Performance Measurements of TD-LTE, WiMAX and 3G Systems

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Abstract

Long Term Evolution (LTE) and *Worldwide Interoperability for Microwave Access* (WiMAX) are two major technologies toward next-generation mobile broadband standards, which are both expected to provide higher throughput and lower transmission latency for mobile users. This paper measures and compares the latency and the throughput of Time Division - Long Term Evolution (TD-LTE), WiMAX, and third-generation (3G) systems based on several technical trials. Our quantitative measures and comparisons provide guidelines for the operators to deploy their future networks.

Keyword: Performance Measurement, Time Division - Long Term Evolution (TD-LTE), Time Division - Synchronous Code Division Multiple Access (TD-SCDMA), Wideband Code Division Multiple Access (W-CDMA), Worldwide Interoperability for Microwave Access (WiMAX)

1 Introduction

Wideband Code Division Multiple Access **(**W-CDMA), CDMA2000, and *Time Division - Synchronous Code Division Multiple Access* (TD-SCDMA) are three major standards for the third generation (3G) mobile telecommunication. Both W-CDMA and CDMA2000 have been deployed in many countries, and are operated in the frequency division duplex (FDD) mode. On the other hand, TD-SCDMA has been mainly deployed in China based on the time division duplex (TDD) mode. In TD-SCDMA, the number of timeslots for uplink and downlink can be dynamically adjusted to accommodate different uplink/downlink data rate requirements.

To provide higher data rate for packet services, *Third Generation Partnership Project* (3GPP) proposed *High Speed Downlink Packet Access* (HSDPA) [1] and *High Speed Uplink Packet Access* (HSUPA) [2] to improve the data rates. The downlink data rate of an HSDPA device is indicated by its category number. For example, an HSDPA device with category 12 can support 1.8 Mbps downlink data rate, while a category 8 device can reach 7.2 Mbps downlink data rate. The data rate of HSDPA and HSUPA can be further improved with *Evolved High Speed Packet Access* (HSPA+), which provides downlink/uplink peak rates up to 84 Mbps and 22 Mbps, respectively.

In 2008, 3GPP Release 8 proposed the *Long Term Evolution* (LTE) that specified downlink/uplink peak rates up to 300/75 Mbps. Targeting on a smooth evolution from the earlier 3G technologies, LTE can operate in either FDD or TDD modes. The evolution of LTE TDD, which is sometimes called TD-LTE, is based on TDD mode and is backward compatible with TD-SCDMA. Similar to TD-SCDMA, the uplink/downlink subframe ratio of TD-LTE can be dynamically adjusted to accommodate different uplink/downlink traffic conditions.

A competitive standard of LTE is *Worldwide Interoperability for Microwave Access* (WiMAX). The set of WiMAX standards are defined and maintained by the IEEE 802.16 working group [3]. The IEEE 802.16-2004 standard is sometimes called 802.16d or “fixed WiMAX” because it only supports fixed or slowly moving users. The subsequent amendment IEEE 802.16e-2005 is also referred to as 802.16e or “mobile WiMAX”, which supports seamless handover for users with mobility. The latest mobile broadband standards are 3GPP Release 10 (LTE-Advanced) and IEEE 802.16m-2011 [3], both of them are expected to meet the *International Mobile Telecommunications Advanced* (IMT-Advanced) requirements [4] and become well-organized 4G systems.

During 2004-2010, Taiwan government had established the Mobile Taiwan Program, and we had conducted performance evaluation of VoIP on WiMAX. The reader is referred to [5] for the details. Based on our experience in WiMAX, we have also developed research capabilities on TD-LTE. Specifically, we have collaborated with China Mobile, Chunghwa Telecom and Nokia Siemens Networks to conduct the world's first cross-strait TD-LTE trial that connected high-definition conference calls between Taiwan and Shanghai via Hong Kong, which was a great success.

This paper measures the latency and throughput performance of W-CDMA, TD-SCDMA, WiMAX and TD-LTE based on several technical trials. The measurement results provide guidelines for the operators to deploy their future networks.

2 Test Environments

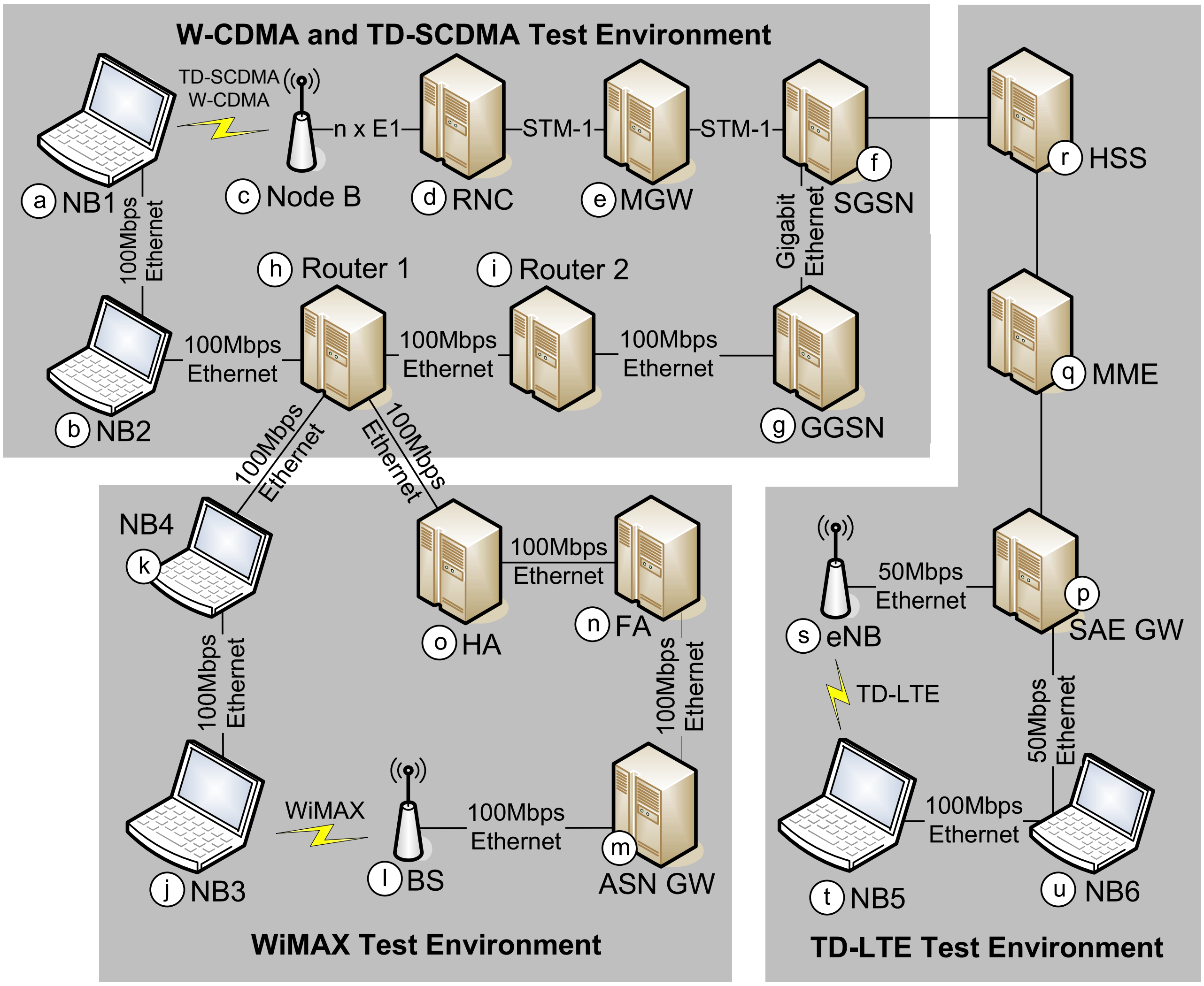


Figure 1. Test Environments of W-CDMA, TD-SCDMA, WiMAX and TD-LTE

Figure 1 introduces the test environments of W-CDMA, TD-SCDMA, WiMAX and TD-LTE. We first illustrate the test environment of W-CDMA and TD-SCDMA. We have developed a software tool for wireless performance measurement [6]. This performance measurement tool is installed in notebook 1 (NB1; see Figure 1 (a)) and notebook 2 (NB2; see Figure 1 (b)), which are connected through a 100 Mbps Ethernet link. To communicate with a *Node B* (the base station; see Figure 1 (c)), NB1 is equipped with a W-CDMA (TD-SCDMA) wireless data card. The Node B connects to the *Radio Network Controller* (RNC; see Figure 1 (d)) through several E1 links with the capacity larger than that at the radio layer (the capacity of one E1 link is 2.048 Mbps). The RNC connects to the *Media Gateway* (MGW; see Figure 1 (e)), *Serving GPRS Support Node* (SGSN; see Figure 1 (f)), and *Gateway GPRS Support Node* (GGSN; see Figure 1 (g)) through STM-1 links and Gigabit Ethernet. On the other hand, NB2 connects to router 1 (Figure 1 (h)) through another 100 Mbps Ethernet link. Similarly, router 1 connects to GGSN via router 2 (Figure 1 (i)) through 100 Mbps Ethernet links. Details of RNC, MGW, SGSN, GGSN can be found in [7].When we measure the uplink performance of W-CDMA or TD-SCDMA, the test packets are generated by NB1 and are sent to NB2 through path (a)→(c)→(d)→(e)→(f)→(g)→(i)→(h)→(b). When NB2 receives the test packets, it forwards the packets to NB1 through path (b)→(a). After NB1 has received the packets it sent out, it computes the latency and packet loss performance. When we measure the downlink performance, the test packets are generated by NB2 and sent to NB1 through the reverse path (b)→(h)→(i)→(g)→(f)→(e)→(d)→(c)→(a)→(b). Note that in this environment, the test packets are generated and received by the same notebook, which allows us to accurately measure the one-way delay without time synchronization of the sender and the receiver. We have also confirmed that the delays produced by routers 1 and 2 are less than 1 ms, and can be negligible as compared with the total delay.

In the WiMAX test environment, NB3 (Figure 1 (j)) sends packets to NB4 (Figure 1 (k)). NB3 is equipped with a WiMAX wireless data card to communicate with the WiMAX *Base Station* (BS; see Figure 1 (l)). The BS connects to the *Access Service Network Gateway* (ASN GW; see Figure 1 (m)), the *Foreign Agent* (FA; see Figure 1 (n)) and the *Home Agent* (HA; see Figure 1 (o)) through

100 Mbps Ethernet links. Similarly, NB4 connects to HA through router 1 (Figure 1 (h)) using 100 Mbps Ethernet links. The packet delivery procedure in the WiMAX test environment is similar to that in the W-CDMA/TD-SCDMA test environment, and the details are omitted.

In the TD-LTE test environement, the LTE core network includes *System Architecture Evolution* (SAE) gateway (Figure 1 (p)), *Mobility Management Entity* (MME; see Figure 1 (q)) and *Home Subscriber Server* (HSS; see Figure 1 (r)). The SAE gateway consists of *Serving Gateway* (SGW) and *Packet Data Network Gateway* (PDN GW). The SGW handles inter-enhanced Node B (eNB; see Figure 1 (s)) handover, and is responsible for routing user data packets. The PDN GW provides connectivity between the user equipment and external data packet networks. The MME is responsible for user authentication, bearer management, and monitoring idle UEs. The HSS is a central database that contains user information, which also connects to SGSN and provides user information for 3G systems. In this environment NB5 (Figure 1 (t)) sends packets to NB6 (Figure 1 (u)). NB5 is equipped with a TD-LTE data card to communicate with the eNB. The eNB connects to the SAE, and the SAE GW connects to NB6 through 50 Mbps Ethernet links. When we measure the uplink performance of TD-LTE, the test packets are delivered through path (t)→(s)→(p)→(u)→(t). For downlink performance, the test packets are delivered through the reverse path.

3 Performance Measurement

This section describes performance measurement of W-CDMA, TD-SCDMA, WiMAX and TD-LTE based on the latency and throughput of user datagram protocol (UDP) and transmission control protocol (TCP) packets. To ensure that the four systems to be evaluated are under the same "controlled" conditions, all measurements are conducted in indoor line-of-sight environments. The detailed configurations for each system are described as follows. In the W-CDMA test, the HSUPA category of the device is 3 (supports 1.46 Mbps uplink data rate), and the HSDPA category of the device is 8 (supports 7.2 Mbps downlink data rate). In our TD-SCDMA environment, the frequency bandwidth is 1.6 MHz and the ratio of uplink/downlink timeslots is set to 2:4, where the theoretical uplink/downlink rates are 384 Kbps and 2.2 Mbps, respectively. In the WiMAX test, the frequency bandwidth is 5 MHz and the uplink/downlink ratio is 2:3. A computation method was proposed in [8] to calculate the WiMAX data rates, where the maximum downlink data rate for 5 MHz bandwidth is 10.32 Mbps, and the maximum uplink data rate is 2.7 Mbps. In the TD-LTE test, the subframe configurartion is set to 1 (uplink/downlink ratio 2:3) for fair comparison with WiMAX. For LTE UE category 3 and the frequency bandwidth of 20 MHz, the theoretical maximum uplink throughput T_U is:

$$T_U = B_r \times R_b \times f_U \times \lambda_F \qquad (1)$$

where B_r is the number of bits that a resource block (RB) can transmit within a subframe. An RB includes 12 subcarriers in frequency domain and 14 symbols in time domain. Among the 14 symbols, 12 symbols are used for data transmission (2 symbols are used as reference signals).

Assume that the modulation is 16-Quadrature Amplitude Modulation (16-QAM) and the coding rate is 3/4 (i.e., best case), then $B_r = 12 \times 12 \times 4 \times 3/4 = 432$ bits. Parameter R_b is the number of RBs used for data transmission within a subframe. For 20 MHz frequency bandwidth, $R_b = 95$. Parameter f_U is the number of subframes used for uplink transmission within a frame. In TD-LTE, each 10 ms frame is divided into 10 subframes of 1 ms, and the number of subframes used for uplink transmission depends on the subframe configuration. In subframe configuration 1, there are four subframes used for uplink transmission and thus $f_U = 4$. Parameter λ_F is the rate of frames per second. Each frame spans 10 ms and $\lambda_F = 100$ frames per second. Therefore, from (1), $T_U = 16.4$ Mbps. Similarly, the maximum downlink throughput T_D is:

$$T_D = \min(B_c, B_r \cdot R_b) \times f_D \times \lambda_F \qquad (2)$$

where B_c is the maximum number of bits that a *Downlink Shared Channel* (DL-SCH) transport block can receive within a subframe. For LTE category 3, $B_c = 102048$ bits [9]. The definitions of Parameter B_r and R_b are similar to those in (1). For TD-LTE downlink, $B_r \cdot R_b = 141960$ bits (the detailed computations are omitted), which is larger than B_c. Therefore, (2) can be simplified as:

$$T_D = B_c \times f_D \times \lambda_F \qquad (3)$$

Parameter f_D is the number of subframes that are used for downlink transmission within a frame. In subframe configuration 1, there are 4 downlink subframes and 2 special subframes used for downlink transmission. Therefore, when the subframe configuration is 1, $f_D = 4 + 2 = 6$. As in (1), $\lambda_F = 100$ frames per second. Therefore, from (3), we have $T_D = 61.2$ Mbps.

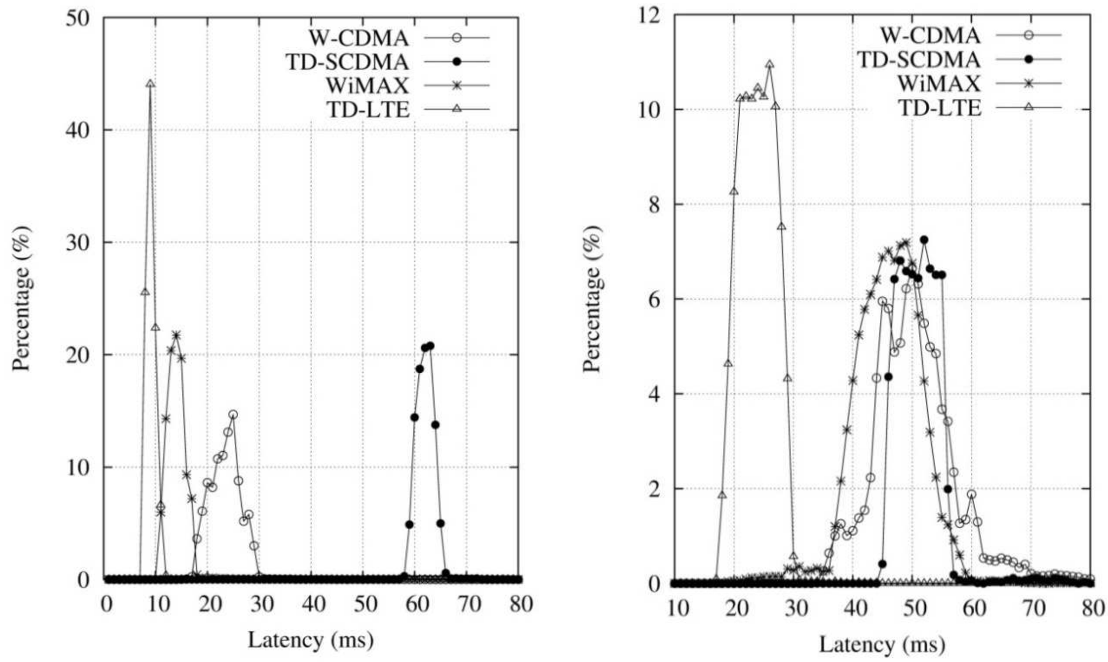
Similarly, for TD-SCDMA, the theoretical maximum downlink throughput is 2.2 Mbps and the uplink throughput is 384 Kbps. The complete configuration parameters are shown in Table 1.

Table 1. The Configuration Parameters

	W-CDMA	TD-SCDMA	WiMAX	TD-LTE
Frequency Band (Center Frequency)	UL: 1920-1975 MHz (1922.6 MHz) DL: 2110-2165 MHz (2112.6 MHz)	2010-2025 MHz (2011 MHz)	2500-2690 MHz (2635 MHz)	2570-2620 MHz (2580 MHz)
Bandwidth	5 MHz	1.6 MHz	5 MHz	20 MHz
Mode	FDD	TDD (UL:DL=2:4)	TDD (UL:DL=2:3)	TDD (UL:DL=2:3)
Maximum Transmitter Power	43 dBm (20 Watt)	36 dBm (4 Watt)	43 dBm (20 Watt)	43 dBm (20 Watt)
Modulation	UL: QPSK DL: 16QAM	UL: QPSK DL: 16QAM	Adaptive Modulation and Coding: QPSK, 16QAM, 64QAM	Adaptive Modulation and Coding: UL: QPSK, 16QAM DL: QPSK, 16QAM, 64QAM
MIMO	Not Support	Not Support	2×2 (Matrix B)	2×2 (Dynamic Open Loop)
BS Data Rate	UL: 1.46 Mbps DL: 14.4 Mbps	UL: 384 Kbps DL: 2.8 Mbps	UL: 25 Mbps DL: 25 Mbps	UL: 50 Mbps DL: 170 Mbps
Dongle Data rate	UL: 1.46 Mbps (HSUPA Category 3) DL: 7.2Mbps (HSDPA Category 8)	UL: 384 Kbps DL: 2.8 Mbps (HSDPA Category 13)	IEEE 802.16e Wave 2 Compliant	UL: 50 Mbps DL: 100 Mbps (LTE Category 3)

3.1 Latency Performance of UDP Transmission

We first measure the latency of 100-byte UDP packets periodically transmitted for every 1 ms (i.e., the IP-layer data rate of the test traffic is 800 Kbps). Then we consider VoIP and TCP performance. For each system under test, we repeated measurements for 10000 times. Figure 2 (a) and Figure 2 (b) illustrate the downlink and uplink latency histograms for each system, where the average downlink latencies of W-CDMA, TD-SCDMA, WiMAX and TD-LTE are 23.0 ms, 61.6 ms, 13.5 ms and 8.6 ms, respectively. The corresponding average uplink latencies are 56.8 ms, 290.9 ms, 45.6 ms and 23.4 ms. Poor uplink performance of TD-SCDMA is expected because TD-HSUPA is not supported in our TD-SCDMA environment. This figure also indicates that the latencies of TD-LTE are the lowest with the smallest standard deviation. Denote “>” as “better performance”, then from Figure 2, we conclude that TD-LTE > WiMAX > W-CDMA > TD-SCDMA under the parameter configurations in Table 1. Since TD-LTE and WiMAX use the same radio access technology in downlink physical layer, this result indicates that TD-LTE has better layer 2/layer 3 designs than WiMAX, which improves the latency performance.

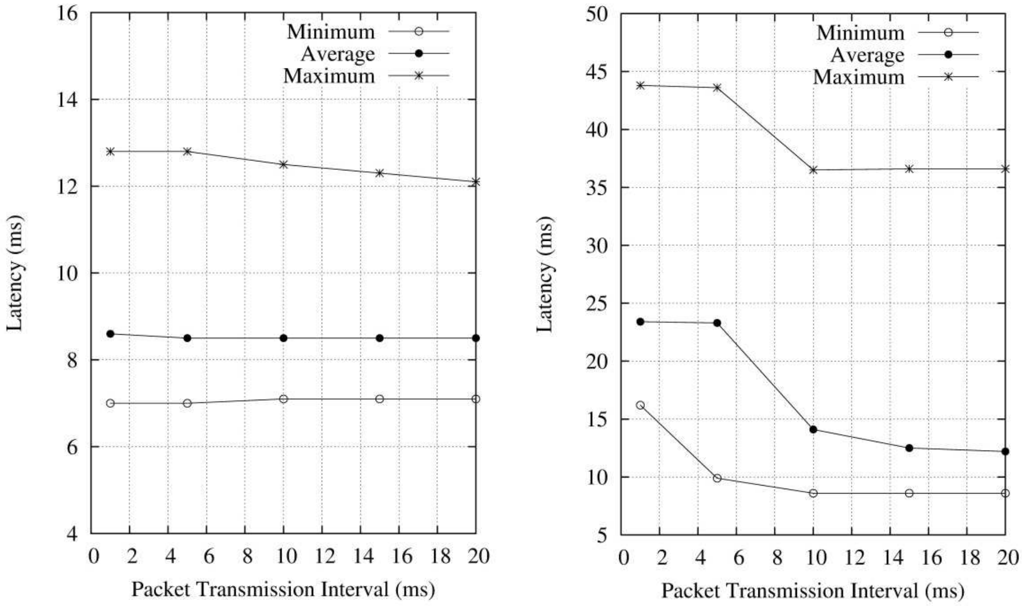


(a) Downlink Latency Histogram (b) Uplink Latency Histogram

Figure 2. Latency Histograms

The above measured results are compared with the previous studies as follows. In [10], the maximum W-CDMA downlink and uplink data rates are 384 Kbps and 64 Kbps, respectively. This work measures the latency of UDP packets periodically transmitted every 20 ms, and the size of packets is up to 40 bytes. The average measured downlink and uplink latencies are 108.3 ms and 101.1 ms, respectively. In [11], the latency performance of a live HSDPA enabled W-CDMA system was measured, where the HSDPA category of the device is 12 (supports 1.8 Mbps downlink data rate). The size of UDP packets is 105 bytes (including IP header), and the packet transmission interval is 20 ms. In this study, the average measured downlink latencies of W-CDMA with and without HSDPA are 50 ms and 111 ms, respectively, and the average uplink latency is 76 ms, which are higher than our measurements. In [12], the UDP latency performance of an operational WiMAX network was measured, which operates in the 4.9 GHz frequency band and uses 5 MHz bandwidth. In this work, 56-byte UDP packets are periodically transmitted, and the measured downlink and uplink latencies are 17 ms and 60 ms, respectively, which are higher (worse) than our measurement results.

We further investigate the TD-LTE latency for UDP packets transmitted at different speeds. Specifically, the size of UDP packet is fixed to 100 bytes and the packet transmission intervals are 1 ms, 5 ms, 10 ms, 15 ms and 20 ms, respectively. The measured results are shown in Figure 3. This figure indicates that different transmission speeds do not affect the TD-LTE downlink latency significantly. When the packet transmission interval increases from 1 ms to 20 ms, the downlink latency slightly reduces from 8.6 ms to 8.5 ms, and the standard deviation of the latencies reduces from 0.8 ms to 0.6 ms. However, for TD-LTE uplink, the shorter interval (i.e., the higher transmission speed) incurs higher latencies. When the packet transmission interval increases from 1 ms to 20 ms, the uplink latency reduces from 23.4 ms to 12.2 ms, and the standard deviations are between 2.1 ms and 4.4 ms.



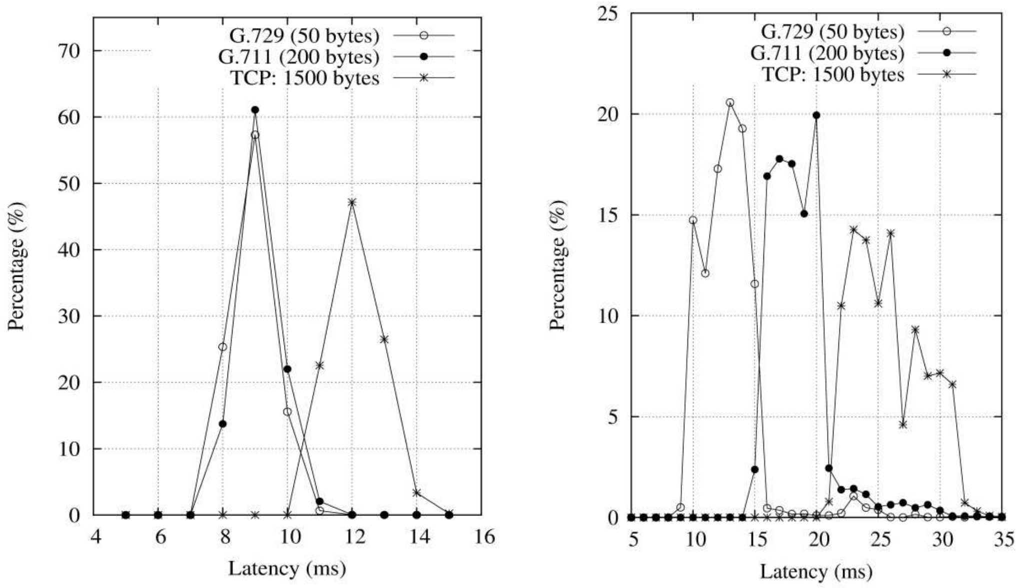
(a) Downlink Latency (b) Uplink Latency

Figure 3. TD-LTE Latency vs Packet Transmission Interval

3.2 Latency Performance of VoIP and TCP Transmissions

In this subsection, we focus on the TD-LTE latency performance of *Voice over IP* (VoIP) and TCP transmissions. G.729 and G.711 codecs are selected in our VoIP tests. The size of a G.729 VoIP packet is 50 bytes (including IP header, UDP header and RTP header), and the packet transmission interval is 10 ms. The size of a G.711 VoIP packet is 200 bytes, and the packets are sent every 20 ms. The maximum segment size of TCP packets is 1500 bytes (including IP header and TCP header), and the packet transmission interval is 10 ms. The measured average downlink latencies of G.729 and G.711 VoIP packets are 8.4 ms and 8.6 ms, and the average latency of TCP data packets is 11.8

ms, respectively. The standard deviations of G.711, G.729, and TCP packets are all 0.6 ms. For TD-LTE uplink, the average latencies of G.729, G.711, and TCP packets are 12.4 ms, 18.1 ms and 25.4 ms, and the corresponding standard deviations are 2.6 ms, 2.7 ms, 2.9 ms, respectively. We notice that TD-LTE incurs low latency in downlink packet transmission (even for large-size TCP data packets). Figure 4 (a) and (b) illustrate the TD-LTE downlink and the uplink latency histograms for G.729, G,711 and TCP packets. In terms of “better performance”, although we have a non-surprising result that G.729 > G.711 > TCP, large-packet transmission of TCP only slightly degrades the latency performance as compared with small-packet UDP transmission (i.e., G.729 and G.711).



(a) Downlink Latency Histogram (b) Uplink Latency Histogram

Figure 4. TD-LTE Latency Histograms for G.729, G.711, TCP Transmissions

3.3 Throughput Performance

In this subsection, we measure the IP-layer throughput performance for each system under test. The measured downlink and uplink IP-layer throughputs are shown in Table 2, where the downlink throughputs of TD-SCDMA, W-CDMA, WiMAX, TD-LTE are 1.8 Mbps, 6.4 Mbps, 9.6 Mbps and 49.2 Mbps. The corresponding uplink throughputs are 0.06 Mbps, 1.3 Mbps, 1.9 Mbps, 14.4 Mbps, respectively. Most measured throughputs approach their theoretical peak data rates. The TD-LTE downlink throughput is lower than the peak data rate because the TD-LTE downlink throughput is limited to the 50 Mbps bandwidth between the eNB and the core network in our environment (see Figure 1). We will elaborate more on TD-LTE downlink throughput later. In terms of "better performance", TD-LTE > WiMAX > W-CDMA > TD-SCDMA.

Table 2. IP-Layer Throughput and Spectral Efficiency

Downlink				
	TD-SCDMA	W-CDMA	WiMAX	TD-LTE
Peak Data Rate	2.2 Mbps	7.2 Mbps	10.32 Mbps	61.2 Mbps
IP-Layer Throughput	1.8 Mbps	6.4 Mbps	9.6 Mbps	49.2 Mbps
Frequency Bandwidth	1.6 MHz	5 MHz	5 MHz	20 MHz
Spectral Efficiency	1.375 bit/s/Hz	1.44 bit/s/Hz	2.06 bit/s/Hz	3.06 bit/s/Hz
Uplink				
	TD-SCDMA	W-CDMA	WiMAX	TD-LTE
Peak Data Rate	0.384 Mbps	1.46 Mbps	2.7 Mbps	16.4 Mbps
IP-Layer Throughput	0.060 Mbps	1.30 Mbps	1.9 Mbps	14.4 Mbps
Frequency Bandwidth	1.6 MHz	5 MHz	5 MHz	20 MHz
Spectral Efficiency	0.24 bit/s/Hz	0.29 bit/s/Hz	0.54 bit/s/Hz	0.82 bit/s/Hz

Since the frequency bandwidths of the investigated systems are different, we need to also consider the spectral efficiency for fair comparison. The spectral efficiency is the peak data rate divided by the frequency bandwidth. The spectral efficiency of each system is listed in Table 2, which indicates that TD-SCDMA and W-CDMA have similar downlink spectral efficiency (a bit less than 1.5 bit/s/Hz) and similar uplink spectral efficiency (a bit less than 0.3 bit/s/Hz). This table also indicates that WiMAX and TD-LTE have higher spectral efficiencies than TD-SCDMA and W-CDMA. This is a non-surprising result because WiMAX and TD-LTE support 64-QAM modulation, while TD-SCDMA and W-CDMA only support 16-QAM modulation. On the other hand, the downlink and uplink spectral efficiencies of TD-LTE are both higher than those of WiMAX under the same uplink/downlink ratio. Therefore, we have a result that TD-LTE > WiMAX > W-CDMA > TD-SCDMA, and TD-LTE has the best spectral efficiency.

We further investigate the TD-LTE throughputs measured by Nokia Siemens Network in Hangzhou, China. In the Hangzhou test environment, the bandwidth between eNB and the core network is sufficient and does not become the bottleneck. The measured downlink throughputs in Hangzhou can reach 59.1 Mbps, which is consistent with the theoretical peak data rate 61.2 Mbps. We also investigate the TD-LTE throughputs for subframe configuration 2 (uplink/downlink ratio 1:4). For subframe configuration 2, the TD-LTE uplink throughput can reach 7.3 Mbps and the downlink throughput can reach 79.8 Mbps in the Hangzhou test environment.

4. Conclusion

In this paper, we conducted the latency and the throughput measurements of W-CDMA, TD-SCDMA, WiMAX and TD-LTE based on several technical trials. Denote “>” as better latency and throughput performance, the measurement results indicate that TD-LTE > WiMAX > W-CDMA > TD-SCDMA. Our quantitative measures and comparisons provide guidelines for the operators to deploy their future networks. Clearly, migrating 3G to LTE will significantly improve the latency and the throughput performance of an operator’s network. In the early stage of migration, LTE could be deployed in the city areas to provide higher data rates. On the other hand, the 3G systems will still play a role to provide service coverage during the migration.

For specific applications such as remote healthcare, it is essential to utilize broadband wireless communications between the users and the healthcare center [13]. In particular, we intend to implement a robot application to watch aging resident at home. In this scenario, the command must be issued from the healthcare center using wireless downlink with short and low-variance delays. Figure 2 (a) indicates that TD-LTE satisfies this requirement the best among the four wireless technologies. Also, the robot monitors the aging persons with high-definition video camera, and the video will be sent back to the healthcare center with real-time wireless uplink. Again, Figure 2 (b) suggests that TD-LTE is the best solution. Currently, we are developing the healthcare robot applications controlled by TD-LTE based on the NSN/Aldebaran solution (see Figure 5).

This work targets on time-to-value impact within 3-5 years to assist network planning of mobile telecom operators who are developing LTE network. Our work can also serve as a tutorial to guide researchers to measure and test future features of LTE. Specifically, we are currently extending our work for video/streaming, circuit switched (CS) fallback, and single radio voice call continuity (SRVCC) measurement/testing for LTE. In our future work, multiple TD-LTE and

WiMAX base stations will be considered to investigate mobility issues such as handover. We will also investigate the inter-operability between TD-LTE/LTE FDD and migration from WiMAX to TD-LTE.

Figure 5. NSN/Aldebaran Robot Solution

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