JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

Performance Evaluation of Layered Cell Structures for 5G Networks Using Simulation-Based Analysis

Muhammad Yaser[1]*

[1] Electrical Engineering, Universitas Pancasila Jakarta

*Corresponding Author email : muhammadyaser@univpancasila.ac.id

Abstract

Mobile devices including smartphones and tablets together with other connected terminals have rapidly grown in popularity which drives the need for fast mobile data services. The solution for this challenge requires 5G networks to implement advanced architectural strategies. A layered cell-based design study for 5G cellular networks uses theoretical analysis along with computer-based simulations to evaluate its results. The network performance evaluation examines the effects of cell layering by transforming traditional single-layer cells into two-layer and three-layer configurations. Within the coverage area user devices connect randomly to a central 5G base station. Layered cell architectures deliver better data capacity results than single-layer designs according to theoretical modeling and simulation outcomes. The three-layer structure achieves the best performance among tested scenarios by reaching speeds up to 39,78 Mbps. The research findings deliver essential information about creating optimal layered architectures for future 5G cellular networks.

Keywords: 5G, layered cell structure, network design, multi-tier architecture, capacity analysis, mobile networks

1. Introduction

Ultra-high-definition video streaming, real-time gaming, driverless cars, and the Internet of Things (IoT) are just a few of the mobile applications that have put tremendous strain on the capacity, scalability, and latency performance of contemporary cellular networks. Improved data throughput, higher connection densities, improved energy efficiency, and lower latency performance are the goals of fifth-generation (5G) cellular networks [1],[2],[3]. The attainment of these goals necessitates the deployment of intelligent and flexible network architectures in addition to physical layer innovations in massive MIMO, beamforming, and millimeter-wave (mm Wave) communication [4],[5],[6].

Among the promising architectural evolutions, layered cell structures (also referred to as multi-layer or hierarchical cell structures) have emerged as a practical and effective solution for increasing spectral efficiency and improving user experience in heterogeneous environments. Instead of relying solely on conventional single-layer deployments, a layered approach divides the macro cell into multiple coverage zones or "layers" each served with different transmission power levels and frequency resources allowing tailored service delivery based on user location or mobility patterns.[7],[8].

A basic 2-layer structure typically consists of an inner layer serving users close to the base station (BS) using low power and narrower bandwidth, and an outer layer covering distant users with higher power and broader coverage. This configuration helps reduce intra-cell interference, enhance signal-to-noise ratio (SNR), and improve spectrum reuse. Furthermore, the concept can be extended to 3-layer architectures, either through additional concentric zones or sectorization, to allow more granular control over frequency allocation and directional coverage. Recent studies have reinforced the viability of layered structures in modern network design. For instance, [9] explores simulation models to quantify the capacity benefits of mixed cell structures using distinct frequency layers (e.g., 3.5 GHz and 28 GHz). Likewise, [7] highlights how multitier network models can be optimized using hardware-aware resource allocation, achieving up to 40% computational gain in ultra-dense 5G deployments. Other works [2] investigate fractional frequency reuse (FFR) and adaptive bandwidth management across cell layers to further boost spectral efficiency and user fairness. In terms of practical simulation techniques, works like [10], have demonstrated the applicability of tools such as ns-3 and machine learning-enhanced modeling to replicate and test 5G system behavior under layered configurations. In addition, advanced topics such as non-terrestrial and integrated satellite–terrestrial multi-layer networks are being studied for future 6G systems [11].

A complete evaluation of single-layer versus multi-layer cell setups through actual network conditions including SNR measurements and user capacity distribution along with user equity remains an unresolved research problem. Various past research investigations study network systems at a high level while they do not verify their results through validated standard performance metrics [12],[13]. The research paper delivers a simulation-based assessment of cellular networks which includes single-layer and 2-layer and 3-layer structures for 5G systems [14]. The system model integrates four key components: user association along distance and layer selection process, layer-specific power distribution and bandwidth distribution, inter-layer interference reduction through frequency separation, and capacity evaluation based on Shannon's theorem with thermal noise conditions [15], [16]. We analyze the simulation data through three performance evaluation methods that combine user capacity CDF curves with capacity histograms and log (SNR)-versus-capacity plots. Our analysis shows that multi-layer network designs deliver better maximum user capacity along with better scalability when spatial limitations exist, despite the single-layer system maintaining a steady average capacity.

The rest of this paper is organized as follows. Section II outlines the system model. Section III discusses the simulation results and comparative analysis. Section IV concludes the paper.

2. System Model

This simulation evaluates two types of cellular network architectures to analyze performance in terms of capacity: single-layer networks and layered cell networks as shown in figure 1. In the single-layer network scenario, a conventional macro cell configuration is applied where the entire coverage area is served by a single base station (BS) using an omnidirectional antenna. In this model, all users share the same set of resources specifically, the full transmission power and bandwidth—without differentiation.

JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

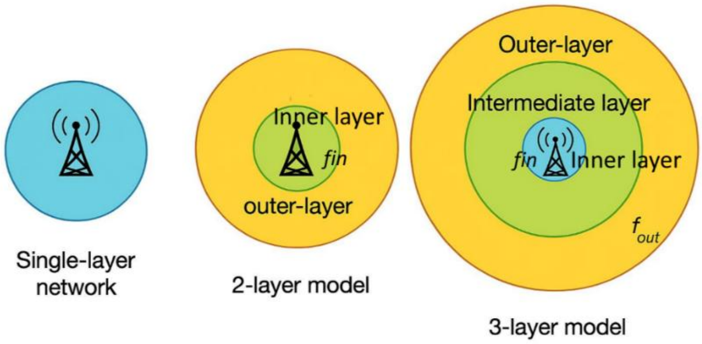

Figure 1. Cellular network architecture modeling

Location dependent. While simple in design, this scheme tends to be afflicted with spectral efficiency and interference cancellation constraints, particularly in dense heavy-loaded urban environments. Layered cell layouts divide the cell into multiple coverage zones based on user proximity to the BS and various capacity requirements. The 2-layer network divides the cell into two zones that are an outer and inner region. The users closer to the BS are provided with the inner layer using lower transmission power while distant users use higher transmission power of the outer layer. The system employs different frequency bands between layers to avoid interference among signals [17], [18]. A third level of coverage extends the 3-layer network on top of the 2-layer network by placing it in between inner and outer layers or by specifying more precise user distribution regions. The model provides better spectral efficiency as well as higher spatial reuse which maximizes network capacity [8]. Network efficiency as well as per-user capacity become much enhanced when layered architecture is applied, especially under heavily loaded deployment scenarios. These architectures are consistent with the requirements of future networks like 5G and 6G that stress flexible topologies of networks and dynamic adaptation of the resources [16]. With proper power and frequency control schemes, hierarchical networks provide better interference management among cell sectors and provide uniform quality of service inside their area of coverage.

3. Results and discussion

To evaluate and compare the capacity performance of 5G cellular networks employing single-layer and multi-layer cell architectures, extensive simulations were conducted. The analysis focuses on two configurations: a two-layer and a three-layer cellular structure. Both scenarios were evaluated using a carrier frequency of 3.5 GHz and a cluster size of N=3. A total of 10,000 Monte Carlo iterations were performed, with user terminals randomly distributed throughout the coverage area to ensure statistical robustness. The key simulation parameters utilized in this study are summarized in Table 1[19], [20], [21].

JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

Table 1. Simulation Parameters

Parameter	Value	Unit
Distance	5000	meter
Base station height	25	meter
Frequency	3.5	GHz
Bandwidth	100e6	Hz
Transmit Power inner	15	Watt
Transmit Power outer	20	Watt
Radius threshold	2500	meter
Temperature / Boltzmann const.	300 / 1.38e-23	K / J/K
Number of iterations	10000	-

In this simulation, the impact of cell layering is evaluated using several performance metrics that provide a comprehensive view of network behavior under different configurations. First, the Cumulative Distribution Function (CDF) of user capacity is analyzed to assess the fairness and variability in capacity allocation across all users within the network. This metric illustrates the proportion of users achieving a given capacity threshold and highlights performance disparities between different cell structures. Second, a histogram of capacity distribution is presented to provide a visual representation of how capacity values are spread across the user population, emphasizing dominant capacity ranges and potential congestion areas. Finally, the SNR vs. capacity trend is examined to explore how signal quality translates into achievable data rates under varying network conditions. These metrics collectively enable a detailed comparison of single-layer, two-layer, and three-layer architectures in terms of their effectiveness in delivering high and consistent user capacity.

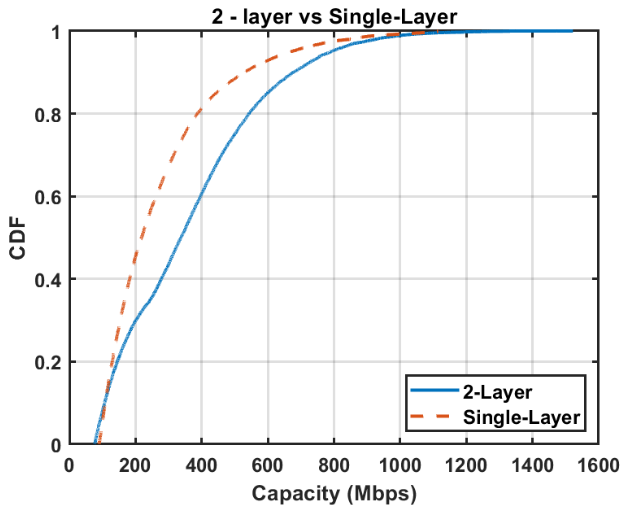

Figure 2. Comparison capacity 2-layer vs Single layer Network

Figure 2 illustrates the Cumulative Distribution Function (CDF) of the capacity for the 2-layer and single-layer cellular network models. The CDF curve of the single-layer increases more quickly than the 2-layer case, which means most of the users in the single-layer system have lower or moderate capacities with fewer fluctuations. In comparison, the 2-layer system spreads wider, with more customers hitting higher capacities, particularly toward the higher end of the range. This means that, while the single-layer network provides a more stable and flat performance for the majority of users, the 2-layer system accommodates some users particularly those positioned best in relation to the base station

JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

and resource allocation to achieve much higher throughput. In brief, the 2-layer system potentially allows for higher peak capacities at the cost of higher variability between users..

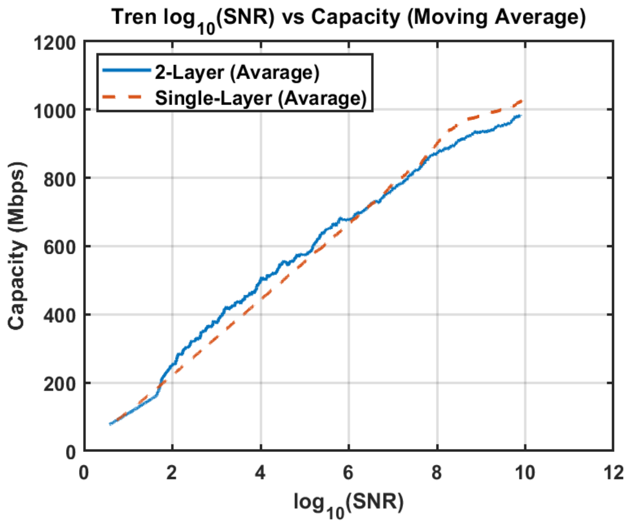

Figure 3. Tren log$_{10}$(SNR) vs Capacity: 2-Layer vs Single-Layer Network

Figure 3 shows the capacity-log$_{10}$(SNR) relationship that is plotted through a moving average for the single-layer and the 2-layer configurations. Both systems, according to the Shannon capacity equation, show an increase in capacity as SNR values become larger. The 2-layer plot (solid blue) shows increased capacity at some intervals of SNR compared to the single-layer (dashed orange) especially in the mid-to-high SNR range. The 2-layer system represents better use of the channel condition thereby enabling users with better SNR to attain high throughput levels. The two systems represent same capacity at low SNR levels but the 2-layer system represents more advantages when SNR rises. The above figure shows that multi-layer systems offer real capacity gains for users with maximum channel conditions.

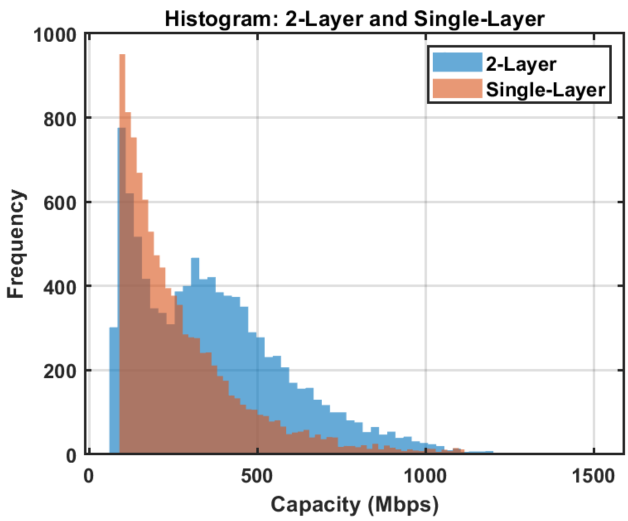

Figure 4. Capacity histogram: 2-Layer vs Single-Layer network

Figure 4's histogram gives the distribution of capacity across 2-layer systems and single-layer systems. Most users in single-layer systems have lower capacities as the distribution

JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

has high peaks at the lower side. In the 2-layer system, there is a larger spread of capacity values so more users are able to get higher levels of capacity. Both of the network designs have a large number of users with low capacity which is most probably because of bad channel conditions or being far away from the base station. The 2-layer network design provides higher capacity potential to more users than the single-layer design..

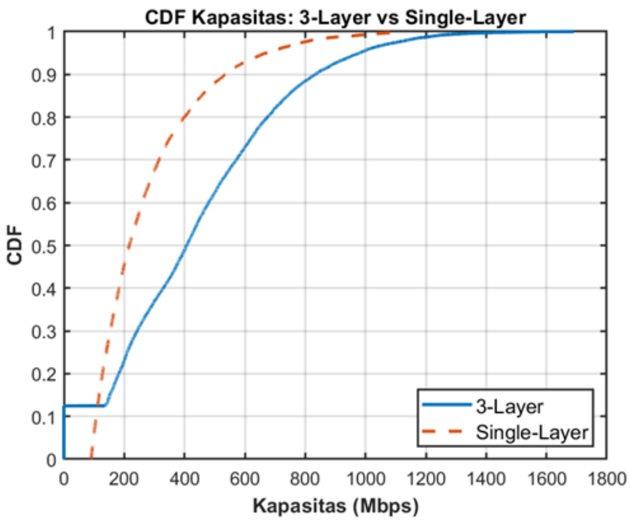

Figure 5. Comparison capacity 3-layer vs Single layer Network

Figure 5 shows how the cumulative distribution function (CDF) of network capacity works in three-layer networks compared to one-layer networks. The CDF of the single-layer network has a sharp rise indicating that the majority of the users are given low uniform capacity values. The 3-layer curve goes to the right showing that certain users obtain significantly higher capacities in the multi-layer configuration. The 3-layer network structure achieves high peak capacities at the expense of non-uniform performance to various users. The single-layer network achieves equal capacity distribution to medium and low-capacity users. The multi-layer network achieves higher capacity potential for users with good channel states but the single-layer system achieves uniform network performance to all users.

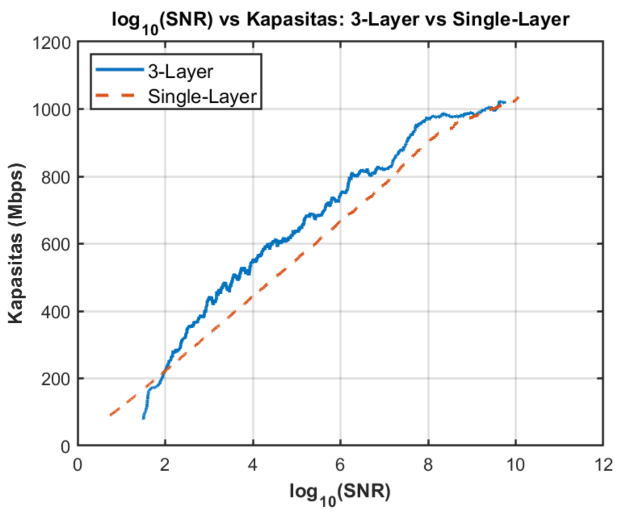

Figure 6. Tren $\log_{10}$(SNR) vs Capacity: 3-Layer vs Single-Layer Network

JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 6, No. 2, pp. 192-200, 2025
e-ISSN 2723-0589

Figure 6 plots log (SNR) against network capacity for single-layer and 3-layer systems. The single-layer system follows a linear capacity slope in accordance with Shannon's theory. The 3-layer system follows a steeper increasing capacity, especially for medium to high ranges of SNR, indicating better utilization of good channel conditions. Though both systems behave in the same way at low SNR, the multi-layer configuration has much higher capacity at high SNR. This indicates the better capability of the multi-layer network to take advantage of SNR fluctuation to achieve capacity.

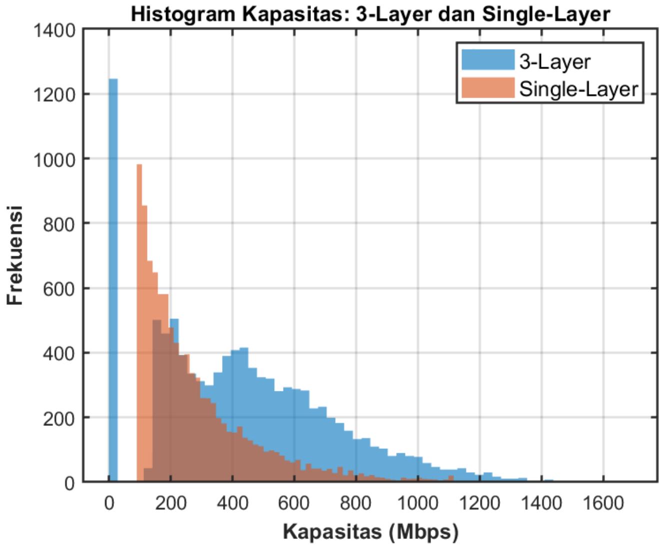

Figure 7. Capacity histogram: 2-Layer vs Single-Layer network

Figure 7 shows a histogram of user capacity distributions for the two configurations. The orange histogram for the single-layer network is dominated by low-to-mid-capacities, with the peak frequency observed at relatively modest values of capacity. The 3-layer histogram (blue) shows a broad, relatively flat spread, with many users achieving capacities above 800 Mbps and even reaching to 1,500 Mbps. Yet, both histograms exhibit a spike at low capacities, showing that some users are still faced with low capacity because they are distant from the base station or have unsatisfactory channel conditions. This observation supports that a 3-layer structure raises the possibility of some users to achieve significantly higher capacities, while the single-layer solution provides more moderate and uniform capacity to most users.

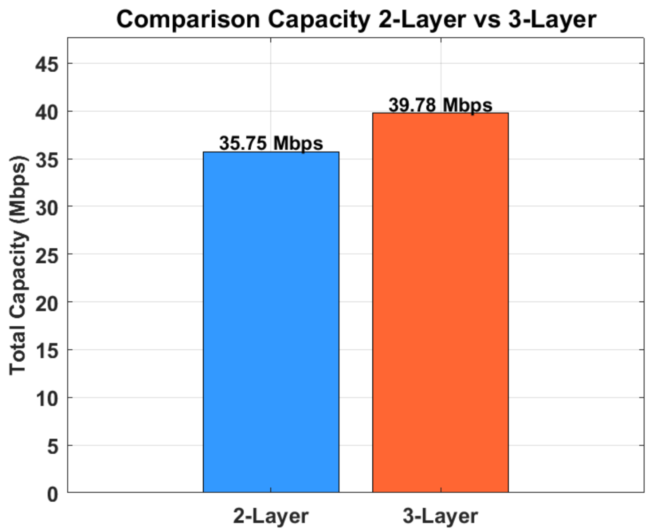

Figure 8. Comparison 2-layer vs 3-layer Network

Figure 8 shows a graph comparing total network capacity for 2-layer and 3-layer cellular systems. From the bar graph, the overall capacity for the 2-layer system is 35.75 Mbps, while the 3-layer system achieves a greater value of 39.78 Mbps. This result indicates that the addition of an additional cell layer brings about an appreciable capacity increase of approximately 11.3% over the 2-layer system. The increased capacity is due to better spectrum utilization and better traffic distribution within the 3-layer structure. With higher cell layers, users can be assigned more appropriately based on their channel conditions and locations, which results in alleviation of interference and bandwidth usage enhancement. These findings reflect that more complex multi-layer network structures, such as the 3-layer model, are more likely to have greater prospects for holding greater data needs in 5G or cellular networks in the future.

4. Conclusion

In this study, a simulation-based performance evaluation of single-layer, two-layer, and three-layer cellular network architectures in 5G systems has been given. It has been demonstrated that layered cell architectures achieve considerable network capacity gains, particularly for users having good channel conditions. The two-layer architecture can offer larger peak capacities than the single-layer system but with larger variance among users. Three-layer architecture also improves the performance up to overall network capacity of 39.78 Mbps an improvement of around 11.3% over the two-layer architecture. All performance metrics such as cumulative distribution function (CDF), capacity histograms, and SNR-to-capacity slopes confirm that multi-layer networks have the potential to utilize available spectrum and channel diversity more effectively. Single-layer systems provide more uniform capacity distribution but with overall lower capacity. These findings confirm that the layered cell structures are efficient in addressing the growing demand for high-throughput services in 5G networks and show promise for the future architecture of wireless networks.

Acknowledgements

We thank all those who willing to help us in completing this research and the editorial team of Jurnal Teknik Elektro Indonesia who has published this paper.

References

[1] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-advanced: next-generation wireless broadband technology [Invited Paper," *IEEE Wireless Commun.*, vol. 17, no. 3, pp. 10–22, Jun. 2010, doi: 10.1109/MWC.2010.5490974.

[2] J. G. Andrews *et al.*, "What Will 5G Be?," *IEEE J. Select. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014, doi: 10.1109/JSAC.2014.2328098.

[3] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014, doi: 10.1109/MCOM.2014.6736746.

[4] T. S. Rappaport *et al.*, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," *IEEE Access*, vol. 1, pp. 335–349, 2013, doi: 10.1109/ACCESS.2013.2260813.

[5] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless Communications Through Reconfigurable Intelligent Surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, 2019, doi: 10.1109/ACCESS.2019.2935192.

[6] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-lin, and Z. Wang, "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015, doi: 10.1109/MCOM.2015.7263349.

[7] M. J. Alam, M. R. Hossain, S. Azad, and R. Chugh, "An overview of LTE/LTE-A heterogeneous networks for 5G and beyond," *Trans Emerging Tel Tech*, vol. 34, no. 8, p. e4806, Aug. 2023, doi: 10.1002/ett.4806.

[8] N. Bhushan *et al.*, "Network densification: the dominant theme for wireless evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 82–89, Feb. 2014, doi: 10.1109/MCOM.2014.6736747.

[9] N. R. Khatiwoda, B. R. Dawadi, and S. R. Joshi, "Capacity and Coverage Dimensioning for 5G Standalone Mixed-Cell Architecture: An Impact of Using Existing 4G Infrastructure," *Future Internet*, vol. 16, no. 11, p. 423, Nov. 2024, doi: 10.3390/fi16110423.

[10] Q. Qin, Z. Liang, S. Liu, and C. Zhou, "A Self-Adaptive Image Encryption Scheme Based on Chaos and Gravitation Model," *IEEE Access*, vol. 11, pp. 47873–47883, 2023, doi: 10.1109/ACCESS.2023.3267485.

[11] H.-W. Lee *et al.*, "Interference Mitigation for Reverse Spectrum Sharing in B5G/6G Satellite-Terrestrial Networks," *IEEE Trans. Veh. Technol.*, vol. 73, no. 3, pp. 4247–4263, Mar. 2024, doi: 10.1109/TVT.2023.3328599.

[12] M. Sandri, M. Pagin, M. Giordani, and M. Zorzi, "Implementation of a Channel Model for Non-Terrestrial Networks in ns-3," in *Proceedings of the 2023 Workshop on ns-3*, Arlington VA USA: ACM, Jun. 2023, pp. 28–34. doi: 10.1145/3592149.3592158.

[13] A. Traspadini, M. Giordani, G. Giambene, and M. Zorzi, "Real-Time HAP-Assisted Vehicular Edge Computing for Rural Areas," *IEEE Wireless Commun. Lett.*, vol. 12, no. 4, pp. 674–678, Apr. 2023, doi: 10.1109/LWC.2023.3238851.

[14] A. A. R. Alsaeedy and E. K. P. Chong, "A Survey of Mobility Management in Non-Terrestrial 5G Networks: Power Constraints and Signaling Cost," *IEEE Access*, vol. 12, pp. 107529–107551, 2024, doi: 10.1109/ACCESS.2024.3438613.

[15] A. Umar, S. A. Hassan, and H. Jung, "Computation Offloading and Resource Allocation in NOMA-MEC Enabled Aerial-Terrestrial Networks Exploiting mmWave Capabilities for 6G," in *ICC 2024 - IEEE International Conference on Communications*, Denver, CO, USA: IEEE, Jun. 2024, pp. 3256–3261. doi: 10.1109/ICC51166.2024.10622807.

[16] L. Bariah *et al.*, "RIS-Assisted Space-Air-Ground Integrated Networks: New Horizons for Flexible Access and Connectivity," *IEEE Network*, vol. 37, no. 3, pp. 118–125, May 2023, doi: 10.1109/MNET.123.2100761.

[17] H. Mei, P. Jiang, and J. Bigham, "Dynamic frequency allocation and network reconfiguration on Relay Based Cellular Network," in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, Paris, France: IEEE, Apr. 2012, pp. 2984–2989. doi: 10.1109/WCNC.2012.6214315.

[18] P. Xia, V. Chandrasekhar, and J. G. Andrews, "Open vs. Closed Access Femtocells in the Uplink," *IEEE Trans. Wireless Commun.*, vol. 9, no. 12, pp. 3798–3809, Dec. 2010, doi: 10.1109/TWC.2010.101310.100231.

[19] J. Whitaker, "Future directions for digital television [Industry Perspectives]," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 4–4, Jun. 2011, doi: 10.1109/MWC.2011.5876493.

[20] X. Ge, S. Tu, G. Mao, C.-X. Wang, and T. Han, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 72–79, Feb. 2016, doi: 10.1109/MWC.2016.7422408.

[21] S. Mukherjee, "Distribution of Downlink SINR in Heterogeneous Cellular Networks," *IEEE J. Select. Areas Commun.*, vol. 30, no. 3, pp. 575–585, Apr. 2012, doi: 10.1109/JSAC.2012.120407.