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Performance of Scheduling Algorithms in 4G and 5G Networks

Rendimiento de los algoritmos de planificación en redes 4G y 5G

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Abstract

In modern society, the implementation of fourth- and fifth-generation mobile technologies (4G and 5G) promises to significantly enhance information and communication technology (ICT) services. These technologies are designed to meet the increasing demand for mobile broadband access from users utilizing a wide range of services, such as web browsing, mobile applications, and cellular communications. Furthermore, 5G represents an advanced evolution of LTE technology, offering greater versatility and resilience [1]. It is also expected to enable new applications, including wireless industrial control, autonomous vehicles, high-quality virtual reality, and telemedicine [2]. This article uses simulation tools as a mechanism to research and evaluate the performance of 4G and 5G networks under different downlink resource scheduling algorithms. The system is based on Frequency Division Duplexing (FDD) and examines algorithms that enable dynamic resource allocation in the downlink. The schedulers considered include Round Robin, Proportional Fairness, and Best CQI.

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Performance is analyzed based on key metrics such as throughput, goodput, and fairness in the 5G network. The simulation results show a strong relationship between resource scheduling algorithms and performance in 4G and 5G mobile networks. The use of the Best CQI (BCQI) algorithm provides high throughput but low allocation fairness, resulting in some users receiving no time–frequency resources for transmission, while others receive excessive allocations. In contrast, the Proportional Fairness and Round Robin algorithms distribute resources more equitably, improving overall performance by nearly 50% compared to BCQI. This demonstrates more efficient resource allocation with these latter algorithms.

Keywords: Scheduling Algorithm, 4G, 5G, Mobile Networks, Performance analysis

Resumen

En la sociedad actual, la implementación de las tecnologías móviles de cuarta y quinta generación (4G y 5G) promete mejorar significativamente los servicios de tecnologías de la información y la comunicación (TIC). Estas tecnologías están diseñadas para satisfacer la creciente demanda de acceso a banda ancha móvil por parte de usuarios que utilizan una amplia gama de servicios, como navegación web, aplicaciones móviles y comunicaciones celulares. Además, 5G representa una evolución avanzada de la tecnología LTE, ofreciendo mayor versatilidad y resiliencia [1]. También se espera que permita nuevas aplicaciones, como el control industrial inalámbrico, los vehículos autónomos, la realidad virtual de alta calidad y la telemedicina [2]. Este artículo utiliza herramientas de simulación como mecanismo para investigar y evaluar el rendimiento de las redes 4G y 5G bajo diferentes algoritmos de programación de recursos de enlace descendente. El sistema se basa en Duplexación por División de Frecuencia (FDD) y examina algoritmos que permiten la asignación dinámica de recursos en el enlace descendente. Los programadores considerados incluyen Round Robin, Equidad Proporcional y Mejor CQI. El rendimiento se analiza en función de métricas clave como el rendimiento, el rendimiento efectivo y la equidad en la red 5G. Los resultados de la simulación muestran una fuerte relación entre los algoritmos de planificación de recursos y el rendimiento en redes móviles 4G y 5G. El algoritmo de Mejor CQI (BCQI) proporciona un alto rendimiento, pero una baja equidad en la asignación, lo que provoca que algunos usuarios no reciban recursos de tiempo y frecuencia para la transmisión, mientras que otros reciben asignaciones excesivas. En contraste, los algoritmos de Equidad Proporcional y Round Robin distribuyen los recursos de manera más equitativa, mejorando el rendimiento general en casi un 50 % en comparación con BCQI. Esto demuestra una asignación de recursos más eficiente con estos últimos algoritmos.

Palabras clave: Algoritmo de planificación, 4G, 5G, Redes móviles, Análisis de rendimiento

Introduction

Today, mobile users demand higher quality of service (QoS) and greater network capacity. In this context, 4G and 5G mobile technologies have emerged as solutions to these challenges. System requirements have evolved to include greater flexibility, reconfigurability, and network resilience. Consequently, the implementation of technologies such as Network Function Virtualization (NFV) and Software-Defined Networking (SDN) has become essential. Additionally, the increasing diversity of users within the network introduces further challenges, making efficient and advanced resource management imperative [3].

Numerous resource scheduling algorithms exist, each employing different approaches aimed at improving network performance and service quality in both uplink and downlink transmissions. This represents a key aspect of ensuring efficient resource utilization. However, mobile environments are inherently complex and dynamic due to constant variations in channel conditions, user distribution, and transmission scenarios, which complicates performance evaluation. Therefore, it is necessary to identify appropriate metrics and methodologies to assess performance and contribute to ongoing research in 4G and 5G networks [4].

Given the complexity of existing and emerging algorithms, there is a need to evaluate the performance of various resource schedulers, such as Round Robin (RR), Proportional Fair (PF), Best CQI, and Max-Sum-Rate (MSR), among others. This evaluation aims to understand how these algorithms influence downlink channel performance under specific scenarios or through targeted modifications [5].

Considering the wide range of variables involved in mobile environments, it is essential to select appropriate evaluation parameters. Therefore, this article focuses on assessing the performance of selected downlink scheduling algorithms to identify the most suitable approaches for improving overall network performance.

1. Scheduling algorithms in 4G networks

Orthogonal Frequency Division Multiple Access (OFDMA) modulation is used in LTE technology. This technique divides the total available bandwidth into multiple subcarriers that maintain orthogonality among them. Each subcarrier can transmit different numbers of symbols depending on channel conditions. By adapting to these conditions, OFDMA mitigates multipath effects and signal fading. Each subcarrier can employ modulation schemes such as QPSK, 16-QAM, and 64-QAM [6], [7].

The orthogonality of the subcarriers prevents inter-carrier interference (ICI), eliminating the need for guard bands and increasing spectral efficiency compared to conventional FDM-based systems. Additionally, it enables the simultaneous transmission of data from multiple users sharing the same channel. Resource allocation is structured in two dimensions—time and frequency—controlled at the Medium Access Control (MAC) layer and dynamically assigned to users in the most efficient manner, as illustrated in Figure 1.

Figure 1. Example of space-time allocation in OFDMA [8].

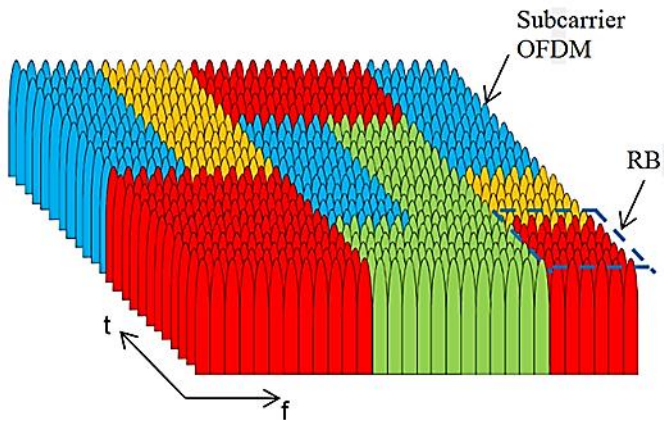
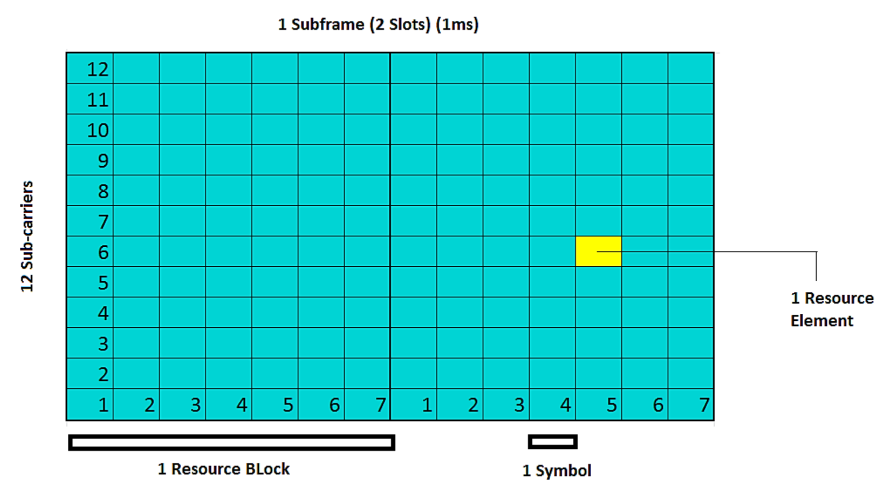


Figure 2 shows a data frame composed of 4 subframes, each containing two slots with a duration of 0.5 ms, and 12 subcarriers with a subcarrier spacing (∆f) of 15 kHz, occupying a total bandwidth of 180 kHz. Each subcarrier contains 6 or 7 OFDM symbols. In each Transmission Time Interval (TTI), two slots—corresponding to one Resource Block (RB)—form an LTE subframe. The TTI represents the minimum time unit that an eNodeB can allocate for transmission, both in the downlink (DL) and uplink (UL) channels [5].

Figure 2. RB - Resource block [8].



Among the Radio Resource Management (RRM) functions that significantly impact system efficiency are the packet schedulers, which are responsible for assigning available radio resources to users in an organized manner. These algorithms are particularly important considering that LTE is a data transmission technology based on shared channels [8], [5].

Therefore, the strategies employed by packet schedulers directly affect the Quality of Service (QoS) that the system can provide to users [8], [5].

The packet scheduling process allocates resource blocks to users connected to the system during each Transmission Time Interval (TTI). The scheduler determines which resource blocks or subframes within the resource grid are assigned to each user. This allocation scheme is illustrated in Figure 3.

Figure 3. OFDMA packet scheduler.

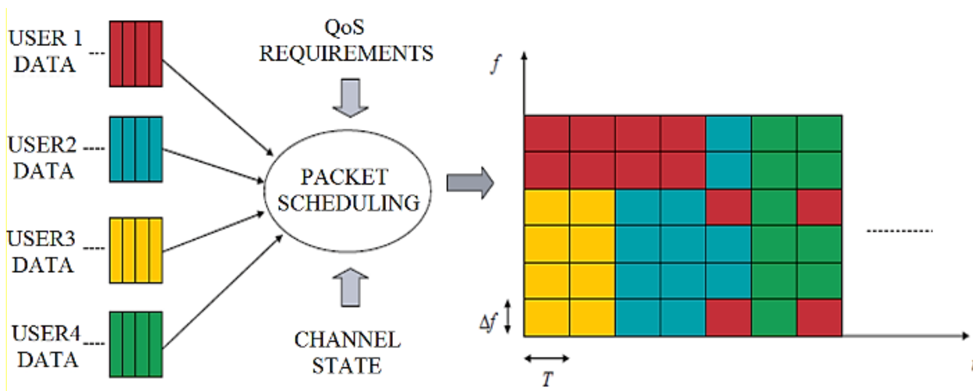
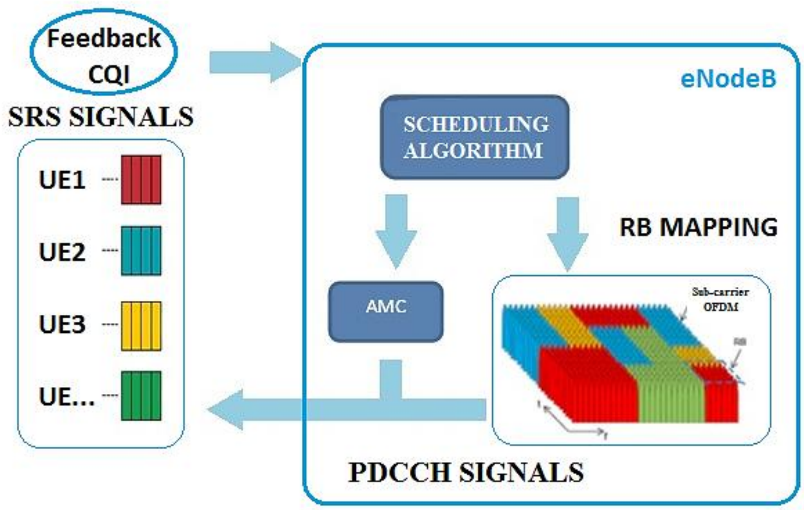


Figure 3 illustrates the signaling scheme and components involved in the packet scheduling process in LTE. For each Transmission Time Interval (TTI), the scheduler allocates resources to be used in the subsequent TTI. This scheduling information is transmitted to each User Equipment (UE) through the Physical Downlink Control Channel (PDCCH).

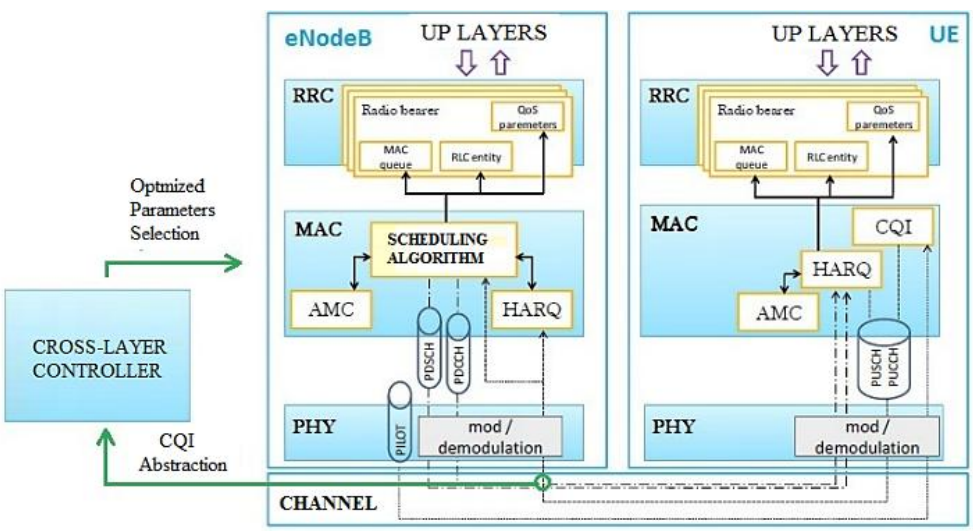
Subsequently, each UE transmits Sounding Reference Signals (SRS) to the eNodeB, providing channel state information, including the Channel Quality Indicator (CQI), as part of the uplink feedback. Based on this information, the scheduling algorithm determines resource allocation for the next TTI. Figure 4 shows the SRS and PDCCH signals, which are part of the LTE physical layer and transport channels.

Figure 4. Packet scheduling model in LTE.



The newly developed multilayer controller introduces an upward communication interface. It collects information from the physical (PHY) layer and forwards it to the controller, which in turn performs the selection of optimized parameters for managing downlink (DL) resources for each network user, as illustrated in Figure 5.

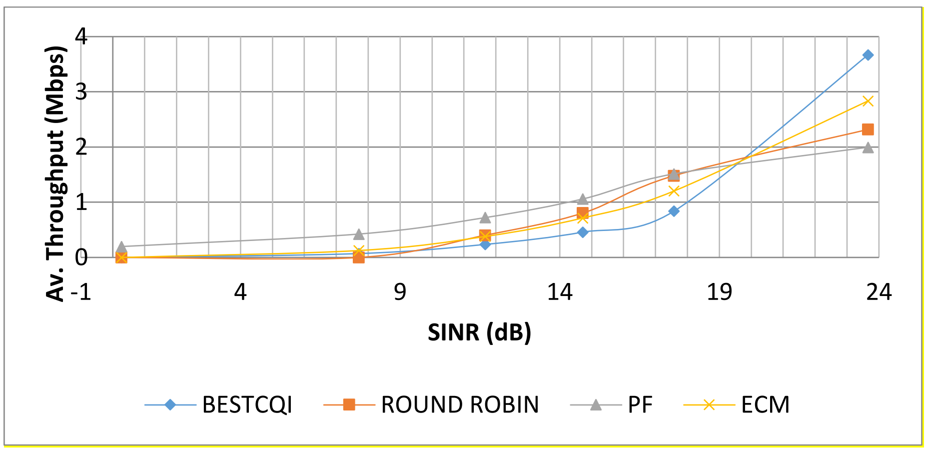
Figure 5. Scheduler in LTE layers.



To verify that the software has been correctly installed and that the results are valid, the simulation begins by reproducing the reference scenarios proposed by the software authors in [9] and [10].

Figure 6 shows the system’s average throughput (Mbps) as a function of the Signal-to-Interference-plus-Noise Ratio (SINR). This figure illustrates how the throughput allocated to a user varies with SINR, reflecting the quality of the received signal, and depending on the scheduling algorithm employed.

Figure 6. Average throughput vs SINR for 1.4 MHz-6UE



In Figure 6, it can be observed that the Best CQI scheduler achieves the highest throughput among the evaluated algorithms. However, this comes at the expense of fairness, as a small number of users experience high throughput, while others are penalized due to the lack of Resource Block (RB) allocation.

In contrast, the Proportional Fair (PF) algorithm achieves the highest level of fairness but sacrifices the overall throughput delivered to users. The Round Robin (RR) algorithm exhibits a moderate level of both throughput and fairness. Meanwhile, the CL-ECM algorithm achieves high throughput with a moderate level of fairness in this scenario, effectively balancing these two metrics for LTE system users.

Figure 7 presents the average eNodeB performance for each scheduler, highlighting the trade-off between system throughput (Mbps) and fairness (%), compared to the other scheduling algorithms.

Figure 7. Throughput and Fairness for 1.4MHz-6 EU

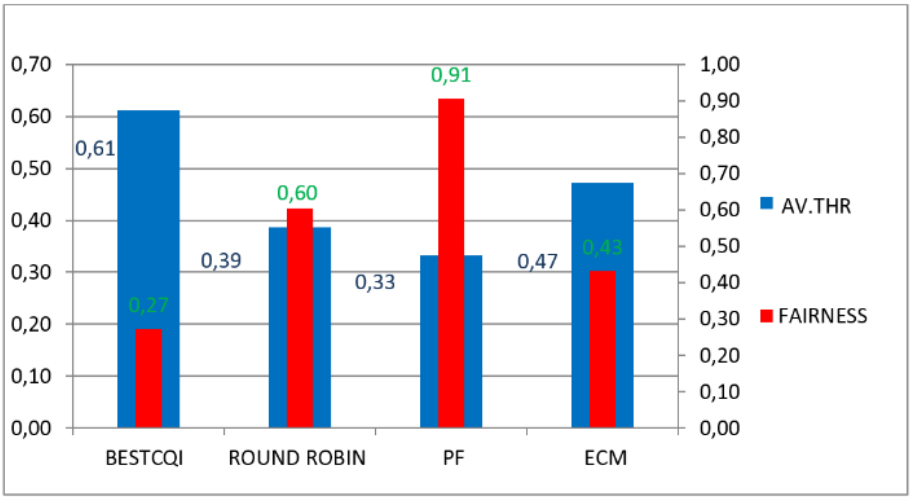
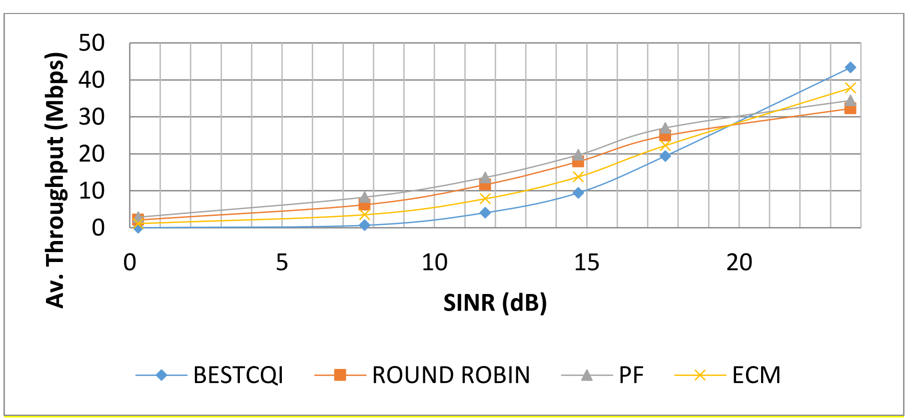


Figure 8 shows the system's average throughput (Mbps) as a function of the Signal-to-Interference-plus-Noise Ratio (SINR). This figure illustrates how the throughput allocated to a user varies with SINR, reflecting the quality of the received signal and the scheduling algorithm employed.

Figure 8. Average throughput vs SINR for 10 MHz-6UE



As shown in Figure 9, the algorithm achieves a balanced trade-off between performance metrics compared to the other three algorithms.

Figure 9. Throughput and Fairness for 1.4MHz-20 EU

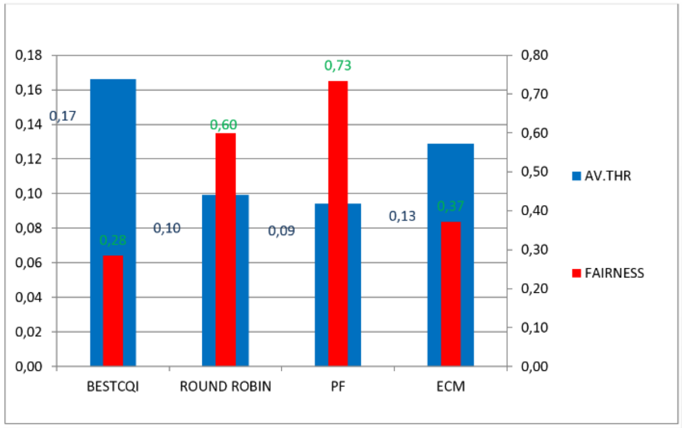
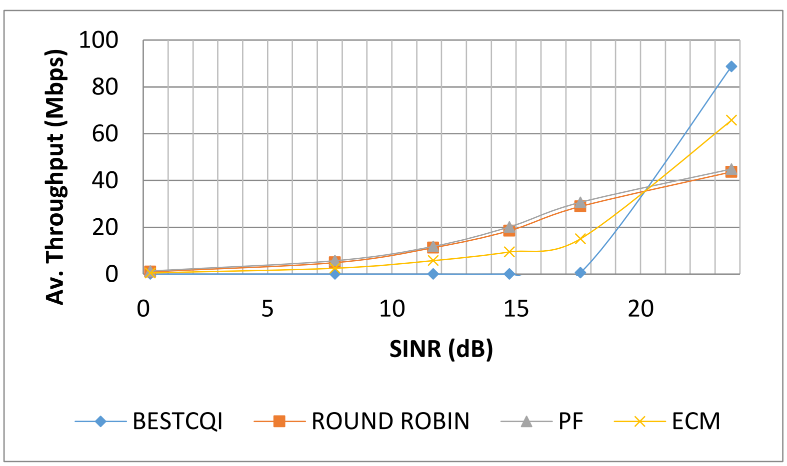


Figure 10 shows the system's average throughput (Mbps) as a function of the Signal-to-Interference-plus-Noise Ratio (SINR). This figure further illustrates how the throughput allocated to a user varies with SINR, reflecting the quality of the received signal and the scheduling algorithm employed.

Figure 10. Average throughput vs. SINR for 20 MHz-6UE



2. Scheduling algorithms in 5G networks

This system represents the latest cellular mobile technology developed and standardized by the 3rd Generation Partnership Project (3GPP), offering superior performance compared to previous cellular technologies in terms of the following service categories [5]:

- Enhanced Mobile Broadband (eMBB)
- Ultra-Reliable Low-Latency Communications (URLLC)

- Massive Machine-Type Communications (MMTC)

Table 1 outlines the key differences in the radio interface characteristics between 5G and LTE technologies.

Table 1. Comparison of Radio Interfaces [11], [12]

	LTE - Advanced	**5G**
Multiplexing method	TDD or FDD	TDD or FDD
Access technique	Uplink: Clustered SC-FDMA Downlink: OFDMA	Uplink: OFDMA, SC-FDMA Downlink: OFDMA
Modulation schemes	QPSK, 16QAM and 64QAM 5G	2-BPSK, π/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM
Bandwidth of each radio channel	1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, with carrier aggregation	20 MHz, 50 MHz, 100 MHz, 200 MHz and 400 MHz, with maximum carrier aggregation 6.4 GHz
Peak Spectral efficiency	Uplink: 15 bit/s/Hz Downlink: 30 bit/s/Hz	Uplink: 15 bit/s/Hz Downlink: 30 bit/s/Hz

2.1. The MAC Scheduler

This entity is responsible for multi-user radio resource allocation, subject to specific system constraints. It provides various strategies to efficiently serve different user terminals. The system performs dynamic allocation of radio transmission resources—namely transport blocks—for both uplink and downlink transmissions, treating each transmission independently. The primary objective of the scheduler is to ensure that the Quality of Service (QoS) requirements for end users are satisfied within the context of Data Radio Bearers (DRBs) [11].

Although there is flexibility in scheduling users across carriers (e.g., selection of PHY numerology, Transmission Time Interval (TTI) sizes, etc.), these decisions are not exposed at the Radio Link Control (RLC) layer. User Equipment (UE) can be configured to be simultaneously served by multiple nodes and cells, enabling multi-connectivity. To mitigate potential data loss during transmission, advanced retransmission mechanisms such as Hybrid Automatic Repeat Request (HARQ) are employed [2], [13].

2.2. Packet Scheduler

For a typical Base Station (BS), the packet scheduler architecture consists of three fundamental components:

- A Quality of Service (QoS) management module and a buffer that stores non-real-time (NRT) IP traffic received from upper layers, while managing the associated QoS information.
- A component responsible for calculating the per-subchannel bit rate (PBR) of buffered packets and managing QoS for each user.
- A packet scheduler that executes the actual scheduling algorithm.

The proposed packet scheduling algorithm is based on the calculation of the bit rate per subchannel, and the channel state information provided by the User Equipment (UE). This information is used to determine the achievable bit rate per subchannel [14] [15].

2.3. Reliability

It is defined as the percentage of network layer packets successfully delivered within a specified time constraint, expressed as a fraction of the total number of packets transmitted at the network layer [16].

2.4. Resource Scheduling

In traditional networks, the primary objective of resource allocation is to enable efficient utilization of resources among users, achieving high spectral efficiency through spectrum partitioning. However, in Radio Access Networks (RAN), which provide a flexible and programmable architecture, the core design of a Resource Allocation Strategy (RAS) is based on the dynamic and adaptable sharing of RAN resources among multiple tenants or operators. In this way, efficient utilization of the RAN infrastructure is achieved [17].

2.5. Round Robin Scheduler

To request access to a shared resource, each client sets a request bit. The Round Robin scheduler subsequently grants access by setting a grant bit when the client is scheduled to use the shared resource. This scheduler is based on the concept of a logical ring, similar to the Token Ring mechanism. The process follows a predefined order that clients must respect when transmitting their data. Depending on the service type, clients are assigned ordered identifiers that determine when they are allowed to transmit. When a client requests service, it must wait for its turn. Once transmission begins, the client temporarily assumes control of the channel, and upon completion, passes control to the next client in the ring.

While one client is transmitting, the scheduling process advances to the next client in the sequence. Thus, resource availability follows the predefined order of the ring, and once the last client is served, the process returns to the first.

A variation of this scheduler incorporates priority into the scheduling decision. In such cases, clients with higher priority or more stringent requirements are served before others, allowing differentiated service provisioning [18].

2.6. Fairness Algorithm: Proportional Fair

The Proportional Fair (PF) algorithm aims to optimize system throughput while maintaining a relatively high level of fairness, enabling users to efficiently access available radio resources. Each user reports the Channel Quality Indicator (CQI) for each Resource Block (RB) at every time slot. Based on this information, the scheduler dynamically determines the priority of each user for each RB in every Transmission Time Interval (TTI) [19].

2.7. Best CQI Scheduler

The Best CQI scheduler is a resource allocation algorithm that selects users with the most favorable channel conditions for scheduling across Resource Blocks (RBs). Its primary objective is to maximize cell throughput; however, this often leads to unfairness, as users experiencing poor channel conditions may receive little or no resource allocation.

Compared to the Round Robin (RR) scheduler, the Best CQI approach is more efficient in terms of throughput but less effective in terms of fairness. In contrast, RR assigns an equal number of RBs to all users without considering the Channel Quality Indicator (CQI). As a result, while Best CQI improves overall system performance, it introduces fairness penalties by favoring users with better channel conditions [1].

2.8. Comparison of Various Schedulers

The Proportional Fair (PF) scheduler achieves a balance between the Best CQI and Round Robin (RR) approaches by employing a utility-based scheduling metric that considers both the Channel Quality Indicator (CQI) and the amount of Resource Blocks (RBs) allocated. This scheduler aims to maximize cell throughput while maintaining a satisfactory level of fairness.

Similarly, the Resource Fair (RF) scheduler is designed to maximize the aggregate data rate among users while ensuring fairness in RB allocation. In contrast, the Max-Min (MM) scheduler focuses on achieving maximum fairness by maximizing the minimum user throughput, thereby promoting uniform service distribution among users. Under this scheme, a user's throughput remains stable unless there are changes in the throughput of other users [1].

Regarding standardization, the first complete set of specifications for 5G was introduced with 3GPP Release 15, which defines New Radio (NR) technology in Non-Standalone (NSA) mode. Release 15 represents Phase 1 of the 5G system, while Phase 2 is defined in Release 16.

Release 16 includes support for Standalone (SA) 5G, featuring a new radio access system integrated with a next-generation core network (5GC). It also incorporates enhancements to LTE and, consequently, to the Evolved Packet Core (EPC) [8].

3. 5G Results

The aim is to evaluate the performance of the 5G network under different bandwidth configurations.

A simulation scenario is defined with 20 User Equipment (UE) devices within a single cell, and a base station located at the center, responsible for allocating Resource Blocks (RBs). This simulation considers the impact of various resource scheduling algorithms.

3.1. Second Scenario

The simulation scenario considers 6, 20, 50, and 100 User Equipment (UE) devices. The Round Robin (RR), Best CQI, and Proportional Fair (PF) scheduling algorithms are evaluated. Each simulation chunk consists of 50 time slots.

Table 2 summarizes the characteristics of the second test scenario, where the number of UEs varies from 6 to 20, 50, and 100 within the same cell. Simulations are conducted using bandwidths of 1.4, 10, and 20 MHz.

Table 2. Scenario Parameters

Number of EUs	6, 20, 50, 100
Number of BSs	1
Scheduler	Round Robin, Proportional Fair, Best CQI
BW	1.4, 10, 20 MHz
Number of RB	6, 15, 25, 50, 75, 100
Number of Subcarriers	12
RB size in frequency	180 kHz
RB size in time	1 ms
# Subcarriers in a Slot	84, 180, 300, 600, 900, 1200

The functionality of the code is to define a simulation area capable of containing the User Equipment (UE) devices, taking into account their spatial distribution, the transmission power of the base station (BTS), and internal configuration parameters such as bandwidth, time allocation, and the number of chunks per transmission. This module gathers information from other code libraries to perform analysis and execution.

3.2. Evaluation of 5G Scenarios

Based on the calculations and the information provided, the following scenarios are evaluated:

The first scenario considers variations in bandwidth while keeping the number of User Equipment (UE) fixed at 20. In this case, the Round Robin (RR), Proportional Fair (PF), and Best CQI (BCQI) schedulers are evaluated in terms of throughput, fairness, and goodput.

The second scenario analyzes variations in both bandwidth and the number of User Equipment, highlighting the impact on throughput and fairness under different conditions.

Using the Vienna 5G SL Simulator, the implemented libraries enable the execution of these variations and the acquisition of results based on the previously defined calculations.

The results obtained from the simulations are presented for the Round Robin, Proportional Fair, and Best CQI schedulers, along with different bandwidth values and numbers of UEs within a cell served by a base station (BS). Based on Equation (3), 50 simulations are performed per scenario to ensure a 95% confidence level in the results, as detailed in Section 6.3.3 regarding sample size estimation. With this in mind, the following scenarios are defined for simulation and subsequent analysis.

3.3. Scenario 1 Results: 20 UEs with Varying Bandwidth

On the board, the characteristics of the first scenario can be observed, where the bandwidth varies from 1.4 to 20 MHz, with 20 User Equipment (UE) devices and a single base station located within the cell.

Figure 11. Throughput Performance Results

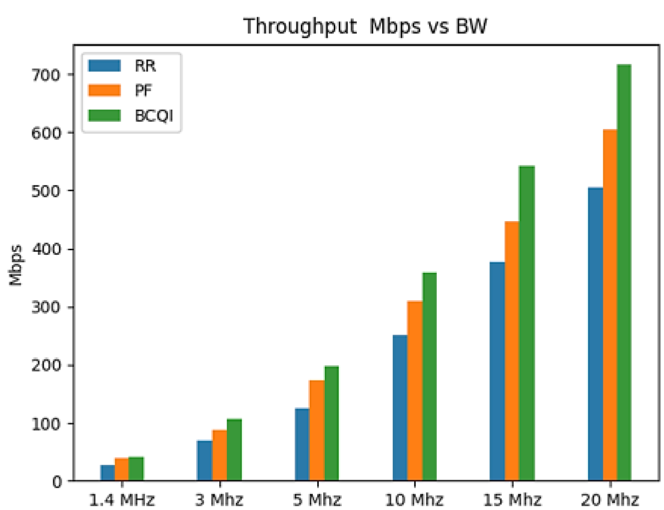
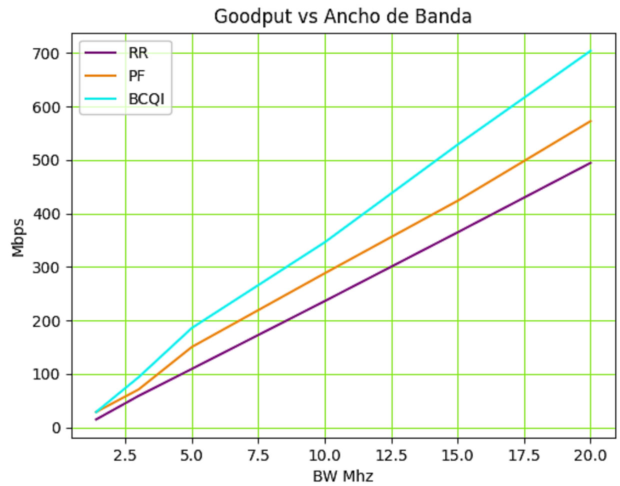


Figure 11 presents a comparison of the throughput allocated to the 20 users under different bandwidth configurations. The results are categorized according to the scheduling algorithm used.

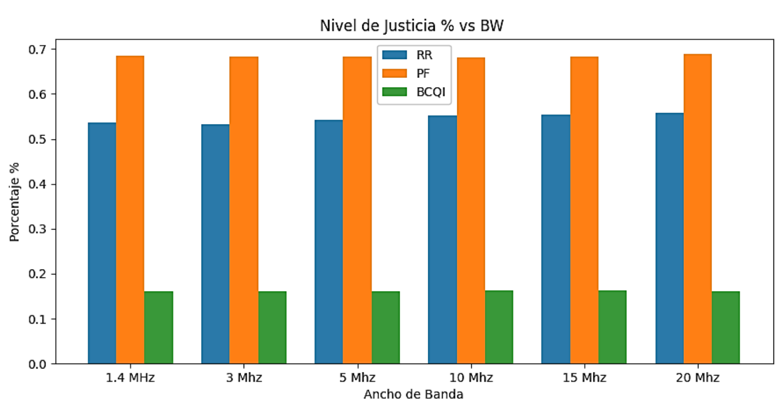
Figure 12. Goodput Performance Results



Goodput refers to the amount of useful information successfully delivered over the link, in contrast to throughput, which represents the total amount of data transmitted without distinguishing between useful and non-useful information. The goodput results are analyzed under different bandwidth configurations and compared across the three scheduling algorithms, as shown in Figure 12.

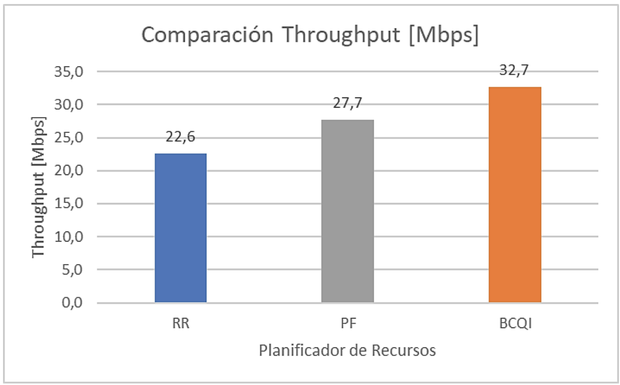
A comparison is made among the different scheduling algorithms to identify which one provides a more equitable distribution of resources among users. In this way, the effectiveness of resource allocation is evaluated by measuring the level of fairness achieved for different bandwidth values (1.4 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz), as illustrated in Figure 13.

Figure 13. Fairness Results



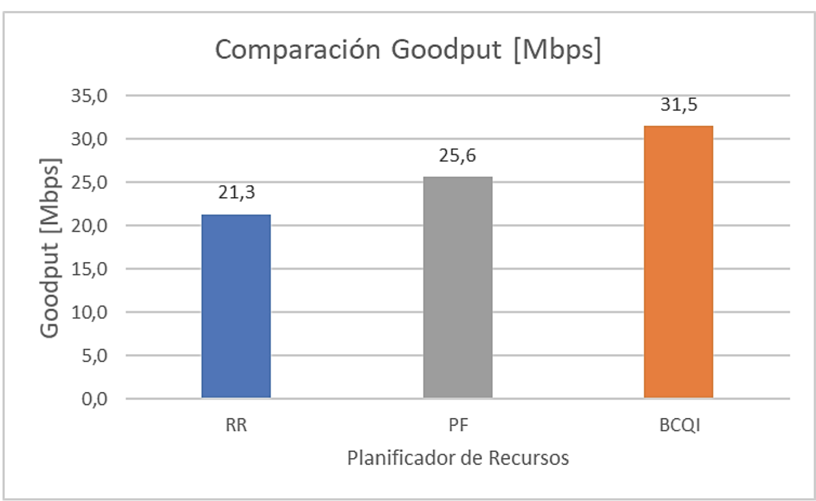
The comparison is conducted in terms of the average throughput for each scheduling algorithm. These values are obtained from the overall average throughput calculated from the throughput results corresponding to each of the previously defined bandwidth values. This approach allows identifying which algorithm achieves the highest performance. These percentages are detailed in Figure 14.

Figure 14. Throughput Comparison of the Three Scheduling Algorithms



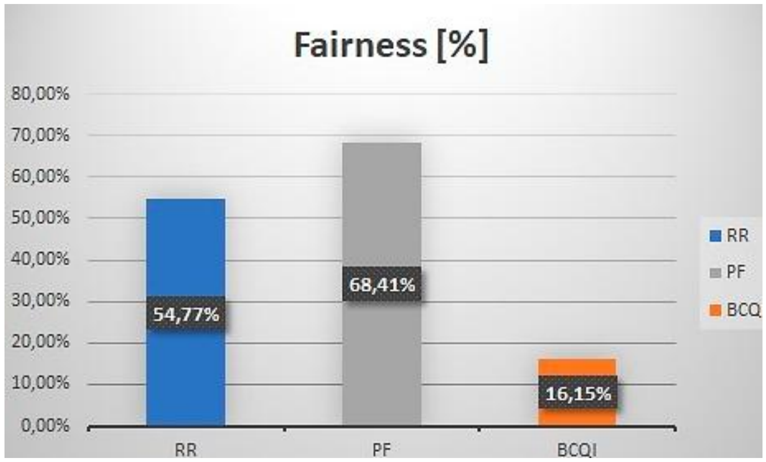
The comparison is conducted in terms of the average goodput for each scheduling algorithm. These values are obtained from the overall average goodput, calculated from the goodput results corresponding to each of the previously defined bandwidth values. This approach allows the identification of the algorithm that achieves the highest performance. These percentages are detailed in Figure 15.

Figure 15. Goodput comparison for the three schedulers.



The comparison is made in terms of percentages of effectiveness in Fairness for each planner, identifying who generates greater efficiency in allocating resources, as identified in Figure 16.

Figure 16. Fairness effectiveness percentage.



4. Conclusions

This work presented a performance evaluation of resource scheduling algorithms in LTE and 5G networks, focusing on throughput, goodput, and fairness under different bandwidth configurations and user densities. An intermediate controller was implemented to manage interactions between the Physical and MAC layers, enabling improved coordination and scheduling decisions.

Simulation results show that channel-aware schedulers such as Best CQI achieve the highest throughput levels; however, this comes at the expense of fairness, as resources tend to be concentrated among users with better channel conditions. In contrast, Round Robin and Proportional Fair schedulers provide more balanced resource allocation, achieving significantly higher fairness indices while maintaining moderate throughput performance.

The analysis also demonstrates that the Proportional Fair scheduler offers the best trade-off between throughput and fairness, maintaining fairness levels above 60% across different scenarios. Meanwhile, Round Robin ensures equitable resource distribution but with lower throughput compared to Best CQI.

Overall, it can be concluded that while Best CQI maximizes system throughput, Proportional Fair and Round Robin schedulers are more suitable for scenarios where fairness and balanced user experience are prioritized. The choice of scheduler should therefore depend on the specific network requirements and service objectives.

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