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Enhancing capacity in 5G network by cell tiering

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Abstract

The growing reliance on data-centric devices like smartphones, tablets, and notepads has led to a sharp increase in the demand for high-speed mobile data. To address this demand, mobile network providers must develop network infrastructures with higher capacity. This research explores the performance of single-tier and multi-tier cellular networks in 5G by upgrading single-tier cells into multiple tiers. Through computer simulations, the capacity of each setup is evaluated for users randomly distributed within the cell and connected to a central 5G base station. The capacity assessment for 2-tier and 3-tier cells is carried out at a 3.5 GHz frequency with a cluster size of N = 3. The outer tier transmits at 20W, which exceeds the 10W used by the inner tier. Both theoretical evaluations and simulations demonstrate that multi-tier designs typically surpass single-tier configurations in capacity. Among the tested models, the 3-tier cell delivers the highest performance, reaching 3 Gbps, compared to 2 Gbps for the 2-tier setup and 1.6 Gbps for the single-tier arrangement. These results aim to support the development and implementation of multi-tier architectures in 5G networks.

Keywords

Single-tier, Multi-tier, Capacity, 5G network, Optimization

Introduction

In wireless networks, the total frequency bandwidth is segmented into smaller sub-bands and assigned to neighboring coverage areas to ensure efficient utilization. This strategy improves the overall Signal-to-Interference-plus-Noise Ratio (SINR) of the system, thereby boosting network capacity. Despite this, single-tier cell deployments typically suffer from significant interference, leading to reduced SINR for users located at the edges of cells, known as Cell Edge Users (CEUs). To address this, Fractional Frequency Reuse (FFR) was introduced as a multi-tier cell technology. FFR partitions the cell into inner and outer areas, assigning different Frequency Reuse Factors (FRFs) to each. For example, the inner tier may have FRF = 1, while the outer tier operates with FRF = 1/3, and power levels are higher in the outer region to mitigate interference for CEUs.

While fourth-generation (4G) systems using Orthogonal Frequency Division Multiple Access (OFDMA) made significant strides in frequency reuse techniques, third-

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generation (3G) systems based on code-division methodologies showed limited improvement. Fifth-generation (5G) networks face persistent challenges in frequency allocation, as the demand for high capacity must be met within the constraints of limited spectrum resources. Worldwide, the objective of 5G is to provide minimal transmission delays, improved use of radio frequencies, faster data rates, and adaptable network architecture.[1].

The practical implications of limited spectrum and the growing demand for higher capacity are evident in both urban and rural areas. In densely populated urban centres, the explosive growth of data-intensive applications on smartphones and tablets necessitates small cells and dense, high-capacity base stations. These base stations must deliver fast, adaptive, and dynamic responses to fluctuating user demand in hot spots. Conversely, rural areas often grapple with inadequate coverage and suboptimal capacity due to sparse infrastructure. Balancing these challenges highlights the critical need for innovative spectrum management strategies to ensure equitable and efficient connectivity across diverse geographic regions [2].

Despite the progress in 5G deployment, gaps remain in achieving optimal spectrum utilization globally. Current 5G implementations often focus on high-band millimetre-wave (mm Wave) technologies, which provide high capacity but are limited in coverage and penetration. Furthermore, many studies overlook the potential benefits of advanced cell-tiering strategies in addressing spectrum efficiency challenges.

Investigating cell-tiering techniques in 5G networks is crucial, as preliminary experiments suggest that this approach may outperform traditional integer frequency reuse methods in capacity optimization. This research investigates how dividing 5G cells into core and peripheral zones, with balanced bandwidth distribution, influences network performance. The effect of this tiering on system capacity is then observed and analysed.

The rest of this paper is organized as follows: Section 2 discusses previous research, Section 3 explains the fundamentals of frequency reuse, Section 4 outlines the system model, Section 5 provides the simulation results, and Section 6 offers the conclusion.

Literature Review

A study conducted in [3] investigated the two primary implementations of Fractional Frequency Reuse (FFR)—Strict FFR and Soft Frequency Reuse (SFR)—by modelling base station locations using a Poisson point process. The outcomes were compared against a conventional grid-based model and a real-world urban network deployment. In real-world scenarios for modern cellular systems, the results simplified into clear analytical expressions, offering insights for network planning and illustrating the comparative benefits of Strict FFR, SFR, universal frequency reuse, and traditional fixed frequency reuse schemes. However, these studies focused primarily on theoretical comparisons without addressing dynamic resource allocation challenges in real-world 5G scenarios, leaving a gap in adaptive FFR strategies for diverse network conditions.

In [4], a unique SFR strategy for LTE-A called Three Band Improved SFR (3B-ISFR) was proposed. This method centralizes the Frequency Reuse Pattern (FRP) allocation for microcells at the macrocell level using a cognitive-assisted approach, which incorporates an intra-cell offloading algorithm to balance the load between the cell-center and cell-edge users. The performance of 3B-ISFR was validated through comparative analysis in terms of outage probability and average cell capacity. However, while effective for LTE-A, the proposed approach does not fully address the scalability and complexity required in heterogeneous 5G networks, where ultra-dense deployments and diverse traffic patterns demand more flexible frequency reuse mechanisms.

The Adaptive SFR (ASFR) algorithm proposed in [5] dynamically optimizes subcarrier and power allocations in multicell wireless networks to enhance system capacity. The ASFR algorithm uses greedy descent and exhaustive search techniques to allocate subcarriers and power and iterates until convergence. Simulation results demonstrate that ASFR outperforms existing frequency reuse techniques in terms of system throughput and cell-edge user performance. Despite its success, the ASFR method primarily focuses on resource optimization within homogeneous networks, neglecting the challenges posed by heterogeneous network environments and inter-cell interference management in 5G.

In [6], Multi-Level Soft Frequency Reuse for Heterogeneous Networks (ML-SFR HetNet) was introduced as a resource allocation strategy that assigns mutually exclusive spectrum among macro and small cells, as well as cell-edge users. Analytical formulas for spectrum and power allocation, area spectral efficiency (ASE), and throughput were developed. Simulation results indicate that ML-SFR HetNet improves throughput by approximately 3.5 times and reduces outage probability by nearly fivefold compared to conventional SFR systems. While this approach demonstrates significant improvements, it requires high computational complexity and lacks adaptive capabilities to respond to real-time variations in user density and traffic demand.

Research conducted by [7] explored several FFR strategies, including Strict FFR and SFR, and compared them with traditional frequency reuse methods. The findings revealed that FFR systems outperform traditional techniques by improving cell-edge user performance in terms of Signal-to-Interference-Plus-Noise Ratio (SINR), throughput, and spectral efficiency. However, these studies do not explore advanced frequency allocation models that adapt dynamically to 5G's unique requirements, such as ultra-low latency and massive device connectivity.

In [8], an algorithm was proposed that assigned different frequency reuse factors to center and edge users, minimizing Inter-Cell Interference (ICI) for edge users. MATLAB simulation results demonstrated that the approach achieved a balance between efficiency and convenience for edge and center users. The reuse-1/reuse-3 framework enabled higher throughput for both user types at a low cost. Nevertheless, this method primarily evaluates throughput performance without addressing key metrics such as spectral efficiency and outage probability in diverse 5G environments.

Frequency Reuse

Frequency reuse technique is a technique of using the same frequency (repeatedly) to maximize the use (utilization) of frequency as a limited resource and increase cell capacity by minimizing interference between adjacent cells.

Frequency reuse factor (FRF) is a factor that shows the amount or percentage of frequencies that can be repeated for all cells. FRF is 1/K if all cells in the network can only repeat 1/K of bandwidth marked with K cells cannot use the same frequency in 1 cluster. For example, Figure 1 illustrates Fractional Frequency Reuse F = 1 (FRF F=1), which is all cells use whole bandwidth. FRF F=1 can achieve high spectrum efficiency, but it potentially generates inter-cell interference (ICI) at the cell boundaries (cell edges).

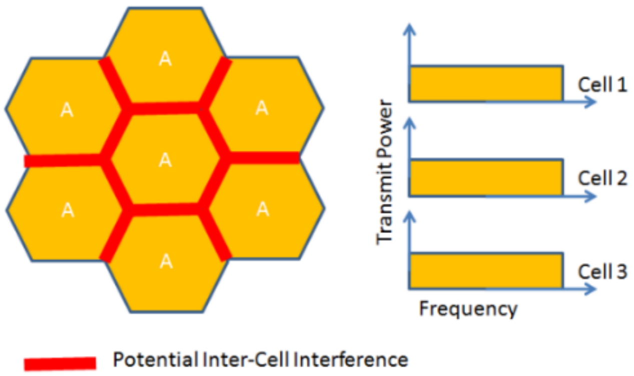

Figure 1. Frequency Reuse Factor F = 1

ICI problem can be solved by adopting frequency reuse factors more than 1 like 3, 4, or 7. Figure 2 illustrates the layout and resource distribution approach in an omni-directional cell using FRF-3. The available spectrum is split into three distinct portions, with each portion assigned to one of the three adjacent cells. This ensures that there is no frequency reuse among the neighbouring cells. Consequently, ICI at the edges of the cells is significantly minimized. Nevertheless, each cell is limited to accessing only one-third of the full spectrum, leading to reduced spectral efficiency

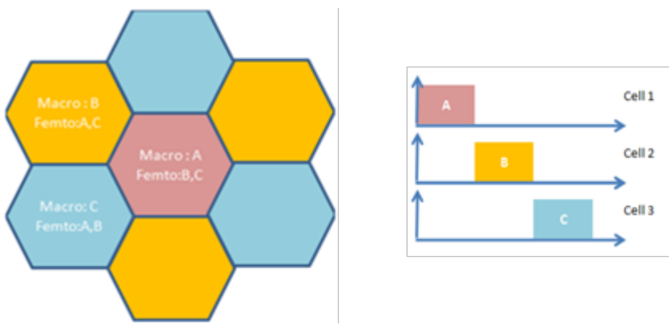

Figure 2. Frequency Reuse Factor F = 3

Figure 3 presents the network layout and resource assignment strategy in an omni-directional cell employing FRF-7. The complete spectrum is partitioned into seven separate segments, with each segment designated to one of the six surrounding cells. This configuration avoids any duplication in frequency usage among the six adjacent cells. As a result, inter-cell interference (ICI) at the cell boundary is better than FRF-3. But, FRF-7 have a consequence that spectral efficiency becomes lower than FRF-3.

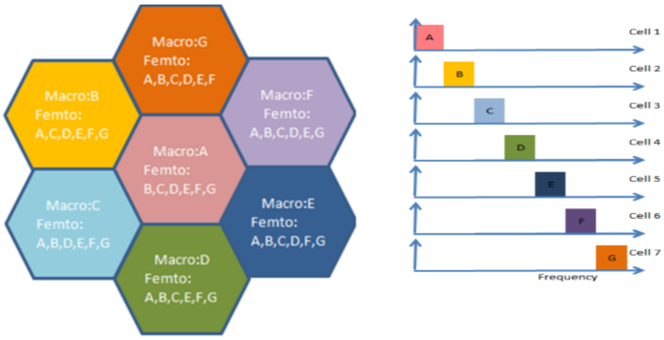

Figure 3. Frequency Reuse Factor F = 7

Method & System Model

An increase in the numerical frequency reuse factor indicates that the division of cells into multiple tiers will result in an increase in spectrum utilization. The total system capacity will rise with increased spectrum use. In this study, we demonstrate that increasing the number of tiers in a cell will boost system capacity.

Single tier N = 3

In this scheme, the bandwidth allocation is divided into three subbands (f_1, f_2, f_3). Each subband is allocated for each cell. The frequency reuse factor for this scheme is FRF = 1/3.

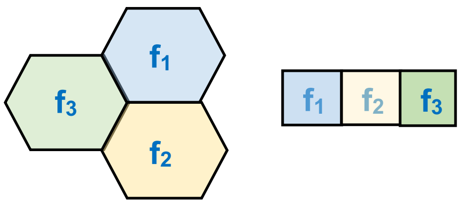

Figure 4. Single tier N = 3

The channel capacity can be calculated using the Shannon channel capacity as follow

$$C = B \log_2(1+SNR) \tag{1}$$

Let's go back to the single tier cluster with N = 3 cells in Fig. 4. Assuming that f1 = f2 = f3 = 1/3 B, each sub band represents one-third of the overall bandwidth B. Let's define the three sub bands as f1, f2, and f3. The first, second, and third cell's channel capacity can be expressed as follows using the (1)

$$C = \frac{1}{3} B \log_2 (1 + SNR) \tag{2}$$

Multi-tier N = 3

The bandwidth distribution in this system is separated into four sub bands (f1, f2, f3, f4). A sub band is assigned to every cell. FRF = 1/2 is the frequency reuse factor for this system.

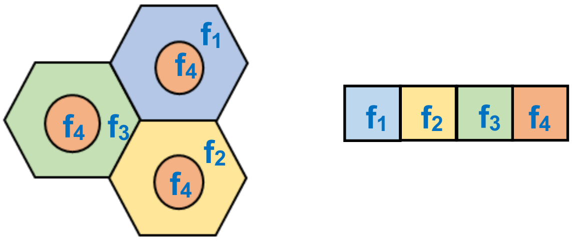

Figure 5. Multi-tier N = 3

Refer to Figure 5, where the sub-bands f1, f2, f3, and f4 represent portions of 1/4B assigned to the inner region of each cell, while the remaining 3/4B is distributed among the outer regions. In a system with N = 3 cells, the outer spectrum is split into three segments [9], allowing each cell to utilize 1/4B as its outer region sub-band. The corresponding channel capacity for each cell is then determined accordingly.

$$Cs = C_{inner} + C_{outer} \tag{3}$$

Here, C_{inner} represents the capacity of the inner region, and C_{outer} denotes the capacity of the outer region. Suppose the sub-band f4 = 1/4B is assigned to the inner portion, while f2, f3, and f4, each equal to 1/4B, are designated for the outer regions. Based on this allocation, the total capacity of the first cell can be expressed as follows.

$$Cs = \frac{1}{4} B \log_2(1 + SNR) + \frac{1}{4} B \log_2(1 + SNR)$$

$$= \frac{1}{2} B \log_2(1 + SNR) \tag{4}$$

Model of Propagation

5G uses a different propagation mechanism than previous technologies. In 5G, the conditions UMa (Macro dense urban/urban/suburban), RMa (rural macro), and UMi (Macro urban/dense urban) are employed in the standard 3GPP propagation model 38.901. The standard propagation equation for the 3GPP 38.901 UMa LOS model is given by equation (1).

Where:

$PL_{Uma-LOS}$ = Pathloss (dB)

d3D = Resultant of distance h_{BS} and h_{UT} (m)

hBS = Antenna Height of gNodeB (m)

hUT = Transmission user height (m)

fc = Frequency of carrier (Hz)

d'BP = Breakpoint distance (m)

$d'_{BP} \le d_{2D} \le 5000$m

Equation (2) is used to get the value of d2D and (3) to obtain the value of d'BP:

$$\sqrt{(d3D)^2 + (hBS - hUT)^2} \quad (6)$$

$$d'BP = 4 \cdot h'BS \cdot h'UT \cdot \frac{fc}{c} \quad (7)$$

Where:

c = Speed of light ($3 \cdot 10^{8)}$ (m/s)

d2D = BS-UT Distance/ Cell Radius (m)

h'BS = Antenna Height of gNodeB-height of equipment (m)

h'UT = Transmission user height -height of equipment (m)

Evaluation and results

To examine and contrast the 5G network's capacity in single-tier and multi-tier cells, simulations were run. A numerical analysis of the capacity of 2 tier and 3 tier cell is performed using a frequency of 3.5 GHz and a cluster size of N = 3. Transmit Power outer tier is 20W which is greater than the inner tier of 10 W. The reason for allocating higher transmit power to the outer tier compared to the inner tier in systems like Fractional Frequency Reuse (FFR) relates to mitigating interference and enhancing the performance of cell-edge users (CEUs), which generally face more challenging signal conditions. Over 10,000 iterations of the simulation were conducted at random user locations. Table 1 provides an overview of the simulation parameters.

Table 1. Parameters of simulation

Parameter	Values
Cluster size	N = 3,
Number of Tier	2,3
Cell radius	5000 (m)
Antenna Height(hBS)	30 (m)
User terminal height (hUT)	2 (m)
Frequency	3.5 GHz
Power outer	20 W
Parameter	**Values**
Power inner	10W
Bandwidth	100 MHz
Noise power density	-174 dBm/Hz
Subcarrier spacing	15 kHz

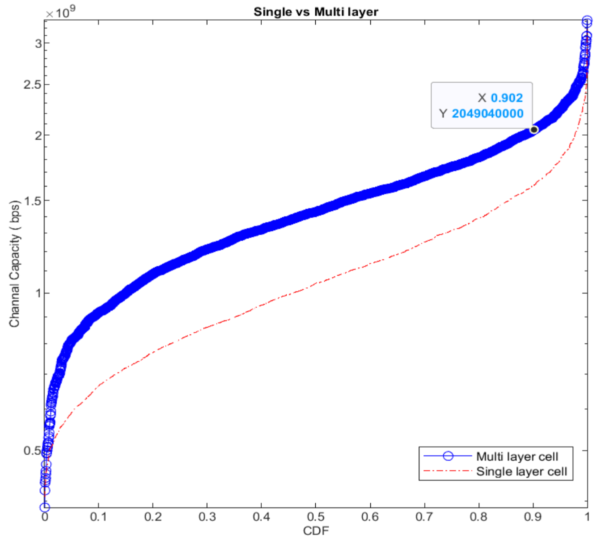

Figure 6. Comparison of single tier vs multi tier in 2 tier cell

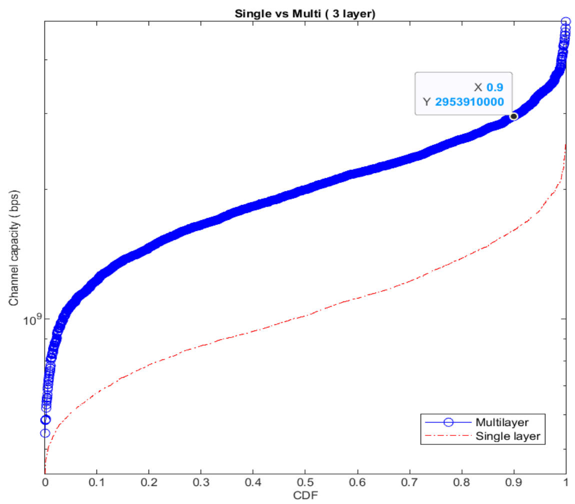

Figure 7. Comparison of single tier vs multi tier in 3 tier cell

We exhibit the results for 2 tier cell and 3 tier cell in terms of the cumulative distribution function (CDF) in Fig. 6 and Fig.7, which demonstrates that the multi-tier cell has a substantially higher capacity than a single tier cell. In 2 tier cell the multi-tier cell can handle 2 Gbps at a CDF of 0.9 while single tier cell can only handle 1,6 Gbps. Meanwhile in 3 tier cell, there is an increase in capacity when compared to 2 tier cell. The capacity of 3 tier cell increase become 3 Gbps in comparison with 2 tier cell.

Conclusion

This study demonstrates that the frequency reuse factor improves in multi-tier cells compared to single-tier cells, a finding verified through both theoretical analysis and computer simulations. The simulation results confirm that multi-tier cells tend to offer higher capacity than their single-tier counterparts. Additionally, increasing the number of tiers in a cell can further enhance overall cell performance, particularly in terms of capacity. However, real-world implementation of multi-tier cells may face challenges, such as increased complexity in network management, higher infrastructure costs, and potential interference issues between tiers. These factors must be addressed to fully harness the benefits of multi-tier cell configurations. Future research should explore adaptive multi-tier configurations that can dynamically adjust based on network conditions, ensuring efficient resource allocation and performance optimization. Additionally, integrating multi-tier cell architectures with advanced 5G technologies such as MIMO (Multiple Input Multiple Output) and mmWave (millimeter Wave) could offer even greater improvements in capacity and coverage. Further studies on the synergy between these technologies will be crucial to realize the full potential of next-generation wireless networks.

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