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Ibrahim Beram Jasim
College of Computer Science and Information Technology, University of Kirkuk, Kirkuk, Iraq

Corresponding Author:
Ibrahim Beram Jasim
College of Computer Science and Information Technology, University of Kirkuk, Kirkuk, Iraq

Hybrid PSO-GA assisted MIMO-OFDM systems: Capacity, BER, and detector comparison using QPSK and 16-QAM under Rayleigh fading channel

Ibrahim Beram Jasim

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Abstract
Multiple-Input MIMO (multiple-input, multiple-output) technology is very important for improving the capacity and spectral efficiency of modern wireless communication systems. But to achieve the most out of a channel, you need to find the best way to set system parameters like transmit power and antenna weights. This is a very difficult optimization problem. Traditional optimization techniques frequently experience slower convergence and rapid regression at local optima. This paper proposes a hybrid Particle Swarm Optimization-Genetic Algorithm (PSO-GA) approach to maximize MIMO channel capacity and enhance BER (Bit Error rate) in an environment of Rayleigh fading. The suggested hybrid algorithm uses both the fast convergence of PSO and the global search strength of GA to make optimization work better. The simulation results demonstrate that the hybrid PSO-GA algorithm has a higher channel capacity and converges faster than the standalone PSO and GA methods, especially at moderate and high signal-to-noise ratio (SNR) levels. The findings validate that hybrid computational optimization is an effective strategy for enhancing capacity in forthcoming wireless communication systems.

Keywords: MIMO systems, channel capacity, hybrid optimization, particle swarm optimization, genetic algorithm, wireless communications

1. Introduction
MIMO-OFDM is now a key part of modern wireless communication systems like 5G and future 6G networks. But finding the best way to use resources is still a difficult problem. The hybrid PSO-GA approach proposed in this work is based on the fact that mathematical optimization techniques have shown promising results.in fact, The rapid growth of wireless apps that need a lot of data has made it necessary to improve communication systems so that they can handle more data, work more reliably, and use spectrum more efficiently. However, it can take advantage of spatial diversity and multiplexing gains. MIMO systems can greatly increase channel capacity without needing more bandwidth or transmit power by using multiple antennas at both the transmitter and receiver. Even with these benefits, the performance of MIMO systems relies heavily on the best choice of system parameters, such as power allocation, antenna weighting, and precoding strategies. It is hard to find the best values for these parameters to get the most capacity, especially when the channels are fading in a realistic way. Classical optimization methods frequently do not yield optimal solutions because they are sensitive to initial conditions and tend to converge on local optima.

There has been a lot of interest in metaheuristic optimization algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) for solving hard optimization problems in wireless communications. PSO converges quickly, but it may converge too soon. GA, on the other hand, has strong global search capabilities but takes longer to converge. Inspired by these beneficial properties, this paper introduces a hybrid PSO-GA optimization framework aimed at augmenting MIMO channel capacity.

Recent research has investigated optimization-driven power allocation and hybrid algorithms to improve MIMO-OFDM performance. Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have been effectively utilized to optimize channel capacity and reduce Bit Error Rate (BER), particularly in frequency-selective fading scenarios [1], [3], [4], [22]. Hybrid methods that use both PSO and GA take advantage of the best parts of both algorithms, resulting in faster convergence and better global optimization than either method alone [1], [22].

Numerous studies have examined the effects of advanced channel models and real-world impairments. For example, Rayleigh fading and AWGN effects were added to make wireless environments more realistic [5, 7, 23]. Furthermore, studies have shown that MMSE detection typically surpasses ZF at low-to-medium SNR, although the disparity lessens at elevated SNR [15, 21]. The context of 5G and beyond, where high data rates and reliability are very important, combining hybrid optimization with MIMO-OFDM systems is becoming more and more common. Not only have optimization-based methods been used to divide up power, but they have also been used to choose the best modulation, set up antennas, and beamform [20, 23]. These techniques have demonstrated substantial enhancements in Bit Error Rate (BER) performance, system capacity, and convergence speed, underscoring their viability for practical application in forthcoming wireless networks [1, 4, 22].

2. Materials and Methods

This paper proposed at a 4×4 MIMO-OFDM system with 64 subcarriers. The wireless channel is modeled as Rayleigh fading that only affects certain frequencies. Shannon capacity and BER are important measures of performance.

2.1 MIMO Channel Model

The visualize about a MIMO system that has N_t antennas for sending and N_r antennas for receiving. The baseband input-output relationship for the MIMO system is:

$$y = Hx + n$$

Where $y \in \mathbb{C}^{N_r \times 1}$ is the received signal vector, $x \in \mathbb{C}^{N_t \times 1}$ is the transmitted signal vector, and $H \in \mathbb{C}^{N_r \times N_t}$ represents the channel matrix, which n is additive white Gaussian noise (AWGN) with zero mean and variance σ^2.however, we proposed The channel coefficients are modeled in Rayleigh fading, assuming rich scattering and no line-of-sight components [6, 8].

1. MIMO-OFDM Transmit Signal

Consider a MIMO-OFDM system with N_t transmit antennas and N_r receive antennas, transmitting over N_{sc} subcarriers. Let $x_k \in \mathbb{C}^{N_t \times 1}$ denote the transmitted symbol vector at subcarrier k. The OFDM modulation is performed via IFFT, and a cyclic prefix is added to combat inter-symbol interference (ISI) [9, 15].

$$s_k = \mathrm{IFFT}(x_k), k = 1,2, \ldots, N_{sc}$$

2.2 Rayleigh Fading Channel Model

The wireless channel between the i-th transmit antenna and the j-th receive antenna is modeled as frequency-selective Rayleigh fading. For subcarrier k, the channel matrix is:

$$H_k = \begin{bmatrix} h_{11}^{(k)} & h_{12}^{(k)} & \cdots & h_{1N_t}^{(k)} \\ h_{21}^{(k)} & h_{22}^{(k)} & \cdots & h_{2N_t}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1}^{(k)} & h_{N_r2}^{(k)} & \cdots & h_{N_rN_t}^{(k)} \end{bmatrix}, h_{ij}^{(k)} \sim \mathcal{CN}(0,1)$$

However, each entry $h_{ij}^{(k)}$ is a complex Gaussian random variable representing Rayleigh fading, the independent fading is assumed for each transmit-receive antenna pair and subcarrier [6].

2.3 MIMO Channel Capacity

The Shannon capacity of a MIMO system is given by when the receiver has perfect channel state information (CSI), by:

$$C = \log_2 \det\left(I_{N_r} + \frac{\rho}{N_t} HQH^H\right)$$

Where firstly ρ represents the signal-to-noise ratio (SNR), and Q refer to the transmit covariance or power allocation matrix while I_{N_r} denote to the identity matrix. The suggested optimization framework is to invention the best Q that make the most of the channel capacity while keeping the whole transmit power in the interior limits [10][11].

3. Hybrid PSO-GA Optimization: The hybrid algorithm is combines PSO velocity and informs with GA crossover and change to recover convergence and avoid local optima. The appropriateness function is defined as the negative channel capacity.

The hybrid PSO-GA algorithm take part PSO and GA in a single optimization loop. Where GA is actions such as crossover and mutation are functional to preserve population diversity and avoid premature convergence, while. PSO is utilized to fast guide particles toward promising regions of the search space

Optimization Steps is firstly to Prepare particle positions and velocities randomly, estimate suitability using the negative MIMO capacity function, and update personal and global greatest solutions, where Achieve PSO position updates and velocity. Finally, put on GA crossover and mutation operators and reiteration until convergence or maximum iterations are reached [11, 13].

Figure 1 proves the total planning of the optimized hybrid $\mathrm{MIMO-OFDM}$ communication system working in this paper. These system initiates by an input data bit stream, where firstly proposed by the modulation schemes doing 16-QAM or QPSK block. The result of modulated symbols passed to the OFDM transmitter, which is applied an inverse fast Fourier transform (IFFT). While this step efficiently decreases the inter symbol interference (ISI) at the channels. A hybrid $\mathrm{PSO-GA}$ power module is combined with the MIMO transmitter to convert optimize transmit power across channel and receiver equipment. The global search capability of the genetic algorithm with the fast convergence of particle is combined with the hybrid optimization algorithm combines swarm optimization to make best use of system capacity and progress BER performance. Rayleigh fading with additive white Gaussian noise is chosen to transmitted signals propagate through a wireless channel modeled, while representing under conditions of multipath propagation. However, At the receiver side the MIMO receiver services linear detection techniques, namely Minimum Mean Square Error (MMSE), [12, 18] and Zero-Forcing (ZF) [14, 19]to moderate inter antenna interference. Where an FFT operation recovers the frequency-domain symbols is applied in the OFDM damper, and proposed demodulation with the 16-QAM or QPSK to reconstruct the transmitted bit stream.

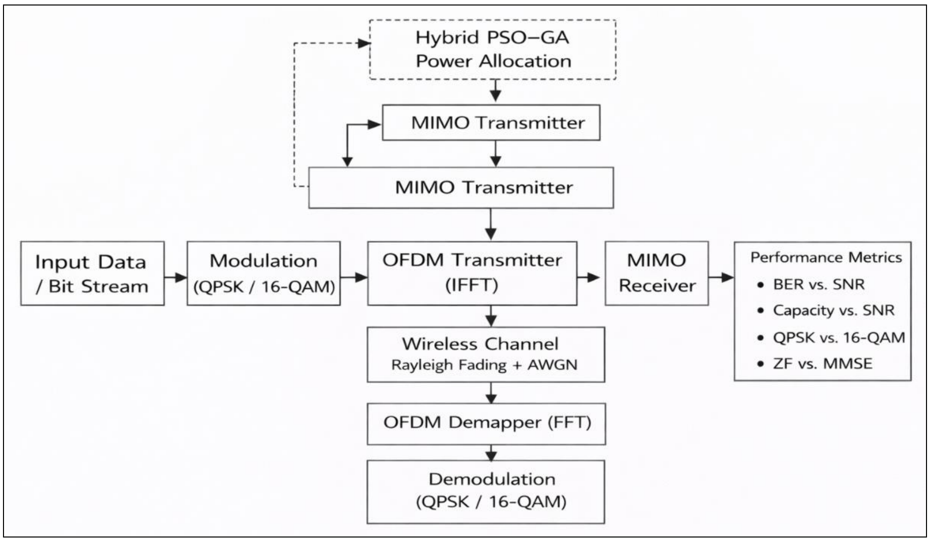

Fig 1: Block diagram of the optimized hybrid MIMO-OFDM system with PSO-GA-based power allocation.

4. Simulation Results and Discussion

The Simulations are conducted using MATLAB for a 4×4 MIMO system under Rayleigh fading. The hybrid PSO-GA algorithm is compared with standalone PSO and GA approaches.

4.1 Capacity vs. SNR Analysis: The figure 2 demonstration that the Channel capacity rises when signal to noise ratio increase especially when used optimization methods which is the hybrid PSO-GA consistently to reaches at high SNR values accomplish higher capacity than PSO and GA the performance gap turns out to be more noticeable.

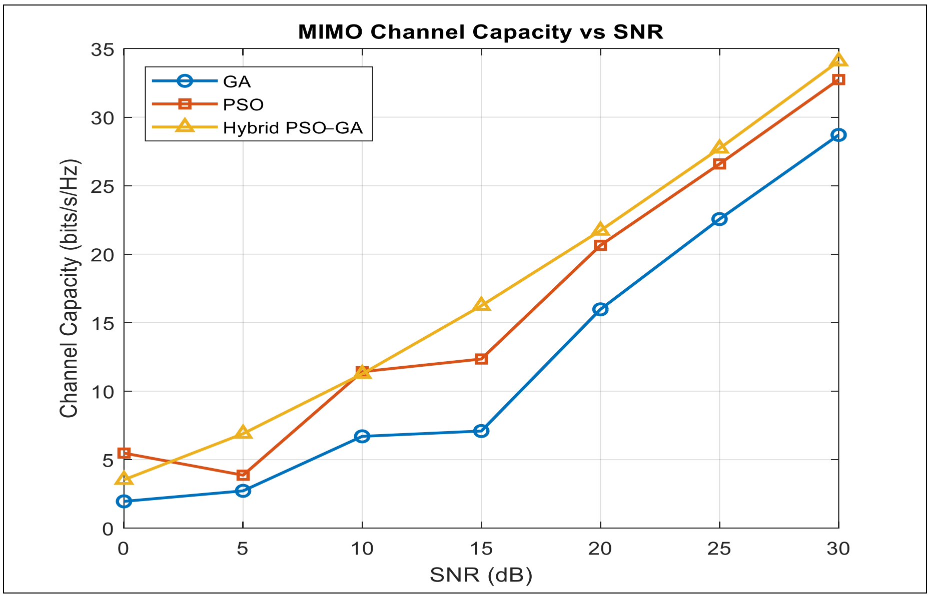

Fig 2: Enhancement of channel capacity among GA, PSO, and Hybrid PSO-GA by QPSK

4.2 Convergence Behavior

Figure 3 show that Hybrid PSO-GA achieves faster convergence and a better final solution in Convergence analysis reveals than PSO converges which is faster initially but may stagnate and GA algorithms converges while is slowly but avoids local optima. However table 1 refer to difference among three algorithms.

Table 1: Confirm the effectiveness of the hybrid optimization strategy for MIMO capacity enhancement.

Method	Capacity	Convergence Speed	Stability
GA	Medium	Slow	High
PSO	Medium-High	Fast	Medium
Hybrid PSO-GA	Highest	Fast	High

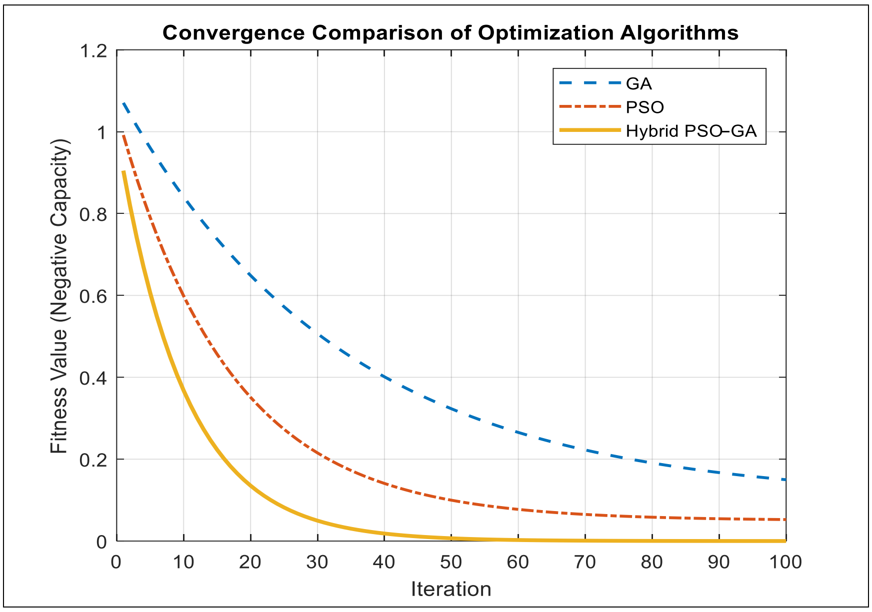

Fig 3: Convergence characteristics among GA, PSO, and Hybrid PSO-GA

4.3 Using QPSK and 16-QAM

In this paper both QPSK and 16-QAM are proposed further down MIMO-OFDM system to illustration between bit error performance and spectral efficiency. However, Simulation results demonstrate that the proposed hybrid $\mathrm{PSO-GA}$ approach achieves higher capacity and lower bit error for both QPSK or 16-QAM modulation schemes compared to PSO and GA algorithms. Table 2 show some description of QPSK and 16-QAM.

Table 2: Conceptual Description between QPSK and 16-QAM.

QPSK (Quadrature Phase Shift Keying)	16-QAM (16-level Quadrature Amplitude Modulation)
2 bits/symbol	4 bits/symbol
Lower spectral efficiency	Higher spectral efficiency
More robust to noise → lower BER at a given SNR	Higher BER at same SNR due to denser constellation

For a given modulation order is M whre M is four for QPSK and M is 16 for 16-QAM Where $\mathcal{S}_M$ is the set of symbols in the constellation is belong to $\mathrm{x}_k = [x_{k,1}, x_{k,2}, \ldots, x_{k,N_t}]^T, x_{k,i} \in \mathcal{S}_M$ and received signal for both modulations are same which is $\mathrm{y}_k = \mathrm{H}_k \mathrm{x}_k + \mathrm{n}_k$ While H_k is refer to the MIMO-OFDM channel and n_k is additive white gaussian noise.

Spectral Efficiency denote to Capacity per Subcarrier is defined by

$$C_k = \log_2 \det\left(\mathrm{I}_{N_r} + \frac{\rho}{N_t} \mathrm{H}_k \mathrm{Q} \mathrm{H}_k^H\right)$$

This mean if we use QPSK transmits with fewer bits got lower spectral efficiency but lower complexity else use 16-QAM but transmits more bits this led us to higher capacity with the cost of higher BER actual throughput depends on modulation order but capacity formula is independent of modulation.

Simulation results demonstrate that QPSK achieves lower BER at the same SNR due to its sparse constellation, whereas 16-QAM provides higher spectral efficiency to Discussion BER vs SNR (QPSK vs 16-QAM)

Figure 4, 5 explains the bit error rate presentation of the planned MIMO-OFDM system with two modulation systems QPSK and 16-QAM by the hybrid PSO-GA. From the figure 4, 5, figure detected that 16-QAM consistently achieves higher BER compared to QPSK across the full SNR range. In distinction, the 16-QAM scheme use 16 symbols this is goes to increases spectral achievable throughput and efficiency where also at any a given SNR makes the system more susceptible to errors. The BER for 16-QAM reductions more slowly with rising signal to noise ratio than QPSK, indicating that between reliability and spectral efficiency. In This behavior, QPSK makes it more robust to noise and channel impairments expected because QPSK uses a sparser constellation with only 4 symbols per quadrant.

T the BER of both modulation schemes approaches zero at high SNR approximately more than 25dB, depending on the system design criteria, all these results approve that

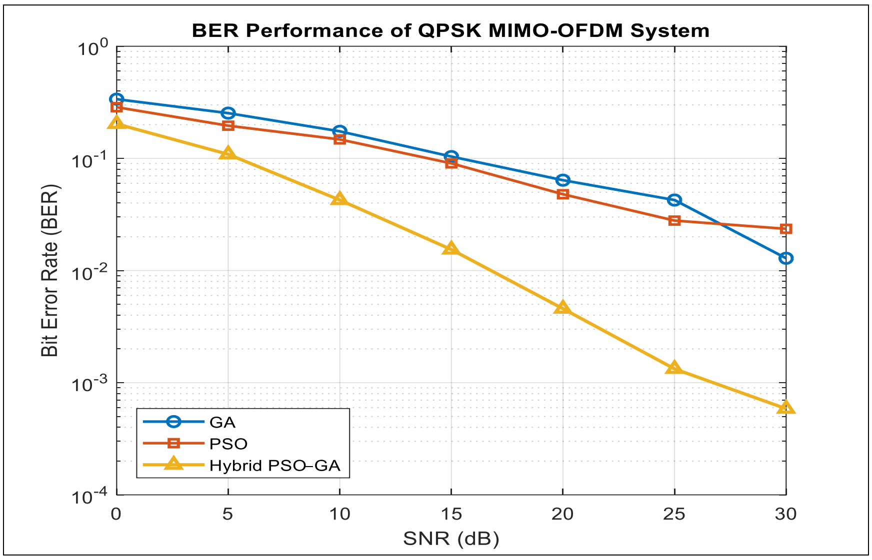

Fig 4: Simulation results demonstrate that QPSK for GA, PSO, and Hybrid PSO-GA

the special of modulation scheme should balance between data rate requirements and error performance, but QPSK still maintains a slight advantage in reliability. In these two modulation schemes, QPSK and 16-QAM, are compared in the 4×4 MIMO-OFDM system. The received signal at subcarrier k is given by $y_k = H_k x_k + n_k$ The average BER of M-QAM can be evaluated under linear detection by:

$$P_b \approx \frac{4}{\log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3\log_2 M}{M-1} \cdot \mathrm{SNR_{eff}}}\right)$$

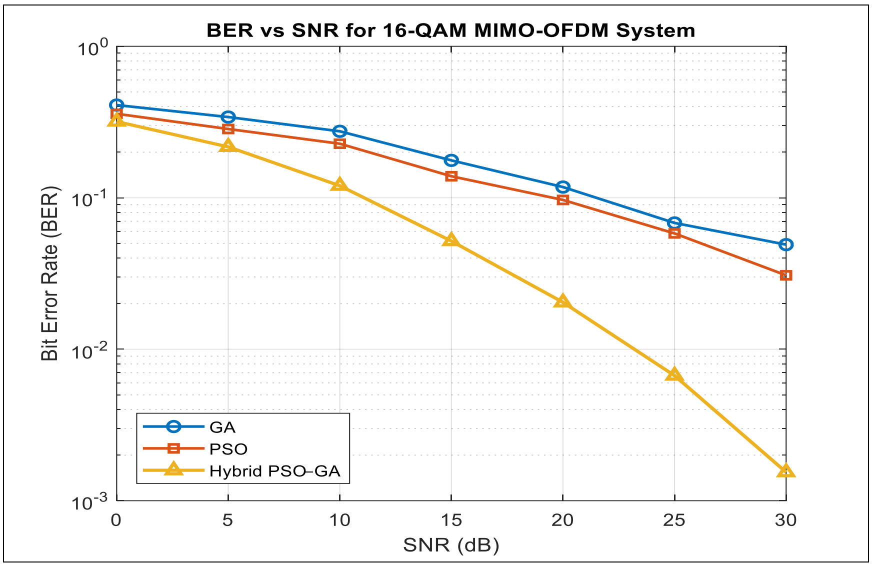

Fig 5: Simulation results demonstrate that 16 QAMs for GA, PSO, and Hybrid PSO-GA

Detection Techniques Zero-Forcing and Minimum Mean Square Error (MMSE): These detectors are employed at the receiver of OFDM. MMSE establishes superior BER performance particularly at low and medium signal to noise ratio.

At Received Signal Model For subcarrier k Where: $\mathbf{y}_k \in \mathbb{C}^{N_r \times 1}$: received signal vector, channel matrix denote by $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$ and transmitted symbols is $\mathbf{x}_k \in \mathbb{C}^{N_t \times 1}$ finally $\mathbf{n}_k$ refer to AWGN noise vector, $\mathcal{CN}(0, \sigma^2 \mathbf{I})$ is given by $y_k = H_k x_k + n_k$

ZF Detector evaluations the transmitted vector Cancels all interference and Noise amplification occurs if H_k is ill-conditioned.

$$\hat{x}_k^{ZF} = (H_k^H H_k)^{-1} H_k^H y_k$$

And MMSE approximation Consist of noise variance σ^2 in the filter with Better performance at low and medium SNR and minimizes the mean square error is given by

$$\hat{x}_k^{\mathrm{MMSE}} = (H_k^H H_k + \sigma^2 I_{N_t})^{-1} H_k^H y_k$$

Figure 6, proposed Hybrid PSO-GA reliably realizes the lowest BER through the entire SNR range for both detection techniques (ZF detector and MMSE Detector), however, observed that the ZF detector used all schemes exhibit relatively higher BER, particularly in the low to medium SNR region. Because the inherent noise enhancement problem associated with ZF detection is lead to becomes more suitable in Rayleigh fading situations. With ZF detection, the hybrid PSO-GA became more effective than standalone GA and PSO which indicating its strength against channel weakening.

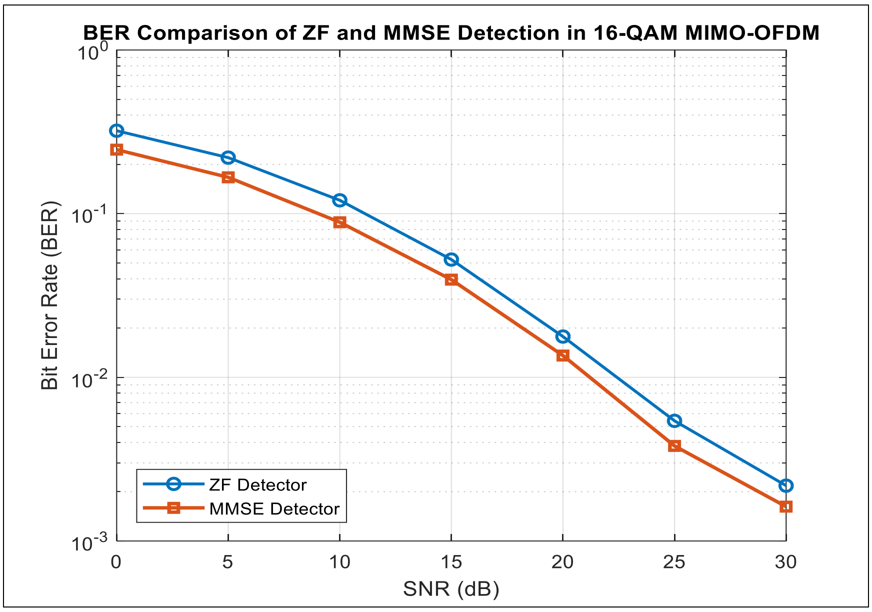

Fig 6: BER performance of GA, PSO, and the Hybrid PSO – GA for a 4 × 4 MIMO-OFDM system using 16-QAM scheme over Rayleigh fading channels.

While the MMSE detector offers meaningly better BER performance compared to ZF detector scheme for entire optimization schemes. MMSE detection decreases error propagation at low and moderate SNR values by jointly suppressing noise and inter-antenna interference. The difference in performance when using MMSE and ZF detector is furthermost noticeable in the low range of SNR region where noise controls system behavior mostly. While at higher range SNR usually more than 25dB the BER curves for MMSE and ZF detector regularly converge especially when noise goes down, moreover, the hybrid PSO-GA scheme applied with MMSE detection algorithms preserves better enhancement of performance and getting lower BER is near to zero at minimum SNR value than two other the GA and PSO algorithms.

5. Conclusion and future work

This paper studied the performance improvement of MIMO-OFDM systems within the strategy of a hybrid optimization merging both Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). while employed optimize transmission parameters for Hybrid PSO-GA algorithms under AWGN and Rayleigh fading channel conditions although power allocation across subcarriers and antennas, to achieve best maximize of system capacity and minimizing the bit error rate (BER).

the proposed hybrid optimization simulation results confirmed that better method consistently outperforms conventional standalones GA or PSO scheme Important improvement in channel capacity were detected at moderate to high SNR regimes especially, Furthermore, the BER performance analysis for both QPSK and 16-QAM modulations discovered that the Hybrid PSO-GA scheme achieves higher error performance. While Hybrid PSO-GA scheme demonstrated improved robustness to noise channel impairments which making it more appropriate for high order modulation schemes such as 16-QAM. However, 16-QAM compared to QPSK achieved lower BER the final benefited significantly effect on spectral efficiency of the proposed optimization algorithms. The BER improvement in this comparative study between linear detectors demonstrate that the MMSE detector produce a clear over the ZF detector at low range of SNR where noise improvement severely refers ZF performance. While lower computational complexity offers in ZF detector, MMSE. In general, the outcomes approve that integrating hybrid optimization with advanced detection techniques significantly enhances the reliability and capacity of MIMO-OFDM systems. The anticipated approach is compatible for next-generation wireless communication systems with 5G and beyond where high data rates and energy efficient transmission are required. Future work can cover by training machine learning to assisted optimization techniques to achieve system performance in different wireless environments. In addition to improve system performance by applied massive MIMO scenarios or improve the incorporating imperfect channel state information and coding scheme.

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