Performance Analysis of Linear Cellular Networks on Highways

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Original scientific article

***Abstract*—This study demonstrates the importance of designing wireless networks along highways efficiently, taking into consideration the linear distribution of cells to improve performance and preserve communication quality in environments with linear structures. Therefore, this paper presents an analysis of the Signal-to-Interference Ratio (SIR) performance of linear cellular networks with rectangular shape in a highway environment. The log-distance and dual-slope propagation models are used to effectively characterize the path loss in microcells, providing an evaluation of network performance. The impact of user location, antenna height, antenna tilt, and propagation channel parameters is also considered when calculating the SIR for both rectangular and hexagonal cell systems. The simulation results demonstrate how these parameters directly affect the effectiveness of both networks; nonetheless, the linear station distribution suggests better performance than the hexagonal system since it reduces interference between neighboring cells and improves signal quality.**

***Index terms*—Interference Analysis, SIR, Propagation models, Linear system, Hexagonal system, Antenna tilt angle.**

I. Introduction

THE rapid advancement of technology and modern societies' dependence on wireless networks for daily communication necessitates the enhancement of network performance to guarantee the delivery of high-quality services [1],[2]. Cellular networks are the basis of modern wireless communications, and their efficiency is dependent on a particular engineering design that ensures broad coverage and optimal signal quality. Transmission station distribution is one aspect that has a direct impact on network performance. Traditionally, cellular networks use a hexagonal arrangement of cells, which is a standard design for efficient frequency reuse. However, some environments, such as highways, require a different method due to the linear pattern of user flow, making hexagonal distribution less efficient.

One of the most significant difficulties for wireless networks is interference. Transmissions from surrounding stations on the same frequency can damage the quality of the received signal and reduce the SIR. The value of SIR is a key indication of wireless service quality, and its performance is determined by station distribution, frequency reuse, and signal propagation in the surrounding environment. The network must be designed to minimize interference and improve the SIR in order to guarantee successful and continuous communications [3],[4].

Many previous studies have examined the design of cellular networks utilizing hexagonal cell distribution, including enhancements in frequency reuse and the reduction of interference among neighboring stations. However, limited research has addressed the effects of employing a linear arrangement of transmitting stations, particularly in longitudinal settings like highways. In [5], the article presents the performance of cellular networks based on predictions of interference from neighboring cells. It introduces a mathematical model for co-channel interference analysis in hexagonal and linear cell configurations using a log-distance propagation model to examine the impact of the path loss exponent on the downlink signal quality. In addition, for both the linear and hexagonal systems, the single cell is shaped like a hexagon.

The primary aim of this study is to do a conceptual comparison between two simplified cellular distribution models: the linear model and the hexagonal model, inside a controlled environment that isolates the structural impact on both interference and performance

So, in this paper, the impact of using a linear approach for transmitting station distribution is examined instead of the conventional hexagonal distribution, where the single-cell configuration for the linear system in this study is designated as a rectangular cell, contrasting with that in [5].

The contributions of this paper are listed as follows:

- This study employs a wireless cellular system utilizing rectangular cells along roads , as opposed to traditional hexagonal cells, to enhance signal quality and network performance. In addition, the distance between the user and the base stations and between the user and the right and left co-channel cells are calculated using the distance calculus equation with the user's actual coordinates (x, y), which differs from that used in [5].
- The performance of the linear cellular system with rectangular shape and the hexagonal cell system is assessed by analyzing the SIR for both systems using various wireless propagation models, such as log-distance and dual-slope, which demonstrate signal propagation characteristics in different environments.

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- The effect of the transmitter antenna tilt angle on the SIR value is also introduced in this paper, where the SIR equations in terms of tilt angle for both rectangular and hexagonal systems are analyzed.
- The impact of several factors on the SIR value for a linear system, including user distance from the station, cluster size, attenuation coefficient, antenna height for both transmission and reception, and antenna tilt angle, is evaluated and compared with the SIR value for hexagonal systems.

The rest of this article is structured as follows: Section II introduces the related works. Section III presents the system model. Section IV outlines the formulation for co-channel interference, which utilizes two distinct propagation models. Section V presents the effect of tilt angle. The paper ends with the outcomes of simulations and comparisons and the conclusions introduced in Sections VI and VII, respectively.

II. Related Works

Numerous facets of the subject that analyze the effects of path loss, tilt angle, cell configuration, and propagation model on SIR of cellular systems have been extensively studied in earlier studies.

In [6], the analysis of channel interference across communication systems in intelligent transportation contexts utilizing modern communication technology is conducted. The impact of frequency and path loss models on spectral efficiency over six frequency bands ranging from 2.6 GHz to 73 GHz, utilizing one- and two-slope path loss models, is examined in [7]. In contrast, [8] investigated path loss modeling in rural fixed wireless networks, where data classification, radio link distance splitting, antenna height, topography integration, and seasonal fluctuations consideration were all improved by a log-distance path loss model. Additionally, environmental data from the sender and receiver, employing machine learning models including artificial neural networks, support vector regression, random forest, and gradient tree boosting to predict path loss between the vehicle and infrastructure, is utilized in [9].

A more recent study introduced a 3GPP path loss model, specifically the multi-slope model for linear and non-linear scenarios, to increase 5G coverage and efficiency as in [10]. Moreover, a study in [5] provided a cellular network performance metrics derived from estimations of interference from adjacent cells. A mathematical model for co-channel interference is analyzed in hexagonal and linear cell configurations and uses a log-distance propagation model to investigate the influence of path loss exponent values on downlink signal quality.

Research in [11] demonstrated a path loss in vehicular-based networks (VANETs) through a field measurement campaign at 700 MHz and 5.9 GHz in realistic traffic environments. A two-slope path loss model was used to study the effect of traffic density on different environments (high-density urban, low-density urban, and suburban. Meanwhile, a study in [12] focused on the performance of 4G and 5G radio networks in field trials on highways. By simultaneously measuring important qualitative indicators, it sheds light on networks' behavior under fast travel conditions. Finally, the impact of the base station antenna tilt angle on LTE-Advanced channel performance in an intercellular interference scenario is investigated in [13].

III. System Model

In this section, an introduction to the hexagonal and linear systems model is provided.

A. Hexagonal System

A hexagonal cell structure is depicted in Fig. 1. In this structure, a central cell and co-channel cells in adjacent tiers are taken into account. From this figure, it can be shown that the first tier comprises six interfering cells $(Ti1, Ti2, \ldots, Ti6)$ situated at a fixed distance, D, starting from the center of the home cell. In comparison, the second tier contains twelve interfering cells positioned at a distance of $2D$ from the center of the home cell and a distance of $3D$ for the third tier [14],[15].

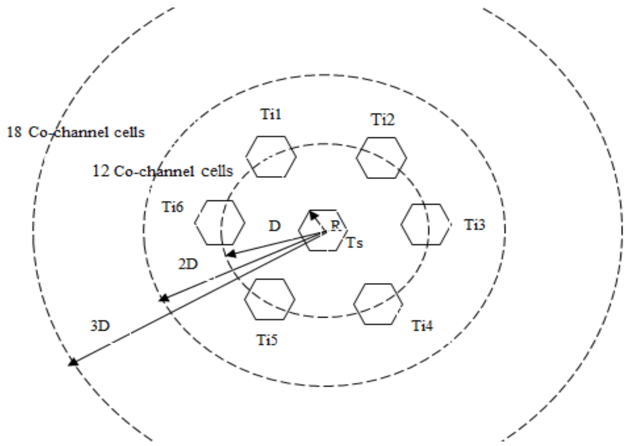


Fig.1. Interfering cells in a hexagonal arrangement [15].

B. Linear System with Rectangular Shape

In a highway environment, a linear system with rectangular shape is aligned with the straight-line path, as seen in Fig. 2, to reduce interference among cells and enhance frequency utilization. This system consists of connected segments (cells), each designed to be rectangular in shape, with a length of L and a width of W. It is important to note that the distance between the base stations is W, and the distance, D_L, between the centered cell A and any co-channel cell centers in the first tier is equal to $2W$ for a cluster size $N = 2$, as shown in Fig. 2(a) and equal to $3W$ for $N = 3$ as Fig. 2(b), and $4W$ for $N = 4$, etc.

III. Formulation for Co-Channel Interference

The value for the SIR is used to calculate the quality of a radio frequency channel. A threshold value is set for the SIR coefficient; a value surpassing this threshold signifies that the mobile phone is within the service range of the base station in a specific cell, whereas a value below this threshold indicates that the handoff process should be carried out because the user is in the coverage area of another cell that surrounds the mobile's initial cell [3]. The formula for calculating the SIR ratio is stated as:

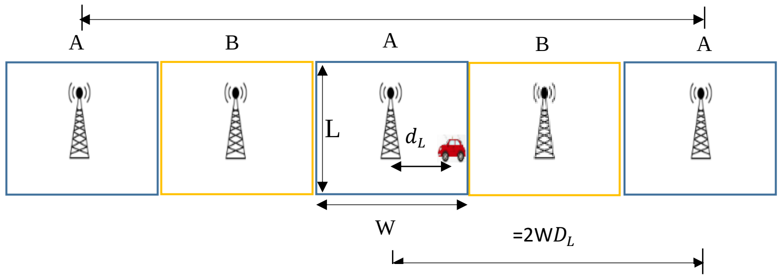
$$SIR = \frac{S}{I} = \frac{S}{\sum_{k=1}^{K} I_k} \tag{1}$$

where S represents the signal power received by the mobile element from its service base unit, while I denotes the interference strength from the *k-th* interfering cell, and K represents the number of cells positioned in the initial tier that disrupts the mobile unit within the home cell encircled by these K cells [3].

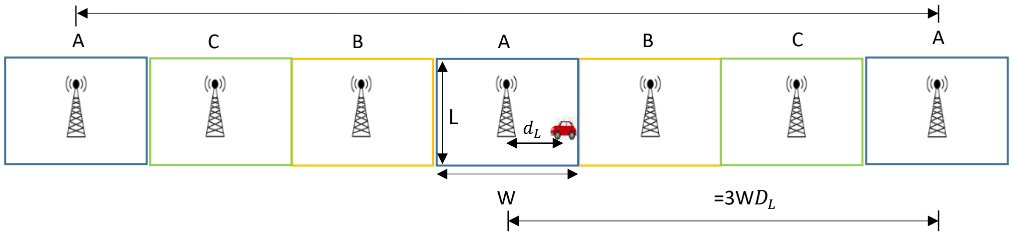
The selection of the propagation model has an important impact on the SIR computation, and this study examined the impact of two diffusion types of propagation models: the log-distance path loss model and the dual-slope model, which are described in the following subsections.

A. Log-Distance Path Loss Model

The distance-dependent propagation model is the log-distance model, in which the signal transmission is inversely proportional to the path loss propagation exponent. The received power S by the mobile unit, positioned at a distance d from the base service station, is directly proportional to the power emitted by the base unit p_t and inversely proportional to the distance d raised to power γ, d^{γ}, as in (2) [3]:



a. Cluster size $N = 2$.



b. Cluster size $N = 3$.

Fig. 2. The linear system with rectangular shape.

$$S \propto \frac{p_t}{d^{\gamma}} \tag{2}$$

where γ represents the path loss exponent.On the other side, the interfering cells around the home cell transmit interference power I, which is proportional to the transmitter's power and inversely proportional to D^{γ} as in:

$$I \propto \frac{p_t}{D^{\gamma}} \tag{3}$$

where D is the distance between the center original cell and the center of any co-channel cells at the first tier. Substituting (2) and (3) into (1) results:

$$SIR = \frac{\frac{p_t}{d^{\gamma}}}{\sum_{k=1}^{K} \frac{p_t}{(D_k)^{\gamma}}}$$

$$SIR = \frac{d^{-\gamma}}{\sum_{k=1}^{K} D_k^{-\gamma}} \tag{4}$$

In addition , Eq. 4 indicates that the value of SIR is dependent upon both d and D; thus, to compute these variables, the distribution system type must be established, namely whether it is hexagonal or linear.

The formulas for distance and SIR for both systems models under the effect of the log-distance path loss model are expressed in the following two subsections:

A.1 For Hexagonal System

In hexagonal cell arrangements,a simplified expressions are used to approximate the distances between interfering cells. This modeling choice improves mathematical tractability while retaining a reasonable level of accuracy. The distance D between the centers of the surrounding cells with the same frequency as the home cell is determined by the cell radius Rc and cluster size N as :

$$D = Rc\sqrt{3N} \tag{5}$$

Therefore, the SIR value can be determined using Eq. 6, assuming the user is placed at the cell's edge (i.e., $d = Rc$), as referenced in [5].This equation presents an approximate expression based on simplified inter-cell distance estimates.

$$SIR = \frac{R_C^{-\gamma}}{2(D-R_C)^{-\gamma} + 2(D+R_C)^{-\gamma} + 2(D)^{-\gamma}} \tag{6}$$

A.2 For Linear System with Rectangular Shape

In [5], the distance for the linear system is determined by the arrangement of base stations along the roadway, which is segmented into linear sections (microcells) of $2Rc$ in length. The distance D between the central cell and any co-channel cell centers in the first tier is $4Rc$ for a cluster size of 2, $6Rc$ for a cluster size of 3, $8Rc$ for a cluster size of 4, and continues accordingly. So, the SIR value was calculated in the first tier by:

$$SIR = \frac{d^{-\gamma}}{(4R_C - d)^{-\gamma} + (4R_C + d)^{-\gamma}} \tag{7}$$

Although the previous approach in [5] is effective for modelng uniform distribution on highways, it is based on a small set of user locations (e.g., 0.2, 0.4, 0.5, 0.7,1), resulting in a simplified representation of user distribution that does not reflect the fine-grained variety of the real environment; thus, the study in this paper takes a different strategy to achieve improved precision in establishing the user's location. In this case, the distance between the user and the base stations is calculated using the distance calculus equation with the user's actual coordinates *(x, y)*, as shown in Fig. 3, allowing for a more detailed assessment of the impact of environmental and traffic conditions on signal quality.

Suppose the home cell's base station is placed at the origin (0,0), nd the mobile unit moves in various directions around its serving base station while remaining inside its range. Therefore, the distance law should be applied when calculating the distance between a mobile user and its serving base station d_L as:

$$d_L = \sqrt{x^2 + y^2} \tag{8}$$

where x indicates the user's position on the x-coordinate and y represents the user's position on the y-coordinate. The limits of the x-coordinate are [-*w*: +*w*], and for the y-coordinate are [–*L:* +*L*].

To analyze how co-channel cell interference affects the mobile unit's performance, the distance D_L between the co-channel cells and the user must be determined. In a linear system with a cluster size of equal 2, the mobile unit in the home cell is affected by the two co-channel cells *K=2* at the first tier, and the distances between the user and the right and left co-channel cells are calculated as:

$$\overline{D_L} = \sqrt{(2w-x)^2 + (y)^2} \tag{9}$$

$$\overline{\overline{D_L}} = \sqrt{(-2w-x)^2 + (y)^2} \tag{10}$$

where $\overline{D_L}$ is the distance from the mobile unit to the co-channel cell located at the right side of the home base station at the coordinates (*2w, 0*), while $\overline{\overline{D_L}}$ signifies the distance from the mobile unit to the co-channel cell situated to the left side of the home base station at the coordinates (*-2w, 0*).

The value of SIR for this system is calculated by substituting (9) and (10) into (4), which yields:

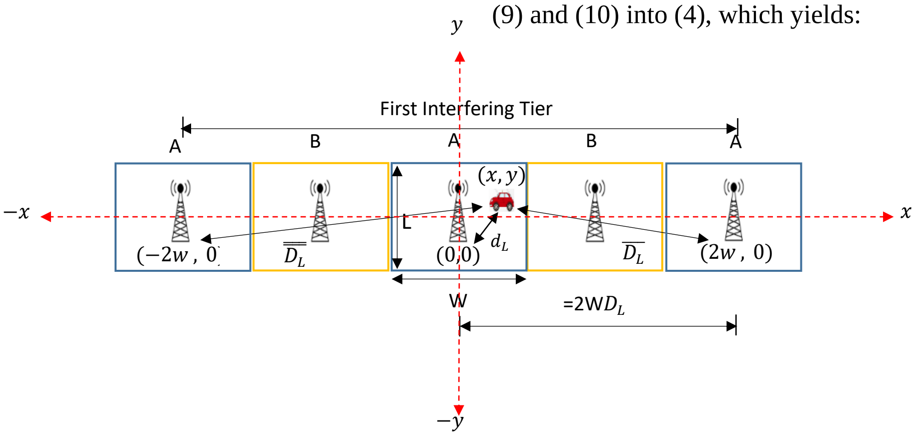


Fig. 3. Analysis of rectangular cells

$$SIR = \frac{(d_L)^{-\gamma}}{\left(\overline{D_L}\right)^{-\gamma} + \left(\overline{\overline{D_L}}\right)^{-\gamma}}$$

$$SIR = \frac{\left(\sqrt{x^2+y^2}\right)^{-\gamma}}{\left(\sqrt{(2w-x)^2+(y)^2}\right)^{-\gamma} + \left(\sqrt{(-2w-x)^2+(y)^2}\right)^{-\gamma}} \tag{11}$$

Generally, regardless of the value of N, the SIR equation is:

$$SIR = \frac{\left(\sqrt{x^2 + y^2}\right)^{-\gamma}}{\left(\sqrt{(Nw - x)^2 + (y)^2}\right)^{-\gamma} + \left(\sqrt{(-Nw - x)^2 + (y)^2}\right)^{-\gamma}} \quad (12)$$

B. Dual-slope Path Loss Model

In wireless communication systems, the average received power is impacted by physical processes such as reflection, diffraction, and scattering. Therefore, analytical models must be used to comprehend these effects fully. The dual-slop propagation model is one of the most straightforward models for examining how the reflected beam affects the received signal.

Despite its simplicity, it offers reasonable estimates, particularly in situations when the base station and the receiver are in direct line of sight or surroundings with high base stations. In this model, transmitted energy is conveyed to the receiver in two ways: directly, based on line of sight, and indirectly, by perfect reflection from a flat ground surface. The physical arrangement of this model is depicted in Fig. 4, where the base station's transmitting antenna radiates from a height h_b above a flat ground surface that perfectly reflects the signal [3],[16].

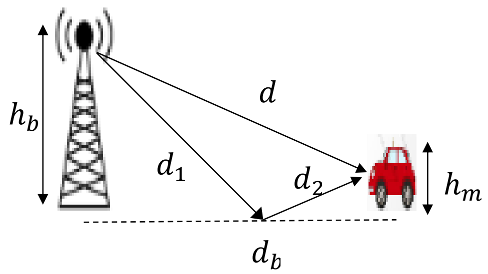


Fig. 4. Physical arrangement of dual-slop propagation.

Fig. 4 illustrates that the direct and reflected pathways create a geometric triangle, with the path difference dependent on the antenna heights and the horizontal distance separating the transmitter and receiver. The receiving antenna of the mobile unit is positioned at a height h_m above the ground surface, and at a distance d in the free space environment from the transmitting antenna. In this context, the indirect beam travels a distance *d1* before being reflected from the ground surface and then continues its travel through a distance *d2* to reach the receiving antenna [3]. The power received P_r by the user depends on the following equation:

$$P_r = kP_tP_l \quad (13)$$

where k is a constant that depends on the antenna gain and other factors that affect the signal transmission, P_t is the transmitted power, P_l represents the attenuation in the dual-slope model, which is usually used in evaluating the performance of macrocellular systems and can be determined by :

$$P_l = d^{-\gamma_1}\left(1 + \frac{d}{d_b}\right)^{-\gamma_2} \quad (14)$$

where γ_1 and γ_2 are path loss exponent values, $d_b$is the breakpoint distance at which a variation in the signal attenuation rate occurs due to the transition from one propagation system to another and is given by:

$$d_b = \frac{4h_bh_m}{\lambda} \quad (15)$$

where h_b, and h_m represent the heights of the base station and mobile user, respectively, and λ is the wavelength. Substituting (14) into (13) results in (16), which represents the power received by the mobile unit, regardless of whether it originates from the central cell or interference cells :

$$P_r = kd^{-\lambda_1}\left(1 + \frac{d}{d_b}\right)^{-\gamma_2} P_t \quad (16)$$

To determine the SIR value, (16) is substituted into (1), getting the following equation:

$$SIR = \frac{P_r(d)}{\sum_{k=1}^{K} P_{rk}(D)} \quad (17)$$

where $P_r(d)$ and $P_r(D)$ represent the power received by the mobile unit from the central cell and interference cells, respectively.

To compute the distances d and D, it is essential to identify the cell distribution system employed in the network, whether it is hexagonal or linear, as this distribution has a direct impact on how the calculation is performed. The following two subsections provide the distance and SIR formulas for both systems models under the influence of the dual-slope path loss model.

B.1 Hexagonal System

In a hexagonal system, the SIR value can be determined using (18), assuming that the user is placed at the cell's edge (i.e., $d = R_c$) and only the impact of the cells in the first tier is considered.This equation also employs a simplified model utilizing approximated distances between cells to depict the interference scenario.

$$SIR = \frac{P_r(R_c)}{2P_r(D - R_c) + 2P_r(D + R_c) + 2P_r(D)} \quad (18)$$

where $P_r(R_c)$ denotes the power received by the mobile unit from the central cell at $d = R_c$ which is given by:

$$P_r = kR_c^{-\gamma_1}\left(1+\frac{R_c}{d_b}\right)^{-\gamma_2} P_t \tag{19}$$

where $P_r(D-R_c)$, $P_r(D+R_c)$, and $P_r(D)$ represent the power received by the mobile user from the interfering cells situated at distances of $(D-R_c)$, $(D+R_c)$ and (D) meters away from the user, respectively, and can be computed as follows:

$$P_r(D-R_c) = k(D-R_c)^{-\gamma_1}\left(1+\frac{(D-R_c)}{d_b}\right)^{-\gamma_2} P_t \tag{20}$$

$$P_r(D+R_c) = k(D+R_c)^{-\gamma_1}\left(1+\frac{(D+R_c)}{d_b}\right)^{-\gamma_2} P_t \tag{21}$$

$$P_r(D) = k(D)^{-\gamma_1}\left(1+\frac{(D)}{d_b}\right)^{-\gamma_2} P_t \tag{22}$$

B.2 Linear System with Rectangular shape

In this system, the SIR value can be calculated in the first tier by:

$$SIR = \frac{P_r(d_L)}{P_r(\overline{D_L}) + P_r(\overline{\overline{D_L}})} \tag{23}$$

where $P_r(d_L)$ signifies the power received by the user from the central cell at a distance d_L and is expressed by :

$$P_r(d_L) = kd_L^{-\gamma_1}\left(1+\frac{d_L}{d_b}\right)^{-\gamma_2} P_t \tag{24}$$

where $P_r(\overline{D_L})$ and $P_r(\overline{\overline{D_L}})$ denote the power received by the mobile user from the interfering cells located at a distance of $(\overline{D_L})$ and $(\overline{\overline{D_L}})$, respectively, and can be determined by:

$$P_r(\overline{D_L}) = k(\overline{D_L})^{-\gamma_1}\left(1+\frac{(\overline{D_L})}{d_b}\right)^{-\gamma_2} P_t \tag{25}$$

$$P_r(\overline{\overline{D_L}}) = k(\overline{\overline{D_L}})^{-\gamma_1}\left(1+\frac{(\overline{\overline{D_L}})}{d_b}\right)^{-\gamma_2} P_t \tag{26}$$

The values of d_L, $\overline{D_L}$, and $\overline{\overline{D_L}}$ can be calculated using (8), (9), and (10), respectively.

IV. The Effect Of Antenna Tilt On The Calculation Of SIR

Antenna tilt is an important design consideration for wireless communication systems because it affects signal coverage and reduces cell interference. The tilt of the antenna can be adjusted to achieve maximum coverage, either mechanically by physically moving it or electronically by modifying its radiation properties. In order to improve the SIR, antenna tilt is essential since it can focus radiation on specific regions, minimizing interference and signal leakage to nearby cells [13],[17],[18]. Fig. 5 illustrates the analysis of the tilt angle.

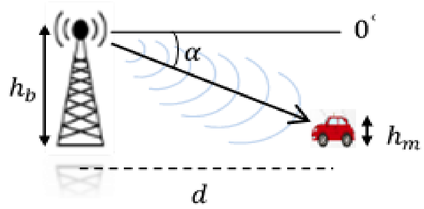


Fig. 5. Antenna Tilt Analysis.

The tilt angle is the angle created by tilting the antenna downward from the horizontal plane to the beam's center, and it can be determined by [13]:

$$\alpha = \tan^{-1}\frac{h_b - h_m}{d} \tag{27}$$

where α, h_b, and h_m are an antenna downtilt angle, base station high , and mobile high, repectively .

Therefore, it is possible to use the following formula in order to determine the distance d between the subscriber unit and the base station that it serves based on the value of the antenna tilt angle:

$$d = \frac{h_b - h_m}{\tan\alpha} \tag{28}$$

To determine the SIR value, (28) is substituted into (4), getting the following equation:

$$SIR = \frac{\left(\frac{h_b - h_m}{\tan\alpha}\right)^{-\gamma}}{\sum_{k=1}^{K} D_k^{-\gamma}} \tag{29}$$

While the method of calculating distances is based on the system used to distribute the cells, whether it is a hexagonal system or a linear system, the equation for calculating the SIR varies as follows:

In a hexagonal system, the SIR value based on the tilt angle can be determined by:

$$SIR = \frac{\left(\dfrac{h_b - h_m}{\tan\alpha}\right)^{-\gamma}}{2\left(D - R_C\right)^{-\gamma} + 2\left(D + R_C\right)^{-\gamma} + 2\left(D\right)^{-\gamma}} \tag{30}$$

This equation provides an approximate representation of inter-cell distances, enabling a simpler analysis of signal-to-interference behavior. While in a linear system, the equation of SIR is:

$$SIR = \frac{\left(\dfrac{h_b - h_m}{\tan\alpha}\right)^{-\gamma}}{2\left(\overline{D_L}\right)^{-\gamma} + \left(\overline{\overline{D_L}}\right)^{-\gamma}} \tag{31}$$

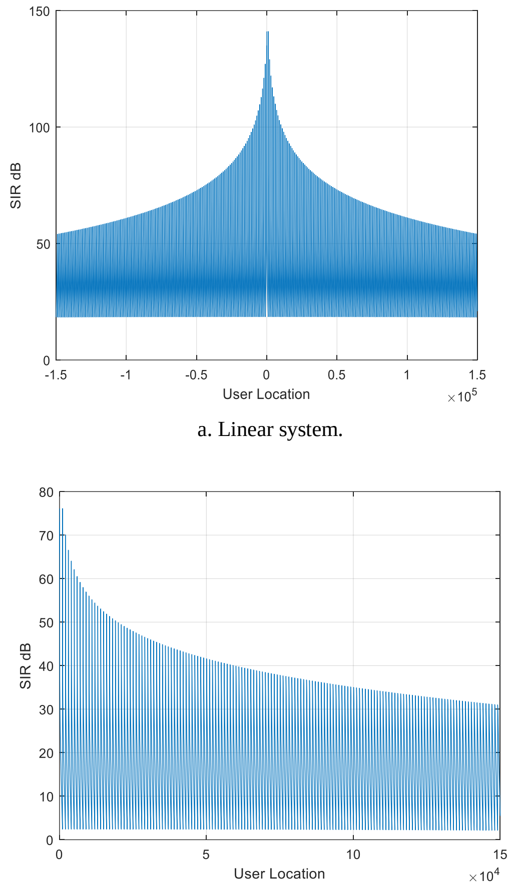
V. Numerical Results

This section assesses the SIR performances of rectangular cells and hexagonal cells in a highway scenario. To provide more insights into system performance, the log-distance, dual-slope propagation models, and the influence of antenna tilt are used to calculate the SIR value for both types of cells. The MATLAB software version (R2018a) was used to program the equations analyzed in this research using the following settings in order to compute the SIR values and compare the two distinct systems: in the linear system, the cell width w is set to be 2 km, with an x-coordinate range of [-1 km, 1 km], and the cell length L is set to be 300 m, with a y-coordinate range of [-150 m, 150 m]. To ensure that both designs have similar coverage areas, the hexagonal system, on the other hand, is modeled with a cell radius Rc of 1000 m. The simulation results for different situations are shown and examined in the following subsections.

A. The Effect of Log-Distance Propagation Model

This subsection presents the SIR performances for both systems under different parameters, such as the user's distance, cluster size, and path loss exponent value, illustrating the impact of the log-distance propagation model.The relationship between the SIR value and the user's distance from the base station at various locations inside the home cell for both linear and hexagonal systems is illustrated in Fig. 6. According to this figure, it can be observed that the SIR value for both systems decreases as the user moves away from the base station. This is because the base station broadcasts stronger signals toward nearby users, while signal strength decreases as distance increases. Furthermore, users who are farther away from their serving base station are more likely to be interfered with by nearby stations using the same frequency. It is noteworthy that the SIR value for rectangular cells surpasses that of hexagonal cells, with a maximum edge value of approximately 55 dB compared to around 32 dB for hexagonal cells.

The cluster size N is another important element determining the SIR performance for both systems, as seen in Fig. 7.



a. Linear system.

b. Hexagonal system.

Fig. 6. Effect of user location on SIR in log-distance model.

Different values for cluster sizes are considered in this paper to evaluate their effect on the system coverage and the signal quality, providing insights on improving cell configurations for improved performance. For both systems, it was noticed from this figure that increasing the cluster size improved the SIR value at the mobile unit; however, the linear system has the best SIR performance compared to the hexagonal system for the same value of N. For instance, the SIR for a linear system increased from 26.76 dB to about 32.26 dB when the cluster size N rose from 3 to 4 with the user positioned near the cell edge. Meanwhile, with the hexagonal configuration, the SIR increased from 8.03 to around 11.35 dB for N=3 and 4, respectively. This improvement for both systems, is due to the higher reuse distance in the system that has a larger cluster size, which minimizes the influence of interference with the surrounding cells.

Fig. 8 depicts the effect of the path loss exponent on the value of SIR for the two configurations. This figure shows that the values of SIR for both systems are growing vertically as the values of the path loss exponent are increased. In addition for the same value of γ, the SIR value is increased exponentially as the value of N increased. For example, the SIR value in a

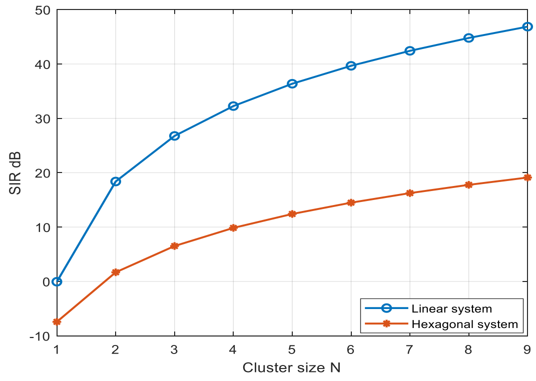
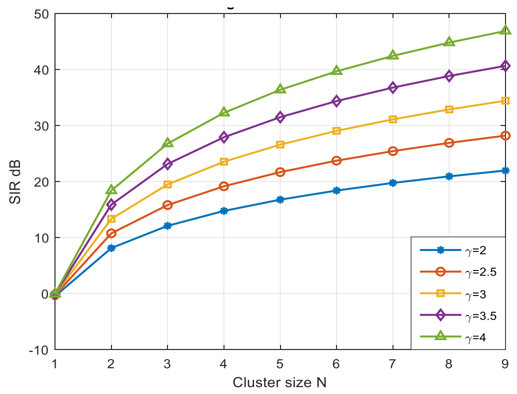
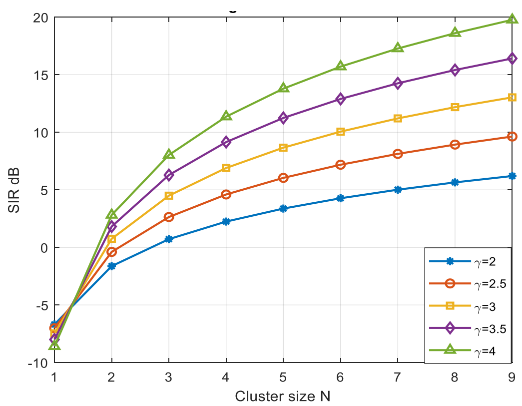


Fig. 7. Effect of Cluster Size on SIR in log-distance model.

linear system with cluster size $N=7$ was 20 dB at $\gamma=2$ and reached about 43.60 dB at $\gamma=4$, as shown in Fig. 8(a). On the other side, for the hexagonal system, the value of SIR was 5 dB at $\gamma=2$ and reached about 17.64 dB at $\gamma=4$, as seen in Fig. 8(b). The longitudinal distribution of users along the roadway and the increasing attenuation of competing signals lead to this outcome, which significantly lessens interference with signals from far-off stations.



a. Linear system



b. Hexagonal system.

Fig. 8. Effect of path loss exponent on SIR in log-distance model

According to the analysis of the SIR performance at different values of distance, cluster size N , and path loss exponent, it can be observed that the linear system outperforms the hexagonal system in all circumstances. This superiority is because the distribution of stations in the linear system follows a straightforward linear path, and this allocation decreases the number of nearby stations using the same frequency, minimizing interference and enhancing signal quality. In contrast, the hexagonal system has a geometric distribution of stations, which increases the number of surrounding stations, leading to increasing interference and weakening the signal.

B. The Effect of Dual-slope Propagation Model

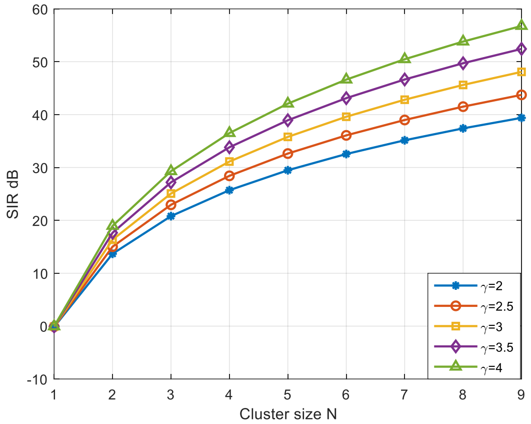
Under the impact of the dual-slope propagation model, the SIR performances for both systems are presented in this subsection under different parameters such as the path loss exponent value, the height of the base station's antenna, and the height of the receiver's antenna.

The effect of the path loss exponent value on the SIR performance for both systems under the impact of the dual-slope propagation model is seen in Fig. 9. Fig. 9(a) illustrates that for a linear system with $N=7$, the value of SIR is improved from 35.20 dB to 50.50 dB when the path loss exponent value γ changed from 2 to 4. On the other hand, for the same value of $N=7$, the SIR's value for the hexagonal system rose from 11.80 dB at $\gamma=2$ to about 18.55 dB at $\gamma=4$, as seen in Fig. 9(b). From this figure, it can also be observed that the SIR value for both linear and hexagonal systems at the effect of the dual-slop model is improved as the value of the path loss exponent increases, as was the case with the log-distance model. However, the results indicate that the linear system continues to outperform the hexagonal system, and this superiority is evident when applying the dual-slope model.

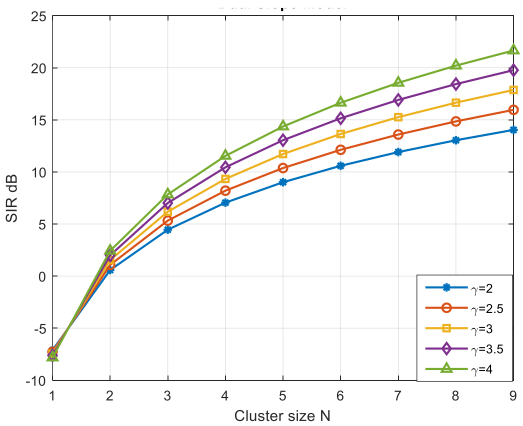
It is important to clarify that the dual-slope model performs better than the log-distance model. This is because it takes into consideration the difference in attenuation between places close to the station, where the signal is stronger, and places farther away, where barriers and distance weaken the signal. Because of this, the model is more appropriate in actual situations than simpler models like long distance.

Fig. 10 depicts the relationship between the SIR value and the height of the transmitting antenna, h_b i.e., the station's height. This figure demonstrates that the SIR value for both systems decreases as the height of the transmitting antenna increases. This reduction can be attributed to the influence of the transmitting antenna's height on signal distribution, where the higher the height, the broader the signals are disseminated, reducing energy concentration in the desired nearby area while increasing interference with signals from other stations operating at the same frequency. This effect is more evident in the hexagonal system since the number of neighboring stations causing interference is greater.

Fig. 11 shows the relationship between the height of the receiver antenna, h_m , and the value of SIR. The results indicated that the value of SIR decreased as the receiver antenna's height increased. This is because increasing the antenna's height enhances the reception of interference signals from nearby stations operating on the same frequency. The impact is more noticeable in the hexagonal system due to the higher number of surrounding stations creating interference than in the linear system.



a. Linear system.



b. Hexagonal system.

Fig. 9. Effect of path loss exponent on SIR in dual-slope Model.

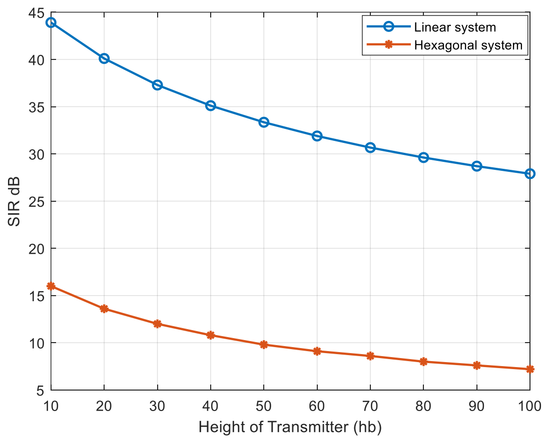


Fig. 10. Effect of base station height h_b on SIR.

C. The Effect of The Base Station Antenna's Tilt

The effect of the transmitter antenna tilt angle on the SIR value for both linear and hexagonal systems is illustrated in Fig. 12 . It was observed that when the tilt angle increased, i.e., tilting the base station antenna downward toward the mobile user, the SIR value increased significantly. This is because orienting the antenna at an appropriate and carefully selected angle towards the receiver enhances the concentration of the signal received and reduces the damaging effect of interfering signals coming from nearby stations. However, while tilting the antenna at a specific angle, a balance must be achieved between optimal coverage and interference minimization.

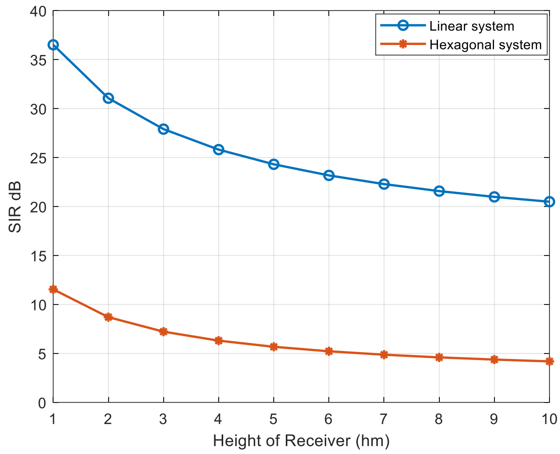


Fig. 11. Effect of Mobile height h_m on SIR.

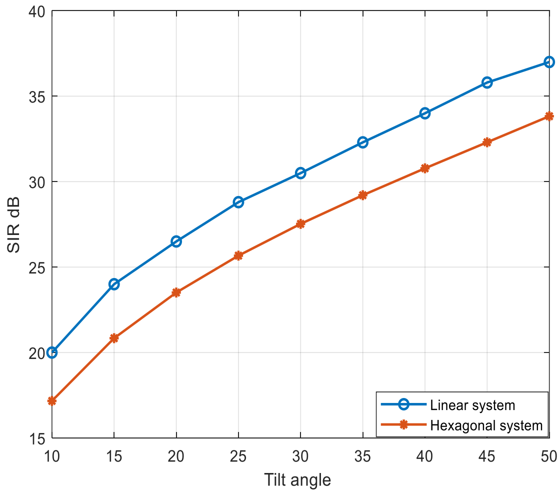


Fig. 12. Effect of base station antenna tilt angle α on SIR

VI. Conclusion

The research presents an analysis of the SIR performance of both linear and hexagonal systems in the highway environment using log-distance and dual-slope propagation models. According to the results, the linear system performs better than the hexagonal system in a variety of factors, including distance, cluster size, path loss exponent, antenna height, and antenna tilt angles. This superior performance is due to the linear distribution of the stations along the highway, which reduces the number of surrounding cells that use the same frequency, resulting in fewer interference signals and higher signal quality. The results confirmed the importance of choosing the appropriate design for wireless network distribution, especially in highway environments with linear distribution. The results also show the importance of choosing the most reliable propagation models in the calculations, such as the dual-slope model, to obtain performance predictions that reasonably represent reality . In the future, it is proposed that the effect of user density and movement between stations on the network be investigated.

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