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Modelling A 5 Km^2 rural area with deployment of IoT devices and user equipment

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Abstract

The growing presence of wireless communication in rural regions calls for the enhancement of network performance to provide stable connectivity to user equipment (UEs) and Internet of Things (IoT) devices. This study presents a simulation-based approach to modelling a 5 km^2 rural environment, evaluating key performance metrics such as antenna gain, path loss, and signal-to-noise ratio (SINR). Using the WINNER II radio propagation model and MATLAB simulation tools, the research simulates the spatial distribution of IoT devices and UEs, calculates received power levels, and determines the optimal placement of devices by selecting the top 50% of cells based on received power, gains, and SINR. The work also considers terrain features, atmospheric conditions, and user density for better predictive accuracy. The results provide valuable insights into rural wireless network optimization via enhanced coverage, interference minimization, and connectivity maximization for low-power IoT devices and mobile users. The results translate to better network planning and deployment strategies, facilitating efficient and cost-effective rural wireless communication systems

Keywords: Wireless Communication; Rural Area; IoT; UE; Radio Propagation; Path Loss; SINR; Antenna Gain; Modeling; and Simulation

1. Introduction

1.1. Cellular communication

Cellular communication, also known as mobile communication, refers to the use of wireless technology to transmit and receive data, voice, and multimedia over a network [1]. Cellular communication systems operate on the principle of cell division, where a geographical area is divided into small cells, each served by low-power radios [2]. This structure ensures efficient utilization of available radio channels and enables a high density of users to reuse radio frequencies at shorter distances [2].

Cellular communication systems can be classified into analogue communication systems, which existed in the first generation (1G), and digital communication systems, which exist in subsequent generations [3]. First-generation (1G) systems, such as the analogue AMPS (Advanced Mobile Phone Service) system, were the first commercial cellular systems and were primarily used for voice communication [3]. Second-generation (2G) systems, including Digital (D)-AMPS, GSM (Global System for Mobile Communications), General Packet Radio Service (GPRS), and CDMA (Code Division Multiple Access), introduced digital communication and added support for data services such as text messaging and internet access [3].

Cellular communication systems have evolved to the third generation (3G), fourth generation (4G), and fifth generation (5G) [3]. Third-generation (3G) systems, such as UMTS (Universal Mobile Telecommunications System) and CDMA2000, introduced high-speed data services, improved voice quality, and robust coverage [3] [4] [5]. Fourth-generation (4G)

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systems, including LTE (Long-Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access), provide high-mobility communication, improved signal quality, and enhanced spectral efficiency [6]. As of 2025, fifth-generation (5G) systems are considered the latest in cellular communication, while research and development for the sixth-generation (6G) remain ongoing [7]. 5G offers Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC) [8].

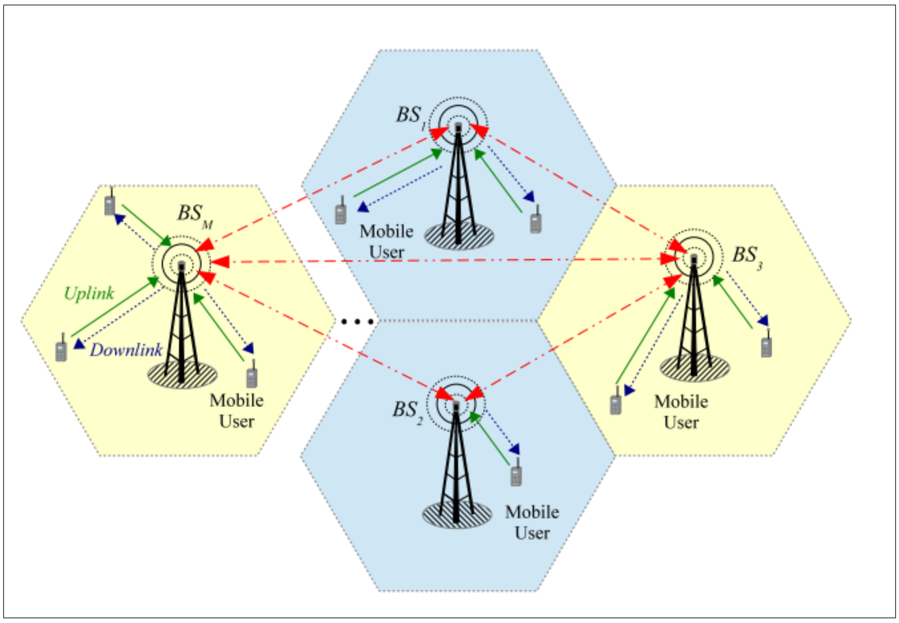

Figure 1 A Typical Mobile Cellular Communication System [9]

1.2. Modeling and simulation

A system is an integrated compilation of hardware, software, or a combination of both, operating to achieve a common goal [10]. A model represents the key characteristics of a system, providing a simplified abstraction of its functionality. Just as scientists and engineers conduct experiments on real-world systems, simulation replicates the behaviour of real-world entities using models [10].

Modeling and simulation are employed to conduct experiments for decision support, system analysis, education, and experience development under controlled conditions [11].

1.3. Rural area modelling

Rural area modelling of wireless communications is the procedure in which mathematical and simulation techniques are applied in the prediction and simulation of the performance of networks in rural environments. Rural environments are characterized by low population density, open spaces, and mixed terrain that affects signal propagation. Some of the key factors that must be taken into consideration when modelling wireless communications in rural environments include terrain, user density and distribution, and infrastructure availability. Also, atmospheric events like atmospheric attenuation and precipitation must be taken into account.

Modelling wireless communication systems in rural areas plays a critical role in network planning by enabling engineers and researchers to predict coverage and capacity, assess system performance in challenging conditions, and optimize network parameters using simulations, mathematical models, machine learning, and optimization algorithms. The insights gained help to identify potential challenges and opportunities, allowing design and deployment choices to be made in an informed way to foster efficiency at minimum cost and time. Frequency selection, modulation schemes, and antenna configurations might be key design factors for realizing optimum network performance.

2. Scope

The research focuses on modelling a rural area with a coverage area of 5 km^2, including the deployment of IoT devices and user equipment (UEs). The objective is to simulate the layout of UEs and IoT devices on a 5 km^2 surface, calculate antenna gain based on the X and Y coordinates of the simulation, determine the path loss between the base station and connected devices, evaluate the signal-to-noise ratio (SINR) of UEs and IoT devices, and generate a layout that selects the top 50% of cells and device locations based on received power, gains, and SINR. This analysis is essential for predicting the performance of the wireless communication system in rural areas and identifying potential challenges and opportunities.

IoT devices are becoming increasingly prevalent in rural areas, requiring low-power, low-cost, and low-data-rate wireless communication systems [12]. These devices typically generate small amounts of data but must maintain constant connectivity [13]. In contrast, UEs are mobile devices used to access various services in cellular networks, including 2G, 3G, 4G, and 5G systems [14]. While high-speed and reliable communication is essential for UEs, bandwidth requirements in rural areas are generally lower than in urban and semi-urban environments [14].

Several factors influencing the performance of wireless communication in rural areas will be considered, including terrain characteristics, user density, and distribution. Atmospheric effects, such as rain and atmospheric attenuation, will also be accounted for, which can be incorporated into a path loss equation.

To address these challenges, mathematical and simulation tools will be utilized to predict and analyze wireless communication system performance in rural environments. These tools will allow measurement of the upper 50% of cells and best device locations, giving the information required to make informed network architecture and deployment decisions.

3. Design and methodology

The approach to modeling rural environments is to utilize a range of data sources and analysis techniques to comprehend and forecast spatial and temporal trends in rural settings. This process may include the use of satellite imagery, demographic data, and socioeconomic indicators to model population dynamics and land use changes.

This section outlines the techniques used to model the system scenario and evaluate the performance of the proposed schemes. The performance metrics considered in the evaluation are also explained. The approach adopted in this study involves the use of MATLAB (Matrix Laboratory) simulation tools and the WINNER II radio propagation model.

3.1. Radio propagation model

Radio propagation involves the use of electromagnetic radiation to transfer energy from a transmitter to a receiver at radio frequencies [15]. A radio wave propagation model is an empirical mathematical model of the path of radio waves in the environment, considering frequency, distance, obstructions, and weather [15]. These models are very important in estimating signal strength, path loss, and coverage area in wireless communication systems [15].

Several widely used radio propagation models include WINNER II channel models, Free Space, Okumura-Hata, COST231, Ericsson, Egli, ECC-33, SUI, Lee, Macro, COST-231-Walfisch-Ikegami, and Dual-Slope models [16] [17]. This research employs the WINNER II channel model, which includes a propagation scenario for rural macro cells (D1), making it well-suited for the study's objectives [17].

3.2. Simulation software

The application of simulation tools for rural area modelling offers deep understanding of the complex interaction between anthropogenic and natural systems. The tools enable the development of virtual models of rural landscapes, hence the possibility to examine various land use alternatives and their likely effects on the environment and local populations. Commonly used simulation software for network modelling includes GNS3 (Graphical Network Simulator 3), OMNeT++, OPNET, and MATLAB [18] [19].

GNS3 is an open-source simulation software used to develop various types of computer network models, including complex and realistic network topologies [19]. OPNET, commercial simulation software, is specifically designed for network modelling and simulation, with a focus on evaluating the performance of wired and wireless communication systems [19]. MATLAB is a multi-paradigm programming language that supports numerical computing for various purposes including network modelling through its extensive toolboxes and libraries [20].

For the sake of this study, MATLAB was preferred to GNS3 and OPNET due to its user-friendly interface, advanced programming features, as well as a broad range of toolboxes and libraries with network modeling details. Besides, MATLAB enables better simulation result analysis and presentation [20]. Its large user and developer community provides extensive resources and tutorials, making it easier to learn and utilize effectively.

MATLAB's high-level programming environment simplifies the development and debugging of simulation models while offering a wide range of libraries to model different types of communication systems, including wireless, wired, and optical networks [20].

The WINNER II D1 channel model is a widely used radio propagation model that describes path loss in rural areas under both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. In this study, the NLOS scenario was considered, as some users may access the network from buildings that obstruct direct visibility to the base station. The WINNER II model accounts for key factors such as the distance between the base station and devices, antenna height, and signal frequency.

Although the WINNER II model is widely applied in rural area studies, it is based on specific assumptions and idealized conditions that may not fully capture real-world complexities. The model offers useful information on the performance of wireless communication systems in rural environments, it is still not a substitute for field measurements or real-world testing.

4. Layout of base station and mobile stations

The distribution of base stations and mobile stations in rural area modeling has an important influence on the coverage and capacity of wireless communication networks. Base stations serve as the fixed infrastructure providing wireless coverage to specific geographic areas. These include cell towers, typically located on elevated points such as hills or rooftops, and microcell sites, which are smaller and designed for denser areas. However, in rural environments characterized by low population density and vast landscapes, base stations are spaced farther apart and often placed on tall structures to maximize coverage.

Rural areas generally have an average population density of up to 400 people per square kilometre [30]. For a 5 km^2 area, this equates to approximately 2,000 people (i.e., 5 × 400). In this study, it is assumed that 80% of the population owns user equipment (UE) and 50% utilizes IoT devices. Consequently, the model considers 1,600 UEs and 1,000 IoT devices within the area. Additionally, a typical base station in rural areas covers approximately 26 km^2, meaning a single base station is sufficient for modelling a 5 km^2 rural region [21]. The figure 2 below illustrates the simulated layout of user equipment, IoT devices, and the base station using MATLAB.

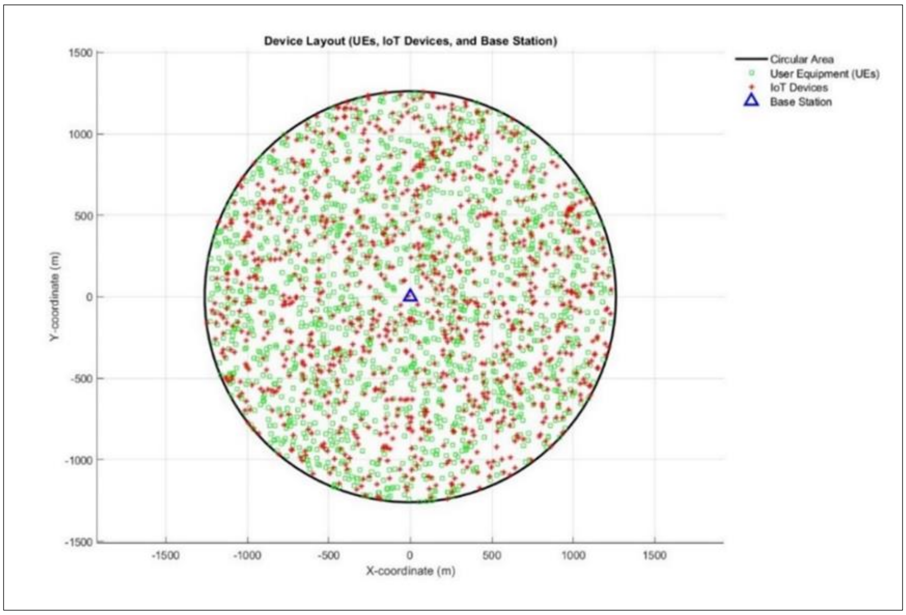

Figure 2 Layout of the User Equipment, Base Station and the IoT devices

5. Antenna gain

Antenna gain is a measure of how effectively an antenna converts input power into radiated power in a specific direction [22]. It is typically expressed in decibels (dB) and represents the ratio of radiated power in a given direction to the input power [23]. A higher antenna gain indicates a stronger concentration of radiated power, resulting in improved signal strength and a larger coverage area [23].

In this study, devices are scattered across predefined x and y coordinates within the simulation environment. The distance between the base station antenna and each device is calculated using the Euclidean distance formula, given by: $d = \sqrt{x^2 + y^2}$

The angle between the antenna's main axis and each device is determined using the arctangent function, given by $\theta = \arctan(\frac{y}{x})$

Gain Calculation: The antenna gain is calculated based on the antenna's radiation pattern using the following equation:

$$G(\theta) = Gmax - \min(12.\sqrt{\frac{|\theta|}{70^0}}, 20)$$

$$Gmax = 10\log_{10} 10(\frac{4\pi A_e}{\lambda^2})$$

$$A_e = \eta\pi\left(\frac{D}{2}\right)^2$$

Taking an assumption that Antenna diameter (D) = 1 meter, Efficiency (η) = 0.6, and Frequency (f) = 6 GHz (from winner II model)

$$A_e = 0.6 * \pi\left(\frac{1}{2}\right)^2$$

$$A_e = 0.6 * \pi * 0.25$$

$$A_e = 0.471\, m^2$$

$$\lambda = \frac{c}{f}$$

Where

$$c{:}\, speed\ of\ light = 3 * \frac{10^8 m}{s}$$

$$f{:}\, carrier\ frequency\ for\ WINNER\ II\ D1\ model = 6 * 10^9 Hz$$

$$\lambda = \frac{3 * 10^8}{6 * 10^9}$$

$$\lambda = 0.05\, m$$

$$Gmax = 10\log_{10} 10(\frac{4\pi A_e}{\lambda^2})$$

$$Gmax = 10\log_{10} 10(\frac{4 * \pi * 0.471}{0.05^2})$$

$$Gmax = 10\log_{10} 10(2368)$$

$$Gmax = 10 * 3.374$$

$$Gmax = 33.74\ dB$$

$$G(\theta) = Gmax - \min(12.\sqrt{\frac{|\theta|}{70^0}}, 20)$$

There is a specific reason for every constant in the equation when calculating the radiation pattern of the antenna. The number 12 is applied as a scaling factor that defines how the gain falls off with an increase in the angle (θ). A large number such as 12 corresponds to an abrupt decrease in gain, while a smaller number would lead to a gradual decrease. The constant 70° acts as a normalizing factor that dictates the angle at which the gain reduction starts to become significant. Specifically, the term $\sqrt{\frac{|\theta|}{70^0}}$ ensures that the reduction begins gradually and increases as (θ) increases. If a smaller value were chosen instead of 70°, the gain reduction would commence at smaller angles, whereas a larger value would delay the reduction.

The term 20 dB represents the maximum allowable reduction in gain. Regardless of how large (θ) becomes, the function min (·,20) ensures that the gain reduction never exceeds 20 dB. This constraint prevents excessive attenuation at larger angles, maintaining a reasonable level of signal strength.

To ensure accurate computation, the modulus of the angle (θ) was used to eliminate imaginary values, and (θ) was also converted from degrees to radians within the simulation. A MATLAB function was implemented to compute the antenna gain using the antenna gain formula along with the x and y coordinates of user equipment (UEs) and IoT devices. The above calculation is an important aspect of the simulation model as it maintains an accurate depiction of signal propagation in rural areas.

In real life, the antenna gain is affected by a large number of parameters, ranging from the antenna type and size to the frequency of the transmitted signal and the local environmental conditions. A bigger antenna, a higher frequency signal, or using a more directional antenna can boost the gain, resulting in higher signal strength and coverage area. As an important parameter of wireless communication systems, antenna gain significantly influences network performance by directly impacting signal propagation and reception quality. While simulation results offer valuable insights into how a wireless communication system performs in rural areas, they do not replace real-world testing or field measurements. Environmental conditions, unforeseen obstacles, and interference can impact actual performance in ways that simulations may not fully capture. The distribution of the antenna gains was simulated as shown in figures 3 and 4 below, based on the antenna gain calculations for both UEs and IoT devices.

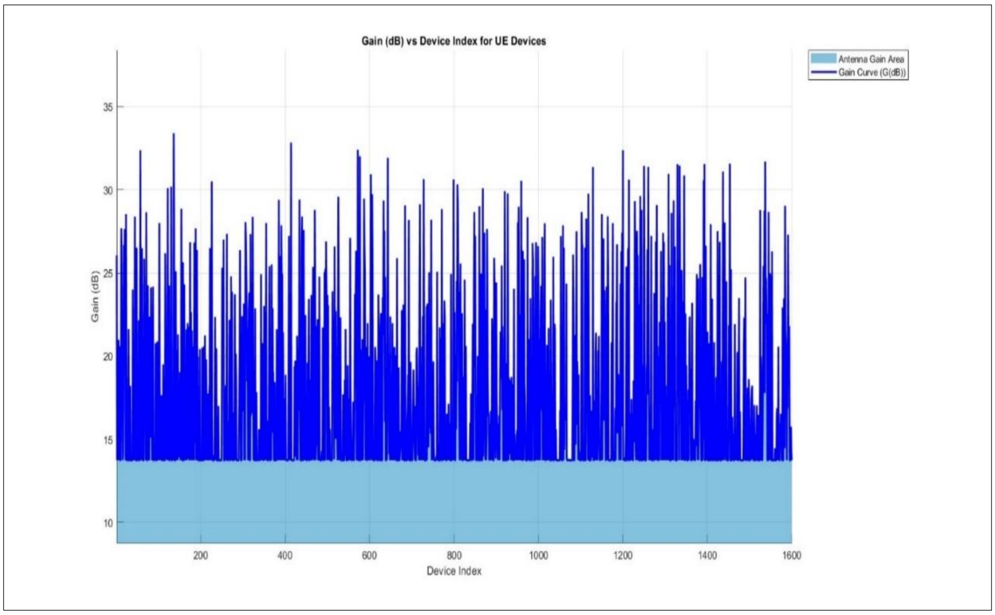

Figure 3 Distribution of Antenna Gains for the UEs

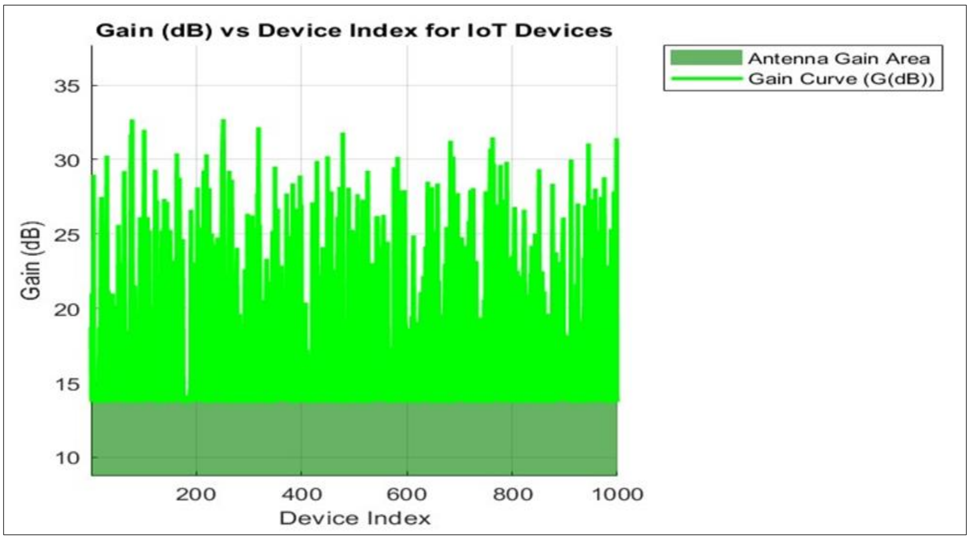

Figure 4 Distribution of Antenna Gains for the IoT Devices

6. Path Loss and Shadow Fading

Path loss refers to the decrease in power density of a signal as it propagates through space [24]. One of the key contributors to total loss is shadowing, also known as shadow fading, which occurs due to obstacles between the transmitter and receiver. These obstacles cause signal attenuation through absorption, reflection, scattering, and diffraction, leading to variations in received signal strength [25] [26].

In this research, the Winner II model was utilized to simulate the path loss between the base station and user equipment (UEs) as well as IoT devices. According to the WINNER II D1 model, shadow fading for NLOS conditions has a fixed value of 8 dB [17].

The Winner II D1 model for NLOS expresses path loss as a function of multiple parameters, including the distance between the base station and devices, the height of both the base station and mobile stations, and the carrier frequency as in the formula below:

$$P_L = 25.1\log_{10}(d) + 55.4 - 0.13(h_{BS} - 25)\log_{10}\left(\frac{d}{100}\right) - 0.9(h_{MS} - 1.5) + 21.3\log_{10}(f_c/5.0)$$

Where;

$$P_L = Pathloss, d = Euclidean\ distance, h_{BS}; base\ station\ height\ = 32\ m\ , h_{MS}; mobile\ station\ height = 1.5\ m, f_c = 6\ GHz$$

Path loss and shadowing loss are critical factors that influence the performance of wireless communication systems, directly impacting signal strength and network coverage. The total signal degradation is determined by the combined effect of path loss and shadow fading. The total loss (path loss + shadowing) was plotted against Euclidean distance as shown in figures 5 and 6 below, based on the total loss calculations for both UEs and IoT devices.

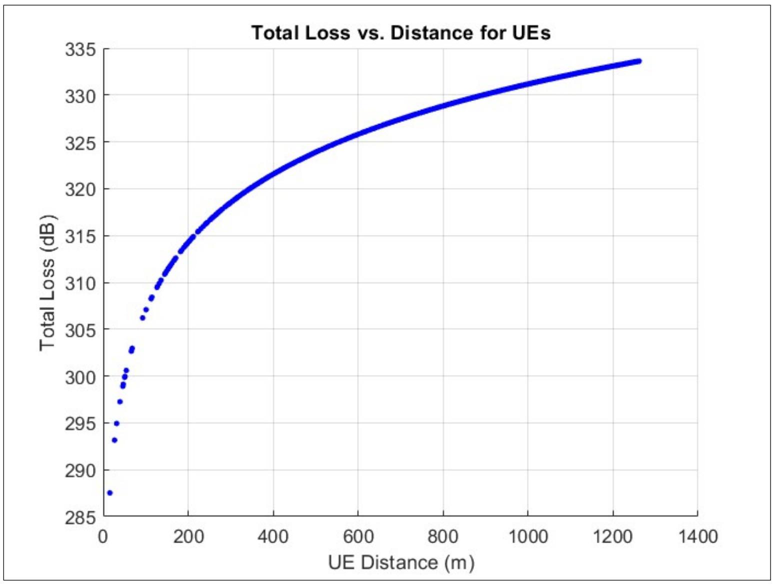

Figure 5 Total Loss (Path Loss + Shadowing Loss) Plot for the UEs

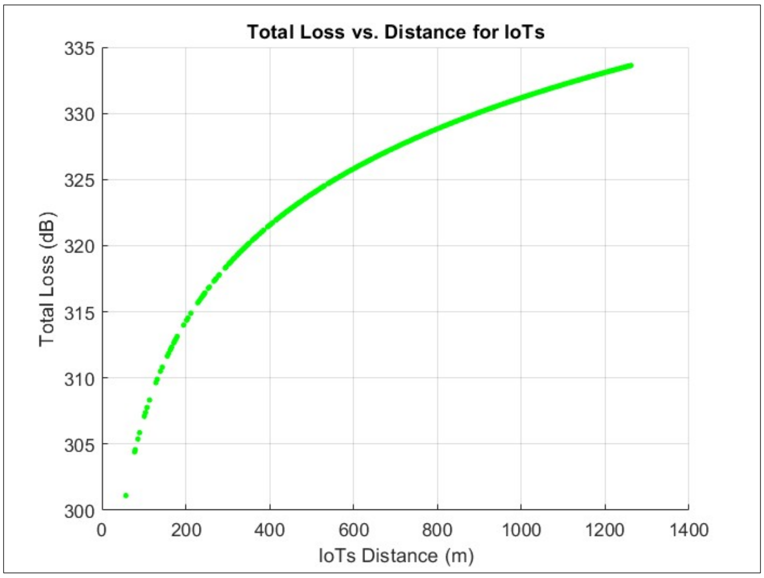

Figure 6 Total Loss (Path Loss + Shadowing Loss) Plot for the IoT Devices

7. Signal-to-interference-plus-noise ratio (SINR)

The SINR for the devices was calculated in the MATLAB program. SINR is a measure of wireless signal quality, representing the ratio of the power of the desired signal to the sum of interference and noise power [27]. A higher SINR value indicates better signal quality and a higher data rate. The received power for each device was calculated using the following formula [28]:

$$P_r(dBm) = P_t(dBm) + \sum dBGains - \sum dB\,Total\ Loss$$

Where $P_r = received\ power\ and\ P_t = transmit\ power$

The transmit power for a macro cell base station is 43 dBm, so P_t was set to 43 dBm [29]. The interference power was determined by summing the received power of all other devices, while the noise power was calculated as the product of the noise figure and the thermal noise power.

$$N = K * T * B$$

Where:
k: Boltzmann constant $\left(1.38 \times 10^{-23} \frac{J}{K}\right)$
T: Temperature in Kelvin (typically 290 K for standard environments).
B: Bandwidth (in Hz); 100 MHz for WINNER II D1 model [17].

The SINR was then calculated as the ratio of the received power to the sum of the interference power and the noise power in dB; $NR = \frac{P_r}{I+N}$.

In the MATLAB simulation, the path loss, received power, interference power, and noise power for all devices were obtained from the required calculations. After computation of these parameters, SINR for every device was computed by dividing the received power by the interference plus noise power. This provides an estimate of the signal quality, which is of utmost importance in ensuring best performance in a wireless communication system. The received power was plotted against total loss (path loss + shadowing), and SINR against received power as shown in figures 7, 8, 9, and 10 below, based on the total loss, SINR, and received power calculations for both UEs and IoT devices.

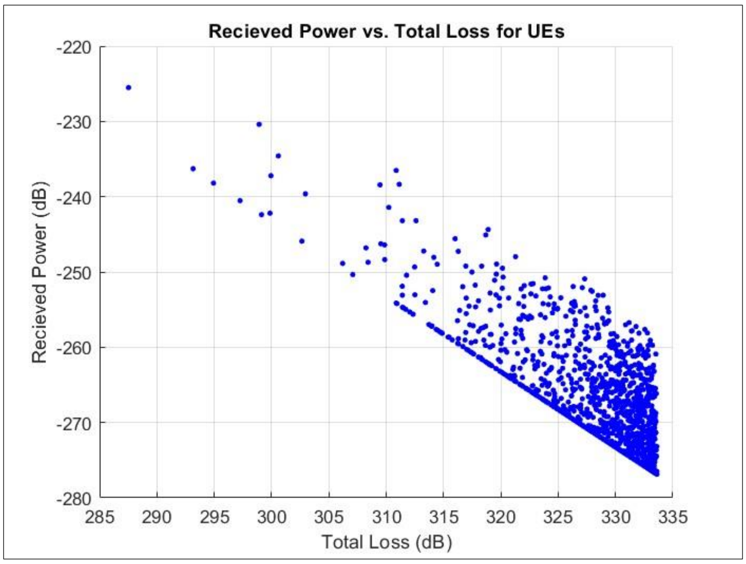

Figure 7 Received Power Plot in respect to Total Loss (Path Loss + Shadowing Loss) for the UEs

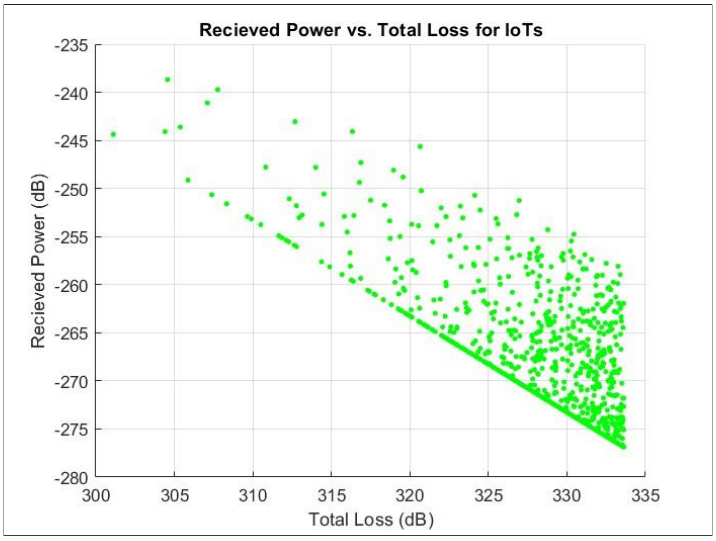

Figure 8 Received Power Plot in respect to Total Loss (Path Loss + Shadowing Loss) for the IoT Devices

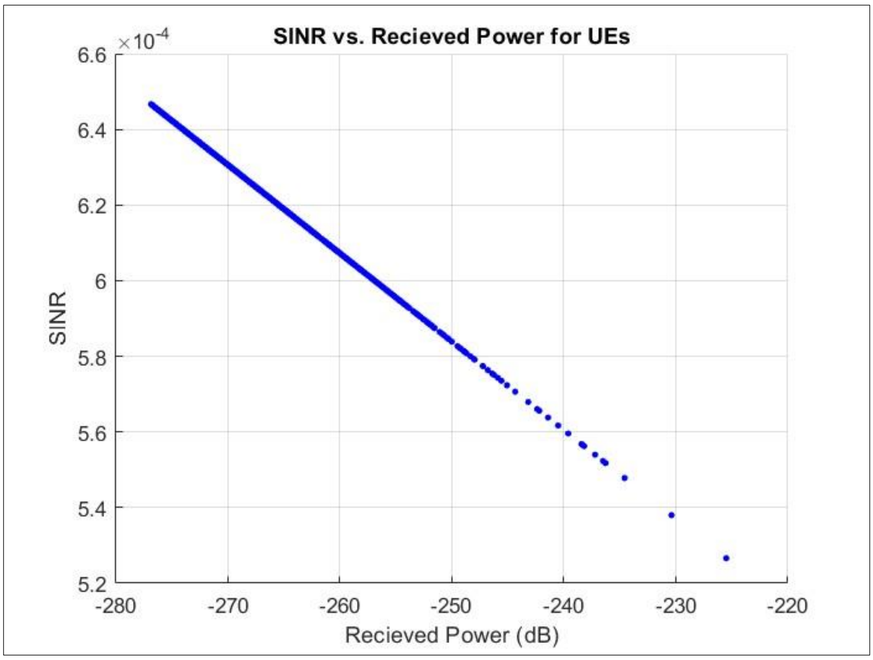

Figure 9 SINR Plot in respect to Received Power for the UEs

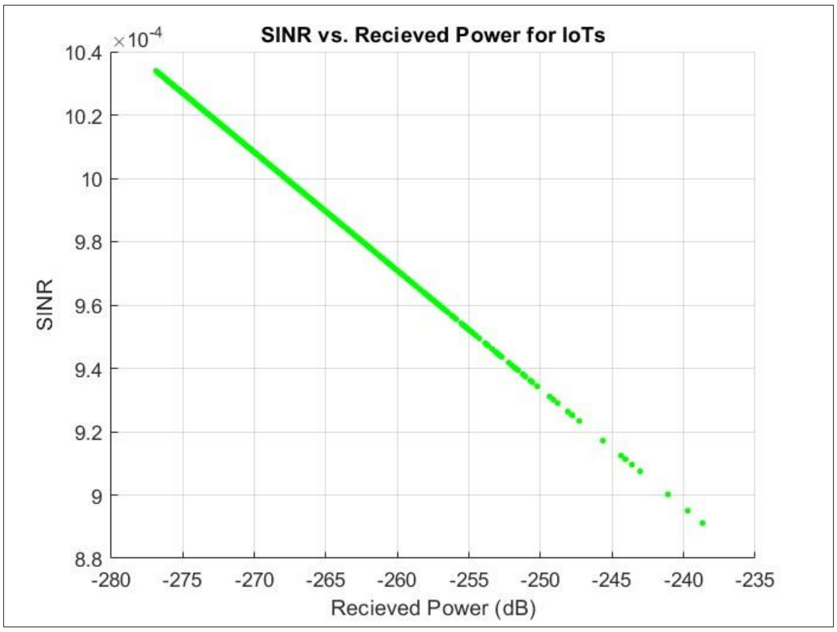

Figure 10 SINR Plot in respect to Received Power for the IoT Devices

8. Cell selection

Cell selection was determined based on received power, antenna gain, and SINR. The simulation was able to identify the optimal cells by selecting the 50% top UEs and IoT devices based on the received power, antenna gains, and maximum SINR values as shown in figures 11 and 12 below. This was for efficient communication as well as for an enhancement in the network.

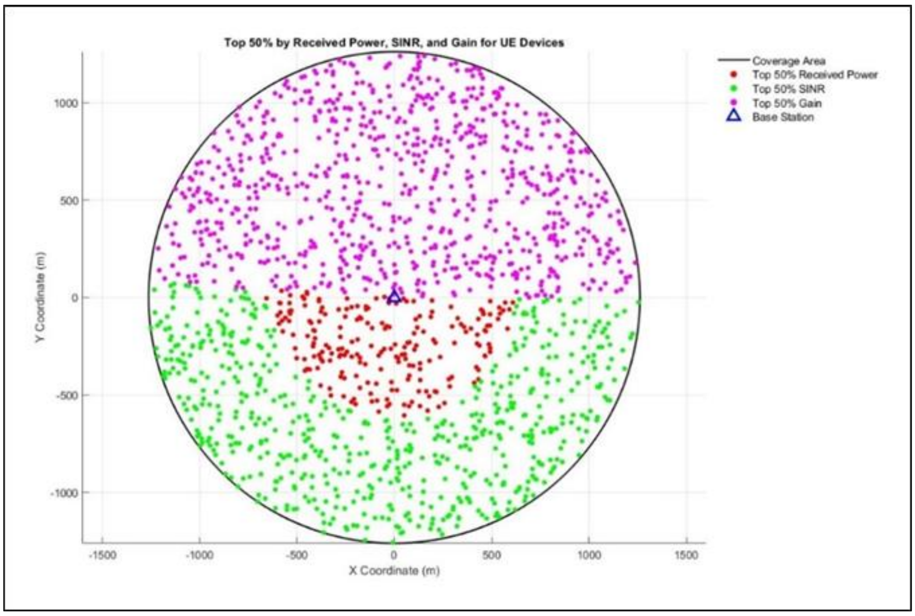

Figure 11 Top 50% Cell Selected Based on Received Power, SINR, and Antenna Gains for UEs

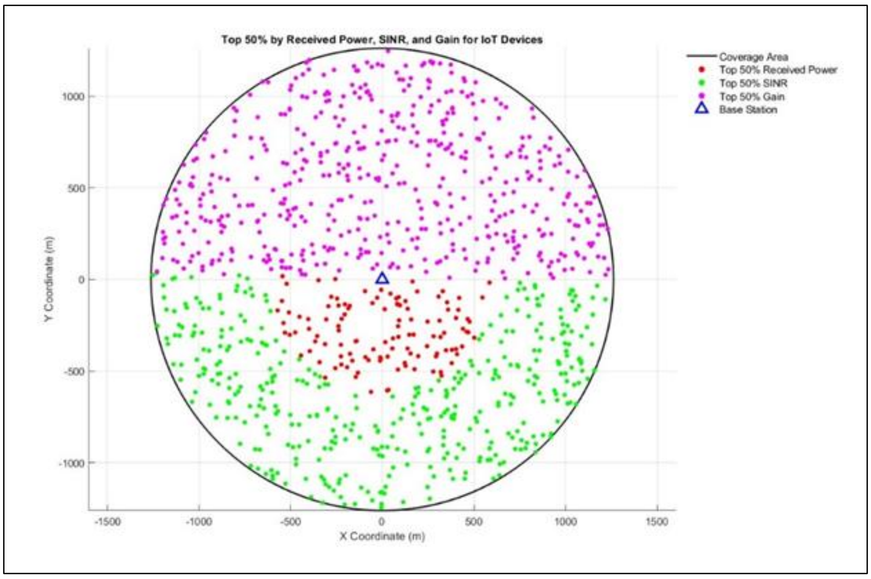

Figure 12 Top 50% Cell Selected Based on Received Power, SINR, and Antenna Gains for IoT Devices

9. Results

The simulation results indicate that for IoT devices, the minimum gain was 13.74 dB, the maximum gain was 32.71 dB, and the average gain was 17.37 dB. Regarding losses, the path loss for IoT devices ranged from a minimum of 289.17 dB to a maximum of 325.61 dB, with an average of 320.36 dB. The total losses had a minimum of 297.17 dB, a maximum of 333.61 dB, and an average of 328.36 dB. The received power for IoT devices varied between -276.87 dB and -232.49 dB, with an average of -267.73 dB. The signal-to-interference-plus-noise ratio (SINR) for IoT devices ranged from 0.000869 dB to 0.001035 dB, with an average of 0.001001 dB.

For user equipment (UE), the minimum gain was 13.74 dB, the maximum gain was 33.40 dB, and the average gain was 17.47 dB. The path loss ranged from 277.00 dB to 325.62 dB, with an average of 320.30 dB, while total losses had a minimum of 285.00 dB, a maximum of 333.62 dB, and an average of 328.30 dB. The received power for UE ranged from

-276.88 dB to -214.36 dB, with an average of -267.98 dB. The SINR for UE had a minimum of 0.000500 dB, a maximum of 0.000646 dB, and an average of 0.000625 dB.

These results are based on a simulation of a 5 km^2 rural area with a radius of 1.264 km, consisting of 1,600 UEs and 1,000 IoT devices.

10. Discussion

Analysis of the simulation results is key to realizing the performance of the base station, user equipment, and IoT devices in a rural area. The derived values for path loss, shadowing, and SINR are within expected ranges in such an environment, which validates the accuracy of the model. The antenna gains measurements for the user equipment, and IoT devices, which were calculated using the Winner II D1 model, are as anticipated, thus enhancing the model's validity. Furthermore, the carrier bandwidth of 100 MHz, as defined in the WINNER II D1 model, has been discovered to be appropriately aligned with the characteristics of this environment, improving effective spectrum utilization.

Cell selection plays a crucial role in ensuring optimal communication performance for each device. The simulation results indicate that received power and gain values are strongly influenced by the antenna aperture, wavelength, path loss, and shadowing, all of which significantly impact cell selection. This highlights the importance of careful antenna design and strategic placement to maximize communication efficiency and network performance

11. Conclusion

This research presents a simulation of a wireless communication system in a rural environment, focusing on key performance metrics such as path loss, shadowing, and antenna gains. These parameters were used to compute the received power and the Signal to Interference plus Noise Ratio (SINR) for both User Equipment (UE) and Internet of Things (IoT) devices. Additionally, a cell selection process was implemented to identify optimal locations for UE and IoT devices, ensuring efficient communication.

The simulation results indicate that both received power and SINR values are within acceptable ranges conducive to effective wireless communication. However, it must be considered that the result of these findings is derived from particular assumptions and simulation parameters, which might not be readily applicable to a range of wireless communication situations. Future work could involve investigating the effect of changing parameters and employing other propagation models on system performance, thereby increasing the flexibility and precision of such simulations.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest to be disclosed.

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