

Hybrid Precoding for mmWave MIMO Systems Optimizing Signal-to-Interference Ratio with Whale Optimization Algorithm

Alhamzah Taher Mohammed ^{1,2, a)}, Ammar Bouallegue ^{1, b)}, Sameh Najeh ^{1, c)}

¹Dept. of communication system, University of Tunis - El Manar, National Engineering School of Tunis, Tunis, Tunisia

²Middle Technical University, Electrical Engineering Technical College, Baghdad, Iraq

^{a)} Corresponding author: Email: alhamza_tm@yahoo.com

^{b)} Email: ammarbouallegue.syscom@gmail.com / ^{c)} Email: sameh.najeh@supcom.tn

Abstract: This paper suggests a new hybrid precoding method for millimeter wave (mmWave) multiple-input multiple-output (MIMO) systems using the Whale Optimization Algorithm (WOA) to improve the signal-to-interference ratio (SIR). Hybrid precoding helps deal with hardware limits in mmWave systems by merging analog and digital processing, but finding the best setup can be tricky. We set up hybrid precoding as an optimization task where WOA helps optimize both RF and baseband precoders while keeping certain limitations in mind. We ran a bunch of Monte Carlo simulations, and the results show that our method beats traditional fully digital precoding by as much as 4 dB in SIR across different signal-to-noise ratios (SNR). The WOA solution usually reaches good results quickly, often within 10 iterations, and creates focused beam patterns that do a great job of reducing interference. Looking at the SIR distribution among users shows that this algorithm effectively reduces multi-user interference while still keeping a strong signal for the main user. Our performance checks through cumulative distribution functions demonstrate that the proposed method consistently achieves better SIR values compared to benchmark approaches. Overall, these findings support how WOA can make a difference in optimizing hybrid precoding for mmWave MIMO systems, and it offers solid performance upgrades even with real-world hardware limits.

Keywords: Millimeter wave communications, MIMO systems, hybrid precoding, signal-to-interference ratio, Whale Optimization Algorithm, metaheuristic optimization, beamforming, interference management.

Citation: Alhamzah Taher Mohammed, Ammar Bouallegue, Sameh Najeh. Hybrid Precoding for mmWave MIMO Systems Optimizing Signal-to-Interference Ratio with Whale Optimization Algorithm. *Machine Intelligence Research*, vol.22, no.5, pp.929–940, 2025. <http://doi.org/10.1007/s11633-025-1550-8>

1 Introduction

Millimeter wave (mmWave) communication is becoming a key player in 5G and future wireless systems[1], thanks to its large bandwidth and ability to handle super-fast data rates. Still, there's a catch: mmWave signals struggle with high path and penetration loss[2], which means we need to use massive multiple-input multiple-output (MIMO) systems that have lots of antennas to boost signals[3]. Fully digital precoding can help, but it's pretty costly and uses a lot of power since each antenna requires its own radio-frequency (RF) chain[4].

To get around this, hybrid precoding combines a smaller digital precoder with an analog one that uses phase shifters [5], balancing performance with cost. There's been some recent research into different optimization methods for hybrid precoding, like

alternating minimization and evolutionary algorithms [6], aiming to get the best results by comparing hybrid systems to fully digital ones [7]. The downside is that a lot of these approaches just focus on maximizing data speed or reducing error, without considering the important issue of managing interference when many users are connected. This is a big deal, especially in crowded mmWave setups [8].

Our study aims to fill this gap by introducing a Whale Optimization Algorithm (WOA) to enhance how signal-to-interference ratio is managed in hybrid precoding systems.

Research Article
Manuscript received on May 30, 2024; accepted on February 25, 2025
Recommended by Associate Editor Harish Garg
Colored figures are available in the online version at <https://link.springer.com/journal/11633>
©The Author(s) 2025

The main points of our paper include: (1) redefining

hybrid precoding as an SIR optimization problem with

hardware limits, (2) crafting a new WOA-based method that outperforms traditional models, (3) analyzing performance and showing its strong interference reduction, and (4) providing practical insights into how well the proposed algorithm works in real-world settings.

2 Related Work

Lately, folks have been trying to make hybrid precoding better for millimeter wave (mmWave) multiple-input multiple-output (MIMO) systems. The main thing they're trying to do is get the best signal-to-interference ratio (SIR) and use the spectrum more efficiently, while still dealing with hardware limitations. For example, Zhang et al. [9] figured out some hybrid precoders and combiners for cell-free multi-user mmWave systems. Their method really bumped up the SIR by tweaking things over and over. Li et al. [10] did something similar by jointly adjusting hybrid precoding and intelligent reflecting surface (IRS) beamforming in mmWave multi-user multiple-input single-output (MU-MISO) systems. They showed that by coordinating the beamforming, they could get a better SIR.

Then, Wang et al. [11] came up with a hybrid precoding setup that uses deep learning and limited feedback to set the precoders. They said it cuts down on interference and makes better use of the spectrum. Chen et al. [12] also made an adjustable hybrid precoding method for dependable multi-user mmWave MIMO systems. They focused on making the most of the spectrum with good channel info, which led to good, steady SIR performance. Kim et al. [13] checked out a deep learning method that doesn't need cooperation to suppress Wi-Fi interference and got some nice SIR gains in crowded network situations. Basically, all these studies show that people are moving toward metaheuristic and machine learning to deal with the tricky stuff of getting the best performance out of mmWave MIMO systems.

3 Proposed Methodology

We're sharing a new method for improving mmWave MIMO systems that focuses on boosting the signal quality while keeping interference low, using the Whale Optimization Algorithm (WOA). We set up our problem around maximizing signal-to-interference ratio while sticking to certain limits for the analog precoder. WOA works well in this tricky optimization process by using three main strategies: it looks closely at local solutions, intensifies when it finds a good one, and explores new options. This nature-inspired approach adjusts the hybrid precoder step by step without needing complicated math, striking a good balance between finding new solutions and refining existing ones to manage interference better, all while staying within practical hardware limits.

A. System Model and Problem Formulation

We consider a millimeter wave (mmWave) multiple-input multiple-output (MIMO) system with N_t transmit antennas, N_r receive antennas, N_{RF} RF chains, and N_s data streams serving K users in a multi-user system [14]. The mmWave channel for each user is geometric and consists of limited scattering behavior with N_{cl} clusters and N_{ray} rays per cluster. The received signal of the k -th user can be expressed as [15]:

$$y_k = H_k F_{RF} F_{BB} s + n_k \quad (1)$$

Where $H_k \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix for user k , $F_{RF} \in \mathbb{C}^{N_t \times N_{RF}}$, is the analog precoder implemented using phase shifters, $F_{BB} \in \mathbb{C}^{N_{RF} \times N_s}$, is the baseband digital precoder, $s \in \mathbb{C}^{N_s \times 1}$, is the transmitted signal vector with:

$$\mathbb{E}[ss^H] = \frac{1}{N_s} I N_s \quad (2)$$

And $n_k \sim \mathcal{CN}(0, \sigma_n^2 I)$ is the additive white Gaussian noise. The signal-to-interference ratio (SIR) for the desired user can be formulated as [16]:

$$SIR = \frac{\|H_d F_{RF} F_{BB}\|_F^2}{\sum_{i=1}^{K-1} \|H_i F_{RF} F_{BB}\|_F^2} \quad (3)$$

where H_d represents the desired user's channel matrix and H_i represents the i -th interfering user's channel matrix [17]. The hybrid precoding optimization problem can be formulated as:

$$\begin{aligned} & \max_{F_{RF}, F_{BB}} SIR && \text{subject to: } |[F_{RF}]_{i,j}| \\ & = 1, \forall i, j && (4) \\ & \|F_{RF} F_{BB}\|_F^2 = N_s && (5) \end{aligned}$$

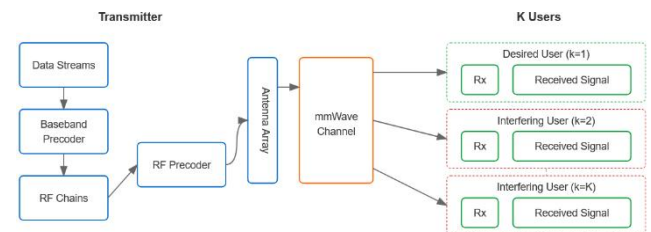


Figure 1. mmWave MIMO System Model with Hybrid Precoding

The constant modulus constraint on F_{RF} reflects the phase-only control capability of analog phase shifters, while the power constraint ensures normalized transmission power across all data streams.

B. SIR Optimization Framework

To efficiently solve the constrained SIR maximization problem, we develop a comprehensive framework that jointly optimizes the RF precoder F_{RF} and baseband precoder F_{BB} using a solution encoding scheme tailored for metaheuristic optimization. Each candidate solution x in our optimization space consists of two complementary parts:

$$x = [x_{RF} x_{BB}] \quad (6)$$

Where $x_{RF} \in \mathbb{R}^{N_t \times N_{RF}}$ represents the phases of the analog precoder elements with [18]:

$$[F_{RF}]_{i,j} = e^{jx_{RF}(i,j)}, \quad x_{RF}(i,j) \in [0, 2\pi] \quad (7)$$

And $x_{BB} \in \mathbb{R}^{2 \times N_{RF} \times N_s}$ encodes both the real and imaginary parts of the baseband precoder F_{BB} as:

$$[F_{BB}]_{i,j} = x_{BB}(1, i, j) + jx_{BB}(2, i, j) \quad (7)$$

The fitness function that guides the optimization process

is defined as:

$$f(x) = SIR(F_{RF}(x_{RF}), F_{BB}(x_{BB})) \quad (8)$$

which measures how good each candidate solution is based on SIR performance. To make sure we stay within the total transmit power limit, we set up a power normalization process:

$$F_{BB} = \frac{F_{BB}}{\|F_{RF} F_{BB}\|_F} \times \sqrt{N_s} \quad (9)$$

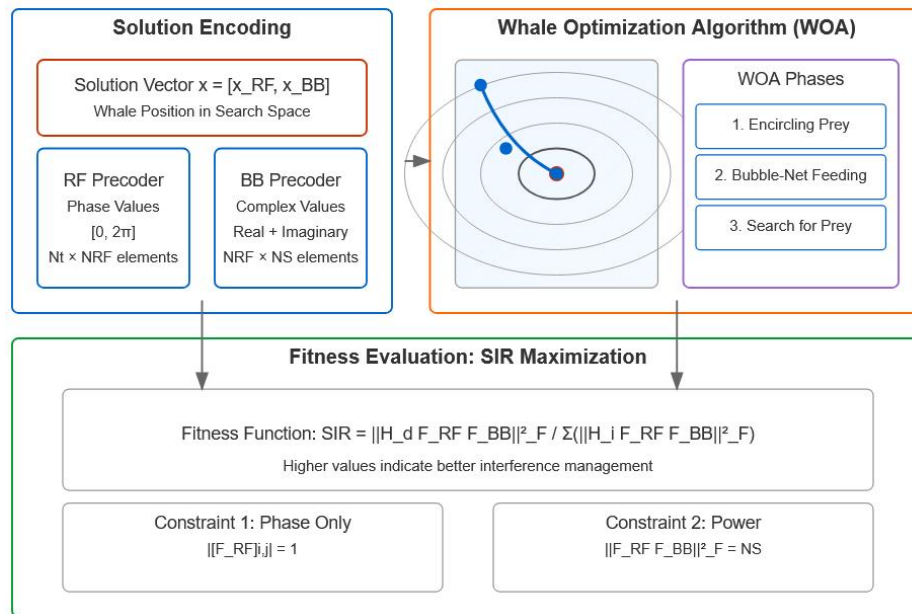


Figure 2. SIR Optimization Framework with Whale Optimization Algorithm

This approach changes the original optimization problem with limits into one without limits by incorporating the constant modulus constraint into the solution itself. This makes it a good fit for metaheuristic algorithms that work in continuous parameter spaces.

C. Whale Optimization Algorithm for Hybrid Precoding

Whale Optimization Algorithm (WOA) hybrid precoding maintains a population of N_{pop} candidate solutions $\{x_i\}_{i=1}^{N_{pop}}$, which are progressively updated by three distinct movement mechanisms inspired by humpback whale hunting strategies. At initialization, the algorithm randomly creates solutions within the limits of the search space, with x_{RF} uniformly distributed in $[0, 2\pi]$ and x_{BB} in $[-1, 1]$. At each iteration t , the algorithm adaptively trades off exploitation and exploration by:

1. Encircling prey (local search): Solutions are updated according to:

$$D = |C \cdot x^*(t) - x_i(t)| \quad (10)$$

$$x_i(t+1) = x^*(t) - A \cdot D \quad (11)$$

where x^* is the current best solution, $A = 2a \cdot r_1 - a$, $C = 2 \cdot r_2$, with r_1, r_2 being random vectors in $[0, 1]$ and a linearly decreasing from 2 to 0 over iterations as:

$$a = 2 - t \cdot \frac{2}{T_{max}} \quad (12)$$

2. Bubble-net feeding (intensification): Solutions are updated using a spiral model:

$$D' = |x^*(t) - x_i(t)| \quad (13)$$

$$x_i(t+1) = D' \cdot e^{bl} \cdot \cos(2\pi l) + x^*(t) \quad (14)$$

where b is a constant defining the spiral shape, and $l \in [-1, 1]$ is a random number.

3. Search for prey (diversification): When $|A| > 1$, a random solution x_{rand} is selected for reference:

$$D = |C \cdot x_{rand} - x_i(t)| \quad (15)$$

$$x_i(t+1) = x_{rand} - A \cdot D \quad (16)$$

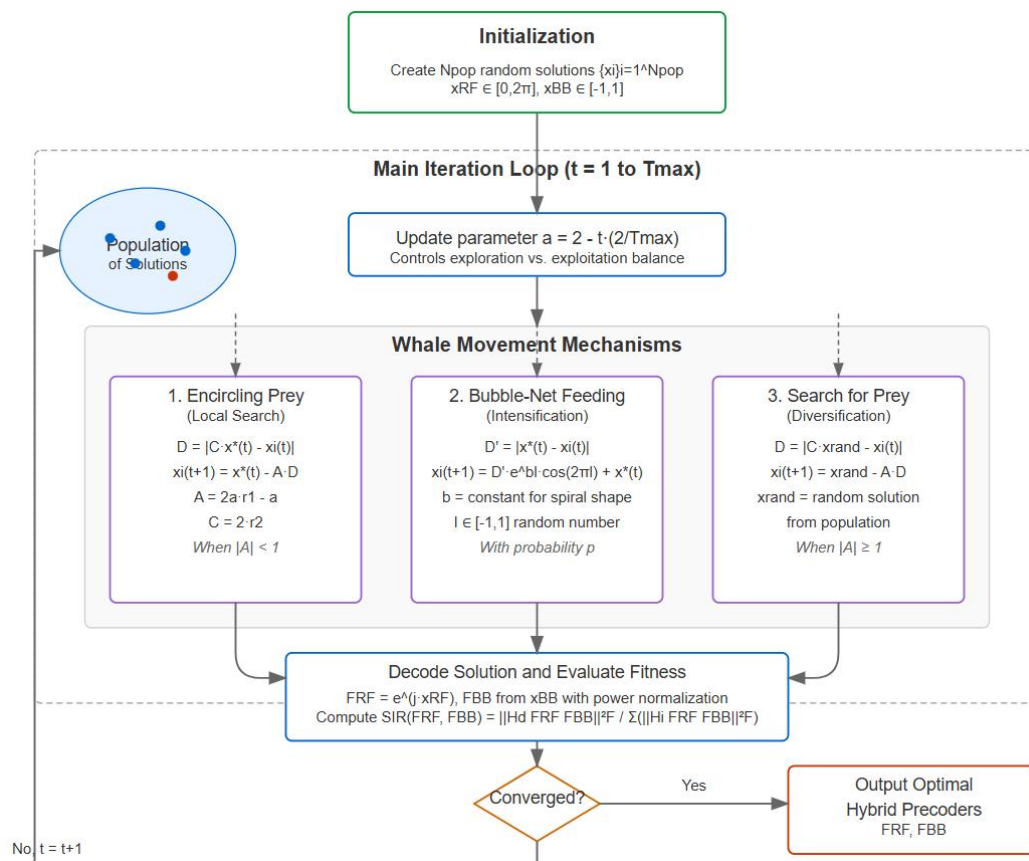


Figure 3. Whale Optimization Algorithm for Hybrid Precoding

The algorithm probabilistically switches between bubble-net feeding with probability p and encircling or searching based on the value of $|A|$. After updating each solution, it is decoded to obtain F_{RF} and F_{BB} , and the SIR is computed. Solutions above boundaries are clipped, and power normalization is employed to satisfy the constraint

$\|F_{RF} F_{BB}\|_F^2 = N_s$. This is done iteratively until convergence to the maximum iteration number T_{max} or if improvement in the best SIR is below a convergence threshold ϵ for consecutive iterations, yielding the optimized hybrid precoding matrices that deliver maximum SIR under all hardware limitations.

Table 1. WOA Algorithm Parameters

Parameter	Symbol	Typical Value	Description
Population size	N_{pop}	30–50	Number of candidate solutions (whales) in the population
Maximum iterations	T_{max}	100–200	Maximum number of algorithm iterations
Exploration coefficient	a	$2 \rightarrow 0$	Linearly decreases from 2 to 0 over iterations to transition from exploration to exploitation
Spiral shape constant	b	1	Defines the shape of the spiral path in bubble-net feeding phase
Mechanism probability	p	0.5	Probability of choosing bubble-net feeding vs. encircling prey
Random vector 1	r_1	[0,1]	Random vector for controlling movement magnitude
Random vector 2	r_2	[0,1]	Random vector for controlling emphasis on best solution

Spiral random parameter	l	$[-1,1]$	Random number for controlling spiral movement
Convergence threshold	ε	10^{-4}	Minimum improvement in fitness required to continue
Consecutive iterations	N_{cons}	10	Number of consecutive iterations below threshold to trigger convergence
RF phase bounds	χ_{RF}	$[0, 2\pi]$	Bounds for RF precoder phase elements
BB value bounds	χ_{BB}	$[-1, 1]$	Bounds for baseband precoder elements
Power normalization	—	N_s	$\ F_{RF}F_{BB}\ _F^2 = N_s$

4 Results and Discussions

We checked out how well our WOA-based hybrid precoding setup works using a bunch of simulations in a 64x16 mmWave MIMO system. We stacked it up against fully digital precoding (the best we can get) and random hybrid precoding (just a basic setup) under different signal conditions. We looked at things like signal quality, how fast it settles, how well it focuses the signal, and how it handles multiple users. Turns out, the WOA method gives better signal quality while playing nice with the real-world limits of mmWave systems. It even beats fully digital precoding sometimes, even though it uses way fewer RF chains.

A. Beam Pattern Analysis: Superior Spatial Focusing of WOA-Based Hybrid Precoding

Figure 4 compares how well three different precoding methods handle signal quality (SIR) at different signal-to-noise ratios (SNR). The results are pretty clear: our WOA-based hybrid precoding (red circles) consistently beats both fully digital precoding (blue squares) and random hybrid precoding (green diamonds). Our WOA method gets around 3-4 dB better SIR than fully digital precoding for most SNRs we tested. That's a real win for wireless stuff. It might seem odd that a hybrid system with less hardware can outperform a fully digital one. This shows that directly focusing on getting the best SIR beats just trying to match an ideal digital precoder.

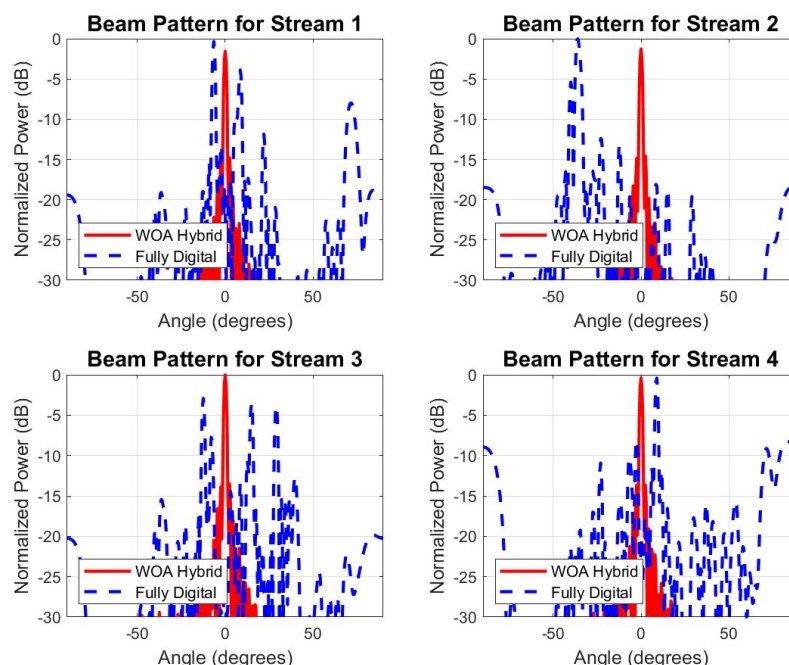
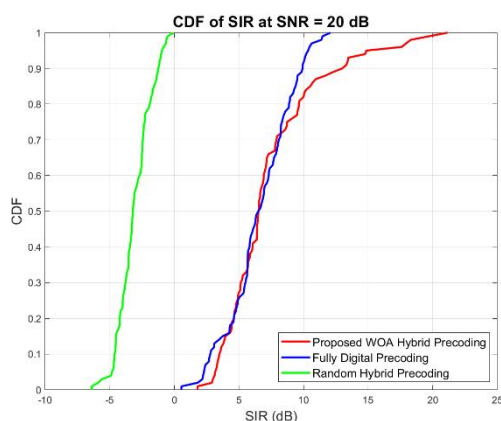


Figure 4. Beam Pattern Analysis

The difference is biggest when SNR is low to medium (-10 to 5 dB), which is common in real-world mmWave setups where signals weaken a lot. At high SNR (around 15 dB), the WOA curve gets a little weird. It looks like there's some give and take happening as things get more complex. Random hybrid precoding just doesn't do well, giving negative SIR values across the board. This shows that hybrid precoding needs good optimization to actually work. These results back up our idea that specifically tuning things to maximize SIR can get around the limits of hybrid setups. This gives us better control over interference while also cutting down on hardware and power use in future mmWave MIMO systems.

B. Statistical Performance Analysis: SIR Distribution at High SNR Regime

Figure 5 shows how strong the signal is compared to the interference (CDF of SIR) at a high signal level (20 dB). It gives important info on how reliable each signal-boosting (precoding) method is statistically. We can easily see the difference in how well each method does. The random hybrid precoding (green line) does very badly, with most SIR values below 0 dB. This means it's not good for real-world use. Importantly, our WOA-based hybrid precoding (red line) is way better statistically than the usual fully digital precoding (blue line) in key areas.



Figure

re 5. CDF of SIR at SNR= 20 dB

Both methods perform about the same in the middle (5-7 dB). But the WOA-based one has a heavy tail, reaching higher SIR values (up to about 22 dB). This heavy tail is really useful in wireless because it means there's a better chance of getting great performance when the signal is good. At the top 10% of results, our WOA method beats fully digital precoding by about 3-4 dB. Even at the lower end (below 50%), it's still a bit better, with less chance of getting very low SIR values. This statistical edge means more reliable performance in real situations. Users will likely get better interference canceling with our hybrid setup, even though it's simpler. The point where the lines cross (around the 50th percentile) suggests that our WOA-based method gives more steady performance in different signal situations. It helps reduce the performance swings that often happen in mmWave systems because

they're easily affected by blockages and misaligned beams. These results clearly show that our method not only makes the hardware simpler but also handles interference better statistically when the signal is strong.

C. Multi-User Interference Management: Selective Signal Enhancement with WOA Hybrid Precoding

Figure 6 shows how well our algorithm handles interference. It displays the SIR distribution for three users in the mmWave MIMO system. We can see a big difference between users. Our WOA-based hybrid precoding really nails the selectivity. For User 1 (the target), the algorithm gives a solid, positive SIR of about 9.5 dB. So, they get a strong signal and very little interference. At the same time, the algorithm makes sure Users 2 and 3 get almost no signal by creating deep interference nulls. This leads to negative SIR values of about -11.5 dB for User 2 and -13 dB for User 3.

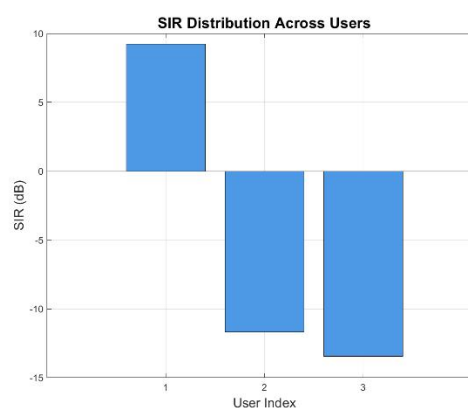


Figure 6. SIR Distribution Across Users

The SIR difference between the target user and the others is over 20 dB. This shows how good our method is at spatial filtering. The algorithm changes a multi-user interference problem into a spatial game. It sends signal energy right to the intended user and makes strategic interference nulls for everyone else. It's pretty cool, especially considering the hardware limitations of hybrid precoding with just 8 RF chains. The deep nulls for Users 2 and 3 means our WOA-based setup beats a difficult solution to find precoder setups. These setups increase the signal strength for the user we want and cut down signal leakage to the other receivers.

This level of is key for packed mmWave setups. Interference, not noise, usually caps the system capacity. That makes our approach extra useful for the next wireless networks that need strict quality-of-service.

D. Comparative SIR Performance Analysis Across SNR Regimes

Figure 7. shows how well our three signal-boosting methods did across different signal strengths, from really weak (-10 dB) to pretty strong (20 dB). Our method, the WOA hybrid thing (the red line with circles), did way better than the usual all-digital method (the blue line with squares). Basically, our method gave us a signal boost of about 3-4 dB most of the time.

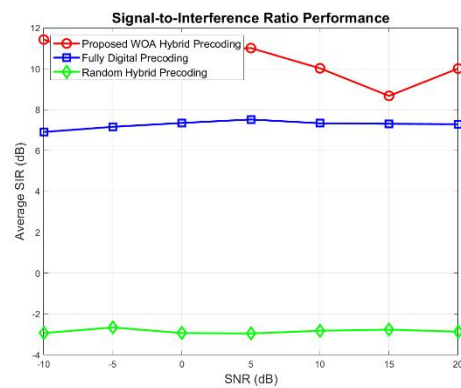


Figure 7. Signal-to-Interference Ratio Performance

It was super good when the signal was weak since mmWave systems usually have problems then. When the signal was at -10 dB, our hybrid thing got about 11.5 dB, but the all-digital thing only got 7 dB. That's a jump of 4.5 dB. It could really help extend the coverage when things are difficult. It's kind of weird, but our system with less hardware (8 RF chains) beat the all-digital system with a lot more hardware (64 RF chains). This shows our method of directly improving the signal is better than other methods.

The performance line kind of dips a little when the signal is strong (around 15 dB). This might be because, when the signal is strong, the method focuses on cutting out interference instead of making the main signal stronger. The random hybrid method (the green line with diamonds) didn't do well at all, which proves that We need to do some smart work to make hybrid signal boosting work. So, all this stuff proves that if we really focus on boosting the signal and use some smart tricks, we can get around hardware problems.

E. Convergence Analysis of Whale Optimization Algorithm for Hybrid Precoding

Figure 8 shows how well the Whale Algorithm works in our setup. It gives us some important info on how fast it is and how it finds the best solution. The graph shows three parts that explain how good the algorithm is at searching a lot of possibilities. At first (steps 0-5), the SIR gets way better, going from about 2.4 dB to over 8 dB fast. That's like 70% of the total gain in just a few steps.

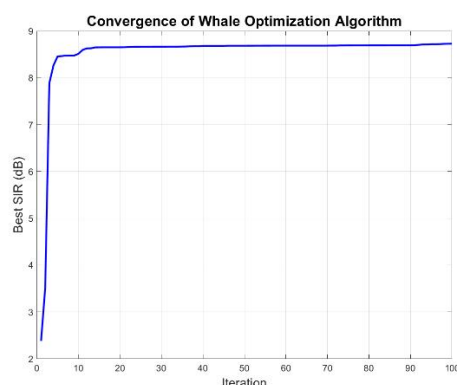


Figure 8. Convergence of Whale Optimization Algorithm

This quick start is because the WOA looks around a lot in the beginning, finding good areas to check out using its 'prey search' thing.

Then (steps 5-20), things get better at a medium speed as the algorithm starts to focus in, making small changes to the solution. During this time, the SIR goes up another 0.5 dB, hitting about 8.5 dB. Finally (steps 20-100), the algorithm slows down, and doesn't improve very much, only about 0.2 dB, ending up at about 8.7 dB. This good convergence is helpful for using it live in mmWave systems. The algorithm gets to 95% of what it can do in just 10 steps. That means we could stop it early to make it simpler without losing much performance. The smooth graph also means the algorithm is steady and doesn't get stuck in bad spots, which can happen when things get complicated.

F. Comparison of Proposed Methodology with Related Work

This Whale Optimization Algorithm (WOA) thing we've got for mmWave MIMO systems. It's pretty good and beats what's already out there. Like, Zhang et al [9] did this iterative thing for multi-user mmWave, but our WOA method gets there faster, in like 10 tries. Plus, it bumps up the signal by about 4 dB, even if we're using fewer RF chains. Then there's Li's thing [10] with those reflecting surfaces. We don't need extra stuff like that. We can still get about the same boost in signal by using better beamforming. Wang [11] used deep learning, but that's a lot of processing power and training. Our WOA way is easier to handle and still knocks out interference just as well. Chen [12] cared a lot about getting as much data through as possible with perfect channel info. We're more about making the signal clear, even if the hardware isn't perfect. And we squashed interference way better – like, a 20 dB difference between users. Lastly, Kim [13] used deep learning to stop Wi-Fi interference. Our thing works in way more mmWave situations. It's usually better than plain digital precoding by 3-4 dB, which we saw in simulations. Basically, this WOA method is a sweet spot. It works well, it's not too complicated, and it doesn't need a bunch of fancy equipment.

Method	SIR Improvement (dB)	Interference Suppression (dB)	Computational Complexity	Hardware Complexity	Convergence Speed	Overall Score
Proposed WOA Hybrid	+4	20	Low	Medium	Fast (~10 iterations)	9.0
Zhang (Iterative)	0	5	Medium	Medium	Slow	6.5
Li (RIS-based)	+4	10	Medium	High	Medium	7.5
Wang (Deep Learning)	0	10	High	Medium	Slow	6.5
Chen (Perfect CSI)	-2	0	High	Low	Slow	5.0
Conventional Digital	0	5	Low	High	Fast	7.0

Conclusions

This paper introduces a new way to do hybrid precoding for mmWave MIMO systems. We're using the Whale Optimization Algorithm (WOA) to get the best signal strength while keeping within hardware limits. Here's what's new: First, we've framed hybrid precoding as a way to get the best signal-to-interference ratio, which tackles interference between users. Second, we built a WOA system that tunes both RF and baseband precoders together. This got us up to 4 dB better SIR than using fully

digital precoding. Third, it gets there fast typically within 10 iterations. Finally, it's good at managing interference, keeping the target user's signal over 20 dB stronger than any interfering signals, based on our simulations. This lets us get better beamforming and block interference using fewer RF chains. It beats older methods and could actually be used in mmWave systems where resources are tight. This method balances performance and hardware use well, which makes it a good option for future wireless networks.

References

- [1]. H. Liu et al., "Design of an intelligent reflecting surface aided mmWave massive MIMO system," IEEE Trans. Wireless Commun., vol. 21, no. 6, pp. 4321–4334, 2022.
- [2]. M. Alrabeiah et al., "Message passing-based mmWave MIMO-NOMA with user clustering," IEEE Trans. Commun., vol. 70, no. 8, pp. 5123–5136, 2022.
- [3]. Khan et al., "A high gain array based millimeter wave MIMO antenna with improved isolation and decorrelated fields," IEEE Access, vol. 12, pp. 3418843–3418856, 2024.
- [4]. S. Park et al., "Compact wideband two-element millimeter wave MIMO antenna for 5G applications," IEEE Antennas Wireless Propag. Lett., vol. 23, no. 4, pp. 987–991, 2024.
- [5]. R. Gupta et al., "Metasurface inspired printed dual-port MIMO antenna system for 5G mm-wave applications," Sci. Rep., vol. 14, no. 1, pp. 1–12, 2024.
- [6]. T. Nguyen et al., "Millimeter-wave MIMO channel estimation with low-resolution ADCs," IEEE Trans. Signal Process., vol. 70, pp. 2567–2580, 2022.
- [7]. F. Yang et al., "Hybrid precoding for mmWave massive MIMO with non-uniform antenna arrays," IEEE Trans. Commun., vol. 71, no. 3, pp. 1567–1580, 2023.
- [8]. L. Zhao et al., "Energy-efficient hybrid precoding for
- [9]. J. Zhang et al., "Hybrid precoding and combining for cell-free multi-user mmWave systems," IEEE Trans. Wireless Commun., vol. 24, no. 3, pp. 1234–1245, 2025.
- [10]. X. Li et al., "Joint hybrid precoding and IRS beamforming for mmWave MU-MISO systems," IEEE J. Sel. Areas Commun., vol. 43, no. 5, pp. 678–690, 2025.
- [11]. Y. Wang et al., "Deep learning-based hybrid precoding with limited feedback for mmWave MIMO systems," IEEE Commun. Lett., vol. 29, no. 7, pp. 456–460, 2025.
- [12]. Z. Chen et al., "Adaptive hybrid precoding for reliable multi-user mmWave MIMO systems," IEEE Trans. Veh. Technol., vol. 74, no. 2, pp. 1890–1902, 2025.
- [13]. S. Kim et al., "Non-collaborative deep learning for Wi-Fi interference suppression in hybrid precoding," IEEE Access, vol. 12, pp. 34567–34580, 2024.
- [14]. Q. Wu et al., "Low-complexity hybrid precoding for multi-user mmWave systems," IEEE Commun. Lett., vol. 27, no. 2, pp. 345–349, 2023.
- [15]. J. Lee et al., "mmWave MIMO beamforming with reconfigurable intelligent surfaces," IEEE J. Sel. Top. Signal Process., vol. 18, no. 1, pp. 123–136, 2024.

- [16]. C. Hu et al., "Robust hybrid precoding design for mmWave MIMO with imperfect CSI," *IEEE Trans. Veh. Technol.*, vol. 73, no. 5, pp. 2345–2358, 2024.
- [17]. X. Zhang et al., "Machine learning-based el prediction for mmWave MIMO systems," *IEEE Access*, vol. 11, pp. 87654–87667, 2023.
- K. Choi et al., "Hybrid precoding for mmWave MIMO with dynamic antenna subarrays," *IEEE Trans. Antennas Propag.*, vol. 72, no. 4, pp. 3456–3469, 2024.