Controlling TCP ACK Transmission: Suitable Value of Discard Ratio in LTE-Advanced Pro

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***Abstract*—The first release of standards for 5th generation (5G) mobile communication has been approved in the 3rd Generation Partnership Project (3GPP). During the 5G standardization, performance of Transmission Control Protocol (TCP) in the 5G mobile networks was studied. It has been observed that the TCP performance is improved when protocols in the Radio Access Network (RAN) take the TCP behavior into consideration. The authors have been studying TCP ACK filtering that can work well with the link layer protocols in RAN, where the TCP ACKs can be intentionally discarded. It has been shown that proposed methods accomplish good TCP throughput while the number of TCP ACKs is largely reduced. In this paper, the authors tackle a remaining issue: finding the suitable value of "discard ratio". It is proposed that the suitable value is obtained based on the average number of TCP ACKs transmitted in one transmission time interval. Simulation results demonstrate that the suitable value for the TCP ACK filtering can further improve the TCP performance when the number of mobile stations is small. In addition, it improves both throughput and fairness of the TCP when the number of mobile stations becomes large.**

Keywords—LTE-Advanced Pro; 5G; TCP; TCP ACK filtering

I. INTRODUCTION

The first release of standards for 5th generation (5G) mobile radio communication has been approved in the 3rd Generation Partnership Project (3GPP) [1]. The main deployment scenario is dual connectivity between LTE-Advanced Pro (LTE-A Pro) [2–3] and 5G New Radio (NR) [4–5], where the potential data rate can be raised up to tens of Gb/s. During the standardization, performance of the Transmission Control Protocol (TCP) in the 5G mobile networks was studied. It has been observed that the TCP performance is improved when link layer protocols in the Radio Access Network (RAN) are properly developed taking the TCP behavior into account. Although specific methods for the TCP performance improvement are not standardized in the first release of the 5G standards, the 3GPP is carrying on the standardization for the TCP performance improvement [6–7].

The authors have been studying TCP ACK filtering [8–9] i.e. intentional discard of buffered TCP ACKs taking detailed behavior of the link layer protocols in LTE-A Pro into account. Starting with our initial work [8], the authors have continued to explore more suitable TCP ACK filtering and developed three schemes: Passive Discard, Active Discard, and Hybrid Discard [9]. The novel feature of three schemes is a generalization of the control of the number of discarded TCP ACKs according to a control parameter "discard ratio". Passive Discard controls the number of discarded TCP ACKs that cannot be transmitted from the mobile station to the base station and still stored in the uplink buffer of the mobile station due to shortage of uplink resources for the TCP ACK transmissions by the discard ratio. Active Discard controls the number of discarded TCP ACKs based on a threshold, corresponds to the discard ratio, set to the uplink buffer of the mobile station. Hybrid Discard implements both Passive Discard and Active Discard, where the control of the discard of TCP ACKs is performed by both Passive Discard and Active Discard. It has been found in Hybrid Discard that there is a value of the discard ratio that minimizes the number of TCP ACKs sent to the base station while maintaining good TCP throughput. Section II describes details of three schemes.

It is highly supposed that the findings can hold with the 5G standards because essential features of the link layer protocols [10–12] are based on LTE-A Pro. Identified remaining issue in the previous work [9] must be addressed to further improve the performance of Hybrid Discard towards the deployment in the 5G networks. Specifically, the discard ratio was a cell-specific parameter i.e. a single common value of the discard ratio was set to all mobile stations in the serving cell. However, radio channel quality of each mobile station is different from each other. It is supposed that suitable value of the discard ratio can be found when the discard ratio is a station-specific value i.e. it is individually set to the mobile stations.

In order to discover the suitable value of the discard ratio, it must be clear that the threshold-based discard showed the best performance. The threshold was used for a generalization of the discard of the TCP ACKs to enable adaptive control of the discard ratio. It is considered that there is an essential reason that the threshold-based discard of the TCP ACKs suitably works with flow control mechanism of the TCP. A hypothesis is given to disclose detailed relation between the threshold-based discard and the flow control mechanism of the TCP. The hypothesis further derives a formula that defines the suitable value of the discard ratio. The formula is written by using a parameter, which is the amount of average TCP segments the mobile station receives in the downlink. Simulation results verify that Hybrid Discard with the proposed suitable value can decrease the number of the TCP ACKs while further improving the TCP throughput. With the findings, it can be concluded that the derived formula provides the best current practice, which is useful guidance for the deployment of the TCP ACK filtering in the 5G networks.

II. Previous Work

To begin with, details of our three schemes in the previous work [9] are described.

A. Proposed Schemes

Passive Discard: The amount of TCP ACKs transmitted in the uplink is decided in such a way that only the latest TCP ACKs in the buffer of the mobile station (UE: User Equipment) is selected for the transmission, where the amount of the TCP ACKs fits the Transport Block (TB) Size (TBS) that is granted (UL grant) from the base station (eNB: Evolved Node B) to the UE. The TB means the data unit in the Layer 2. The TBS is determined based on the amount of data stored in the UE buffer and the wireless channel conditions. The other TCP ACKs are intentionally discarded. Passive Discard controls the intentional discard according to a parameter "discard ratio", defined by *ratio*. The intentional packet discard must not be applied to the duplicated TCP ACKs since these are used for retransmission triggers for lost TCP data in any end-to-end path. In the case of *ratio* = 1.0, Passive Discard is called Granted ACK from the viewpoint that TCP ACKs that only fit the TBS can only be transmitted. In the case of *ratio* = 0.0, it becomes the current scheme in LTE-A Pro since no discard of TCP ACKs are performed.

The upper figure in Fig. 1 depicts an overview of Passive Discard when the TSB = 2. In the case of *ratio* = 1.0 (Granted ACK), two latest TCP ACKs ($n+3$ and $n+4$) are sent as shown by dotted black line and other threes (n to $n+2$) are discarded. In Hybrid Discard with *ratio* = 2/3, two TCP ACKs (n and $n+1$) among threes (n to $n+2$) are discarded and two latest TCP ACKs ($n+2$ and $n+3$) are sent as shown by red line.

Active Discard: This scheme controls the number of discarded TCP ACKs by a threshold T. The number of stored TCP ACKs is allowed up to T but other TCP ACKs are discarded. The intentional TCP ACK discard is performed every arrival of TCP ACKs in the UE buffer. In the case of $T = \infty$, it becomes the current scheme in LTE-A Pro since all TCP ACKs are kept in the UE buffer.

The lower figure in Fig. 1 depicts an overview of Active Discard. The UE discards two old TCP ACKs (n and $n+1$) and

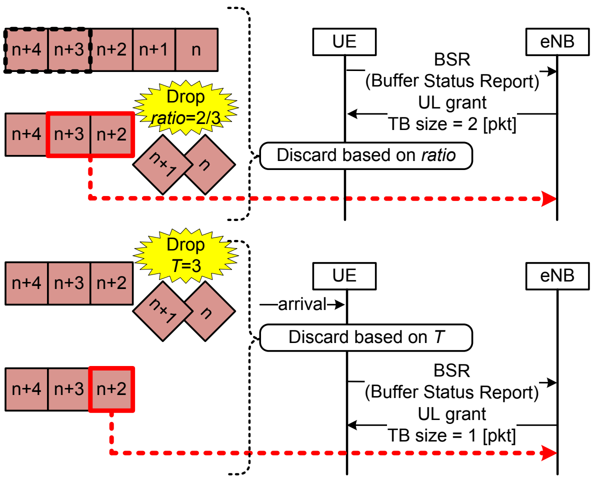


Fig. 1: Scheduling Request procedure in LTE-A Pro

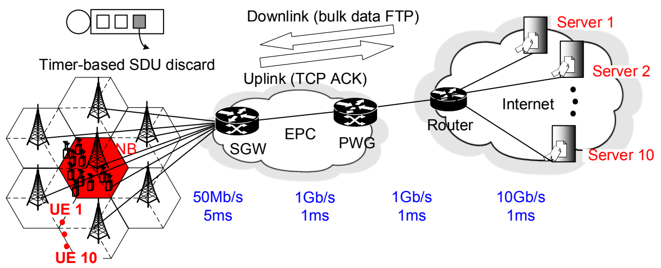


Fig. 2: Simulation model

others are kept according to $T = 3$. As a result, the latest TCP ACK ($n+2$) is transmitted based on the UL grant (i.e. TBS = 1) received from the eNB. The threshold T can be transformed to *ratio*. Specifically, *ratio* is defined by *ratio* = $1.0 - T/100$. When $T = 100$, it is observed in the simulation that only few TCP ACKs are discarded. Thus, it can be defined that $T = 100$ is equivalent to *ratio* = 0.0. When $T = 1$, it is called Highest ACK from the viewpoint that only the TCP ACK with highest sequence number is transmitted. Here, *ratio* becomes 0.99 but it is defined as 1.0 for simplicity.

Hybrid Discard: This scheme implements both Passive Discard and Active Discard at the same time. It controls the discard of TCP ACKs in such a two-step way that the discard occurs according to Active Discard when the TCP ACKs arrive at the UE buffer and then additional discard of the TCP ACKs occurs according to Granted ACK (i.e. *ratio* = 1.0) when the uplink transmission opportunity is given from the base station.

B. Simulation Model

The simulation model used in this paper is the same with that used in [8–9] in order to obtain consistent results. Fig. 2 shows the network topology. The right-hand side is the public Internet where the application servers are deployed. The left-hand side is the LTE-A Pro network. Three-sectored seven cells are deployed and a serving cell is placed in the center of the seven cells. Details e.g. parameters of the physical layer and the high layer are described in [8–9].

According to the previous works, it has been observed that Hybrid Discard with *ratio* = 0.96 (i.e. $T = 6$) shows the best performance among three proposed schemes. The reason is clarified in the next section and the suitable value of *ratio* (i.e. the suitable threshold T_{opt}) in Hybrid Discard is derived. The performance of the Hybrid Discard with the proposed suitable value is examined by carrying out the simulations.

III. Simulations

First, a hypothesis is provided so that a detailed relation between the threshold-based discard and the flow control mechanism of the TCP is clarified. Based on the hypothesis, a formula that determines the suitable value of the discard ratio is defined. Secondly, it is verified by computer simulation that Hybrid Discard with the suitable value derived by the formula can decrease the number of the TCP ACKs while further improving TCP throughput.

TABLE I. TBS ALLOCATED TO TCP DATA AND T

Sector	UE	DL MCS (average)	DL TBS [byte]	T_{opt} [num]
1	UE8	12	2481	2
	UE5	9	1960	1
2	UE1	21	5477	4
	UE3	23	6378	5
	UE7	24	6882	5
	UE9	19	4587	3
3	UE4	22	5861	4
	UE2	20	4904	4
	UE10	19	4587	3
	UE6	18	4107	3

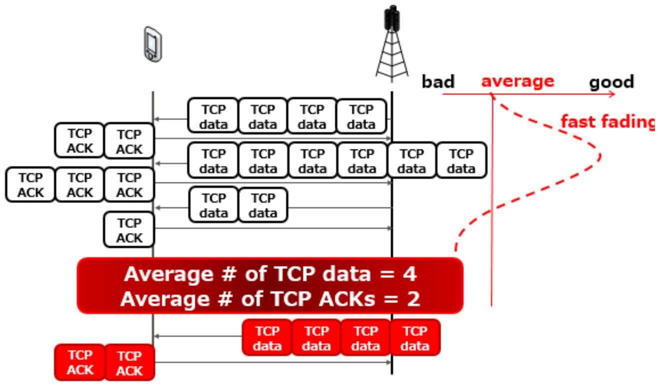


Fig. 4: Example scenario to understand *N_ack* in Equ. (1)

A. Discardng TCP ACKs in two-step manner

It can be deduced that there is a close relation between the threshold-based discard and the flow control mechanism of the TCP in Hybrid Discard and it leads to the best TCP throughput among three schemes. Here, a hypothesis is provided to find the detailed relation. The TCP data transmission is carried out by implicit estimation of available network resources. The TCP sender increases the transmission window when receiving TCP ACKs while reducing the transmission window when detecting data losses. In such a way, the data rate is dynamically adjusted to the currently available network resource and it is limited to that in a bottleneck link through which the TCP connection is set up. Eventually, the long-term TCP throughput converges in the average available network resource in the bottleneck link. When the TCP connection goes through mobile radio networks, radio links are typically the bottleneck links.

Given the TCP behavior above, the mechanism that Hybrid Discard with the *ratio* = 0.96 (i.e. T = 6) achieves the best performance can be cleared. The value of *ratio* = 0.96 implies that it has close relation to the average available radio resource in the serving cell, which can be evaluated by the average TBS in the downlink allocated to each UE. Tab. I shows average MCS level allocated to the downlink TCP data transmission, by which corresponding average downlink TBS is derived. The TBS can be considered as the average available radio resource of the radio link each UE is connected to. The value of the TBS derives the number of average TCP ACKs generated in the uplink denoted by N_{ack} as follow.

$$N_{ack} = \frac{S_{TBS}}{(S_{TCP\_segment} + S_{Header}) \times 2} \qquad (1)$$

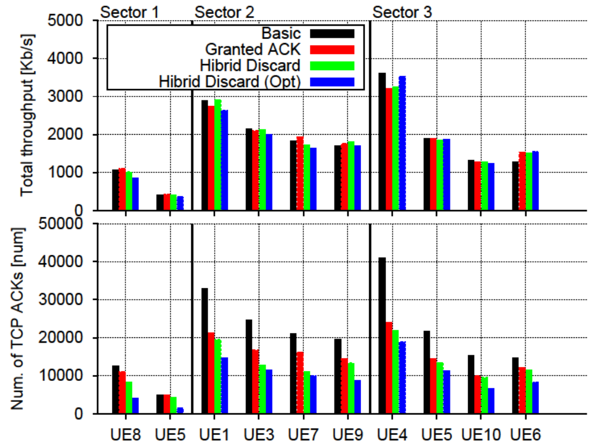


Fig. 5: The UE throughput and the number of transmitted TCP ACKs

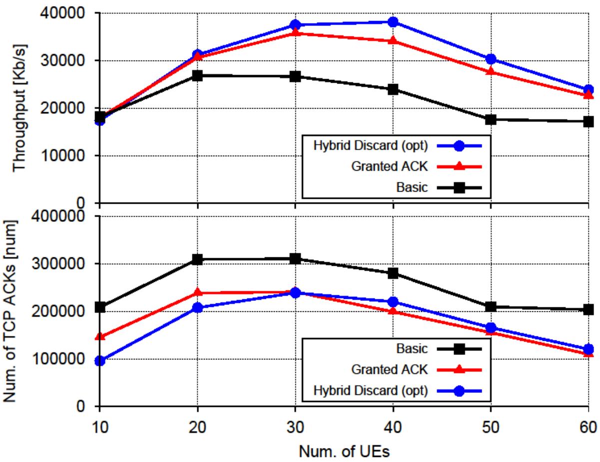
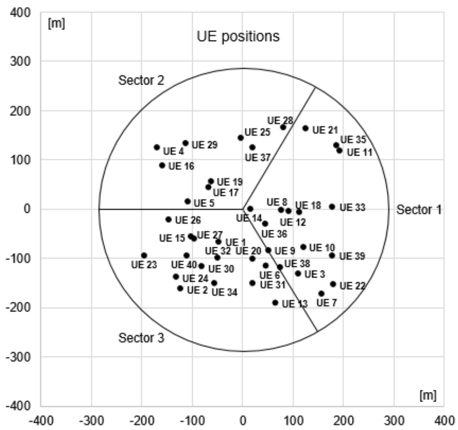


Fig. 6: The total throughput and the number of transmitted TCP ACKs

Specifically, N_{ack} can be obtained as the average downlink TBS (S_{TBS}) divided by the summation of the size of the TCP segment ($S_{TCP\_segment}$) and that of the TCP/IP and the MAC/RLC/PDCP headers (S_{Header}) times two. The formula is derived taking the delayed TCP ACK into consideration i.e. one TCP ACK is generated by every two TCP segments.

Fig. 4 shows an example scenario to explain the meaning of N_{ack} to give a better understanding of the hypothesis. The eNB is transmitting the TCP data in the downlink where the amount of the TCP data is depending on the radio channel quality due to fast fading. If the channel quality is good, large amount of TCP data is transmitted (e.g. six TCP data), and accordingly TCP ACKs are generated (e.g. three TCP ACKs). On the other hand, if the channel quality goes bad, small amount of TCP data is transmitted (e.g. two TCP data) and the number of TCP ACKs is small (e.g. one TCP ACKs). The average available radio resource becomes four TCP segments in the downlink, which determines the number of average TCP ACKs generated in the uplink of two. With Equ. (1), the suitable value of the threshold T_{opt} in Hybrid Discard can be derived as follow.

$$T_{opt} = max\{N_{ack}, 1\} \qquad (2)$$



Sector	UE	T_{opt} [num]	Fairness Index		
			Basic	Granted ACK	Hybrid ACK (opt)
1	UE14	6	0.27	0.47	0.55
	UE21	4			
2	UE19	6	0.37	0.68	0.74
	UE28	1			
3	UE1	6	0.30	0.67	0.70
	UE13	4			

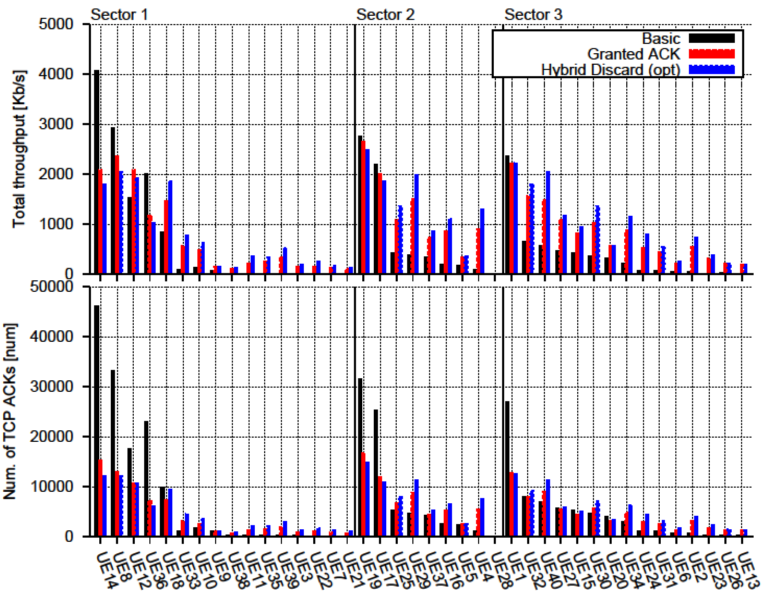


Fig. 7: The UE throughput and the number of transmitted TCP ACKs

This ensures that at least one TCP ACK must be stored in the uplink buffer. The suitable thresholds derived by Equ. (2) are shown as T_{opt} in Tab. I. This can be translated to the discard ratio i.e. *ratio* = $1.0 - T_{opt}/100$ as explained in Section II.

B. Simulation Results

The TCP performance when adopting Equ. (2) is examined. S_{Header} becomes 58 bytes in Equ. (1), where the header size of the TCP/IP is 52 bytes and that of the MAC/RLC/PDCP is 6 bytes. N_{ACK} is set to $[N_{ACK}]$, which derives T_{opt} in Equ. (2). Fig. 5 depicts the TCP throughput of ten UEs randomly placed in the serving cell. Basic means the legacy scheme where no TCP ACK discard is applied. Granted ACK is Passive Discard with *ratio* = 1.0. Hybrid Discard is the scheme in the previous work with *ratio* = 0.94. Hybrid Discard (opt) is the proposed scheme with T_{opt} (i.e. *ratio* = $1.0 - T_{opt}/100$). From this figure, the TCP throughput is almost the same among all schemes. There is the small variation observed in this figure but it is in a permissible range for the TCP throughput evaluation. It can be found that Hybrid Discard (opt) further reduces the number of TCP ACKs compared to Hybrid Discard, where the maximum reduction is 65.2% for UE5 and 23.9% on average. Compared to Basic, the maximum reduction is 70.5% for UE5 and 54.2% on average.

Next, the validity of the formulas is further examined. One of important factors to decide N_{ack} is S_{TBS} as in Equ. (1). It is thus essential to carry out simulations where various values of S_{TBS} appear during the simulations. For the purpose, the number of UEs in the serving cell is increased in the simulations. The locations of each UE are randomly distributed in the serving cell, so that various values of S_{TBS} can be appeared.

Fig. 6 depicts the total TCP throughput in the downlink and the total number of the TCP ACKs sent in the uplink when the number of the UEs varies from ten up to sixty. From this figure, it can be seen that the TCP throughput in Hybrid Discard (opt) outperforms both Basic and Granted ACK when the number of UEs is between twenty and sixty. The maximum improvement is 59.1% compared to Basic and 11.9% compared to Granted ACK when the number of UEs is forty, respectively. When it is over forty, the TCP throughput is saturated and/or decreased as the number of UEs increases in all schemes. The reason is that the RAN gets heavily congested, which causes the TCP servers to suppress the increase of the transmission window. Turning now to the number of the TCP ACKs in Hybrid Discard (opt), it is decreased compared to Basic. When the number of UEs is forty where the maximum throughput is obtained, the reduction becomes 21.4%. Yet compared to Granted ACK, it is slightly increased when the number of UE is over thirty. The increase is supposed to be due to the improvement of the TCP throughput in Hybrid Discard (opt).

With these results, it can be said that Hybrid Discard (opt) reduces the number of the TCP ACKs while keeping high TCP throughput when the number of UEs is small. In addition, when the number of UEs becomes large to some extent where the RAN is not heavily congested, the TCP throughput is largely improved. Furthermore, it can be said that Hybrid Discard (opt) increases capacity of RAN from the viewpoint of the number of UEs served in the serving cell. For example, if a target TCP throughput of the serving cell is set to be 25 Mb/s, roughly, thirty UEs can be accommodated in Basic while sixty UEs can be accommodated in Hybrid Discard (opt).

Finally, Fig. 7 depicts the TCP throughput and the number of the TCP ACKs of each UE when the number of UEs is forty in Hybrid Discard (opt). The UE positions are shown in the top left figure and the suitable thresholds are shown as T_{opt} in the bottom left table (showing values of typical UEs due to space limitations). The most interesting simulation result here is that Hybrid Discard (opt) improves fairness of the TCP throughput of each UE compared to both Basic and Granted ACK. More specifically, there is a reduction for UEs that show high TCP throughput but there is an increase for UEs that show poor TCP throughput. The fairness can be measured by Fairness Index [13] and the high values in Hybrid Discard (opt) [13] is the evidence for the fairness improvement. The reason for that can be deduced from the simulation result of the number of TCP ACKs. Compared to Basic, there is a great reduction for UEs that send large amount of the TCP ACKs while there is an increase for UEs that can only send small amount of TCP ACKs. With these results, it can be said that radio resources are allocated for "greedy" UEs in Basic while being allocated for "plain" UEs in Hybrid Discard (opt).

With these observations, it is concluded that the proposed suitable setting of the discard ratio by the two-step TCP ACK filtering accomplishes the best TCP performance among all our proposals in terms of the TCP throughput and the reduction of the number of TCP ACKs. The novel feature of the suitable setting is that the discard of the TCP ACKs in the uplink is performed based on the long-term radio channel quality in the downlink. The reduction of the TCP ACKs improves efficiency of radio resource usage. In addition, it reduces traffic overhead of the EPC. For example, according to the number of the TCP ACKs observed in Fig. 7, the data rate of the TCP ACKs in the SGW is 397.2 Mb/s in Hybrid Discard (opt) while it is 866.4 Mb/s in Basic when one thousand eNBs each of which serves ten UEs conducting FTP are connected to the SGW. The large reduction of 469.2 Mb/s is never negligible in the EPC since the traffic load in the recent cellular networks is increasing due to the increase of the data rate and the number of UEs. Note again that it must be stressed that the simulation results in this paper are supposed to hold with simulation model based on the 5G standards since essential features of radio link protocols in the 5G standards [10–12] align with LTE-A Pro.

C. Practical future work

There are some interesting topics worth exploring in future. First, it is valuable to examine if the proposed hypothesis holds with millimeter wave (mmWave) which is new frequency band in 5G. There may be difficulty in estimating available resource of the radio link for TCP senders since the mmWave signal is sensitive to blockages. Secondly, there are some variants of the delayed TCP ACK implemented in commercial mobile stations depending on operating systems. The TCP ACK filtering for such variants of the delayed TCP ACK deserves further study.

IV. CONCLUSIONS

This paper tackles a remaining issue found in our previous work [9]. In the previous work, the amount of the TCP ACKs to be discarded is controlled by a cell-specific discard ratio and a proper value is found by simulations. The TCP ACKs are discarded by Hybrid Discard i.e. the discard occurs when the TCP ACKs arrive at the uplink buffer in the UE and then when the uplink transmission opportunity is granted from the eNB. In this paper, the discard ratio is proposed to be station-specific parameter and a formula is given to define the suitable value.

First, a hypothesis is provided to discover the suitable value of the discard ratio. The flow control of TCP is based on long-term network resource availability so that the TCP throughput is obtained based on average available network resource of a bottleneck link. In mobile communications, the bottleneck link is still considered to reside in radio link. The available network resource is thus equivalent to the amount of average TCP data transmitted from the eNB to the UE. Accordingly, the amount of the TCP ACKs is limited to a value derived by the amount of the average TCP data that the UE can receive. Based on the hypothesis, the formula to define the suitable value is proposed as such. Secondly, it is observed by simulations that Hybrid Discard with the suitable value can largely reduce the number of the TCP ACKs while maintaining the TCP throughput when the number of UEs is small. In addition, when the number of UEs is large, it can greatly improve the TCP throughput. It is also found that it can improve fairness of the TCP throughput.

It is concluded throughput our continuous work that the novelty of the two-step discard in Hybrid Discard is the way of the TCP ACK discard: instantaneous discard of TCP ACKs based on fast fading and persistent discard of TCP ACKs based on long-term radio channel quality. Hybrid Discard with the suitable discard ratio accomplishes the best TCP performance among all our proposals without modifying the existing TCP stacks already deployed in TCP end hosts. It provides the best current practice, which is useful guidance for deploying the TCP ACK filtering in the 5G mobile communications.

In future, it is worth exploring applicability of the proposed formula to RAN using mmWave. TCP ACK filtering for other variants of the delayed TCP ACK also deserves further study.

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