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Maximum expansion with contiguity constraints scheduling algorithm: enhancing uplink transmission in long-term evolution vehicular environments

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ABSTRACT

Uplink scheduling has become increasingly important due to increased activities like uploading videos, photos, and file sharing. Many users share or stream live videos and engage with social networks, significantly increasing uplink data traffic volume. Single carrier frequency division multiple access (SC-FDMA) is favored for its power efficiency and high data rates, benefiting user equipment (UE) battery life. However, maintaining the contiguity of resource blocks (RBs) poses challenges in uplink scheduling. The maximum expansion with contiguity constraints (MECC) algorithm has been introduced to address this challenge. MECC prioritizes contiguity, fairness, and throughput for users at the cell edge. The algorithm operates in two phases: initially allocating RBs proportionally and assigning RBs with the highest metrics while ensuring contiguity. Performance evaluation of MECC, conducted under conditions simulating vehicular movement at 30 km/h, demonstrates its superiority over other algorithms. MECC provides high fairness and throughput for both real-time (RT) and non-real-time (NRT) traffic, making it the preferred scheduler for ensuring quality of service (QoS) for both traffic types. Its focus on contiguity, fairness, throughput, and spectral efficiency establishes MECC as a valuable tool for optimizing uplink transmission in mobile networks, addressing the evolving needs of users in today's digital landscape.

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1. INTRODUCTION

In today's internet and communication network infrastructure, quality of service (QoS) is essential for all users. QoS is considered crucial across all internet protocol networks, including video and voice streaming, and is increasingly emphasized in the expanding field of the internet of things (IoT) [1]. The introduction of long-term evolution (LTE) marks a significant milestone in wireless communication technology, representing a pivotal advancement and serving as the cornerstone of the 4G standard. The third-generation partnership project (3GPP) has led the development of LTE, building upon earlier technologies such as global system for mobile communications (GSM) and Universal Mobile Telecommunications System (UMTS). It addresses the growing demand for high-speed data transfer and enhanced network capacity, making it a crucial evolution in the telecommunications industry [2], [3]. LTE was established to address the rising demand for enhanced data speeds, improved application performance, and secure, reliable connections.

It uses a 20 MHz spectrum to give high-performance wireless access with 75 Mbit/s uplink and 300 Mbit/s downlink speeds. The radio access network must also fulfill QoS criteria, requiring transmission latency of fewer than 20 milliseconds [4], [5].

Orthogonal frequency division multiplexing (OFDM) is widely utilized in wireless communication systems for efficient data transmission. By dividing the frequency spectrum into multiple orthogonal subcarriers, OFDM enables simultaneous data transmission across these subcarriers while avoiding interference. This technique maximizes spectral efficiency and supports high data rates, making it a key technology for modern wireless networks. Conversely, single carrier frequency division multiple access (SC-FDMA) is designed to optimize uplink transmissions by minimizing power consumption [6]. This multiple-access scheme tailored for uplink communication allocates a single subcarrier to each user, differentiating it from OFDMA, which allows multiple users to share subcarriers in the frequency domain.

One critical advantage of SC-FDMA is its ability to achieve a lower peak-to-average power ratio (PAPR) than OFDMA. This lower PAPR reduces the demands on the power amplifier, resulting in improved power efficiency and extended device battery life, which are essential features for mobile and portable wireless devices [7]. These characteristics make SC-FDMA particularly well-suited for uplink transmission in systems such as LTE, where efficient and reliable communication is a priority. By limiting the number of users per subcarrier, SC-FDMA minimizes the complexity of power amplifiers and enables more efficient use of battery power in mobile devices [8], [9]. Therefore, SC-FDMA addresses the limitations of OFDMA in the uplink direction, making it a suitable choice for power-constrained environments such as mobile communication systems [10], [11]. SC-FDMA offers simplified equalization, improved coverage, and resilience to frequency-selective fading compared to OFDMA. However, it necessitates contiguous allocation of subcarriers within each time slot, potentially limiting flexibility in resource allocation. Uplink scheduling algorithms are specifically designed to tackle challenges such as the high PAPR associated with OFDM modulation, which can lead to inefficient operation of power amplifiers [7].

Radio resource management (RRM) plays a vital role in the system architecture of 3GPP LTE, particularly at LTE base stations (eNodeB), as described in [12]. It serves as the foundation for enabling packet scheduling within LTE networks. LTE services are designed to support both real-time (RT) and non-real-time (NRT) applications, catering to various communication needs. These two application types are distinguished by their unique QoS requirements, including delay, packet loss rate, and data throughput metrics. RT applications typically demand stringent QoS to ensure low latency and reliable performance, while NRT applications are generally more tolerant to parameter variations. The integration of RRM into LTE ensures the effective allocation of resources to meet these diverse QoS demands, enhancing the overall network performance [13], [14].

Resource allocation and scheduling in LTE networks are crucial to optimum results due to multimedia applications' more excellent data rates and radio resource requirements. While single carrier frequency division multiple access (SC-FDMA) offers numerous advantages, its performance in the uplink direction may be constrained by packet scheduling. LTE's radio resource management (RRM) is essential to enhance data transmission speed by optimizing network resources. The scheduler must fulfill QoS criteria and appropriately distribute physical resource blocks (PRBs) [15], [16].

There are still several issues with uplink packet scheduling that might restrict its efficiency. Specific challenges must be addressed in the uplink packet scheduling architecture to ensure the smooth operation of the LTE uplink interface. Challenges addressed in the research include performance metrics, time constraints, and power limitations in uplink transmissions. Using the SC-FDMA transmission scheme introduces the contiguity constraint as a significant limitation in uplink packet scheduling. Contiguous frequency domain allocation is crucial for optimizing the PAPR across all resource blocks (RBs). However, this constraint reduces the spectral efficiency of uplink transmissions, as a physical resource block (PRB) is assigned to user equipment (UE) even if other UEs have superior channel quality for the same PRB. Consequently, when providing the QoS, the LTE uplink scheduling algorithm needs to adhere to this restriction.

Previous research has examined round Robin (RR), minimum area difference (MAD_E), recursive maximum expansion (RME), and first maximum expansion (FME) as uplink scheduling algorithms [17]. The outcomes demonstrated that RME, FME, and MAD_E enhanced spectrum efficiency and fairness. Elgazzar *et al.* [18] presented modified FME (MFME), a better FME with better throughput, fairness, and spectrum efficiency. Further research conducted by Safa and Tohme [19] analyzed the performance of the FME, RME, and Riding Peak algorithms. This evaluation demonstrated that the FME method performed less well than the RME and RME algorithms in both the channel-dependent (CD) and proportional fairness (PF) paradigms. The throughput and fairness of the maximum throughput (MT), FME, and RR scheduling algorithms for service classes were evaluated by Ahmad and Almuhallabi [20]. FME and MT had poor RT throughput but ensured fairness across all traffic flows. Other pedestrian scheduling algorithm research examined performance and compared algorithms like MT, FME, and RR for service class throughput and fairness [9]. FME optimized packet loss rate (PLR) but had low throughput for real-time multimedia applications. The three-phase hierarchical algorithm (3PHA) [21] and a two-phase scheduling technique proposed by Hwang *et al.* [8] were developed to meet QoS requirements and ensure fairness. This method outperformed FME and PF in RT service QoS, resource allocation, and fairness. The RR, MT, and FME scheduling algorithms were examined by Dardouri [22] for their impact on service class throughput, fairness, PLR, and spectral efficiency (SE). It was observed that while the RR scheduler emphasized the FME scheduler, it enhanced user spectral efficiency, device performance, and user efficiency without increasing PLR.

Additionally, various optimization schemes such as particle swarm optimization (PSO) [23] and modified dynamic Hungarian algorithm with modification (DHAM) [24] were introduced to improve LTE transmission speed and optimize traffic prioritization. Sirhan and Martinez-Ramon [25] examined user and scheduler interactions and evaluated standard scheduling techniques, algorithms, characteristics, ideal circumstances, and direction changes to separate LTE downlink and uplink scheduling processes. Time-domain packet schedulers (TDPS) and frequency-domain packet schedulers (FDPS) SA schedulers were also classified [26]. SA schedulers manage resources based on channel circumstances, fairness, and QoS to avoid cell-edge users from starving.

Recent advancements in wireless network scheduling techniques have significantly improved the QoS, ensuring robust end-to-end support for various traffic types, including RT and best-effort (BE) traffic. These advancements prioritize delivering high-quality network performance while accommodating non-critical traffic. Among these techniques, the proportional fair (PF) scheduling approach has been widely adopted due to its ability to balance throughput, fairness, and spectral efficiency. However, achieving optimal throughput for users at the cell edge remains a crucial challenge, requiring targeted evaluation and solutions.

The study referenced in [27], investigates the maximum expansion with contiguity constraint (MECC) scheduling algorithm's performance within a high-speed vehicular LTE network environment, specifically at 120 km/h speeds. The evaluation focuses on critical metrics such as throughput, fairness index, delay, and PLR for various traffic types, including VoIP, video, and BE flows. The MECC algorithm achieves superior throughput for both RT and NRT traffic, outperforming RR, channel-dependent-FME (CD-FME), and proportional fairness-FME (PF-FME) algorithms. It also demonstrates significant reductions in delay and PLR, particularly benefiting RT traffic when compared to CD-FME. Moreover, MECC ensures satisfactory fairness for users at the cell edge, making it a strong candidate for vehicular LTE networks.

However, the studies in [27] have not considered spectral efficiency, which is reduced by the contiguity limitation in uplink transmission. As a result, the MECC scheduling algorithm must comply with this requirement while providing QoS. MECC demonstrates performance in maximizing spectral efficiency and improving cell edge user throughput in uplink transmission environments. MECC addresses the unique challenges that cell edge users face, supports multiple traffic types, and focuses on providing QoS metrics. The paper's structure is as follows: section 2 details the proposed algorithm, section 3 discusses the simulation results, and section 4 outlines the conclusions.

2. THE PROPOSED METHOD

Uplink transmission in LTE refers to the process of transmitting data from UEs to the base station (eNodeB) within LTE networks. In this transmission direction, UEs send data, such as user-generated content or requests, to the eNodeB for further processing and routing within the network. Uplink transmission enables bidirectional communication between users and the LTE network infrastructure. The configuration of the LTE frame plays a vital role in LTE networks as it governs the organization of data and control information within radio frames for transmission. It comprises several key components [28].

Each LTE frame has a fixed duration of 10 milliseconds (ms). LTE frames are divided into ten subframes, numbered from 0 to 9, each lasting 1 ms, as shown in Figure 1. LTE subframes are divided into two slots each, with a duration of 0.5 ms, resulting in 20 slots per frame. The duration of each slot, known as the transmission time interval (TTI), is fixed at 0.5 ms. LTE frames utilize a resource grid, a two-dimensional grid of time-frequency resource elements, to allocate physical channels and signals for data transmission and control purposes. Specific subframes within the LTE frame structure are dedicated to control channels and used for signaling and control functions such as synchronization signals, reference signals, and scheduling information. These channels are crucial in managing and coordinating communication among the base station and user devices. Overall, the LTE frame structure facilitates efficient data transmission, synchronization, and resource allocation in LTE networks, ensuring optimal performance and reliability [13].

Hence, this section delineates the methodology employed in this study, focusing on the proposed scheduling algorithm known as MECC. MECC is designed to address the specific needs of cell-edge users in LTE uplink transmission. One of its primary objectives is to ensure fairness and optimal performance for users at the periphery of the cell coverage area. Additionally, MECC is equipped to manage contiguity restrictions, which dictate the allocation of contiguous radio resources to users for efficient data transmission.

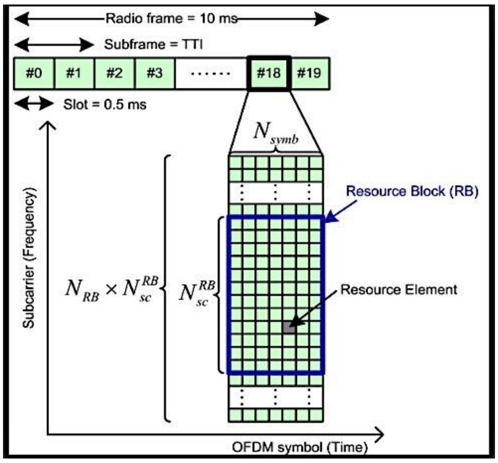

Figure 1. LTE frame structure [28]

2.1. Blind equal throughput algorithm

The blind equal throughput (BET) method uses a scheduling metric [26]. The BET scheduler was chosen to emphasize guaranteeing performance and fairness to users near the cell edge. The BET algorithm seeks to distribute a uniform quantity of resource blocks to all users regardless of traffic flow, channel circumstances, or signal-to-noise ratio (SNR). The scheduler is given an input matrix Q of dimensions [$N_{UE} \times N_{RB}$], where each component $Q_{i,k}$ is computed using the BET equation shown in Figure 2.

	RB_1	RB_2	….	RB_N
UE_1	$Q_{1,1}$	$Q_{1,2}$	….	$Q_{1,N}$
UE_2	$Q_{2,1}$	$Q_{2,2}$	….	$Q_{2,N}$
:	:	:	:	:
:	:	:	:	:
UE_N	$Q_{N,1}$	$Q_{N,2}$	….	$Q_{N, NRB}$

Figure 2. Input matrix of Q

The BET algorithm desires to provide an equitable throughput to all users within the system. The specific metric for BET is determined by (1).

$$m_{i,k}^{BET} = \frac{1}{\overline{R^i}(t-1)} \quad (1)$$

where the historical average throughput attained by the i^{-th} user until time *t*, denoted as $\overline{R^i}(t)$, is computed using (2),

$$\overline{R^i}(t) = \beta\overline{R^i}(t-1) + (1-\beta)r^i(t) \quad (2)$$

In the study by Noh *et al.* [29], the parameter β, representing the weighted moving average factor ($0 < \beta < 1$), was investigated across a range from 0.1 to 0.9. However, to optimize throughput and fairness, a value of 0.1 was assigned to β in this study.

The BET algorithm assigns resources by considering each user's historically lower average throughput in every TTI. This approach favors users with lower throughput until their performance matches that of other users in the cell. As a result, devices experiencing poorer channel conditions receive a greater allocation of resources compared to those with better conditions, leading to enhanced fairness.

2.2. MECC resource allocation in LTE systems

There are two stages to the MECC scheduler's uplink resource allocation process. PRBs are randomly assigned to UEs, classifying the available RBs according to the N_{RB} to N_{UE} ratio. Subsequently, it allocates RBs equitably across UEs to preserve equity, enhancing spectral efficiency. RBs are distributed to UEs using multiuser diversity gain according to their channel conditions in the second allocation phase. The allocation of RBs, extending from both sides of matrix Q, is determined by the most significant metric value. Each UE is deemed serviced when another UE with an improved measured value is discovered. The allocation procedure commences with the UE-RB combination from $Q_{i,k}$ with the highest metric value to expand the allocation on both sides of matrix Q. The scheduler looks at every column in matrix Q to see whether the highest metric is still associated with the UE that is getting resources or if it is associated with a different UE. The RB is assigned to the selected UE if the requirements are satisfied; if not, the current UE is deemed serviced, and the RB is assigned to an alternative user. Iteratively, this procedure is repeated. Transferring the RB to a different user equipment would breach continuity limitations.

2.3. Simulation parameters

Throughput, a key performance indicator, measures the rate at which successfully delivered packets traverse a physical channel. Expressed mathematically, it is calculated by dividing the total number of bits successfully received by the flow length.

$$Throughput = \frac{P_{transmit}}{t} \quad (3)$$

The time required to transmit the packets for each user is denoted by 't,' and the variable $P_{transmit}$ refers to the quantity of the transmitted packets.

To guarantee equitable distribution of resources among all system users, the fairness index is calculated based on the throughput achieved by each flow after every simulation instance. To ensure that consumers are treated fairly, Jain's Fairness Index is used, which is represented by (4).

$$Fairness\ Index = \frac{(\sum x_i)^2}{n\ x\ \sum x_i^2} \quad (4)$$

The throughput of user i is represented by x_i, while the total number of active transactions is denoted by n.

In systems, the 5th percentile of the cumulative distribution function (CDF) of user throughput represents the cell edge user throughput. This value signifies the minimum throughput experienced by users at the periphery of the cell. The CDF of cell edge user throughput shows how throughput values are distributed among these users, offering insights into their performance within the system.

A simulation model is employed to represent a single cell, characterized by a radius of 1 km, where the eNodeB is centrally positioned within the cell. The number of users ranges from 20 to 200. UE movement within the cell adheres to a random direction model with a 30 km/h speed, representing vehicular scenarios. UDP is implemented as the transport protocol, with a 10 MHz bandwidth configuration. VoIP G.729 voice flows follow an ON/OFF Markov chain pattern, transmitting 20-byte packets every 20 ms at 8 kbps during active periods, with no data transmitted during inactive periods due to voice activity detection. Video traffic is simulated using genuine video trace files; preferred flows are H.264 encoded at 242 kbps [30].

Additionally, the best-effort application operates as an infinite buffer, maintaining a constant supply of packets for transmission without guaranteeing delivery or meeting quality of service standards. The video and VoIP streams simulate real-time applications, and an infinite buffer represents the best effort flow for non-real-time services. The metrics, including throughput and fairness index, were assessed to evaluate the MECC, RR, PF-FME, and CD-FME schedulers. Table 1 provides a summary of the simulation parameters that are involved in LTE-SIM. The Jakes model was applied to the fast-fading channel as the propagation model. The propagation loss model is briefly outlined in Table 2.

Table 1. LTE uplink simulation parameters

Parameter	Value
Transmission power	43 dBm
Cell radius	1 km
Number of users	20 to 200 Users
Traffic flows	1 BE, 1 VoIP, 1 video
Mobility model	Random direction
Transport protocol	UDP
System bandwidth	10 MHz
Frequency carrier	1.98 GHz
Number of RBs	50
RB bandwidth	180 kHz
TTI	1 ms
Maximum delay	0.1 s
Speed	30 km/h
VoIP bit rate	8 kbps
Video bit rate	242 kbps

Table 2. Propagation loss model

Parameter	Value
Path loss	L = 128:1 + 37:6 log10 d, where d is the kilometers-long distance between the user and eNodeB
Penetration loss	10 dB
Shadowing fading	Log-normal distribution has a mean of 0 dB and a standard deviation of 8 dB
Fading channel	Jakes Model

3. RESULTS AND DISCUSSION

In this scenario, with the user's speed kept constant at 30 km/h, comparisons are made between the MECC algorithm and others, including RR, PF-FME, and CD-FME, as shown in Figures 3 to 10. The focus is on throughput and the fairness index in vehicular settings. The evaluation involves three traffic categories: RT services such as video flow and VoIP and NRT services described as best-effort flow.

3.1. Throughput

Figures 3 to 5 display the throughput performance of different scheduling strategies for VoIP, video, and BE traffic. In Figure 3, the VoIP throughput for both the MECC and RR algorithms increases exponentially as the number of users rises. However, once the user count surpasses 100, the RR algorithm outperforms MECC, achieving a 7.89% higher throughput by evenly distributing resources for more efficient packet transmissions. On the other hand, the PF-FME and CD-FME algorithms demonstrate significantly lower throughput compared to MECC, with decreases of 97.64% and 97.15% respectively. This reduction is due to packet collisions and decreased throughput with an increasing number of users, resulting in higher network data traffic.

Figure 4 shows the throughput for video flows, with MECC achieving throughput levels of 6 Mbps to 7 Mbps, outperforming all other algorithms as the number of users increases. MECC's throughput is 90.81%, 80.16%, and 75.54% higher than that of RR, PF-FME, and CD-FME, respectively, due to its fair RB allocation across users. MECC maintains consistent throughput by allowing users with lower past averages to transmit in subsequent iterations, ensuring all users are scheduled. In contrast, the throughput for the RR algorithm decreases as the user count rises, and after 120 users, RR has the lowest throughput, 53.66% lower than PF-FME, primarily due to packet drops that result in inefficient use of assigned PRBs. CD-FME and PF-FME schedulers show similar throughput trends, with lower performance from low to high loads, as these algorithms prioritize BE traffic, causing more packet loss during transmission.

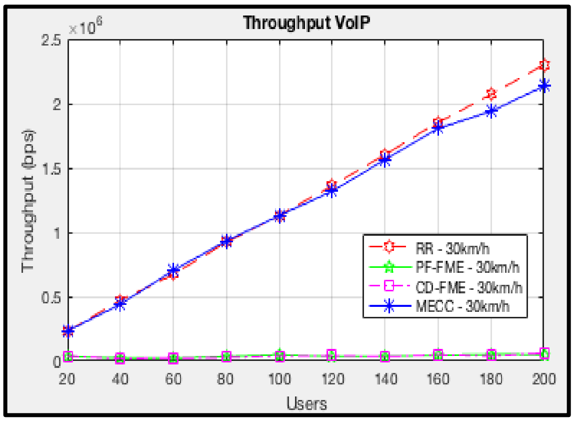

Figure 3. Throughput for VoIP flows

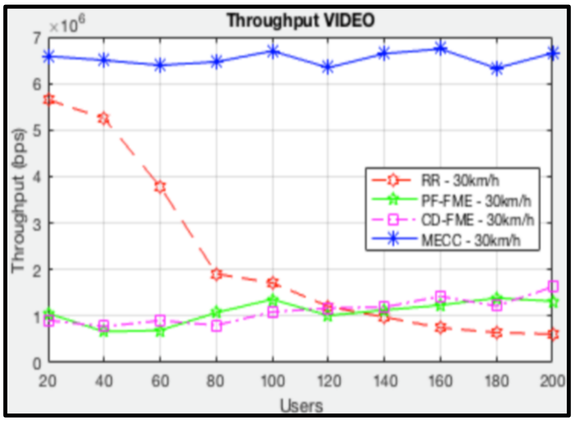

Figure 4. Throughput for video flows

In Figure 5, the BE flow throughput is highest for the MECC algorithm, which surpasses RR by 93.99% and PF-FME and CD-FME by 1.45% and 13.77%, respectively. A noticeable throughput drop occurs between 40 and 80 users, caused by the prioritization of RT traffic, which pushes NRT services to the background, reducing their performance. Conversely, the RR algorithm exhibits the lowest throughput of all algorithms, with performance declining as more users are added due to its significant allocation to VoIP and video traffic. The CD-FME and PF-FME algorithms, which allocate fewer RBs to VoIP and video streams, show the slowest performance for RT flows as they prioritize NRT traffic.

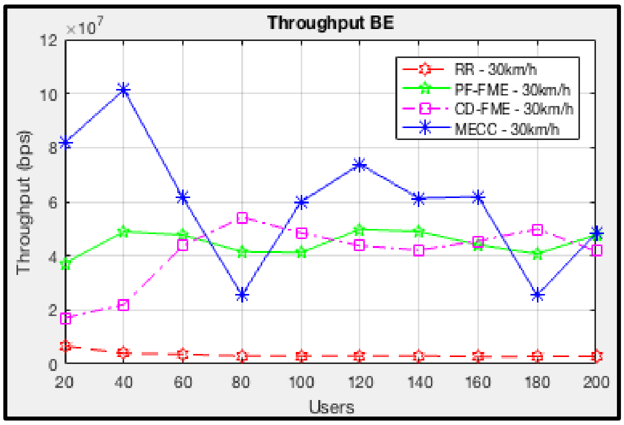

Figure 5. Throughput for BE flows

3.2. Cumulative distribution function

The cumulative distribution function (CDF) in Figure 6 depicts the user throughput. In a network with 200 users, MECC shows significantly higher throughput at the cell edge compared to RR, CD-FME, and PF-FME algorithms, with improvements of 99.38%, 37.50%, and 34.38%, respectively. The observed improvement can be attributed to MECC's fair distribution of resources among its users, focusing on prioritizing those with weakened channel conditions at the cell boundary. Consequently, this results in an overall increase in throughput for all users. In contrast, PF-FME and CD-FME algorithms show lower throughput for users at the cell edge because they favor users closer to the base station, neglecting those with weaker channel conditions. On the other hand, RR, which requires more significant consideration of users' channel conditions, ensures reasonable throughput for cell-edge users, though it tends to approach zero in the system. Therefore, MECC guarantees that cell edge user throughput remains above the 5th percentile of the user throughput CDF, showcasing its efficacy in vehicular scenarios.

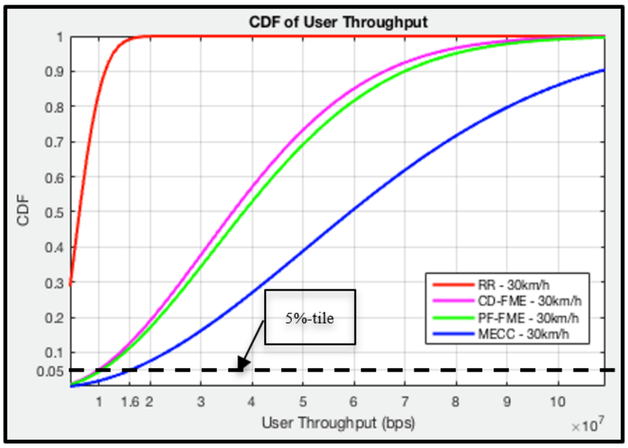

Figure 6. CDF of user throughput

3.3. Fairness index

Figures 7 to 9 display the Jain fairness index for VoIP, video, and BE traffic. Both CD-FME and PF-FME exhibit similar fairness trends. However, the fairness value for CD-FME decreases between 60 and 80 users as it prioritizes users with better channel conditions, disregarding those with poorer channel quality. Beyond 80 users, CD-FME's fairness value increases and stabilizes between 0.7 and 0.9. In contrast, PF-FME's fairness index peaks between 60 and 80 users compared to other algorithms, as it allocates resources based on the channel condition ratio, reducing the likelihood of neglecting users with poorer channel conditions. PF-FME aims for equitable distribution across all traffic streams, although its fairness value diminishes after 80 users, reaching its lowest efficacy at 200.

MECC and RR demonstrate comparable fairness levels for VoIP and video traffic flows, consistently ranging between 0.7 and 0.8 as the user count increases. Both methods offer increased throughput for real-time flows. However, MECC exhibits superior fairness performance for BE flows compared to RR. The fairness value of MECC decreases rapidly as the user count reaches 140 to 160, which is attributed to allocating more resources to users with inferior channel conditions instead of those with superior channel conditions. The MECC fairness value starts increasing after 160 users and eventually reaches its peak fairness compared to other algorithms, maintaining a range of 0.7 to 0.8. The RR method maintains a constant fairness index across all traffic flows, ensuring allocation fairness and making it fairer than other schedulers.

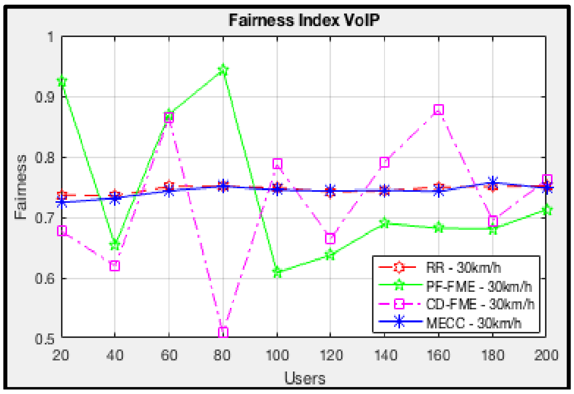

Figure 7. Fairness index for VoIP flows

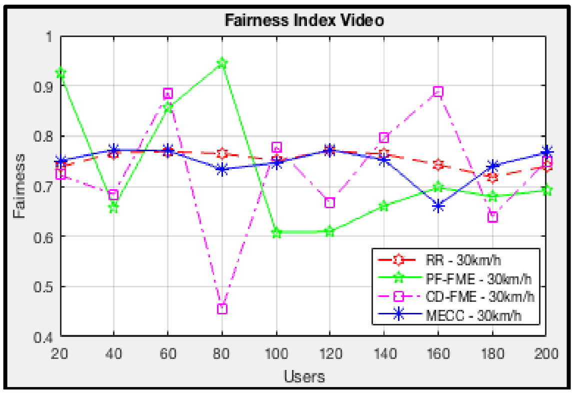

Figure 8. Fairness index for video flows

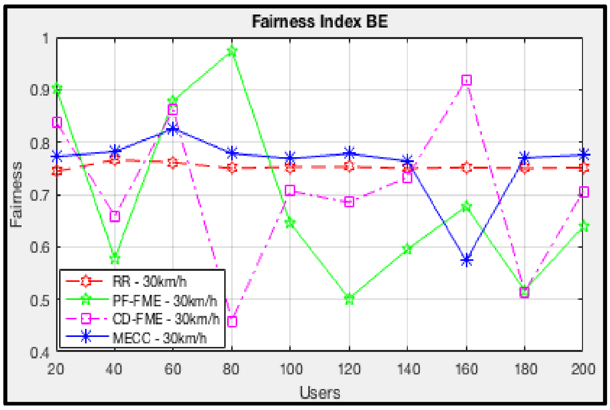

Figure 9. Fairness index for BE flows

3.4. Spectral efficiency

Figure 10 presents the spectral efficiency of the vehicle environment. At 40 users, MECC demonstrates the most substantial improvement in spectral efficiency, outperforming RR, CD-FME, and PF-FME by 33.82%, 38.24%, and 85.29%, respectively. This is due to MECC's more efficient utilization of the full available spectrum compared to the other algorithms. However, the throughput performance of BE flows experiences a sharp decline between 40 and 80 users, indicating that while increased spectral efficiency can boost throughput, it negatively impacts fairness.

CD-FME's spectral efficiency improves steadily from 20 to 80 users, maintaining a range of 4 to 5 bps/Hz. This is achieved by allocating RBs to higher-priority data, thereby optimizing overall network usage. PF-FME, on the other hand, balances spectral efficiency and fairness, but this trade-off prevents it from prioritizing high-priority flows, resulting in a consistent spectral efficiency of 4 to 5 bps/Hz as the number of users grows. The RR method delivers the lowest spectral efficiency because it allocates resources without considering QoS criteria, which diminishes its spectrum utilization.

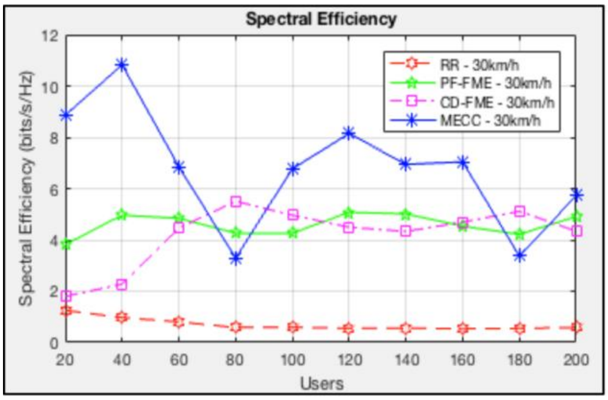

Figure 10. Spectral efficiency for vehicular environment

4. CONCLUSION

The growing demand for live video streaming and social media engagement has heightened the significance of uplink transmission for mobile users. SC-FDMA is a preferred technology due to its power efficiency and ability to support high data rates, enhancing user equipment's battery life (UE). However, maintaining the contiguity of RBs remains a critical challenge in uplink scheduling. The MECC algorithm addresses this challenge by focusing on contiguity, fairness, throughput, and spectral efficiency, particularly for users at the cell edge. Performance evaluations, simulating vehicular speeds of 30 km/h, show that MECC outperforms alternative algorithms, providing superior fairness and throughput for RT and NRT traffic. With its optimized spectrum usage, MECC achieves the highest spectral efficiency, making it the ideal scheduler for ensuring QoS across different traffic types.

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REFERENCES

[1] C. Basumallick, "What Is QoS (quality of service)? meaning, working, importance, and applications QoS measures network performance and enables the network to run high-priority apps and services," *spiceworks.com*, 2022. https://www.spiceworks.com/tech/iot/articles/what-is-qos/ (accessed Jul. 26, 2024).

[2] A. A. Salih, S. R. M. Zeebaree, A. S. Abdulraheem, R. R. Zebari, M. A. M. Sadeeq, and O. M. Ahmed, "Evolution of mobile wireless communication to 5G revolution," *Technology Reports of Kansai University*, vol. 62, no. 05, 2020.

[3] M. Pandeeswari, "Survey on wireless communication in radio networks," *International Research Journal (TIJER)*, vol. 10, no. 6, pp. 600–603, 2023.

[4] S. D. Muruganathan *et al.*, "An overview of 3GPP release-15 study on enhanced LTE support for connected drones," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 140–146, 2021, doi: 10.1109/MCOMSTD.0001.1900021.

[5] MCMC, "Proposal for review the mandatory standards for QoS (wired broadband access service)," Malaysian Communications and Multimedia Commission (MCMC), 2019.

[6] M. M. Hamdi and M. S. Abood, "Transmission over OFDM and SC-FDMA for LTE systems," in *International Conference on Intelligent Systems Design and Applications*, 2021, pp. 722–731.

[7] G. Obulesu *et al.*, "PAPR and SER performance analysis of OFDMA and SCFDMA," *Studies in Computational Intelligence*, vol. 1117, pp. 131–140, 2024, doi: 10.1007/978-3-031-43009-1_12.

[8] I. S. Hwang, B. J. Hwang, and C. H. Chen, "Two-stage channel-aware uplink transmission scheme with SC-FDMA in LTE networks," *Journal of Internet Technology*, vol. 20, no. 7, pp. 2099–2107, 2019, doi: 10.3966/160792642019122007008.

[9] S. B. Ismail, D. B. M. Ali, and N. Ya'acob, "Performance analysis of uplink scheduling algorithms in LTE networks," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 9, no. 2, pp. 373–379, 2018, doi: 10.11591/ijeecs.v9.i2.pp373-379.

[10] F. Imam, M. A. Mitu, S. Akter, E. Khanam, S. R. Das, and A. Al-Mamun Bulbul, "Comparative analysis between OFDMA and SC-FDMA: model, features and applications," *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*, vol. 2, no. 2, pp. 75–82, 2019.

[11] K. K. Vaigandla and D. N. Venu, "BER, SNR and PAPR analysis of OFDMA and SC-FDMA," *Gis Science Journal*, vol. 8, no. 9, pp. 970–977, 2021.

[12] O. Shurdi, A. Rakipi, and A. Biberaj, "Performance analysis of scheduling algorithms in simulated LTE network," in *1st International Conference on Frontiers in Academic*, 2023, pp. 479–486.

[13] B. M. Kuboye, "Comparative analysis of scheduling algorithms performance in a long term evolution network," *Journal of Computer Science Research*, vol. 3, no. 4, pp. 20–25, 2021, doi: 10.30564/jcsr.v3i4.3555.

[14] J. I. A. Y. Yaqoob, W. L. Pang, S. K. Wong, and K. Y. Chan, “Enhanced exponential rule scheduling algorithm for real-time traffic in LTE network,” *International Journal of Electrical and Computer Engineering*, vol. 10, no. 2, pp. 1993–2002, 2020, doi: 10.11591/ijece.v10i2.pp1993-2002.
[15] D. H. Y. Taha, H. Haci, and A. Serener, “Novel channel/QoS aware downlink scheduler for next-generation cellular networks,” *Electronics (Switzerland)*, vol. 11, no. 18, 2022, doi: 10.3390/electronics11182895.
[16] S. Khoshnavaz and A. Ghaffarpour, “Improving QoS and fairness of packet scheduling in Wimax networks,” *Seybold Report Journal (TSRJ)*, vol. 17, no. 11, pp. 1516–1532, 2022.
[17] L. Á. M. R. De Temiño, G. Berardinelli, S. Frattasi, and P. Mogensen, “Channel-aware scheduling algorithms for SC-FDMA in LTE uplink,” *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, 2008, doi: 10.1109/PIMRC.2008.4699645.
[18] K. Elgazzar, M. Salah, A. E. M. Taha, and H. Hassanein, “Comparing uplink schedulers for LTE,” in *IWCMC 2010 - Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, 2010, pp. 189–193, doi: 10.1145/1815396.1815441.
[19] H. Safa and K. Tohme, “LTE uplink scheduling algorithms: performance and challenges,” in *2012 19th International Conference on Telecommunications, ICT 2012*, 2012, pp. 1–6, doi: 10.1109/ICTEL.2012.6221230.
[20] R. E. Ahmed and H. M. Almuhallabi, “Throughput-fairness tradeoff in LTE uplink scheduling algorithms,” in *2016 International Conference on Industrial Informatics and Computer Systems, CIICS 2016*, 2016, pp. 1–4, doi: 10.1109/ICCSII.2016.7462415.
[21] A. Hassebo, M. Obidat, and M. Ali, “Four LTE uplink scheduling algorithms performance metrics: delay, throughput, and fairness tradeoff,” in *2017 IEEE International Symposium on Signal Processing and Information Technology, ISSPIT 2017*, 2018, pp. 300–305, doi: 10.1109/ISSPIT.2017.8388659.
[22] S. Dardouri, “Modeling and performance evaluation of packet scheduling in Uplink 3Gpp Lte systems,” *Journal of Mechanics of Continua and Mathematical Sciences*, vol. 15, no. 3, 2020, doi: 10.26782/jmcms.2020.03.00023.
[23] O. O. Ogunrinola, I. O. Olaniyi, S. A. Afolabi, G. A. Olaniyi, and O. E. Ajeigbe, “Modelling and development of a radio resource control and scheduling algorithm for long-term evolution (LTE) Uplink,” *Review of Computer Engineering Studies*, vol. 8, no. 2, pp. 23–34, 2021, doi: 10.18280/rces.080201.
[24] C. Yang and J. He, “Research on scheduling algorithms in Uplink of LTE system,” *IOP Conference Series: Materials Science and Engineering*, vol. 782, no. 3, 2020, doi: 10.1088/1757-899X/782/3/032097.
[25] N. N. Sirhan and M. Martinez-Ramon, “LTE cellular networks packet scheduling algorithms in downlink and Uplink transmission: a survey,” *International Journal of Wireless & Mobile Networks*, vol. 14, no. 2, pp. 1–15, 2022, doi: 10.5121/ijwmn.2022.14201.
[26] S. N. K. Marwat, M. Shuaib, S. Ahmed, A. Hafeez, and M. Tufail, “Medium access-based scheduling scheme for cyber physical systems in 5G networks,” *Electronics (Switzerland)*, vol. 9, no. 4, 2020, doi: 10.3390/electronics9040639.
[27] S. Ismail, D. M. Ali, and A. L. Yusof, “MECC scheduling algorithm in vehicular environment for uplink transmission in LTE networks,” *International Journal of Electrical and Computer Engineering*, vol. 9, no. 2, pp. 1191–1200, 2019, doi: 10.11591/ijece.v9i2.pp1191-1200.
[28] N. Seraji, T. Ahmed, F. Al Muntasir, S. Yeasmin, and M. Shaory, “Performance analysis of the physical layer of long-term evolution (LTE),” *Australian Journal of Engineering and Innovative Technology*, pp. 72–93, 2023, doi: 10.34104/ajeit.023.072093.
[29] K. S. S. K. M. Noh, D. M. Ali, A. A. A. Rahman, A. K. Samingan, Y. Yusuf, and N. M. Yusuff, “Performance analysis of EXP-BET algorithm,” *Journal of Telecommunication, Electronic and Computer Engineering*, vol. 9, no. 1–4, pp. 15–19, 2017.
[30] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda, “Simulating LTE cellular systems: an open-source framework,” *IEEE Transactions on Vehicular Technology*, vol. 60, no. 2, pp. 498–513, Feb. 2011, doi: 10.1109/TVT.2010.2091660.

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