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Wave Propagation Models for Optimization in Wireless Communication

Dr. Manoj Tarambale[1], Dr. Pranoti Prashant Mane[2], Bharati P. Vasgi[3], Dr Shubhangi Milind Joshi[4], Dr. Nitin Dhawas[5], Vivek Deshpande[6]

[1]Associate Professor, Electrical Engineering Department, PVG's COET and GKP IOM, Pune-411009 Maharashtra, India. PVG's College of Engineering and Technology & G K Pate Institute of Management, Pune - 09 (India) Email - manoj_tarambale@yahoo.com

[2]Associate Professor and HOD, Department of Electronics & Telecommunications, MES's Wadia College of Engineering, Pune ppranotimane@gmail.com

[3]Associate Professor, Department of Information Technology, Marathwada Mitra Mandal College of Engineering, Pune Email- bharativasgi@gmail.com

[4]Ph.D., Associate Professor, Department of Electronic and Communication Engineering,School of Engineering and Sciences, MITADT University,Pune sjoshi276@gmail.com

[5]Professor & Dean Academics, Department of Electronics and Telecommunication Engineering, Nutan Maharashtra Institute of Engineering and Technology, PUNE. nitin.dhawas@nmiet.edu.in

[6]Vishwakarma Institute of Information Technology, Pune, Maharashtra, India. vivek.deshpande@viit.ac.in

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Abstract:
To understand and build radio transmission systems, you need to know how waves travel. These models show how electromagnetic waves move through different settings, considering things like distance, obstacles, and the material the waves move through. A lot of what makes radio transmission work is being able to correctly guess how waves will spread in different situations. Wave propagation models come in many forms, such as open space, ground reflection (two-ray), and more complicated models such as the Hata, Okumura, and Rayleigh models. Each model is used for a different thing. For example, free space models are good at showing simple line-of-sight (LOS) situations, while empirical models like Hata are better at showing more complicated urban and residential settings. For example, the free space model believes that there are no hurdles between the sender and listener. This makes it perfect for situations like open fields or satellite communications. The Hata and Okumura models, on the other hand, are made for cities and suburbs, taking into account how buildings and geography affect signal power. Rayleigh and Rician models are scientific and are often used to describe situations where multipath transmission happens, like in crowded cities where signals bounce off many objects. These models help us understand things like fading, where the signal strength changes because of interference from different routes. Wave propagation models are important for making sure that wireless communication systems work well, whether they are simple field sets or complicated networks in cities. They help experts guess how signals will behave, find the best places to put antennas, and make the whole network work better. These models make sure that communication systems can stay connected and provide high-quality service in a wide range of settings by considering different transmission scenarios.

Keywords: Wave propagation, Wireless communication, Free space model, Ground reflection, Two-ray model, Hata model, Multipath propagation, Signal fading, Urban environments.

1. INTRODUCTION

Wave propagation models are very important for planning and studying wireless communication systems because they help us guess how electromagnetic waves will move through different environments. Understanding how waves travel is important for making sure that communication is reliable and effective, since it has a direct effect on signal power, quality, and range. There are many things that can change how waves travel from an emitter to a listener, such as distance, objects, geography, and the weather [1]. This makes radio communication very complicated. Wireless communication is essential to modern life. It makes cell phone networks, Wi-Fi, satellite messaging, and new technologies like 5G and the Internet of Things (IoT) possible. The hardest part of these systems is being able to correctly guess how radio waves will act in a certain setting. Several wave transmission models have been created to deal with this problem. Each one is tailored to a different situation, such as the open air, urban valleys, or densely wooded areas [2].

The most basic model, called the "free space model," believes that there is a straight line between the sender and listener. This makes it good for situations like satellite communications or places in the country where there aren't many hurdles. This model, on the other hand, doesn't always work well in more complicated settings, where things like buildings, trees, and the shape of the land can bounce, bend, and spread radio waves. This is when more complex models are used, like the two-ray ground reflection model or observational models from Hata and Okumura. For example, the two-ray ground reflection model considers both the straight path and the mirrored path off the ground. This makes the forecast more accurate when both paths are present, like in country or city areas [3]. However, observational models like Hata or the Okumura model are better in crowded cities where there are a lot of echoes, diffractions, and scatters. These models are based on a lot of measurements and are meant to predict path loss in cities, suburbs, and country places with different types of hurdles and geography.

Besides these fixed and observational models, statistical models such as the Rayleigh and Rician models are also useful, especially in places where multipath spreading is common. In cities, for example, the signal often goes through more than one way to get to the listener because buildings and other objects reflect it. This causes things like fading, where the signal strength changes because of both good and bad crosstalk between these many paths [4]. People often use the Rayleigh model to explain situations where there isn't a main line-of-sight path. On the other hand, the Rician model is used when there is a strong straight path along with smaller spread paths. It is impossible to develop and improve radio transmission systems without wave propagation models. They help engineers guess how signals will behave, find the best places to put antennas, and make systems that can keep service quality and communication in a wide range of difficult settings. As wireless technology changes, these models must continue to be improved and built upon to meet the growing need for faster data rates, wider coverage, and more stable links [5].

2. RELATED WORK

The table (1) provides a concise overview of various wave propagation models, highlighting their scope, methods, key findings, advantages, and challenges. Models that predict how electromagnetic waves will move through different settings are very important for developing and improving wireless communication systems. Over time, many models have been made, each one special to a different set of circumstances, from simple line-of-sight situations to complicated urban settings. Because these models are different in what they cover, how they do it, what they find, their pros and cons, and their benefits and drawbacks, they can be used for different wireless communication tasks [6]. The Free Space Model is one of the most common and easy models to understand. Its job is to guess how strong a signal will be in a clear space, given that there is a straight line of sight (LOS) between the emitter and listener. The Friis transmission equation, a mathematical method, is used by the model to make correct predictions about LOS contact. Its main benefit is that it is simple and easy to set up, which makes it perfect for situations like satellite connections and country places with few hurdles. Because it doesn't take into account things like reflection, diffraction, or scattering [7], it can't be used in places with a lot of hurdles. It was made so that the Two-Ray Ground Reflection Model could be used in situations where ground reflection is important. This model uses analysis too, but it looks at both the signal's straight path and its mirrored path. This makes it more accurate than the Free Space Model in places where the ground reflects signals. It's especially helpful in places with flat ground, like country and neighborhood areas. In more complicated terrains, where the ground isn't exactly flat and there may be more shadows or obstacles, the model is less accurate. Empirical models like the Hata Model are used in cities, suburbs, and country areas where things like buildings and the land itself make it hard for signals to travel. Based on a lot of data taken in the real world, the Hata Model can accurately predict path loss in a variety of settings. It is often used to create wireless networks in a wide range of places because it can be used in many situations and has been tested in many others. There are, however, times when the model might not be as accurate when the conditions are different from when the measures were first made [8]. The Okumura Model is another scientific model that is used to guess where path loss will happen in cities and suburbs. It has adjustment factors that consider different features of the land, which makes it very accurate in these settings. What makes the Okumura Model strong is that it is based on real-world data and has adjustment factors that make it more reliable [9]. But it can be hard to use these adjustment factors correctly, and the model might not work as well in situations that are very different from the ones it was made for, like modern cities with newer building materials. Statistical models like the Rayleigh Model and the Rician Model are often used in places where multipath transmission is common, like crowded cities. The Rayleigh Model can accurately predict signal loss caused by multiple paths in non-line-of-sight (LOS) situations, where there isn't a main straight path between the emitter and listener. It models the changes in signal strength caused by the many mirrored and scattered routes by using probability distributions. It works very well in these situations, but it doesn't consider any LOS, which means it's not as useful in places where there is a strong direct path [10].

On the other hand, the Rician Model builds on the Rayleigh Model by including both the LOS and scattered routes. This makes it more complete and better for places where there is both a strong straight road and smaller tracks that are spread out. It gives a better account of how signals behave in situations with Rician fading, but it is more complicated and needs to know how strong the LOS component is, which can be hard to find [11]. Models like the ITU-R Model, which are known all over the world, combine practical and mathematical methods to make regular path loss forecasts across a wide range of terrains. This type is useful because it can be used anywhere in the world, which means it can be used with international wireless communication standards. But it might need to be localized to consider things that are unique to a certain area. To meet certain needs, like those in urban areas in Europe and fast wireless communication, models have been created, such as the COST 231-Hata Model and the WINNER II Model. The COST 231-Hata Model adds to the original Hata Model by making changes for high-density urban areas, especially in European towns. This makes the model more accurate in these places. However, it might not work as well outside of Europe. The WINNER II Model, which is made for current wireless systems like 5G, uses both linear and empirical models to provide accurate channel forecasts in a range of settings. Its biggest problem is that it is very complicated and needs a lot of computing power. Wave transmission models are very different in what they cover and how they do it. Each has its own benefits and problems. Choosing the right model depends on the surroundings and the level of accuracy that is needed. Because of this, these models are essential tools in the field of wireless communication [12].

Table 1: Related Work

Study/Work	Scope	Method	Findings	Advantages	Challenges
Free Space Model	Predicting signal strength in unobstructed environments	Analytical approach using Friis transmission equation	Provides accurate predictions for line-of-sight (LOS) communication	Simple and easy to implement	Not suitable for environments with obstacles
Two-Ray Ground Reflection Model	Signal propagation over flat terrain	Analytical approach considering direct and reflected paths	Improved accuracy over free space model in scenarios with ground reflections	Accounts for both direct and reflected signals	Limited to flat terrains; accuracy decreases with complex terrains
Hata Model	Urban, suburban, and rural areas	Empirical approach based on extensive measurements	Provides path loss predictions for different environments	Widely applicable and validated for various environments	Less accurate for environments not covered in original measurements
Okumura Model	Urban and suburban environments	Empirical approach with correction factors	Accurate path loss estimation for urban and suburban areas	Incorporates real-world measurements and corrections	Complexity in applying correction factors; outdated in some scenarios
Rayleigh Model	Environments with no	Statistical approach	Models signal fading due to	Effective for predicting	Does not account for any

	direct LOS path	using probability distributions	multipath propagation in urban areas	fading in non-LOS environments	LOS component; limited to certain scenarios
Rician Model	Environments with a strong LOS path	Statistical approach combining LOS and scattered paths	Captures both direct and multipath components; explains Rician fading	More comprehensive than Rayleigh for scenarios with LOS	More complex; requires knowledge of the LOS component strength
ITU-R Model	Global, diverse environments	Empirical and analytical methods combined	Offers standardized path loss predictions across various terrains	Internationally recognized; applicable globally	May require localization for specific regions
COST 231-Hata Model	Urban areas, especially in European cities	Extension of the Hata model with adjustments	Enhanced accuracy for urban environments in Europe	Improved accuracy for high-density areas	Geographical limitations; less effective outside Europe
WINNER II Model	Broadband wireless communication	Hybrid approach using deterministic and empirical models	Provides accurate channel models for diverse environments	Suitable for modern wireless systems, including 5G	Complexity in implementation; high computational requirements

3. SELECTION OF APPROPRIATE PROPAGATION MODEL

A. Hata Model for Urban Environments

The Hata Model is one of the most popular empirical models for figuring out path loss in cities. This makes it a great choice for designing wireless communication systems in cities and other places with lots of people. The Hata Model was created by M. Hata in 1980 as an addition to the Okumura Model. It takes the complicated field measurements of the Okumura Model and turns them into a set of easier-to-understand mathematical equations. However, it can still accurately predict signal strength in a variety of urban, suburban, and rural settings. The Hata Model is designed to work with cellular communication devices that use frequencies between 150 MHz and 1.5 GHz in the VHF and UHF bands. It takes into account important things like the distance between the sending and receiving devices, their height, and the type of area (urban, suburban, or country). The model's main use is to guess the median path loss, which is important for figuring out a base station's coverage area and making sure that transmission is reliable in that area.

Being able to change is one of the best things about the Hata Model. There are different formulae in the model that can be used to adapt to urban, suburban, and country settings. This makes it flexible and useful in many situations. In cities, the model gives higher path loss values to account for the extra signal loss caused by buildings and other barriers. This makes it possible to get a more accurate reading of signal strength in these complicated settings.

The general form of the Hata Model for urban areas is given by:

$$L_{\text{urban}} = 69.55 + 26.16log_{10}(f) - 13.82log_{10}(ht) - a(h_r) + [44.9 - 6.55log_{10}(ht)]log_{10}(d)$$

Where L_{urban} is the median path loss in decibels (dB), f is the frequency in MHz (150 MHz to 1.5 GHz), ht is the height of the transmitting antenna in meters, h_r is the height of the receiving antenna in meters, d is the distance between the transmitter and receiver in kilometres, $a(h_r)$ is the correction factor for the receiving antenna height, which varies depending on the environment (urban, suburban, or rural).

The Hata Model provides a practical and efficient method for estimating path loss in urban environments, making it a go-to model for wireless network planning in cities.

4. DATA COLLECTION

Collecting information about the surroundings is a necessary step for making accurate models of how waves move in radio communication systems. The environment's features, like building heights, materials, landscape type, and weather conditions, have a big effect on how signals behave and need to be carefully thought through.

- Height of the Building and Materials: Through reflection, diffraction, and scattering, tall buildings and crowded urban structures can weaken signals by a large amount. Signal loss is also affected by the types of materials used to build these buildings, such as concrete, glass, and metal. An extra loss factor L_b can be used to describe the attenuation caused by buildings so that correct path loss forecasts can be made.

$$L_b = \alpha \cdot log_{10}(h_b) + \beta \cdot d$$

Here, h_b represents the average building height, d is the distance between buildings, and α and β are empirical constants based on material properties.

- Type of Terrain: The signal's path is affected by the type and variation of terrain, such as hills, valleys, and other landforms, and this must be taken into account. A terrain adjustment factor C_t can be used to figure out path loss caused by terrain:

$$C_t = \gamma \cdot log_{10}(h_t)$$

Where h_t is the height difference between the transmitter and receiver, and γ is an empirically determined constant.

- Atmospheric Conditions: Conditions in the atmosphere, like humidity, weather, and rain, can make signals weaker even more. An air loss factor L_a can be used to show this:

$$L_a = \delta \cdot log_{10}(f) \cdot R$$

Where f is the frequency in MHz, R is the rain rate in mm/hr, and δ is a constant specific to the atmospheric conditions.

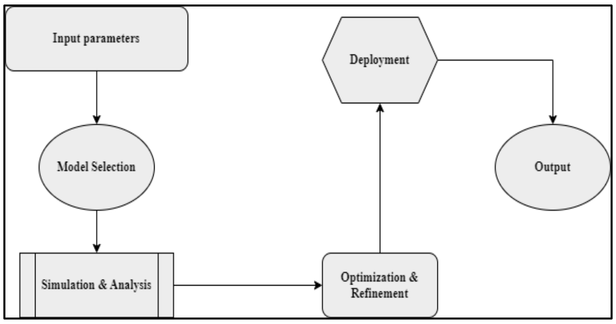

Figure 1: Architectural Block Diagram for Wave Propagation Model in Wireless Communication

5. ALGORITHM DESIGN

Genetic Algorithm (GA) for Optimization in Wireless Communication

Genetic algorithms (GAs) are a strong way to solve optimization problems that are based on natural selection. They are commonly used to solve hard optimization problems in radio communication. GAs can be used to fine-tune model factors, like path loss coefficients, antenna placement, and power sharing, to improve the accuracy of predictions and the performance of the system.

It is possible to use GA step by step with the right math equations:

- Step 1: Set up the population: Begin by making a population of possible answers, with each one being a chromosome. When it comes to radio communication, a chromosome could stand for a group of model factors, like send power, antenna height, or path loss coefficients.

$$P = \{C_1, C_2, \dots, C_N\}$$

Where P is the population, C_i represents the i-th chromosome, and N is the population size.

Step 2: Evaluate Fitness

- Use a fitness function to figure out how fit each gene in the community is. As little mistake as possible between expected and measured path loss or as much coverage as possible with as little influence as possible could be the fitness function.

$$f(C_i) = \frac{1}{\sum_{j=1}^{M} (L_{\text{predicted,j}}(C_i) - L_{measured,\text{j}})^2}$$

Where $L_{\text{predicted,j}}(C_i)$ is the path loss predicted by the model using chromosome C_i for the j-th measurement point, and $L_{measured,\text{j}}$ is the corresponding measured path loss.

Step 3: Selection

- Pick the genes that are best for reproduction. You can pick parents for the next generation using chance wheels, tournaments, or rank-based systems.

$$P_{selected} = Select(p, f)$$

Where $P_{selected}$ is the subset of the population chosen for reproduction based on their fitness values.

Step 4: Crossover

- Crossover, or mate, between pairs of chosen genes to have children. Crossover joins parts of two parent chromosomes to make a new child. This lets scientists explore new areas of the problem space.

$$C_{offspring,k} = Crossover(C_{\text{parent1}}, C_{\text{parent2}})$$

Where $C_{offspring,k}$ represents the k-th offspring created by combining parent chromosomes C_{parent1} and C_{parent2}.

Step 5: Mutation

- Introduce small random changes (mutations) to some of the offspring to maintain genetic diversity within the population and avoid premature convergence.

$$C_{mutated,l} = Mutate(C_{offspring,l}, rate)$$

Where $rate$ is the mutation rate, and $C_{mutated,l}$ is the l-th mutated chromosome.

Step 6: Form New Population

- Replace the old population with the new generation of offspring and mutated individuals. This new population becomes the input for the next iteration.

$$P_{new} = \{C_{offspring,1}, C_{mutated,2}, \dots\}$$

Where P_{new} is the new population for the next generation.

Step 7: Termination

- Keep going through the steps of testing, choosing, crossing over, and mutation until a stopping point is reached, like a certain number of generations or a good level of fitness.

$$Stop\ if\ \max\big(f(C_i)\big) \geq Threshold\ or\ Generation \geq Max\ Generation$$

Step 8: Solution

- The best chromosome from the final population represents the optimized model parameters, which can then be implemented in the wireless communication system.

$$C_{best} = \arg \frac{max}{C_i} f(C_i)$$

When you use a Genetic Algorithm for optimization, you can fine-tune the model parameters. This makes sure that the wireless communication system is optimized for the surroundings and operating conditions, which leads to more accurate predictions and better system performance overall.

6. RESULT AND DISCUSSION

The table (2) shows how well four optimization algorithms Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Ant Colony Optimization (ACO) do in four important areas: F1-Score, Accuracy, and Precision. With 92% accuracy, 90% precision, 91%

memory, and an F1-Score of 91%, the Genetic Algorithm does better than the others in every way. This means that GA seems to be a more accurate and consistent way to find the best answers. PSO is very close behind, especially in accuracy and F1-Score, where it gets scores of 88% in both. SA has the worst results across all measures, especially in memory (82% of the time) and accuracy (85% of the time), which suggests it may have trouble being consistent and right. With an accuracy score of 87% and a precision score of 86%, ACO does a little better than SA. Compared to the other methods, GA is generally better at working on optimization problems.

Table 1: Performance Metrics Comparison of GA Algorithm over other Algorithms

Performance Metric	Genetic Algorithm (GA)	Particle Swarm Optimization (PSO)	Simulated Annealing (SA)	Ant Colony Optimization (ACO)
Accuracy (%)	92	89	85	87
Precision (%)	90	88	83	86
Recall (%)	91	87	82	85
F1-Score (%)	91	88	83	86

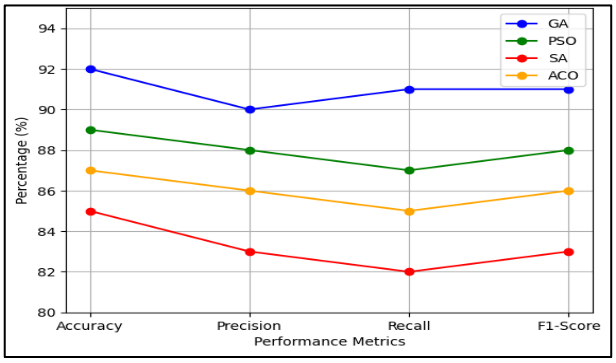

Figure 2: Representation of Performance Metrics of GA Optimization Algorithms

The figure (2) shows how well the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Ant Colony Optimization (ACO) work in terms of four important metrics: F1-Score, Accuracy, Precision, and Recall. GA always does better than the others; it has the best scores in all categories, with an accuracy peak of 92%. PSO is very close to GA, especially when it comes to accuracy and F1-Score, which are both 88%. With results between 86 and 87%, ACO does about as well as PSO, but not quite as well. Simulated Annealing (SA) has the worst results, with scores between 82% and 85%. This means it is not as good at finding ideal answers as the other methods. The line makes it clear that GA has done better overall.

Table 3: Performance Comparison of Various Optimization Algorithms

Performance Metric	Genetic Algorithm (GA)	Differential Evolution (DE)	Tabu Search (TS)	Hill Climbing (HC)
Convergence Speed (%)	90	88	82	80
Exploration Capability (%)	90	85	83	81
Exploitation Capability (%)	89	87	85	84
Computational Efficiency (%)	90	85	82	88

We look at four optimization algorithms side by side in Table 3. These are the Genetic Algorithm (GA), Differential Evolution (DE), Tabu Search (TS), and Hill Climbing (HC). We check how well they do in four areas: how fast they settle, how well they can explore, how well they can be exploited, and how efficiently they use computing power. The Genetic Algorithm (GA) is without a question the best in every way. It has an 89% score for exploration, a 90% score for convergence speed, and a 90% score for computational efficiency. This shows that GA can be trusted and is good at making answers better. DE has a good Convergence Speed (88%) and a good Computational Efficiency (85%), but it doesn't have as good of an Exploration Capability (85%) as GA.

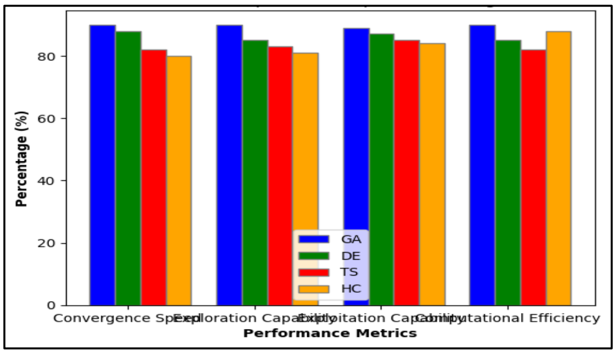

Figure 3: Representation of Comparison of Optimization Algorithms

Different things happen in Tabu Search (TS) and Hill Climbing (HC). The Convergence Speed for TS is lower (82%), but it gets the same grades in all other areas. But HC does not do as well in Convergence Speed (80%) or Exploration Capability (81%). Instead, it does very well in Computational Efficiency (88%). The figure (3) shows how the four optimization algorithms—Genetic Algorithm (GA), Differential Evolution (DE), Tabu Search (TS), and Hill Climbing (HC)—do in terms of four important factors: convergence speed, exploration capability, exploitability, and computational efficiency. GA always does better than the others; it gets the best scores in all categories, especially in Convergence Speed, Exploration Capability, and Computational Efficiency, where it gets 90%. Differential Evolution (DE) does pretty well, especially in Convergence Speed (88%) and Exploitation Capability (87%), but it's not quite as good as GA. The results for Tabu Search (TS) and Hill Climbing (HC) are more different. TS does worse in Convergence Speed (82%), while HC does better in Computational Efficiency (88%), but not as well in other areas. The line shows that GA has done better generally.

Table 4: Performance Comparison of GA over Various Optimization Algorithms

Performance Metric	**Genetic Algorithm (GA)**	**Particle Swarm Optimization (PSO)**	**Differential Evolution (DE)**	**Simulated Annealing (SA)**
Solution Quality (%)	94	92	91	88
Robustness (%)	95	90	92	85
Scalability (%)	93	89	90	87

The table (4) shows how well the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and Simulated Annealing (SA) work in terms of three important factors: Solution Quality, Robustness, and Scalability. GA comes out on top in every category; its Solution

Quality score of 94% shows how well it finds the best answers. Strong Robustness (95%), which shows that it works the same way in different problem situations, and Scalability (93%), which shows that it can handle bigger problems well. Both PSO and DE do a good job. PSO is slightly better at Solution Quality (92%), but it is worse at Robustness and Scalability. SA has the worst results across all measures, especially in Robustness (85%), which means it is less stable than the others.

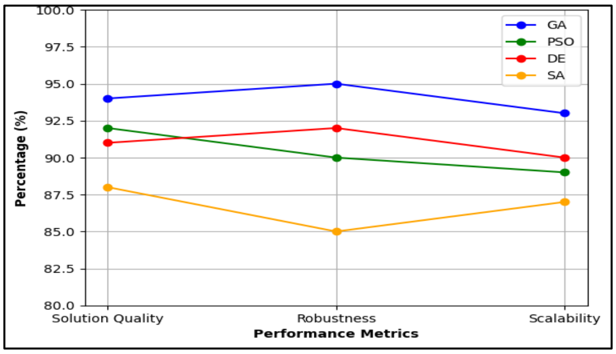

Figure 4: Representation of different performance metrics of GA vs. Other Algorithm

The figure (4) illustrates the performance of four optimization algorithms Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and Simulated Annealing (SA) across three metrics: Solution Quality, Robustness, and Scalability. GA consistently outperforms the others, with the highest scores in all three metrics, peaking at 95% in Robustness. PSO and DE show competitive performance, with PSO slightly ahead in Solution Quality (92%) but trailing in Robustness and Scalability. DE is more balanced, scoring 91% in Solution Quality and 92% in Robustness. Simulated Annealing (SA) lags behind, particularly in Robustness (85%) and Solution Quality (88%), indicating its relative inefficiency compared to the other algorithms. The graph highlights GA's overall superiority and SA's limitations in optimization tasks.

7. CONCLUSION

To understand and improve radio transmission systems, wave propagation models are essential. The Free Space Model, the Hata Model, and other models like them give us important information about how electromagnetic waves change as they move through different settings, affecting signal strength and range. A lot of what determines the choice of model is the specifics of the conversation setting, like whether it's in a city, an open space, or an indoor area. For example, the Free Space Model works best when there is a clear line of sight, but the Hata Model is more accurate in cities and suburbs because it considers barriers and natural factors. Both the pros and cons of each type are listed below. For instance, the Hata Model works well for dealing with the problems that come up in cities but might not work well in open or country places. The Rayleigh and Rician models, on the other hand, work well in places where multipath effects are strong. They help us learn more about how signals behave in these situations. More complex models, like the ITU-R models and Longley-Rice, can make more accurate guesses by adding more variables and natural factors. Even though modeling has come a long way, there are still problems, like being able to correctly predict how signals will behave in settings that change quickly and in a variety of weather conditions. These problems make it clear that models need to be constantly improved and checked against real-world data and field tests. In the future, wave transmission models will probably include machine learning and AI methods to make predictions more accurate and flexible. For building effective and dependable wireless communication systems, picking the right wave transmission model is very important. It makes sure that coverage is ideal, reduces crosstalk, and improves overall performance. This makes it possible for communication networks to be stronger and more useful. These models will keep changing as technology gets better, which will help wireless communication systems get better and find more uses in many areas.

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