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Optimizing Cellular Network Performance: A Link Budget Analysis for Enhanced Coverage and Capacity in LTE and 5G

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Abstract

The rapid proliferation of mobile devices and the burgeoning demand for high-speed data services have driven the continuous evolution of wireless communication technologies. Long Term Evolution (LTE) and Fifth Generation (5G) networks have emerged as transformative milestones in this journey, offering significant enhancements in terms of data rates, latency, and connectivity. 5G is the buildup broadband wireless access (BWA) technology that former get the GSM/EDGE and UMTS/HSxPA technologies. LTE is prospective sponsor 3GPP's contestant edge over other cellular technologies. The calibration process of LTE is almost at its end. This research paper presents a comprehensive analysis of Radio Frequency (RF) link budgets for LTE and 5G networks with a primary focus on their coverage and capacity capabilities. Through theoretical models, simulations, and practical insights, this study aims to shed light on the fundamental factors that determine the coverage and capacity of these advanced wireless systems. The analysis includes detailed assessments of the radio frequency link budgets, considering factors such as path-loss (PL), shadowing, and fading, to provide a holistic view of the coverage and capacity characteristics of LTE and 5G networks. Additionally, the study explores the impact of antenna configurations, cell sizes, and other network parameters on coverage and capacity, providing valuable insights for network planning and optimization.

Keywords: LTE, 5G, Radio network planning, Urban and suburban environments, Antenna technologies

1. Introduction

There is an ongoing global need for faster and more reliable wireless communications, and continuous improvements are being made in the telecommunications industry. Long Term Evolution (LTE) (Isa Bakare et al., 2022), and 5G networks are leading this technological revolution (Kachhavay & PThakare, 2014). Not only do you get faster data speeds, but you also get better coverage and capacity. Understanding the performance of these networks is an important part of radio frequency (RF) link budget analysis (Tuovinen et al., 2017). This analysis is important to know the area the network can cover and the amount of data it can process (Basnayaka & Haas, 2017). LTE, developed by the 3rd Generation Partnership Project (3GPP) (Jiang et al., 2021), is a wireless communication standard renowned for its high throughput, low latency, and compatibility with both Frequency Division Duplexing (FDD) (Xu et al., 2014), and Time Division Duplexing (TDD) on the same platform (Lee et al., 2021). It offers a plug-and-play approach, ensuring an improved end-user experience and a simplified architecture, which in turn leads to lower operating costs (Hoikkanen, 2007). The downlink transmission structure of LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA) (Hosein, 2009), which effectively transforms the wide-band frequency-selective channel into a collection of many fading sub-channels (Naidu, 2020). The LTE specification boasts downlink peak rates of at least 100 Mbps, uplink rates of at least 50 Mbps, and Round-Trip Times (RTT) of less than 10 ms. LTE supports scalable carrier bandwidths ranging from 1.4 MHz to 20 MHz, and as previously mentioned, it supports both FDD and TDD (Jimaa et al., 2011; Wylie-Green & Svensson, 2010). Moreover, LTE enables seamless handover between cell towers using older network technologies such as GSM, CDMA One, W-CDMA (UMTS), and CDMA2000 (Fodor et al., 2009; Zyren, 2007). Radio network planning plays a crucial role in the implementation of wireless communication technologies (Nawrocki et al., 2006). While there is existing literature on radio network planning for various environments, there is a lack of specific guidelines tailored to the unique characteristics of the city of Johor Bahru. Existing studies often provide general methodologies that may not fully address the specific challenges and requirements of this urban area. This research aims to fill this gap by developing detailed radio network planning guidelines specifically for Johor Bahru. The approach involves a systematic, step-by-step method that starts with the collection of preplanning information and progresses to comprehensive coverage and capacity analysis.

2. Radio Network Planning

2.1. Initial Phase

Effective radio network planning is essential for the successful deployment and operation of wireless communication systems (Nawrocki et al., 2006). The initial phase of this planning process is critical, as it lays the foundation for the entire network design. This phase relies on several key pieces of information to make informed decisions about network configuration and optimization. Topography and structure information provide insights into the physical environment in which the network will operate (Abbas & Tufvesson, 2013). This includes details about building locations, altitudes, and any obstructions like foliage or highways that may impact signal propagation (Boban et al., 2011). Additionally, information about terrain height, topography, and atmospheric absorption properties is crucial for predicting signal strength and coverage areas

(Imtiaz Bin Hamid et al., 2012). The initial phase of radio network planning is a crucial step that requires careful consideration of user-related data, topography and structure information, and ENodeB/UE-related factors. By analyzing these factors, network planners can design a wireless communication system that meets the needs of users while optimizing coverage and capacity (Hassan et al., 2014). The initial phase of radio network planning relies on several crucial pieces of information:

- User-related data: This includes user distribution across different regions, reflecting user profiles in various areas based on factors such as data volume, application area, consumer data traffic class, required quality, and capacity demands (Fadlan, 2017).
- Topography and structure: Information about the building's location and altitude, as well as any obstructions like foliage or highways. This also includes general descriptions of the land cover at specific sites, such as terrain height, topography, and atmospheric absorption properties (Hosein, 2009).
- ENodeB/UE-related factors: This encompasses eNodeB/UE transmitted power, antenna type and gain, feeder losses, and body losses (Damanik et al., 2013).

2.2. Network Dimensioning

Efficient planning is crucial for the successful deployment and operation of wireless communication networks. Network dimensioning, a key aspect of this planning process, involves determining the coverage area and the number of sites needed to serve specific areas while meeting coverage and capacity requirements (Abdul Basit, 2009). These settings are necessary to optimize network performance and ensure quality of service. In this section, we will discuss the steps involved in network dimensioning, including input collection, device development, coverage analysis, and broadcast model selection. Overall, network dimensioning plays an important role in the design and optimization of wireless networks, helping to ensure that they are efficient and reliable to meet user requirements (Głąbowski et al., 2017). Overall, network dimensioning plays a vital role in the design and optimization of wireless networks, helping to ensure their effectiveness and reliability in meeting user demands. Network dimensioning can predict how these results may vary over time. Network dimensioning provides the number and position of sites, range and area of cells, and throughput of site and sector. Network dimensioning also involves calculating the number of sites needed to serve the target sites to meet coverage and capacity requirements. The process of network dimensioning includes the following steps:

1. Input Gathering: Pre-planning information, such as the probable altitude of Base Stations (BSs) at the site and other parameters, is collected.

2. Tool Development: A spreadsheet-based tool is developed to meet specific requirements. A system-level simulator may be used to estimate capacity, which is then used as input for the tool along with the link budget for cell coverage estimation.
3. Coverage Analysis: The spreadsheet-based tool uses coverage analysis to define the cell range. The tool calculates the number of cells and their locations based on the required capacity within the coverage range. If the capacity requirement overrides the coverage requirement, an iterative process is needed to adjust cell configuration to meet both requirements.
4. Propagation Model Selection: Proper selection of a propagation model is crucial for coverage calculation. Empirical models like Modified Cost231-Hata or SUI models may be more suitable than physical models in certain scenarios.

2.3. Link Budget

Link budget calculations are necessary to determine the maximum allowable path between cellular and BS antennas by considering factors such as free space, cable, waveguide and fiber losses. This statistic is important for comparison of coverage between different systems. The path-loss (PL) estimates are based on various factors such as distance, frequency, weather conditions, indoor/outdoor factors (Sari, 2018). Using maximum PL calculation, one can choose the appropriate propagation model to maximize the range of the cell such as Cost 231-Hata model (Isabona Joseph, 2013). The ranges estimated then allows the designers determine the number of BS sites needed to adequately cover the area (Carrión et al., 2019).

2.3.1 RF Link Budget's Main Components

An RF Link Budget is a crucial tool for analyzing the performance of wireless communication systems. It considers two key factors:

1. Transmit Power: This is the signal strength emitted by the transmitter, typically measured in decibel-milliwatts (dBm). Higher transmittance power allows for longer ranges or better penetration through obstacles, but it also consumes more energy.

2. PL: This is the weakening of the signal as it travels through the environment, often expressed in decibels (dB). PL depends on factors like distance, frequency, and terrain. Obstacles like buildings and trees can further increase PL. In Free space model for example, PL value can be calculated by Friis Transmission: ($PL = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(\frac{4\pi}{c})$); where the path loss (PL) in decibels (dB) experienced by a signal as it propagates through free space over a distance (d) in meters between the transmitter and receiver, the frequency (f) of the signal in Hz and the speed of light (c) in m/s.

3. Receiver Sensitivity: This sets the minimum signal strength the receiver needs to operate properly, typically measured in dBm. Lower sensitivity signifies better reception capabilities.

4. Signal-to-Noise Ratio (SNR): This ratio compares signal strength to background noise, impacting data clarity. An adequate SNR is crucial for accurate data recovery.

5. Link Margin (LM): This safety buffer accounts for unexpected signal degradation due to distance, obstacles, or interference. A sufficient margin ensures reliable communication even in challenging conditions. LM accounts for variations and uncertainties of the systems and can be described mathematically by $LM = P_{tx} - PL - P_{rx\,min.} - Margin$; where LM is the link margin in decibels (dB), P_{tx} is the transmitter power in dBm, P_{rx} is the minimum receiver sensitivity in dBm and *Margin* is an additional safety margin in dB. The link budget calculation parameters are listed in table below:

Table 1: Link Budget Parameters for both ends (Tx & Rx)

Transmitting End	Receiving End
BS/customer-provided equipment (CPE) transmits power per antenna	Noise figure
BS antenna height	Antenna Gain
Transmit power growth with multiple-input and multiple-output (MIMO)	Gain against shadowing
Feeder and Body losses	Receiver sensitivity
Antenna gain (about 18dBi for directional antenna and 8 dBi for Omni-directional antenna at BS, CPE has 0 dBi	

3. Radio Planning in Johor Bahru, Malaysia

Johor Bahru, the second largest urban area in Malaysia, presents significant challenges for well-organized RF planning due to limited resources. Specific calculations have been conducted for the state of Johor Bahru, with the intention of incorporating them into a comprehensive radio planning strategy for the entire state. Radio planning involves assigning frequencies, determining power levels for required services, selecting transmitter locations, and designing the structures necessary for a wireless communications system (Al-Hilfi & Daghal, 2020). In cellular communication, radio planning focuses on two key aspects: coverage, which refers to the geographical area within the system where RF signal strength is sufficient to support a call session, and capacity, which denotes the system's ability to accommodate a given number of subscribers (Elnashar, 2018).

4. Link Budget Calculation

The link budget calculation for LTE involves assessing the various factors that affect signal strength and quality in both the uplink and downlink directions (Lunttila et al., 2007). For the uplink, assuming a 64-kbps data rate and a 360 kHz transmission bandwidth, the UE terminal power is set at 30 dBm. No body loss is considered for a data connection. The eNodeB receiver is assumed to have a noise figure of 2 dB, and a Signal to Noise and Nosiness Ratio (SINR) of 6 dB is deemed necessary for the uplink (Table 2). An interference margin of 2 dB is also included in the calculation. A cable loss of 2 dB is factored in, but this is offset by assuming a masthead amplifier (MHA) with a gain of 2 dB. An RX antenna gain of 15 is assumed for a 3-sector macro-cell with 65-degree antennas. The maximum acceptable PL for this scenario is calculated to be 150 dB (Marzuki et al., 2023). For the downlink, assuming a 1 Mbps data rate with antenna diversity and a 10 MHz bandwidth, the eNodeB power is set at 40 dBm, which is a typical value for most manufacturers. The SINR value for the downlink is found to be 5 dB. 3 dB interference margin and a 1 dB control channel overhead are assumed.

Table 2: Uplink Budget for 64KBPS with dual antenna receiver BS

Symbol	Quantity	Note
Transmitter - UE		
A	Max. Tx Power (dBm)	30
B	Tx antenna gain (dBi)	0
C	Body loss(dB), Receiver - eNode B	0
D	EIRP (dBm) = A+B+C	30
E	E Node B noise figure (dB)	2
F	Thermal noise (dBm)	- 115
G	receiver noise floor (dBm)	-113 (E+F)
H	SINR (dB)	6

The maximum acceptable PL for the downlink scenario (Table 3) is calculated to be 155.5 dB (Carrión et al., 2019; Marzuki et al., 2023). The link budget calculation is essential for determining the maximum allowable PL and ensuring that the signal quality and strength meet the requirements for reliable communication in LTE networks.

Table 3: Downlink link Budget for 1 MPBS with dual – antenna receiver terminal

Symbol	Quantity	Note
Transmitter - eNode B		
A	Tx Power (dBm)	40
B	Tx antenna gain (dBi)	18
C	Cable loss (dB)	2
D	EIRP (dBm), Receiver -EU	56
E	UE noise figure (dB)	4
F	Thermal noise (dBm)	- 112.5
G	Receiver noise floor (dBm)	-108.5 (E+F)
H	SINR (dB)	5
I	Receiver sensitivity (dBm)	-103.5(G+H)
J	Interference margin (dB)	3
K	Control Ch. Overhead (dB)	1

5. Target Coverage Calculation

Target coverage calculation involves determining the extent of signal coverage required to serve the population of Johor Bahru effectively. This calculation will consider factors such as the population density, the distribution of users across the area, and the desired quality of service. By combining the link budget analysis with the population and area data, network planners can determine the number and placement of BSs needed to provide adequate coverage to the population of Johor Bahru. This information is crucial for optimizing network performance and ensuring that the network can meet the demands of its users. To estimate target coverage, it is necessary to consider the link budget and pre-planning information. One notable feature displayed in Figure 1is the coverage of different mobile phone networks (2G, 3G, 4G, 4G+, and 5G) in the area. For Johor Bahru, the following pre-planning information is available:

- Johor Bahru Population: 1.4 million
- Area: 185 km²

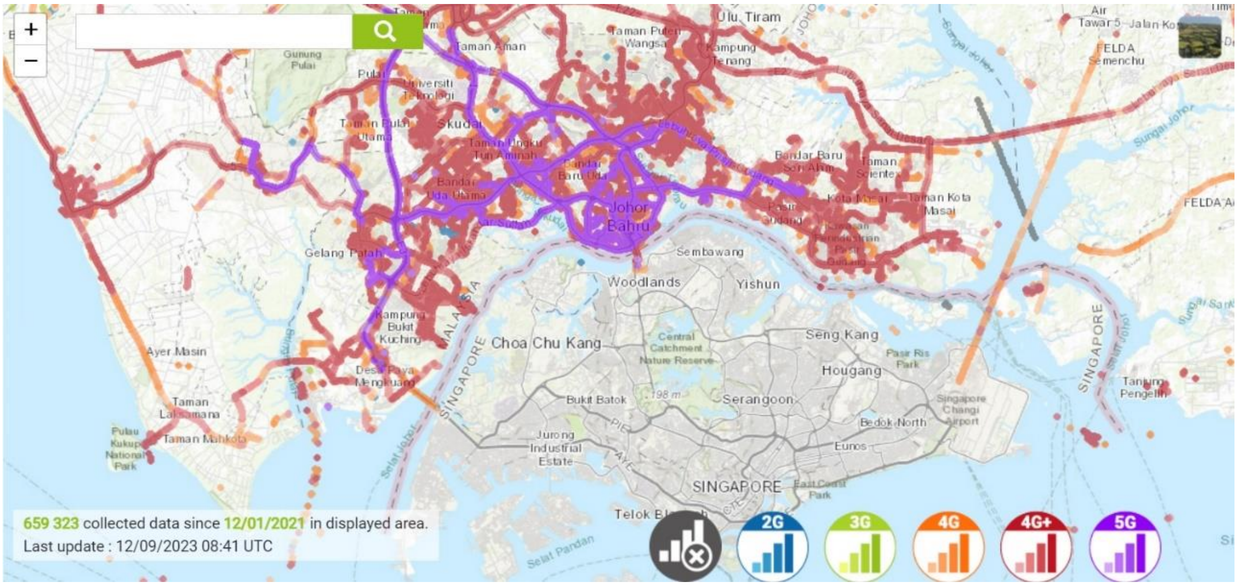

Figure 1. Comparative Coverage Analysis of 2G, 3G, 4G, 4G+, and 5G Mobile Networks in the Area.

6. Cost231-Hata Propagation Model

The Cost231Hata propagation model, an extension of the Hata model, is widely used in the field of wireless communication. It is designed for frequencies up to 2000 MHz and is particularly useful for estimating PL in urban areas as follows:

$$\mathrm{PL_{urban}(dB)} = 46.3 + 33.9\,\mathrm{Log(f)} - 13.02\,\mathrm{Log(h_b)} - \mathrm{a(h_r)} + [44.9 - 6.55\,\mathrm{Log(h_b)}].\,\mathrm{Log(d)} + \mathrm{c} \quad (1)$$

Here f obtained the frequency in MHz, d represent the distance between the transmitter & receiver, $\mathrm{h_b}$ & $\mathrm{h_r}$ the correction factors for BS height and receiver height in that order. The parameter c is zero for suburban & rural environments, while it has value 3 for urban area. The function $\mathrm{a(h_r)}$ for urban area is defined as (Naidu, 2020):

$$\mathrm{a(h_r)} = 3.2(\mathrm{Log}(11.75\,\mathrm{h_r}))^2 - 4.97 \quad (2)$$

The free space PL, when there is Line of Site (LOS) between the transmitter and receiver, the PL is given by the following formula (Jimaa et al., 2011):

$$\mathrm{PL_{free\ space}} = 32.44 + 20\,\mathrm{Log\,f(MHz)} + 20\,\mathrm{Log\,d(km)} \quad (3)$$

Here in ours research L=150 dB, f=2600 MHz, $\mathrm{h_b}$ =35 m, $\mathrm{h_r}$ =1.6 m, a($\mathrm{h_r}$)=0.22, As Cost-Hata transmission Model provides a PL of 150 dB for d=3km area of the Hexagonal shape (six edges and six vertices) = $3\sqrt{3}\,\mathrm{d}^2/2 = 23.38\ \mathrm{km}^2$ for one eNodeB site, where d = cell radius, so number of eNodeBs for coverage =185/23.38 which about 8 (Binti Shukri et al., 2021).

7. Results and Discussion

The PL experienced by radio signals varies significantly depending on the propagation environment. In free space, where there are no obstacles to impede the signal, the PL is minimal and increases logarithmically with distance. However, in urban environments characterized by tall buildings and numerous obstacles, the PL is much higher due to the increased attenuation caused by these structures. Suburban areas, while less dense than urban environments, still experience higher PL compared to rural areas, primarily due to the presence of buildings and vegetation. The difference in PL between these environments becomes more pronounced with increasing distance. Understanding these variables in PL is important for the design and optimization of wireless communication systems, as it allows the selection of appropriate transmission power and antenna configuration to provide reliable signal coverage to be ensured. The link budget is necessary to determine the minimum signal strength required for reliable communication between the mobile device and the BS and antenna. It also helps to calculate the maximum PL and determines the maximum distance the cell can reach. These calculations are usually performed using an appropriate propagation model like Cost231 - Hata. Cell range is another important metric that tells us how many BS sites are needed to cover a particular area. The channel budget calculation can be further used to compare the coverage capacity of different systems.

Figure 2 provides a detailed comparison of PL values for different propagation models and different terrain distances between the BS and the mobile station (MS). The data show that, in general, all models exhibit lower PL values in suburban landscapes compared to urban landscapes, consistent with our previous discussion e.g., PL values a in the 3GPP model at a distance of 10 km is 118 dB in the suburbs and 161 dB in the urban areas. Similarly, for the Cost231-Hata model, urban and urban areas have PL values of 157 dB and 172 dB, respectively. This trend is consistent across distances and models, highlighting the influence of soil properties on PL. In addition, it is found that the Cost231-Hata model tends to predict higher PL prices compared to the other models in both landscapes, which may indicate a more rigorous estimation approach. Understanding these variations in PL is crucial for optimizing network planning and deployment strategies to ensure reliable and efficient communication systems.

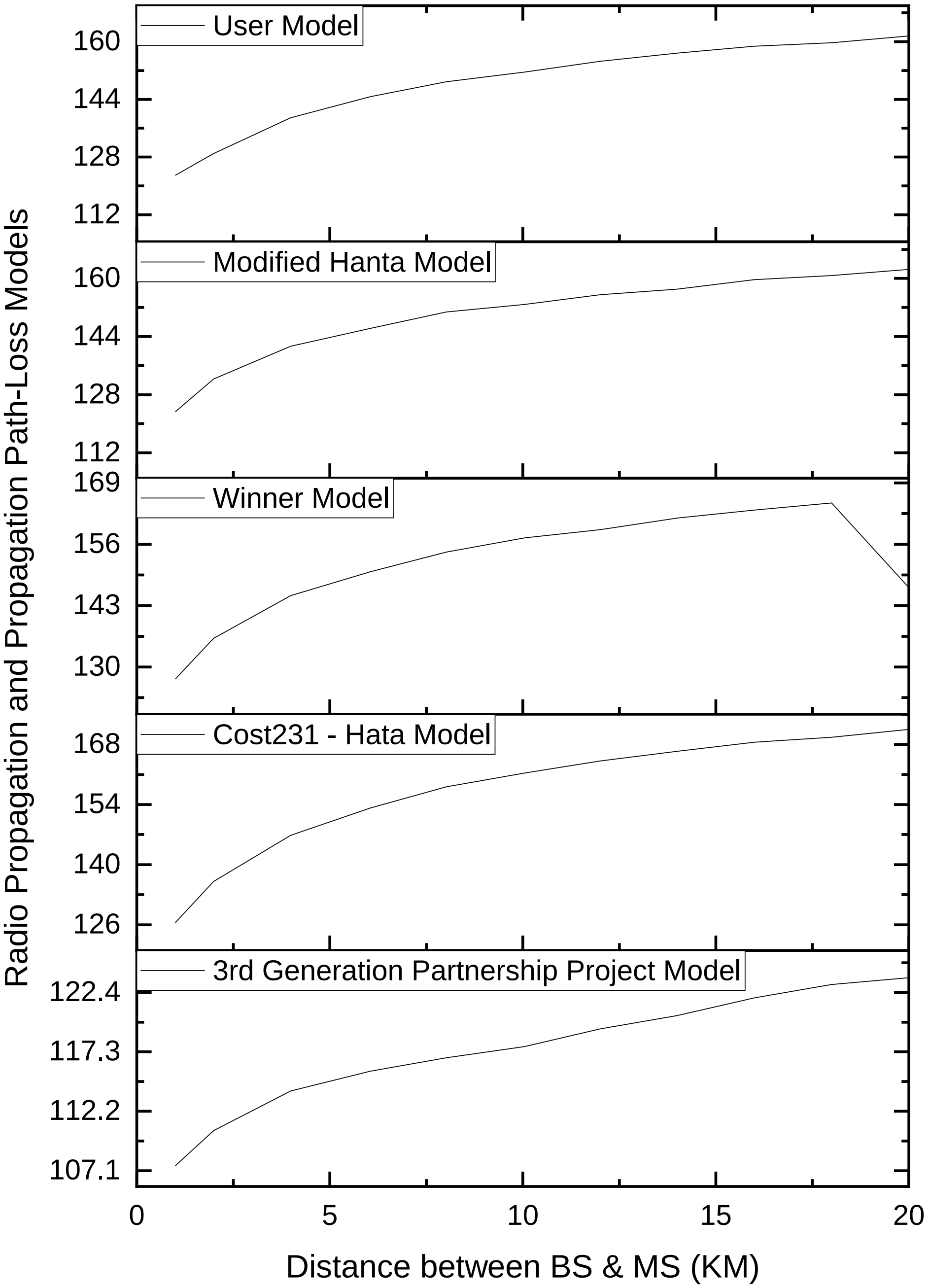

Figure 2. PL Comparison Across Different Propagation Models and Terrains

Figure 3 presents a comparative analysis of PL in various radio propagation environments at different distances. Apparently, PLs in free space are always lower than other areas, which is expected because there is a little or no obstacles. Dense urban areas exhibit the highest PL, due to nearly uniform tall buildings and other obstacles. Suburban areas exhibit higher PL than rural areas, which are within 10 km. Interestingly, the PL values between the Walfisch-Ikegami and COST 231 Hata samples show a small difference at different distances. This comparison highlights the impact of different diffusion models on PL estimates at different locations, and emphasizes the importance of choosing an appropriate model for accurate planning and optimization to design and build a network.

Numerical comparison of PL values at different propagation sites at different distances reveals interesting insights. In rural settings, PL is consistently lower than in densely populated suburban, urban, and urban areas, indicating lower barrier and housing availability. As at 10 km, PL is 154 dB in rural areas, 169 dB in suburban areas, 177 dB in urban environments and 179 dB in complex urban environments. This trend shows as PL increases significantly due to barriers and structures in urban areas. In addition, the comparison between the Walfisch-Ikegami and COST 231 Hata models shows that although there is a small difference in PL values, the overall shape and magnitude of PL remain similar between the two models at locations and beyond. This emphasizes the importance of selecting an appropriate propagation model based on specific environmental characteristics for accurate PL estimation in radio communication systems.

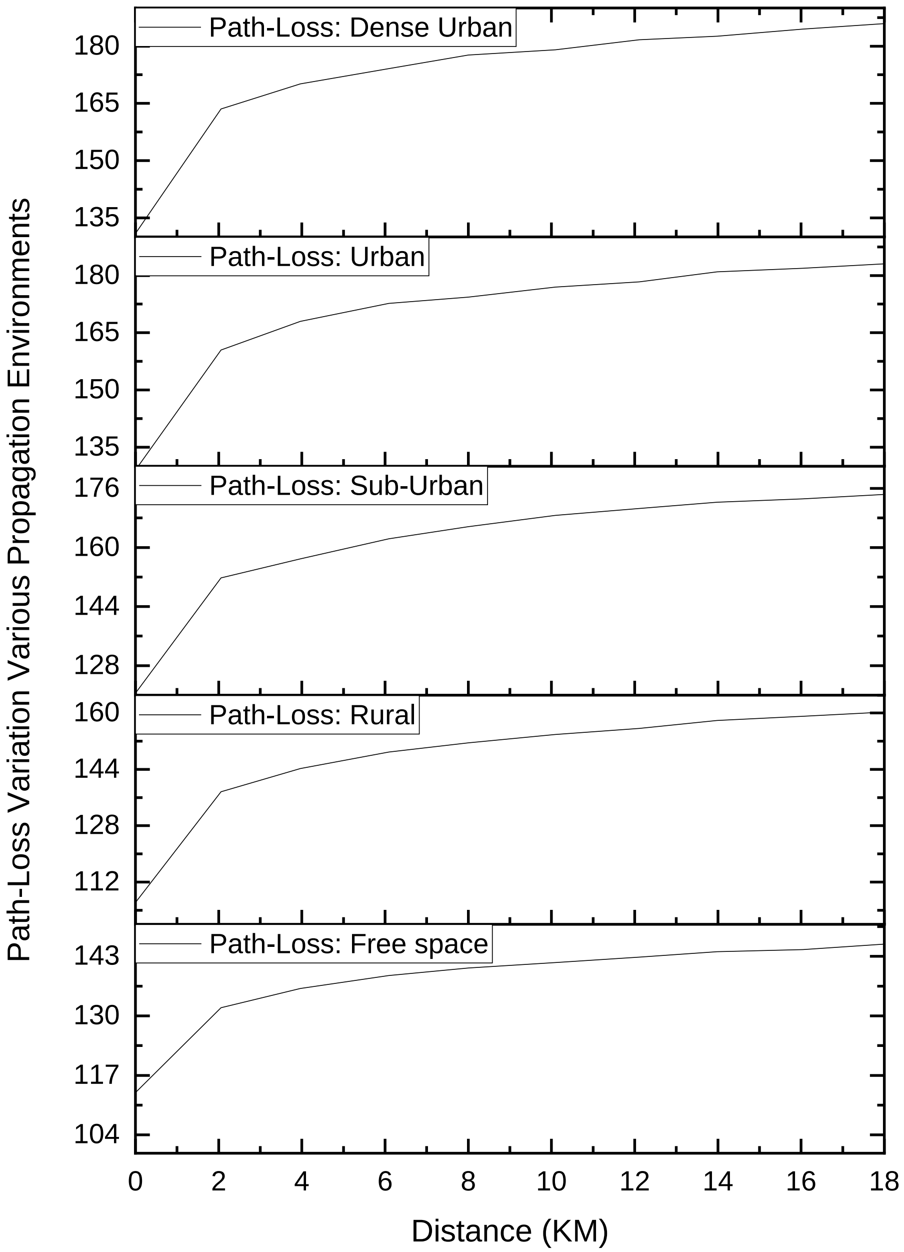

Figure 3. PL Variation with Distance Across Various Propagation Environments

It is evident from the numerical analysis of Figure 4 that all models generally exhibit lower PL values in suburban terrain compared to urban terrain, which is consistent with our earlier observations. For instance, at 10 km, the PL values for 3GPP model are 118 dB in suburban terrain and 158 dB in urban terrain. Similarly, for the Cost231-Hata model, the PL values are 154 dB and 172 dB in suburban and urban terrains respectively. This trend holds true across all distances and models, highlighting the impact of terrain characteristics on PL. Additionally, it is noted that the Cost231-Hata model consistently predicts higher PL values compared to other models for both terrains, indicating a potentially more conservative estimation approach. Understanding these variations in PL is essential for optimizing network planning and deployment strategies to ensure reliable and efficient communication systems in suburban environments.

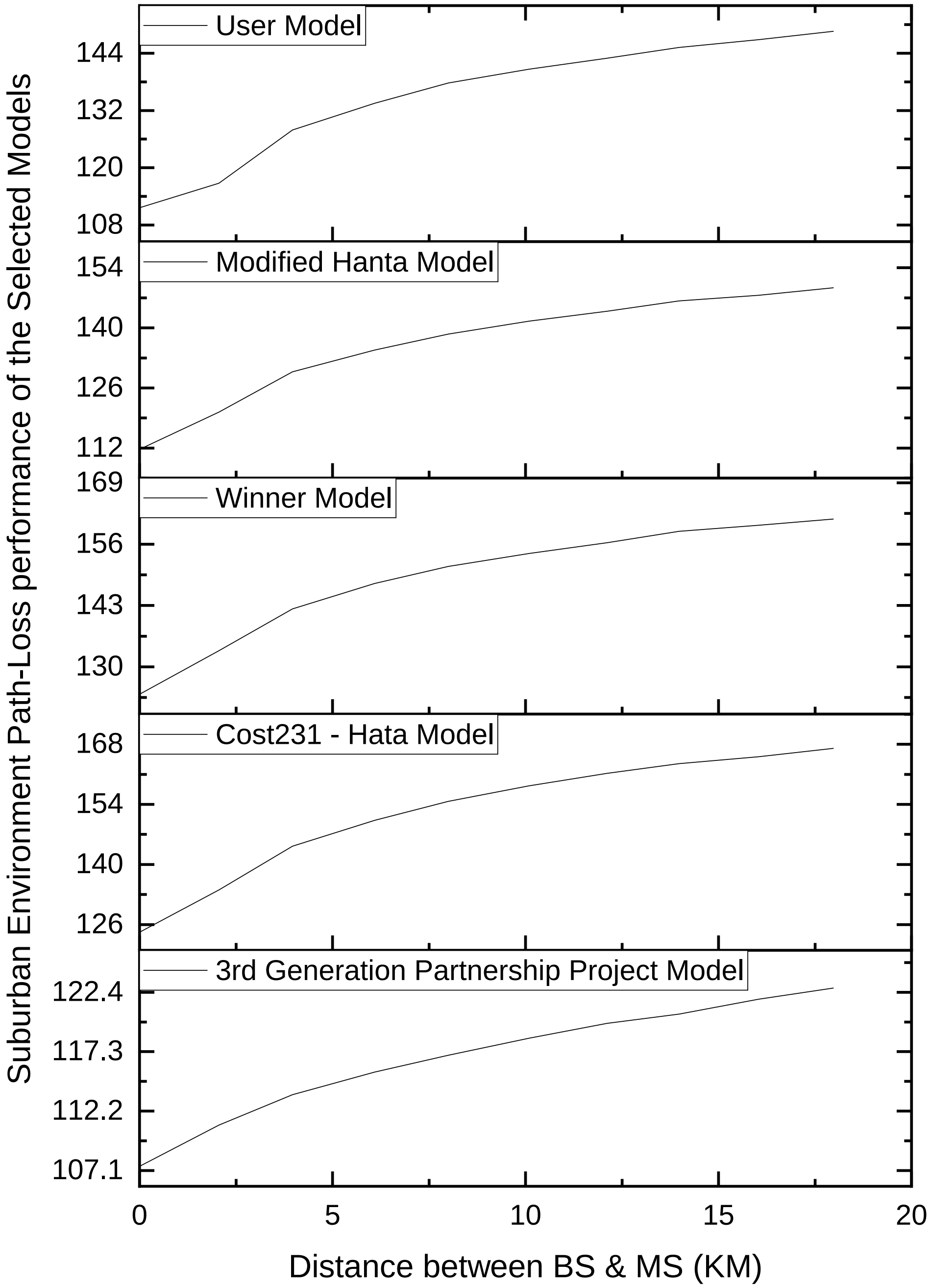

Figure 4. Suburban Environment PL performance of the selected Models

In our study, we conducted simulations with a distance of 3 km in both urban and free space environments to compare the number of eNodeBs required for capacity and coverage. We observed that the number of cells needed for coverage exceeded that required for capacity, indicating that the capacity can be effectively managed. To achieve the target capacity and coverage values, detailed radio planning using tools designed for complete radio network planning is essential. These tools can help in optimizing the network configuration and ensuring efficient resource allocation. The difference in PL between free space and urban environments is significant. In free space, where there are no obstacles to obstruct the signal path, the PL is minimal, primarily due to distance and transmission medium losses. In contrast, in urban environments, various factors such as scattering, reflection, and shadowing contribute to PL. Buildings, trees, and other objects in urban areas attenuate the signal, leading to a decrease in signal power. This difference underscores the importance of accurate radio planning and modeling to account for the specific characteristics of different environments.

Coverage analysis is conducted to determine the required capacity based on the estimated cell size and the number of sites. It helps determine if a system with a certain location density can adequately support the user load or if additional sites are necessary. The number of eNodeBs deployed in the network places a limit on the potential network capacity. Factors such as interference levels, packet scheduler implementation, allowed modulation and coding schemes, and other elements impact the cell throughput in LTE and 5G networks. The channel budget, which considers interference, provides the maximum permissible PL and cell coverage, thereby offering a suitable model for coverage planning. Additionally, like 4G networks, 5G networks exhibit soft capacity, which means there is more interference and network capacity can vary. To further analyze the network performance, we plan to calculate the free space PL and urban PL (using the COST-321 Hata Model) for our parameters in the simulated area of "Johor Bahru." By comparing these values, we aim to gain insights into the differences between the two PL models and their implications for network coverage and performance.

8. Conclusion

In this study, we aimed to establish the LTE radio network planning procedure, focusing on identifying applicable LTE features, describing basic radio propagation planning models, and estimating coverage and network element count. The insights gained from this study can aid in the development of tools used in RNP. RF link budget analysis emerged as a fundamental tool for evaluating LTE and 5G network performance in terms of coverage and capacity. As society increasingly relies on wireless connectivity for various applications, understanding and optimizing these networks becomes imperative. The link budget was established based on standard or preferred values from link calculations, and coverage studies were conducted during the dimensioning stage. Initial network deployment typically involves a small number of subscribers, leading to a gap for future capacity improvements. These results are crucial for the subsequent detailed radio planning stage, where tools are utilized to plan the network layout on a digital map of Johor Bahru. This approach enables the creation of a detailed traffic map with coverage and capacity solutions for strategically placed eNodeBs. The evolution from LTE to 5G represents more than just an increase in speed; it signifies a transformative shift in connectivity, communication, and innovation. RF link budget analysis serves as a guiding principle for network providers and engineers, helping them unlock the full potential of these groundbreaking technologies. In a world where connectivity is vital, RF link budget analysis remains pivotal in ensuring that LTE and 5G networks deliver on their promise of a connected, high-speed, and data-rich future.

Future Recommendations

One potential future research topic could be the investigation of advanced antenna technologies for improving the coverage and capacity of LTE and 5G networks. This could include the study of Massive Multiple-Input Multiple-Output (MIMO) systems, which use many antennas to improve spectral efficiency and increase network capacity. Another area of interest could be the development of beamforming techniques to enhance signal quality and reduce interference in dense urban environments. Additionally, research could focus on the integration of Wave frequencies into existing networks to enable higher data rates and support for emerging applications such as augmented reality and virtual reality.

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