An IP-Based Packet Test Environment for TD-LTE and LTE FDD

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ABSTRACT

In recent years, Long Term Evolution systems have been developed to replace 3G mobile networks. During LTE network deployment, it is essential that mobile operators and manufacturers conduct tests on user equipment and the base station (eNB). Besides conformance testing at the radio layer, it is also important to conduct network-layer performance tests between UE and eNB. This article develops an LTE test environment that can be used to test the IP-based packet performance for TD-LTE and LTE FDD. Specifically, we consider the latency and the throughput performance of IP, TCP, and VoIP (i.e., G.711) packet delivery. This multi-purpose test environment can be utilized to investigate the performance of the UE and/or eNBs of various manufacturers. Furthermore, we use this environment to compare TD-LTE and LTE FDD. The measurement results provide guidelines for UE and eNB vendors to improve their products, and operators to deploy their LTE networks and subsidized UE devices.

INTRODUCTION

Due to the availability of smartphones and diversified Internet applications, mobile data services have become popular, and the number of broadband mobile subscribers has increased significantly in recent years. To provide better service quality for mobile subscribers, the data rate of the mobile network must be further improved. In 2008, the Third Generation Partnership Project (3GPP) Release 8 proposed Long Term Evolution (LTE), which specifies downlink/uplink peak data rates up to 300/75 Mb/s. Targeting a smooth evolution from the earlier 3G technologies, LTE can operate in either frequency-division duplex (FDD) or time-division duplex (TDD) modes. LTE FDD is evolved from wideband code-division multiple access (W-CDMA). On the other hand, LTE TDD (TD-LTE) is based on TDD mode and is backward compatible with time-division–synchronous code-division multiple access (TD-SCDMA). In 2010, 3GPP Release 10 proposed LTE-Advanced, which is expected to meet the International Mobile Telecommunications Advanced (IMT-Advanced) requirements and become a 4G system specification [1].

Several studies evaluated TD-LTE and LTE FDD performance via simulation. These studies investigated throughputs but did not consider one-way latency [2, 3, references therein]. For example, [2] compared the throughput performance of TD-LTE and LTE FDD through the OPNET simulator. Reference [3] measured LTE FDD physical layer throughput based on field tests. This study did not measure the IP layer throughput and latency performance. Reference [4] measured LTE FDD physical layer throughput and round-trip latency performance for LTE category 2 user equipment (UE). This work did not consider TD-LTE, and did not separately measure the uplink and downlink one-way latencies. Reference [5] measured LTE FDD IP-layer throughput based on field tests. This work did not consider TD-LTE, and did not measure latency performance. Lin's work [6] pioneered the IP performance measurement of TD-LTE system and compared it with WiMAX, TD-SCDMA, and W-CDMA systems. Since 2010, the Broadband Mobile Laboratory (BML) of National Chiao Tung University (NCTU) has deployed a test environment originally designed for radio conformance testing of TD-LTE UE, which has been utilized to test commercial TD-LTE UE products based on the test cases provided by China Mobile. Driven by customer needs, it is also essential to conduct network layer (i.e., IP layer or even application layer) performance tests for both UE and base stations. This article develops an LTE test environment that can investigate the IP-based packet performance of LTE UE and enhanced Node B (eNB; i.e., the base station). Furthermore, we compare the latency and throughput of TD-LTE and LTE FDD for IP, TCP, and VoIP (i.e., G.711) packet delivery. For latency performance, we measure the downlink and uplink one-way latency, respectively. The measurement results provide guidelines for UE and eNB vendors to improve their products, and for operators to deploy their future networks and subsidized UE devices. The article is organized as follows. First, we describe the proposed test environment. We then investigate the IP performance of various UE devices and eNBs for both TD-LTE and LTE FDD. Finally, we summarize our findings.

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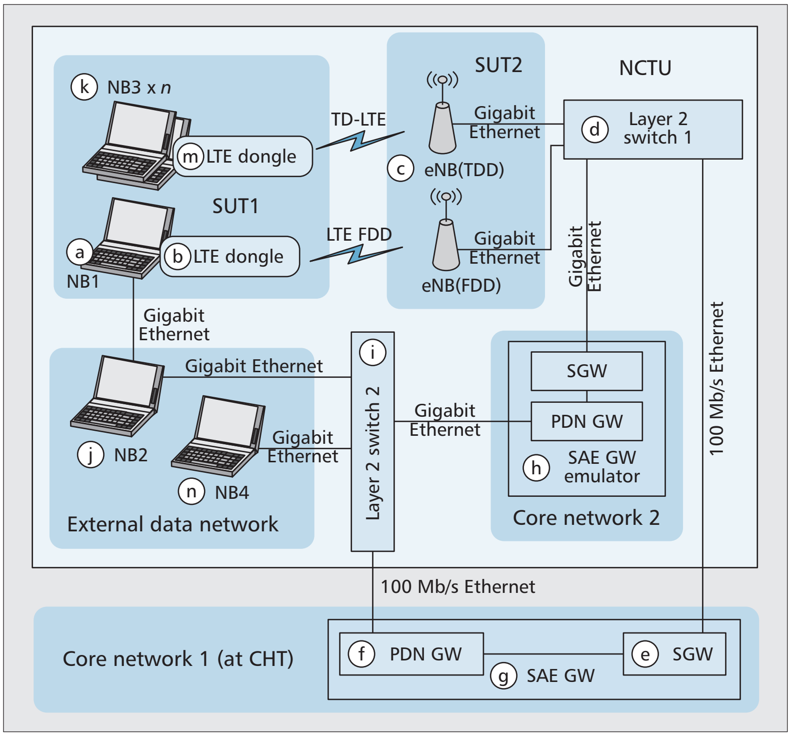

Figure 1. *A TD-LTE and LTE FDD test environment.*

TEST ENVIRONMENT

Figure 1 illustrates the proposed test environment for TD-LTE and LTE FDD. In this environment, the system under test (SUT) can be a UE device (Fig. 1b) or an eNB (Fig. 1c). That is, an eNB can be used to measure the performance of a UE and vice versa. In the current test setup, the UE device is a wireless dongle attached to a notebook (NB; Fig. 1a). The UE communicates with an eNB through LTE radio interfaces. Our environment accommodates both TD-LTE and LTE FDD eNBs that connect to the core network through layer 2 switch 1 (Fig. 1d). For testing purposes, we design two alternatives for the core network (CN). The first alternative, CN 1, is a commercial LTE CN including the serving gateway (SGW; Fig. 1e) and the packet data network gateway (PDN GW; Fig. 1f). The SGW handles inter-eNB handovers, and is responsible for routing user data packets [7]. The PDN GW provides connectivity between the UE and external data networks. In some commercial implementations, the SGW and PDN GW are combined in one physical node called the system architecture evolution gateway (SAE GW; Fig. 1g). NB2 (Fig. 1j), located in the external data network, serves as a traffic source and/or destination in the tests. NB2 connects to the SAE GW through layer 2 switch 2 (Fig. 1i). In our test environment, the UE, TD-LTE and LTE FDD eNBs, two layer 2 switches, and external data network are located at NCTU in Hsinchu, Taiwan. The SAE GW (Fig. 1g) is located at Chunghwa Telecom (CHT) in Yangmei, Taiwan. The distance between Hsinchu and Yangmei is about 20 mi (32.2 km). We consider a minimal number of hops in the CN to emphasize the impact of LTE radio on end-to-end IP packet transmission.

To provide a test environment for eNB, the LTE CN should be able to accommodate eNBs from different manufacturers. Unfortunately, extra effort is incurred to port the tested eNBs to the commercial CN1 (Fig. 1g). Specifically, we need to match the parameters in the S1 interface, which requires special management tools to access the eNB parameters. To simplify this issue, we deploy an alternative CN with an SAE GW emulator (called CN2; Fig. 1h). The SAE GW emulator is ng4T [8], which can easily be connected to different eNBs without much porting and interworking efforts. The SAE GW emulator is located at NCTU in Hsinchu, and is connected to layer 2 switches 1 and 2 through Gigabit Ethenet links. CN2 is particularly convenient for conformance tests of the eNB's radio functions. Although CN1 (a real LTE CN) is not as "convenient" as CN2 (an emulator), the real CN is often required in testing when the potential customers (i.e., the operators) request the eNB vendors to provide access to it.

Software tools are used to investigate the performance of the latency and throughput between UE devices and eNBs. We have developed a software tool, NCTU-VT, for latency measurement [9], which is installed in both NB1 and NB2. These two notebooks are directly connected through a Gigabit Ethernet link (Fig. 1j ↔ Fig. 1a) to synchronize their clocks for latency measurement (to be elaborated on later). In CN1, when we measure the uplink latency between a UE device (i.e., the wireless dongle attached to NB1) and an eNB, the test packets are generated by NB1 and are sent to NB2 through path (a) → (b) → (c) → (d) → (g) → (i) → (j). In CN2, the SAE GW emulator (Fig. 1h) replaces the SAE GW (Fig. 1g); thus, the packet path is (a) → (b) → (c) → (d) → (h) → (i) → (j). When NB2 receives the test packets, it forwards the packets to NB1 through path (j) → (a). Then NB1 computes the latency and the packet loss based on the received packets it sent out. In other words, in the latency measurement, the packets travel in a loop, which allows us to accurately measure the one-way delay without time synchronization between the sender and the receiver. Similarly, when we measure the downlink latency, the test packets are generated by NB2 and sent to NB1 through the reverse path, (j) → (i) → (g) → (d) → (c) → (b) → (a) for CN 1 and (j) → (i) → (h) → (d) → (c) → (b) → (a) for CN 2, respectively. The delays for paths (c) ↔ (d) ↔ (g) ↔ (i) ↔ (j) and (c) ↔ (d) ↔ (h) ↔ (i) ↔ (j) can be measured accurately, and are much smaller than the delay between (b) and (c). Therefore, by excluding the wired path latency, we can accurately measure the radio interface latency between (b) and (c).

We also measure the TD-LTE and LTE FDD throughput for multiple UE devices. In this measurement, *n* dongles (Fig. 1m) attached to *n* notebooks (NB3; Fig. 1k) are included in the test environment. In the current setup, $n = 2$. Besides NB2, another notebook (NB4 in Fig. 1n) at the external data network also connects to the SAE GW through layer 2 switch 2. Like NB2, NB4 is responsible for sending/receiving test packets to/from NB3s. NB1, NB2, NB3, and NB4 have installed the iperf network testing software [10] to measure the throughput. For

	TD-LTE	LTE FDD
Frequency band (Center Frequency)	Band 38 2570–2620 MHz (2580 MHz)	Band 17 UL: 704–716 MHz (710 MHz) DL: 734–746 MHz (740 MHz)
Bandwidth	20 MHz	2 × 10 MHz
Mode	TDD subframe configuration 2 (UL: DL = 1:4)	FDD
Maximum transmitter power	43 dBm (20 W)	43 dBm (20 W)
Modulation	Adaptive modulation and coding: UL: QPSK, 16-QAM DL: QPSK, 16-QAM, 64-QAM	Adaptive modulation and coding: UL: QPSK, 16-QAM DL: QPSK, 16-QAM, 64-QAM
Maximum MCS index	UL: 24 DL: 28	UL: 24 DL: 28
MIMO	UL: not supported DL: 2 × 2	UL: not supported DL: 2 × 2
Dongle data rate	UL: 50 Mb/s DL: 100 Mb/s (LTE Category 3)	UL: 50 Mbs DL: 100 Mb/s (LTE Category 3)

Table 1. *The TD-LTE and LTE FDD radio configuration parameters.*

Software tools are used to investigate the performance of the latency and the throughput between UEs and eNBs. We have developed a software tool (named NCTU-VT) for latency measurement, which is installed in both NB1 and NB2.

TD-LTE (LTE FDD) uplink throughput with CN1, NB1 generates the test packets and sends them to NB2 through path (a) → (b) → (c) → (d) → (g) → (i) → (j). At the same time, n NB3s send test packets to NB4 through path (k) → (m) → (c) → (d) → (g) → (i) → (n). When we measure the downlink throughputs, the test packets are sent from NB2 and NB4 to NB1 and NB3 through the reverse paths (j) → (i) → (g) → (d) → (c) → (b) → (a) and (n) → (i) → (g) → (d) → (c) → (m) → (k), respectively. The packet paths for CN2 are similar to those of CN1 except that the SAE GW is replaced by the SAE GW emulator.

PERFORMANCE MEASUREMENT

This section conducts performance measurements of UDP, TCP, and G.711 VoIP packets for both TD-LTE and LTE FDD. The complete radio configuration parameters are listed in Table 1. In this table, most parameters are preset for commercial operation and are consistent with the setups in [2, 3, 5, 6]. For fair comparison, we configure both TD-LTE and LTE FDD to occupy the same amount of frequency bandwidth (20 MHz, which is the same as [2] and is within the range of commercial operation). That is, both the LTE FDD uplink and downlink frequency bandwidths are set to 10 MHz. The TD-LTE subframe configuration can be set to 1 or 2. In this article, we measure the TD-LTE performance for subframe configuration 2. The performance of TD-LTE subframe configuration 1 can be found in our previous work [6]. The category of TD-LTE and LTE FDD UE devices under test is 3, which supports downlink/uplink data rates up to 100/50 Mb/s.

As previously described, the SUT in our test environment can be a UE device or an eNB. We conduct performance measurements for the products of H, Q, and N companies, including Q-company's TD-LTE UE, and H-company's TD-LTE and LTE FDD UE devices. We also measure the performance for two eNB products from N-company (TD-LTE only) and H-company (TD-LTE and LTE FDD dual-mode). Therefore, there are four combinations for configuring eNBs and core networks:

Case TD-R-N: The N-company TD-LTE eNB is connected to the real SAE GW.

Case TD-E-N: The N-company TD-LTE eNB is connected to the SAE GW Emulator.

Case TD-E-H: The H-company TD-LTE eNB is connected to the SAE GW Emulator.

Case FDD-E-H: The H-company LTE FDD eNB is connected to the SAE GW Emulator.

TD represents a TD-LTE eNB, FDD represents an LTE FDD eNB, R represents the real SAE GW, E represents the SAE GW Emulator, N represents N-company, and H represents H-company.

LATENCY PERFORMANCE

In this subsection, we first measure the latencies of G.711 VoIP packets for both H-company and Q-company UE devices. Then we consider UDP and TCP latency performance. The size of a G.711 VoIP packet is 200 bytes (including the IP, UDP, and RTP headers), and the packet transmission interval is 20 ms. For each UE device, we repeated packet transmission 20,000 times. Table 2 lists the average one-way downlink latencies t_D (in milliseconds) with standard deviations s_D and the average one-way uplink latencies t_U with standard deviations s_U.

Table 2 indicates that both H-company and Q-company UE devices have almost identical performance for G.711 packet latency. The one-way latency difference between cases **TD-R-N** and **TD-E-N** is due to the overhead of the CN transmission. Table 2 shows that the downlink and uplink latencies of case **TD-R-N** (with the commercial CN 1) are larger than those of case **TD-E-N** (with the CN emulator CN2). As described earlier, we have measured the delay of CN1's data path (c) ↔ (d) ↔ (g) ↔ (i) ↔ (j), which is 2.25 ms with standard deviation 0.07 ms. On the other hand, the average delay for CN2's data path (c) ↔ (d) ↔ (h) ↔ (i) ↔ (j) is 0.56 ms with standard deviation 0.03 ms. Clearly, the difference between Cases **TD-R-N** and **TD-E-N** is incurred by the delays of the wired paths. When we exclude the overhead of wired transmission and CN node processing, we can obtain an average wireless downlink delay around 6.34–6.45 ms, and the average wireless uplink delay is around 8.35–8.44 ms.

Downlink								
UE brand	TD-R-N		TD-E-N		TD-E-H		FDD-E-H	
	t_D	s_D	t_D	s_D	t_D	s_D	t_D	s_D
H-company	8.7	0.6	6.9	0.6	6.8	0.7	6.6	0.5
Q-company	8.7	0.6	6.9	0.6	6.8	0.7	—	—
Uplink								
UE brand	TD-R-N		TD-E-N		TD-E-H		FDD-E-H	
	t_U	s_U	t_U	s_U	t_U	s_U	t_U	s_U
H-company	10.6	2.1	9.0	2.1	13.9	1.9	13.6	1.8
Q-company	10.7	2.1	9.1	2.5	14.0	1.9	—	—

Table 2. *One-way latency performance of G.711 VoIP packets (unit: ms).*

Downlink								
Packet Type	TD-R-N		TD-E-N		TD-E-H		FDD-E-H	
	t_D	s_D	t_D	s_D	t_D	s_D	t_D	s_D
G.711	8.7	0.6	6.9	0.6	6.8	0.7	6.6	0.5
UDP	11.0	0.6	8.4	0.6	5.9	0.7	5.8	0.6
TCP	11.5	0.8	8.6	0.8	7.6	0.7	7.2	0.6
Uplink								
Packet Type	TD-R-N		TD-E-N		TD-E-H		FDD-E-H	
	t_U	s_U	t_U	s_U	t_U	s_U	t_U	s_U
G.711	10.6	2.1	9.0	2.1	13.9	1.9	13.6	1.8
UDP	22.3	3.0	20.1	3.0	18.1	3.0	13.6	2.7
TCP	24.5	2.9	20.9	2.9	19.2	2.0	18.2	3.7

Table 3. *G.711, UDP and TCP one-way latencies for H-company UE (unit: ms).*

The eNBs in cases **TD-E-N** and **TD-E-H** are manufactured by different companies. Table 2 indicates that both cases have similar downlink latency performance (only 0.1 ms difference), but the uplink latency of case **TD-E-H** is 4.9 ms longer than that of case **TD-E-N**. That is, the N-company TD-LTE eNB provides shorter uplink latency (better performance) than the H-company TD-LTE eNB. Table 2 also shows that the average latencies and their standard deviations for case **FDD-E-H** are smaller than those of case **TD-E-H**. This result indicates that for the same LTE CN configuration, the latency performance of LTE FDD is better than that of TD-LTE.

The UDP and TCP one-way latencies for H-company UE are listed in Table 3. Since the previous experiments indicate that the performance of Q-company UE is almost identical to that for H-company UE, it suffices to consider H-company UE for the subsequent experiments. Following the experiment setups in [6], the size of a UDP packet is 100 bytes (including the IP and UDP headers), and the packet transmission interval is 1 ms. The maximum segment size of a TCP packet is 1500 bytes (including the IP and TCP headers), and the transmission interval is 10 ms.

Table 3 indicates that the latencies of UDP packets are 2.3–22.4 percent smaller than those of TCP packets for downlink transmission, and 3.8–25.3 percent smaller for uplink transmission. The UDP performance of case **TD-E-H** is 29.8 percent better than that of case **TD-E-N** because in case **TD-E-H**, both the UE and eNB are manufactured by the same company, H, and have been enhanced for handling heavy UDP downlink traffic (i.e., when the packet inter-arrival times are short). On the other hand, the UE (H-company) and eNB (N-company) in case **TD-E-N** come from different companies, and its performance is not as good as that of case **TD-E-H** for heavy UDP downlink traffic. The difference between the two brands of eNBs indicated by our work gives eNB manufacturers directions to improve the performance of their products.

In general, the UDP t_D (t_U) and s_D (s_U) are larger than those for G.711 because the interval for sending UDP packets (1 ms) is much shorter than that for G.711 (20 ms). An exception occurs for downlink transmission in cases **TD-E-H** and **FDD-E-H**. As mentioned previously, these two cases use H-company UE and eNBs, which have been enhanced for handling heavy UDP downlink traffic. Therefore, the UDP performance is better than the G.711 performance for cases **TD-E-H** and **FDD-E-H**. The latency performance for LTE FDD (case **FDD-E-H**) is slightly better than that for TD-LTE (case **TD-E-H**).

Tables 2 and 3 show that the TD-LTE and LTE FDD uplink latencies are larger than the downlink latencies for the following reason. Before every uplink packet transmission, the LTE UE must send an uplink scheduling request to the eNB to obtain the uplink resource, and then the eNB responds with an uplink scheduling grant to the UE. These uplink scheduling requests and scheduling grants incur additional delay. The LTE FDD uplink latencies caused by the uplink scheduling request and scheduling grant are estimated to range from 4 to 9 ms in [11], which is consistent with our measurements for case **FDD-E-H**.

THEORETICAL MAXIMUM THROUGHPUTS

We describe the computation for both LTE FDD's and TD-LTE's theoretical maximum throughput. Computation equations for LTE theoretical maximum layer 1 throughput can be found in [11]. We reiterate the details and show how these equations can be used according to our experimental setups.

In LTE FDD, let f be the number of subframes within a frame. Since each 10 ms frame is divided into 10 subframes of 1 ms, we have $f = 10$. Let λ be the rate of frames per second. Since each frame spans 10 ms, we have $\lambda = 100$ fps. Let B_u be the maximum bit number that a physical uplink shared channel (PUSCH) can transmit within a subframe. The B_u value is mapped from the frequency bandwidth and the maximum modulation and coding scheme (MCS) index defined in 3GPP TS 36.213 [12]. For LTE FDD uplink in our setup, the frequency bandwidth is 10 MHz and the maximum MCS index 24. According to the mapping table defined in [12], we have $B_u = 24{,}496$ bits. For LTE UE category 3 and frequency bandwidth of paired 10 MHz, the theoretical maximum LTE FDD layer 1 uplink throughput U_F is the product of f, λ, and B_u. Therefore, $U_F = 24.5$ Mb/s. Similarly, let B_d be the maximum number of bits a physical downlink shared channel (PDSCH) can receive within a subframe. For LTE FDD downlink, the frequency bandwidth is 10 MHz, the maximum MCS index is 28, and the mapped B_d is 36,696 bits. Let M be the amount of supported spatial multiplexing in LTE downlink. For LTE UE category 3, $M = 2$. The LTE FDD theoretical maximum layer 1 downlink throughput D_F is the product of f, λ, B_d, and M. Therefore, $D_F = 73.4$ Mb/s.

The theoretical maximum layer 1 throughput for TD-LTE is computed as follows. In this article, the frequency bandwidth is 20 MHz. For TD-LTE uplink, the chosen maximum MCS index is 24, and the mapped B_u is 51,024 bits. Let f_U be the number of subframes used for uplink transmission within a frame. In LTE FDD, all 10 subframes are used for downlink (or uplink) transmission. On the other hand, in TD-LTE, the 10 subframes are shared between the uplink and downlink transmissions, and the uplink/downlink ratio is determined by the subframe configuration. In subframe configuration 2, $f_U = 2$. For LTE UE category 3 with frequency bandwidth 20 MHz and subframe configuration 2, the TD-LTE theoretical maximum layer 1 uplink throughput U_T is the product of f_U, λ, and B_u. Therefore, $U_T = 10.2$ Mb/s. Note that in our previous work [6], the maximum MCS index the TD-LTE eNB supports was 20, and the corresponding maximum uplink throughput was 8.2 Mb/s. In this article, the upgraded TD-LTE eNB supports a higher MCS index 24; thus, the maximum uplink throughput for TD-LTE has been significantly improved.

Case TD-R-N ($D_{T,1}$ = 81.6 Mb/s, $D_{T,n}$ = 120.6 Mb/s)				
Amt. of UE	**UE1 (H)**	**UE2 (H)**	**UE3 (Q)**	**eNB**
1	77.9 Mb/s	—	—	77.9 Mb/s
1	—	—	78.0 Mb/s	78.0 Mb/s
2	44.7 Mb/s	44.8 Mb/s	—	89.5 Mb/s
3	29.8 Mb/s	29.9 Mb/s	29.8 Mb/s	89.5 Mb/s
Case TD-E-N ($D_{T,1}$ = 81.6 Mb/s, $D_{T,n}$ = 120.6 Mb/s)				
Amt. of UE	**UE1 (H)**	**UE2 (H)**	**UE3 (Q)**	**eNB**
1	78.0 Mb/s	—	—	78.0 Mb/s
1	—	—	78.0 Mb/s	78.0 Mb/s
2	48.8 Mb/s	49.1 Mb/s	—	97.9 Mb/s
3	31.2 Mb/s	31.1 Mb/s	31.2 Mb/s	93.5 Mb/s
Case TD-E-H ($D_{T,1}$ = 81.6 Mb/s, $D_{T,n}$ = 120.6 Mb/s)				
Amt. of UE	**UE1 (H)**	**UE2 (H)**	**UE3 (Q)**	**eNB**
1	77.3 Mb/s	—	—	77.3 Mb/s
1	—	—	77.4 Mb/s	77.4 Mb/s
2	51.4 Mb/s	51.4 Mb/s	—	102.8 Mb/s
3	34.3 Mb/s	34.3 Mb/s	34.3 Mb/s	102.9 Mb/s
Case FDD-E-H (D_F = 73.4 Mb/s)				
Amt. of UE	**UE1 (H)**	**UE2 (H)**	**UE3 (H)**	**eNB**
1	70.1 Mb/s	—	—	70.1 Mb/s
2	34.2 Mb/s	34.2 Mb/s	—	68.4 Mb/s
3	22.8 Mb/s	22.8 Mb/s	22.8 Mb/s	68.4 Mb/s

Table 4. *TD-LTE and LTE FDD downlink throughput performance.*

Now we consider TD-LTE downlink. For UE category 3 and subframe configuration 2 with frequency bandwidth 20 MHz and maximum MCS index 28, the mapped B_d is 75,376 bits. Let B be the maximum bit number a single UE can receive within a subframe. For LTE UE category 3, $B = 102{,}048$ bits [13]. Let f_D be the number of subframes used for downlink transmission within a frame. In subframe configuration 2, $f_D = 8$. As in the LTE FDD throughput computation, $\lambda = 100$ fps. For a TD-LTE eNB connecting to n UE devices, the theoretical maximum downlink throughput $D_{T,n}$ is

$$D_{T,n} = \sum_{i=1}^{n} \min\left(B_{d,i} \times M, B\right) \times f_D \times \lambda \tag{1}$$

<table>
<tr><th colspan="5">Case TD-E-H (U_T = 10.2 Mb/s)</th></tr>
<tr><th>Amt. of UE</th><th>UE1 (H)</th><th>UE2 (H)</th><th>UE3 (Q)</th><th>eNB</th></tr>
<tr><td>1</td><td>9.26 Mb/s</td><td>—</td><td>—</td><td>9.26 Mb/s</td></tr>
<tr><td>1</td><td>—</td><td>—</td><td>9.29 Mb/s</td><td>9.29 Mb/s</td></tr>
<tr><td>2</td><td>4.68 Mb/s</td><td>4.67 Mb/s</td><td>—</td><td>9.35 Mb/s</td></tr>
<tr><td>3</td><td>3.18 Mb/s</td><td>3.17 Mb/s</td><td>3.20 Mb/s</td><td>9.55 Mb/s</td></tr>
<tr><th colspan="5">Case FDD-E-H (U_F = 24.5 Mb/s)</th></tr>
<tr><th>Amt. of UE</th><th>UE1 (H)</th><th>UE2 (H)</th><th>UE3 (H)</th><th>eNB</th></tr>
<tr><td>1</td><td>23.2 Mb/s</td><td>—</td><td>—</td><td>23.2 Mb/s</td></tr>
<tr><td>2</td><td>11.5 Mb/s</td><td>11.5 Mb/s</td><td>—</td><td>23.0 Mb/s</td></tr>
<tr><td>3</td><td>7.7 Mb/s</td><td>7.7 Mb/s</td><td>7.7 Mb/s</td><td>23.1 Mb/s</td></tr>
</table>

Table 5. *TD-LTE and LTE FDD uplink throughput performance.*

where $M = 2$ for LTE UE category 3. For UE i, $B_{d,i}$ is the bit number a PDSCH receives within a subframe. If $n = 1$, we have $B_{d,1} = B_d$, and $B_{d,1} \times M$ is larger than B in Eq. 1, which gives $D_{T,1}$ = 81.6 Mb/s. For $n \geq 2$, PDSCH is evenly shared by n UE devices; that is, for $i = 1$ to n, $B_{d,i}$ is B_d divided by n, and $(B_d \times M)/n$ is smaller than B. Therefore, Eq. 1 can be expressed as

$$D_{T,n} = n \times \left(\frac{B_d}{n}\right) \times M \times f_D \times \lambda = 120.6 \text{ Mb/s}$$

Although increasing the number of users reduces the throughput per user [14], an interesting finding is that $D_{T,n} > D_{T,1}$ for $n \geq 2$. That is, when the number of UE devices increases from one to many, the downlink cell throughput increases for TD-LTE.

THROUGHPUT PERFORMANCE

In this subsection, we measure the IP layer throughput. Under the configuration parameters listed in Table 1, we calculated theoretical maximum throughput as $D_{T,1}$ = 81.6 Mb/s (TD-LTE downlink with one UE), $D_{T,n}$ = 120.6 Mb/s (TD-LTE downlink with n UE devices for $n \geq 2$), U_T = 10.2 Mb/s (TD-LTE uplink), D_F = 73.4 Mb/s (LTE FDD downlink), and D_T = 24.5 Mb/s (LTE FDD uplink). We use two H-company UE devices and one Q-company UE device for throughput measurements. For each UE, we repeat 120-s packet transmission (millions of packets) 10 times to obtain stable measured results. Tables 4 and 5 list the measured downlink and uplink throughput, respectively. The tables indicate that the throughput performance for Q-company UE is slightly better than H-company UE, but not significantly.

The measured downlink throughput for a single UE device are 94.7–95.6 percent of their theoretical maximum values (i.e., 95.5-95.6 percent for case **TD-R-N**, 95.6 percent for case **TD-E-N**, 94.7–94.9 percent for case **TD-E-H**, and 95.5 percent for case **FDD-E-H**). The single-UE-device downlink throughput of cases **TD-R-N** and **TD-E-N** (i.e., N-company eNB) is 0.6–0.7 Mb/s higher than that of case **TD-E-H** (i.e., H-company eNB). That is, the N-company TD-LTE eNB provides slightly better single-UE-device downlink throughput than the H-company TD-LTE eNB. For multiple UE devices, the cell throughput for TD-LTE is 74.2–85.3 percent of the theoretical maximum values (i.e., 74.2 percent for case **TD-R-N**, 77.5–81.2 percent for case **TD-E-N**, 85.2–85.3 percent for case **TD-E-H**). In other words, the H-company eNB outperforms the N-company eNB for TD-LTE downlink cell throughputswith multiple UE devices. Table 4 indicates that the throughput in case **TD-E-N** are higher than that for case **TD-R-N** due to less CN overheads.

Table 4 also shows that the downlink cell throughput for TD-LTE is affected by the number of connected UE devices. The TDD cell throughput with multiple UEdevices is 11.6–25.5 Mb/s higher than that with a single UE device. This phenomenon is explained earlier.

For an FDD eNB, the downlink cell throughput with multiple UE devices is 1.7 Mb/s lower than that with a single UE device. This result is caused by extra scheduling overhead of the eNB for multiple UE transmission. For both TD-LTE and LTE FDD, Table 5 indicates that the uplink cell throughput of the eNB is not affected by the number of UE devices connected to the eNB. The measured uplink throughputs are 90.8–94.7 percent of their theoretical maximum values (i.e., 90.8–93.6 percent for case **TD-E-H** and 94.7 percent for case **FDD-E-H**). The discrepancies between the theoretical maximum values and the measured data are mainly due to the IP layer implementation, which indicates the space for both H- and N-companies to improve their SUTs.

CONCLUSION

The Broadband Mobile Laboratory of National Chiao Tung University has deployed a test environment originally designed for TD-LTE radio conformance testing of TD-LTE UE products. Driven by customers, it is also essential to conduct network-layer (i.e., IP-layer or even application-layer) performance tests for both UE and eNBs. Therefore, based on NCTU's LTE radio test platform, we have developed an IP-based packet test environment for both TD-LTE and LTE FDD to investigate the latency and throughput performance of IP, TCP, and VoIP (i.e., G.711).

In this article, we use two brands (H-company and Q-company) of TD-LTE and LTE FDD UE devices and two brands (H-company and N-company) of eNBs as examples to illustrate how the test environment can investigate the IP network layer performance for LTE. Our experiments indicated the following results:

- Both H and Q brands of TD-LTE UE achieve almost identical performance, where the one-way end-to-end delays range from 6.8 to 14.0 ms.
- The measured throughput can reach 74.2–95.6 percent of their theoretical maximum values. The H-company eNB outper-

forms the N-company eNB for TD-LTE downlink cell throughput with multiple UE devices by 5.1–15 percent. This result reverses when the eNB connects to a single UE device.

- The eNB throughput for a single UE device can achieve 90.8–95.6 percent of the theoretical maximal values. For the cell throughput with multiple UE devices, the eNB can achieve over 74.2 percent of the theoretical maximal values. The downlink cell throughput for TD-LTE is affected by the number of connected UE devices.
- The LTE FDD latencies are 74.8–76.1 percent shorter than those of W-CDMA, and the TD-LTE latencies are 82.2–93.8 percent shorter than those of TD-SCDMA [6]. Therefore, LTE significantly outperforms the 3G mobile technologies.
- The TD-LTE uplink throughput performance can be improved significantly by upgrading the MCS index. In our previous work [6], the measured TD-LTE uplink throughput was 7.2 Mb/s. By changing the MCS index from 20 to 24, the measured uplink throughput increases to 9.26–9.29 Mb/s (90.8–91.1 percent of the theoretical value).
- LTE FDD outperforms TD-LTE in terms of the IP layer throughput performance. The average IP layer latencies and their standard deviations for LTE FDD are slightly smaller than those of TD-LTE. Although the IP performance of LTE FDD is better than that of TD-LTE, the TD-LTE spectrum is less expensive than that for LTE FDD. Whether to choose FDD or TDD is a trade-off between budget and performance in an operator's business strategic decision.

As a final remark, our test environment can be extended to investigate the performance of core networks, where CN2 serves as a baseline for comparison. For example, CN1 is manufactured by N-company, and our measurements show that the latency of IP packet delivery for CN1 is 2.25 ms, which is 1.69 ms more than that of CN2.

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BIOGRAPHIES

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