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A Study on Packet Scheduling Algorithms for Healthcare Contents over Fifth Generation (5G) Mobile Cellular Network

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***Abstract*—This paper models the downlink Fifth Generation (5G) network that supports a flexible frame structure and a shorter Round-Trip Time (RTT) for Hybrid Automatic Repeat Request (HARQ). Moreover, the design of the renowned Time Division Multiple Access (TDMA) packet scheduling algorithms is revised to allow these algorithms to support packet scheduling in the downlink 5G. Simulation results demonstrate that the Proportional Fair provides a comparable performance to the delay–aware Maximum-Largest Weighted Delay First for simultaneously providing the desired transmission reliability of the Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (Non-GBR) healthcare contents whilst maximizing the downlink 5G performance.**

***Keywords*— packet scheduling, 5G, flexible frame structure, transmission reliability, scalable TTI**

I. INTRODUCTION

THE advancement of healthcare applications with extensive novel features and massive number of healthcare devices that will be connected to the internet has somewhat triggered for the fast standardization of the Fifth Generation (5G) [1] mobile cellular network. It is observed that the healthcare industry nowadays is evolving with an array of Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (Non-GBR) healthcare intensive applications (as demonstrated in Table I) for providing healthcare services to anyone, anywhere and anytime. This is to allow the provision of good quality and satisfactory transmission reliability of healthcare services using limited financial and human resources. The majority of the contents collected from these applications should be delivered via the radio channels to the healthcare database in a timely fashion without disruption and distortion to ensure the healthcare professionals have immediate access to these online healthcare contents so that the best possible clinical decisions and diagnoses can be made.

This 5G mobile cellular network is expected to ensure satisfactory transmission reliability for a mixture of GBR and Non-GBR healthcare contents on the same radio channels [2]. This will be of a great challenge given the conflicting transmission reliability of GBR and Non-GBR healthcare contents and due to the essential balance between throughput, fairness, capacity, energy efficiency and delay of the time-variant and frequency-variant radio channel [3]. Packet scheduling that is responsible to select a user to receive its packets on each radio channel in each Transmission Time Interval (TTI) becomes one of the most prominent 5G features to address the challenge. This brings us to a question: *is there an efficient packet scheduling algorithm that meet the desired transmission reliability of a mixture of GBR and Non-GBR healthcare contents whilst simultaneously maximizing the downlink 5G performance*? The downlink 5G network is considered given a massive volume of multimedia/healthcare contents are communicated in the downlink.

TABLE I
HEALTHCARE APPLICATIONS AND THEIR REQUIREMENTS [4]

Resource type	Packet delay	Packet loss	Typical examples from mHealth applications
GBR	100 ms	10^{-2}	Emergency VoIP call
	150 ms	10^{-3}	Consultation video call
	50 ms	10^{-3}	Patient tracking in remote video
	300 ms	10^{-6}	Daily health monitoring
Non-GBR	100 ms	10^{-6}	Tele-medicine and consulting video
	300 ms	10^{-6}	Medical data transmission with TCP
	100 ms	10^{-3}	Healthcare self-learning systems
	300 ms	10^{-6}	Daily health condition notices
	300 ms	10^{-6}	Medical image download, etc.

In our attempt to address this question, substantial study of packet scheduling algorithms in the extant literature were conducted. It was observed based on the study that the majority of packet scheduling algorithms were developed for meeting the desired transmission reliability of either GBR or Non-GBR multimedia contents. It should be noted that healthcare is a subset of multimedia services. This is not realistic given the current scenario that demands for simultaneous transmission of GBR and Non-GBR multimedia contents generically and healthcare contents specifically. Moreover, these packet scheduling algorithms were mostly developed for the legacy mobile cellular networks that may be designed on different framework and support slightly different features and characteristics as compared to the new 5G network. Motivated by these limitations, this paper investigates packet scheduling performance for simultaneous support of the GBR and Non-GBR healthcare contents at the desired transmission reliability whilst simultaneously maximizing the downlink 5G performance. It should be noted that the transmission reliability can be obtained by deducting 100% with the packet loss column of Table I.

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The remaining sections of the paper are arranged as follows: Section II explains the method use in the study of packet scheduling algorithms for healthcare contents over the downlink 5G network followed by the discussions on the renowned packet scheduling algorithms developed for the legacy mobile cellular networks in Section III. Section IV highlights assumptions made for simulation whereas results obtained are analysed in Section V. The conclusion of this paper is drawn in Section VI.

II. METHODS

The methods used in this study is by modelling the downlink 5G network and revise the design of the renowned packet scheduling algorithms. This section contains an explanation of the downlink 5G network model whereas a revision of packet scheduling algorithms is provided in Section III.

Given that there is no specific decision on the standard that is going to be used for the 5G, this paper revised the Long Term-Evolution Advanced (LTE-Advanced) which is the Fourth Generation (4G) standard and added features that are relevant to 5G requirements. The LTE-Advanced standard uses Orthogonal Frequency Division Multiple Access (OFDMA) as its multiple access technique in the downlink. The minimum radio channel in the downlink LTE-Advanced is known as Resource Block (RB) [5]. This RB is divided into time and frequency domains. The time domain contains 14 OFDMA symbols (using a normal cyclic prefix) and the frequency domain has a total of 12 subcarriers of 15 kHz bandwidth each. This constitutes to a total of 180 kHz bandwidth of the RB in frequency domain. In terms of Resource Element (RE) in an RB, there will be a total of 14*12=168 REs (see fig. 1). Most of these REs is used to carry user data while the rest for control and signaling purposes.

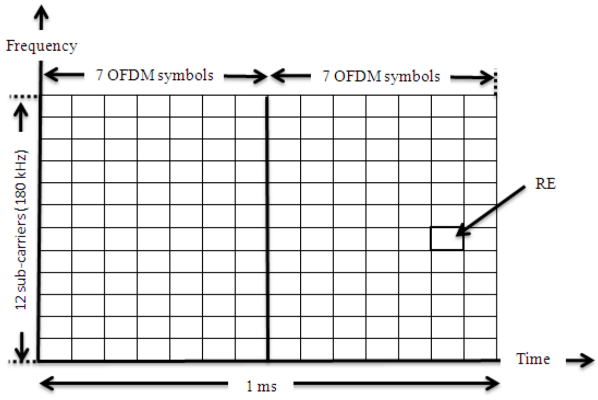

Fig. 1. RB time and frequency domain representation

A cellular network consisting of one base station and a variable number of users is considered. All active users periodically report their Channel Quality Information (CQI) on each RB to the base station. It is assumed that this CQI report arrives at the base station after a certain delay. This CQI report will be used to determine the Modulation and Coding Scheme (MCS) that maps to the data rate supportable by the user on the reported RB. Other features that are relevant and used in modelling the downlink LTE-Advanced can be found in [6][7].

Packet scheduling in the LTE-Advanced is performed in every 1 ms TTI and uses a total of 180 kHz bandwidth. Fig. 2 shows a generalized model of the packet scheduling in the downlink LTE-Advanced network illustrating that CQI is periodically reported by active users to the base station and packet scheduling algorithm is used to select a user to receive its packets on each RB. It should be noted based on the figure that only one Component Carrier (CC) is assumed. However, the LTE-Advanced may contain more than one CCs given that the standard supports Carrier Aggregation (CA) feature. At each TTI, a user may be assigned to more than one RBs but an RB may be used to transmit packets to a user only.

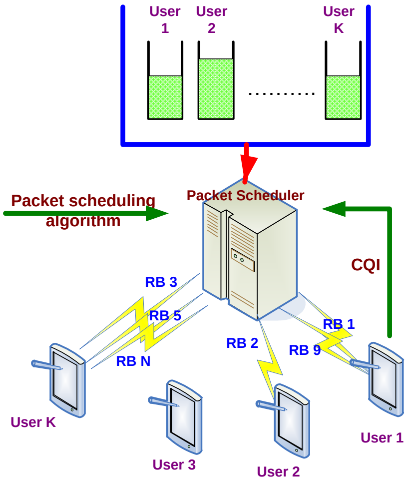

Fig. 2. A generalized model of packet scheduling in LTE-Advanced [8]

The 5G is expected to push its performance limit substantially towards zero delay optimized throughput end user experience [9]. Consequently, it was suggested that highly flexible frame structure that allows time-frequency multiplexing of users (as shown in fig. 3) as one of the fundamental design options. This design option is integrated in the current downlink LTE-Advanced to allow the network to support the 5G capabilities. The minimum TTI size that a user can be scheduled in this 5G network varies from 0.14 ms, 0.25 ms, 0.5 ms, 1 ms, 2 ms and 4 ms as illustrated in Table II. With a variable TTI, an RB can no longer has exactly 14 OFDM symbols. For example, if 0.14 ms TTI is chosen, there will be 2 OFDM symbols in an RB which constitutes to 192 REs (2 OFDM symbols*12 sub-carriers *8 RBs) given that the frequency domain contains a total of 8 RBs (see Table II) that will be used to transmit packets to a user.

Therefore, based on the earlier version of the 4G LTE-Advanced model and assuming a 10 MHz bandwidth is available; a maximum of fixed 50 users can receive their packets in a 1 ms TTI. However, this will be limited to 6 users that can receive their packets in a 0.14 ms TTI in the revised model of the LTE-Advanced network (referred to as downlink 5G network). On the other hand, the maximum bandwidth used for packet transmission in 1 ms TTI is up to 180 kHz bandwidth whereas for the 0.14 ms TTI, the maximum bandwidth that is used to carry packets of a user is up to 1440 kHz (as depicted in Table II). Though the number of users is reduced by 16% (i.e. (1 ms / 0.14 ms) * 6 users = 42 users (approximately) in a total of 1 ms TTI scaled from 0.14 ms TTI), wider bandwidth is allocated per user for packet transmission in the downlink 5G network.

Besides the significant change made in the frame structure, the ambitious requirement that demand for zero latency is impossible to be met if the Round-Trip Time (RTT) the Hybrid

Automatic Repeat Request (HARQ) is not shortened. To deal with this important requirement, another change was made on the RTT where instead of having 8 ms RTT (in the earlier version of the LTE-Advanced network), it has been revised to 4 ms RTT for the HARQ in the 5G network [10].

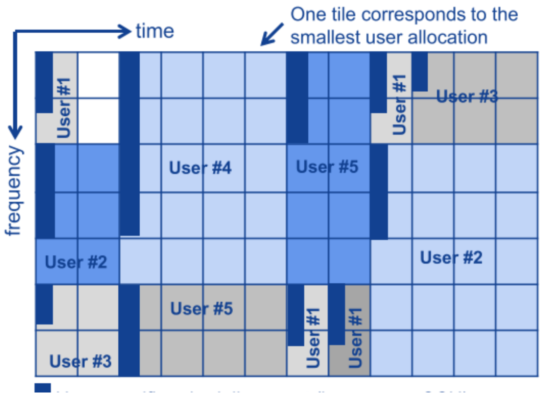

Fig. 3. Sketch of flexible time-frequency multiplexing of users [2]

TABLE II
TTI AND SUB-BAND SIZE [2]

TTI size	Frequency domain scheduling block size (subband size)	Resource elements (REs) per block size
0.14 ms	8 PRBs (1440 kHz)	192
0.5 ms	4 PRBs (720 kHz)	336
1.0 ms	3 PRBs (540 kHz)	432
2.0 ms	2 PRBs (360 kHz)	576
4.0 ms	1 PRBs (180 kHz)	576

III. RENOWNED PACKET SCHEDULING ALGORITHMS

To validate the modeled 5G network described in Section II, four renowned packet scheduling algorithms that were available in the extant literature were investigated. These packet scheduling algorithms were developed in the legacy Time Division Multiple Access (TDMA) systems that allocates a whole bandwidth to a selected user in each scheduling period. These packet scheduling algorithms are discussed next:

A. Maximum Channel Quality Information (Max-CQI) Algorithm [11]

This algorithm chooses a user that has the best channel quality in every scheduling period as shown in Equation (1). The Max-CQI algorithm provides a good throughput performance for transmitting packets to a user located closer to the base station but may not be good in fairness for depriving users located at cell edge from receiving their transmission opportunity.

$$priority_i(t) = cqi_i(t) \tag{1}$$

where $priority_i(t)$ the priority of the *ith* user at scheduling period t and $cqi_i(t)$ is the channel quality of the *ith* user at scheduling period t.

B. Round Robin (RR) Algorithm [12]

Due to the poor fairness performance of the Max-CQI, the RR algorithm was developed. This algorithm aims to ensure fair share of resources among the users by transmitting packets to users in sequential order. However, since the channel quality is not accounted, the throughput performance of the RR degraded.

C. Proportional Fair (PF) Algorithm [13]

To address the fairness and throughput limitations faced in the Max-CQI and RR, the PF algorithm was developed. This algorithm takes the channel quality and the average throughput of each user into consideration (as shown in Equation (2)) when selecting a user to receive packets. A remarkable volume of research has shown improvement in fairness and throughput achieved by this algorithm [14][15].

$$priority_i(t) = \frac{cqi_i(t)}{R_i(t)} \tag{2}$$

$$R_i(t) = \left(1 - \frac{1}{t_c}\right) R_i(t-1) + I_i(t) * \frac{1}{t_c} * cqi_i(t) \tag{3}$$

where $priority_i(t)$ the priority of the *ith* user at scheduling period t, $cqi_i(t)$ is the channel quality of the *ith* user at scheduling period t, $Ri(t)$ is the average throughput of the *ith* user at scheduling period t, t_c is a constant and $I_i(t)$ is a function indicating whether *ith* user is scheduled or not at scheduling period t.

D. Maximum-Largest Weighted Delay First (M-LWDF) Algorithm [16]

The GBR is delay sensitive multimedia/healthcare contents. Therefore, the packet delay should be accounted when selecting packets of each user for transmission. Given that the Max-CQI, RR and PF do not take packet delay into account, it may degrade the GBR performance. To encounter this drawback, the M-LWDF was proposed. Besides channel quality and the average throughput, the M-LWDF algorithm considers the packet delay and the desired Quality fo Service (QoS) of each user when making scheduling decision. The desired QoS is vital when a mixture of GBR and Non-GBR users simultaneously exist in the network. It allows the M-LWDF algorithm to prioritize the most sensitive users based on desired QoS to receive its transmission opportunity. The M-LWDF algorithm is defined as follows:

$$priority_i(t) = a_i * W_i(t) * \frac{cqi_i(t)}{R_i(t)} \tag{4}$$

$$a_i = -\left(\frac{\log \delta_i}{PDT_i}\right) \tag{5}$$

where $priority_i(t)$ the priority of the *ith* user at scheduling period t, $cqi_i(t)$ is the channel quality of the *ith* user at scheduling period t, $Ri(t)$ is the average throughput of the *ith* user at scheduling period t (see Equation 3), $W_i(t)$ is the Head-of-Line (HOL) packet delay of the *ith* user at scheduling period t, a_i is the desired QoS of the *ith* user, δ_i is the Packet Loss Ratio (PLR) threshold of *ith* user and PDT_i is the packet delay threshold of the *ith* user.

Packet scheduling in the downlink 5G network is performed in time and frequency domains and more than one radio channels (i.e. RBs) are available to be competed among the users (as stated in Section II). Therefore, the renowned packet scheduling algorithms should be revised to allow these algorithms to support packet scheduling in the downlink 5G network. When compared with the downlink LTE-Advanced network that performs packet scheduling on each RB and in each 1 ms TTI, the packet scheduling modelled for the downlink

5G network discussed in this paper implements packet scheduling in each 0.14 ms TTI (other variant of TTI is also supported) and on each 8 RBs (see Table II). Though the TTI has been shortened, the frequency bandwidth used to transmit packets to users is wider. Based on this revised design (i.e. for each 0.14 ms TTI and for each sequential 8 RBs), the priority of a user is determined based on Equation (6) to Equation (8) for the Max-CQI, PF and M-LWDF respectively whereas scheduling of users in the RR take a sequential turn on each 8 RBs.

$$priority_i(t) = cqi\_avg_i(t) \tag{6}$$

$$priority_i(t) = \frac{cqi\_avg_i(t)}{R_i(t)} \tag{7}$$

$$priority_i(t) = a_i * W_i(t) * \frac{cqi\_avg_i(t)}{R_i(t)} \tag{8}$$

$$cqi\_avg_i(t) = \frac{\sum_{j=1}^{j=\max\_RB} cqi_{i,j}(t)}{\max\_RB} \tag{9}$$

where *priority$_i$(t)* the priority of the *ith* user at TTI *t, cqi_avg$_i$(t)* is the average channel quality of the *ith* user at TTI *t*, *Ri(t)* is the average throughput of the *ith* user at TTI *t* (see Equation 3), *W$_i$(t)* is the HOL packet delay of the *ith* user at scheduling period *t, a$_i$* is the desired QoS of the *ith* user (as defined in Equation 5), *cqi$_{i,j}$(t)* is the channel quality of the *ith* user on RB *j* at TTI *t* and *max_RB* is the total number of available RBs.

It can be observed in Equation (6) – Equation (8) that the average channel quality on all RBs is accounted given that the wide bandwidth is divided into a number of RBs using the OFDMA technology.

IV. SIMULATION METHODOLOGY

The performance of the renowned packet scheduling algorithms in supporting a mixture of GBR and Non-GBR healthcare contents in the downlink 5G network are evaluated by a series of computer simulation developed on a C++ platform. The network operates on 2 GHz and 2.6 GHz CCs (assuming CA feature is incorporated in the downlink 5G network) and a total of 10 MHz bandwidth which maps to 50 RBs is available. The transmit power use by the base station is at 43.01 and frequency division duplex mode is assumed. Each user periodically reports its CQI at 5 ms interval and this CQI report arrives at the base station after 2 ms delay. The maximum number of retransmissions is capped at 4 times and the RTT of HARQ is set at 4 ms. Pending HARQ retransmission is prioritizes over new packets to further minimize the packets being discarded for delay violation. New packets of users will only be transmitted if remaining RBs are available after retransmission of HARQ packets completes.

It is also assumed that the downlink 5G network contains an equal number of GBR and Non-GBR users. The GBR represents consultation video call whereas the Non-GBR represents the daily health condition notices. The packet delay threshold of 150 ms as shown in Table I for the consultation video call represents the end-to-end delay threshold. Given that this performance evaluation considers the packet delay threshold from the base station to users, it is capped to 80 ms. Similarly, the packet delay threshold for the Non-GBR daily health condition notices is set to 200 ms. The transmission reliabilities of the GBR and Non-GBR are considered satisfactory if they are maintained above 99.99% and 99.99999% respectively. Table III summarizes the simulation assumptions of this performance evaluation.

TABLE III
SIMULATION ASSUMPTIONS

Description	Assumption
Frequency spectrum	2 GHz and 2.6 GHz
Bandwidth	10 MHz (5 MHz bandwidth on each CC)
Number of available RBs	50 RBs
Base station transmit power	43.01 dB
CQI	Periodic CQI every 5 ms with 2 ms delay
HARQ RTT	4 ms
Maximum number of HARQ retransmissions	4 times
GBR healthcare content	Consultation video call
Non-GBR healthcare content	Daily health condition notices
GBR packet delay threshold and desired transmission reliability	80 ms and 99.99%
Non-GBR packet delay desired threshold and transmission reliability	200 ms and 99.99999%
GBR and Non-GBR user proportion	50%:50%

The transmission reliability has been a well-known metric in evaluating the performance of the GBR and Non-GBR multimedia/healthcare contents. Given its popularity, this metric is considered. The transmission reliability metric of both GBR and Non-GBR is defined as follows:

$$transmission\ reliability = 100 - \left(\frac{\sum_{i=1}^{i=N} \sum_{t=1}^{t=T} pd_i(t)}{\sum_{i=1}^{i=N} \sum_{t=1}^{t=T} ps_i(t)} \right) \tag{10}$$

where *pd$_i$(t)* is the size of discarded packets of the *ith* user at time *t*, *ps$_i$(t)* is the size of packets of the *ith* user that arrive at the base station at time *t*, *T* is the maximum simulation time and *N* is the maximum number of users.

The expected increase in greenhouse gas emissions due to the massive increase in the volume of multimedia/healthcare contents has placed the Energy Efficiency (EE) metric at the forefront in the design of 5G mobile cellular network [17][18][19]. Given its importance, *EE$_{gain}$*, which is the EE of renowned packet scheduling algorithm and benchmark packet scheduling algorithm is derived as in the Equation (11).

$$EE_{gain} = \left(\frac{EE_{PS}}{EE_{BM}} - 1 \right) * 100 \tag{11}$$

$$EE_{PS} = \frac{\frac{1}{T} \sum_{i=1}^{i=N} \sum_{t=1}^{t=T} pr_i(t)}{powerBS} \tag{12}$$

where *EE$_{gain}$* is the percentage of the relative gain of a packet scheduling algorithm, *EE$_{PS}$* is the EE achieved by a packet scheduling algorithm, *EE$_{BM}$* is the EE achieved by the benchmark packet scheduling algorithm, *pr$_i$(t)* is the size of correctly received packets at the *ith* user at time *t*, *powerBS* is the total transmit power used by the base station, *T* is the maximum simulation time and N is the maximum number of users.

Besides the transmission reliability and EE, fairness (as defined in Equation (13)) is another crucial metric for measuring the performance of packet scheduling in the mobile cellular networks and hence is considered in this paper.

$$fairness = \frac{\left(\sum_{i=1}^{i=N}\sum_{t=1}^{t=T} pr_i(t)\right)^2}{N * \left(\sum_{i=1}^{i=N}\left(\sum_{t=1}^{t=T} pr_i(t)\right)^2\right)} \quad (13)$$

where $pr_i(t)$ is the size of correctly received packets at the *ith* user at time t, T is the maximum simulation time and N is the maximum number of users.

It should be noted that these EE (that takes throughput into account in its equation) and fairness are considered as the metrics for measuring the downlink 5G performance given that the aim of this paper is to simultaneously meet the desired transmission reliability for more GBR and Non-GBR healthcare users whilst maximizing the downlink 5G performance.

V. RESULTS AND DISCUSSIONS

The GBR and Non-GBR transmission reliability of the renowned packet scheduling algorithms are illustrated in fig. 4 and fig. 5. It can be seen in both figures that the transmission reliability degrades with increasing number of users. This is because, with increasing number of users, there will be more packets residing in the base station competes for the limited and fixed RBs. As RBs are insufficient to transmit packets to all users, packets of users that approached the packet delay deadline are discarded. This contributes to the degradation of the transmission reliability of both GBR and Non-GBR healthcare contents.

However, when compared with the Non-GBR healthcare contents, the GBR healthcare contents are more sensitive to delay and this is proven based on both figures indicating significant degradation in the GBR transmission reliability as compared to the Non-GBR transmission reliability (i.e. the transmission reliability is below the 99.99% threshold in PF and M-LWDF when number of users is 45 whereas both PF and M-LWDF maintain the Non-GBR transmission reliability above the 99.99999% threshold even for more than 100 users). It is demonstrated in Table 4 that, when compared with the RR, the M-LWDF and PF can simultaneously support 50% more users whilst meeting the satisfactory transmission reliability of both GBR and Non-GBR healthcare contents. Though it is expected that the delay-aware M-LWDF algorithm to be superior to the PF in providing more users at the desired GBR and Non-GBR transmission reliabilities, but this situation is not observed in Figure 4 and Figure 5. One possibility is that the expectation may only be valid for the case when the downlink 5G network only contains either GBR or Non-GBR healthcare contents but not a mixture of these healthcare contents. To verify this assumption, further study on PF and M-LWDF when supporting different proportions of GBR and Non-GBR users may need to be conducted.

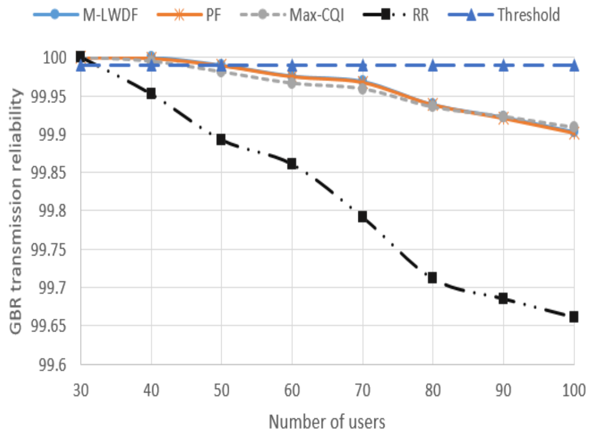

Fig. 4. GBR transmission reliability vs number of users

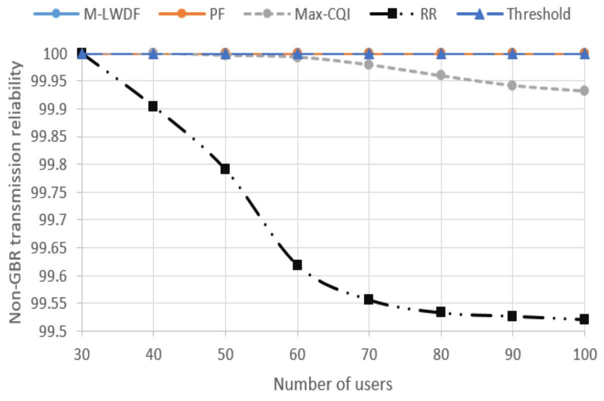

Fig. 5. Non-GBR transmission reliability vs number of users

TABLE IV
MAXIMUM NUMBER OF USERS TO SIMULTANEOUSLY SATISFY THE DESIRED TRANSMISSION RELIABILITY OF THE GBR AND NON-GBR HEALTHCARE CONTENTS

Packet scheduling algorithms	Maximum number of users that can satisfy the desired transmission reliability of GBR and Non-GBR healthcare contents	Percentage of improvement (%) over RR algorithm
Max-CQI	31	3.33
RR	30	-
PF	45	50
M-LWDF	45	50

Fig. 6 shows the EE_{gain} been benchmarked with the RR packet scheduling algorithm. The RR is selected as benchmark because the algorithm does not take channel quality into account when making scheduling decision. Therefore, it has the least throughput that maps to the worst EE performance. It is demonstrated in the figure that the EE_{gain} increases with increasing number of users as more packets are successfully transmitted to the users in the downlink. The available RBs are efficiently utilize as more users compete to use the scarce RBs for packets transmission. It is also illustrated in the figure that all three renowned algorithms are energy efficient for having a comparable performance in terms of EE_{gain}. This is because these algorithms consider the channel quality allowing them to transmit packets of users on RBs with good channel quality.

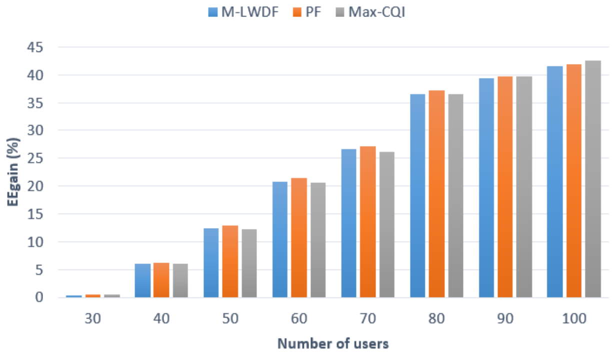

Fig. 6. Relative EE_{gain} of packet scheduling algorithms with respect to RR packet scheduling

Figure 7 illustrates the fairness performance of the evaluated packet scheduling algorithms. It can be observed in the figure that the M-LWDF, PF and Max-CQI have a comparable fairness performance. Though, it is anticipated that the RR to have a better fairness, the result obtained in Figure 7 contradicts the anticipation. This can be explained on the basis of Equation (13) where the equation considers the throughput of users for calculating the fairness, but the RR has the worst fairness for not taking the channel quality of each user into account when making scheduling decisions, as indicated in fig. 6. If fairness is measured based on the amount of time each user is allocated the RBs, then the fairness in RR will outperform the other packet scheduling algorithms.

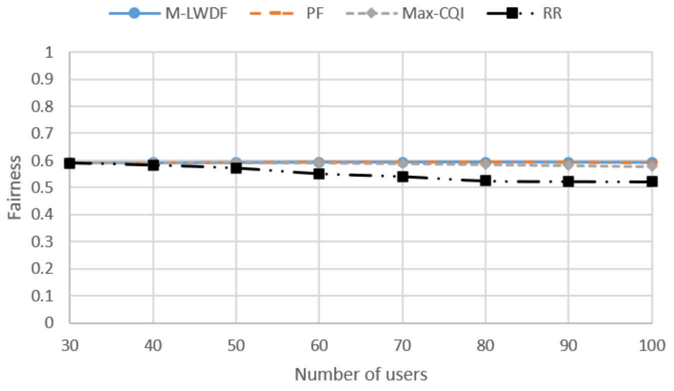

Fig. 7. Fairness vs number of users

It can be concluded based on the results represented in Figure 4 – Figure 7 and taking the modelled downlink 5G network, the PF and M-LWDF algorithms are the most efficient packet scheduling algorithms (when compared with RR and Max-CQI) in maximizing the number of GBR and Non-GBR healthcare users that received their desired transmission reliability while at the same time is able to maximize the downlink 5G performance.

CONCLUSION

This paper studies TDMA based packet scheduling performance in the downlink 5G network. Minor revisions were made on the Max-CQI, RR, PF and M-LWDF to allow these algorithms to support packet scheduling in the downlink OFDMA-based 5G network. A detailed description of the downlink 5G network model that incorporates flexible frame structure and a shorter RTT of HARQ is provided. The simulation results showed the effectiveness of the PF and M-LWDF in maximizing the number of GBR and Non-GBR healthcare users that receive their desired transmission reliability and simultaneously maximize the downlink 5G performance. Further study involves performance evaluation of the PF, M-LWDF and other renowned packet scheduling algorithms for different proportions of GBR and Non-GBR healthcare users in the downlink 5G mobile cellular network.

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