JTEIN: Jurnal Teknik Elektro Indonesia, Vol. 7, No. 2, pp. 284-292, 2026
e-ISSN 2723-0589

Performance and Fairness Analysis of Two-Layer FFR Networks under Different Traffic Composition.

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Abstract

This paper investigates how the distribution of users between the inner and outer regions affects the performance of a two-layer Fractional Frequency Reuse (FFR) macrocell network operating at 3.5 GHz. The system is evaluated using Monte Carlo simulations with an urban macro propagation model, six neighboring interfering cells, reuse-1 in the inner region, reuse-3 in the outer region, and equal bandwidth sharing within each layer. Three user distributions are considered: inner-user dominant, balanced, and outer-user dominant. The evaluation considers total cell throughput, spectral efficiency, per-user throughput, and Jain's fairness index. The results show that user distribution has little effect on aggregate cell performance, with the average spectral efficiency remaining close to 5.7-bit/s/Hz across the three scenarios. Differences are more apparent at the user level. As the proportion of outer users increases, inner-user throughput increases, while outer-user throughput and overall fairness decrease. Jain's fairness index drops from approximately 0.87 in the inner-user-dominant case to about 0.41 in the outer-user-dominant case. Thus, the two-layer FFR configuration provides relatively stable aggregate performance across the considered user distributions, but the throughput experienced by individual users varies considerably. Among the three scenarios, the balanced case provides a reasonable compromise between aggregate performance and user fairness.

Keywords: Fractional Frequency Reuse (FFR), two-layer networks, user distribution, throughput, spectral efficiency, fairness, Monte Carlo simulation.

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1. Introduction

The fifth-generation (5G) mobile network is being deployed with wider carrier bandwidths around 3.5 GHz and increasingly dense macrocell layouts to support rapidly growing mobile broadband traffic and diverse service requirements [1],[2],[3]. In such interference-limited macrocell environments, especially in urban macro (UMa) scenarios, inter-cell interference remains a key bottleneck for cell-edge throughput and overall spectral efficiency, even when advanced receivers and link adaptation techniques are employed [4], [5]. Fractional Frequency Reuse (FFR) has therefore attracted significant attention as a low-complexity interference coordination mechanism, in which the cell area is divided into an inner region and an outer (edge) region that operate with different reuse factors to protect edge users while attempting to preserve spectral efficiency [6].

Conventional FFR studies typically focus on how the reuse pattern, threshold radius, or bandwidth partitioning between inner and outer regions affect cell-edge performance and aggregate capacity [7], [8]. However, in practical networks the spatial distribution of active users is rarely uniform: at certain times the load may be concentrated near the base station (inner-dominant traffic), while at others it may be shifted toward the cell edge (outer-dominant traffic) [9]. When the FFR configuration

and bandwidth split are kept fixed, changes in the inner–outer user composition may substantially modify the contention level for radio resources in each layer and, consequently, the experienced throughput and fairness among users [10], [11] . How sensitive FFR performance is to such traffic composition shifts is still not fully quantified in a simple, transparent framework.

This observation motivates the main problem addressed in this paper: to characterize the impact of different inner–outer user compositions on the performance of a two-layer FFR macrocell with a fixed geometric threshold radius and fixed bandwidth allocation between layers. More specifically, the study seeks to answer three related questions: (i) how robust is the total cell throughput to variations in the proportion of inner versus outer users when the FFR parameters are unchanged; (ii) how do these compositions affect the throughput distributions of inner and outer users individually; and (iii) what are the implications for cluster-wide fairness when the traffic load is shifted from the inner region to the outer region.

A considerable body of literature has investigated FFR and its variants, including strict and soft reuse patterns, dynamic FFR schemes, and enhancements combined with inter-cell interference coordination and scheduling strategies [12] . Prior works generally report gains in cell-edge spectral efficiency and user throughput, but most analyses implicitly assume a given spatial user distribution or emphasize edge-user improvement without systematically varying the inner–outer traffic share [13],[14], [15]. In addition, many system-level studies rely on complex simulators in which the specific effect of traffic composition on a given FFR structure can be difficult to isolate [16], [17]. Consequently, there is still a need for a focused numerical evaluation that treats inner–outer user composition as an explicit design variable while keeping the FFR layout and bandwidth split fixed.

To address this gap, this paper proposes a numerical evaluation framework for a downlink macrocell operating in the 3.5 GHz band and employing a two-layer FFR scheme. A single reference cell is modeled with a circular coverage area divided into inner and outer regions by a fixed threshold radius. The base station (BS) is located at the cell center with different effective isotropic radiated power (EIRP) levels for inner and outer layers, and user equipment (UEs) are randomly dropped according to a spatially uniform distribution. Three representative traffic compositions are considered, namely inner-dominant (75% inner / 25% outer), balanced (50% / 50%), and outer-dominant (25% / 75%). For each composition, a Monte Carlo simulation is conducted in which realistic UMa-like path-loss, a ring of six neighboring interferers, reuse-3 for the outer layer, partial reuse for the inner layer, and equal bandwidth sharing within each layer are applied.

The main contributions and novelty of this work can be summarized as follows. First, the study explicitly treats the inner–outer user composition as a key variable in the design and assessment of two-layer FFR, rather than as a fixed or implicit assumption. Second, it introduces a lightweight numerical framework that combines realistic BS EIRP settings, urban macro path-loss modeling, and a simple yet representative interference layout (reuse-3 for outer users and thinned interference for inner users), so that the influence of traffic composition on FFR can be transparently examined. Third, the paper jointly evaluates total cell throughput, spectral efficiency, per-user throughput distributions for inner and outer users, and Jain's fairness index, thereby revealing trade-offs between aggregate performance and user-level fairness when the user population is shifted between regions. Finally, the numerical results provide practical insight into how a near-balanced inner–outer composition can maintain high spectral efficiency while avoiding severe fairness degradation, offering useful guidelines for traffic engineering and FFR configuration in 5G macrocell deployments. Finally, the numerical results provide practical insight into how a near-balanced inner–outer composition can maintain high spectral efficiency while avoiding severe fairness degradation, offering

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useful guidelines for traffic engineering and FFR configuration in 5G macrocell deployments.

The rest of this paper is structured as follows: Section 2 outlines the two-layer FFR system model, Section 3 details the simulation methodology and discusses the numerical results, and Section 4 concludes the work.

2. System Model

This study considers a downlink macrocellular network operating in the 3.5 GHz band and employing a two-layer Fractional Frequency Reuse (FFR) scheme. A single reference cell with a circular coverage area is modeled and divided into an inner region and an outer region. The two regions are separated by a fixed threshold radius of $R_{th} =$ 1000 m, corresponding to one-half of the cell radius. The base station (BS) is located at the cell center with a fixed antenna height, while user equipment (UEs) are randomly distributed within the cell according to a spatially uniform distribution. To investigate the impact of traffic composition, three representative scenarios are considered, namely inner-dominant, balanced, and outer-dominant user distributions. The principal simulation parameters are summarized in Table I.

In the proposed two-layer FFR architecture, the inner and outer regions operate on different carrier frequencies within the same 5G NR band. The available spectrum is partitioned into two non-overlapping sub-bands assigned to the inner and outer layers, respectively, following a conventional FFR configuration. Different effective isotropic radiated power (EIRP) levels are employed for the two layers, with the outer layer using a higher transmit power to provide additional coverage support for cell-edge users. At the receiver side, the noise power is modeled as thermal noise density scaled by the receiver noise figure and the bandwidth allocated to each layer.

Large-scale propagation is modeled using a simplified 3GPP Urban Macro (UMa) path-loss model with breakpoint correction. The path-loss depends on the three-dimensional distance between the BS and each UE, while the breakpoint distance accounts for the combined influence of antenna heights and carrier frequency. The resulting path-loss is converted into a linear channel gain for signal-to-interference-plus-noise ratio (SINR) calculations. The received SINR of user (u) is expressed as

$$\gamma_u = \frac{P_t G_u}{\sum_{k=1}^{N_I} P_k G_{k,u} + N} \quad (1)$$

where Pt denotes the transmit power of the serving BS, G_u is the corresponding channel gain, P_k and $G_{k,u}$ represent the transmit power and channel gain of the k-th interfering BS, respectively, N_I is the number of active interferers, and N denotes the receiver noise power.

Inter-cell interference is modeled by placing six neighboring BSs on a hexagonal ring surrounding the reference cell. For the outer layer, a reuse-3 pattern is implemented by considering only the co-channel interferers that operate on the same outer-layer frequency resources. For the inner layer, a partial reuse scheme is adopted, in which only a subset of neighboring BSs contributes interference, thereby representing a simplified form of inter-cell interference coordination (ICIC).

The study adopts a system-level abstraction in which user throughput is estimated directly from SINR using the Shannon capacity formula, without explicit modeling of OFDM waveform processing, link adaptation, scheduling, or retransmission mechanisms. Within each layer, the available bandwidth is shared equally among active users. Consequently, the instantaneous throughput of user (u) is given by

$$R_u = B_u \log_2(1 + \gamma_u) \quad (2)$$

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where (B_u) denotes the effective bandwidth allocated to user (u). For each network realization, the total cell throughput is obtained by summing the throughput of all active users:

$$R_{cell} = \sum_{u=1}^{N} R_u \quad (3)$$

where (N) denotes the total number of active users within the cell. The cell spectral efficiency is computed by normalizing the total cell throughput with respect to the total bandwidth utilized by the inner and outer layers:

$$\eta = \frac{R_{cell}}{B_{in}+B_{out}} \quad (4)$$

where (B_{in}) and (B_{out}) denote the bandwidth allocated to the inner and outer layers, respectively. To evaluate the fairness of throughput distribution among users, Jain's Fairness Index is employed:

$$J = \frac{\left(\sum_{u=1}^{N} R_u\right)^2}{N \sum_{u=1}^{N} R_u^2} \quad (5)$$

Where values approaching unity indicate a highly uniform throughput distribution among users, whereas smaller values correspond to increasing disparity among users.
A Monte Carlo simulation procedure with a large number of statistically independent user drops is performed to obtain reliable estimates of cell throughput, spectral efficiency, and fairness. The resulting performance metrics are analyzed and discussed in Section 3.

3. Results and discussion

In Section 3, a numerical evaluation is carried out for the proposed two-layer FFR scheme introduced in the system model. The assessment relies on Monte Carlo simulation for several inner–outer user compositions namely inner-dominant, balanced, and outer-dominant user distributions, while keeping the FFR configuration and bandwidth partitioning fixed. The analysis investigates how these compositions affect performance at both cell and user levels, using total cell throughput, spectral efficiency, inner- and outer-user throughput distributions, and Jain's fairness index as key metrics.

Table 1. Simulation Parameters

Parameter	Values
Cell radius	2000 m
BS height	25 m
UE height	1.75 m
Inner carrier frequency	3.4125 GHz
Outer carrier frequency	3.4875 GHz
BS EIRP (inner layer)	50 dBm
BS EIRP (outer layer)	53 dBm
Total system bandwidth	100 MHz
Fixed threshold radius	1000 m
Iteration	1000

Simulation parameters are summarized in Table 1, the main results are presented in the form of CDF curves and bar charts in Figures 1–5, and subsequently discussed to

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highlight the trade-offs among total throughput, per-user throughput, and fairness when the traffic load is shifted from the inner region to the outer area.

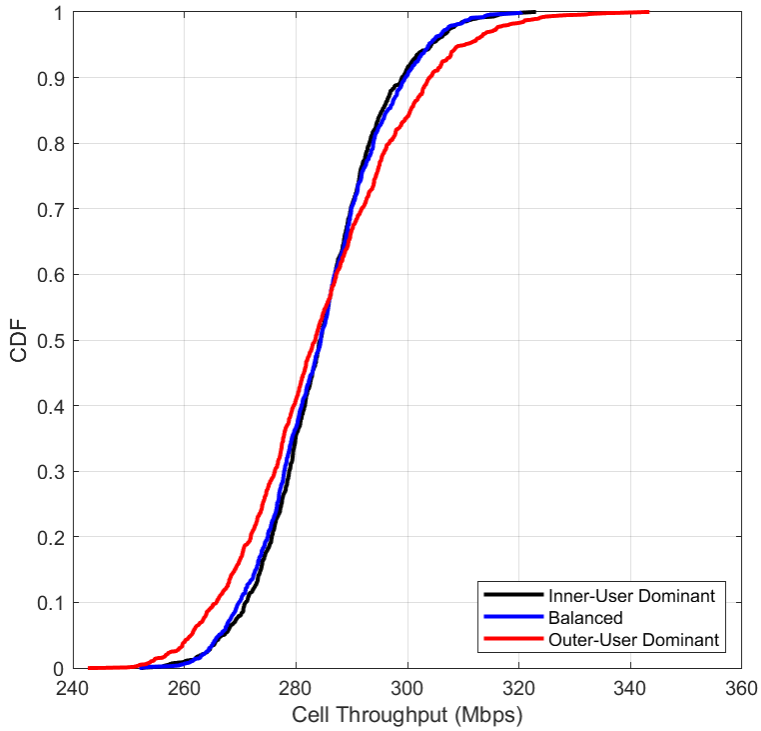

Figure 1. CDF of Total Cell throughput for Different Inner–Outer User Compositions.

Figure 1 presents the CDF of total cell throughput for the three inner–outer user compositions. The distributions are relatively close, with most throughput values falling between approximately 260 and 320 Mbps. The inner-user-dominant and balanced cases show similar behavior across much of the distribution. The outer-user-dominant case differs slightly, particularly at the lower and upper percentiles, but the curves intersect around the middle of the distribution. The median throughput remains within approximately 285–290 Mbps for all three cases. These relatively small differences suggest that the total cell throughput remains fairly stable across the considered user compositions under the two-layer FFR configuration.

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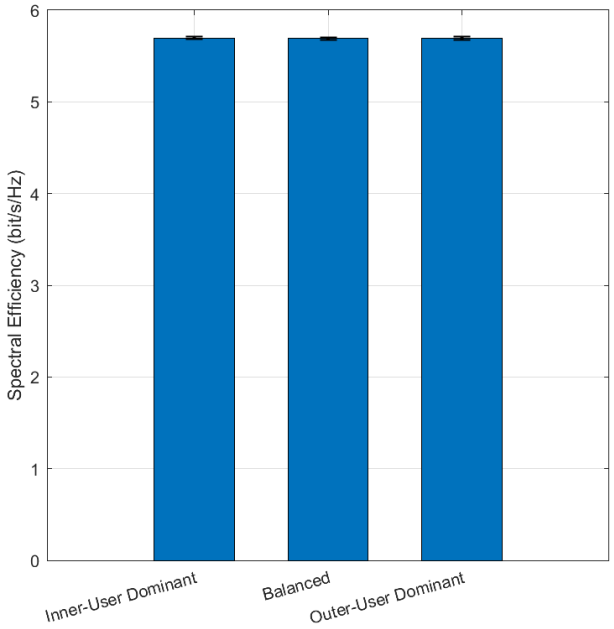

Figure 2. Average Cell Spectral Efficiency for Different Inner–Outer User Compositions

Figure 2 presents the average spectral efficiency for the three inner–outer user compositions. The spectral efficiency remains close to 5.7 bits/s/Hz in all three scenarios, with only minor differences between the inner-user-dominant, balanced, and outer-user-dominant cases. The narrow 95% confidence intervals also indicate low variability across the simulation realizations. These results suggest that changes in the inner–outer user composition have little effect on the overall spectral efficiency under the considered two-layer FFR configuration. In particular, the similar values across the three scenarios indicate that spectrum utilization remains relatively stable as the user distribution changes from inner-user dominant to outer-user dominant.

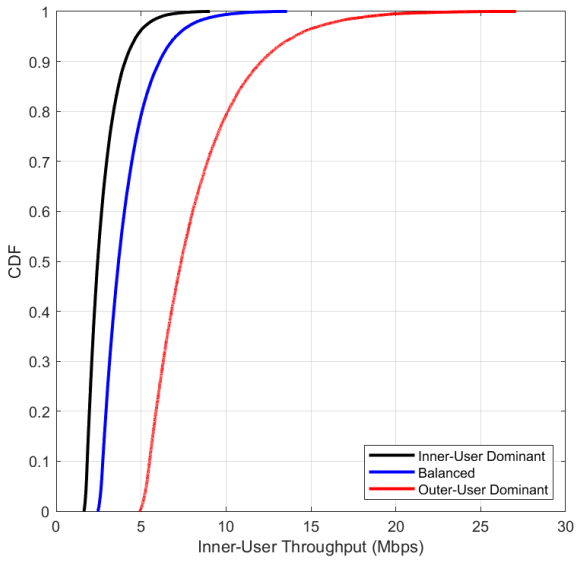

Figure 3. CDF of Inner-User Throughput for Different Inner–Outer User Compositions.

Figure 3 presents the CDF of inner-user throughput for the three inner–outer user compositions. The distributions shift progressively to the right as the proportion of inner users decreases. In the inner-user-dominant case, throughput is concentrated at lower values because the inner-layer resources are shared among more users. The balanced case shows higher per-user throughput as the number of users sharing these resources decreases. A further improvement is observed in the outer-user-dominant case, where fewer inner users share the available inner-layer bandwidth. The clear separation among the three distributions indicates that inner-user throughput is strongly influenced by the number of users sharing the inner-layer resources.

Figure 4 presents the CDF of outer-user throughput for the three inner–outer user compositions. The distributions shift progressively to the left as the proportion of outer users increases. In the inner-user-dominant case, outer users achieve higher throughput because fewer users share the available outer-layer resources. The balanced case shows intermediate performance, while the outer-user-dominant case has the lowest per-user throughput, with most values below approximately 2 Mbps. This trend reflects the effect of resource sharing in the outer layer, where increasing the number of outer users reduces the bandwidth available to each user. The clear separation among the three distributions indicates that outer-user throughput is strongly influenced by the number of users sharing the outer-layer resources.

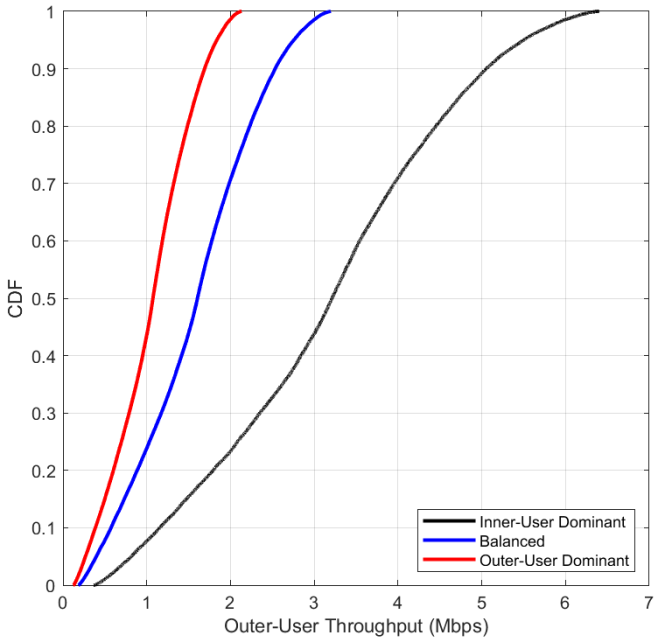

Figure 4. CDF of Outer -User Throughput for Different Inner–Outer User Compositions.

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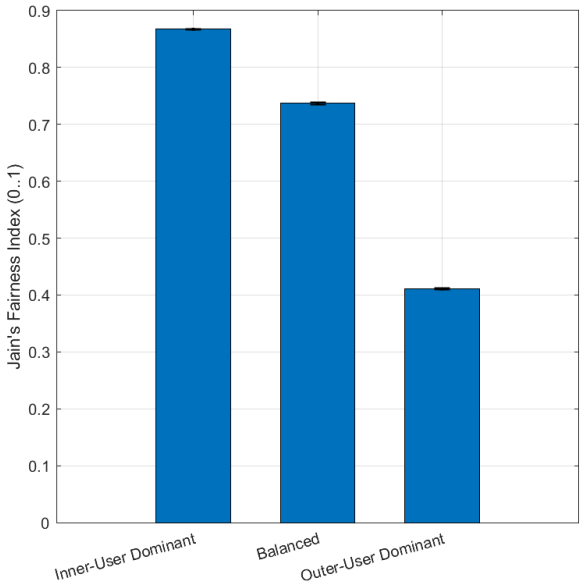

Figure 5. Mean Jain's Fairness Index for Different Inner–Outer User Compositions.

Figure 5 presents the average Jain's fairness index for the three inner–outer user compositions. The inner-user-dominant case achieves the highest fairness, with an index of approximately 0.87, indicating a relatively even distribution of throughput among users. The fairness index decreases to about 0.74 in the balanced case and further to approximately 0.41 in the outer-user-dominant case. This decline reflects the growing disparity in per-user throughput as the proportion of outer users increases, consistent with the throughput distributions observed in Figures 3 and 4. In particular, the larger number of users sharing the outer-layer resources results in lower per-user throughput in the outer region, increasing the throughput difference across users. Although the aggregate cell throughput and spectral efficiency remain relatively stable, the fairness results show that the distribution of throughput among individual users is strongly affected by the inner–outer user composition.

4. Conclusion

This paper examined how the inner–outer user distribution affects the performance of a two-layer Fractional Frequency Reuse (FFR) macrocell network operating at 3.5 GHz. Changes in user composition have little effect on aggregate cell throughput and spectral efficiency, with the average spectral efficiency remaining close to 5.7-bit/s/Hz across the three scenarios. The effect is more noticeable at the user level. As the proportion of outer users increases, inner-user throughput increases, while outer-user throughput and overall fairness decrease. Jain's fairness index falls from approximately 0.87 in the inner-user-dominant case to about 0.41 in the outer-user-dominant case. Thus, although aggregate performance remains relatively stable across different user compositions, the throughput distribution among individual users changes considerably. Among the cases considered, the balanced scenario offers a reasonable compromise between aggregate performance and user fairness.

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.

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References

[1] C. Sudhamani, M. Roslee, J. J. Tiang, and A. U. Rehman, "A Survey on 5G Coverage Improvement Techniques: Issues and Future Challenges," *Sensors*, vol. 23, no. 4, p. 2356, Feb. 2023, doi: 10.3390/s23042356.

[2] M. M. Ahamed and S. Faruque, "5G Network Coverage Planning and Analysis of the Deployment Challenges," *Sensors*, vol. 21, no. 19, p. 6608, Oct. 2021, doi: 10.3390/s21196608.

[3] E. Björnson, F. Kara, N. Kolomvakis, A. Kosasih, P. Ramezani, and M. B. Salman, "Enabling 6G Performance in the Upper Mid-Band by Transitioning From Massive to Gigantic MIMO," 2024, *arXiv*. doi: 10.48550/ARXIV.2407.05630.

[4] K. Bechta, C. Ziółkowski, J. M. Kelner, and L. Nowosielski, "Modeling of Downlink Interference in Massive MIMO 5G Macro-Cell," *Sensors*, vol. 21, no. 2, p. 597, Jan. 2021, doi: 10.3390/s21020597.

[5] W. Yang, J. Zhang, and J. Zhang, "On Performance of Ultra-Dense Neighborhood Small Cell Networks in Urban Scenarios," *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1378–1382, Apr. 2021, doi: 10.1109/LCOMM.2020.3043205.

[6] M. Osama, S. El Ramly, and B. Abdelhamid, "Interference Mitigation and Power Minimization in 5G Heterogeneous Networks," *Electronics*, vol. 10, no. 14, p. 1723, Jul. 2021, doi: 10.3390/electronics10141723.

[7] S. C. Lam and X. N. Tran, "Fractional Frequency Reuse in Ultra Dense Networks," *Physical Communication*, vol. 48, p. 101433, Oct. 2021, doi: 10.1016/j.phycom.2021.101433.

[8] M. Seo, S.-H. Chang, J.-M. Lee, K.-H. Kim, H. Park, and S.-H. Kim, "Optimal Coverage of Full Frequency Reuse in FFR Networks in Relation to Power Scaling of a Base Station," *Sensors*, vol. 23, no. 21, p. 8925, Nov. 2023, doi: 10.3390/s23218925.

[9] L. Xu *et al.*, "Pivoting on the spatial dimension for mobile telecom energy-saving," 2023, *arXiv*. doi: 10.48550/ARXIV.2303.06529.

[10] P. Kihato, S. Musyoki, and A. Onim, "Fractional Frequency Reuse Optimal SINR Threshold Selection Using NIR and ISODATA," *Telecom*, vol. 3, no. 3, pp. 433–447, Jul. 2022, doi: 10.3390/telecom3030023.

[11] M. Morini, E. Moro, I. Filippini, D. De Donno, and A. Capone, "Shaping Radio Access to Match Variable Wireless Fronthaul Quality in Next-Generation Networks," 2024, *arXiv*. doi: 10.48550/ARXIV.2406.15899.

[12] W. Zhang, Y. Wang, M. Xu, and P. Zhang, "Interference management with adaptive fractional frequency reuse for LTE-A femtocells networks," *The Journal of China Universities of Posts and Telecommunications*, vol. 20, no. 2, pp. 86–91, Apr. 2013, doi: 10.1016/S1005-8885(13)60033-3.

[13] 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.

[14] V. M. Nguyen and M. Kountouris, "Performance Limits of Network Densification," *IEEE J. Select. Areas Commun.*, vol. 35, no. 6, pp. 1294–1308, Jun. 2017, doi: 10.1109/JSAC.2017.2687638.

[15] R. Nasri and A. Jaziri, "Analytical Tractability of Hexagonal Network Model With Random User Location," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3768–3780, May 2016, doi: 10.1109/TWC.2016.2528245.

[16] M. Manalastas *et al.*, "Design Considerations and Deployment Challenges for TurboRAN 5G and Beyond Testbed," *IEEE Access*, vol. 10, pp. 39810–39824, 2022, doi: 10.1109/ACCESS.2022.3166947.

[17] J. Lorincz and Z. Klarin, "How Trend of Increasing Data Volume Affects the Energy Efficiency of 5G Networks," *Sensors*, vol. 22, no. 1, p. 255, Dec. 2021, doi: 10.3390/s22010255.

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