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Quality of Service Based Radio Resources Scheduling for 5G eMBB Use Case

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Abstract: Several use cases appear with 5G and beyond networks such as enhanced mobile broadband (eMBB), where ultra-high data rates and low-latency connections become essential demands for asymmetric services, e.g., 8K video streaming and virtual reality (VR). The millimeter-wave (mmWave) band can be a promising player to handle these applications under the condition of efficient implementation of radio resource management (RRM) schemes, which distribute resources among user equipment (UEs) in the network. Firstly, mmWave UE channels are highly affected by the distance between the access point (AP) and UEs. Secondly, static and dynamic obstacles can easily block the AP-UE line-of-sight (LOS) link; hence, it highly attenuates mmWave signals. Moreover, eMBB applications lack symmetry in their data rate requirements, from 75 Mbps up to 300 Mbps; consequently, UE quality of service (QoS) should be considered in designing RRM schemes. In this paper, we study possible scheduling schemes that can be implemented for the 5G eMBB use case. Moreover, we propose a new demand-based proportional fairness (DPF) scheduling algorithm that first depends on both UE channel conditions and quality-of-service demands, then, if certain UEs reach the requirement, the algorithm prioritizes it only based on their channel quality. Furthermore, in this work, we consider a real model to simulate the effect of blockage occurrence on the performance of scheduling schemes. Results prove that the proposed DPF scheduling scheme outperforms conventional algorithms in terms of UE satisfaction while maintaining high total system throughput and fairness among UEs. For example, assuming blockage occurrence with 16 and 32 UEs, it guarantees satisfaction for more than 99% and 60% of UEs and, at the same time, obtains 3.29 and 4.24 Gbps system throughput and maintains fairness between UEs at 0.99 and 0.82, respectively. In contrast, conventional proportional fairness highly degrades satisfaction to only 74% and 30% to achieve total throughput equal to 3.1 and 4.3 Gbps, respectively.

Keywords: scheduling; quality of service; proportional fairness; blockage; enhanced mobile broadband; beyond 5G network; millimeter wave

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1. Introduction

5G and beyond networks come with several new use cases, such as massive-machine-type communication (mMTC), ultra-reliable low-latency communication (URLLC), and enhanced mobile broadband (eMBB) services [1–3]. Based on the Cisco annual report, at the end of 2023, more than 14 billion machine-to-machine connections will exist in the world, while the average speed of Wi-Fi networks will increase to 92 Mbps [4]. 5G use cases need different asymmetric data rates and end-to-end latency demands, according to user equipment (UE) applications [2]. For example, the eMBB use case implies video streaming and virtual reality (VR) applications, where the UEs required data rates vary from 75 Mbps to 300 Mbps, and round-trip delay time reaches 10 ms in real-time applications, which means that each UE experiences different asymmetric quality of service (QoS). A millimeter-wave (mmWave) network, which uses 60 GHz band allocation, seems to be a promising candidate to provide these demands to eMBB UEs. However, mmWave networks face different challenges that impact their performance [5]. First, the received mmWave signal is highly attenuated due to propagation and penetration losses [6]. Although the reified IEEE 802.11 ad standard [7] overcomes this issue by proposing directional transmission for mmWave networks using the beamforming concept, hence increasing the received signal power and expanding coverage. mmWave channels are still dynamic, being highly dependent on UE positions [8]. Moreover, a sharper beam, i.e., a beam with a width smaller than 120°, distributes the signal in a narrow direction and covers a smaller area, causing the second mmWave challenge, which is the line-of-sight (LOS) link between transmitter (TX) and receiver (RX) that can simply be blocked because of static and dynamic objects [9–11]. Although solutions using diversity techniques, handover, and intelligent reflecting surfaces (IRSs) are adapted to handle the blockage effect [10,12], the problems of LOS link blocking and attenuation still exist.

Thus, implementing a radio resource management (RRM) scheme based on UE channel qualities is highly vital in order to efficiently make use of precious mmWave resources. Furthermore, any performed study to evaluate the performance of resource allocation schemes has to consider the blockage impact on the mmWave channel. Existing mmWave standards, i.e., IEEE 802.11 ad and 3GPP standards, discuss and explain different scenarios and use cases, e.g., eMBB, mMTC, and URLLC, for 5G and beyond networks. However, they neglect to define a specific radio resource allocation (RRA) mechanism that can efficiently work in single or multiple use cases. Both standards introduce the wireless local area network (WLAN) scenario, where the mmWave access point (AP) or base station (BS) is the node responsible for performing RRA processes, e.g., UE scheduling, merely describing the frame structure and its contents. The RRA operation is very critical in the eMBB use case in order to maintain a certain quality of service for UEs in which resource blocks (RBs) are distributed among different UEs in the system, which highly affect the overall performance of the 5G network. Motivated by that, this work contributes to the following points:

- We study the possible scheduling algorithms that can be adapted to efficiently distribute mmWave AP resources to UEs that experience asymmetrical eMBB applications.
- Moreover, we propose an efficient quality of service (QoS)-based proportional fairness (PF) scheduling scheme, also named the demand-based proportional fairness (DPF) approach. The proposed scheme depends on considering both UE channel qualities and UE data rate demands when it distributes RBs among UEs. Furthermore, when a certain UE reaches a total provided throughput equal to its required data rate, i.e., it achieves its satisfaction, the priority function of this UE only depends on its channel condition, thus offering the possibility to allocate more RBs to other UEs that are unsatisfied with their quality of service. The main idea of this scheme, at first, is to prioritize the UEs with lower demands and better channel conditions while ranking UEs with higher demands and bad channel qualities at the end.
- We consider the human body blockage effect on the performance of the different scheduling schemes studied in this paper.

Our scheme guarantees satisfaction for more UEs and, simultaneously, better system throughput while maintaining fairness among UEs. In addition, it secures higher average throughput per UE.

The remainder of the paper is organized as follows: In Section 2, we present and discuss other related works that use different resource allocations and scheduling schemes for 5G networks. Section 3 introduces the use case of the eMBB network and explains the system model. In Section 4, we describe different scheduling algorithms that can be implemented to serve eMBB 5G networks. Meanwhile, the proposed QoS-based PF scheme is described in Section 5. In Section 6, we illustrate and discuss our simulation results to evaluate the proposed scheme in comparison to conventional schemes. Finally, we conclude our paper in Section 7. For a better presentation, Table 1 lists all acronyms in the paper, while all symbols and notations are listed in Table 2.

Table 1. List of acronyms.

Abbreviation	Definition	Abbreviation	Definition
3GPP	3rd-Generation Partnership Project	PF	Proportional fairness
AP	Access point	PFS	Proportional fairness scheduling
BCQI	Best channel quality indicator	RB	Resource blocks
BS	Base station	RRA	Radio resource allocation
CDF	Cumulative distribution function	RR	Round robin
DKED	Double knife-edge diffraction	RRM	Radio resource management
DPF	Demand-based proportional fairness	RX	Receiver
eMBB	Enhanced mobile broadband	SPF	Standard proportional fairness
EPF	Enhanced proportional fairness	TDD	Time-division duplex
GPF	generalized proportional fairness	TDMA	Time-division multiple access
IRSs	Intelligent reflecting surfaces	TX	Transmitter
LOS	Line of sight	UE	User equipment
MAC	Medium access control	UHD	Ultra-high definition
MCS	Modulation and coding scheme	URLLC	Ultra-reliable low-latency communication
MIMO	Multiple input multiple output	QoS	Quality of service
mMTC	Massive-machine-type communication	VoIP	Voice over internet protocol
mmWave	Millimeter wave	WLAN	Wireless local area network

Table 2. List of symbols and notations.

Symbol	Description	Symbol	Description
K	Number of UEs	S_k	k-th UE satisfaction
N	Number of time slots	FI	Fairness index
P_k	Priority function of UE k in PF schemes	$P_k{}^*$	Priority function of UE k in DPF scheme
$r_k(n)$	Current achievable data rate for UE k	$w_k(n)$	Weighted required rate value for UE k
$R_k(n)$	Past average data rate given to UE k	$R_{req_k}(n)$	k-th UE required data rate at time slot n
ρ	Relative value between minimum and maximum Required data rates of all UEs in the system	R^*_{req}	Maximum data rate required by any associated UE in the system
T_c	Constant window length	R_k	Actual UE k throughput
α	Exponential weight of current data rate	β	Exponential weight of average data rate
$\gamma(n)$	Current channel quality	h	Height of human body blockage
$\delta(n)$	MCS index	l	Length of human body blockage
N_{MCS}	Number of MCS indices	w	Width of human body blockage

2. Related Work

Existing mmWave standards have introduced different scenarios and use cases for 5G and beyond networks, but no radio resource allocation mechanism has been defined yet. Several works in the literature have discussed and proposed scheduling algorithms for 5G network implementation. The authors in [13] surveyed RRM schemes in 5G and beyond networks, where they described the procedure of different scheduling algorithms and compared them. In addition, this work discussed the factors that impact the RRA decision and reflected on the performance of the scheduling scheme. In [14], an enhanced broadband scheduler is proposed based on the lean production method by the combination of the best channel quality indicator (BCQI) and SPF algorithms. This work improves system performance in terms of throughput; however, it highly decreases the fairness between the UEs comparable to the SPF and RR algorithms. The authors in [15] proposed a channel-gain-based scheduling scheme for a massive multiple input multiple output system. This scheme obtains higher throughput while maintaining fairness between UEs. In [16], the authors studied and compared the performance of different scheduling schemes, i.e., RR, SPF, and BCQI, on time-division duplex (TDD) mode, where various traffic types were considered, e.g., voice over internet protocol (VoIP), video streaming, and cloud storage. This study evaluated scheme performance in terms of throughput, but it neglects other metrics such as UE fairness and satisfaction. In addition, it studied each traffic type separately, which is not a practical case where all traffic is requested at the same time frame by different UEs.

In [17], the authors discussed the effect of blockage probability in mmWave network on the performance of the SPF scheme and compared it with the RR scheme performance in terms of UE data rates and fairness. The authors in [18–22] modified the priority function exponential parameters to make the SPF scheme more generalized, hence improving throughput and fairness in different communication systems, depending on the case. Although these algorithms can obtain promising results, if they are adapted in 5G and beyond networks, all of them neglect UE demands in their procedures. In addition, they did not consider the varied traffic between UEs based on the used application, which is the common scenario in the eMBB use case. Moreover, the authors in [23] proposed an enhancement to the SPF scheme by increasing the priorities of UEs with bad channel conditions. This methodology proves its efficiency in handling mmWave channel fluctuations in industrial internet of things applications. Although the aforementioned works provided studies for well-known scheduling algorithms, or proposed modifications to improve the performance of scheduling schemes, they ignore the effect of UEs' demands on system performance. Moreover, even if certain study considered the traffic type, it assumed that this traffic is homogenous in all UEs, i.e., within each time frame, users require the same amount of data rate in the form of an equal number of required packets, though data rate demands are varied from one UE to another based on the used eMBB applications, e.g., video streaming and VR, in 5G and beyond networks. Thus, considering non-homogeneous traffic for UEs is a more practical scenario when studying and proposing scheduling algorithms. Our previous work [24] discusses the disparity between UEs demands based on experienced application and its effect on the performance of the DPF scheduling scheme. However, it neglects the occurrence of blockage on the overall system performance. Moreover, it considers an impractical scenario, where lower-demand applications are experienced by more UEs. Furthermore, in this work, we adapt 3GPP standard channel models, while our previous work assumed the MiWEBA channel model.

3. System Model

The eMBB 5G and beyond network use case is presented in Figure 1, in which a 5G AP works in the millimeter-wave band with a 60 GHz center frequency. This figure describes the WLAN that is used to serve eMBB services such as entry-level virtual reality and UHD video streaming. In this network, one mmWave AP with multiple antennas and K UEs with a single antenna are considered. The AP performs all operations in the system, e.g., initial access and radio resource management. The AP adapts three-dimensional beamforming, while the UE antenna is assumed to be quasi-omni. During beamforming training and association process phases, the mmWave AP can collect all required information, e.g., UE channel quality, to be used for the multi-user scheduling process, where time-division multiple-access (TDMA)-based medium access control (MAC) will be used, as standardized in [7]. We assume a medium-sized indoor study environment, with high and varied traffic, where the centrally placed AP manages these traffic requirements. In heterogenous traffic, each UE requires different average data rates depending on its application, as we will present in the Simulation section (Section 5), e.g., the UE that plays 8K video streaming needs 300 Mbps, while the one that strongly interacts with VR requires 120 Mbps. For modeling the human blockage effect, we consider the geometrical–empirical model explained in [25]. This model modifies the well-known double knife-edge diffraction (DKED) model to describe the shadowing effect of the human body through the blockage time period. To calculate the throughput of the k-th UE that can be obtained from the mmWave AP at time slot n, we use the modulation and coding scheme (MCS) given in ([7], Tables 14–21).

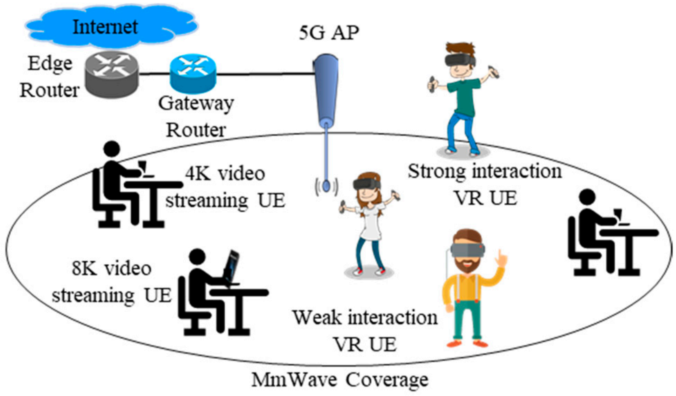


Figure 1. The eMBB 5G and beyond network use case.

4. Scheduling Schemes in 5G Networks

Scheduling is a critical RRM function in 5G networks, as it determines the overall performance of the system in terms of user throughputs, end-to-end latency, fairness between users, and satisfaction of users. There are two categories for scheduling schemes in wireless networks [26]: channel-independent schemes and channel-sensitive schemes.

The round-robin (RR) scheduling algorithm, shown in Figure 2, is the most famous approach in the independent channel category because it is simple and provides efficient performance in terms of throughput and fairness between UEs. The main drawback of RR is that it neglects the UEs' traffic and channel conditions; hence some UEs with bad conditions can be provided with more than enough resource blocks, while other UEs lack resources comparable to their needs. Therefore, the RR-based scheme wastes valuable resource blocks in 5G networks, therefore degrading the overall system performance. Due to its straightforward implementation and acceptable performance, we will consider RR as a reference scheme.

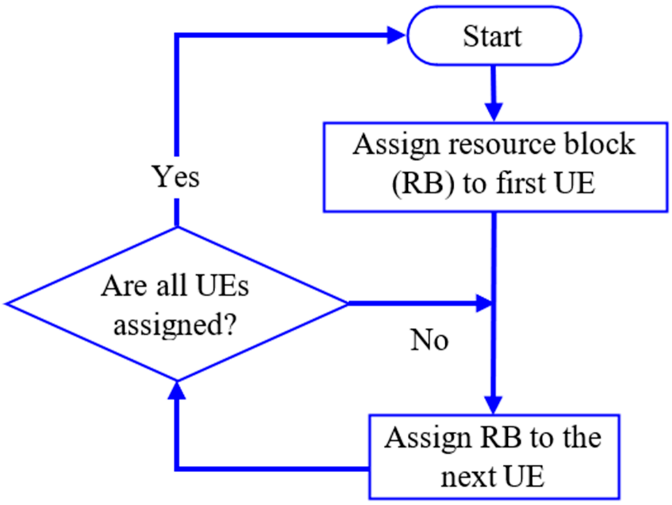


Figure 2. Round-robin scheduling algorithm.

Because of the highly variant mmWave channels due to receiver positions and blockage, it is more convenient to use channel-dependent scheduling schemes in mmWave-based 5G networks. Several algorithms from the literature can be used, e.g., BCQI, the maximum–minimum (max–min) algorithm, and the proportional fairness (PF) approach, as well as its versions, to distribute resources between UEs in 5G networks. BCQI prioritizes UEs with the best channel conditions in order to assign them more RBs. Based on this criteria, the network obtains the best throughput value, but other performance metrics are highly degraded. First, some UEs are ignored and not assigned RBs, and, as a result, no fairness between users can be provided. In addition, UEs with BCQIs may take more than what they require, leading to resource wasting. On the other hand, the max–min scheme performs the opposite of BCQI, where it obtains optimum fairness between UEs while reducing total throughput. The max–min scheme simply searches for the lowest-rate UE and assigns the RB to it, then it repeats this process until the end; hence, it guarantees equal throughput between UEs. This methodology may allocate more RBs to UEs with bad channel conditions. In addition, it can provide UEs with more RBs than necessary. These two techniques optimize one metric at the expense of the others.

Proportional fairness scheduling (PFS) schemes have been proposed to balance performance metrics, mainly between UE throughput and fairness. Moreover, these schemes depend on the indicators of the current and previous UE channel quality, i.e., instantaneous and average data rate, respectively, in determining their priority function. Hence, they guarantee fairly distributed RBs between all UEs in a network. PFS algorithms can be categorized into three main classes: standard proportional fairness (SPF), generalized proportional fairness (GPF), and enhanced proportional fairness (EPF). In SPF, at each time slot n, the scheduler gives priority to the UE with the maximum priority function, where the k-th UE priority function, P_k, is expressed as:

$$P_k = \mathrm{arg}max \frac{r_k(n)}{R_k(n)}. \quad (1)$$

Here, $r_k(n)$ refers to the current achievable data rate for the k-th UE when it is associated with the mmWave AP at time slot n, and $R_k(n)$ indicates the past average data rate that was given to the k-th UE until time slot n. This $R_k(n)$ is updated as [27]:

$$R_k(n) = \begin{cases} \left(1 - \frac{1}{T_c}\right) R_k(n-1) + \frac{1}{T_c} r_k(n), & k \text{ is scheduled} \\ \left(1 - \frac{1}{T_c}\right) R_k(n-1), & k \text{ is not scheduled} \end{cases}. \quad (2)$$

where T_c is the constant window length.

In the SPF scheduling scheme procedure, using the feedback channel quality indicators, the system performs the algorithm in two main steps, which are calculating and sorting UE priority functions, then assigning the RB to the UE with the highest priority function. These steps are repeated at every time slot while updating the average UE data rate according to (3). Tracking and updating the average achievable rate of UEs continues until the end of the frame.

GPF scheduling schemes try to improve SPF performance by modifying the UE priority function using two parameters α and β, which are the exponential weights of the current data rate and the previous average data rate, respectively. Hence, these algorithms redefine the UE priority function in (1) to a more generalized form as [18–22]:

$$P_k = \mathrm{arg}max \frac{r_k(n)^{\alpha}}{R_k(n)^{\beta}}. \quad (3)$$

This function becomes the SPF metric when $\alpha = \beta = 1$.

The EPF scheme leaves the priority function without change, but it modifies the function that updates the average achievable data rate, in which the MCS rate for each channel condition is considered as an exponent to instantaneous rate. This new priority function is expressed as [23]:

$$R_k(n) = \begin{cases} \left(1 - \frac{1}{T_c}\right) R_k(n-1) + \frac{1}{T_c} r_k(n)^{\Upsilon(n)}, & k \text{ is scheduled} \\ \left(1 - \frac{1}{T_c}\right) R_k(n-1), & k \text{ is not scheduled} \end{cases}. \quad (4)$$

where $\gamma(n) = \delta(n)/N_{MCS} + 0.5$ refers to current channel quality, $\delta(n)$ is the MCS index, and N_{MCS} is the number of MCS indices.

5. Proposed Demand-Based Proportional Fairness Scheduling Scheme

In future 5G and beyond networks, several applications are experienced by UEs, e.g., in the eMBB use case, UEs can experience VR or video streaming. Hence, each UE needs to receive a different amount of packets depending on its application. Consequently, it becomes mandatory to consider UE demands in distributing RBs among them in order to achieve high QoS. Motivated by this, a QoS-based proportional fairness scheduling scheme is proposed, in which we modify the SPF priority function of each UE based on its required data rate relative to the maximum required data rate by any associated UE in the network. Hence, the new ${P_k}^*$ will be expressed as:

$$ {P_k}^* = \arg max \frac{1}{w_k(n)} \frac{r_k(n)}{R_k(n)}. \quad (5) $$

where $r_k(n)$ and $R_k(n)$ have the same definition as in the SPF scheme, while the weighted required rate value $w_k(n)$ can be defined as

$$ w_k(n) = \begin{cases} \frac{R_{req_k}(n)}{R^*_{req}}, & R_k(n) < R_{req_k} \\ 1, & R_k(n) \geq R_{req_k} \end{cases}. \quad (6) $$

where $R_{req_k}(n)$ is the k-th UE required data rate at time slot n, and R^*_{req} refers to the maximum data rate required by any associated UE in the system. In addition, $R_{req_k}(n)$ is updated at every slot as follows

$$ R_{req_k}(n) = R_{req_k} - R_k(n). \quad (7) $$

Here, $R_k(n)$ is the average rate that is provided to the k-th UE up to time slot n, which is defined in (2). At the beginning of the scheduling process, the initial required data rate by the k-th UE equals the rate that it demands when requesting association with the AP, namely, R_{req_k}, i.e., the rate required by the ongoing eMBB application. Moreover, $w_k(n) \in [\rho, 1]$, where ρ refers to the relative value between the minimum and maximum required data rates of all UEs in the system, and $w_k(n) = 1$ corresponds to the case when the proposed DPF is similar to the SPF scheme, where the priority function of scheduling will not be affected by the UE demand.

The procedure of the proposed DPF scheduling algorithm is presented in Algorithm 1. This procedure is based on the idea of providing lower required data rate UEs with higher priority to be scheduled and assigned to RBs. Hence, it guarantees a higher satisfaction level for more UEs and simultaneously maintains the balance between system throughput and fairness among users as the SPF scheme. The weighted required data rate value, w_k, is updated until $R_k(n)$ becomes larger than or equal to R_{req_k}, which means the k-th UE is satisfied; thus, its priority function will only depend on its channel quality. In the proposed algorithm, all UEs have the opportunity to be served by mmWave links and to obtain satisfaction based on their channel quality and required QoS. However, UEs with low required data rates have more chance to quickly obtain that because they need a fewer number of RBs to experience their applications. Comparable to the SPF scheme, the proposed scheme produces a little increase in the system complexity due to adding Steps 2, multiplying w_k as in (5) for Step 3, and updating UE required data rate as in Step 6 according to (7). However, all these required operations are performed using matrices multiplication principles. Moreover, nowadays, calculation computers are very powerful and can perform these operations quickly and easily. Hence, the consumed time due to adding these calculations is very short in comparison to the benefits gained from this proposed algorithm in terms of throughput, fairness, and satisfaction.

Algorithm 1: Proposed QoS-based Proportional Fairness Scheduling

1: **Input:** R_{req_k}, R_k, r_k for all UEs
2: **Output:** Scheduling all UEs along the time frame
3: **Start**
4: **For** each time slot n
5: **Calculate** w_k using (6)
6: **Calculate** $P_k{}^*$ using (5)
7: **Sort** $P_k{}^*$ for all UEs
8: **Assign** current time slot to the UE k with the higher PF
9: **Update** R_k and R_{req_k} using (2) and (7), respectively
10: **End**
11: **Stop**

6. Numerical Simulation

In this section, due to the importance of considering the probability of blocking of the main LOS link, we first investigate the effect of blocker density on the blockage occurrence in the network. Then, we study the performance of the proposed quality of services based proportional fairness scheduling and compare it with the conventional RR and SPF algorithms.

6.1. Performance Metrics, Simulation Scenarios, and Parameters

In this study, we focus on total system throughput, fairness among UEs, satisfaction of UEs, and average throughput per UE metrics. These metrics are highly important to 5G and beyond networks. The first two metrics are vital from the network point of view, while the third and fourth metrics maximize the UE benefits. The RRA operation is very critical in the eMBB use case in order to maintain a certain quality of service for UEs, where users have a great desire nowadays to be provided with their required demands to efficiently experience their used application. Hence, UE satisfaction becomes an important metric for eMBB application UEs. Providing satisfaction for a UE means that enough resource blocks are allocated to this UE, hence guaranteeing a throughput for it that equalizes its required data rate, R_{req_k}, or more. UE satisfaction S_k can be introduced as given in [28] as:

$$S_k = \frac{R_k}{R_{req_k}}. \tag{8}$$

where R_k is the actual UE throughput. In our system, R_k cannot exceed R_{req_k}; thus, $S_k \in [\alpha, 1]$. Moreover, we adapt Jain's fairness index as a metric to describe the fairness among UEs, which is defined as [28],

$$\text{FI} = \left(\sum_{k=1}^{K} S_k\right)^2 / K \sum_{k=1}^{K} S_k{}^2 \tag{9}$$

In this study, we assume the number of associated UEs with the mmWave AP is 16 and 32 UEs, where these two cases are considered a good examples to explain the performance of the proposed DPF scheme. In addition, we consider two scenarios in the network, and, within each scenario, UEs experience different eMBB applications. These applications are 4K ultra-high-definition (UHD) video streaming, which requires a 75 Mbps data rate; weak-interaction and strong-interaction entry-level virtual reality (VR), which needs 120 and 200 Mbps, respectively; and 8K UHD video streaming, which requires 300 Mbps [2]. This leaves us with four categories in each scenario. For the first scenario, all applications are required by UEs with the same probability equal to 0.25. For example, in the case with 32 UEs, each group of 8 UEs will experience one application. In the second scenario, we try to make it more practical for future 5G requirements, where we assume higher-demand applications will be experienced by more UEs. Hence, we assume 4K video streaming, weak and strong interactions, VR, and 8K video streaming are experienced by 12.5%, 18.75%, 31.25%, and 37.5% of the total number of UEs, respectively. Considering different UE applications guarantees to present the effect of UE demands on the final performance of the scheduling algorithm.

Additionally, we uniformly distribute the UEs in the network assuming an indoor area with dimensions 25 m × 25 m × 5 m, where the UE plane height from the ground is 1 m. In addition, we take into consideration the human body dimension, which affects the blockage probability, as human height is h, human length, is l and human width is w. Moreover, we distribute blockers with different densities B, united by blockers per m^2 (bl/m^2). The simulation parameters are presented in Table 3. This simulation is conducted with 100,000 Monte Carlo trials.

Table 3. Simulation parameters.

Parameters	Value
Room dimensions	25 m × 25 m × 5 m
UEs height from floor	1 m
Human blockage dimension, h, l, w	1.75 m × 0.5 m × 0.2 m
Number of served UEs	16, 32
Number of mmWave APs	1
TX power of mmWave AP	10 dBm
MmWave beamwidth	20°
Carrier frequency	60 GHz
Length of one subframe	100µs
OFDM symbols per subframe	24
Modulation scheme	Adaptive modulation and coding
MmWave bandwidth	1.825 GHz
UEs required data rate	75, 120, 200, and 300 Mbps

6.2. Simulation Results

Figure 3 shows the effect of the density of the blockers on the blockage occurrence in the studied area. As expected, a denser area with many human bodies increases the probability of blocking the main LOS link between the AP and UEs. This increase in blockage means lower channel qualities for more UEs; hence, the variation in channel state information of UEs increases, and the channel-sensitive scheduling algorithms become more needed, as we will discuss in the following paragraphs. From Figure 3, with 0.5 and 1 bl/m^2 blockers densities, the blockage probabilities are 0.8 and 0.15, respectively. The average human density in indoor environments is 1 UE/m^2; thus, we will consider and study the case with a 0.15 blockage probability through our study.

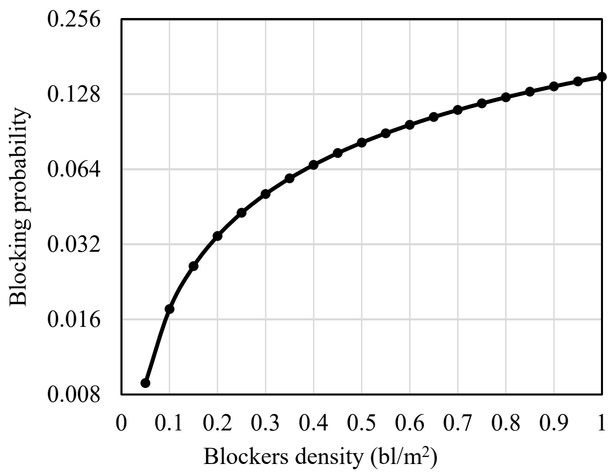


Figure 3. Probability of link blocking versus different blocker densities.

In Figures 4a,b and 5a,b, the comparison between the performance of the proposed scheduling scheme and other conventional schemes is performed and presented from the network-side perspective. Figure 4a,b shows the total system throughput in the case of adapting the two aforementioned discussed scenarios, while Figure 5a,b presents the fairness among UEs. In the case of 16 UEs, the proposed demand-based scheduling scheme outperforms the RR and SPF schemes for both scenarios, even if the blockage of the main LOS link happens. For example, the DPF approach guarantees 2.77 and 3.29 Gbps total throughput in the case of adapting first and second scenarios with a blockage probability of 0.15 for both, respectively, which are 130 Mbps and 200 Mbps increases comparable to the system throughput obtained using the standard proportional fairness algorithm for both scenarios, respectively. Moreover, the proposed scheme maintains the fairness among UEs higher than that obtained using the RR and SPF scheduling schemes.

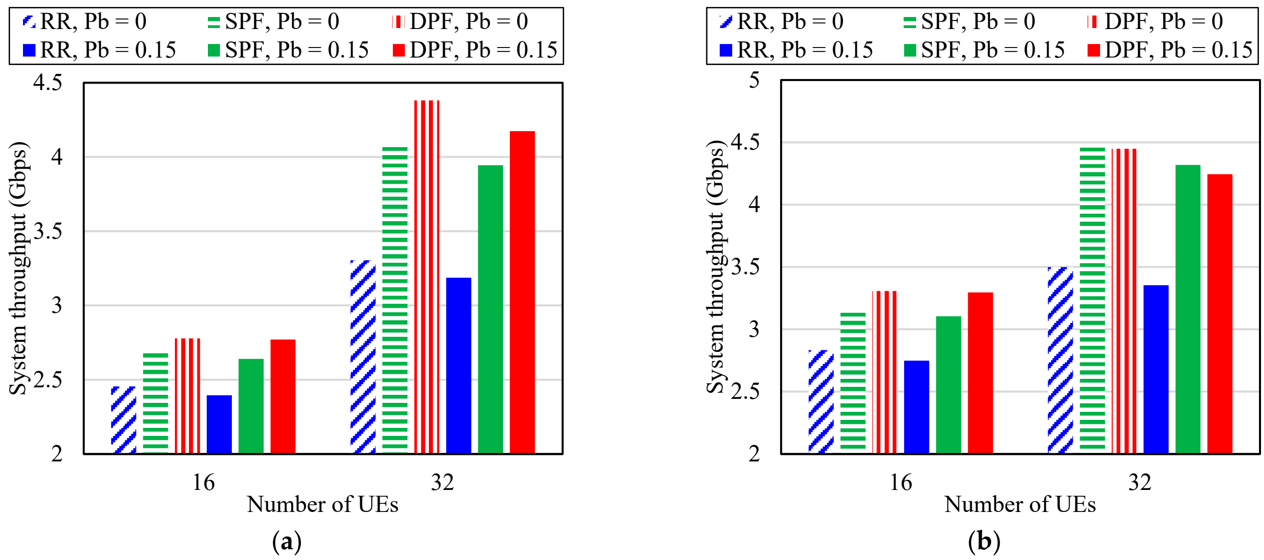


Figure 4. System throughput of RR, SPF, and DPF schemes versus number of UEs with/without blocking existence when (**a**) first scenario and (**b**) second scenario are adopted.

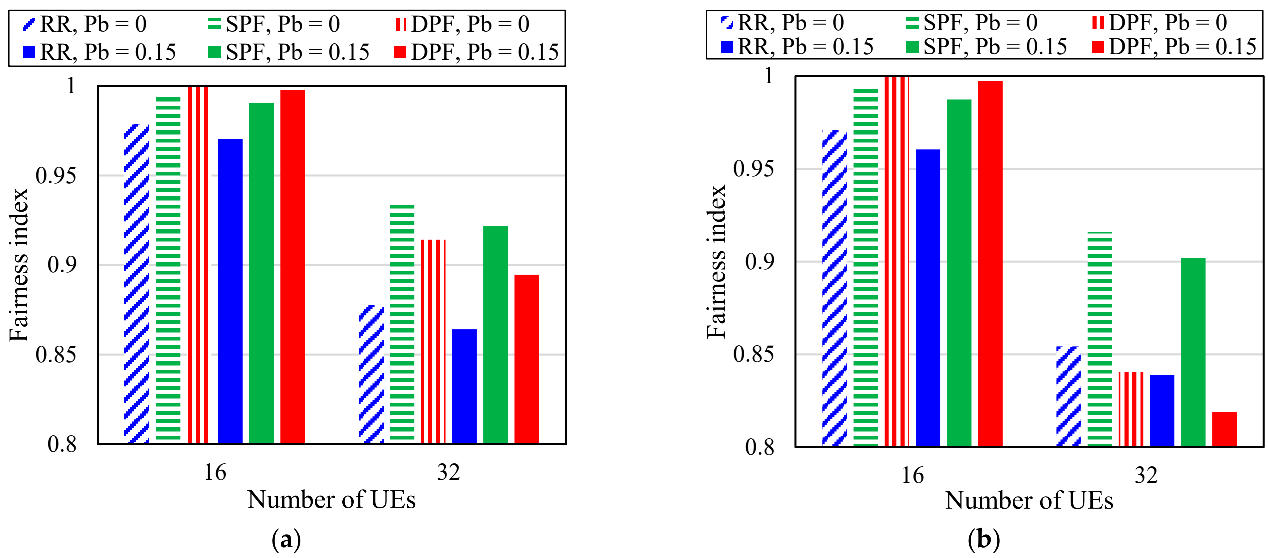
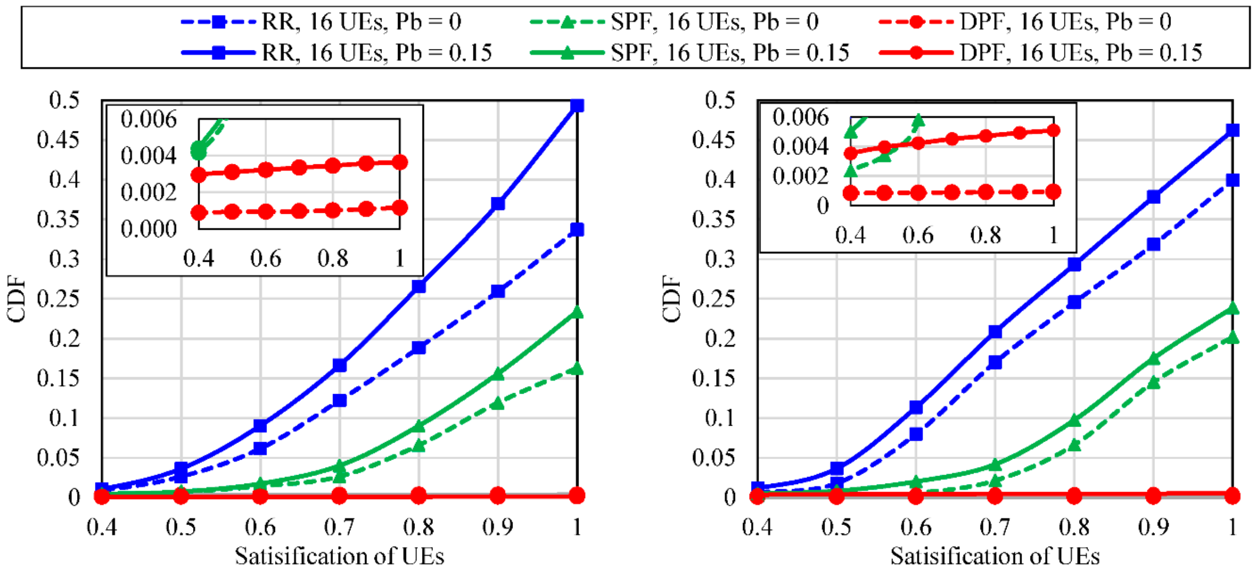


Figure 5. Fairness index of RR, SPF and DPF schemes versus number of UEs with/without blocking existence when (**a**) first scenario and (**b**) second scenario is adopted.

Regarding the case of 32 UEs associated with the AP, the proposed DPF scheme still works well and obtains promising results in the first scenario, as it guarantees 4.38 and 4.17 Gbps system throughput with no blockage and a 0.15 blockage probability, respectively, which is higher than the throughput obtained using RR and SPF with 1080 and 310 Mbps for no blockage condition and 390 and 230 Mbps for 0.15 blockage probability condition, respectively. Meanwhile, it maintains the fairness index at 0.91 and 0.89, respectively, which are acceptable values. It is true that, in the second scenario, the proposed DPF scheme cannot obtain similar promising results in terms of system throughput and fairness as in the first scenario; however, it can preserve high UEs satisfaction and average throughput per UE comparable to RR and SPF schemes, as we will explain when discussing satisfaction figures for the 32 UEs case. The degradation of performance is not because of the proposed algorithm itself but owing to the fact that UEs require massive data rates in the second scenario compared to the available throughput that the system can provide. For example, the sum of the required data rates of UEs, experiencing the studied applications, will be (0.125 × 32) × 75 = 300, 720, 2000, and 3600 Mbps on average, respectively. This means the total data rate demand is 6620 Mbps, which is higher than the data rate that can be provided by the single mmWave AP on average, nearly double the average provided rate, which is 3700 Mbps. Hence, although the proposed scheme tries to efficiently schedule UEs, it fails to achieve higher system performance. Specifically, the QoS-based PF scheme fails to provide higher-demand UEs, i.e., 8K video streaming UEs, with enough RBs quickly, as we will clarify with average throughput per UE figures. For results comparison, the proposed DPF scheme guarantees only 4.45 and 4.24 Gbps system throughput with no blockage and a 0.15 blockage probability, respectively, which is a little lower than the throughput obtained using SPF, 4.48 and 4.32 Mbps, respectively. In addition, the fairness between UEs decreases to 0.84 and 0.82 using the proposed scheme comparable to 0.92 and 0.9 when the SPF scheme is used with no blockage and a 0.15 blockage probability, respectively.

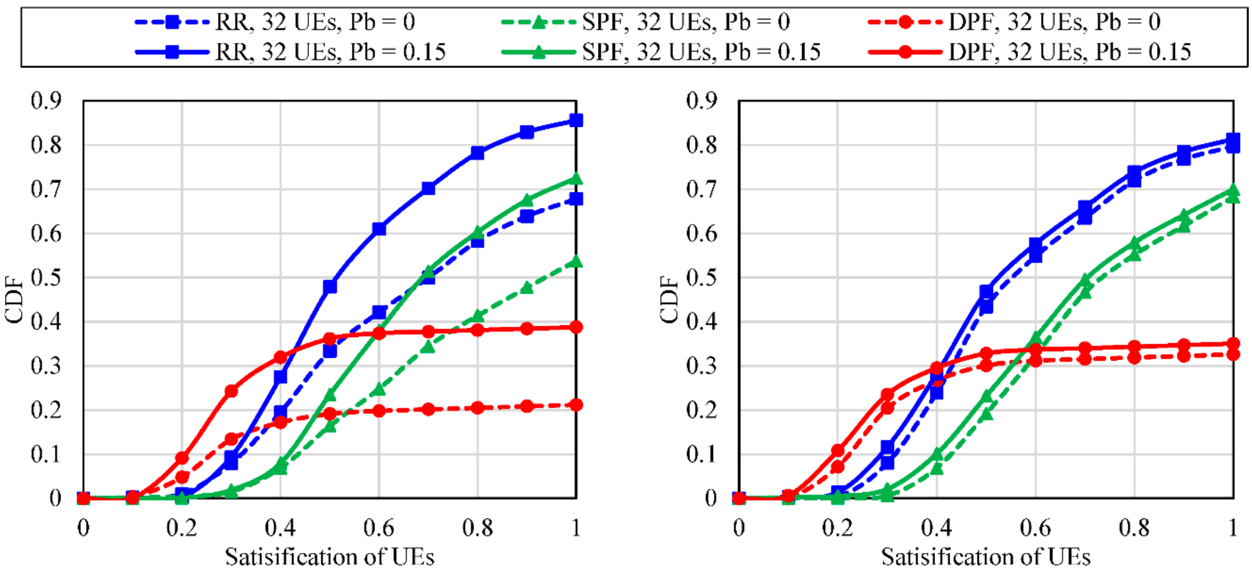
Figure 6 presents the cumulative distribution function (CDF) of UEs satisfaction in the case of 16 UEs associated with the AP for the first and second scenarios in Figure 6a,b, respectively, with no blockage and with a 0.15 probability of blockage occurrence. The CDF curve is an indication of the event occurrence, i.e., the probability that the UEs are provided with their required data rate or more. In other words, using CDF, we can determine how many UEs are satisfied with a certain satisfaction level x. The CDF, F_X, is the probability, $P(X \leq x)$; thus, to find a certain satisfaction, e.g., UEs satisfaction of 50%, we perform this calculation $(1 - P(satisfaction\ of\ UEs \leq 0.5)) \times 100$, and so on. It is clear that the proposed DPF guarantees the best satisfaction for nearly all UEs as it outperforms both the RR and SPF schemes in the case of adapting the first or second scenario. For example, in Scenario 1 in Figure 6a, it achieves about 99.9% and 99.6% of full satisfaction for all 16 UEs with no blockage and 0.15 blockage probabilities, respectively. While the SPF scheme can guarantee satisfaction for only 84% and 76.6% of the network UEs, the RR scheme obtains satisfaction for only 66.3% and 50.07 of the UEs in the case of no blockage and 0.15 blockage occurrence, respectively. Although the second scenario decreases the satisfaction level with a little difference, the QoS-based PF scheme still provides higher satisfaction for all the 16 UEs. For example, the DPF achieves full satisfaction for 99.5% of network UEs with 0.15 blockage probabilities; in contrast, SPF and RR obtain this for only 76% and 54% of the UEs, respectively.

For the 32 UEs case, the performance of the scheduling schemes in terms of UE satisfaction is shown in Figure 7a,b for the first and second scenarios, respectively. In the first scenario, for 50% UEs satisfaction or lower, the SPF outperforms both the proposed scheme and the RR schemes. However, it is not the required satisfaction, as the final goal is to obtain 100% satisfaction for UEs. Hence, it is proven that the proposed scheme satisfies more UEs, as it obtains full satisfaction for nearly 78.8% and 61.23% of all UEs on average with no blockage and a 0.15 blockage probability, respectively. These satisfaction levels are higher than that guaranteed by using the SPF by nearly 33% in both blockage cases. Moreover, in the second scenario, the proposed QoS-based PF scheme outperforms both the RR and SPF algorithms. For instance, in the case of the 0.15 blockage probability, it guarantees 100% satisfaction for nearly 65% of all network UEs on average, while the SPF and RR schemes guarantee this for only 30% and 19% of the UEs, which highly degrade the system performance from the perspective of UEs quality of service. This high enhancement of UE satisfaction due to using the proposed scheme, at the expense of a slight decline in throughput and fairness, as explained before, makes it more convenient and desirable to use the DPF scheme over both RR and SPF for eMBB 5G networks.



(a) **(b)**

Figure 6. CDF of UEs satisfaction of RR, SPF, and DPF schemes when (**a**) first scenario with 16 UEs and (**b**) second scenario with 16 UEs are adopted.



(a) **(b)**

Figure 7. CDF of UEs satisfaction of RR, SPF and D-PF schemes when (**a**) first scenario with 32 UEs and (**b**) second scenario with 32 UEs are adopted.

Nevertheless, it is important to investigate the reason that makes the system throughput of the SPF better than that obtained using the proposed DPF scheme in the second scenario with the 32 UEs case, as shown and described in Figures 4b and 5b. Hence, we study the average throughput per UE for every eMBB application separately in Figure 8a,b. In the case of 16 UEs, there is no problem, and the proposed scheme achieves higher average throughput per UE in all applications, and, at the same time, it provides UEs with all their full required data rate. For example, UEs experience 8K video streaming supplied by their 300 Mbps data rate on average; meanwhile, the RR and SPF schemes provide them with only 219 and 268 Mbps, respectively. However, in the case of associating 32 UEs with the AP, the proposed scheme provides higher throughputs for all UEs, nearly equal to the required data rate, for all applications except for the 8K video streaming UEs. For instance, UEs are provided with about 130 and 106 Mbps using the DPF in Scenario 1 and 2, respectively, which are lower than the throughput provided using the SPF scheme, which supplies UEs with about 152.5 Mbps in both scenarios. This is because the proposed QoS-based PF scheme prioritizes UEs with lower demands, i.e., 4K video streaming and VR UEs, to be allocated to RBs first. However, it can be noticed that the provided throughputs for 8K video streaming UEs are far from the required demands in the case of using any scheduling scheme, which indicates that the available resources of the used AP are insufficient. Hence, if the resources are increased by adapting MIMO techniques or wider bandwidth, the proposed scheme will outperform the conventional RR and SPF schemes as in the case when 16 UEs are associated with the AP.

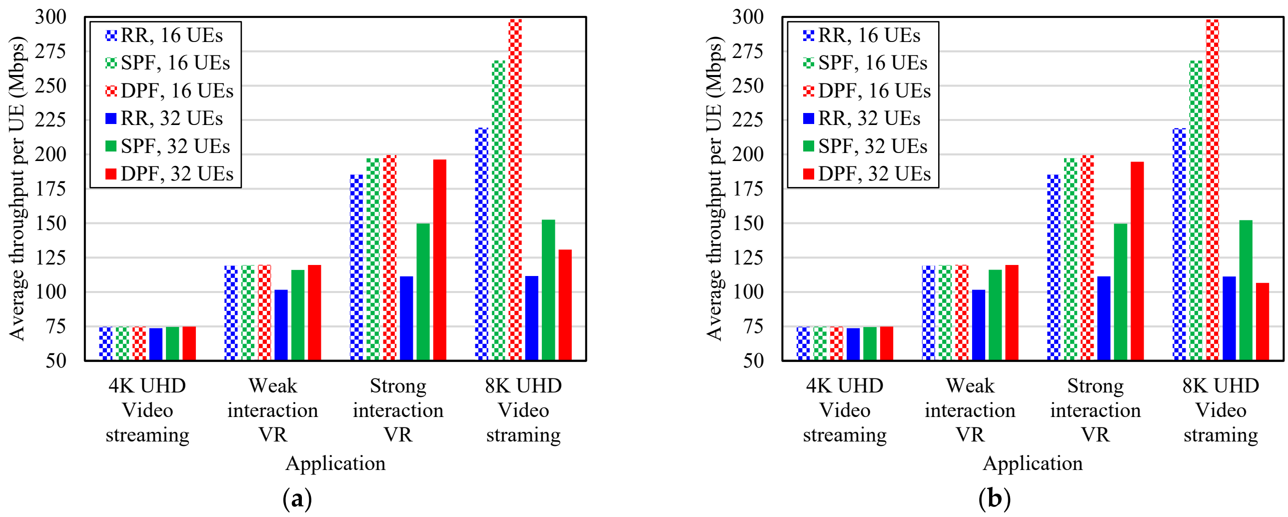


Figure 8. Average throughput per UE of all scheduling schemes with blocking probability equals 0.15 when (**a**) first scenario and (**b**) second scenario are adopted.

7. Conclusions

In this paper, we study the scheduling algorithms that can possibly be adapted for the eMBB use case in 5G and beyond networks. Furthermore, we propose an efficient QoS-based PF scheduling scheme, which, at first, depends on UEs' demands besides the channel qualities of UEs, then relies only on UEs' channel conditions when UEs reach their satisfaction point. Additionally, the occurrence of blocking and its effect on scheduling schemes, especially the proposed one, is considered in this study. The principle of the proposed scheme is to prioritize UEs with lower demand and better channel conditions to be scheduled first; hence, it can guarantee satisfaction for more UEs in the network, as it gives them their actual needs of throughput. Moreover, it secures higher total system throughput and, simultaneously, maintains fairness between UEs. For example, with 32 UEs in the network, 78.8% and 61.23% of full satisfaction can be guaranteed to UEs using the proposed DPF scheme, comparable to only 47.3% and 27.5% using the SPF scheme.

In addition, it guarantees 4.38 and 4.17 Gbps overall system throughput, maintaining fairness at 0.91 and 0.89 considering no blockage and a 0.15 blockage probability in the first scenario, respectively. Meanwhile, with a more practical second scenario and assuming a 0.15 blockage probability, the proposed scheme satisfies 65% of network UEs and guarantees 4.24 Gbps total throughput with 0.82 fairness among UEs, while the SPF and RR schemes satisfy only 30% and 19%, respectively, which highly degrade system performance from the perspective of UE QoS. Moreover, the proposed DPF scheme provides almost all UEs with their asymmetric required data rate except for UEs that experience 8K video streaming. In the future, a system considering MIMO techniques will be studied, as it will provide higher throughputs for UEs and will be able to overcome the degradation in the performance that occurs in the second scenario with 32 UEs in the network. In addition, the performance of scheduling will be studied considering UEs experience different heterogenous traffic coming from all 5G network use cases, i.e., massive-machine-type communication, ultra-reliable low-latency communication, and eMBB, at the same time frame.

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References

1. Lin, X.; Lee, N. (Eds.) *5G and Beyond*; Springer International Publishing: Cham, Switzerland, 2021. [CrossRef]
2. Lei, W.; Soong, A.C.K.; Jianghua, L.; Yong, W.; Classon, B.; Xiao, W.; Mazzarese, D.; Yang, Z.; Saboorian, T. *5G System Design*; Springer International Publishing: Cham, Switzerland, 2020. [CrossRef]
3. Ranjha, A.; Kaddoum, G. URLLC-Enabled by Laser Powered UAV Relay: A Quasi-Optimal Design of Resource Allocation, Trajectory Planning and Energy Harvesting. *IEEE Trans. Veh. Technol.* **2022**, *71*, 753–765. [CrossRef]
4. Cisco Systems Inc. Cisco Annual Internet Report (2018–2023) Whitepaper. Cisco Public, 9 March 2020. Available online: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html (accessed on 15 June 2022).
5. Rappaport, T.S.; Sun, S.; Mayzus, R.; Zhao, H.; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Guierrez, F.; et al. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! *IEEE Access* **2013**, *1*, 335–349. [CrossRef]
6. Rappaport, T.S.; Xing, Y.; MacCartney, G.R.; Molisch, A.F.; Mellios, E.; Zhang, J. Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks-With a Focus on Propagation Models. *IEEE Trans. Antennas Propag.* **2017**, *65*, 6213–6230. [CrossRef]
7. *IEEE Std 802.11-2007*; IEEE Computer Society. IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band. 2012; pp. 1–628. Available online: https://ieeexplore.ieee.org/document/6392842/citations?tabFilter=papers#citations (accessed on 13 June 2022).
8. Nor, A.M.; Halunga, S.; Fratu, O. Survey on positioning information assisted mmWave beamforming training. *Ad Hoc Netw.* **2022**, *135*, 102947. [CrossRef]
9. Gapeyenko, M.; Samuylov, A.; Gerasimenko, M.; Moltchanov, D.; Singh, S.; Aryafar, E.; Yeh, S.-P.; Himayat, N.; Andreev, S.; Koucheryavy, Y. Analysis of human-body blockage in urban millimeter-wave cellular communications. In Proceedings of the 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, 22–27 May 2016; pp. 1–7. [CrossRef]
10. Alyosef, A.; Rizou, S.; Zaharis, Z.D.; Lazaridis, P.I.; Nor, A.M.; Fratu, O.; Halunga, S.; Yioultsis, T.V.; Kantartzis, N.V. A Survey on the Effects of Human Blockage on the Performance of mm Wave Communication Systems. In Proceedings of the 2022 IEEE International Black Sea Conference on Communications and Networking, Sofia, Bulgaria, 6–9 June 2022; pp. 249–253. [CrossRef]
11. Jain, I.K.; Kumar, R.; Panwar, S.S. The Impact of Mobile Blockers on Millimeter Wave Cellular Systems. *IEEE J. Sel. Areas Commun.* **2019**, *37*, 854–868. [CrossRef]

12. Nor, A.M.; Halunga, S.; Fratu, O. Neural Network Based IRSs-UEs Association and IRSs Optimal Placement in Multi IRSs Aided Wireless System. *Sensors* **2022**, *22*, 5216. [CrossRef] [PubMed]
13. Mamane, A.; Fattah, M.; El Ghazi, M.; El Bekkali, M.; Balboul, Y.; Mazer, S. Scheduling Algorithms for 5G Networks and Beyond: Classification and Survey. *IEEE Access* **2022**, *10*, 51643–51661. [CrossRef]
14. Saglam, M.I.; Kartal, M. 5G Enhanced Mobile Broadband Downlink Scheduler. In Proceedings of the 2019 11th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkey, 28–30 November 2019; pp. 687–692. [CrossRef]
15. Chataut, R.; Akl, R. Channel Gain Based User Scheduling for 5G Massive MIMO Systems. In Proceedings of the 2019 IEEE 16th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT and AI (HONET-ICT), Charlotte, NC, USA, 6–9 October 2019. [CrossRef]
16. Mamane, A.; Fattah, M.; El Ghazi, M.; El Bekkali, M. 5G Enhanced Mobile Broadband (eMBB): Evaluation of Scheduling Algorithms Performances for Time-Division Duplex Mode. *Int. J. Interact. Mob. Technol.* **2022**, *16*, 121. [CrossRef]
17. Nor, A.M.; Esmaiel, H.; Omer, A. Performance evaluation of proportional fairness scheduling in MmWave Network. In Proceedings of the 2019 International Conference on Computer and Information Sciences (ICCIS), Sakaka, Saudi Arabia, 3–4 April 2019; pp. 1–6. [CrossRef]
18. Kim, H.; Kim, K.; Han, Y.; Lee, J. An efficient scheduling algorithm for QOS in wireless packet data transmission. In Proceedings of the 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Lisbon, Portugal, 18 September 2002; Volume 5, pp. 2244–2248. [CrossRef]
19. Bechir, N.; Nasreddine, M.; Mahmoud, A.; Walid, H.; Sofien, M. Novel scheduling algorithm for 3GPP downlink LTE cellular network. *Procedia Comput. Sci.* **2014**, *40*, 116–122. [CrossRef]
20. Aniba, G.; Aïssa, S. Adaptive proportional fairness for packet scheduling in HSDPA. In Proceedings of the In IEEE Global Telecommunications Conference GLOBECOM, Dallas, TX, USA, 29 November–3 December 2004; Volume 6. [CrossRef]
21. Yang, D.; Shen, D.; Shao, W.; Li, V.O.K. Towards opportunistic fair scheduling in wireless networks. In Proceedings of the IEEE International Conference on Communications, Istanbul, Turkey, 11–15 June 2006; Volume 11. [CrossRef]
22. Xu, N.; Guillaume, V.; Zhou, W.; Qiang, Y. A dynamic PF scheduler to improve the cell edge performance. In Proceedings of the 2008 IEEE 68th Vehicular Technology Conference, Calgary, AB, Canada, 21–24 September 2008; pp. 1–5. [CrossRef]
23. Ma, J.; Aijaz, A.; Beach, M. Recent Results on Proportional Fair Scheduling for mmWave-based Industrial Wireless Networks. In Proceedings of the IEEE Vehicular Technology Conference, Victoria, BC, Canada, 18 November–16 December 2020. [CrossRef]
24. Nor, A.M.; Fratu, O.; Halunga, S.; Alyosef, A.; Zaharis, Z.D.; Rizou, S.; Lazaridis, P.I. Demand based Proportional Fairness Scheduling for 5G eMBB Services. In Proceedings of the 2022 IEEE International Black Sea Conference on Communications and Networking, Sofia, Bulgaria, 6–9 June 2022; pp. 263–268. [CrossRef]
25. Bhardwaj, A.; Caudill, D.; Gentile, C.; Chuang, J.; Senic, J.; Michelson, D.G. Geometrical-empirical channel propagation model for human presence at 60 GHz. *IEEE Access* **2021**, *9*, 38467–38478. [CrossRef]
26. Wee, K.; Hilmi, M.B.A.H.; Wee, Y.Y.; Saed, N. A performance study of downlink scheduling algorithms in wireless broadband networks. *J. Commun.* **2014**, *9*, 39–47. [CrossRef]
27. Yaser, B.; Ivica, K. Performance evaluation of proportional fairness scheduling in LTE. *Proc. WCECS* **2013**, *2013*, 712–717.
28. Nor, A.M. Access point selection in beyond 5G hybrid MmWave/Wi-Fi/Li-Fi network. *Phys. Commun.* **2021**, *46*, 101299. [CrossRef]