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Queuing-Theory-Based Performance Study of Interference in FFR Cellular Environments

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Abstract

Fractional Frequency Reuse (FFR) is a significant technique employed in cellular networks to manage co-channel interference, particularly in environments with dense base station deployments. FFR partitions the bandwidth of a cell to minimize interference among neighbouring cells while maximizing the efficiency of frequency reuse. This method is particularly beneficial for mitigating inter-cell and cross-tier interference, which predominantly affects users at the edges of cells. Implementing FFR within multi-tier cellular networks presents several technical challenges. The development of accurate analytical models is crucial for understanding and optimizing the performance of FFR in cellular networks. Queuing theory provides a framework for analysing the behaviour of networks under various loads and conditions. In this paper by modelling user arrivals, service rates, and the distribution of users across the network for different FFR strategies, influence on network stability and performance is determined.
Keywords: *FFR, Co-Channel, Arrival, Service, Channel.*

1. Introduction

FFR partitions the available spectrum into different regions within a cell, reducing interference for users located in the cell centre while allowing frequency reuse for users at the cell edge. Despite the benefits of FFR, users at the cell edge remain susceptible to co-channel interference (CCI) from neighbouring cells. This interference can degrade the Signal-to-Interference-plus-Noise Ratio (SINR), leading to reduced data rates and increased blocking probability. Therefore, understanding and modelling the impact of CCI on network performance is essential for optimizing the design and operation of FFR cellular networks. The architecture of a FFR cell cluster is shown in figure1.

Queuing theory provides a robust mathematical framework for modelling and analysing various aspects of cellular networks, including traffic dynamics, user behaviour, and resource allocation. By applying queuing models such as the M/G/C queue, which allows for general service time distributions and multiple servers, we can gain valuable insights into the performance of cellular systems under different traffic loads and interference conditions. This paper aims to model and analyze the impact of co-channel interference in FFR cellular networks using an M/G/C queue framework. We investigate how different traffic intensities, interference levels, and numbers of frequency channels affect key performance metrics such as blocking probability, average waiting time, and system utilization. The results of this study provide a foundation for optimizing FFR network designs to balance interference mitigation and spectral efficiency.

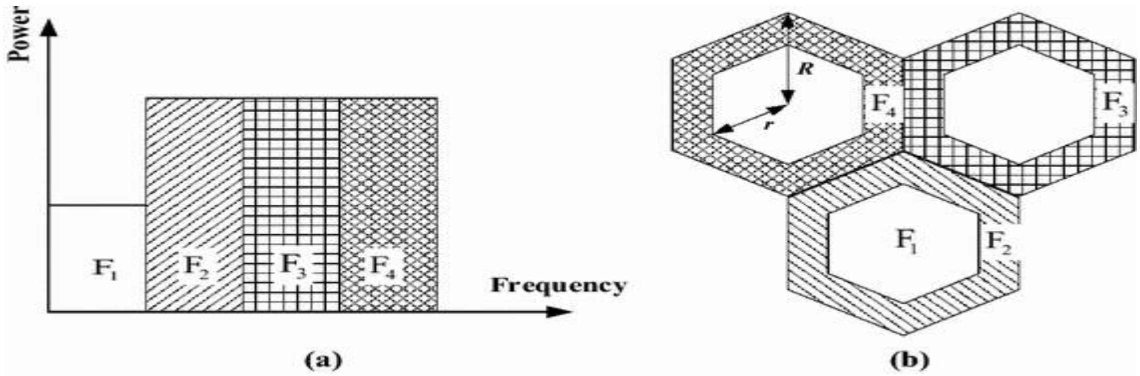

Figure 1: Architecture of a FFR Cell Cluster

Rest of the paper describe as: Section 2 represents literature review, System modelling co-channel interference is illustrated in Section 3. Mathematical Analysis of CCI using M/G/C Queue is depicted in section 4. Performance analysis and results are presented in section 5. Section 6 concludes the paper.

2. Literature Review

[1] This paper describe the obstacles facing in the 4G cellular wireless communication networks, such LTE-Advanced networks, are increasing network capacity and improving cell coverage. To improve the spectral efficiency of the network per unit area, hierarchical layering of cells is seen to be an effective approach. In this case, macro base stations coexist with low-power and short range base stations (equivalent to Pico cells or femtocells) in a service area.

[2] In multicellular ecosystems, interference mitigation has a greater influence and is a crucial factor in NOMA. The limitations that can occur in a NOMA cellular network are first briefly described, along with the contributing variables. There is a discussion of the many methods used to reduce these conditions. Hence a strategy that coordinates the various cells within the NOMA region to reduce interferences and boost user throughput is suggested as a potential solution. The goal of adaptive fractional frequency reuse (FFR) in NOMA is to reduce intercellular interference.

[3] This article focuses on analysing two FFR deployment schemes: Strict FFR and Soft Frequency Reuse (SFR). Using a suggested mechanism that relies on Monte Carlo simulations and takes performance parameters like Signal to Interference plus Noise Ratio (SINR), capacity, and throughput into account, a thorough evaluation of all these frequency reuse strategies is carried out. According to simulation results, Soft Frequency Reuse (SFR) can increase cell-edge throughput by increasing the power control factor.

[4] Fractional frequency reuses (FFR) offers little overhead and complexity, making it a desirable solution for managing interference. It also improves coverage significantly for users in the lower percentile (cell edge). This work provides an analytical model for analysing Strict FFR and Soft Frequency Reuse (SFR) deployments based on the spatial Poisson point process, as an alternative to depending on system simulations based on deterministic access point placements.

[5] The mobile traffic offloading in this study is done from a nearby unloaded femto cell to a crowded macro cell. In order to maintain Quality of Service, the user must expend additional energy if they are near the edge of the macro cell. Offloading to the closest femto cell may be favoured by the user. The energy efficiency (EE) of the macro cell will rise and the femto cell's spectrum utilization will improve when the user equipments (UEs) are offloaded to the femto cell.

[6] In this study, mobile traffic offloading is done from an adjacent, unloaded femto cell to a busy macro cell. The user must expend more energy to maintain the Quality of Service (QoS) if they are near the edge of the macrocell. There is a chance that the user will offload to the closest femto cell. User equipment (UE) offloading to femtocells improves femtocell spectrum usage while also increasing energy efficiency (EE) of the macrocell.

[7] In this paper Poisson point process are considered to represent the base station locations, this work focuses on analytically evaluating the two primary forms of FFR deployments: Strict FFR and Soft Frequency Reuse (SFR). The outcomes are contrasted with an actual urban deployment and the industry standard grid model.

[8] In this work, the three frequency allocation strategies were covered. There are three types of schemes: one with no Femtocell application, one with Femtocell applied randomly, and one with a prearranged Femtocell scheme. The cell is divided into inner and exterior portions by the FFR mechanism. Based on overall average throughput and overall user satisfaction, the inner radius and inner region resources are identified.

[9] The emerging technologies discussed in this article have the potential to shape and enable 5G mobile communication standards and cellular networks in the future. In order to measure, test, and validate the performance of 5G system components, we highlight the main concepts for each technology as well as the main unresolved research issues. We then highlight the basic research issues related to resource management in 5G systems.

[10] All cells and sectors use the same frequency channel to enhance spectral efficiency in the Orthogonal Frequency Division Multiple Access (OFDMA) communication technology, which is supported by LTE. However, the quality of the link between UEs at the cell boundary may deteriorate as a result of significant Co-channel Interference (CCI) in frequency reuse one deployment.

3. Modelling Co-Channel Interference

In FFR cellular networks, the effect of co-channel interference is modelled by considering various parameters, such as the distance between users and base stations, the power allocated to each channel, and the specific frequency reuse strategies employed. For instance, signals in the centre area of a cell may operate on the same frequency, while outer regions use different frequencies, effectively mitigating interference by reducing overlap.

3.1 Interference Estimation

The co-channel interference experienced by a user is modelled as the sum of the signal power received from all interfering base stations. The interference power is influenced by factors such as the distance between the user and interfering base stations, the transmit power of the interfering cells, and the path loss. For simplicity, we assume a path loss model of the form:

$$L(d) = \left(\frac{d}{d_0}\right)^{-\alpha}$$

Where d_0 is a reference distance, d is the distance between the user and the interfering base station, and α is the path loss exponent.

3.2 SINR Calculation

The SINR is calculated as:

$$\text{SINR} = \frac{P_{signal}}{P_{interference} + P_{noise}}$$

Where P_{signal} is the received signal power from the serving base station, $P_{\text{interference}}$ is the total interference power from neighbouring cells, and P_{noise} is the noise power. The SINR is used to determine the data rate for each user, which in turn affects the service time in the queue.

3.3 Service Time Model

The service time for a user is inversely proportional to the data rate, which depends on the SINR. Higher SINR values result in higher data rates and shorter service times, while lower SINR values result in longer service times. For simplicity, we model the data rate using Shannon's capacity formula:

$$R = \log_2(1 + \text{SINR})$$

The service time is then given by:

$$T_{\text{service}} = \frac{\text{Data Size}}{R}$$

4. Mathematical Analysis of CCI using M/G/C Queue

4.1 Interference Modelling in FFR Networks

Co-channel interference occurs when multiple users transmit on the same frequency. In FFR, co-channel interference is managed by the reuse pattern (e.g., centre users might have different frequencies than edge users). However, interference from adjacent cells still exists.

To model this using the **M/G/C** queue:

- Arrival Process (M): The arrival of users to the network can be modelled as a Poisson process, where users arrive randomly with a certain rate λ.
- Service Time (G): The service time depends on various factors, including user position (centre vs. edge), Signal-to-Interference-plus-Noise Ratio (SINR), and the modulation scheme. The service time could be modeled with a general distribution reflecting the varying conditions in the network.
- Number of Servers (C): In this context, "servers" are the available channels in the cell. For each subregion (e.g., centre or edge), different numbers of servers may be available due to the frequency reuse patterns in FFR.

4.2 Interference Influence

1. **Interference on Arrival Rate (λ):** Co-channel interference can increase blocking or handover failures, impacting the effective arrival rate of users into the system.
2. **Interference on Service Rate (μ):** Interference affects the service time of users by reducing the throughput or data rate. More interference generally means longer service times, as users need more time to complete their transmissions due to reduced signal quality.

4.3 Scenario Setup

Consider a cellular network using Fractional Frequency Reuse (FFR), where the frequency spectrum is divided between the centre and edge users of the cell. Let's assume:

- **Cell Layout:** Hexagonal cells with base stations (BS) at the centre.
- **FFR Pattern:** Centre users have exclusive access to certain frequencies, while edge users share frequencies with neighbouring cells, potentially leading to co-channel interference.

Assumptions:

- **Number of Channels (C):** The system has 10 channels for users in a specific region (edge or centre).
- **Arrival Rate (λ):** Users arrive at the network with a Poisson arrival rate of 5 users per minute.
- **Service Time Distribution (G):** The service time follows a general distribution with a mean service time of 3 minutes per user. However, due to co-channel interference, edge users experience a 50% increase in service time (making the average service time for edge users 4.5 minutes).
- **Interference Impact:** Assume that 30% of users are edge users who experience co-channel interference, leading to a degraded service rate.

Step 1: Model the M/G/C Queue

We need to calculate key performance metrics such a**s** blocking probability and average waiting time using the M/G/C queuing model.

Traffic Intensity (ρ) Calculation:

The traffic intensity (or utilization factor) is defined as-

$$\rho = \frac{\lambda \cdot E[S]}{C}$$

Where:

- λ is the arrival rate.
- E[S] is the average service time.
- C is the number of servers (channels)

For centre users (no interference):

- Arrival rate: λcenter=0.7×5=3.5 users/min.
- Average service time: E [Scented] = 3 minutes.
- Traffic intensity:

$$\rho_{\text{center}} = \frac{3.5 \times 3}{10} = 1.05$$

For edge users (with interference):

- Arrival rate: λedge =0.3×5=1.5 users/min.
- Average service time: E [Sedge] = 4.5 minutes.
- Traffic intensity:

$$\rho_{\text{edge}} = \frac{1.5 \times 4.5}{10} = 0.675$$

Step 2: Calculate Blocking Probability

We can use the Erlang B formula to calculate the blocking probability Pb in the system. The

$$P_b = \frac{\frac{\rho^C}{C!}}{\sum_{k=0}^{C} \frac{\rho^k}{k!}}$$

Erlang B formula is given as:
For center users**:**

- C=10 (channels).
- ρcenter=1.05

Step 3: Calculate Average Delay (W)

The average delay in an M/G/C queue can be calculated using the Pollaczek-Khinchine formula for the waiting time in an M/G/1 queue, generalized to the M/G/C system.
The average delay (W**)** is:

$$W = \frac{L_q}{\lambda}$$

Where:

- L_q is the average number of users waiting in the queue, which depends on the traffic intensity and the number of servers.

Step 4: Estimate Co-Channel Interference Impact on Service Time

The co-channel interference impacts the service rate of edge users. To model this, we adjust the service time by increasing it due to interference.

For centre users: $\mu\ centre = \frac{1}{E[S_{center}]}$ = 1/3 users/min.

For edge users (due to interference): $\mu edge = \frac{1}{E[S_{edge}]}$ = 1/4.5 users/min.

These adjusted service times reflect the slower service rate for edge users affected by co-channel interference.

Now we calculate the blocking probability using the Erlang B formula for both user types.

- **Centre users (no interference):** Pb≈1.57×10−7
- **Edge users (with interference):** Pb≈2.76×10−9

These probabilities are extremely low, indicating that the system can handle the current load effectively, with minimal chance of blocking for both centre and edge users under the given conditions.

5. Performance Evaluation

5.1 Simulation Setup

We conduct a simulation to evaluate the performance of the FFR network under varying arrival rates, interference levels, and numbers of channels. The simulation considers users located at both the cell centre and edge, with different SINR values and corresponding service times.

Parameters:

1. Arrival Rates: Simulates the network performance with varying traffic loads from 5 to 20 calls per second.
2. Interference Levels: Considers different levels of co-channel interference ranging from 0.01 to 0.05 Watts.
3. Channels: Evaluates scenarios with 5, 10, and 15 available channels.

5.2 Results and Discussion

5.2.1 Blocking Probability

The results in figure 2 show that blocking probability increases with higher arrival rates and interference levels. Users at the cell edge experience significantly higher blocking probabilities compared to center users, primarily due to longer service times resulting from lower SINR values.

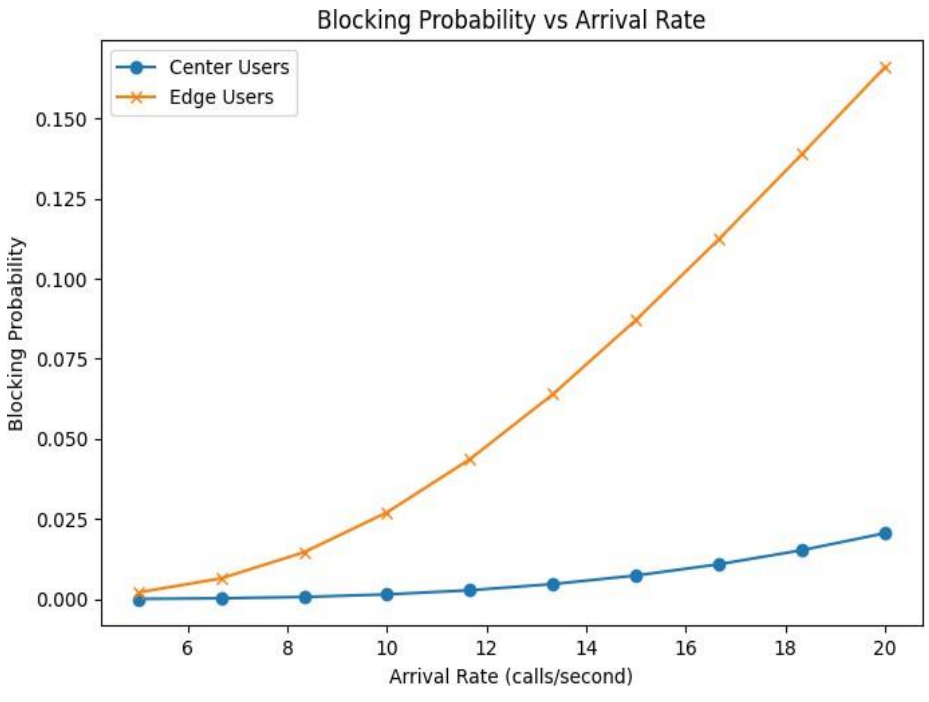

Figure 2: Blocking Probability Vs Arrival Rate

5.2.2 Average Waiting Time

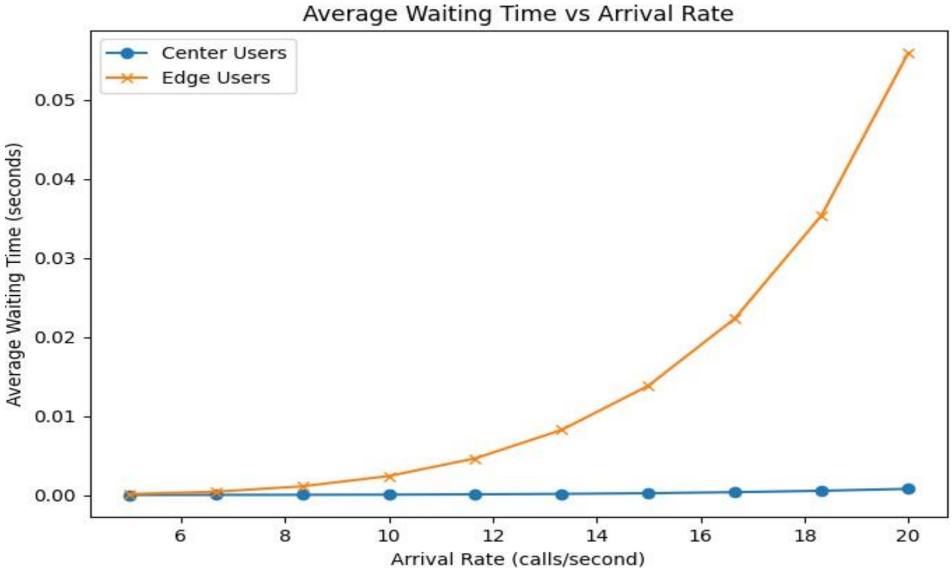

Figure 3: Average Weighting Time Vs Arrival Rate

The average waiting time also increases with arrival rates and interference levels. Centre users generally experience shorter waiting times due to higher SINR and faster data rates. Edge users, on the other hand, face longer waiting times as a result of increased co-channel interference as shown in figure 3. Figure 4 shows the relation between SINR and arrival rate. It can be seen that centre users have higher SINR since they experience less interference and are closer to the base station. Meanwhile edge users have lower SINR due to increased distance and higher co-channel interference.

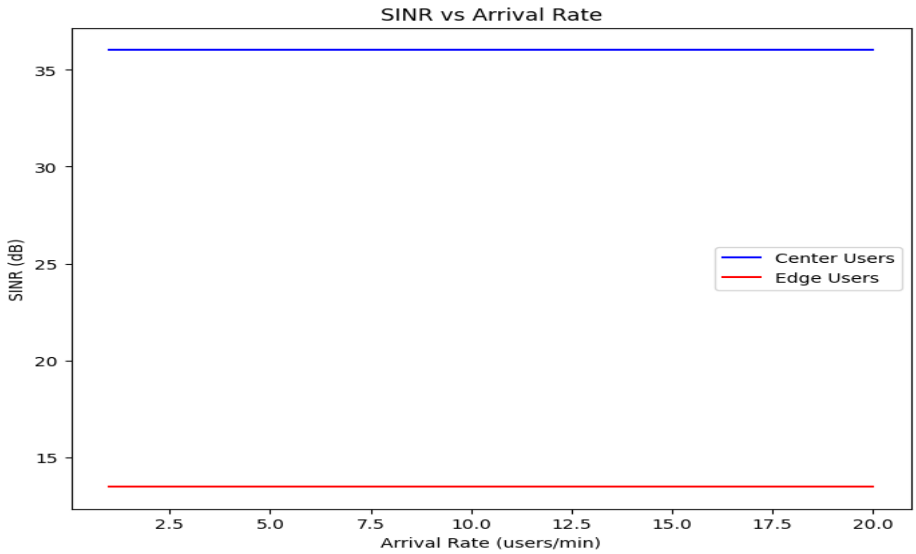

Figure 4: SINR Vs Arrival Rate

6. Conclusion

The combination of FFR techniques and M/G/C queue modelling represents a robust approach to addressing co-channel interference in cellular networks. By systematically analyzing service performance and interference impacts, network operators can enhance capacity and service quality across varying user demands and deployment scenarios. The simulation presented here is effectively models the impact of co-channel interference on performance metrics in an FFR cellular network. The results illustrate how varying traffic loads, interference levels, and the number of channels affect key performance metrics such as blocking probability, waiting time, and system utilization and SINR. The model can be further refined with more realistic SINR models and dynamic interference adjustments.

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