Novel Approach for Prioritization of TCP Acknowledgements in Beyond 4G and 5G network

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***Abstract*— Evolution in cellular wireless communication and standardization has brought out technological advancements in physical and medium access (MAC) layer protocol to scale the data rate on the air interface like in Long Term Evolution (LTE) or New Radio (NR) 3GPP standards, by 10X to 100X compared to older technologies. At the same time there is not much thrust given on the interworking with TCP/IP, resulting in poor user experience, as a similar scale of improvement is not seen at application level, once the technologies are deployed in field. The problem related to delayed TCP acknowledgement (ACKs) acts as bottleneck at application level, which in turn results in low uplink (UL) or downlink (DL) Throughput (TP) at the User Equipment (UE). Solutions available in the literature to address the same increase either the processing complexity or wastage of resources, or both. In this paper, two novel solutions are presented to address prioritization of TCP ACKs by Sequence Number (SN) reservation and SN space management in simultaneous UL/DL traffic scenarios while maintaining low complexity. Through mathematical modelling and simulation in a standard setup for LTE network, we are able to achieve the effective decrease in downloading time by 5 ~ 25% in comparison to standard schemes. The solution is easy adoptable in NR based 5G network**

Keywords*— *NR, 5G, LTE, Cross Layer, TCP/IP, MAC, ACK, Deep Packet Inspection

I. INTRODUCTION

With advancement in wireless communication, we have seen various cellular standards starting from 1G to 5G focusing on Throughput (TP) improvement, latency reduction, enhanced coverage and increased system capacity. With this trend though the lower layers like physical layer and Medium Access Control (MAC) are getting equipped with procedures and protocols to improve air-interface and link level TP, at same time transport layer creates a bottleneck specially with Transmission Control Protocol (TCP)/Internet Protocol (IP) which results in lower TP at application level thereby affecting user experience. TCP/IP protocol works by providing an Acknowledgement (ACK) to the transmitting entity after receiving a number of Protocol Data Units (PDUs) at the receiving entity [1].

In a 3rd Generation Partnership Project (3GPP) based cellular network, e.g. Long Term Evolution (LTE), TCP/IP Packet is mapped to corresponding Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC) PDU [2][3]. Both PDCP and RLC allocates sequence numbers to these packets in their order of arrival. Each layer in 3GPP LTE or New Radio (NR), i.e. MAC, RLC and PDCP has its own control packet, which has more priority than the data packets; and are prioritized while handling UL grant. However, Link layer treats TCP ACK packet as a normal data packet and is not given any preferential treatment in the current literature [2][3]. Figure 1, from [9], captures the flow of packets across the various layers in the LTE Protocol Stack.

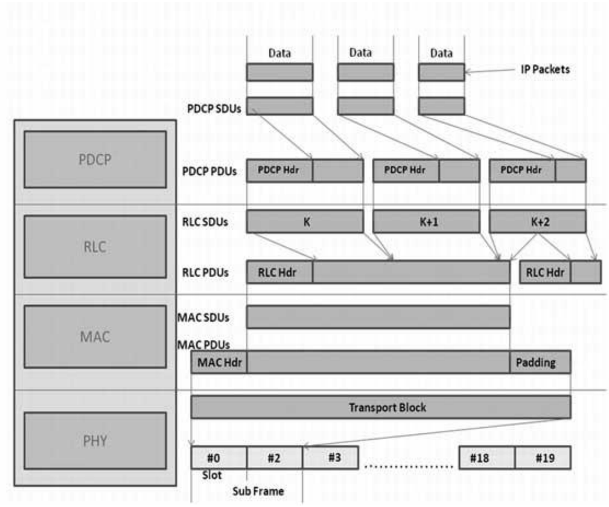

Fig 1. Data Flow through LTE Protocol Stack from [9]

When eNodeB (eNB) scheduler allocates Uplink (UL) grant, i.e. frequency-time resource, the User Equipment (UE) prepares a MAC Transport Block (TB) using RLC PDUs. In case of bi-directional traffic scenario with high UL traffic, the Sequence Number (SN) allocated to the TCP ACK for the corresponding Downlink (DL) packet will be after large gaps, i.e. farther in SN space. This TCP ACK will be sent only after all the earlier UL data packets (with allocated SNs) are sent; this delay in sending the TCP ACK will lower the DL TP, as DL packets will be sent slowly from the server side.

In [4] and [5] Deep Packet Inspection (DPI) is performed to prioritize selective packets at link level. The solution proposed in [4] discusses reserving SNs for future TCP ACK packets from application to UL packet queue, at the cost of increased computation during MAC TB preparation, wherein while handling the grant it either ciphers all the PDCP SDUs, or re-ciphers some of the PDCP SDUs. Along with increased computational cost [4] lacks the idea of advance packet creation. Here, by advance packet creation, we mean that on reception of TCP/IP packet at PDCP and RLC layer in NR/LTE, corresponding PDCP/RLC PDU be formed at earliest by allocating SN and ciphering. In [5], TCP ACK prioritization is achieved by introducing a new radio bearer to serve the purpose. In NR [6], approach of creating the PDCP and RLC packets in advance (irrespective of UL grant availability) due to high computational and low latency is discussed. Based on literature survey we have observed that the problem of delayed TCP ACK, especially in case of advanced packet creation, can cause possible transmission bottleneck at TCP level due to slower TCP window update. Based on upcoming trends of social media and content generation by end user data [8], we have observed a tremendous rise in uplink traffic. The ratio of UL traffic to Downlink (DL) traffic is finally going beyond "1" whereas earlier it was mostly below "1". Therefore, the problem of delayed TCP ACK sending will be even more prevalent in coming days and more particularly in enhanced Mobile Broadband (eMBB) in NR.

To solve the aforementioned problem of delayed TCP ACK, the paper presents below two novel solutions, which to the best of our knowledge are first of its kind, namely

1. SN reservation by
    a. creating 'hole-SN' to be utilized by TCP ACKs
    b. SN reservation for TCP ACKs with advance packet creation scheme
2. SN space division for handling data packet and ACKs separately

We captured the gains of our proposal in a standard setup for LTE network, and verified the gains against a mathematical model. We are able to achieve the effective decrease in downloading time by 5 ~ 25% in comparison to LTE based standard schemes with no TCP ACK prioritization at link level.

The rest of the paper is organized as follows, Section II discusses the TCP ACK Prioritization Proposal and Section III shows the simulation model and test bed details. Section IV discusses the results and Section V describes the conclusion.

II. TCP ACK PRIORITIZATION

At Link Layer, LTE simultaneously supports at max eight Quality of Service (QoS) Class Identifier (QCI) services. Also in LTE, traffic of similar nature is mapped on logical channel with same CQI. Thus, in bidirectional traffic, which is mapped on same logical channel, the TCP packets (non-ACK) pertaining to UL traffic will mostly utilize UL SN space; and the TCP ACKs, acknowledging the DL packets, will generally be sitting last in the UL packet queue, as shown in Fig 2.

Therefore, the advance packet creation creates bottleneck for downlink traffic as TCP ACK will be scheduled later. And, TCP Server pushes data based on arrival of TCP ACK of transmitted packets.

Below we present three variants of our two novel solutions, where we will achieve TCP ACK prioritization in conjunction with 'advance packet creation' requirement

A. Proposed Scheme -1a: Reserve SN

In this proposal, one or more SN numbers are reserved in the PDCP SN or RLC SN space at regular (fixed) or adapted (dynamic) intervals of UL SN space. These are called 'hole-SNs'. Thus, when a TCP ACK arrives, these hole-SNs are assigned to them for creating the corresponding PDCP or RLC PDU. This makes sure that the earlier SN(s) in UL SN space is assigned to TCP ACK(s) and hence will be transmitted earlier on UL grant reception. The rate at which the "number of hole-SNs reserved for TCP ACK packets" and "the interval in the UL SN space when the first hole-SN starts" is either static or dynamically adaptive. The dynamically adaptive rate is decided based on a function of UL TP and TCP ACK rate being perceived at link layer; whereas static rate implies fixed interval size in UL SN space and fixed number of hole-SNs. TCP ACK rate is proportional to the DL TP. Since the proposed solution allocates relatively earlier SNs to the TCP ACK packets, it reduces the delay in TCP ACK sending for majority of the TCP ACK packets. The whole purpose is to achieve immediate TCP ACK sending as if UE is handling unidirectional traffic. In case, the hole-SNs are unused, the rate at which hole-SNs are being generated will be reduced. In case hole-SNs being unused, LTE/NR network can face PDCP reordering delay in Dual Connectivity (DC) scenario. Therefore, this scheme addresses the possible reordering delay problem by using one of the procedures – "the previous or next PDCP SDU will be mapped to the hole-SN and transmitted; the duplicated SDU will be automatically dropped at the receiver"; or "PDCP data headers are mapped to the hole-SNs and transmitted". Figure 1 depicts hole-SNs and regular SNs in UL SN space.

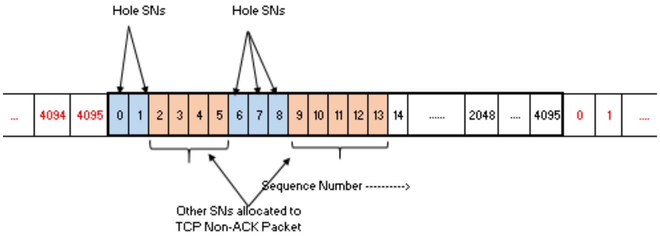

Fig. 1: 'Hole-SNs' inside UL SN space.

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B. Proposed Scheme-1b: Allocate SN to UL Packets in advance

The scheme does not allocate SN to UL packets, i.e. TCP non-ACK packets related to UL traffic or TCP ACK packets acknowledging the DL traffic, as they arrive in the UL packet queue from the application. The scheme computes a number of UL packets $'N_{UL_1}'$, which can be transmitted in a time period, $'T'$, and allocates SNs in the PDCP and or RLC SN space only to these UL packets even if there are more UL packets in the queue. $'N_{UL_1}'$, and $'T'$, are computed based on one or more factors or the combination thereof like UE's computation capability, UL grant rate, signal conditions, network load, Carrier aggregation (CA) behavior and other similar factors. In other words, the proposal limits the advance packet creation to meet the UE transmission needs of time *'T'.*

The scheme further initiates advance packet creation for subsequent number of UL packets $'N_{UL_2}'$, once a portion of the $'N_{UL_1}'$ UL packets has been successfully transmitted. In other words, the scheme triggers advance packet creation at time 'T', 'T + Delta', 'T + 2 x Delta' … 'T + N x Delta'; where Delta is a non-zero, fixed or dynamic value. From time 'T' to 'T + Delta', UL packet queue can receive mix of TCP ACK packets or TCP non-ACK packets, but due to packet creation only to start at 'T + Delta', multiple TCP ACK packets accumulated in packet queue by time 'T +

Delta' will be allocated SNs first followed by TCP non-ACK packets in their order of arrival.

Therefore, the method performs well in prioritizing TCP ACKs since it waits for 'additional time' at link level for possible arrival of future TCP ACK packets from application to UL packet queue. This time is actually the time spent in sending the portion of UL packets with allocated SNs.

Figure 2 depicts the scheme well.

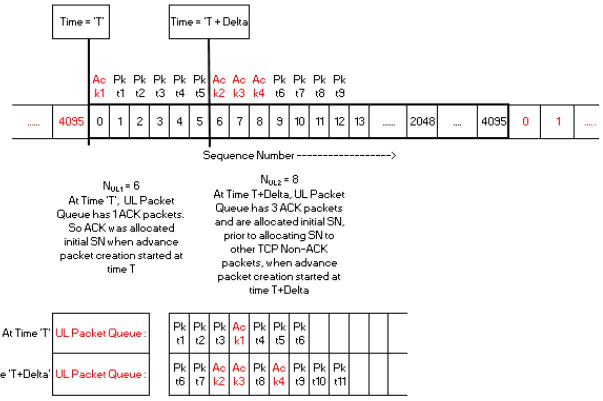


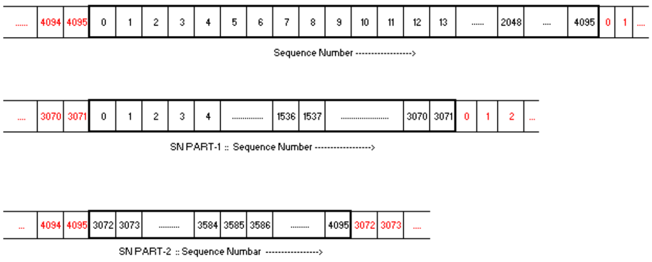
Fig. 2: Reserve SN with advance packet creation

C. Proposed Scheme-2: Divide SN Space

Both the scheme 1 and 1A are standalone UE implementation. The scheme-2 betters earlier proposed schemes and requires minimal 3GPP standard change. The method divides the PDCP/RLC SN space into two parts, where allocation of SNs from the first part is done for only TCP Non-ACK packets and from the second part for only TCP ACK packets. The respective part of SN space follows in sequence delivery procedure. While forming the UL MAC TB, UE first prioritizes packet from the SN space belonging to TCP ACK and then from the other part. Thus TCP ACK packet gets transmitted earlier.

This scheme dedicates a segment of SN space itself specifically for TCP ACKs, therefore, it performs comparatively better than both Scheme-1 and 1A. In this scheme allocation for SN to TCP ACK packet is not limited by its arrival time in UL packet queue; it gets immediate SN allocation and prioritization during transmission.

Fig 3. Depicts the UL SN Space division at PDCP/RLC layer, where SN size is 4096 and is divided into 2 parts, part 1 for UL TCP Non-ACK packets of size 3072 and part 2 for TCP ACK packets of size 1024.



NOTE 1 - SN PART -1 is wrapping to initial sequence number 0 after reaching MAX_SN 3071. UL SN SPACE PART-1 SIZE = 3072

NOTE 2 - SN PART -2 is wrapping to initial sequence number 3072. UL SN SPACE PART-2 SIZE = 1024

Fig. 3: Division of SN Space

III. SIMULATION AND RESULTS

We have modeled all proposed schemes mathematically and simulated on a standard setup for several scenarios of simultaneous UL and DL as captured in Table 1. Scheme-1 was modeled in accordance with the reserving hole-SNs in static way at every Nth packet; where N was fixed to different value ranging from 3 to 10 depending on the ratio of UL to DL TP.

Scheme-1A is modeled by limiting the advance UL PDU formation by next K TTI; where K was fixed to 4ms.

Both Network and UE side PDCP behavior was modeled in accordance with the proposed Scheme-2; where PDCP SN is broken into 2 parts: PDCP SN Part 1 size limited to 3072 and SN Part 2 as 1024. ACK Packet was scheduled prior of data packet while scheduling UL resources.

We simulated a faster TCP ACK as perceived by the server and its effect on TCP window update, which affected the total download time for a test file based on our novel solution. The data traffic for both UL and DL was mapped on the same LTE radio bearer, and having same Quality of Service (QoS) Class Identifier (QCI) [7].

Table 1: DL/UL TP (Mbps) scenarios - respective gains (reduction in download time)

Scenario	DL (Mbps)	UL (Mbps)	Scheme-1	Scheme-1A	Scheme-2
scenario 1	15	45	23%	25%	26%
scenario 2	15	30	17%	20%	20%
scenario 3	30	30	12%	16%	18%
scenario 4	30	15	5%	8%	10%

Two key takeaways are (a) higher the UL/DL traffic ratio, higher is the gain and (b) Scheme-1A improves the performance as compared to Scheme-1, as it prioritizes TCP ACK better. Gain in terms of reduction in downloading time is observed in the range of 5 ~ 25% for different scenarios.

IV. CONCLUSION

This paper discusses two novel solutions to prioritize TCP ACK which addresses low TP in simultaneous UL/DL traffic scenarios. Through mathematical modelling and simulation on standard LTE setup, it shows effective decrease in downloading time by 5 ~ 25% for two variants of the first scheme. Therefore, it enriches user experience. The computation cycle consumed to figure out the TCP packet type is very minimal and hence not causing any overhead in the UE; suitable for low-end UEs. Both the solutions can be extended to prioritize other TCP select packets too like Domain Name Server (DNS) query, SYN or SYN ACK packet etc. to achieve faster TCP SYNC and DNS response from network. In full paper, Scheme-2 results as well as the procedure and protocol between UE and eNB to apply Scheme-2 to achieve maximum gains from our proposal will be discussed.

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