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Research Article

ONU Placement Optimization in FiWi Networks Using Mountain Gazelle Algorithm with Hyperbolic, Archimedes and Logarithmic Spirals

Neha Sharma[1], Puja Singh[2], Jaiveer Singh[3]
[1]Prestige Institute of Engineering, Management and Research, Indore, India
[2]Department of Electronics Engineering, Medicaps University, Indore, India
[3]Department of Physics, ISR, IPS Academy, Indore, India
**corresponding Author: nsharma@piemr.edu.in*

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ABSTRACT

Fiber-Wireless (FiWi) networks are promising hybrid solutions, bringing together high capacity and low latency of optical fiber technology with flexibility and broad coverage of wireless technologies. The results offer efficient, cost-effective, and provide scalable broadband connectivity. The strategic placement of Optical Network Units (ONUs) is crucial for improving network performance, reducing implementation costs, and improving service quality. This paper proposes a novel way to determining optimal ONU placement using the Mountain Gazelle Optimization (MGO) algorithm, which explores spiral path, approaches such as hyperbolic, Archimedes and logarithmic spirals. Extensive simulations indicate how each spiral path affects resource allocation, network speed and latency. The results reveal that the logarithmic spiral path outperforms hyperbolic and Archimedes in terms of cost function and network efficiency. This research paper also gives important insights that how different spiral paths affect MGO algorithm performance, allowing for better options in FiWi network planning.

Keywords: FiWi network, Optical Network Unit, Mountain Gazelle Optimization, spiral path, wireless access network, optical network.

INTRODUCTION

In the current era of communication networks, FiWi technology is an innovative solution that combines the benefits of fiber optics and wireless access network [1-2]. Fiber optics provides flexibility, huge bandwidth, reliability in terms of transmission capabilities while wireless access network provide mobility and gives extensive coverage. FiWi network is also known as hybrid network or Wireless Optical Broadband Access Network (WOBAN). Fiber optics is used as a back-end while wireless network is used as a front-end in WOBAN [3]. The advantages of hybrid network are adaptability, cost effective, reliable, huge bandwidth and low latency. FiWi networks play an important role in enabling next-generation applications such as Internet of Things (IoT) deployments, smart cities and remote healthcare systems, which need high bandwidth and low latency [4-5].

Extensive research is being conducted to improve the performance, reliability and effectiveness of FiWi access networks, but FiWi network is facing a number of challenges such as survivability [6-8], energy consumption [9], routing [10-11], ONU placement [12-26], bandwidth allocation etc. Optimal ONU placement in FiWi networks direct affects on network performance, including latency, bandwidth utilization and service coverage. Traditional methods for ONU placement usually fail to account for the various topologies and spatial demands seen in FiWi systems. To overcome this, heuristic and metaheuristic algorithms have been extensively studied [13].

This research paper proposes the Mountain Gazelle Optimization (MGO) algorithm to improve ONU Placement in FiWi networks. It is inspired by gazelles' adaptive foraging behaviors. The proposed algorithm maintains the balance between exploration and exploitation suitable for difficult optimization issues in dynamic network environments [27]. The MGO algorithm has been incorporated with three different spiral path strategies—

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hyperbolic, Archimedes and logarithmic spirals. Each spiral path has unique geometrical qualities that may influence the search space and convergence behaviour of the algorithm resulting in the effectiveness of the overall placement scheme.

Simulations have been conducted to assess the performance of each spiral-based strategy. It includes the impact of spiral shape on network parameters like throughput, latency, and cost function (minimum distance between ONUs and users). The result shows that spiral path selection within the MGO framework has a considerable impact on network efficiency and resource allocation. This work gives useful insights into spiral-based optimization for ONU placement, contributing a novel opportunities for improving FiWi network planning and performance.

The content of the research paper is described as follows: Section II describes the architecture of FiWi access network. Literature review for the optimal placement of ONUs is described in section III. Section IV covers the system model, constraints abbreviations and objectives. Section V describes the concept and implementation of MGO for the placement of multiple ONUs with different spiral paths in FiWi access network. Results are discussed in section VI. Section VII concludes the work and provides insights for future work.

ARCHITECTURE OF FIWI ACCESS NETWORK

This architecture combines high-capacity fiber optics with flexible wireless technologies to fulfill the growing need for high-speed, reliable internet connectivity in both urban and rural locations. The architecture consists of four components such as Optical Line Terminal (OLT), splitter, ONUs and wireless access points as shown in Figure 1. The OLT in the central office is crucial for managing data flow between the core network and the ONUs in the FiWi system. The OLT collects data from many ONUs and connects it to the Internet Service Provider (ISP's) backbone, enabling centralized control and management [20]. The Optical Distribution Network (ODN) is a FiWi network segment that provides fibre access from the OLT to various ONUs using Passive Optical Network (PON) setups. Passive optical splitters in the ODN separate signals from the OLT, allowing them to reach many ONUs without the need for active components. This leads to lower power consumption and reduced costs. The ODN provides reliable, low-latency distribution that extends high-speed connectivity to local areas, from where wireless extensions can reach end users [20-21].

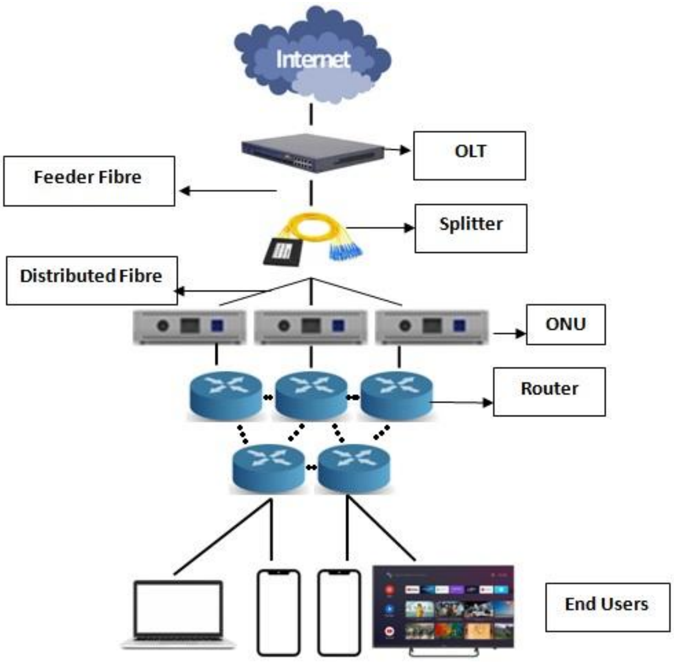

Figure 1. Architecture of FiWi network

ONUs are strategically located network nodes those indicate the transition from the fiber-optic backbone to the wireless segment. Each ONU acts as an interface between ODN and wireless access points or base stations,

Journal of Information Systems Engineering and Management
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Research Article

providing network connectivity to the end users such as smart phones, laptops and IoT devices [22]. Proper ONU placement is critical for optimal coverage, low latency, and effective resource allocation since ONUs act as gateways, transforming optical signals from the fiber network to wireless signals and vice versa.

The wireless segment represents the final connection layer, linking ONUs to the end-user devices. Depending on the FiWi setup, this segment includes WiFi, 4G/5G, or other standards. For bigger areas, base stations connected to ONUs act as centralized nodes, enhancing wireless coverage and allowing network scalability to handle an increasing number of users. End-user devices connect to the FiWi network to access speed, flexible and data services [23].

LITERATURE SURVEY

FiWi networks serve a wide range of applications, including household broadband, enterprise networks, rural broadband, smart city deployments, and IoT applications that require huge bandwidth, low latency and flexible connectivity [1-5]. However, FiWi networks are facing various challenges such as survivability [6-8], routing [9-11], ONU placement [12-26], and many more. In this research paper, ONUs placement problem has been considered. The authors explored the technologies and opportunities used in FiWi network [1-3]. The authors proposed the design of FiWi networks and the arguments for integrating optical and wireless networks. Additionally, they examined the performance of the FiWi network in terms of fault tolerance and network connection [4-5]. In [13-14], the authors compared various metaheuristics techniques for ONU placement, including random placement, deterministic placement, Greedy algorithm with initial deterministic placement and Greedy algorithm with initial random placement and a swarm-based optimization approach. The authors presented a Mixed Integer Programming (MIP) based technique to efficiently setting up Base Station (BS) and ONUs in FiWi network while complying with restrictions such as co-channel interference, signal quality, and installation, among others [15]. The Lagrangean relaxation approach is used for this purpose. The authors of [16-17] explained how Greedy, SA and mixed heuristic algorithms can be utilized for ONU placement in hybrid FiWi network. Greedy and SA algorithms are employed to optimize the position of ONUs, reducing the cost function. The cost function calculates the average distance between ONUs and users. In [18], a population-based MFO algorithm is implemented for the ONU placement showing superior performance over Greedy and SA algorithms with the lowest cost function. For the enhanced network efficiency the authors compared MFO algorithm configurations employing logarithmic, Archimedes and hyperbolic spirals to solve ONU placement problems [19]. Logarithmic spiral provides the best performance followed by Archimedes and hyperbolic spirals [19].

This paper proposes the MGO algorithm with a novel application of three spiral paths to enhance ONU placement. The MGO algorithm, inspired by gazelles' adaptive foraging behavior, aims to achieve an improved balance between exploration and exploitation in complex placement environments [27]. The proposed algorithms are used in parameter estimation of single and double diode photovoltaic cell models [28], standalone hybrid power system design [29], photo voltaic model [30], mechanical design problem [31] and truss structure [32]. By applying and comparing these distinct spiral paths, this research aims to expand upon prior optimization methods, aiming for improved accuracy in ONU positioning, better network performance and enhanced adaptability across different network configurations.

SYSTEM MODEL

In the present research paper, the network covers an area of 100 × 100 m². The network is designed based on input parameters such as the number of users and ONUs. In the proposed model, 100 users and 3 ONUs are considered. The output includes the optimal ONU positions (X and Y coordinates) along with the cost function value, represented by the average distance. The objective function, or fitness value of the given problem, is represented by the total cost function. The network is divided into non-overlapping segments called grids, each with a size of 10 × 10. Two user placement strategies are considered: initial deterministic (uniform) placement and initial randomc placement. In the Uniform strategy, ONUs or users are positioned at the center of each grid, while in the random strategy, they are placed anywhere within the grid. In this system model, the terms users and routers are used interchangeably and users are assumed to be static [21-22]. The abbreviations used in this research paper are as follows:

Journal of Information Systems Engineering and Management
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Research Article

x_{jj}, y_{jj} : j's location of users along X/Y

X_{ii}, Y_{ii}: i's location of ONU along X/Y

U_i: Number of premium users

N, K: Number of ONUs and users in the network

X'_{ii}, Y'_{ii} : Optimized location of ONUs

D_{eucl} : The Euclidean distance (cost) for positioning the i[th] ONU relative to its associated users

D_{ij}: Distance between primary ONUi and premium users

C_{indi} : Individual cost function

Objectives

- The ONU that is closest to the users are known as primary ONUs. Users who have access to this primary ONU are known as premium users. The Euclidean distance has been calculated from users to ONUs as follows:

$$D_{eucl} = \frac{1}{Ki} * \sum_{J=1}^{Ki} \sqrt{(x_{jj} - X_{ii})^2 - (y_{jj} - Y_{ii})^2} \quad (1)$$

- To determine the optimal position of ONUs, the mean of premium users' x and y coordinates has been evaluated.

$$X'_{ii} = \sum_{j=1}^{ki} x_{jj}/k_i \text{ and } Y'_{ii} = \sum_{j=1}^{k_i} y_{jj}/k_i \quad (2)$$

- Individual cost is calculated by taking the average distance between primary ONUs and their premium users by dividing it by the total number of premium users. These steps will be repeated for the rest of ONUs.

$$C_{indi} = 1/\ U_i \sum_{j \in Ui} d'_{ij} \quad (3)$$

- The overall objective function or overall cost function is calculated by taking the mean of individual cost function.

$$Coverall = \left(\frac{\sum_{i=1}^{n} C_{indi}}{n}\right) \quad (4)$$

- In the present research, the MGO algorithm has been implemented by introducing different spiral paths such as logarithmic, hyperbolic and Archimedes. The detailed descriptions are described in section V.

MGO ALGORITHM

It is the novel swarm based optimization algorithm inspired by the social life and hierarchy of wild mountain gazelles. Gazelles frequently travel quickly and agilely over landscapes in order to evade predators or locate resources, making their pathways useful models for optimization problems [24-26]. This algorithm considers four elements in mountain gazelle behaviour: bachelor male herds, maternity herds, solitary, territorial males migrate in quest of food [27]. MGO algorithm has been applied in different applications such as single and double diode solar cell models [28], hybrid power systems [29], parameter estimation in photovoltaic cells [30], mechanical design difficulties [31] and truss structure optimization [32]. In this research work, the present novel algorithm finds optimal ONU position by imitating gazelle-like movement patterns in the search space. This allows effective exploration and exploitation of prospective locales. MGO simulates the gazelle's movement by employing several spiral paths to navigate the search process towards optimum solutions. In the present proposed work, different spiral paths such as logarithmic, hyperbolic and Archimedes to define the motion of gazelles have been defined.

i. Logarithmic Spiral Path

It is a mathematical curve that grows outwards with each turn, follows an exponential relationship between radius and angle as shown in Figure 2, point in a smooth outward sweep.

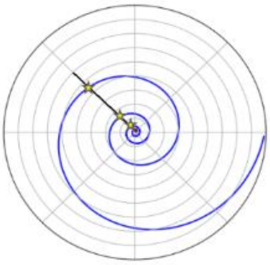

Figure 2. Logarithmic Spiral Path

The polar coordinate of logarithmic spiral is as follows:

$$R(\theta) = ae^{\wedge}b\theta \quad (5)$$

In eq. 5, R represents the radial distance from the origin, θ is the angle measured in radians, a is a scaling constant that regulates the spiral's starting radius and b is a growth factor that determines how tightly the spiral winds; a greater b value results in a more open spiral. Convert the polar coordinates into cartesian coordinates (X,Y) to use the logarithmic spiral path on a 2D grid.

$$X(\theta) = R(\theta)\cos(\theta) = X(\theta) = ae^{\wedge}b\theta\cos(\theta) \quad (6)$$

$$Y(\theta)) = R(\theta)\sin(\theta) = X(\theta) = ae^{\wedge}b\theta\sin(\theta) \quad (7)$$

$X(\theta)$ and $Y(\theta)$ coordinate, allows the MGO algorithm to move over the FiWi network's network area.

Implementation of placement of ONUs using logarithmic spiral path

- In the initialization phase, the search area is considered to be 100×100 m^2, and the network area is divided into non-overlapping segments called grids. The centre of each grid segment might be the starting point for a logarithmic spiral search. The initial radius (a) is determined by the desired starting distance from the centre.
- In spiral path exploration phase, the algorithm uses the aforementioned formulas to produce new (X, Y) coordinates for each increment in angle θ to define the spiral path from the beginning point.
- Each calculated (X, Y) coordinate denotes a possible ONU location. The MGO algorithm examines this point using network performance parameters such as user coverage area within the FiWi network and distance from other ONUs. The spiral path helps to strike a balance between exploring new places and exploiting promising parts within each grid.
- The value of b has been optimized based on search area's features and desired exploration intensity. Lower value of b allows the spiral path to span more of each grid and higher value of b concentrates the spiral route near the centre.
- The spiral search continues the process until it covers the grid area or an optimal position is found based on predefined coverage and connectivity metrics. The algorithm can move on to the next when one grid has been fully explored, ensuring that the network is completely covered.

Journal of Information Systems Engineering and Management
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ii. **Hyperbolic Spiral Path**

It has a reciprocal relationship between radius and angle and the spiral tightens around a focus point shown in Figure 3. This approach improves solutions by narrowing the search to a more focused area and allowing for finer tuning. In MGO, the hyperbolic spiral path helps to focus the search in a smaller region, allowing for precise modifications in areas around identified optimal locations, which is perfect for precision ONU placement. The hyperbolic spiral allows the MGO algorithm to focus intensively in the centre, adapt dynamically, and ensure detailed exploration. Its mathematical expressions are as follows:

$$R(\theta) = (a/\theta) \quad (8)$$

In eq. 8, R represents the radial distance from the centre, θ is the angle in radians, and a is a scaling constant determining how rapidly the spiral converges to the centre. A greater value of a indicates a longer spiral from the centre, whereas a smaller a indicates a tighter spiral. As θ approaches infinity, R(θ) approaches 0, indicating that the spiral grows closer to the centre. To implement the hyperbolic spiral in a 2D grid for the FiWi network, we convert the polar coordinates into cartesian coordinate(X, Y).

$$X(\theta) = R(\theta)\cos(\theta) = \left(\frac{a}{\theta}\right)\cos(\theta) \quad (9)$$

$$Y(\theta)) = R(\theta)\sin(\theta) = \left(\frac{a}{\theta}\right)\sin(\theta) \quad (10)$$

The hyperbolic spiral path is defined by (X, Y)coordinates, which allow the MGO algorithm to move smoothly within the grid segments of the FiWi network. As the value of θ increases, R(θ) is going to decrease this shows that it is moving approaches towards the center which is suitable for local fine-tuning in locations with high user density.

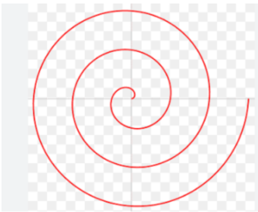

Figure 3. Hyperbolic Spiral Path

iii. **Archimedes Spiral Path**

It is a spiral path in which the radial distance from the centre grows linearly with angle as shown in Figure 4. Unlike the logarithmic or hyperbolic spirals, the Archimedes spiral has a constant distance between its arms, making it useful for equally exploring an area. It ensures uniform coverage of a specific grid segment within the search region and it provides flexible parameter tuning, consistent network coverage and reliability. The Archimedes spiral can be expressed in polar coordinates as:

$$R(\theta)=a + b\theta \quad (11)$$

In eq. 11, R is the radial distance from the origin to a point on the spiral, θ is the initial radius measured in radians which regulates the starting point of the spiral. Spacing between successive turns of the spiral are determine by the constant a and b. To employ the Archimedes spiral in a 2D grid of a FiWi network, convert the polar coordinates (R,θ) to cartesian coordinates (X, Y) as shown below:

$$X(\theta)=R(\theta)\cos\theta = (a + b\theta)\cos\theta \quad (12)$$

$$Y(\theta) = (a + b\theta)\sin(\theta) \quad (13)$$

These equations enable the MGO method to trace the Archimedes spiral path in the network region, systematically covering each part to determine the optimal ONU location.

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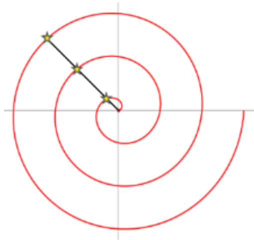

Figure 4. Archimedes Spiral Path

TABLE 1: Comparison between logarithmic, Archimedes and hyperbolic spiral path

Parameter	Logarithmic	Archimedes	Hyperbolic
Property	Radius increases exponentially with each round, making the spiral larger and wider [18, 19, 33].	Radius grows linearly, keeping spiral arms equally spaced [18, 19, 34].	A tight, inward-focused spiral is produced when radius decreases reciprocally with angle [19, 20, 34].
Equation	$R(\theta)=ae^\wedge b\theta$ [33]	$R(\theta) = a + b\theta$ [19, 20, 34].	$R(\theta) = a/\theta$ [19, 20, 34].
Advantage	Wide searching coverage and it balances between exploration and precision [18, 19, 33].	Uniform coverage, constant parameter adjustment and reliability [19, 20, 34].	Suitable for local fine-tuning, focusing on high-density areas [19, 20, 34].
Drawback	Slower convergence towards the centre results overshoots optimal positions [19, 33].	Less accurate in densely populated regions; may need to be adjusted for close clustering [19, 34].	Exploration area is limited which may not completely cover huge areas [19, 34]
Applicability	Preferred in situations requiring a balance between exploration and exploitation [33].	Preferred in situation where uniform coverage and balance performance is required [34].	Local searches in densely populated regions or where accuracy in limited areas is crucial [34].

SIMULATIONS AND RESULT DISCUSSION

In the present research, the simulation is carried out on the MATLAB (R2023 online version) environment and the initial parameter is same in all scenerios. Table 2 shows the simulation parameters for the MGO algorithms. Simulation has been carried out on three ONU and hundred users. M1, M2, and M3 represent the separate cost functions for ONU1, ONU2 and ONU3 and the overall cost function is represented by M. The simulation results summarized in Table 3 depict that the logarithmic spiral consistently yields the lowest cost function across various user and ONU distributions. This performance can be due to its exponential expansion, which enables full exploration of the search space and reduces the possibility of inappropriate placement. The result shows that the logarithmic spiral has a cost function of (19.588), which outperforms the Archimedes spiral (26.269) and the hyperbolic spiral (30.657) especially under random scenarios. The Archimedes spiral has a uniform rate of convergence throughout the search space. The Archimedes spiral, with its linear expansion, had a uniform convergence rate, making it suitable for uniform distributions. The hyperbolic spiral which gives better performance in precision tasks because to its inward-focused trajectory, struggled with broad exploration, resulting in higher cost function values across all situations. Figure 5 depicts the performance of the MHO algorithm using logarithmic, Archimedean, and hyperbolic spirals, taking into account different distributions of wireless mesh routers and ONUs. However, in hyperbolic spirals, the rate of convergence varies which impacts the efficiency of placement.

TABLE 2. Simulation parameter of MHO

No. of users	No of ONUs	Network Size (m^2)	No. of gazelle	Lower bound	Upper Bound	dimensions
100	3	100x100	20	0,0,0,0,0,0	100,100,100,100,100,100	6

TABLE 3. Value of cost function for different variants of MHO algorithm

Distribution of users	Placement of ONUs	Placement schemes	M1	M2	M3	M
Uniform	Uniform	MGO-L	20.964	19.963	27.550	22.826
		MGO-H	22.522	21.115	26.166	23.268
		MGO-A	21.711	21.466	26.453	23.210
	Random	MGO-L	26.478	21.574	21.610	23.221
		MGO-H	18.024	29.352	30.140	25.839
		MGO-A	25.676	24.704	23.182	24.521
Random	Uniform	MGO-L	30.898	16.196	16.734	21.276
		MGO-H	27.233	22.072	25.615	24.973
		MGO-A	22.350	28.268	18.320	22.979
	Random	MGO-L	20.988	23.669	14.106	19.588
		MGO-H	33.794	29.208	28.969	30.657
		MGO-A	15.978	31.053	31.775	26.269

TABLE 4. Execution Time of Spiral Path

Placement Scheme	Execution Time in second		
	MGO-L	MGO-H	MGO-A
Both ONUs and users are located uniformly.	0.29	0.36	0.51
ONUs deterministic and users random	0.26	0.25	0.33
ONUs random and users deterministic	0.23	0.97	1.03
Both ONUs and users are located randomly.	0.29	1.26	1.04

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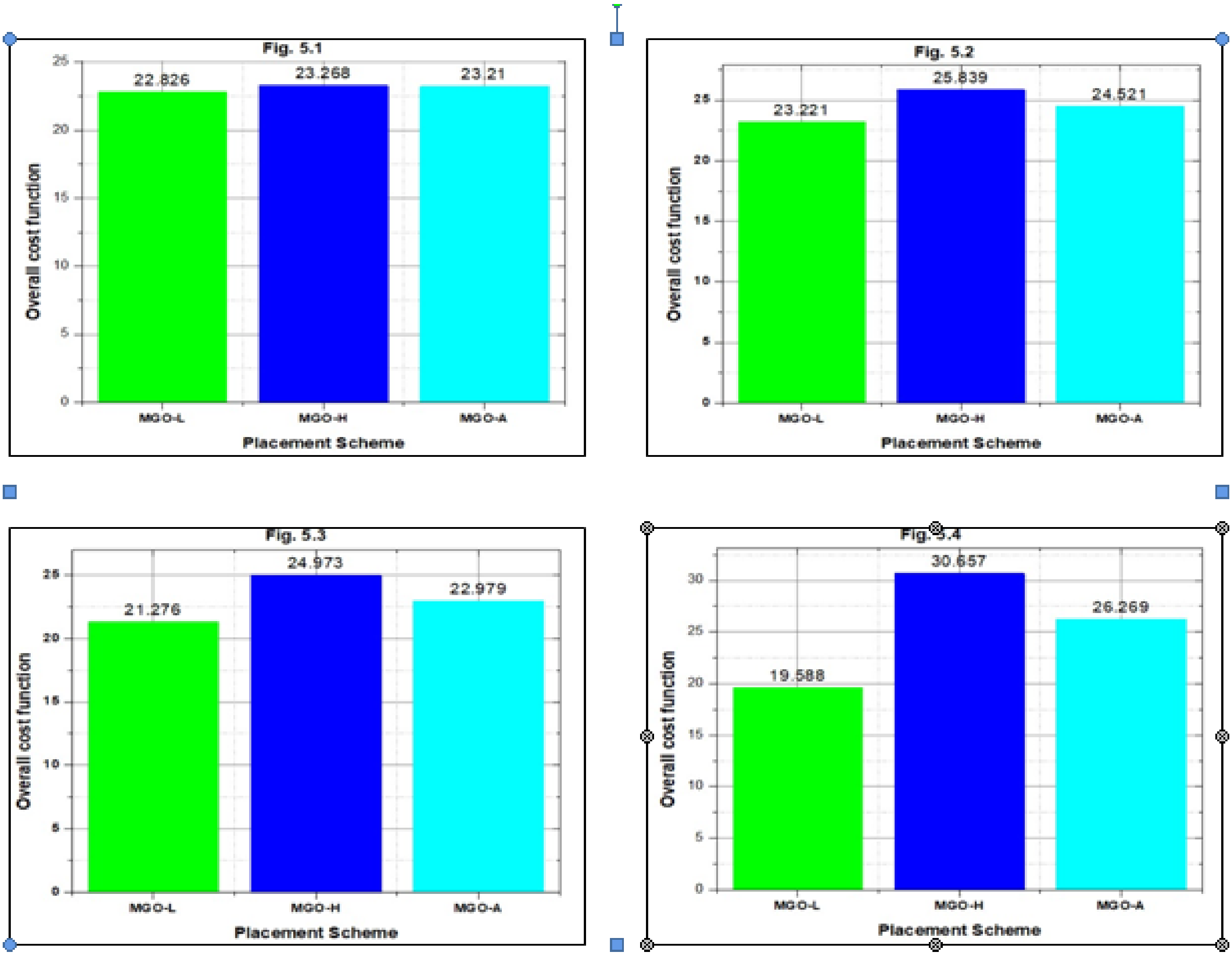

Figure 5 Values of cost function for the different placements of ONUs and users for MGO-L, MGO-H and MGO-A (i) Uniform positions of ONUs and users (ii) ONUs are located in random and users are located in uniform position (c) ONUs are in uniform placement and users are in random placement (iv) ONUs and users are located in random fashion

CONCLUSION

This research paper evaluates the performance of the MGO algorithm applied to ONU placement in FiWi networks, specifically across three spiral paths: logarithmic, Archimedes and hyperbolic. Simulation results show that the logarithmic spiral path consistently outperforms Archimedes and hyperbolic spiral in terms of placement efficiency for various users and ONUs distribution. It returns the lowest cost function observed when both the ONUs and users are randomly distributed. In comparison, the Archimedes path outperforms the hyperbolic path. Archimedes spiral path provides balance between exploration and reliable coverage. The proposed work provides valuable insights into the role of spiral path selection in optimizing FiWi network efficiency and supporting more informed decisions in ONU placement. In future research, the MHO algorithm can be adapted for multi-objective optimization, potentially addressing additional network requirements, such as load balancing and energy efficiency, there by further enhancing the robustness and adaptability of FiWi networks.

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