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Optimised channel propagation modelling and ray tracing for 5G network planning in urban areas

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Abstract: The increasing demand for high-speed communication in urban areas has required development of efficient optimisation methods in planning of fifth generation (5G) terrestrial mobile radio networks. The 5G terrestrial mobile radio network has been widely deployed around the world in frequency range of 3.5 GHz and 28 GHz bands. The planning of 5G terrestrial mobile radio networks involves assessing coverage for regional characteristics of different locations. This study focuses on channel propagation analysis for planning 5G terrestrial mobile radio networks in Bahir Dar City, Ethiopia. We have considered free space, atmospheric gas, rain attenuation, and close-in models to analyse propagation losses in three-dimensional urban scenarios. The results of this study have shown that close-in and free space models have best and lowest performance in signal to interference noise ratio (SINR) with 19.76 dB and 12.515 dB respectively; using ray tracing model at distance of 0.5 km and 0.041 km height of transmitters.

Keywords: mobile radio network planning; terrestrial network; propagation models; pathloss; reflection; coverage before optimisation; atmospheric models; SINR; signal to interference noise ratio; reconfigurable intelligent surfaces; offload traffic.

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1 Introduction

The advancement of fifth generation (5G) mobile radio network planning is a requirement in the evolution of telecommunications for optimising speed, reducing latency, increased coverage, capacity and signal to interference noise ratio (SINR) to achieve the growing needs of future smart cities (Singh et al., 2023; Rafie et al., 2025). Urban area scenarios are described with population densities, demands, and challenges of 5G mobile radio network planning in urban environments (Shafi et al., 2017). The technique is critical for enabling enhanced current and future applications in urban such as smart autonomous vehicles, and real-time healthcare services (Taufique et al., 2017). Urban areas has signal propagation issues caused by high-rise buildings, traffic transportation of mobile networks, and limited infrastructure deployment (Islam et al., 2024). The methods such as beamforming, and massive multiple input multiple output (MIMO) are vital to ensure optimal coverage, SINR and capacity for the urban scenarios (Gupta and Jha, 2015). To analysis and optimised 5G terrestrial mobile radio network communication system to enhance the performance such as minimising pathloss, and maximising coverage, SINR and capacity with in urban environments (Zhang et al., 2017).

The 5G mobile radio network planning in urban environment requires the integration of optical communication

system with wireless mobile radio network planning in urban environment (Agiwal et al., 2016). These are used for collaborating government bodies, Telecom operators, and urban planners is used to align the deployment of local regulation, public need, and urban development plan (Kamel et al., 2016). The deployment of 5G mobile radio network planning in urban areas environment has different problems due to densely populated areas, technological demand, and regulatory requirements (Maheswaran et al., 2024). These problems must be addressed to ensure optimised deployment and operation of 5G mobile radio network planning in urban environment (Konhäuser, 2021). The signal strength has a critical problem for 5G mobile radio network planning deployment, particularly in urban areas for high-capacity mobile radio network planning in the urban areas (Yu et al., 2024). The assignment of mobile radio signal that has low, mid, and high-frequency bands with critical problems in the urban area environment (Ullah et al., 2025). To optimise these listed issues in 5G mobile radio network planning utilising ray tracing model is essential in urban area environment (Gupta and Jha, 2015).

The urban areas demands high number of mobile radio network infrastructure to provide efficient coverage, SINR, and capacity in urban area environment (Rafique et al., 2024). However, the deployment of mobile radio network infrastructure has faced advanced mobile radio network

technologies (Kamel et al., 2016). These comes due to the buildings, trees, atmospheric attenuation that significantly affects mobile radio signal propagation in urban area scenarios (Yigit et al., 2024). The frequency used in 5G mobile radio network with 3.5 GHz and 28 GHz bands for path loss and penetration losses urban areas environment (Zhang et al., 2017). The required number of 5G mobile radio network planning infrastructure has coverage area, SINR and capacity of urban environmental limitations (Fong et al., 2023). These limitation requires integrating and mitigating with critical problems in 5G mobile radio network planning urban environment (Agiwal et al., 2016). These limitation exists in 5G terrestrial mobile radio network planning affects infrastructure deployment in with different locations urban area environments (El-Badawy et al., 2023). The 5G terrestrial mobile radio network planning in Bahir Dar City infrastructure is required to provide seamless communication with mobile radio network using ray tracing in urban area environments (Simkó and Mattsson, 2019). The main problem of this research work is non line of site with signal blockage by building of 5G mobile radio network planning in urban area. This problem is optimised by using ray tracing models. This paper performs analysing and optimising of 5G terrestrial mobile radio network planning using ray tracing model in the case of Bahir Dar City. Finally, the remaining part of this paper is organised as follows: section 2 summarises some of most related works with terrestrial mobile radio network planning; specifically, geographical location based channel propagation consideration studies. Section 3 presents about methods and materials

- 1 propagation models such as free space, gas, rain and close-in models using ray tracing models.
- 2 The 5G terrestrial mobile radio network planning components including data collections techniques and software tools.

Section 4 provide detailed information on results and discussions. These results and discussion conducting with simulation using software tools, collecting real data, simulation data, processing data, and analysing obtained results. Finally, in Section 5 presents about conclusion and future works regarding the usefulness of the simulations conducted using ray-tracing to optimise channel propagation models, with a particular focus on bands of 3.5 GHz and 28 GHz within a specific environment and application. In this paper, also recommends for future research directions in urban area issues.

2 Related works

Gómez et al. (2023) studied, the high-performance mobile radio simulation tools for cellular radio network planning in wireless communication systems. The focus was on cellular radio network platforms using geographical data from base station site selection for base station sites to access terrestrial networks. The achievement of base station site selection and minimising the limitations of cellular radio network planning

in the terrestrial environment for cellular radio networks. The research gap was integration of 3D with 2D map that both can not work seamlessly. Also the ray tracing launching models that used for path loss calculation was not discussed in this study.

Zerihun et al. (2014) studied the LTE mobile radio network planning for Bahir Dar City in cellular radio networks. The problem was using geographical data from the Bahir Dar City site selection for 4G base station equipment that connects with downlink limitation in the mobile radio network. The suggested solution for base station site selection minimised the limitations of cellular radio network planning in Ethiopia terrestrial environment for Bahir Dar City. The research gaps was base station site selections for 5G mobile radio system to enhance future wireless network access in Bahir Dar City.

Chiaraviglio et al. (2018) studied the 5G cellular mobile radio network planning under electromagnetic field (EMF) constraints. The problem was on 2G, 3G, and 4G using geographical data from Italy's site selection for a 5G base station to connect with downlink communication in mobile radio network systems. The cellular mobile radio network planning limitation with minimisation using site selection of base station in the terrestrial landscape of Italy. This paper, research gap are base station site position, outdoor WiFi, and high-voltage transmission lines in wireless communication system.

Tyokighir et al. (2023) studied, the cellular radio network planning of fixed wireless networks in a terrestrial landscape. The design parameters were path loss, area coverage, attenuation loss, and interference using frequencies from 3.5 GHz to 28 GHz with a power of 1 watts over the geographical sites. These geographical sites located 9.09 north to 7.47 east were receivers of Maitama, Abuja, and Nigeria. The author provides insights with minimum frequency using 3.5 GHz, which performs better than 28 GHz, and finally, future research direction on long distance for wireless communication systems. The research gap that was not disusing about long distance wireless communication system.

Guijarro et al. (2024) studied, the wave propagation with four models to compare performance of the Quito City mobile radio planning channel model. The problems were frequency specification of 5G, pathloss, diffraction, reflection, blocking, and fading between transmitters and receivers. The objective was to design an mm-wave MIMO antenna with beamforming for 28 GHz frequency. The simulation uses a dominant path model, knife-edge diffraction, third-generation partnership project, advanced space bore thermal emission, and reflection radiometer ray-tracing models with $2 \times 2/4 \times 4$ and 64×64 array tools of WINPROP and ATOLL respectively. This was solved by comparing these four-wave propagation models and selections among those listed with the ray-tracing model. The research gaps that are not considered terahertz communication using those propagation models for urban, suburban, and rural environments.

Shayea et al. (2021) studied, 5G mobile broadband performance analysis using four service parameters in Malaysia for the four states of urban areas. These four states were Sabah, Johor, Sarawak, and Klang Valley/Selangor. The four service parameters were satisfaction, coverage, speed,

Table 1 The summary of related works that used to identify the research gaps

<i>Reference</i>	<i>Problem</i>	<i>Objective</i>	<i>Method</i>	<i>Research gap</i>
Gómez et al. (2023)	Site selection	Minimise limitation	Site selection	Integration 3D & 2D
Zerihun et al. (2014)	Site selection(4G)	Minimise limitations	Site selection	Site selection(5G)
Chiaraviglio et al. (2018)	Site selection(5G)	Minimise limitation	Site selection	Site position
Tyokighir et al. (2023)	(PL)short distances	Design a solution	Parameter	(PL)long distance
Guijarro et al. (2024)	Frequency of 5G	Antenna design	Array antenna	THz
(Shayea et al., 2021)	Limited coverage	realistic (5G)	Future 5G	Heterogeneous
Wang et al. (2020)	Site selection	Optimisation	Cooperative	Channel model
Bellary et al. (2022)	Antenna selection.	MIMO antenna	dipole antenna	Path loss

and latency. The problems were limited coverage services, latency, satisfaction, and speed issues. The objective was to present a road map for service providers that used to establish realistic for 5G networks plans. The comparison of 3G and 4G performance to select and predict future 5G and beyond mobile broadband technology in Malaysia's urban environments. The research gaps of this paper in urban environment, heterogeneous network with handover and mobility management issues are not discussed.

Wang et al. (2020) studied, the 5G base station deployment approach with cost and signal coverage. The problem were 5G macro and micro site with location selection of base stations. The cooperative operation and deployment optimisation methods were used to locate 5G heterogeneous base stations. The objective was optimisation with setup cost reduction and improvement of signal coverage strength. The author focused only on cost, signal coverage, site selection, location, position, and distance. The research gap of this paper that effects of channel propagation model, capacity, SINR, and BER performance of 5G were not considered.

Bellary et al. (2022) studied, the analysis of the channel wave propagation model of radio network planning using MIMO dual-polarised antenna of 5G base stations. There was antenna performance and channel wave propagation model selection problem. The specific objectives were:

- 1 design a dual-polarised MIMO antenna for 42 GHz frequency bands
- 2 comparative analysis with a dominant path model, knife-edge diffraction, and extended wolfish-Ikegami
- 3 evaluate the dominant path model, knife-edge diffraction, and extended wolfish-ikegami models using quadrature phase shifting key (QPSK) and quadrature amplitude modulation (QAM) schemes, signal strength and quality reference signal received power (RSRP), received signals strength indicator (RSSI), reference signal received quality (RSRQ), and SINR
- 4 channel wave propagation model selection is based on its performance. Finally, the DPM channel wave propagation model is selected using its performance.

Also, the 8×8 dipole antenna performs better than the 2×2 and 4×4 dipole antenna. The simulation was performed using

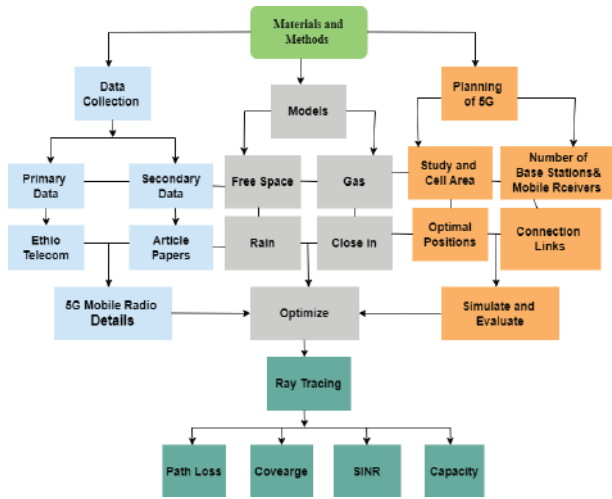
the FEKO WinProp platform for selected geographical site area signal coverage in this environment. The capacity and bit error rate (BER) were not discussed in 5G.

As shown in Table 1, the most problems are related with site selection and our focused is on research gaps with optimisation of free space, gas, rain, and close-in models to enhance path loss, coverage, SINR, and capacity using ray tracing model in 5G mobile radio network in urban areas. The remaining research gaps will consider as our future work.

3 Materials and methods

3.1 Materials

5G terrestrial mobile radio network planning for Bahir Dar City in Ethiopia requires a procedural method to ensure mobile radio network pathloss, coverage, SINR, and capacity. The process can be used in the 5G mobile radio network planning for Bahir Dar City. The required materials are data collection, channel wave propagation models and software tools used to simulate and analysis 5G mobile radio networks. These are described as follows: Data collection (1): from EthioTelecom Addis Ababa Ethiopia about Bahir Dar City 5G details such as sites location, height of transmitter antenna, latitude, longitude and altitude as shown in Tables 2 and 3 for mobile receiver respectively. The geospatial data and literature review also used to enhance data quality of 5G mobile radio network system of Bahir Dar City. Channel wave propagation models (2): are path loss model (free space, close-in, and ray tracing) and atmospheric attenuation models (gas, and rain) by considering different distributions such as log normal, and log distance. Software tools (3): are available to assist in designing and optimising 5G mobile radio network planning for Bahir Dar City. These are matlab, openstreetmap, site viewer, and 5G toolbox are used for mobile radio network planning and optimising tools that can generate pathloss, coverage maps, SINR and capacity predictions for analysis. It also supports 5G mobile radio network planning and integrates with GIS data to create accurate models of Bahir Dar City environments. The work flow diagram Figure 1 shows, the details of each procedures in mobile radio network planning in Bahir Dar City. The evaluation simulation setup are listed in Table 2.

Figure 1 Workflow diagram for planning of Bahir Dar City 5G mobile radio networks (see online version for colours)**Table 2** Simulation setup

Parameters	Values	Units
Study environment Area	4.75	km ²
Frequency	28	GHz
Radius	0.5	km
Transmitter Height	0.041	km
Receiver Height	0.0015	km
Transmitter Power	20	dB
Gain of transmitter antenna	2.1	dBi
Gain of receiver antenna	2.1	dBi
Distance from transmitters	0.25	km
Bandwidth	100	MHz
Speed of light	3×10^8	m/s
Threshold SINR	-5	dBm

3.2 Planing of 5G mobile radio networks in Bahir Dar City

Study Area Selection(1): The 4.75 km² contour area(A_{co}) is selected from Bahir Dar City sites using open stream map. Determine cell area coverage (2): Select the maximum horizontal distance in 5G terrestrial mobile radio network planning system that is 0.5 km as radius and the find area of the cell(A_{ce}) that is $(0.5 \times 0.5 \text{ km})$ equal to 0.25 km². Calculated Number of Base Stations (3): The required number of base stations(N_{bs}) in the selected contour area is can be calculated by the contour area divide by cell area.

$$N_{bs} = \frac{A_{co}}{A_{ce}} \quad (1)$$

Based on (36), N_{bs} is 4.75/0.25 equal to 19 that used in 5G terrestrial mobile radio network planning for Bahir Dar city. Find Position of Base Stations(4): Finding the optimal position of each base station is mandatory to transmitted power with minimum threshold for mobile receiver in 5G terrestrial mobile radio network planning in Bahir Dar City. The position

of base station determined by latitude,longitude and altitude as described in Table 3.

Add Random Number of Mobile Receivers (5): Adding the random number of mobile receivers with its maximum horizontal distance of 0.25 km from base station, which are used in 5G terrestrial mobile radio network planning of Bahir Dar City. Finding Position Mobile Receivers (6): Here, there are 3 number of random mobile receivers and then assign latitude,longitude and altitude to find the right position of mobile receivers for receiving maximum signal power. The positions of mobile receiver is shown in Table 4.

Table 3 5G terrestrial mobile radio network planning in Bahir Dar City

Site	Height (m)	Latitude (°)	Longitude (°)	Altitude (m)
1	41	11.596895	37.387607	1794
2	41	11.594647	37.391582	1796
3	41	11.592398	37.395558	1797
4	41	11.587902	37.395558	1794
5	41	11.583405	37.395558	1795
6	41	11.581157	37.391582	1797
7	41	11.585654	37.391582	1798
8	41	11.59015	37.391582	1797
9	41	11.592399	37.387607	1797
10	41	11.587902	37.387607	1805
11	41	11.583405	37.387607	1797
12	41	11.578909	37.387607	1795
13	41	11.581157	37.383632	1804
14	41	11.585654	37.383632	1795
15	41	11.59015	37.383632	1797
16	41	11.594647	37.383632	1797
17	41	11.592398	37.379657	1795
18	41	11.587902	37.379657	1794
19	41	11.583405	37.379657	1794

Table 4 Mobile receiver position of 5G terrestrial mobile radio network planning in Bahir Dar City

Site	Height(m)	Latitude (°)	Longitude (°)	Altitude (m)
1	1.5	11.591301	37.38901	1797
2	1.5	11.585099	37.389034	1797
3	1.5	11.587449	37.38509	1796

Link Mobile Receiver to Base Stations (7): The link that connects mobile receivers with base stations, and analysis pathloss,coverage,SINR, and capacity using free space,gas,rain,close-in and ray tracing models. Simulate and Evaluate (8): The simulation and evaluation of 5G terrestrial mobile radio network planning using open stream map, Matlab, 5G toolbox, and site viewer.

3.3 Methods

3.3.1 Channel wave propagation models

The selected channel wave propagation models are free space, close-in, gas, and rain models for analysing of pathloss, coverage, SINR and capacity in 5G terrestrial mobile radio

network planning and optimise using ray tracing model in Bahir Dar City. The line of sight (LOS) and non line of sight (NLOS) probability between base station transmitter and mobile receiver can find (TR, 2020), and shown in Figure 2:

$$P_{LOS} = \left[\frac{18}{r} + \exp\left(-\frac{r}{63}\right) \left(1 - \frac{18}{r}\right) \right] \quad (2)$$

where r is the horizontal distance between transmitter and receiver.

$$P_{NLOS} = 1 - P_{LOS} \quad (3)$$

Free space path loss model(FS_{PL}) (1): the FS_{PL} can be calculated using frequency in and maximum distance between base station transmitter and mobile receiver (TR, 2020), as shown equation (2):

$$FS_{PL} = 20 \log_{10}(f_c) + 30 \log_{10}(d) + 32.4 \quad (4)$$

where frequency (f_c) in gigahertz (GHz), and maximum distance(d) between the transmitter and receivers in kilo meter(km). The maximum distance (d) can be calculated using transmitter base station height (h_{bs}), horizontal distance(r) and receiver mobile height (h_m), as shown equation (3):

$$d = \sqrt{r^2 + (h_{bs} - h_m)^2} \quad (5)$$

The mobile receiver power using free space model is find with equation (4):

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (6)$$

where the transmitter base station power(P_t), transmitter antenna gain(G_t), mobile receiver antenna gain(G_r), the wavelength (λ) that can be calculated using speed of light(c) and frequency; the value of c with 3×10^8 m/s. Close-In Model(2): in 5G terrestrial mobile radio network planning, urban planning must analyse coverage and interference while considering pathloss(PL) in the environment. PL can be calculated using a close-in (ci) free space reference distance model with one (1m) meter. ci is a model that defines large-scale PL with a single parameter and PL exponent (n) can be find equation (5) (Shakya et al., 2024).

$$PL_{ci}(f_c, d) = FS_{PL}(f_c, 1m) + 10n \log_{10} \left(\frac{d}{d_0} \right) + x_\sigma \quad (7)$$

where, carrier frequency in GHz at 1 m ($FS_{PL}(f_c, 1m)$), pathloss exponent(n) and large scale shadow fading (X_σ) in dB as shown in equation (6).

$$FS_{PL}(f_c, 1m) = 32.45 + 20 \log_{10} \left(\frac{f_c}{1GHz} \right) \quad (8)$$

Gas Model (3): the gas attenuation affects the signal strength of the 5G terrestrial mobile radio network planning in Bahir Dar City. This attenuation is influenced by water vapor and oxygen levels, which fluctuate based on frequency, temperature, pressure, and atmospheric composition (Geneva, 1997). The gas attenuation(A_g) is calculated using equation (7):

$$A_g = (\gamma_0 + \gamma_w) d_1 \quad (9)$$

where the path length(d_1) in Km and the dry air specific attenuation(γ_0) in dB/Km and depends on frequency (GHz), temperature ($^{\circ}C$) and pressure (Pa). Also, the water vapor specific attenuation(γ_w) in dB/Km and depends on the same parameters as γ_0 and also on the water vapor density in g/m.

Rain Model (4): the rain attenuation over a terrestrial path is defined as the product of specific attenuation (dB/km) and the effective propagation path length (km). The link length and the horizontal distribution of the rain along the path determine the effective path length. Rain attenuation (A_r) (dB) exceeded at percent (p) of the time is calculated using equation (8):

$$A_r = \gamma_R d_{eff} \quad (10)$$

$$d_{eff} = \gamma_R d_{xr} \quad (11)$$

where the path reduction factor (r) at time percentage (p) and the radio path length(d) in km. The specific attenuation with the rain intensity. The particular attenuation(γ_R (dB/km)) is obtained from rain rate R (mm/hr) exceeded at percent (p) of the time using power law relationship as:

$$\gamma_R = k R^\alpha \quad (12)$$

where α and k depend on the polarisation and frequency of the electromagnetic wave. Numerical values that can be obtained by interpolation considering a logarithmic scale for linear for α and k . These coefficients' values are determined as frequency functions(f) in GHz that is used 28 GHz. The k values can be either k_V or k_H , and for α can be either α_V or α_H for vertical and horizontal polarisation respectively (Series, 2005). Ray Tracing Model(5): in Bahir Dar City's environment, signal propagation is affected by reflection, diffraction, and scattering due to buildings, vehicles, and trees. To minimise these effects, the ray tracing model tracks the multiple paths a signal transmits from transmitter to receiver and vice versa received power of ray (Anderson, 1993). Reflection(a): The reflection coefficient is crucial in determining the phase and amplitude of reflected energy. It is influenced by several factors, including angle of incidence, conductivity and permittivity of materials involved, the roughness of reflecting surface, and the polarisation of incoming wave. The plane wave incidence, the general expression for the reflection coefficient (R) is fundamental in analysing the behaviour of reflected energy is shown in equation (11):

$$R = R_s \rho \quad (13)$$

where smooth surface reflection coefficient(R_s), and surface roughness attenuation factor (ρ). R_s is for parallel and perpendicular polarisation with smooth surface reflection coefficients are describe in equations (12) and (13) respectively.

$$R_s = \frac{\sin\theta - \sqrt{\epsilon - \cos^2\theta}}{\sin\theta + \sqrt{\epsilon - \cos^2\theta}} \quad (14)$$

$$R_s = \frac{\epsilon \sin\theta - \sqrt{\epsilon - \cos^2\theta}}{\epsilon \sin\theta + \sqrt{\epsilon - \cos^2\theta}} \quad (15)$$

where, angle of incidence(θ) and complex permittivity(ϵ) can be find using equation (14):

$$\epsilon = \epsilon_r - j60\sigma\lambda \quad (16)$$

where relative dielectric constant of the reflecting surface(ϵ_r), conductivity of reflecting surface(σ) in Siemens/m, and wavelength(λ) of incident radiation. The roughness attenuation factor(ρ) is calculated using equation (15):

$$\rho^2 = 2^{-2\delta} \quad (17)$$

$$\delta = \frac{4\pi\Delta h}{\lambda} \sin\theta \quad (18)$$

where standard deviation of the normal distribution for the surface roughness(Δh). The diffraction(b): the diffracted energy from illuminated corners can be modeled using wedge diffraction coefficients that reflect the physical characteristics of the corner. Complete solution for this canonical problem has been addressed using the uniform theory of diffraction, initially presented for perfectly conducting wedges (Luebbers, 1984). For both parallel and perpendicular cases express of diffractions(D_k) with equation (17):

$$\begin{aligned} D_k = & \frac{-e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi}\beta} \left[\cot\left(\frac{\pi + (\psi - \psi')}{2n}\right) F(\beta La^+(\psi - \psi')) \right. \\ & + \cot\left(\frac{\pi - (\psi - \psi')}{2n}\right) F(\beta La^-(\psi - \psi')) \\ & + R_{||,0}^+ \cot\left(\frac{\pi - (\psi + \psi')}{2n}\right) F(\beta La^-(\psi + \psi')) \\ & \left. + R_{||,n}^+ \cot\left(\frac{\pi + (\psi + \psi')}{2n}\right) F(\beta La^+(\psi + \psi')) \right] \end{aligned} \quad (19)$$

where,

$$F(x) = 2j\sqrt{x}e^{jx} \int_{\sqrt{x}}^{\infty} e^{-j\tau^2} d\tau \quad (20)$$

$F(x)$ is a Fresnel integral,

$$L = \frac{mm'}{m + m'} \quad (21)$$

A distance (L) term for the two dimensional case with distance(m) from observation point to the edge of wedge and distance (m') from source to the edge.

$$a^\pm(\psi \pm \psi') = 2\cos^2\left(\frac{2n\pi N^\pm - (\psi \pm \psi')}{2}\right) \quad (22)$$

In equation (20), the integers($N^\pm$) that satisfy the equation:

$$2n\pi N^+ - (\psi \pm \psi') = \pi \quad (23)$$

$$2n\pi N^- - (\psi \pm \psi') = -\pi \quad (24)$$

The reflection coefficients of the incident wedge face (R_0) and opposite wedge face (R_n), and β is can be defined as shown in equation (23)

$$\beta = 2\pi n N^\pm \pm (\pi - \epsilon) \quad (25)$$

Scattering(c): The computation of scattered receiver ray energy, power density on wall and then multiplied by σ to yield the total scattered power from the surface. This power is then

attenuated by the geometric spreading as a function (l/d_s^2): where, the distance (d_s) from scatter to receiver. When used in combination with the free space power transmission model in equation (4), coefficient of scattering become:

$$A_s = \frac{\sigma}{4\pi d_s^2} \quad (26)$$

This coefficient of scattering is used along with propagation primitives to find the scattered ray energy of receiver.

These five propagation primitives are combined according to the propagation environment ray encounters from transmitters to receivers. In ray tracing model the power received can be calculated:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \left[\prod_j R_j \right]^2 \left[\prod_k A_k(m', m) D_k \right]^2 \quad (27)$$

where the free space component from (2), reflection coefficient(R_j) from equation (3) or (4) for the j^{th} path reflection, and diffraction coefficient(D_k) from equation (7) for the k^{th} path diffracting wedge. The diffraction coefficients are also multiplied by a special spatial attenuation function ($A_k(m', m)$) which finds the correct multiplicative diffraction coefficient given the l/d^2 dependence in equation (14). Also this equation is used for received power, in the propagation model all rays are handled as complex voltage values which are affected by the complex reflection and diffraction coefficients and finally, $\prod$ is variable values of π . Coverage Area: The coverage area is analysis using hexagonal cell shapes in Bahir dar city 5G terrestrial mobile radio network planning with base stations on the roofs of buildings. A hexagonal cell shape is used because it minimises handover and shadowing problems as compared with circular cell shapes as shown in Figure 3. Here are some merits of hexagonal cell shape: The length of a side is equal to the distance between its centre and its vertex. Deployed equally spaced antennas. Without overlapping, cells can be positioned adjacent to each other. There are no shadowing area in the coverage area of entire geographical maps. If SINR value is equal/greater to the threshold value that mobile receiver is in the coverage area, and else SINR is less than threshold which is out of coverage area.

$$Total\ area = 4 \times \frac{3\sqrt{3}R^2}{8} = \frac{3\sqrt{3}R^2}{2} \quad (28)$$

$$Coverage\ area = \frac{4 \times \int_x \int_y P_A x Area(1)}{Total\ area} \quad (29)$$

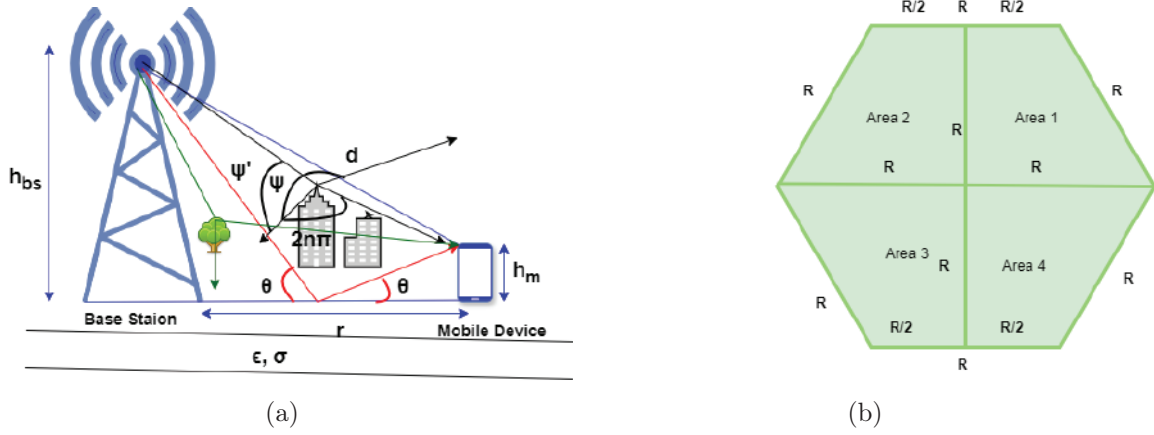
where P_A is the area of selected study environment, and R is the side of hexagonal cell shape system.

SINR: SINR is the SINR that is the ratio of between received and transmitted power in 5G terrestrial mobile radio network planning for Bahir Dar City.

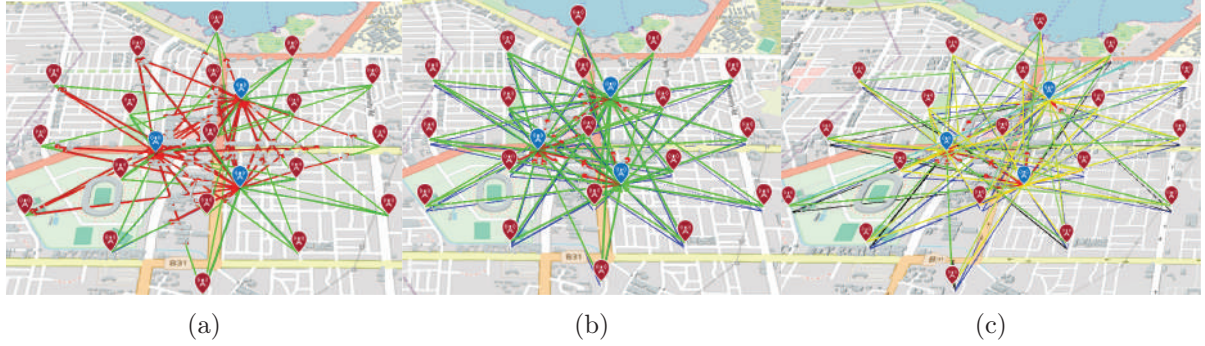
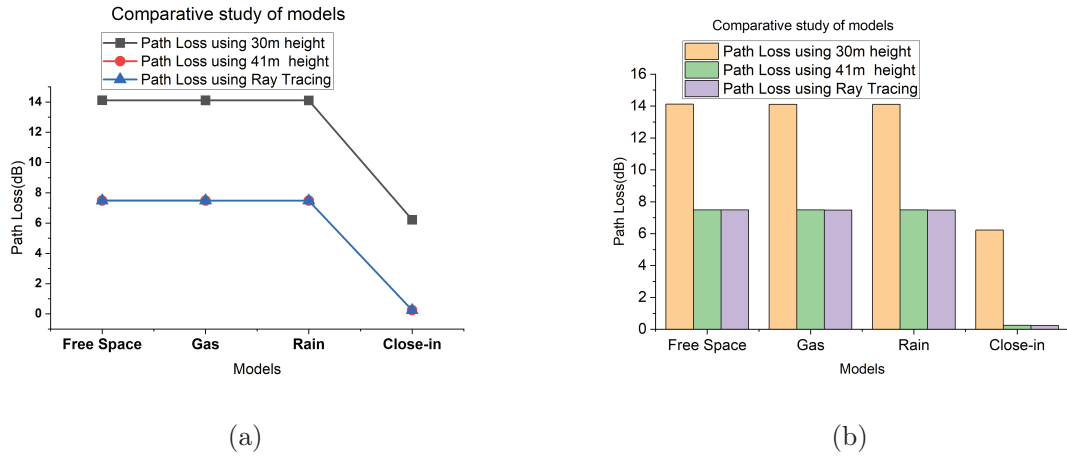
$$SINR = \frac{P_r}{P_t} \quad (30)$$

Capacity: the capacity is used for analysis the number of mobile users in 5G terrestrial mobile radio network planing of Bahir Dar City. The capacity(C) can be calculated as follows:

$$C = B \log_2(1 + SINR) \quad (31)$$

Figure 2 (a) System model and (b) hexagonal cell (see online version for colours)

Source: TR (2020)

Figure 3 Path loss model with: (a) 30 m height; (b) 41 m height and (c) ray tracing (see online version for colours)**Figure 4** Path loss comparative study of models with: (a) 2D-graph and (b) piechart (see online version for colours)

where B is the bandwidth that frequency difference between minimum and maximum.

4 Results and discussions

This section provides the results obtained from the simulations conducted to optimise the performance of 5G terrestrial mobile radio networks planning with 19 base station transmitters using ray tracing model. The ray tracing optimisation algorithm was implemented to enhance the performance

metrics such as path loss, coverage, SINR, and capacity. The brief details of this section are described as follows.

The path loss model using 5G ITU standards, Bahir Dar City locations of geographical particularities and ray tracing optimisation models were evaluated with LOS and NLOS effects for urban environments of Bahir Dar City. Figure 3(a)–(c) shows that performance of pathloss model using transmitters height of (30 m, 41 m and using ray tracing model) respectively in Bahir Dar city. The results indicate that the close-in model using ray tracing performs the lowest average path loss, demonstrating its effectiveness

Figure 5 Free space model with: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)

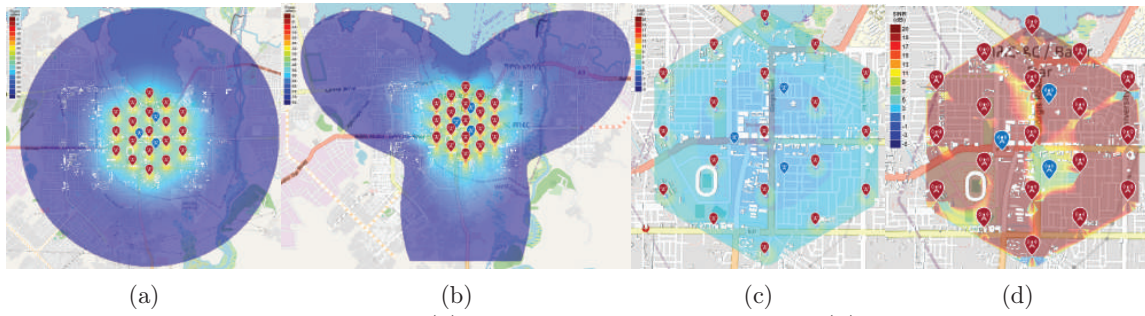


Figure 6 Gas model with: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)

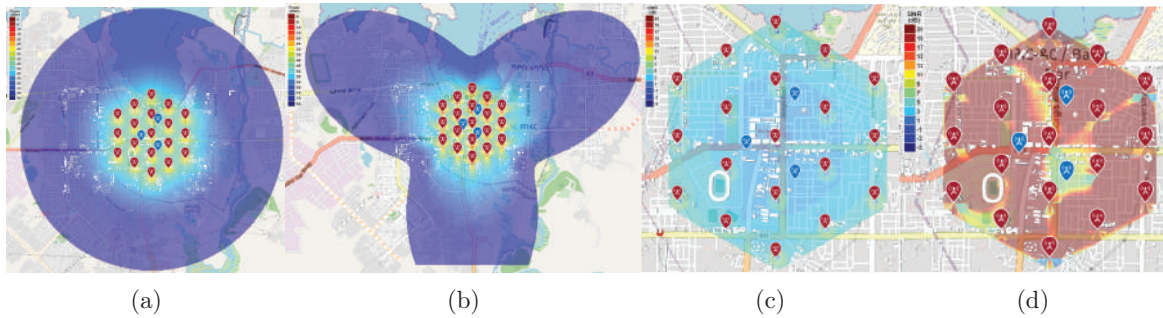
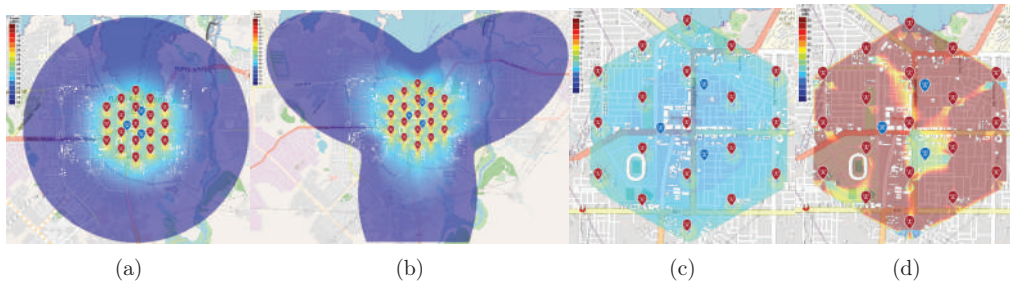


Figure 7 Rain model with: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)



in optimising base station positioning parameters. While free space model performs with the highest path loss. This leads to prediction for improved signal quality and reduced attenuation in 3.5 GHz and 28 GHz frequency bands.

Figure 4(a) and (b) shows that the comparative performance analysis of free space, gas, rain and close-in models before and after optimisations using height and ray tracing with pathloss. This is also discussed in Table 5.

The coverage area and SINR are the vital parameters for analysing 5G terrestrial mobile radio network planning effectiveness. The results for coverage area of free space model before and after optimisation using ray tracing model are described in Figure 5(a) and (b) respectively. The maximum power values that are used in these causes are -29 dBm and -19 dBm respectively. The results for SINR of free space model before and after optimisation using ray tracing model are shown in Figure 5(c) and (d) respectively. The maximum SINR values that are used in these causes are 5.8854 dB and 12.515 dB respectively.

The coverage area and SINR are the vital parameters for analysing 5G terrestrial mobile radio network planning effectiveness. The results for coverage area of gas model before and after optimisation using ray tracing model are described in Figure 6(a) and (b) respectively. The maximum power values that are used in these causes are -29 dBm and -19 dBm respectively. The results for SINR of gas model before and after optimisation using ray tracing model are shown in Figure 6(c) and (d) respectively. The maximum SINR values that are used in these causes are 5.8916 dB and 12.52 dB respectively.

The coverage area and SINR are the vital parameters for analysing 5G terrestrial mobile radio network planning effectiveness. The results for coverage area of rain model before and after optimisation using ray tracing model are described in Figure 7(a) and (b) respectively. The maximum power values that are used in these causes are -29 dBm and -19 dBm respectively. The results for SINR of rain model before and after optimisation using ray tracing model are

Figure 8 Close-in model with: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)

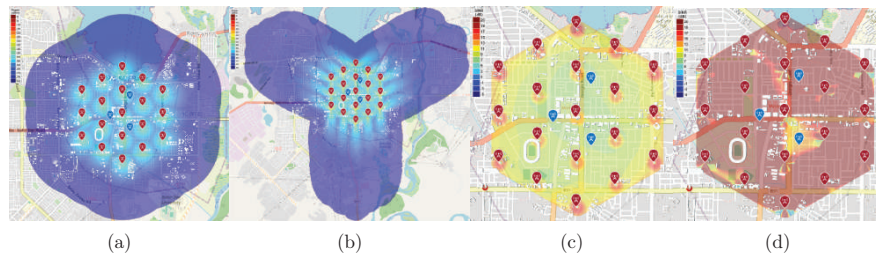


Figure 9 Comparative study of the models with 2D-graph: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)

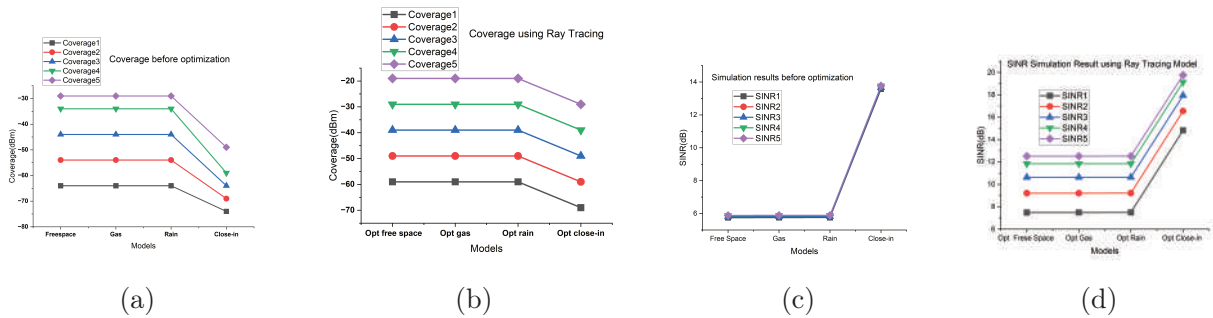


Figure 10 Comparative study of the models with piechart: (a) coverage before optimisation; (b) optimised coverage; (c) SINR before optimisation and (d) optimised SINR (see online version for colours)

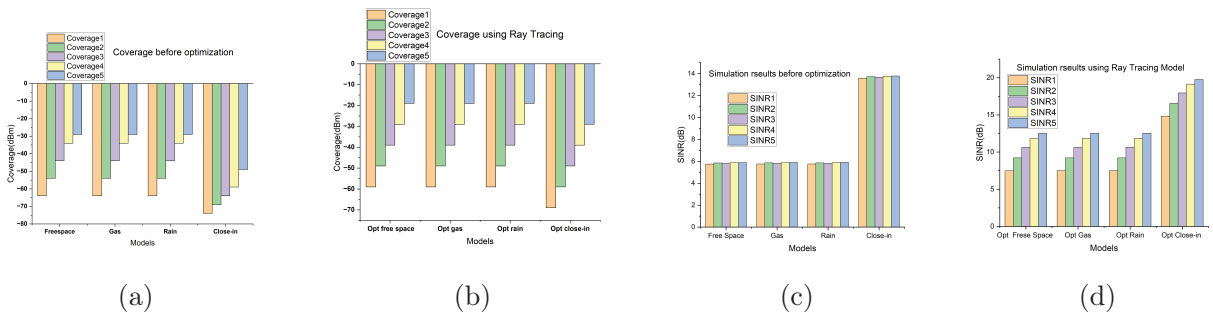
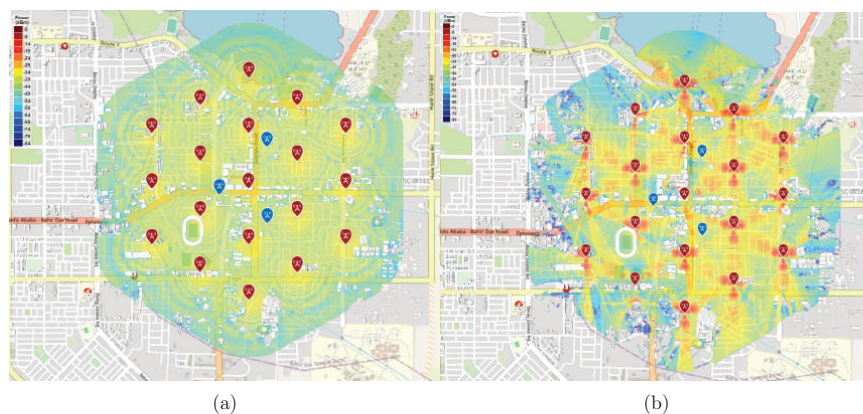
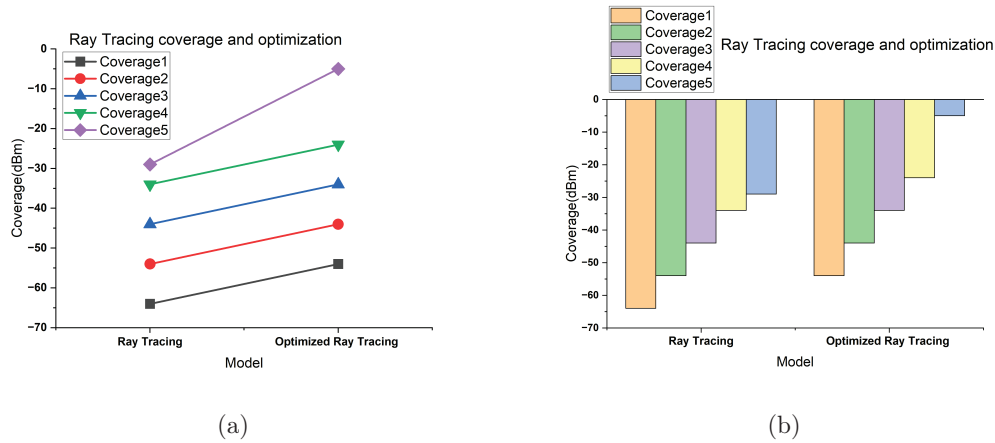
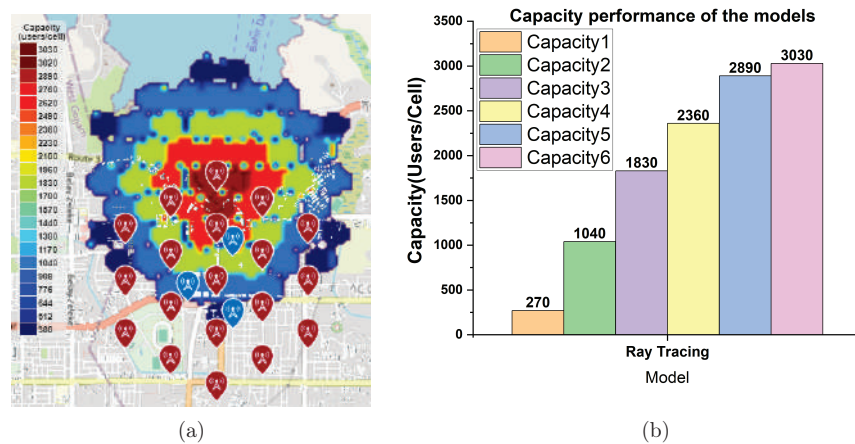


Figure 11 Coverage using ray tracing model with 3D graph: (a) before optimisation and (b) optimised coverage (see online version for colours)



shown in Figure 7(c) and (d) respectively. The maximum SINR values that are used in these causes are 5.8947 dB and 12.523 dB respectively.

The coverage area and SINR are the vital parameters for analysing 5G terrestrial mobile radio network planning effectiveness. The results for coverage area of close-in model

Figure 12 Coverage using ray tracing Model with: (a) 2D-graph and (b) piechart (see online version for colours)**Figure 13** Capacity with (a) 3D-graph and (b) piechart (see online version for colours)**Table 5** Summary of propagation model performances with before and after optimisation results

Models	Pathloss (dB)	Coverage (dBm)	SINR (dB)	Capacity(user/ C_a)
Free-space	14.254 to 14.115	-84 to -29	5.745 to 5.886	270 to 3030
Opt-free-space	12.511 to 7.485	-84 to -19	7.488 to 12.515	270 to 3030
Gas	14.247 to 14.109	-84 to -29	5.752 to 5.892	270 to 3030
Opt-gas	12.506 to 7.48	-84 to -19	7.493 to 12.52	270 to 3030
Rain	14.244 to 14.106	-84 to -29	5.755 to 5.895	270 to 3030
Opt-rain	12.503 to 7.477	-84 to -19	7.496 to 12.523	270 to 3030
Close-in	6.426 to 6.222	-84 to -49	13.574 to 13.778	270 to 3030
Opt-close-in	5.17 to 0.24	-84 to -29	14.83 to 19.76	270 to 3030

before and after optimisation using ray tracing model are described in Figure 8(a) and (b) respectively. The maximum power values that are used in these causes are -49 dBm and -29 dBm respectively. The results for SINR of close-in model before and after optimisation using ray tracing model are shown in Figure 8(c) and (d) respectively. The maximum SINR values that are used in these causes are 13.778 dB and 19.76 dB respectively.

In both Figures 9 and 10(a)–(d) are showing that the comparative performance analysis of free space, gas, rain and close-in models before and after optimisations using ray tracing with SINR. This is also discussed in Table 5.

The coverage area is a vital parameter for analysing 5G terrestrial mobile radio network planning effectiveness. The results for coverage area using ray tracing model before and after prediction of optimisation placement base stations are described in Figure 11(a) and (b) respectively. The maximum power values that are used in these causes are -24 dBm and -5 dBm respectively.

Figure 12(a) and (b) are showing that the comparative performance analysis of free space, gas, rain and close-in using ray tracing model before and after optimisation with Coverage.

The capacity of 5G terrestrial mobile radio network in Bahir Dar city, computed using the Shannon capacity

formula, is illustrated in Figure 13(a) and (b). The capacity results underscore the effectiveness of ray tracing model in maximising number of mobile users per cell area while minimising interference. The results show that the ray tracing model significantly improve the capacity in the 5G terrestrial mobile radio network during planning, especially in urban environments of Bahir Dar City, the minimum and maximum number of mobile users 270 and 3030 respectively, where demand for bandwidth is high. The capacity can be measured using (users/cell area (C_a)) as shown in Table 5. Table 5 shows that the summary of result all selected model with evaluation parameters.

5 Conclusion and future work

This study presented a comprehensive analysis and optimisation for the four propagation model for mobile radio Terrestrial Networks in 5G, utilising 19 base station transmitters. By employing a ray tracing model that combines various propagation and atmospheric models, including free space, gas, rain, and close-in models by ray tracing optimisation model, there search effectively addressed critical performance metrics, such as path loss, coverage area, SINR, and capacity in the case of Bahir Dar City. The findings revealed significant improvements in terrestrial mobile radio network performance through ray tracing optimisation model. The key outcomes included minimised path loss the ray tracing model demonstrated the best path loss performance, which is essential for maintaining high-quality communication. Enhanced coverage area with increasing in SINR. Increased coverage and SINR using ray tracing provided extended coverage while maintaining high SINR values, crucial for supporting numerous simultaneous users. Overall, the research confirms that ray tracing optimisation technique is enhance the diverse requirements of 5G terrestrial mobile radio network planning, particularly in densely populated urban areas of Bahir Dar City. The optimised pathloss in (dB) values of free space, gas, rain and close-in models are 7.485, 7.48, 7.477, and 0.24 respectively. The optimised coverage in (dBm) values of free space, gas, rain and close-in models are -19, -19, -19, and -29 respectively. The optimised SINR in (dB) values of free space, gas, rain and close-in models are 12.515, 12.52, 12.523, and 19.76 respectively. The all models have equal performance that is from 270 to 3030 $user/C_a$ in capacity. final close-in model has best performance as compared with free space, gas, and rain models specially in pathloss and SINR. Future work of 5G terrestrial mobile radio network planning will be enhance by using reconfigurable intelligent surfaces (RIS), machine learning approach, and integration of optical communication with wireless networks. Also the 5G mobile radio networking planning using satellite for city analysis and deployment in high-traffic, dense city areas to offload traffic from city and provide additional capacity.

Conflicts of interest

All authors declare that they have no conflicts of interest.

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