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Comparative Empirical Analysis of Downlink Scheduling Algorithms with Emphasis on the User Satisfaction – Based Scheduler

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ABSTRACT

The increasing demand for mobile broadband services and multimedia applications has intensified the need for efficient radio resource management in Long Term Evolution (LTE) networks. Downlink packet scheduling plays a critical role in allocating limited radio resources among multiple users while satisfying diverse Quality of Service (QoS) requirements. However, existing scheduling algorithms exhibit varying performance under heterogeneous traffic conditions, making it difficult for a single scheduler to satisfy diverse user requirements simultaneously. This study presents a comparative empirical analysis of selected LTE downlink scheduling algorithms with emphasis on providing insights towards the development of a user satisfaction-based scheduler. Four representative algorithms were evaluated: Modified Exponential Rule (MEXP) and Enhanced Fair Earliest Due Date First (EF-EDDF), which represent unified scheduling approaches, as well as Downlink Scheduling Algorithm with Imperfect Channel Quality Indicator (DSA) and Enhanced Exponential Rule (EnEXP), which represent differentiated scheduling approaches. Simulations were conducted using the LTE-Sim platform under a single-cell LTE environment with heterogeneous traffic consisting of Video, Voice over Internet Protocol (VoIP), and Constant Bit Rate (CBR) services. Performance evaluation was based on packet delay, packet loss ratio, throughput, and Jain's fairness index. Results show that differentiated schedulers perform better for delay-sensitive multimedia traffic, while unified schedulers exhibit superior performance for non-real-time traffic. The findings provide useful insights towards the development of a user satisfaction-based scheduler capable of improving fairness, QoS delivery, and overall user experience in LTE networks.

Keywords: LTE networks, Downlink Packet Scheduling, Quality of Service, multimedia traffic, channel quality

1. INTRODUCTION

The increasing demand for information and seamless communication, regardless of the distance between communication parties, has resulted in rapid growth in the number of mobile device users with diverse application requirements. Such rapid growth is associated with great challenges, such as the ability of wireless networks to efficiently support multiple simultaneous users within a single cellular environment while maintaining reliable communication. This highlights the necessity for robust, high-capacity networks that meet the performance requirements of multimedia applications and high-speed data services (Hatta et al., 2022).

Long Term Evolution (LTE) networks have demonstrated significant improvements in mobile broadband performance over the years. However, their efficiency is increasingly challenged by the rising demand for bandwidth-intensive multimedia applications. The performance of LTE networks is influenced by several factors, including the dynamic nature of mobile user equipment (UE), the number of active users within a cell, transmission power, antenna efficiency, and varying channel conditions. Regardless of these variations,

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users expect consistent Quality of Service (QoS), which ultimately translates into improved Quality of Experience (QoE). The presence of numerous users with varying multimedia service demands further emphasizes the need for fairness in bandwidth allocation to ensure satisfactory service delivery (Hatta et al., 2022). Consequently, effective management of scarce radio resources is crucial for sustaining high traffic and maintaining acceptable level of performance in LTE networks (Kibria et al., 2017).

In mobile communication systems, scheduling refers to the process of allocating available resource blocks to a subset of user equipment (UEs) to optimize network performance metrics (Kukade et al., 2021). Unlike earlier systems such as High-Speed Downlink Packet Access (HSDPA), where scheduling was performed only in the time domain, LTE scheduling operates in both the time and frequency domains. This dual-domain scheduling allows the network to exploit variations in channel quality among users, thereby improving overall system throughput (Kwan & Leung, 2010). The primary objective of scheduling algorithms is to balance competing system requirements in order to achieve efficient radio resource allocation while satisfying QoS constraints (Zaki et al., 2013) (Capozzi et al., 2013). However, the concept of optimal scheduling is inherently subjective, as different researchers emphasize different performance objectives when designing scheduling algorithms. In practice, the end-to-end QoS experienced by users results from the combined effects of several network components. Key QoS indicators in LTE networks include fairness, packet delay, packet loss ratio, average transmission rate, and throughput. To effectively maintain these QoS indicators, a scheduling algorithm must possess adaptive capabilities that would enable it to respond to the dynamic variations in wireless channel conditions (Elhadad et al., 2020).

In wireless communication networks, extensive research has been carried out over the years, with various researchers aiming to develop schedulers that perform optimally, either by improving existing schemes or by designing new ones. Schedulers can be opportunistic, exploiting disparities in users' channel conditions to give preference to users with good channel conditions, or fairness-oriented, aiming to ensure that all users receive a fair share of the allocated network resources. In this work, we categorize the scheduling algorithms into two approaches namely; unified scheduling and differential scheduling algorithms, based on how the algorithms handle the different applications as shown in Figure 1.

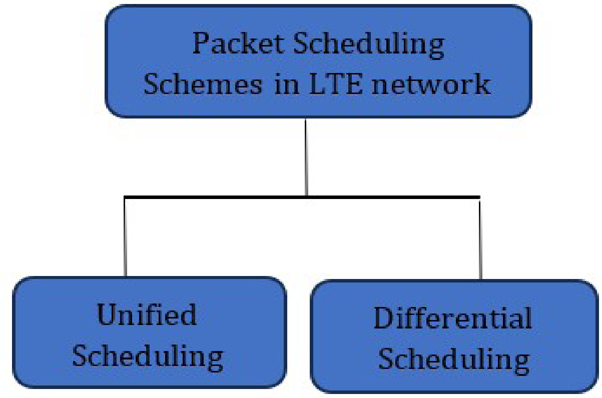

Figure 1: Scheduling approaches

Unified Scheduling algorithms

Unified schedulers treat all traffic types equally during resource allocation. Their key advantages include simplicity, flexibility, and inherent fairness since resources are distributed uniformly among users. However, equal treatment may overlook the specific QoS requirements of heterogeneous traffic classes.

The Proportional Fair (PF) scheduler (Jalali et al., 2000) occupies a foundational basis for many LTE scheduling algorithms. It balances throughput maximization and fairness by selecting users based on the ratio of instantaneous achievable rate to average throughput. PF provides an effective trade-off between fairness and throughput (Dadi & Chibani, 2017; Kayali et al., 2017; Kwan et al., 2009; Mahfoudi et al., 2015), but it performs poorly for delay-sensitive real-time services (Monikandan et al., 2020).

Various improvements have been proposed. Dynamic PF improves cell-edge performance by adjusting scheduling metrics over time (Ning et al., 2008), while the Exponential Linear Scheduler exploits channel variation to enhance throughput (Gougousis & Paterakis, 2006). Hybrid mechanisms such as the Frame Level Scheduler (FLS-PF) combine different policies to reduce packet loss and improve QoS (Piro et al., 2011)

Other unified schemes focus on particular performance objectives. Blind Equal Throughput (BET) ensures equal long-term user throughput but suffers from inefficient resource utilization (Zaki et al., 2013). Conversely, the MaxT scheduler prioritizes users with favorable channel conditions to maximize cell throughput but compromises fairness (Zaki et al., 2013).

Recent enhancements include Quadratic Proportional Fair (QPF), which improves spectral efficiency through modified throughput estimation (Elshennawy, 2020), and Enhanced Fair Earliest Due Date First (EF-EDDF), which integrates channel quality, historical throughput, and packet loss statistics into scheduling decisions (Elhadad et al., 2020). Channel-Aware Optimized Proportional Fair (CAOPF) further introduces channel-weighting factors to improve throughput and reduce blocking probability (Monikandan et al., 2020).

More recent developments such as the Advanced Fair Throughput Optimized Scheduler (AFTOS) integrate optimization techniques with QoS-aware scheduling to enhance spectral efficiency, fairness, delay, and packet loss performance (Taha et al., 2022).

Differential Scheduling Algorithms

Differential schedulers allocate resources based on the QoS requirements of different traffic classes. This enables better support for heterogeneous services, although implementation complexity is typically higher.

The Modified Largest Weighted Delay First (M-LWDF) algorithm integrates delay sensitivity with channel conditions to guarantee QoS for real-time applications (Andrews et al., 2001). Similarly, the Exponential Rule (EXP Rule) combines delay constraints with channel awareness to improve fairness and throughput (Shakkottai & Stolyar, 2000).

To simultaneously support real-time and non-real-time services, the Adaptive Exponential Proportional Fair scheduler applies the EXP rule to real-time traffic while PF scheduling is applied to non-real-time traffic (Rhee et al., 2003). The Virtual Token MLWDF (VT-MLWDF) further incorporates traffic burstiness and packet arrival rates to enhance multimedia QoS performance (Iturralde et al., 2011).

Additional improvements include the Optimized Service Aware (OSA) scheduler, which differentiates traffic types through priority modules (Zahariev et al., 2012), and the Delay Priority Virtual Token MLWDF (DP-VT-MLWDF), which improves real-time performance through delay-priority functions (Li et al., 2016). A handful of MLWDF extensions incorporate user demand variations, retransmission mechanisms, and user-location awareness to improve system performance (Chayon et al., 2017, 2018; Esheikh et al., 2018; Lodwal et al., 2019; Nnamani et al., 2016).

Another notable development is the Enhanced Exponential Rule (EnEXP) which incorporated additional features to enhance the performance of EXP Rule (Yaqoob et al., 2020). The algorithm computes its scheduling metrics separately based on each traffic's inherent characteristics- achieving good performance in terms of throughput, PLR, packet delay and fairness for both Video and VoIP but not without limitations due to its complexity. Downlink Scheduling Algorithm with imperfect CQI (DSA) employs Kalman filtering in estimating channel conditions and mitigating CQI estimation errors (Sulthana & Nakkeeran, 2021). Application-specific scheduling has also been explored; for instance, the Largest Weight Importance First (LWIF) algorithm prioritizes important video frames to enhance perceived video quality (Rahi & Abdualsada, 2022).

2.0 MATERIALS AND METHODS

This study adopts a simulation-based empirical research approach to evaluate the performance of selected LTE downlink scheduling algorithms. The objective is to quantitatively compare the algorithms under identical network conditions and identify their strengths and weaknesses in supporting heterogeneous multimedia traffic.

2.1 Selection of Scheduling Algorithms:

Four representative LTE scheduling algorithms were selected based on their relevance in recent literature and their representation of two major scheduling paradigms. While the Modified Exponential Rule (MEXP) and Enhanced Fair Earliest Due Date First (EF-EDDF) represent unified algorithms, the Downlink Scheduling Algorithm with Imperfect CQI (DSA) and Enhanced Exponential Rule (EnEXP) represent differentiated algorithms. These algorithms were selected because they incorporate different scheduling principles such as channel awareness, delay sensitivity, fairness, and QoS differentiation. Their preference metrics are as shown (Elhadad et al., 2020; Nasralla, 2020; Sulthana & Nakkeeran, 2021; Yaqoob et al., 2020):

$$m_i^{\mathrm{MEXP}} = \max_i \left(\exp\left(\frac{\alpha_i D_{HOL,i}(t)}{1+\sqrt{\frac{1}{N}\sum_i D_{HOL,i}(t)}} \right) \frac{r_i(t)}{\overline{r_i}(t-1)} \right) \quad for\ i \in \frac{RT}{NRT} \tag{1}$$

$$m_{i,j}^{EF-EDDF} = \max_i \left(\frac{(-\log\delta_i)}{\tau_i} \times \frac{D_{HOL,i}(t)}{d_i(t)} \times \frac{r_i^j(t)}{\overline{R}_i(t)} \times \frac{nd_i(t)}{\overline{ND}(t)} \right) \tag{2}$$

$$m_{i,j}^{DSA} = \begin{cases} \zeta_{GBR} \frac{R_i^j(t)}{R_N} D_i & for\ GBR \\ \zeta_{nonGBR} \frac{R_i^j(t)}{R_N} & for\ Non\_GBR \end{cases} \quad (3)$$

$$m_i^{EnEXP} = \begin{cases} \frac{r_{i,j}}{\bar{R}_i} & for\ Best\ effort \\ \exp\left(\frac{\alpha_i D_{HOL,i}(t)}{1+\sqrt{\frac{1}{N_{rt}} \sum_i D_{HOL,i}(t)}} \frac{r_{i,j}}{\bar{R}_i} \right) & for\ VoIP \\ \exp\left(\frac{\alpha_i D_{HOL,i}(t)}{1+\sqrt{\frac{1}{N_{rt}} \sum_i D_{HOL,i}(t)}} \right) r_{i,j} & for\ Video \end{cases} \quad (4)$$

Where: δ_i is the allowed PLR for the ith UE; τ_i is the target delay of the ith UE; $r_i^j(t)$ is the throughput for the ith UE at time t; $\bar{R}_i(t)$ is the previous average throughput delivered to the ith UE until time t; $nd_i(t)$ is the number of packets dropped after exceeding target delay; $\overline{ND}(t)$ is the average of the overall number of packets dropped after their target was exceeded; $d_i(t)$ is the expiration period for the ith UE Head-of-Line (HoL) packet at time t; $\zeta_{GBR} \in [o, 1]$ is the GBR bearer coefficient; $R_i^j(t)$ is the achievable data rate; R_N is the maximum achievable data rate; D_i is the delay indicator given by $D_i = \frac{D_{HOL,i}(t)}{T_d}$, where $D_{HOL,i}(t)$ is the HoL delay and T_d is the packet deadline. In equation 4, $\alpha_i \in \left[\frac{5}{(\tau_i)}, \frac{10}{(\tau_i)}\right]$, $\bar{R}_i$ is the average estimated data rate.

2.2 Simulation Scenario

A single-cell LTE scenario without intra-cell interference was considered. The eNodeB (eNB) is centrally located in the cell, while users are uniformly distributed and follow a random mobility model. The number of users varies from 10 to 100 and each user moves at a constant speed of 3 km/h. Simulation was performed using the LTE-Sim open-source simulator which supports single-cell and multi-cell LTE scenarios and QoS differentiation according to 3GPP specifications (Capozzi et al., 2013). The simulation parameters used are as shown in the Table 1.

Table 1: Simulation Parameters.

	Parameter	Value used
1	Simulation duration	120 s
2	Flow duration	100 s
3	Frame structure	FDD
4	Bandwidth	10MHz
5	UE Speed	3 km/hr
6	Maximum delay	0.1 s
7	Cell radius	1 km
8	Cell scenario	Single cell without interference
9	Number of RBs	50
10	Propagation model	PED-A, Typical Urban
11	Video bit rate	242 kbps
12	VoIP bit rate	8.0 kbps
13	CBR bit rate	100 kbps
14	Mobility	Random
15	Flow Distribution	1 Video flow, 1 VoIP flow, 1 CBR flow

2.3 Traffic model

The CBR application- representing non-real-time services, generates packets of 500 bytes (4000 bits) with inter-arrival time of 0.04 s, giving a constant bit rate of 100 kbps. VoIP traffic- representing delay-sensitive conversational traffic, is modelled using an ON/OFF Markov chain. The ON period follows an exponential distribution with mean 3 s while the OFF period has a truncated exponential distribution with upper limit 6.9 s and mean 3 s. A G.729 codec encodes the VoIP stream at 8 kbps (20-byte packets every 20 ms) during the ON period, while the transmission rate becomes zero during the OFF period. Video traffic is trace-based and encoded at 242 kbps using the H.264 encoder.

2.4 Performance metrics used for comparing the algorithms

Performance comparison used four metrics: packet delay, packet loss ratio, average throughput and fairness index.

$$Average\ Packet\ Delay = \frac{\sum_{\forall i}(tAck(i) - tArriv(i))}{N(T)} \quad (5)$$

Where $tAck(i)$ is the acknowledgement timestamp for the last piece of packet i received by the UE in accordance with HARQ feedback information; $tArriv(i)$ is arrival timestamp for packet i arrives; $N(T)$ is the total number of packets as observed during the period, T, of measurement.

$$Average\ user\ Throughput = \frac{Number\ of\ received\ bits}{Time\ of\ flow} \quad (6$$

$$Packet\ loss\ rate = \frac{Transmitted\ packets - Received\ packe}{Transmitted\ packets}$$

Fairness Index metric based on Raj Jain's fairness index criterion which states that in allocating system resources to n users, if user i is allocated x_i resources, then the fairness index is given by:

$$Fairness\ Index = \frac{|\sum_{i=1}^{n} x_i|^2}{\sum_{i=1}^{n} x_i^2} \quad (8)$$

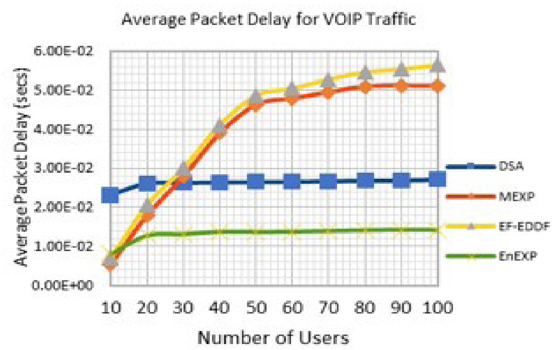

Figure 3: VoIP Packet Delay

3.0 RESULTS AND DISCUSSION

This section presents the simulation results used to compare the performance of the four selected scheduling algorithms: DSA, MEXP, EF-EDDF, and EnEXP. The results are analyzed based on packet delay, packet loss ratio (PLR), throughput, and fairness index for three traffic types: CBR, VoIP, and Video.

3.1 Packet Delay:

Figure 2 illustrates the packet delay performance for CBR traffic.

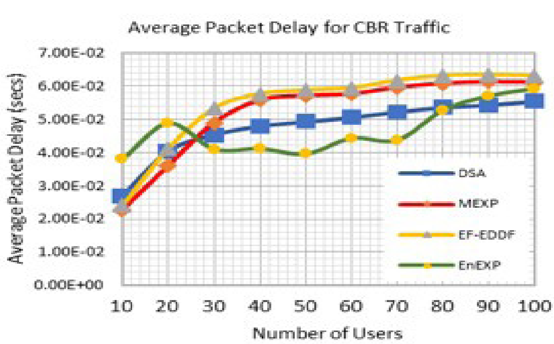

Figure 2: CBR Packet Delay

The results show that DSA, MEXP, and EF-EDDF recorded increasing average packet delay as the number of users increased. However, EnEXP exhibited a wave-like pattern between 10 and 70 users before showing a consistent increase beyond 70 users. Generally, MEXP provides the best performance when the number of users is below 25. Between 25 and 80 users, EnEXP records the lowest delay values, indicating better performance within that range. At 80 users, DSA overtakes EnEXP and records the lowest delay. EF-EDDF, on the other hand, consistently records the highest delay as the number of users increases.

Figure 3 presents the packet delay performance for VoIP traffic. All the algorithms show increasing delay values as the number of users increases. DSA and EnEXP demonstrate similar behavior, maintaining delay values below 0.03 seconds. In contrast, MEXP and EF-EDDF exhibit similar increasing patterns with higher delay values as the number of users increases. Overall, EnEXP performs best beyond approximately 15 users, while EF-EDDF records the poorest performance from around 25 users. The results also indicate that the performance of DSA and EnEXP for VoIP applications is relatively insensitive to the increase in the number of users.

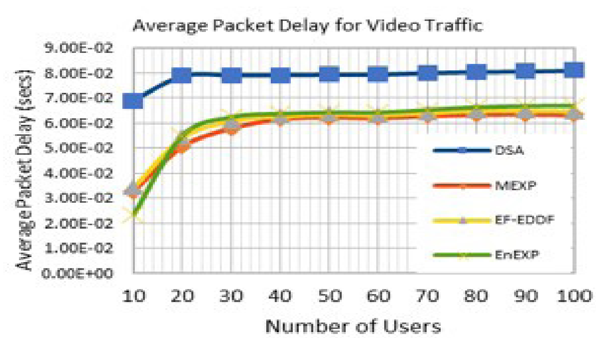

Figure 4: Video Packet Delay

Figure 4 shows the packet delay performance for video traffic. All the scheduling algorithms exhibit a similar trend, with delay increasing sharply up to about 20 users. Among the algorithms, MEXP records the best performance, followed by EF-EDDF. DSA records the highest delay values. However, since packet delay typically increases with the number of users, the performance of DSA is still acceptable as it satisfies the delay constraints specified in the simulation setup.

3.2Packet Loss Ratio

For CBR applications (Figure 5), DSA records the lowest PLR and therefore provides the best performance when the number of users is below 15. At higher numbers of users, MEXP and EF-EDDF outperform the other algorithms. EnEXP shows poor performance, recording extremely high PLR values from 20 users upward within the range of 0.948–0.999. Beyond 20 users, EnEXP maintains an almost constant PLR value, indicating that further increases in the number of users do not significantly affect its performance.

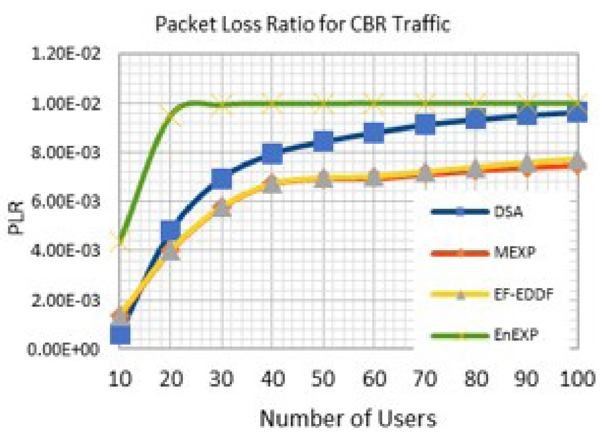

Figure 5: CBR Packet Loss Ratio

Figure 6: VoIP Packet Loss Ratio

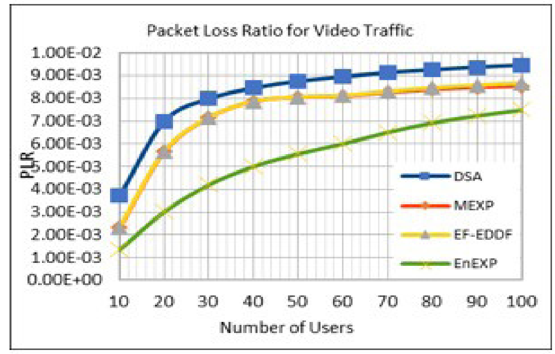

Figure 7: Video Packet Loss Ratio

Figure 6 presents the PLR performance for VoIP traffic. DSA records the best performance, while MEXP exhibits the worst performance among the considered algorithms. DSA also demonstrates the highest level of stability, as increases in the number of users do not significantly degrade its PLR performance.

Figure 7 shows the PLR performance for video traffic. EnEXP provides the best performance, while MEXP and EF-EDDF record similar PLR values. DSA exhibits the worst PLR performance, although its pattern closely follows those of MEXP and EF-EDDF.

3.3Throughput

Figure 8 shows the throughput performance for CBR traffic. MEXP and EF-EDDF exhibit similar patterns, with average user throughput increasing as the number of users increases. DSA throughput increases from $9.45 \times 10^5\ bps$ for 10 users to $1.051 \times 10^6\ bps$ for 20 users before decreasing as the number of users increases further. EnEXP records the lowest throughput for all user scenarios. Additionally, increasing the number of users has minimal effect on the performance of EnEXP compared to the other algorithms. Overall, MEXP achieves the best average user throughput for CBR traffic.

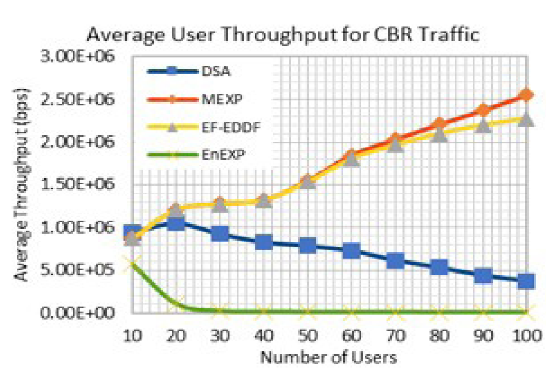

Figure 8: CBR Throughput

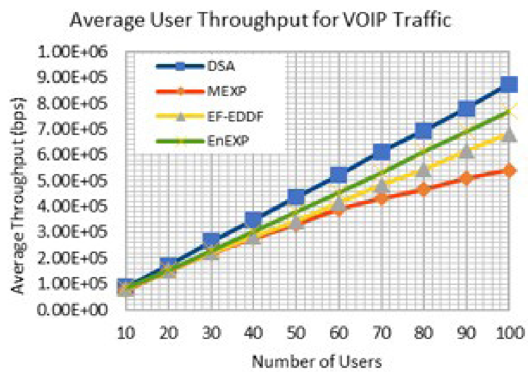

Figure 9: VoIP Throughput

Figure 9 shows a uniform throughput trend for all the algorithms in VoIP traffic, with throughput increasing as the number of users increases. DSA achieves the best performance, increasing from $8.84 \times 10^4\ bps$ for 10 users to $8.74 \times 10^5\ bps$ for 100 users. MEXP records the poorest throughput performance, with values ranging from $7.696 \times 10^5\ bps - 5.411 \times 10^5\ bps$.

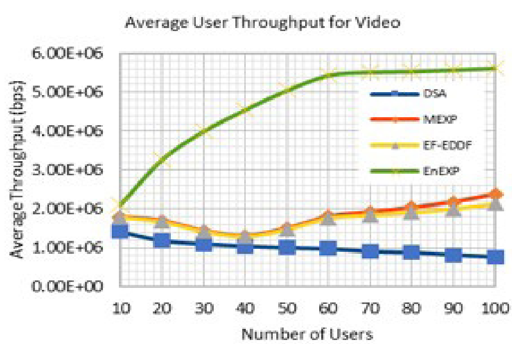

Figure 10: Video Throughput

Figure 10 presents the throughput performance for video traffic. EnEXP achieves the best performance, with throughput increasing rapidly from $2.112\ Mbps$ for $10\ users\ to\ 5.438\ Mbps$ for 60 users, and then rising gradually to $5.62\ Mbps$ for 100 users. DSA records the lowest performance, with throughput decreasing as the number of users increases.

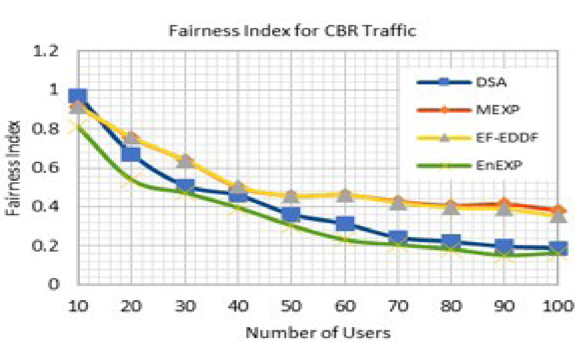

Figure 11: CBR Fairness

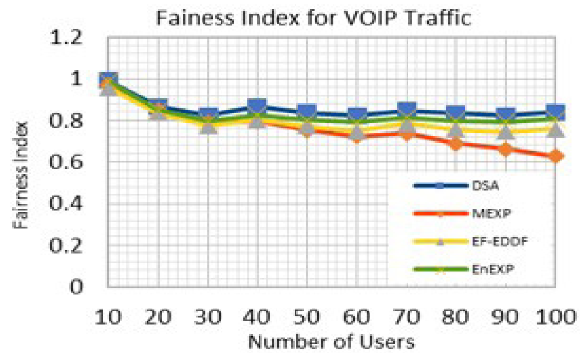

Figure 12: VoIP Fairness

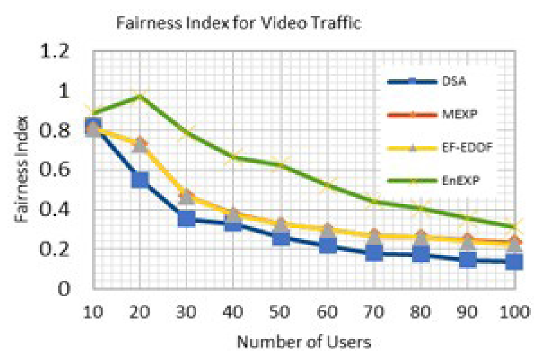

Figure 13: Video Fairness

Figs. 11, 12, and 13 present the fairness index results for CBR, VoIP, and video traffic respectively. For CBR traffic (Fig. 10), MEXP and EF-EDDF achieve the highest fairness index values, while EnEXP records the lowest fairness performance. For VoIP traffic (Fig. 11), all the algorithms show similar behavior. DSA consistently records the highest fairness index across all user scenarios. EF-EDDF records the lowest fairness values when the number of users is below 40, while MEXP records the lowest fairness beyond 40 users. For video traffic (Fig. 12), the fairness index values are generally low for all algorithms. However, EnEXP achieves the best fairness performance across all user scenarios. The results in Figs. 10 and 12 also show that increases in the number of users have a more pronounced effect on fairness index for CBR and video traffic.

4.0 CONCLUSION

The results of the empirical comparative analysis indicate that the differentiated scheduling algorithms generally provide better performance for VoIP and video traffic than the unified service schedulers. In contrast, the unified scheduling algorithm MEXP achieves the best PLR, throughput, and fairness performance for CBR traffic. This performance difference can be attributed to the fact that differentiated scheduling algorithms incorporate the inherent characteristics and QoS requirements of individual traffic types into their design, allowing them to better satisfy the specific requirements of multimedia applications.

Among the differentiated schedulers, EnEXP provides the best PLR, throughput, and fairness index performance for video traffic, while DSA achieves the best performance for VoIP traffic.

The findings from this comparative analysis provide valuable insights into the potential for developing a hybrid scheduling algorithm that leverages the strengths of these existing algorithms to achieve improved performance across multiple multimedia traffic types.

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