ISSN: 2182-2069 / E-ISSN: 2182-2077

OFDMA-Based Resource Allocation in Next-Gen Wireless Internet Systems

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Received: August 22, 2025; Revised: September 27, 2025; Accepted: November 04, 2025; Published: November 28, 2025

Abstract

5G is part of next-generation internet systems, and Orthogonal Frequency Division Multiple Access (OFDMA) is a vital technology for efficient and effective spectrum use. The resource-allocation strategies based on OFDMA discussed in this paper help address the needs for data rate, latency, and device connectivity. It is possible to enhance throughput and fairness within the system by dynamically allocating the available bandwidth, partitioned across several orthogonal subcarriers, to multiple users. We focus on the central issues of resource assignment in OFDMA-based heterogeneous networks, including user scheduling, power allocation, and interference suppression. In addition, the use of machine learning and optimization technologies to distribute resources in an adaptive, intelligent manner is presented as the direction for the future. This study proposes to develop scalable, energy-efficient wireless networks by examining existing allocation schemes to enhance them. The varied simulation outputs, along with comparative studies, indicate how the different methods differ in terms of performance trade-offs, such as spectral efficiency, service quality (QoS), and energy consumption. These findings justify concluding that resource allocation strategies using OFDMA improve performance and establish OFDMA's future in many applications, including mobile broadband with ultra-reliable low-latency communications.

Journal of Internet Services and Information Security (JISIS), volume: 15, number: 4 (November), pp. 589-603.
DOI: *10.58346/JISIS.2025.I4.043*

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Keywords: OFDMA, Resource Allocation, Next-Generation Networks, Wireless Internet, Spectrum Efficiency, 5G and Beyond, QoS (Quality of Service).

1 Introduction

1.1 Summary of OFDMA Technology

Most current wireless networks use Orthogonal Frequency Division Multiple Access (OFDMA), which supports simultaneous transmission to multiple users. OFDMA increases overall throughput and user fairness by dividing the available frequency into closely spaced subcarriers and allocating them on demand (Chakraborty et al., 2020). It provides flexible space to exchange resources between the time and frequency domains, making it a natural fit for the rapidly changing, mixed-device wireless environment (Kanonakis et al., 2013). This flexibility has led recent standards, from 4G LTE to 5G New Radio (NR), to adopt OFDMA, which offers scalable bandwidth, low delay, and dynamic user scheduling (Wang & Li, 2021). In urban centres with dense populations, where echoes and overlaps cause severe fading, OFDMA today offers significantly greater protection to smartphones and sensors than older spread-spectrum systems like CDMA or pure-time TDMA. The method is also becoming a real saviour for future wireless networks, thanks to its strong computational capabilities and improved channel estimation (Zhang & Xu, 2019; Agiwal et al., 2016). The introduction of new mobile broadband services, ultra-reliable and low-latency services, and extensive M2M services by operators can be facilitated by using OFDMA to provide seamless coverage in all situations (Feng et al., 2021).

1.2 Overview of Wireless Internet Systems Resource Allocation

Since the spectrum is finite and users have heterogeneous demands, resource allocation is a significant challenge in OFDMA systems (Shamakhi et al., 2014). Resource allocation involves a variety of activities, such as assigning subcarriers and setting power levels, and determining the priority for serving a particular user, to achieve better throughput, lower energy consumption, fairness, and quality-of-service objectives (Ali & Leung, 2020; Kumar et al., 2019). The main difficulty is to update those decisions in real time as fading, interference, channel speed, and other channel conditions change. Currently, many applications demand higher QoS targets, and the old, fixed tricks do not always work. More advanced ones are superseding these approaches to enhance allocation effectiveness, including machine learning, game theory, and convex optimization (Nguyen & Tran, 2021). In the example, ML frameworks may predict power control and demand scheduling using user and channel state information (Ali & Leung, 2020; Miglani et al., 2020). Inter-cell and intra-cell interference is a new problem in dense networks, particularly in device-to-device (D2D) communications (Chen & Li, 2022; Udayakumar et al., 2023; Majstorović et al., 2023).

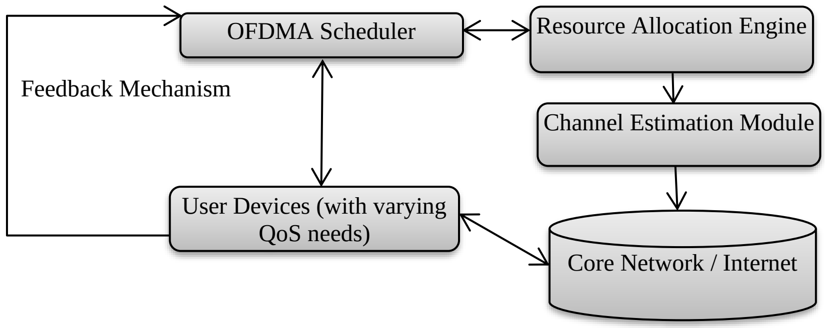

Figure 1: OFDMA-Enabled next-generation wireless internet system

The upper-level design of an internet system using OFDM (Orthogonal Frequency Division Multiple Access) is presented in the diagram (Figure 1). The most important element is the OFDMA Scheduler, which dynamically assigns network transmission resources based on current network conditions and user demands. The Resource Allocation Engine allocates resources and makes decisions based on the scheduler, while the Channel Estimation Module analyzes channel conditions to inform those allocations. The system also interacts with user devices with varying Quality-of-Service requirements, which can feed back and enable the scheduler to control adaptation. The Core Network/Internet handles requests for data and services, and users can access them. The user experience is enhanced by closed-loop feedback, ensuring that real-time scheduling and resource allocation changes improve user satisfaction.

Fractional frequency reuse and interference-aware scheduling are both coordinated resource allocation schemes that are important for ensuring high-quality links and effective spectrum management (Miranda & Garcia, 2017). Cost-effective allocation schemes play a critical role in preserving the battery life of Internet of Things (IoT) equipment and reducing operational costs in mass deployment (Xie et al., 2020; Priyanka et al., 2023). Some of these power-efficient strategies include adaptive modulation and coding, energy-aware subcarrier allocation, and sleep-mode scheduling for base stations. Balancing system performance and energy consumption becomes a central optimization goal as wireless networks scale (Slobodan et al., 2023). Methods that focus on users and take into consideration the application needs and QoS levels are becoming more popular (Nath et al., 2010). Industrial IoT applications may prioritize ultra-low latency, while video streaming services demand high throughput with minimal jitter (Park & Kim, 2020; Majstorović et al., 2023). Because these services are context-aware, the allocation algorithms must also be adaptive in order to provide differentiated services. In modern OFDMA, resource allocation, fairness, and scalability are significant. The problem of equitable access for all users while enabling massive user connections persists, even in 5G and the upcoming 6G networks (Ganti & Kuchi, 2012). Increasingly, multi-objective optimization frameworks are being used to balance competing objectives, such as maximizing throughput while ensuring fairness among users (Khan et al., 2021).

1.3 Problem Statement

This research focuses on the adaptive, intelligent, and self-scaling needs for resource allocation strategies in next-generation OFDMA-based wireless internet systems (Lanante et al., 2020). It is designed to help develop efficient wireless infrastructures in real-world settings, addressing challenges in resource allocation strategies and in emerging techniques for adaptive wireless networks. The rest of the paper is structured as follows: In Section II, the background of OFDMA technology is presented alongside that of other wireless technologies. It also discusses prior work on resource allocation in wireless networks. Section III focuses on resource allocation in OFDMA systems, discussing the advantages and disadvantages, conversion techniques to improve performance, and various efficiency-enhancing mathematical models. Some case study appraisals using primary evaluative measures are used in Section IV, where the application of these methods and their relative impact on performance is evaluated. Section V presents the potential future growth areas of ODFMA technology in next-generation wireless networks, including probable developments, areas that need further exploration, and their general effects on communication. Section VI concludes the paper by presenting the results, explaining the key findings and the recommendations for further studies, and outlining practical steps to implement the results.

2 Background

2.1 OFDMA Technology Explanation

OFDMA, short for Orthogonal Frequency Division Multiple Access, builds on the multiuser concept already present in OFDM (Orthogonal Frequency Division Multiplexing). In plain terms, OFDM slices the available radio band into many tight, parallel subcarriers so bits can race down each one at high speed. OFDMA goes a step further by assigning entire groups of subcarriers to different users simultaneously (Prasad et al., 2020; Vakhguelt & Jianzhong, 2023). Since transmissions and responses co-occur, the system squeezes every hertz while simultaneously satisfying diverse speed and latency needs on each device (Rehman et al., 2023). A significant part of its strength is attributed to a time-frequency grid so fine that the network can load, change, and shield every resource slot in response to changing conditions. One advantage is channel-aware scheduling, which monitors link quality and relocates subcarriers rather than keeping them idle or frozen (Sharma & Rajput, 2024). This agility, combined with the possibility of wider or narrower separations between subcarriers, enables OFDMA for fast phones and low-power IoT sensors, as well as for mission-critical radio connections (Shabani & Akbarpour Shirazi, 2024).

2.2 Comparison to Other Wireless Technologies

OFDMA provides a severe advantage in speed and scale when compared to older protocols such as TDMA, CDMA, or FDMA. TDMA and FDMA are simple to comprehend, but their time blocks or frequency bands are fixed, and thus, any room is wasted each time there is a change in traffic. CDMA has a decent ability to overcome interference, but the instant the number of users accumulates, the performance and spectral economy become compromised (Kumar et al., 2019). Due to the way the OFDMA assigns orthogonal subcarriers in small portions, many clients can coexist simultaneously without interfering with each other. The design will leave engineers without the code-matching and cancellation pain of CDMA to allow the receiver hardware to remain simpler (Alavi et al., 2021). The combination of pair of data minimum frequency allocation and multi-input multi-output antennas, combined with the additional throughput and stability of the link, justifies the 4G LTE, 5G NR, and even initial 6G architectures relying on it (Ren et al., 2020). The LTE uplink utilizes SC-FDMA, which reduces peak-average power ratios, but with the help of OFDMA in the downlink, the users can have low-lag and bandwidth-witty connections (Huang et al., 2021). Due to all these reasons, OFDMA occupies the core of the existing systems and continues to attract a lot of research interest.

2.3 Prior Studies on Resource Allocation in Wireless Networks

People have invested efforts in ensuring that wireless resource sharing with over OFDM is not only faster and fairer, but also users are made fair, quality of service is solid, lower power consumption, and simply better than ever (Choudhary & Verma, 2025). Initial papers addressed the subcarrier and power chores heuristically and using pure mathematics, relying on well-known tricks such as the water-filling rule and convex optimization (Jang & Lee, 2003; Rahim, 2024). They wanted to extract the optimum overall bittage over the channel and yet not spill power or saturate the air with unnecessary interference. More recent investigations spin towards wiser, on-the-fly systems executed on machine learning, where the software modulates assignments as circumstances evolve. The most notable one is dynamic spectrum swapping in combination with deep reinforcement learning, which provides the network with the opportunity to acquire winning moves based on its own experience (Sun et al., 2020; Jalood, 2022). Multi-objective trade-offs in mixed networks are also simulated using other teams by fuzzy logic or genetic algorithms, which balance speed, power, and coverage during a single sweep (Nasir et al., 2021). When it comes down to ultra-low latency and high throughput, fairness-conscious schemes intervene to ensure that all users of the scheme are served reasonably. Researchers have also met the conflicting needs of users by proposing proportional-fairness scheduling and utility-based schemes (Chien et al., 2019; Al-Yateem et al., 2024). Simultaneously, the integration of edge computing with the cloud-backed control is enabling 5G and beyond networks to steer resources in a more thoughtful and timely manner (Bala Krishna, 2021). These concepts can be found in current frameworks like 5G NR, which clearly demonstrate that research push. New standards bring the flexibility of numerologies, agile TDD, and learning-conscious scheduling, all based on the strengths of the underpinnings, OFDMA.

3 OFDMA-Based Resource Allocation

3.1 How OFDMA Technology Improves Resource Allocation

OFDMA divides the available radio band into numerous small parallel channels, referred to as subcarriers, and allocates them to users on demand. Since it is capable of scheduling every user both in time and frequency, this technique outcompetes older access schemes that considered all devices as equal. This kind of granularity allows the system to balance even the most differentiated service levels, ranging from latency-sensitive sensors to ultra-HD video streams. Increasing traffic and a blizzard of IoT devices drive operators to make decisions in real-time, with the help of real-time channel-state information (CSI) about each subcarrier (Ahn et al., 2016). By then doing so, not only does OFDMA eke out additional bits per hertz, but it also distributes the load in such a way that it does not make any one user feel crowded. As an illustration, the devices that have strong, definite links receive bigger blocks of subcarriers, which carry the networks, overall increasing the throughput of the networks. On the other hand, the user at the edge is given additional power and a more concentrated cluster of subcarriers to protect against dropout. The intelligent design maintains the subcarriers orthogonal, and the subcarrier spill-over interference in the cell is maintained at near-zero. All these characteristics raise the average signal quality and satisfaction of users. OFDMA and NOMA are the high-priority technologies in solving the problem and issues relating to resource allocation in 5G Networks. OFDMA divides the spectrum into orthogonal subcarriers, which provides effective control of interference (Saquib et al., 2012). On the other hand, NOMA provides an opportunity to share the same subcarrier among multiple users using power domain multiplexing. NOMA has high throughput and low latency in highly congested environments, thereby supporting latency-sensitive services, including autonomous vehicles, smart cities, and industrial IoT. However, it is problematic when it comes to ultra-dense situations because there are interference and synchronization problems. Future research is mainly in the areas of further development of interference cancellation and synchronization, and scaling of massive IoT. Furthermore, it is necessary to explore hybrid models, which can be used to combine OFDMA and NOMA in order to achieve high performance in the 5G architecture. The improved hybrid models will ease the strain on resource management. The 5G networks should be supported because the models contribute to dealing with heterogeneous 5G Services.

The total throughput can be captured in the following mathematical expression:

$$R_{total} = \sum_{k=1}^{K} \sum_{n=1}^{N} x_{k,n} \cdot \log_2\left(1 + \frac{P_{k,n} h_{k,n}}{N_0}\right) \tag{1}$$

Where:

$x_{k,n}$ = 1 if subcarrier n is allocated to user k; 0 otherwise

$P_{k,n}$: Power given to user k on subcarrier n

$h_{k,n}$: Channel gain for user k on subcarrier n

N_0: Power of noise

K: Total number of users

N: Total amount of subcarriers

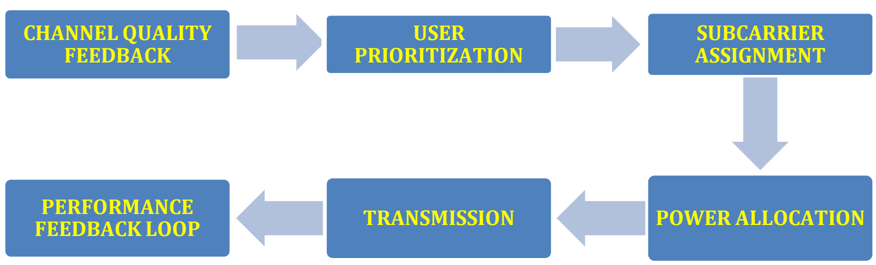

Figure 2: Resource allocation flow in OFDMA systems

The diagram (Figure 2) showcases the upper-level design of a wireless internet system that uses OFDMA (Orthogonal Frequency Division Multiple Access). The core component is the OFDMA Scheduler that allocates network transmission resources in real-time based on the current network state and user requirements. The Resource Allocation Engine works with the allocation of resources and makes decisions using the scheduler, while the Channel Estimation Module analyzes conditions of the channel to improve those allocations. User Devices with different levels of QoS (Quality of Service) requirements interact with the system and provide feedback that helps the scheduler for control adaptation. Requests for data and services are located in the Core Network/Internet, so that a user can use services and applications. The closed-loop feedback user experience model guarantees that real-time scheduling and resource allocation adjustments improve user satisfaction.

3.2 Concerns in Next-Gen Wireless Systems Resource Allocation Strategies

The use of OFDMA in next-generation wireless systems offers some advantages, but it also clearly has drawbacks. The most challenging problem is user and device heterogeneity. 5G and beyond is expected to simultaneously provide enhanced mobile broadband (eMBB) alongside ultra-reliable low latency communications (URLLC) and massive machine-type communications (mMTC). Each of these use cases has resource allocation parameters that need optimization, which makes resource allocation a multi-objective optimization problem. Channel variability is another concern. In high mobility scenarios, channel conditions vary quickly and require real-time channel state information (CSI) feedback, which is costly in terms of resources, real-time feedback, and adaptation. Moreover, interference control is significant in densely deployed overlapping cell scenarios, as the control of the base stations has to be optimally coordinated. In addition, energy efficiency is of critical concern now. In battery-operated devices, IoT, and edge devices, dynamically assigning the power and subcarriers needs to take energy constraints into account.

3.3 OFDMA Resource Allocation Strategies

To these ends, a number of strategies have been proposed:

1. Proportional Fairness Scheduling (PFS): Balances user throughput and user fairness by maximizing the ratio of instantaneous to average data rate.
2. Dynamic Subcarrier Allocation: Allocates subcarriers based on real-time CSI by placing them where they will be most efficient. This can be expressed as:

$$\max_{x_{k,n}} \sum_{k=1}^{K} \sum_{n=1}^{N} x_{k,n} \cdot \log_2\left(1 + \gamma_{k,n}\right) \quad s.t \sum_{k} x_{k,n} \leq 1 \qquad (2)$$

where $\gamma_{k,n}$ represents the SINR (Signal-to-Interference-and-Noise Ratio) metric for user k on subcarrier n.

3. Power Control Algorithms: Enhancers of SINR strive to minimize interference and boost energy efficiency, redistributing it across users and subcarriers.
4. Machine Learning-Based Allocation: Uses reinforcement learning to optimize allocation strategies in environments with uncertain or incomplete Channel State Information (CSI).

Proposed Model: Utility-Based OFDMA Resource Allocation

We propose a resource allocation model based on user utilities designed to maximize the weighted sum of user utilities whilst optimizing system throughput, fairness, and energy efficiency.

Let:

(R_k) shows user ks utility, with R standing for that person's total data rate.

Objective:

$$\max_{x_{k,n}, P_{k,n}} \sum_{k=1}^{K} w_k \cdot U_k(R_k) \qquad (3)$$

These constraints have to do with power and bandwidth:

$$\sum_{n=1}^{N} x_{k,n} \cdot P_{k,n} \leq P_{max}, \sum_{k=1}^{K} x_{k,n} \leq 1 \qquad (4)$$

The updated model now lets providers fine-tune each service by applying task-specific weights w_k and personal utility curves, so it better matches what future mobile networks will ask for.

4 Case Studies

4.1 Successful OFDMA Resource Allocation Cases

The latest wireless networks, such as LTE, WiMAX, and 5G NR, are today based on OFDMA due to its suitability for the heavy traffic requirements. They are subcarrier sharing and dynamically adjust the power, increasing user contentment and spectrum density per cell. An example of this is LTE, which has an inbuilt scheduler that breaks blueprints of time-frequency Resource Blocks into tens of subcarriers and delivers them to phones and tablets. Each grant aligns with the Channel Quality Indicator CQI data already returned by users of the data. Devices with good channels acquire additional blocks for fast downloads, whereas those with poor connections earn their portion courtesy of proportional fairness. In the densely 5G cities, a similar OFDMA scheme collaborates with network slicing and real-time beam steering to ensure that eMBB video calls, factory machines, and self-driving cars all receive the bandwidth they desire. Tests indicate that this agile combination of resources can increase edge throughput by more than 30 percent and reduce latency in the process.

One of the most crucial technologies used by wireless technologies such as LTE, WiMAX, and 5G NR is known to be the OFDMA (Orthogonal Frequency Division Multiple Access), which helps allocate resources effectively and efficiently in circumstances of high traffic. Subcarriers are allocated and transmission changed in real time to maximize resources and enhance consumer experiences. LTE includes an embedded resource manager named downlink scheduler, which assigns Resource Blocks (RBs) based on the CQI (Channel Quality Indicator) feedback of the devices. CQI devices are given preference in the allocation of RBs. OFDMA is also improved in 5G NR with network slicing and beam steering, both of which guarantee that resource multiplexing achieves the bandwidth requirement of communication. Applications of this allocation policy in Enhanced Mobile Broadband (eMBB) and on-demand factory car control have proven the throughput increase with this policy of more than 30 percent, with a corresponding reduction in latency. OFDMA is still an essential technology in resource allocation to modern use cases that have significant data needs.

4.2 Comparison of Various Approaches to Allocating Resources

The precise choice of resource allocation methods in OFDMA systems hinges on the context at hand, the channels on offer, and the network's overall goals. Under those circumstances, a handful of core strategies usually takes center stage:

Max-Min Fairness (MMF): Ensures minimum throughput for all users and tries to maximize the minimum value of all users to guarantee fairness, particularly in diverse networks.

Proportional Fair Scheduling (PFS): Uses logarithmic increase to sum proportional to fairness among all users to achieve fairness while considering the efficiency of system capacity.

Opportunistic Scheduling: To maximize overall spectral efficiency, this strategy actively allocates resources to users with the best instantaneous channel conditions.

Utility-Based Optimization: This strategy seeks to optimize a defined utility function of the network, which contains elements of the Quality of Service (QoS) requirements, user satisfaction, or some specified priorities of the applications.

Throughput, fairness, and spectral efficiency are some of the key metrics that can be used to evaluate the performance of these strategies. For instance, allocation fairness can be quantified using Jain's fairness index:

$$J(x_1, x_2, \ldots . x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} x_i{}^2} \quad (5)$$

Here, x_i refers to the throughput of user i, and n is the number of users—closer to 1 shows better allocation fairness.

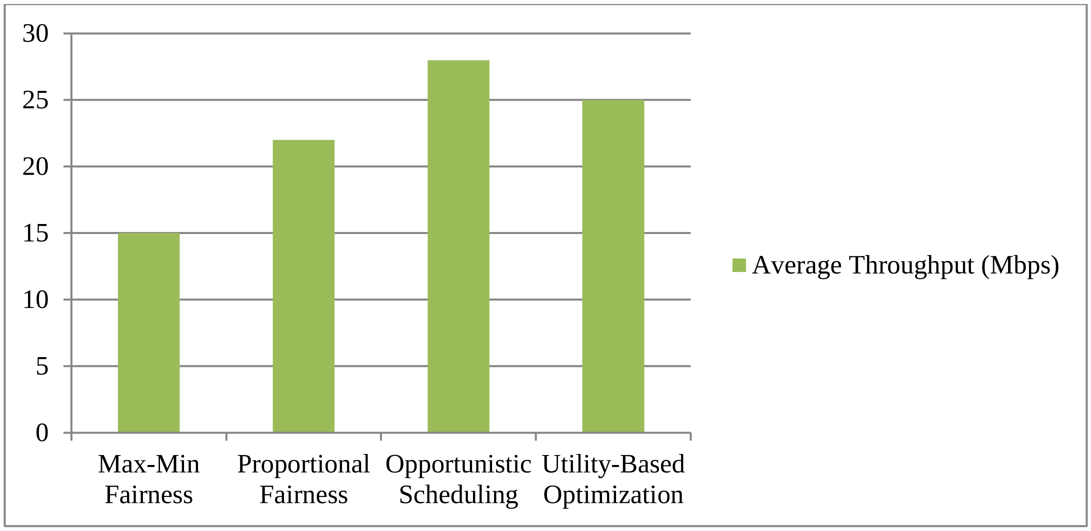

Figure 3: Throughput comparison of allocation strategies

This bar chart (Figure 3) compares average user throughput for various resource allocation strategies in an OFDMA-based wireless system. The findings show that opportunistic scheduling achieved the highest average throughput of 28 Mbps because it uses the best channel conditions for the users. This method is not very fair, however. Utility-based optimization is more fair, reaching 25 Mbps but still meeting key QoS targets. Proportional fairness reaches 22 Mbps and is a better balance between user equity and throughput. Max-min fairness is the fairest, but results in the lowest throughput of 15 Mbps because it focuses on the most disadvantaged users. This graph illustrates the competing goals of maximizing throughput and fairness across all strategies.

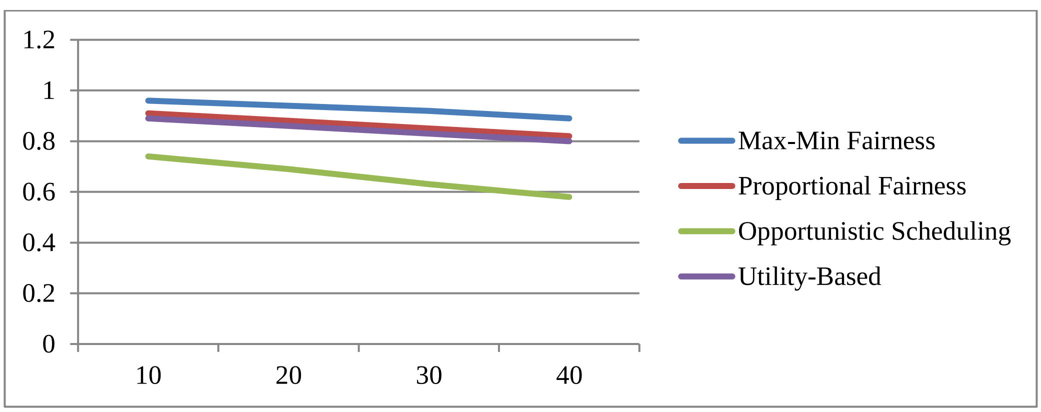

Figure 4: Jain's fairness index for different strategies

Figure 4 shows Jain's Fairness Index for each Strategy as the number of users increases from 10 to 40. Max-min fairness is always best, staying well above 0.89 even at higher user counts. Proportional fairness and utility-based strategies do moderately well, although fairness does drop slightly with increasing users. Conversely, opportunistic scheduling is highly biased toward high-SINR users, showing a steep drop in fairness from 0.74 with 10 users to 0.58 with 40 users. This graph further exemplifies that some strategies improve performance, but instead, worsen equity.

4.3 Impact of Resource Allocation on Network Performance

The core metrics like throughput, latency, energy cost, and user Quality of Experience (QoE) have a direct impact on resource allocation. In OFMA systems, dynamic subcarrier assignment improves overall system throughput efficiency and can be expressed as:

$$Total\,Throughput = \sum_{k=1}^{K}\sum_{n=1}^{N} B_n \cdot \log_2(1+\gamma_{k,n}) \qquad (6)$$

Where:

B_n indicates the bandwidth of subcarrier n ;

$\gamma_{k,n}$ is the SINR for user k on subcarrier n

$K\ and\ N$ are the total users and subcarriers, respectively.

The parallel transmission capability of OFDMA also minimizes latency. URLLC servicing takes advantage of low transmission delays enabled by rapid resource reallocating and minimized queuing. In addition, power-efficient algorithms embedded in the OFDMA scheduling framework reduce power consumption without performance degradation. Lastly, user QoE improves with adaptive resource allocation tailored to specific requirements, particularly in mixed traffic scenarios (video-streaming, voice calls, IoT telemetry). Integrating metrics such as packet error rate (PER) alongside mean opinion score (MOS) enables operators to more effectively use network resources to achieve desired network performance relative to end-user needs.

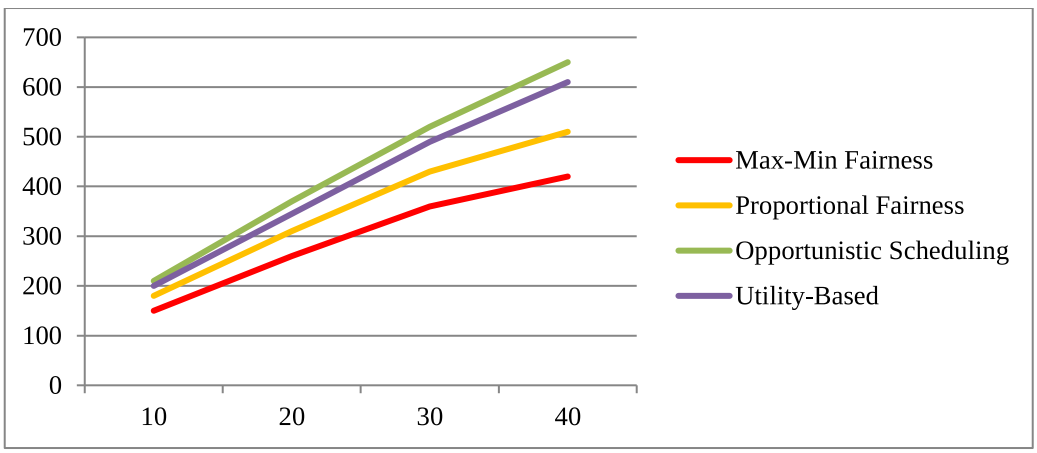

Figure 5: Total system throughput vs. number of users

As the number of users increases, the total system throughput for each strategy is shown in the line graph (Figure 5). The throughput growth of opportunistic scheduling reaches 650 Mbps at 40 users, exhibiting the highest growth through selective allocation to users with favorable channel conditions. Utility-based optimization follows closely, achieving 610 Mbps, owing to its adaptive nature that balances throughput and fairness. Proportional fairness continues to rise steadily, reaching 510 Mbps, while max-min fairness grows more slowly and plateaus earlier, peaking at 420 Mbps. These trends suggest that throughput-centric strategies scale more effectively under heavier loads, but may sacrifice equality among users or energy efficiency. Figure 6 illustrates the distribution of latency over time measured in milliseconds for users of ultra-reliable low-latency communication (URLCC) on four different strategies. From this figure, we can observe that the utility-based optimization strategy provides the lowest median latency of 9 ms with the lowest range, which means it is easy to predict and ideal for applications needing low latency. Opportunistic scheduling does exhibit low latency, although with a broader range. Proportional fairness and max-min fairness showed higher and more variable latency compared to the other strategies, with medians of 11 ms and 12 ms, respectively. This strongly indicates that utility-based and opportunistic strategies outperform proportional fairness and max-min fairness in meeting the strict latency needs of URLLC services, which is essential for 5G and later networks.

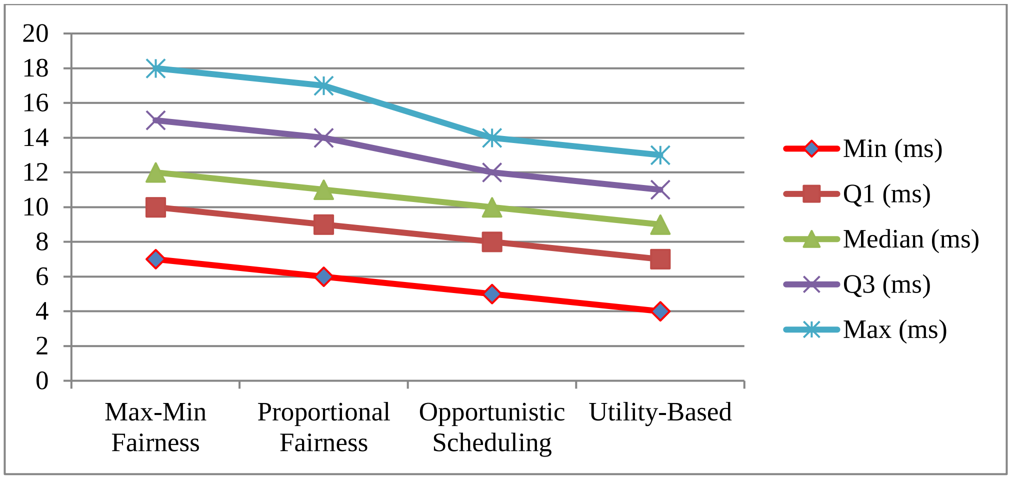

Figure 6: Latency comparison for URLLC users

5 Future Directions

5.1 Possible Further Developments of OFDMA Technology for Resource Allocation

Wireless communication systems moving toward 6G and later are expected to enhance OFDMA technology to meet the requirements of ultra-high speed data transmission with low latency and high reliability. One expected change is the addition of adaptive OFDMA that applies elasticity for the allocation of resource blocks in time, frequency, space, and coding, thus enabling more detailed customization. Such multi-dimensional allocation could dramatically improve dense metropolitan networks and heterogeneous urban environments. Another possible change focuses on intelligent schedulers based on machine learning with real-time analytics capable of high-precision forecasting of user engagement, traffic, and channel dynamics. These allow base stations to allocate resources optimally in advance. Also, the parallel use of NOMA Non-Orthogonal Multiple Access with OFDMA may enhance user access and total throughput in congested environments by enabling multiple users to share a resource block using power domain separation. Lastly, the combination of OFDMA with communication on the terahertz level and Reconfigurable Intelligent Surfaces (RIS) will likely change the approach taken to resource allocation. These technologies will require OFDMA to be modified to support directional beamforming and reflective pathways of transmission, requiring even greater context-aware and adaptable scheduling algorithms.

5.2 Next Generation Wireless Internet Systems: Areas of Further Research

Despite the effectiveness of OFDMA in the 4G and 5G systems, there are some critical gaps that could still be worked on for enhancement in the performance of the technology within upcoming networks.

Among such gaps is the energy-saving resource distribution, particularly with machine-type communication on a vast scale, mMTC, and IoT implementations. Also, explore hybrid energy-aware scheduling mechanisms that have a trade-off between battery life, spectral efficiency, and quality of service. The other area of focus is the use of artificial intelligence (AI), especially reinforcement and federated learning, with OFDMA. Such strategies would enable the edge-of-the-network to be dynamically responsive, with resource distribution and decentralized, privacy-preserving resource allocation that would offload the central controllers. In addition to this, security-conscious resource allocation must be dealt with, where the network utility may be corrupted by malicious practices such as jamming, spoofing, or unfair use. Further research on mobility management of high-speed applications involving self-driving cars and drones in the OFDMA system should be performed in the future. There are still significant issues in such areas as efficient handover and redistribution of resources. Finally, cross-layer optimization approaches, which consider physical, MAC, and network levels under the consideration of latency, reliability, and energy consumption, can be used to meet competing diverse application requirements.

5.3 Effects on the Evolution of Wireless Communication

The development of the process of resource distribution in the technology of the ODFMA will have a significant influence on the whole field of wireless communication. The future state-of-the-art OFDMA will support more diverse applications such as immersive virtual and augmented reality experiences, remote surgery, advanced industrial automation, and smart transport. Having profound user-specific customization and very dense connectivity, the subsequent iterations of the OFDMA will become the precursor of 6G networks that aim at not merely providing communication but also intelligent connectivity everywhere around. Furthermore, future systems of OFDMA will also form a connection between edge and centralized intelligence, with the network environments becoming more heterogeneous and dynamic. The combination of AI, smarter modulation, and more efficient resource allocation will transform wireless communication to be more efficient, sustainable, and user-centered. Such changes will transform the understanding of the concept of performance, extending the boundaries between throughput and latency to situational sensitivity, flexibility, reliability, etc., which will solidify the idea of the use of the OFDMA as a fundamental technology in the next generation of digital connectivity.

6 Conclusion

Overall, the application of OFDMA in resource allocation is one of the essential enablers of the work of the next generations of wireless internet settings in terms of throughput, fairness, and latency. The main characteristics of the technology, its development compared to the older methods of multiplexing, as well as its role in enhancing the performance, have been discussed in the current paper. Due to the accuracy in subcarrier allocation, the wireless networks are able to support highly diverse user requirements and applications, including bandwidth-intensive high-definition streaming to extremely reliable low-latency communications. Proportional fairness, utility-based optimization, and opportunistic scheduling can be used to allocate resources in order to achieve a balance between efficiency and fairness. The use of real-life case studies and performance metrics demonstrated the effect of such strategies on the network performance under different load conditions. To the right, predictive models of resources that are intelligent, energy-conscious, and AI-based will continue to optimize resource allocation in dynamic heterogeneous environments. Further emphasis on mobility management, security-conscious allocation, and cross-layer design must also be given priority to enable

6G system requirements. OFDMA will remain one of the essential technologies in the design of wireless systems, and its development will become important to achieve the objective of seamless access, reliable coverage, and quality service in the digital age.

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