Evaluation of TCP Performance with LTE Downlink Schedulers in a Vehicular Environment

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***Abstract*—Packet scheduler at the medium access control (MAC) layer is essential to improve radio resource utilization in the Long Term Evolution (LTE) network. The MAC scheduler allocates resource blocks to user terminals (UEs) according to the priority metric, which varies in different scheduling algorithms. Although there have been many studies on the performance of LTE schedulers at the MAC layer, it is interesting to evaluate the impact of different LTE MAC schedulers on the transport layer, particularly on the transmission control protocol (TCP). In this study, we implement three mainstream LTE MAC schedulers in Network Simulator-3 (NS-3), namely, maximum throughput (MT), blind equal throughput (BET) and proportional fair (PF). Extensive simulations are conducted to examine the different TCP throughput achieved with the frequency domain version and the time domain version of these schedulers in a vehicular environment. The performance difference is attributed to important factors such as the resource allocation granularity, channel-awareness in scheduling, and the number of UEs.**

***Index Terms*—LTE, packet scheduler, MAC, TCP, downlink, vehicular mobility.**

I. Introduction

Long Term Evolution (LTE), developed by the third generation partnership project (3GPP), is one of the most promising standards for the fourth generation (4G) wireless networks. Extending the third-generation (3G) technologies, LTE provides a much higher transmission speed and a larger system capacity. By integrating cutting-edge technologies such as multiple input and multiple output (MIMO) and orthogonal frequency-division multiple access (OFDMA), LTE supports a peak downlink rate of 300 Mbit/s and a maximum uplink rate of 75 Mbit/s, while it guarantees a low transfer delay of less than 5 ms in the radio access network (RAN) [1]. LTE also provides improved mobility support for terminals moving at a velocity up to 350 km/h or 550 km/h depending on the frequency band [2]. This offers a good opportunity for mobile users to run bandwidth-intensive applications such as video streaming and video conference [3]. It is known that a significant amount of multimedia applications run on top of the transmission control protocol (TCP), e.g., hypertext transfer protocol (HTTP)-based video streaming [4]. It is easier for TCP traffic to traverse the firewall system, whereas user datagram protocol (UDP) traffic is often blocked due to security and performance concerns. Hence, it is essential to translate the upgraded LTE network support to the upper layers such as with a high and stable TCP throughput in order to really benefit end users. We are interested in evaluating the impact of LTE downlink schedulers on achievable TCP performance in a high-mobility vehicular environment.

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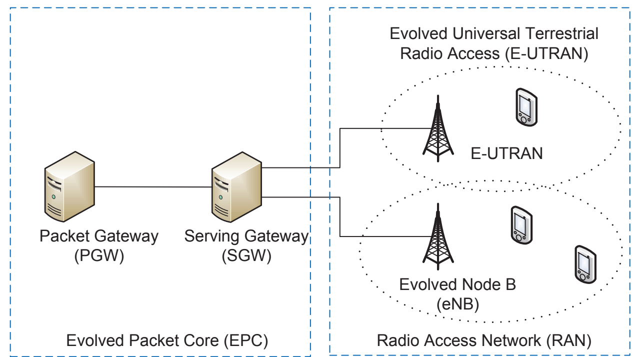


Fig. 1. LTE network architecture.

As shown in Fig. 1, the LTE network follows a general architecture consisting of two major parts, namely, the evolved packet core (EPC) and the radio access network (RAN). EPC is mainly responsible for mobility management, connection establishment, intra-LTE handover, and connecting RAN to the public Internet. RAN defines the evolved universal terrestrial radio access (E-UTRA) as the air interface that provides wireless transmission to user terminals (UEs). One key component in LTE that affects the system performance is the packet scheduler at the medium access control (MAC) layer. It aims to allocate radio resources to UEs so that various quality-of-service (QoS) requirements at the downlink and uplink are satisfied. LTE MAC scheduler is located at the base station of LTE network, known as evolved Node B (eNB) in LTE. Depending on specific design objectives, LTE MAC scheduler may apply different resource allocation algorithms. For instance, the blind equal throughput (BET) scheduler [5] uses the reciprocal of past average throughput as a priority metric in resource allocation, so that all UEs connected to the same eNB are provided an equal MAC-layer throughput. In contrast, the maximum throughput (MT) scheduler [5] uses the achievable data rate as the priority metric so as to maximize the aggregate throughput of the eNB. The different behaviors of LTE MAC schedulers can have a great impact on the achievable performance at the TCP transport layer. As an example, we can easily see that, since MT scheduler prefers to serve UEs with a good channel quality, UEs located at the edge of eNB may suffer from a large packet delay, which can cause slowing down the sending rate at the TCP source.

In recent years, a joint scheduler design in the frequency domain (FD) and time domain (TD) is proposed by many researchers so as to balance the implementation complexity and resource utilization performance. For example, a group of UEs can be first selected in the time domain, while radio resources are then allocated to selected UEs in the frequency domain. In order to better understand the performance of joint FD and TD MAC schedulers, it is necessary to examine the unique features of the schedulers in the frequency domain and time domain. Although there has been some initial work that evaluates the performance of TD or FD schedulers as in [5,6], we further investigate the impact of different LTE MAC schedulers on the performance of TCP-based traffic. We focus on three mainstream schedulers considered in the LTE-EPC network simulator project (LENA) [7], including BET, MT, and PF. As part of the Google Summer of Code 2012 project, we implement the three schedulers in Network Simulator-3 (NS-3) [8]. We also compare the performance of the time domain (TD) version and the frequency domain (FD) version of each scheduler.

The remainder of this paper is organized as follows. In Section II, we introduce the background on LTE MAC scheduler and the three scheduling algorithms under study. Simulation results are presented in Section III to demonstrate the perceived TCP performance with different LTE MAC schedulers in a vehicular environment. Related work is reviewed in Section IV, followed by conclusions in Section V.

II. LTE MAC Schedulers

A. Background

The wireless access of LTE is based on OFDMA at the downlink and single-carrier frequency division multiple access (SC-FDMA) at the uplink. We focus on the downlink in this study. The minimum resource unit that the MAC scheduler allocates to a UE in OFDMA is a resource block (RB), as shown in Fig. 2. Specifically, an RB in the time domain is one transmission time interval (TTI) that lasts for two time slots and one subband in the frequency domain. In LTE, each time slot is 0.5ms, while one subband is 180kHz. The MAC scheduler is active for every TTI to allocate the resource blocks to each UE based on a specific priority metric. For the FD version, the MAC scheduler distinguishes the resources along both the frequency and time scales. Hence, the minimum resource unit to allocate is a subband RB within a TTI. In contrast, the TD version of MAC scheduler assigns all RBs of the wideband to one UE in the current TTI. Obviously, the FD scheduler allocates radio resources in a finer granularity, but at the cost of a higher implementation complexity. Based on our evaluation, we find that there are certain scenarios that the FD version and the TD version behave similarly in terms of the TCP performance. Hence, it is worthwhile to select the TD scheduler in such cases to reduce complexity.

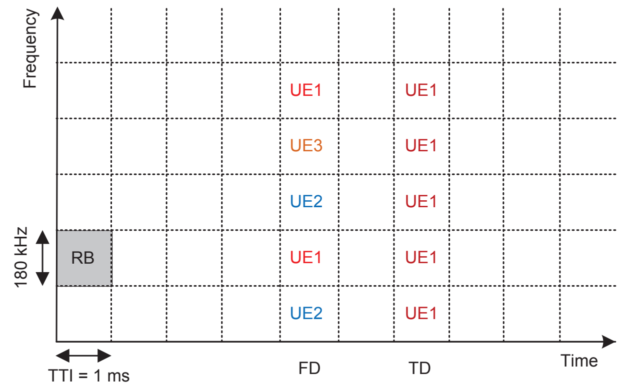


Fig. 2. LTE resource allocation in the time domain and the frequency domain.

In LTE eNB, there is a radio resource management (RRM) module that assimilates the channel quality indicator (CQI) reports from UEs to estimate the wireless channel quality. Currently, there are two critical values in the CQI report, namely, `wideband cqi` that estimates the channel quality over the entire wideband, and `subband cqi`, which is the channel quality value for a specific subband. The MAC scheduler can then make use of such CQI information for the scheduling decision. LTE standard does not specify the CQI report types used in the scheduler. In order to study the different behavior of FD and TD schedulers, we assume that the FD version of a channel-aware scheduler can exploit `subband cqi` to evaluate the priority while the corresponding TD version utilizes `wideband cqi` in the scheduling. As such, for the same type of MAC scheduler, the FD version has the finest control granularity for radio resource allocation but the highest implementation complexity, whereas the TD version has the coarsest resource units but the lowest implementation complexity. The channel-unaware scheduler, such as BET, uses `wideband cqi` in both FD and TD versions.

B. Maximum Throughput

The maximum throughput (MT) scheduler [5] aims to maximize the overall throughput of an eNB. It allocates each RB to the user that can achieve the maximum expected data rate in the current TTI. Given N UEs, the priority metrics used in the frequency domain MT (FD-MT) and the time domain MT (TD-MT) are respectively

$$\hat{i}_k(t) = \max_{j=1,\dots,N} R_j(k,t) \tag{1}$$

$$\hat{i}(t) = \max_{j=1,\dots,N} R_j(t) \tag{2}$$

where $\hat{i}_k(t)$ is the priority metric of FD-MT for the RB of subband k and time interval t, and $\hat{i}(t)$ is the priority metric of TD-MT for all the subband RBs at time interval t. Here, $R_j(k,t)$ and $R_j(t)$ are the achievable data rates of UE j

TABLE I
SYSTEM PARAMETERS FOR EXPERIMENTS.

Parameter	Value
Number of RBs	24
AMC mode	Piro
Error mode of control	Deactivate
Error mode of data	Deactivate
RLC mode	UM mode
Transmit power of eNB	30 dBm
Transmit power of UE	23 dBm
Noise figure at eNB	5 dB
Noise figure at UE	5 dB
TTI	1 ms
Number of UEs	7, 14, 21, 28
TCP	NewReno

for FD-MT and TD-MT, respectively. In FD-MT, $R_j(k,t)$ depends on `subband cqi` of each RB, while $R_j(t)$ in TD-MT is determined by `wideband cqi`. By using the above priority metrics, MT scheduler always allocates radio resources to UEs with the best channel quality. As such, the network utilization efficiency can be maximized since the network resources are always fully utilized. However, this opportunistic behavior cannot ensure fairness to UEs, which is another key performance factor.

C. Blind Equal Throughput

The blind equal throughput (BET) scheduler [5] aims to provide an equal throughput to all UEs associated with the same eNB. Unlike MT, BET is channel-unaware in the sense that both FD-BET and TD-BET use `wideband cqi` in packet scheduling. The priority metric for BET is given by

$$\hat{i}(t) = \max_{j=1,\dots,N} \frac{1}{T_j(t)} \quad (3)$$

where $T_j(t)$ is the past average throughput of UE j at time t, which is calculated by

$$T_j(t) = \beta T_j(t-1) + (1-\beta) R_j(t). \quad (4)$$

Here, β $(0 \leq \beta \leq 1)$ is the weight factor for moving average, and $R_j(t)$ is the achievable data rate of UE j at time t as defined above. The TD-BET scheduler selects the UE with the largest priority metric and allocates all subband RBs in the current TTI to this UE. In contrast, the FD-BET scheduler first selects the UE with the lowest past average throughput (largest priority metric) and assigns one RB to this UE. Then, the scheduler recalculates its expected throughput and continues to allocate more RB blocks to this UE if the updated past average throughput is still no greater than other UEs. This procedure continues until the expected throughput of this UE is no longer the lowest. The scheduler assigns RB blocks to other UEs in the same way until all RBs are allocated. The rationale behind this algorithm is to ensure an equal throughput for all UEs in every TTI.

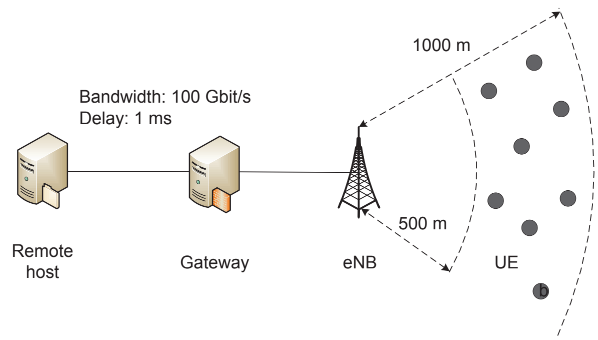


Fig. 3. Simulation topology.

D. Proportional Fair

As seen above, the MT scheduler and BET scheduler aim to optimize either efficiency or fairness. Proportional fair (PF) is another popular scheduling algorithm which can balance between efficiency and fairness [5]. By incorporating channel-awareness to BET, the PF scheduler uses the following priority metrics for the FD version and the TD version respectively

$$\hat{i}_k(t) = \max_{j=1,\dots,N} \frac{R_j(k,t)}{T_j(t)} \quad (5)$$

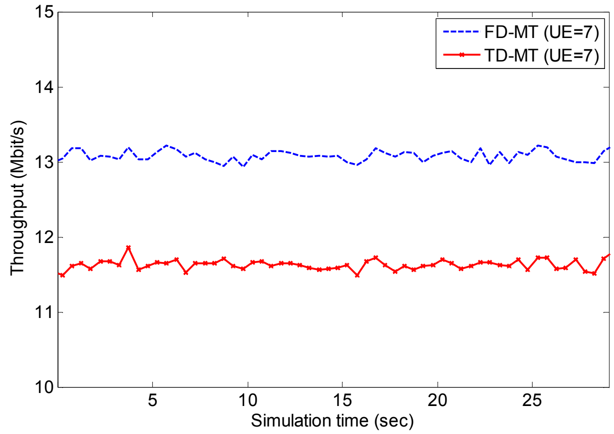
$$\hat{i}(t) = \max_{j=1,\dots,N} \frac{R_j(t)}{T_j(t)}. \quad (6)$$

We see that the achievable rate is considered together with the past average throughput, so that it prefers to allocate resources to UEs with a good channel quality in the short term while providing an equal throughput to each UE in the long term.

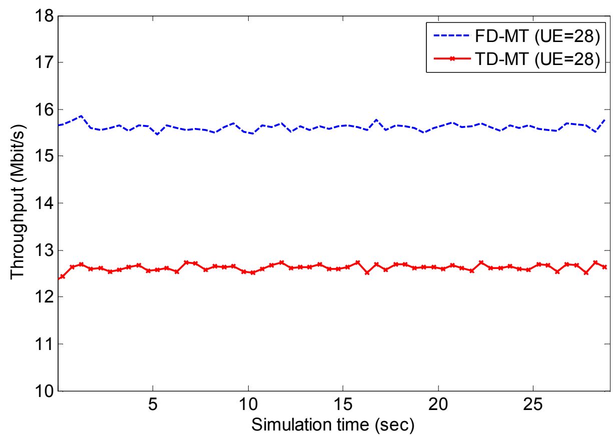
III. SIMULATION RESULTS AND DISCUSSIONS

In order to evaluate the impact of LTE MAC schedulers on TCP performance, we implement the above three schedulers in the Network Simulator-3 (NS-3). Currently, NS-3 provides a complete LTE module which contains both EPC and RAN. Our implementation of MAC schedulers in NS-3 refers to the LTE MAC scheduler interface specification [9].

Fig. 3 shows the simulation topology. There is one TCP flow from a remote host to each UE. All UEs are distributed within a random distance to eNB from 500m to 1000m. We use a 30-second trace developed in the LENA project to simulate the fading channel in a vehicular environment at a speed of 60 km/h. The general system parameters of pre-defined scenarios are given in Table I. In order to highlight the impact of MAC scheduler on TCP performance, we use the unacknowledged mode (UM) of the radio link control (RLC) module. Also, the error mode at the physical layer is turned off so that eNB forwards a TCP packet without any loss immediately after the MAC scheduling. We use saturated bulk traffic with a fixed packet size of 1024 bytes at the source, since varying traffic may cause side effects that hinder proper interpretation of simulation results. Based on the specific objective of each scheduler, we take different performance measures, including the aggregate TCP throughput of all UEs in a certain time interval, as well as the average TCP throughput and its



(a) Number of UEs = 7.



(b) Number of UEs = 28.

Fig. 4. Aggregate TCP throughput of UEs with MT.

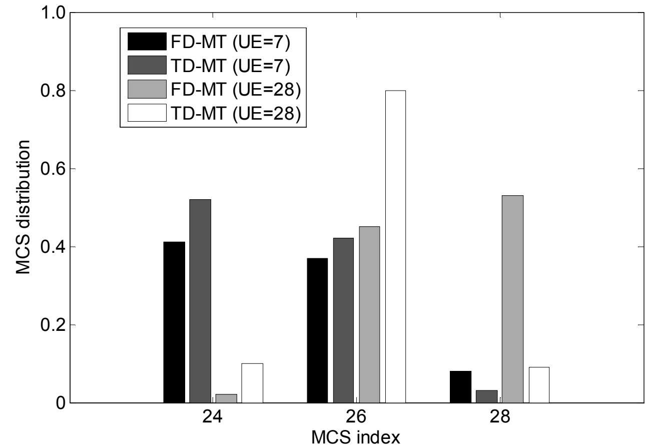


Fig. 5. Modulation and coding scheme distribution with MT.

variation of individual UEs. The throughput is computed for every 500ms.

A. *Maximum Throughput*

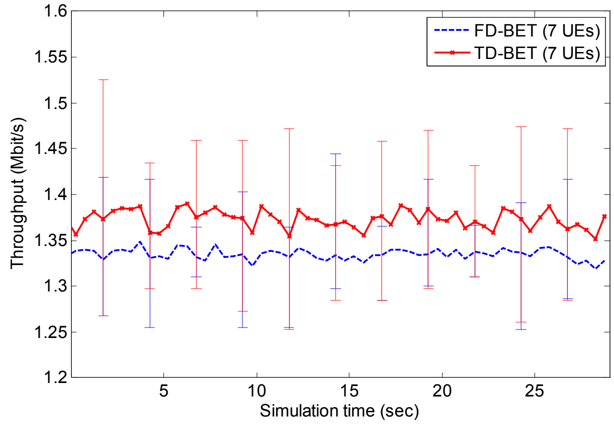
Fig. 4 shows the aggregate throughput of FD-MT and TD-MT with a different number of UEs. As seen clearly, FD-MT achieves an aggregate throughput larger than that of TD-MT. FD-MT exploits `subband cqi` so as to utilize channel resources more efficiently. Also, FD-MT can serve multiple UEs in each TTI, which results in a finer granularity in resource allocation. Comparing Fig. 4(a) and Fig. 4(b), we can see that the performance gap between FD-MT and TD-MT is much larger when the number of UEs is increased. This is mainly because the aggregate throughput of TD-MT improves little when there is a larger traffic load from an increasing number of UEs. FD-MT always selects the UE with the best `subband cqi`, while TD-MT only chooses the UE with the best `wideband cqi`. As a consequence, TD-MT is less sensitive and adaptive to channel quality variation. TD-MT cannot explore the available resources as opportunistically as FD-MT.

Fig. 5 shows the distribution of modulation and coding schemes (MCS) when the MT scheduler is applied with a different number of UEs. An MCS scheme with a higher index requires a better channel quality to ensure satisfactory transmission. FD-MT determines the MCS scheme based on `subband cqi`, while TD-MT uses `wideband cqi`. Here, we only show the distribution of MCS schemes indexed at 24, 26, and 28. Because MT tends to allocate resources to UEs with the best channel quality, the probabilities that lower indexed MCS schemes are selected are negligible. It can be seen that, when the number of UEs is increased, FD-MT almost converges to the MCS scheme of 26 and 28, which is the highest two indexes of MCS schemes defined in LTE [10]. In contrast, with an increasing number of UEs, the MCS of TD-MT is mostly distributed to the schemes of 26.

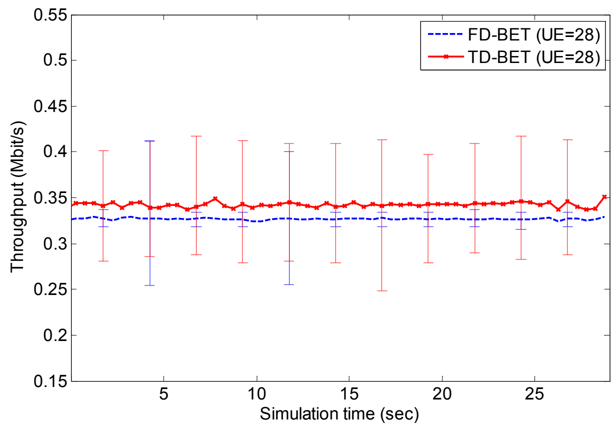
B. *Blind Equal Throughput*

Fig. 6 shows the TCP throughput of individual UEs with FD-BET and TD-BET for a varying number of UEs. While the curves give the average TCP throughput, the two points in the vertical lines represent the maximum and minimum TCP throughput. As seen in Fig. 6(a), when there is a small number of UEs, FD-BET and TD-BET performs similarly with close average throughput and variation. This is because both FD-BET and TD-BET are channel-unaware in packet scheduling and use `wideband cqi` for adaptive modulation and coding (AMC). Moreover, the past average throughput is taken into account when the priority metric is calculated. Hence, although TD-BET picks one UE in each TTI, more TTI intervals can be allocated to UEs of a low channel quality to balance the resources allocated among UEs.

On the other hand, when the number of UE is increased from 7 to 28 in Fig. 6(b), the TCP throughput variation with TD-BET is much larger than that of FD-BET. This is because it takes longer in TD-BET for a UE to obtain a transmission opportunity. For UEs experiencing similar `wideband cqi`, TD-BET performs similarly to the round robin scheduler. For example, suppose that there are M UEs having the same `wideband cqi`. It will take each of the M UEs to wait for M TTI intervals to obtain the next transmission opportunity. As a result, when the number of UEs is increased by 4 times,

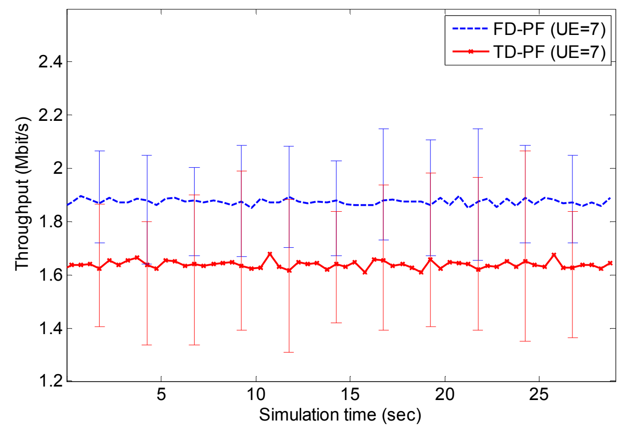


(a) Number of UEs = 7.

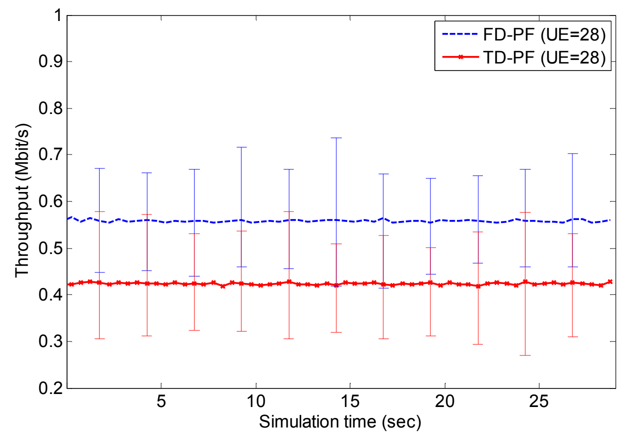


(b) Number of UEs = 28.

Fig. 6. Average TCP throughput of UEs with BET.



(a) Number of UEs = 7.



(b) Number of UEs = 28.

Fig. 7. Average TCP throughput of UEs with PF.

the transmission delay is greatly increased, which further slows down the TCP sending rate.

We also observe that the average throughput of TD-BET is slightly higher than that of FD-BET in Fig. 6(a) and Fig. 6(b). In LTE, the MAC-layer frame is encapsulated into the transport block of the physical layer and then transmitted to the UE. The transport block size of a UE is determined by the modulation and coding scheme (MCS) and how many RB blocks are allocated to the UE. Specifically, the transport block size increases slightly faster than linearly with the number of RBs allocated to a UE [11]. For example, for the modulation and coding scheme indexed of 26, the transport block size with 2 RBs, which is 157 bytes. In contrast, the transport block size with 24 RBs is 1908 bytes, which is slightly larger than 12 times of 157 bytes for 2 RBs (i.e., 1884 bytes). As a result, when TD-BET allocates all RB blocks in a TTI interval to one UE, more TCP data can be carried than by multiple UEs in FD-BET.

C. *Proportional Fair*

Fig. 7 illustrates the average TCP throughput of FD-PF and TD-PF with a varying number of UEs. As seen, FD-PF and TD-PF achieves a similar average TCP throughput. This is because PF takes into account past average throughput and balances the resource allocation in the long term. On the other hand, when there are 7 or 28 UEs, the variation of TCP throughput with FD-PF and TD-PF is close in both cases. This random variation is due to the achievable data rate used in calculating the priority metric, which may result in more RBs allocated to UEs with a better channel quality in the short term.

Fig. 7(a) and Fig. 7(b) also clearly demonstrate that PF achieves a trade-off between the maximum efficiency of MT and the pure fairness of BET. On one hand, PF is more efficient than BET with a higher average TCP throughput. This is because PF makes use of the achievable data rate in the priority metric so as to allocate more resources to UEs with a better channel quality in the short term. On the other hand, PF is more fair than MT since it considers the past average throughput to balance the resource allocation among UEs in the long term.

D. *Comparison of MT, BET and PF Schedulers*

Last, we compare the aggregate throughput of the MT, BET and PF schedulers at the MAC layer and the TCP layer. As shown in Fig. 8, FD-MT and TD-MT achieve the highest aggregate throughput, while the throughput of FD-BET and TD-BET is the lowest due to the channel-unaware scheduling feature. Another interesting observation is that, when the number of UEs is increasing, the aggregate TCP and

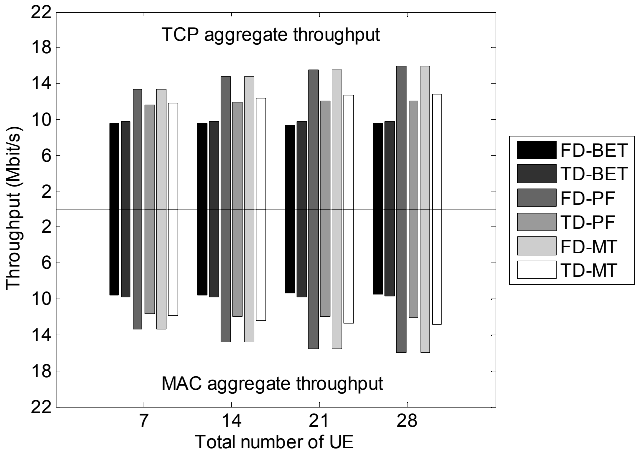


Fig. 8. MAC and TCP throughput of MT, BET and PF schedulers.

MAC throughput of TD-MT increases much slower than that FD-MT. This is because TD-MT is less adaptive to channel quality variation. In addition, FD-MT and FD-PF achieve an aggregate throughput higher than their TD counterparts, because the FD versions use `subband cqi` in scheduling and therefore utilize channel resources more efficiently. In contrast, the channel-unaware FD-BET and TD-BET perform similarly in terms of the aggregate throughput.

IV. Related work

There have been many studies on the performance of LTE MAC schedulers at the physical layer or the MAC layer. In [12], Elgazzar *et.al.* compare the performance of several LTE uplink schedulers. In [13], LTE uplink schedulers are evaluated for mixed traffic. In [5], Capozzi *et.al.* evaluate the aggregate and average MAC throughput of LTE downlink schedulers including MT, proportional fair (PF), and throughput to average (TTA). In [14], PF is studied together with round-robin (RR) in the frequency domain based on a new channel quality indicator (CQI) feedback scheme. The authors of [6] focus on the performance of combining different schedulers in the time domain and the frequency domain. For example, they jointly consider the BET in the time domain and TTA in the frequency domain. On the other hand, some work aims to enhance the LTE MAC scheduler so as to guarantee QoS for a specific class of applications. In [15], the proportional fair scheduling is adapted to better support video streaming. A two-level LTE downlink scheduling algorithm is proposed in [16] to improve QoS for real-time multimedia services. In this study, we take into account the impact of high mobility in a vehicular environment on LTE downlink schedulers. Furthermore, we investigate the co-working between LTE MAC layer and TCP layer. LTE schedulers in the frequency domain and time domain demonstrate different effects on TCP performance.

V. Conclusions

In this paper, we implement three mainstream schedulers for the LTE downlink in NS-3, namely, maximum throughput (MT), blind equal throughput (BET) and proportional fair (PF). Also, we evaluate and compare the impact of the FD version and TD version of these MAC schedulers on TCP performance. As shown in the simulation results, FD-MT achieves a higher aggregate TCP throughput than its TD version, especially in case of a large number of UEs. This is because TD-MT is less adaptive to channel quality variation. In contrast, FD-BET provides an average TCP throughput and variation similar to that of TD-BET when there are a small number of UEs (e.g., 7 in this study). In other words, all UEs can evenly share the bandwidth with FD-BET and TD-BET. However, when the number of UEs is increased, TD-BET brings up a larger variation to TCP throughput than FD-BET, which is because it takes a longer time for a UE to obtain a transmission opportunity. PF balances a trade-off between a high efficiency and pure fairness. FD-PF and TD-PF perform closely, although FD-PF achieves a TCP throughput slightly higher than that of TD-PF due to a finer granularity in allocating radio resources.

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