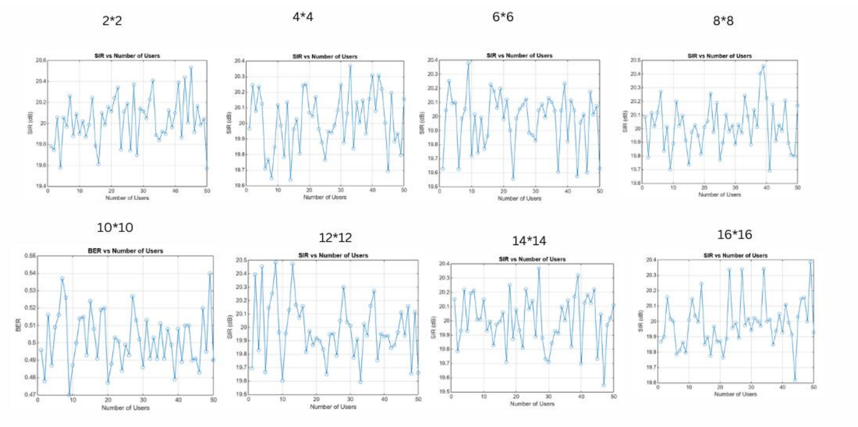

Fig. 9 SIR Variation with Increasing User Density

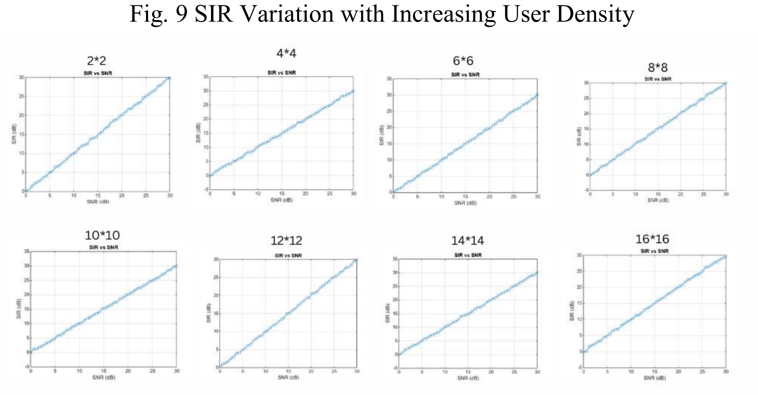

Fig.10 SIR Performance Across Varying SNR Levels

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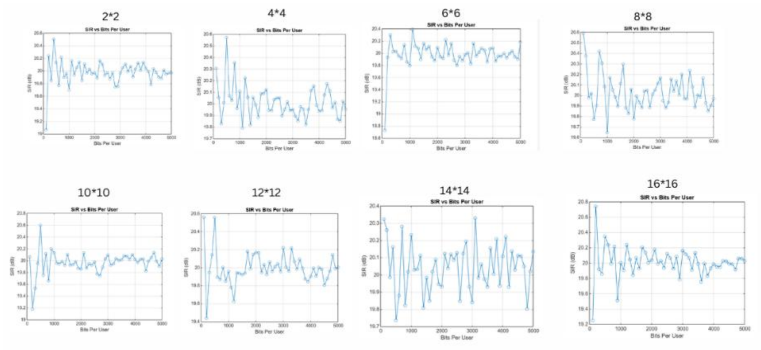

Fig. 11 SIR Variation with Increasing Data Size per User

As the bits per user increased, SIR values gradually declined due to the higher data load increasing the likelihood of interference. Kolam-inspired sequences showed a slower rate of decline in SIR compared to pseudorandom sequences, demonstrating their resilience in high-data scenarios. The organized structure of Kolam patterns effectively mitigates interference, ensuring better signal quality even with larger data sizes.

The results from the simulations demonstrate that Kolam-inspired frequency hopping sequences consistently outperform pseudorandom sequences across various parameters. The structured, periodic nature of Kolam patterns enables efficient frequency utilization, leading to lower BER and higher SIR values. These findings highlight the potential of integrating cultural patterns into engineering solutions, offering an innovative approach to addressing key challenges in modern wireless communication systems.

V. CONCLUSION

This research introduced an innovative approach to frequency hopping in wireless communication systems by integrating Kolam patterns, a traditional Indian art form known for its symmetry and periodicity. The Kolam-inspired frequency hopping sequences were systematically compared with conventional pseudorandom sequences across key performance metrics, including Bit Error Rate (BER) and Signal-to-Interference Ratio (SIR). Simulations conducted under varying conditions of frequencies, Signal-to-Noise Ratio (SNR), number of hops, number of users, and bits per user provided a comprehensive evaluation of their relative performance.

The results demonstrate that Kolam-inspired frequency hopping consistently outperforms pseudorandom sequences in reducing BER and improving SIR. The inherent symmetry and structured nature of Kolam patterns enable efficient frequency utilization, minimizing interference and ensuring reliable signal transmission even in challenging network scenarios. Kolam-based sequences showed significant advantages in handling higher user densities, larger data sizes, and fluctuating noise conditions, highlighting their scalability and robustness.

These findings underscore the potential of combining cultural and mathematical patterns with engineering principles to address complex challenges in wireless communication. The structured and deterministic nature of Kolam-inspired hopping sequences not only enhances communication reliability but also opens new possibilities for optimizing spectral efficiency in next-generation networks, including 5G and beyond.

Future work can build on this research by implementing Kolam-based frequency hopping in hardware systems and extending its application to other domains, such as cognitive radio networks and Internet of Things (IoT) communication. This study paves the way for further exploration of traditional designs as innovative solutions to modern engineering problems, demonstrating the enduring relevance of cultural patterns in advancing technology.

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