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TCP Performance Degradation of In-Sequence Delivery in LTE Link Layer

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Abstract

LTE networks have been rapidly commercialized for 4G cellular communications systems in all over the world as well as Korea. Because many internet applications use TCP as their transport layer protocol, TCP throughput measurements and its performance improvements in LTE networks is very important. In this paper, we analyze the impact of "in-sequence delivery" in LTE link layer on TCP RTT increment. When HARQ or ARQ in LTE link layer is working frequently for error recovery, it increases TCP RTT and decreases TCP throughput seriously. Therefore, in order to get better TCP throughput with the same packet error probability, we should decrease TCP RTT when HARQ or ARQ in LTE link layer is working for error recovery. We propose "out-of-sequence delivery" in LTE link layer in order to decrease TCP RTT. From our test results, "out-of-sequence delivery" outperforms "in-sequence delivery". While "out-of-sequence delivery" makes LTE link layer design simpler, but its throughput gain is considerable.

Keywords: *LTE, 4G, ARQ, HARQ, TCP, In-Sequence Delivery*

1. Introduction

The surge of smartphone and tablet and emergence of new applications such as multimedia gaming, mobile TV, Web 2.0, high-definition streaming incurred recent rapid increase of mobile data usage. Consequently, this is driving the need for continued innovations in wireless data technologies to provide more capacity and higher quality of service. It has motivated the 3GPP (3rd Generation Partnership Project) to work on the LTE (Long Term Evolution). LTE is the most promising 4G (the 4th Generation) candidate technology and the latest standard in the mobile network technology tree that previously realized the 2G (the 2nd Generation) and 3G (the 3rd Generation) network. 3GPP technologies have evolved from 2G GSM (Global System for Mobile Communications) / EDGE (Enhanced Data Rates for GSM Evolution) to 3G UMTS (Universal Mobile Telecommunications System) / HSPA (High Speed Packet Access) to provide increased capacity and user experience, and the evolution continues in the coming years with further enhancements to HSPA+ and the introduction of LTE.

LTE has been commercialized since 2009 and is the hottest key issue of mobile communication industries currently in 2011. Based on report [1] from GSA (Global mobile Suppliers Association), 185 firm commercial LTE network deployments, 64% higher than a year ago, are in progress or planned in 66 countries, including 35 networks in 21 countries including Korea, now commercially launched. Another 63 operators in 21 additional countries are engaged in LTE technology trials, tests or studies. Also GSA now expects over 100 network launches by end of 2012.

3GPP specified LTE radio interface to meet the increasing performance requirements of mobile broadband. LTE provides a peak data rate of up to 300Mbps in the downlink and 75Mbps in the uplink with 20MHz bandwidth. Currently, the 3GPP is specifying the LTE-Advanced radio interface to meet the IMT-Advanced requirements. LTE-Advanced provides a peak data rate of up to 1Gbps in the downlink with peak spectral efficiency 30bps/Hz and 500Mbps in the uplink with peak spectral efficiency 15bps/Hz using up to 100MHz bandwidth [2]. In January 2011, ETRI demonstrated successfully the world's first LTE-Advanced system. The system provides a peak data rate of up to 600Mbps and a peak effective data rate, i.e., application layer throughput, of up to 440Mbps in the downlink and 220Mbps in the uplink with 40MHz bandwidth [3].

While LTE was already commercialized, there is almost nothing study on application layer performance measurement and analysis in LTE networks in either standard or literature. In December 2010, the 3GPP approved the new Release 11 study item, "UE Application Layer Data Throughput Performance." The GCF (Global Certification Forum) indicated that they want 3GPP to perform UE application-layer data throughput measurements under various simulated network conditions. The test will measure the achieved average application-layer data rates using TCP (Transmission Control Protocol) or UDP (User Datagram Protocol) in HSPA and LTE networks [4].

In this paper, we analyze the impact of "in-sequence delivery" in LTE link layer on TCP RTT (Round Trip Time) increment. When HARQ (Hybrid Automatic Repeat reQuest) or ARQ (Automatic Repeat reQuest) in LTE link layer is working frequently for error recovery, "in-sequence delivery" in LTE link layer increases TCP RTT and decreases TCP throughput seriously. Therefore, in order to get better TCP throughput with the same packet error probability, we should decrease TCP RTT when HARQ or ARQ in LTE link layer is working for error recovery. The more often HARQ or ARQ is working, the larger "In-sequence delivery" in LTE link layer increase TCP RTT and the smaller TCP throughput can be get, because TCP throughput is inversely proportional to the TCP RTT. Based on analysis, when HARQ BLER (Block Error Rate) is 10% and HARQ failure rate is 0.1% as LTE protocol design, if DL (Downlink) HARQ RTT is 8ms and TCP RTT is 10ms, TCP throughput is seriously decreased up to only 36% of maximum bandwidth. And if DL HARQ RTT is 16ms and TCP RTT is 10ms, TCP throughput is decreased up to only 19% of maximum bandwidth.

To alleviate this problem, we propose "out-of-sequence delivery" in LTE link layer in order to decrease TCP RTT while HARQ or ARQ in LTE link layer is working for error recovery. The "out-of-sequence delivery" can decrease TCP RTT up to end-to-end RTT. While "out-of-sequence delivery" makes LTE link layer design simpler, but its throughput gain is considerable to the extent of 30% in average and 58% in maximum from our test results.

Section 2 briefly introduces the LTE radio interface protocol focusing on the user plane protocol. Section 3 analyzes the impact of in-sequence delivery in LTE link layer on TCP RTT increment. Section 4 proposes "out-of-sequence delivery" in LTE link layer in order to decrease TCP RTT while HARQ or ARQ in LTE link layer is working for error recovery and shows its considerable throughput gain from test results. Some concluding remarks, including future works, are given in section 5.

2. LTE User Plane Protocol

LTE radio interface protocol [5, 6] is applied between UE (User Equipment) and eNB (E-UTRAN NodeB). LTE protocol consists of user-plane protocol and control-plane protocol. LTE user-plane provides the function of transferring user traffic data. LTE user-plane protocol is comprised of PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), MAC (Medium Access Control) and PHY (Physical Layer). LTE control-plane provides the function of transferring control messages. LTE control-plane protocol is comprised of NAS (Non-Access Stratum) layer, which is on UE and MME (Mobility Management Entity), RRC (Radio Resource Control), PDCP, RLC, MAC, PHY.

In the LTE user plane, the PHY layer provides a bit pipe with AMC (Adaptive Modulation and Coding) by protected turbo-coding and a CRC (Cyclic Redundancy Check), and processes CRC ACK/NACK feedback. The MAC sub-layer provides multiplexing/de-multiplexing, error correction through HARQ, and scheduling. The RLC sub-layer provides the segmentation/concatenation/reassembly of RLC SDUs, reordering of RLC PDUs, in-sequence delivery, and error correction through ARQ. The PDCP sub-layer provides header compression, ciphering/integrity protection, and in-sequence delivery and retransmission of PDCP SDUs at handover. Figure 1 shows the LTE user plane protocol stack.

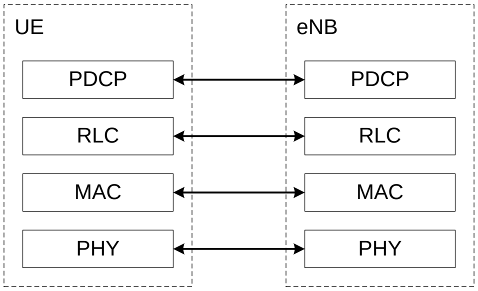

Figure 1. LTE User Plane Protocol Stack

If the receiver detects a transmission error, the receiver sends CRC NACK feedback to the sender. When the MAC sub-layer HARQ function of the sender receives CRC NACK feedback from the receiver, it performs retransmissions of the corrupted TB (transport block), and thereby corrects the majority of all transmission errors. The HARQ protocol uses eight stop-and-wait HARQ processes, and HARQ RTT in the uplink is 8ms and that in the downlink is minimum 8ms [7].

LTE supports two types of bearer, an UM (Unacknowledged Mode) bearer and an AM (Acknowledged Mode) bearer. The UM bearer makes use of a fail recovery by the HARQ at the MAC sub-layer only, and thus can be used for radio bearers that can tolerate a certain amount of loss. The AM bearer provides more reliability than the UM bearer by the help of ARQ retransmission at the RLC sub-layer.

If the RLC sub-layer receiver detects a gap in the sequence of the received PDUs, it starts a reordering timer assuming that the missing PDU still is being retransmitted in the HARQ protocol. HARQ failures appear if a maximum number of HARQ transmission attempts are exceeded or HARQ feedback NACK-to-ACK errors occur. When the timer expires, usually in a HARQ failure case, an RLC UM receiver delivers SDUs to PDCP with a certain amount of loss. However, an RLC AM receiver sends a status message comprising the sequence number of the missing PDUs to the sender. The ARQ function of the RLC AM sender performs retransmissions based on the received status message. The RLC ARQ protocol is a window-based selective repeat ARQ [8].

3. Analysis of the Impact of "In-Sequence Delivery" on TCP RTT

In this chapter, we analyze the impact of "in-sequence delivery" in LTE link layer on TCP RTT increment. The LTE link layer only provides "in-sequence delivery" of SDUs to the upper layer. When HARQ (Hybrid Automatic Repeat reQuest) or ARQ (Automatic Repeat reQuest) in LTE link layer is working frequently for error recovery, "in-sequence delivery" in LTE link layer increases TCP RTT and decreases TCP throughput seriously. If an RLC receiver detects a gap in the SN (sequence number) of received PDUs, it starts a reordering timer (t_Reordering) assuming that the missing PDU is still being retransmitted in the HARQ protocol. After the gap is filled by HARQ retransmissions, an RLC receiver stops t_Reordering timer and delivers reassembled SDUs from received PDUs to PDCP. Therefore, the TCP RTT of packets which are contained PDUs from the gap SN to SN which received in-sequence, are proportional to the MAC HARQ RTT. If t_Reordering timer expires, usually in a HARQ failure case, an RLC UM receiver delivers SDUs to PDCP with a certain amount of loss. Therefore, the TCP RTT of packets which are contained PDUs from the gap SN to SN which received in-sequence, are proportional to the t_Reordering timer which is generally set as maximum HARQ transmission number times of MAC HARQ RTT. And an RLC AM receiver sends a status message comprising the sequence number of the missing PDUs to the sender. The ARQ function of the RLC AM sender performs retransmissions based on the received status message. Therefore, the TCP RTT of packets which are contained PDUs from the gap SN to SN which received in-sequence, are proportional to the RLC ARQ RTT.

If TCP RTT is RTT_{e2e} and "in-sequence delivery" in LTE link layer increases TCP RTT with amount of RTT_{inc}, the TCP throughput utilization is expressed as below equation.

$$\rho = \frac{RTT_{e2e}}{RTT_{e2e} + RTT_{inc}} \quad \text{, where}$$

$$RTT_{inc} = \sum_{j=0}^{m} \sum_{i=1}^{n} p_{i,j} \sum_{k=0}^{N} d_k \quad \text{, where}$$

ρ: TCP throughput utilization, RTT_{e2e}: TCP end-to-end RTT,

$P_{i,j}$: probability of successful transmission with i HARQ transmissions and j ARQ retransmissions,

N: number of delayed PDUs due to "in-sequence delivery" reordering,

d_k: delivery delay

From an LTE design [6], the HARQ BLER is on the order of 10^{-1}, the HARQ feedback NACK-to-ACK error probability is on the order of 10^{-4} and the RLC PDU loss probability after the HARQ is on the order of 10^{-3}. And we assumed that residual BLER is on the order of 10^{-2}, $5*10^{-3}$, $2*10^{-3}$, and 10^{-3}, after two, three, four and five HARQ transmissions each. If TB is successfully received with only one HARQ transmission, i.e., i = 1, j = 0, d_k is 0. If TB is successfully received after two HARQ transmissions, i.e., i = 2, j = 0, $P_{i,j}$ is 10^{-1}, maximum of

N is 8 and d_k is HARQ RTT in maximum and 0 in minimum. Therefore, if HARQ RTT is 8ms, RTT_{inc} is calculated [$P_{2,0}$ * 8 * 9 / 2 = 3.6]. If TB is successfully received after three HARQ transmissions, i.e., i = 3, j = 0, $P_{i,j}$ is assumed as 10^{-2}, maximum of N is 16 and d_k is HARQ RTT*2 in maximum and 0 in minimum. Therefore, if HARQ RTT is 8ms, RTT_{inc} is calculated [$P_{3,0}$ * 16 * 17 / 2 = 1.36]. In this way, Table 1 shows the calculated RTT increment with ARQ and HARQ operations. These values are only including one-way delay and if UL and DL is considered, total RTT increment is more than two times of one-way delay.

Table 1. TCP RTT Increment with ARQ and HARQ Operations

NACK2ACK	# of ARQ	# of HARQ	P*100	N	dmax	RTTinc
	0	1				0
	0	2	10	8	8	3.6
	0	3	1	16	16	1.36
	0	4	0.5	24	24	1.5
	0	5	0.2	32	32	1.056
NACK2ACK	1	1	0.01	48	48	0.1176
	1	1	0.1	48	48	1.176
	1	2	0.01	56	56	0.1596
	1	3	0.001	64	64	0.0208
	1	4	0.0005	72	72	0.01314
	1	5	0.0002	80	80	0.00648
NACK2ACK	2	1	0.0001	96	96	0.004656
	2	1	0.0001	96	96	0.004656
	2	2	0.00001	104	104	0.000546
	2	3	0.000001	112	112	6.328E-05
	2	4	0.0000005	120	120	0.0000363
	2	5	0.0000002	128	128	1.651E-05
NACK2ACK	3	1	0.000001	144	144	0.0001044
	3	1	0.0000001	144	144	1.044E-05
	3	2	1E-08	152	152	1.163E-06
	3	3	1E-09	160	160	1.288E-07
	3	4	5E-10	168	168	7.098E-08
	3	5	2E-10	176	176	3.115E-08
Total						9.0197103

Figure 2 shows the TCP throughput utilization with TCP end-to-end RTT of from 10ms to 200ms and average DL HARQ RTT of 8ms, 12ms and 16ms.

Table 2. TCP Throughput Utilization with TCP E2E RTT and DL HARQ RTT

	8ms	12ms	16ms
10	0.3566407	0.2593183	0.1930696
20	0.5257704	0.4118392	0.3236519
30	0.6244871	0.5122719	0.4178576
40	0.6891868	0.5834081	0.4890287
50	0.7348681	0.6364348	0.5446932
60	0.7688422	0.6774865	0.5894212
70	0.7950984	0.7102082	0.6261473
80	0.8159983	0.7369017	0.6568426
90	0.8330293	0.7590924	0.6828798
100	0.8471746	0.7778309	0.7052446
110	0.8591104	0.7938647	0.7246626
120	0.8693169	0.8077401	0.7416803
130	0.8781445	0.8198652	0.7567168
140	0.8858549	0.8305517	0.7700991
150	0.8926477	0.8400413	0.7820859
160	0.8986774	0.8485244	0.7928847
170	0.9040658	0.856153	0.8026638
180	0.90891	0.86305	0.811561
190	0.9132884	0.869316	0.8196906
200	0.9172653	0.8750336	0.8271477

If DL HARQ RTT is 8ms and TCP RTT is 10ms, TCP throughput is decreased up to only 36% of maximum bandwidth. If DL HARQ RTT is 12ms and TCP RTT is 10ms, TCP throughput is seriously decreased up to only 26% of maximum bandwidth. And in the worst case, if DL HARQ RTT is 16ms and TCP RTT is 10ms, TCP throughput is decreased up to only 19% of maximum bandwidth. If DL HARQ RTT is 8ms and TCP RTT is 50ms, TCP throughput is decreased up to only 74% of maximum bandwidth. If DL HARQ RTT is 12ms and TCP RTT is 50ms, TCP throughput is decreased up to only 64% of maximum bandwidth. And if DL HARQ RTT is 16ms and TCP RTT is 50ms, TCP throughput is decreased up to only 55% of maximum bandwidth. If the shorter TCP end-to-end RTT and the longer DL HARQ RTT, the TCP throughput utilization is the lower. Figure 2 shows the graph of TCP throughput utilization with TCP end-to-end RTT of from 10ms to 200ms and average DL HARQ RTT of 8ms, 12ms and 16ms.

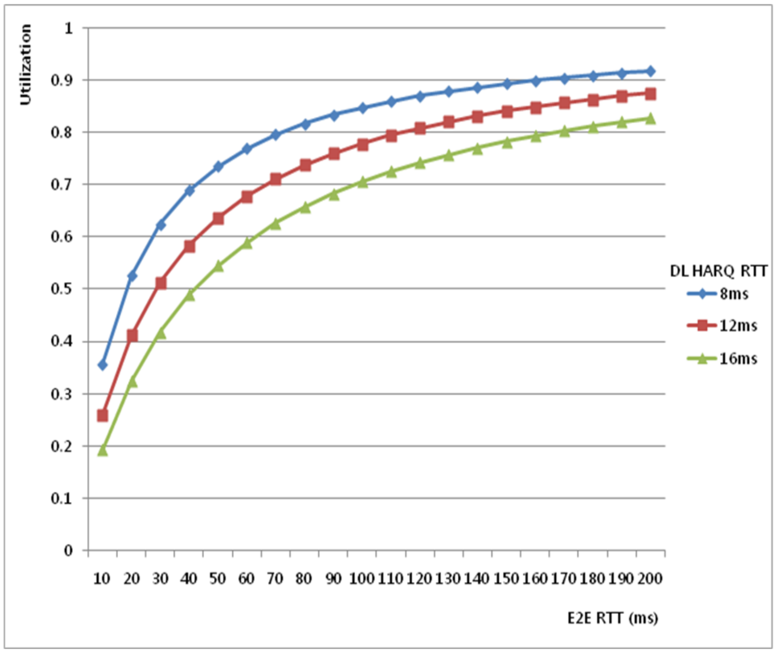

Figure 2. TCP Throughput Utilization with E2E RTT and DL HARQ RTT

4. “Out-of-Sequence Delivery” in LTE Link Layer

When HARQ or ARQ in LTE link layer is working frequently for error recovery, “in-sequence delivery” in LTE link layer increases TCP RTT and decreases TCP throughput seriously as shown in previous chapter. Therefore, in order to get better TCP throughput with the same packet error probability, we should decrease TCP RTT when HARQ or ARQ in LTE link layer is working for error recovery. To alleviate this problem, we propose "out-of-sequence delivery" in LTE link layer in order to decrease TCP RTT while HARQ or ARQ in LTE link layer is working for error recovery. As soon as a PDU is received, link layer can deliver reassembled SDUs in that PDU with “out-of-sequence delivery”. If an RLC receiver detects a gap in the SN (sequence number) of received PDUs, it starts a reordering timer (t_Reordering) assuming that the missing PDU is still being retransmitted in the HARQ protocol. But link layer with “out-of-sequence delivery” can deliver reassembled SDUs in newly received PDUs after the gap without delaying delivering SDUs after the gap is filled.

The “in-sequence delivery” increases the TCP RTT of all SDUs in every PDU from the SN of the HARQ or ARQ retransmitted PDU. Therefore, this frequently incurs delay spikes in the TCP data and TCP ACK compression. On the other hand, an “out-of-sequence delivery” can increase the TCP RTT of the SDUs in the retransmitted PDU only. The "out-of-sequence delivery" can decrease TCP RTT up to end-to-end RTT.

We implemented "out-of-sequence delivery" in LTE link layer and measured TCP throughput of “in-sequence delivery” and “out-of-sequence delivery”. We tested only ARQ impact on TCP RTT increment and throughput with ARQ retransmission rate of 0.1%, 1% and 5%. We measured the TCP throughput in the ETRI LTE-Advanced system with varying ARQ retransmission rate. In the test, the TCP client in the UE is on Windows 7 and the TCP server is on Linux. We use various plug-in TCP variants [9] of TCP server on Linux. In our testbed, the RTT between the TCP client and TCP server is about 13ms. Also, a UE can use two carriers, and the maximum bandwidth between a

UE and eNB is 110Mbps per carrier, so the maximum bandwidth per UE is 220Mbps in total. The Robust Header Compression (ROHC) function at the PDCP sub-layer is disabled in the test. We repeated each test ten times and measured the average TCP throughput. Table 3 shows the test parameters.

Table 3. Test Parameters

FTP File size	122.24MB MPG file
TCP segment size (MSS)	1380Bytes
TCP Receive Window Size (rwnd)	Auto-tuning (Windows 7)
Average TCP end-to-end RTT	13ms
UE IP connection	IPv6
Bandwidth	220Mbps
PDCP/RLC/MAC Header overhead	Under 0.005% (Minimum)
Max HARQ TX	5
Max ARQ ReTX	3
HARQ BLER (Block Error Rate)	Under 0.1%
HARQ RTT	8ms
PUSCH	Always scheduled
RF Bandwidth	40MHz (20MHz*2 Carriers)
RF Frequency	3.56 ~ 3.60GHz

Table 4 shows the test results. In case of TCP Illinois, the relative throughput of “out-of-sequence delivery” is 103%, 121% and 141% with ARQ retransmission rate of 0.1%, 1% and 5% each. In case of TCP Westwood, that is 98%, 158%, 141% and in case of TCP YeAH, that is 90%, 133% and 125%. In case of TCP CUBIC, that is 107%, 125%, 131% and in case of TCP NewReno, that is 103%, 122% and 118%. Figure 3 shows the relative throughput gain of “out-of-sequence delivery” when the throughput of “in-sequence delivery” is set as 100. The relative throughput gain of “out-of-sequence delivery” is about 130% in average and about 158% in maximum.

Table 4. TCP Throughput of “in-sequence delivery” (IN) vs. “out-of-sequence delivery” (OUT)

	0.1%		1%		5%	
	IN	OUT	IN	OUT	IN	OUT
Illinois	132.3	136.4	51.7	62.2	18.5	26.1
Westwood	85.6	84.0	35.0	55.3	13.8	19.5
YeAH	106.8	95.8	45.6	60.6	14.9	18.5
CUBIC	34.0	36.5	22.0	27.5	12.1	15.8
NewReno	56.7	58.4	30.7	37.3	16.2	19.2

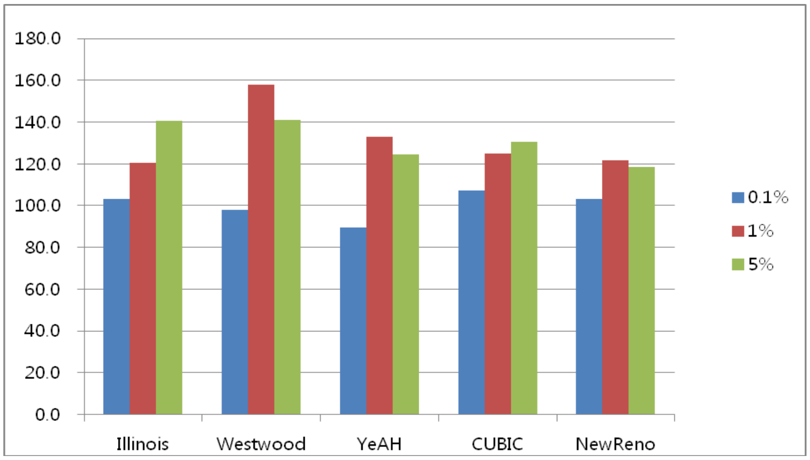

Figure 3. Throughput gain of "out-of-sequence delivery" vs. "in-sequence delivery"

5. Conclusions

In this paper, we analyzed the impact of "in-sequence delivery" in LTE link layer on TCP RTT increment. When HARQ or ARQ in LTE link layer is working frequently for error recovery, it increases TCP RTT and decreases TCP throughput seriously. If DL HARQ RTT is 8ms and TCP RTT is 10ms, TCP throughput is seriously decreased up to only 36% of maximum bandwidth. And if DL HARQ RTT is 16ms and TCP RTT is 10ms, TCP throughput is decreased up to only 19% of maximum bandwidth. Therefore, in order to get better TCP throughput with the same packet error probability, we should decrease TCP RTT when HARQ or ARQ in LTE link layer is working for error recovery. We propose "out-of-sequence delivery" in LTE link layer in order to decrease TCP RTT. From our test results, "out-of-sequence delivery" outperforms "in-sequence delivery". While "out-of-sequence delivery" makes LTE link layer design simpler, but its throughput gain is considerable to the extent of 30% in average and 58% in maximum from our test results.

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