High-end LTE Service Evolution in Korea: 4 Years of Nationwide Mobile Network Measurements

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***Abstract*—This paper provides a temporal cellular and WiFi networks analysis from a nationwide crowdsourcing measurement study. Our dataset consists of 2.98M user-initiated quality tests on 3G/LTE/WiFi involving 157K mobile devices from Nov. 2012 to July 2016 (187 weeks) in South Korea. Our analysis explains changes in QoS from the user perspective, not Mobile Network Operators (MNO). We revealed that WiFi shows twice higher compounded quarterly growth rate for download throughput against LTE. Yet, LTE and WiFi show almost no difference in absolute download throughput value as of mid 2016. Second, LTE delivers relatively low latency, less-varying loss rate, and higher throughput in overall. Finally, the result shows that the evolution for the high-end LTE services has been faster than user adoption, where the majority of the LTE users stays below 75 Mbps of throughput.**

***Index Terms*—Traffic Measurement, LTE, LTE-A, WiFi**

I. Introduction

Akamai's 2016 Q2 report[1] on Internet connection speed ranks South Korea as #1 with 27 Mbps. Also, the 2015 OECD broadband survey[2] states the country's mobile network speed varying between 7 and 75 Mbps. The local MNOs' in-house measurements often announce that their nationwide wireless coverage reaches to hundreds of Mbps. We get these mixed signals on how much mobile speed that we can actually get in everyday life. We are missing a long-term analysis in which the country has fairly seamless cellular/WiFi connection in underground subway, buses, and buildings.

In this paper, we investigate mobile network performance using the 4 years of crowdsourcing data in a collaboration with the government organization, called National Information Society Agency (NIA). Our focus is to understand spatial-temporal 3G/LTE/WiFi performance characteristics from these years of data. We present the quality evolution from the user side. Several major findings are:

- After a few years of LTE's superiority over WiFi, we observe very close absolute values of download throughput between the two in mid 2016.
- Unlike the previous reports from other countries, LTE delivers low jitter, less-varying loss rate, and higher and reliable throughput overall.
- The majority of LTE users is still kept under 75 Mbps regardless of years-long advances in high-end LTE services.

We consider mobile network as an essential life necessity and public resource, and LTE and WiFi complement each other. The results show that the high-speed services are indeed available and the observed throughputs are impressive. At the same time, their availability is fairly limited; only small fraction of users benefit from the latest LTE-A technologies. Even when we take it into consideration that new features are only available on latest devices[3] and in limited areas, the fraction exceeding 75 Mbps seems much smaller than what we expect from MNOs' advertisement.

This paper is organized as follows. It first provides a brief overview of crowdsourcing measurement app and the collected dataset in Section II. In Section III, we characterize our performance test results. Section IV discusses evidence for user shifting in market and invisible (yet observed) ceiling of users' throughput. Section V presents the related work. Section VI concludes with the future work.

II. Dataset

As part of NIA's network performance measurement platform[1], its crowdsourcing mobile app (Fig. 1(a)) has been available for user-initiated voluntary testing since 2012. The dataset is collected from Nov. 2012 through July 2016 (1,313 days, 187 weeks). In total, we observe 2,988,376 tests from 157,013 unique devices. We filter 2,949,120 valid test results (98.7% of all tests) where the rest of 39,256 tests (1.3%) report out-of-range values due to timeout or poor network condition. On average, the dataset shows 19.0 tests per device and 2,275.9 tests per day. The app is based on iPerf[4], supporting both Android and iOS, to observe basic metrics in nomad, such

[1] http://speed.nia.or.kr

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(a) (b) (c)

Fig. 1: (a) Performance measurement app in Android & iOS; (b) OpenSignal's 3G/4G signal coverage map of South Korea (2016), green –> strong, red –> poor signal; (c) GPS locations of collected user tests (approximately 300 km by 600 km).

TABLE I: Allocated band spectrum for country's top 3 MNOs

MNO	3G (MHz)	LTE (MHz)
A	UMTS: 2100, CDMA2000: 1800	900, 1800, 2100
B	CDMA2000: 1800	850, 2100, 2600
C	UMTS: 2100, CDMA2000: 800	850, 1800, 2100

as download/upload throughput, loss, jitter, etc. Along with the metrics, the following information is gathered for further analysis: GPS, device ID, MCC, MNC, network type, duration, etc. NIA does not disclose the detailed measurement method, but we can observe that a single round of measurement consists of two TCP-based 10-second-long throughput tests, one for download and the other for upload, and one UDP-based 5-second-long loss/jitter test. For the loss/jitter test, the client sends short packets including a sequence number and timestamp at 100ms interval, and receives echoed responses from the server. Although the test method could have slightly evolved over the 4 years, we believe that the basic mechanism remains the same.

Fig. 1(b) and 1(c) shows OpenSignal's 3G/4G signal coverage map [5] of South Korea in 2016 and GPS locations of our user collections, respectively. These maps illustrate nationwide strong signal coverage and user datasets.

The measurement server locations are undisclosed, but they are located within the major MNOs' data centers with dedicated lines under the government regulation. We observe 339 mobile country codes (MCC) and mobile network codes (MNC) and exclude the tests having the overseas codes in our analysis (e.g., China Telecom, Verizon, T-mobile, etc.). The 97% of all valid tests belong to the Korean MCC.

In this paper, we refer both 4G LTE and LTE-Advanced (LTE-A) as LTE. The country's top 3 MNOs share 99% of all mobile subscribers and provide very competitive QoS. Table I shows the band spectrum monitored. A certain set of spectrums (e.g., MNO C) can have higher connectivity with relatively less resources. Fig. 2 illustrates the deployment of high-end LTE services in the country. Its quality is typically classified by the maximum download throughput at the user side. According to the timeline, we should be benefiting from 500 Mbps theoretically for now.

Fig. 3 shows monthly distribution of test counts for all years. Since the wide deployment of LTE, 3G is disappearing fast in mobile subscriber market and repositioning itself for lightweight IoT communications. Test counts also reflect the change between LTE and 3G. The LTE test counts have been consistently higher than WiFi since the beginning of our study.

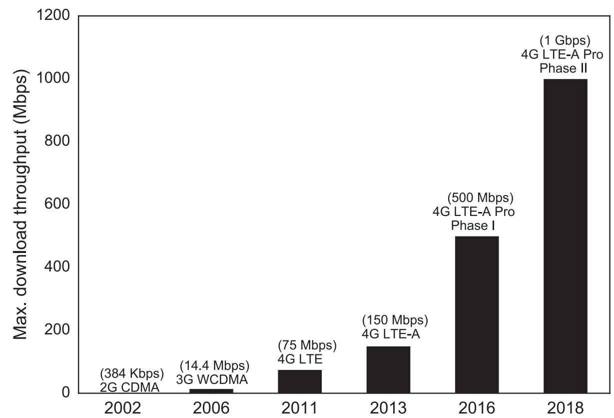


Fig. 2: Cellular network deployments evolution in South Korea [6]

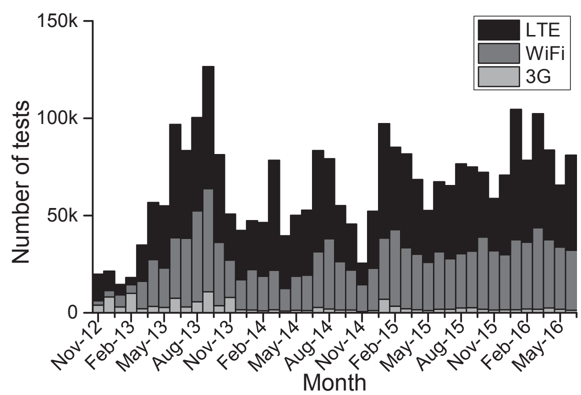


Fig. 3: Monthly test counts of 3G/LTE/WiFi

III. Observations

A. Download and upload throughput

Our temporal throughput analysis (Fig. 4) shows monotonically increasing trends for WiFi. However, the LTE throughput is slightly decreasing after jumping up in early 2015, which we believe is due to the invisible ceiling to be discussed in Section IV-B. Table II shows the compounded quarterly growth rates (CQGR) of download and upload throughput of 3G/LTE/WiFi. We observe that WiFi's CQGR almost doubles the LTE's (6.02 vs. 11.35%), yet their absolute download throughput values are comparable as of mid 2016 (62.84 vs. 62.87 Mbps). From the beginning of this experiment, LTE outperforms WiFi downloading by more than twice (26.15 vs. 12.53 Mbps) and this gap continues until 2015 3Q (71.86 vs. 51.82 Mbps). Deploying LTE-A in late 2013 increases the gap even further. In 2016, a slight drop in LTE (2016 2Q and 3Q) and the government influence on WiFi upgrade led to the competitive throughput performance. 3G is no longer a comparison where its throughput is 10 to 15 times lower than LTE and WiFi. Overall, LTE outperforms WiFi continuously ever since its rollout in South Korea, unlike the other studies showed [7][8].

In terms of upload throughput, only WiFi shows significant increase over the years. The MNOs have no intention to allocate more spectrum for uploading purpose in LTE. On the other hand, upgrade in WiFi has an impact on both upload and download. In this paper, we omit the further analysis on upload since its nature remains steady.

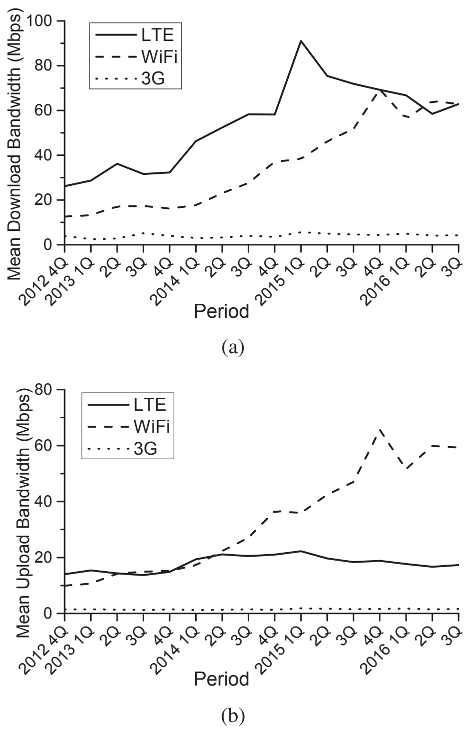


Fig. 4: (a) Quarterly download throughput of 3G/LTE/WiFi; (b) Quarterly upload throughput of 3G/LTE/WiFi

By looking at the 95^{th} percentile, Fig. 5 finds the three distinguishing periods indicating major performance improvements:

- Period 1: Nov. 2012∼Nov. 2013 (52.00∼69.15 Mbps)
- Period 2: Dec. 2013∼Nov. 2014 (98.54∼141.82 Mbps)
- Period 3: Dec. 2014∼July 2016 (154.02∼228.20 Mbps)

This phenomenon is related to the deployment of high-end LTE technologies. A wideband LTE was commercially deployed in the metropolitan areas around Dec. 2013, in between Period 1 and 2. In Dec. 2014, all three MNOs launched multi-band aggregated LTE-A services. Our test results correctly reflect these newer technologies in place and verify that they work effectively from the user perspective.

Table III highlights the time bias in download throughput. For 3G and WiFi, their daytime throughputs are higher than those of the night throughout the whole period, except for 3G in 2012. The most significant bias was present in 2014 WiFi; its difference was 25.6%, about 10 Mbps in absolute value. On the contrary, the LTE throughput is higher at the night and its gap increases over the years. Our finding here corresponds to [9] considering its network performance dependency on time.

B. Jitter and loss

Fig. 6(a) clearly shows the improvement of UDP jitter on both LTE and WiFi in recent years. We observe, while the WiFI and LTE jitters are getting close (39.77 ms vs. 39.55 ms in 2016, while 71.78 ms vs. 47.39 ms in 2013), the WiFi jitter is highly varying compared to LTE.

Regarding to the UDP loss rate, we exclude the loss rate of 100% from our analysis which implying traffic filtering middlebox or policy in place at the time of measurement. We

TABLE II: CQGR for Quarterly download and upload throughput of 3G/LTE/WiFi

	3G	LTE	WiFi
CQGR for Download Throughput (%)	0.47	6.02	11.35
CQGR for Upload Throughput (%)	0.58	1.40	12.65

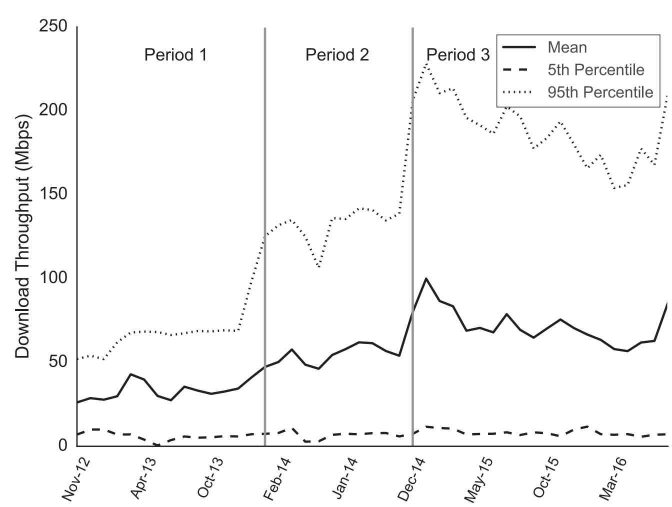
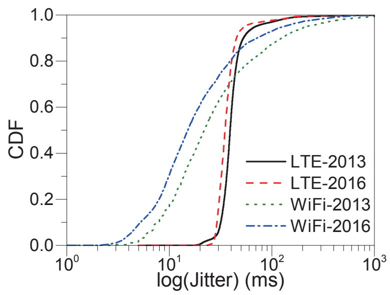


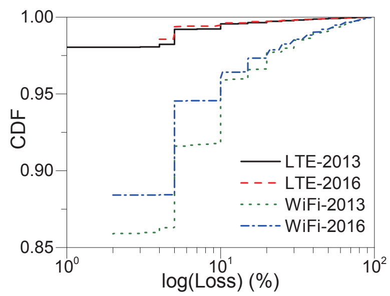
Fig. 5: Monthly mean, 5^{th}, and 95^{th} percentile download throughput for LTE

TABLE III: Spotting time bias in measurement: Daytime (9 am. to 7 pm.) and Night (7 pm. to 9 am.)

	Mean Download Throughput (Mbps)								
	3G			LTE			WiFi		
year	Day	Night	Difference	Day	Night	Difference	Day	Night	Difference
2012	3.81	3.86	-1.19%	33.40	32.37	3.19%	18.36	17.52	4.78%
2013	3.93	3.85	2.07%	44.99	45.34	-0.78%	25.76	21.28	21.09%
2014	4.83	4.03	19.75%	67.57	69.62	-2.94%	48.89	38.92	25.63%
2015	5.01	4.34	15.39%	69.93	79.82	-12.40%	61.47	52.29	17.54%
2016	4.39	3.93	11.81%	60.72	74.71	-18.73%	64.82	60.05	7.94%

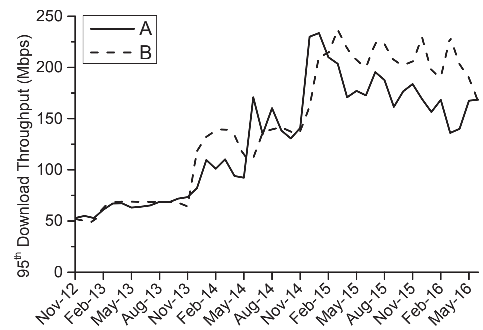


(a) jitter

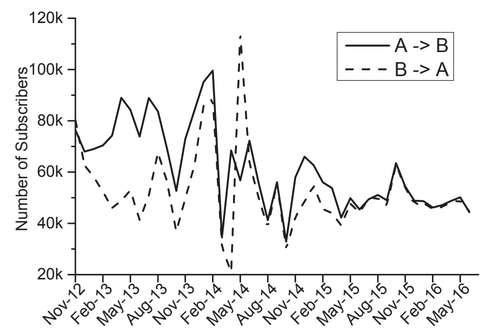


(b) loss

Fig. 6: CDFs of jitter and loss for LTE and WiFi: 2013 to 2016



(a) 95^{th} download throughput



(b) Number of subscribers shifts

Fig. 7: (a) Monthly 95^{th} percentile LTE download throughputs of MNO A and B; (b) The number of subscriber shifts from A to B and vice versa.

observe that the loss rate distribution shows a similar pattern of the jitter analysis. LTE consistently outperforms WiFi (1.97% vs. 0.19% on average) and the variation of WiFi is severe. Fig. 6(b) shows that more than 97% of LTE tests show 0% loss rate, it is likewise for 85% of WiFi. However, WiFi itself has some improvements from 2013 to 2016. LTE's loss rate remains steady from the beginning.

IV. Discussion

This section presents empirical evidence for user shifting according to the demand for higher quality services. We also observe that the users are not fully enjoying QoS that high-end LTE services can offer.

A. *Speed competition*

The mobile market is saturated where there are 57M subscribers in the country of 45M people. The MNOs have been playing a zero-sum-game for market share and yet trying to steal more customers from their competitors. The network performance is often used as marketing hype. We focus on the implication of throughput competition in the aspect of subscriber shifts between the MNOs. Fig. 7(a) shows the monthly 95^{th} percentile LTE download throughput for MNO A and B. To avoid bias, we exclude MNO C from here since its monthly stats are inconsistent throughout the entire monitoring period. There has been many up and downs between the two till Feb. 2015. After 2015, MNO B shows continuously better throughput for one and half years (approximately 10 to 50 Mbps gap). Fig. 7(b) depicts the number of subscriber shifts from MNO A to B and vice versa for every month. A subscriber can switch his/her MNO without changing the phone number. When MNO A and B are in a close competition for throughput, these subscriber shifts also fluctuate closely and no clear winner is present overall. As MNO B shows improvement over A from 2015, the subscriber shifts remain steady in a scale of 50K per month. From the early phase of measurements, we observe that a rigorous throughput competition contributes to more dynamic subscriber shifts.

Of course, our throughput analysis is not the sole reason for this phenomenon. There could be other issues such as pricing, device lifecycle, government regulation, etc. We leave this for future work.

B. Invisible ceiling: Limited to 75 Mbps

Although LTE data plans range from premium to economic in terms of throughput and data cap, our study shows that a majority of users are bounded by an invisible ceiling, which empirically limits to certain degree of QoS status. Table IV shows a throughput range distribution of the LTE users. Since the plain LTE deployment in 2011 (Fig 2), the ratios of throughput under 75 Mbps are 98%, 77%, 63%, and 74% from 2012-2016. The ratio for over 75 Mbps is increasing slowly after the high-end LTE services in 2013, such as LTE-A: 75-150, LTE-A Cat.6: 150-300, and LTE-A Cat.9: 300+ Mbps. Only 13% and 6% are enjoying within 150-300 Mbps in 2015 and 2016, respectively. After almost three years of high-end LTE services in place, the user-side QoS is not growing as much as we have seen in 2011. The benefit of LTE-A is not just the maximum speed but also providing more stable performance by exploiting new features (e.g., carrier aggregation). Unfortunately, we do not observe clear improvement in throughput for the majority of users in the last few years.

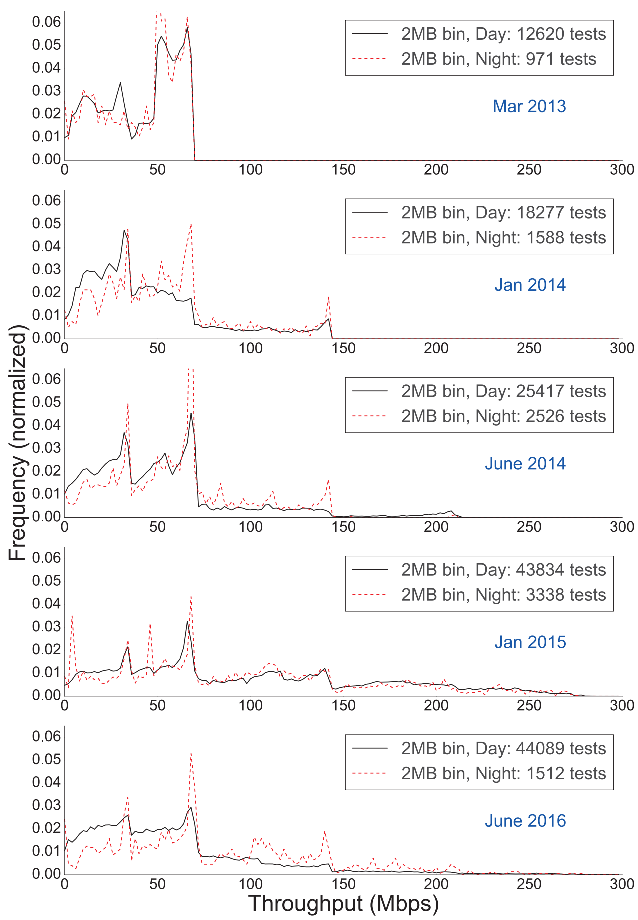


Fig. 8: LTE download throughput distributions of day and night on Mar. 2013, Jan. 2014, June 2014, Jan. 2015, and June 2016. 2MB bin is used to sort (normalized).

Fig. 8 shows the evolution of download throughput distributions for daytime (9am-7pm) and nighttime (7pm-9am) to observe possible congestion impacts in daytime. However, there is no clear sign of throughput degradation during daytime.

We can also observe the deployment of new high-speed services but the fraction exceeding 75Mbps is not growing. It is often the case that one cannot observe expected performance even with a latest device in an LTE-A service area. Mobile speedtest results are highly sensitive to the user environment; throughputs differ by geographical location (e.g., service availability) and time (e.g., congestion) as well as other factors such as signal interference, device position, and background tasks on the device [10]. One of our contributions is to reveal the limited availability of high-speed services by the actual throughput distributions over time.

Table V summarizes available LTE data plans for MNO B. The other MNOs keep very similar plans as well. Tethering and P2P services are only allowed under the data cap and they are blocked winthin the rate limiting stage. Some plans provide free data access for selective services only: music or video streaming, which requires maximum 2-3 Mbps in trasnfer. It will not be accounted for data cap. The user average of LTE data usage in Korea reaches 6.2 GB per month in Jan. 2017 [11]. Meanwhile, the users in their twenty's show 12.2 GB on average per month. And the users in their twenty's and taking 'Premium Unlimited' plan reveal 21.5 GB. The rate limiting mechanism after the data cap may compromise the overall throughput experience.

There seems to exist a gap between supply and demand for high-speed services. The average revenue per mobile subscription is reported to be declining [12], and MNOs are trying to increase revenue from high-end services. However, the current quality of LTE services is good enough for most applications, and a majority of users prefer affordable subscription plans to high-speed. Another factor could be the lack of user motivations. The transition from LTE to LTE-A is less visible than that from 3G to LTE; it is rare for users to notice differences by performance and also psychologically there is no LTE-A sign shown on a device.

V. Related Work

We focus on the related studies of the cellular and WiFi performance in real-world crowdsourcing cases.

Event-based measurements: Farshad et al. [13] used mobile crowdsourcing to characterize the WiFi performance in Edinburgh. Erman et al. [14] analyzed the Super Bowl and provided a detailed analysis of the AT&T's performance and the user behavior. Shafiq et al. [15] described network provider observations of two crowded events and made suggestions to improve with minimal costs. Frommgen et al. [16] described also another serious cellular performance degradation at the German music festival, having 1,000 visitors per day. Analysis done on these crowded events is to cope with the difficulties in future event.

Weeks or month-long measurements: Sommers et al. [7] show that WiFi outperforms the cellular network from 3M

TABLE IV: LTE download throughput range distribution

	Throughput Ranges				
Year	(0-15] Mbps	(15-75] Mbps	(75-150] Mbps	(150-300] Mbps	300+ Mbps
2012	5,290 (22%)	18,563 (78%)	0	0	0
2013	102,154 (25%)	294,617 (73%)	9,026 (2%)	0	0
2014	48,461 (13%)	249,611 (64%)	81,175 (21%)	8,459 (2%)	0
2015	47,709 (10%)	255,341 (53%)	112,879 (24%)	62,667 (13%)	1 (0%)
2016	35,189 (12%)	183,512 (62%)	57,472 (19%)	17,683 (6%)	926 (0.3%)

TABLE V: LTE data plans as of 2016 (MNO B)

LTE Plans	Data Cap (GB/month)	After Exceeding Data Cap	Pricing (approx. $/month)
Premium Unlimited	30, 25, 17, 15, 12, 10, 5	Extra 2 GB per day is given. After 2 GB, unlimited with max 3 Mbps rate limiting (5 Mbps for 30 GB plan).	$95, 92, 70, 60, 45, 40, 35
Partial Unlimited	6, 3, 2, 1, 0.3	For designated 3 hours per day only, unlimited with max 3 Mbps rate limiting.	$45, 40, 35, 30, 25
Unlimited A	15	Unlimited with max 3 Mbps rate limiting.	$50
Unlimited B	0.45	Unlimited with max 400 Kbps rate limiting.	$35
Unlimited C (kids only)	4.7, 4.5, 3, 2.5, 2, 1.4	Max 400 Kbps rate limiting for 4.7G, 4.5G plans only. With an extra data cap purchase, max 2 Mbps rate limiting.	$32, 27, 25, 28, 23, 20
Limited	2.5, 1.5, 0.75	No access. The left over data can be transferred to next month.	$40, 35, 30

user-initiated tests for 15 weeks in US cities. Nikravesh et al. [9] evaluated a long time crowdsourcing measurement and found a high variance in performance metrics as well as carriers. Xu et al. [17] used 23 users' data to investigate 3G performance in Singapore and identified unique traffic characteristics in a newer 3G type. Sundaresan et al. [18] characterized the WiFi throughput variance from 66 home routers in 15 countries. Fukuda et al. [19] focused on smartphone user behavior from the 15-days-long samples over a couple of years in Tokyo. Our previous work [8] presented WiFi's favor over LTE from several weeks-long data sets from 83 users in Seoul.

In Japan, the government took a different approach from crowdsourcing, and set guidelines in 2015 for MNOs on publishing actual throughputs. Three major MNOs publish their own measurement reports [20][21][22], sampling 1,500 locations from 10 cities, as defined in the guidelines. The results shown as quartiles along with the maximum and minimum values are consistent with our observations: the 75^{th} percentile is far below the maximum, even though they are using high-end devices for measurements.

We are yet to find a similar work on years-long crowdsourcing for all 3G/LTE/ WiFi measurements together. Our dataset is also geologically sparse for a large crowd: 2.9M tests, 157K unique users across the nation. To the best of our knowledge, this paper is the first of its kind discussing a long-term scale advance in LTE and its competition to WiFi from user-side stats.

However, there is possible bias in our analysis. The measurements are from more tech-savvy users than ordinary users. Users often try speedtest after upgrading their devices or services. On the other hand, users experiencing poor performance may try speedtest. But we see only a small fraction for poor performing users. So, high-end users may be over-represented in the results (especially, the high speed in 2015 may be explained by this bias). Nontheless, the results capture the trend for overall mobile users.

VI. Conclusion

This paper investigated temporal 3G/LTE/WiFi performance characteristics from the 4 years of crowdsourcing mobile user tests. We find that LTE has been consistently outperformed WiFi in throughput, jitter, and loss rate with relatively less variances since its wide deployment in the country. Their performance gap is recently reduced due to a slight drop in LTE and gain in WiFi. Overall, we show an empirical evidence of invisible performance ceiling which implies that the evolution of the high-end LTE service deployment has been faster than user adoption. The majority of the LTE users stays under 75 Mbps throughput where its theoretical bound should be well over 300 Mbps as in 2016.

Our results indicate that just competing for high-speed may not bring overall customer satisfaction. MNOs and policy makers might need to seek a better strategy to raise overall throughput. To this end, this is an important step to make the detailed speedtest measurements available for analysis. For future work, we plan to integrate the wired and wireless network measurement results to research a possible cause for longitudinal network performance stability.

Acknowledgment

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References

[1] D. Belson, "akamai's state of the internet - q2 2016 report," akamai, Tech. Rep., September 2016.

[2] OECD, "Oecd broadband portal," OECD, Tech. Rep., 2015. [Online]. Available: http://www.oecd.org/sti/broadband/oecdbroadbandportal.htm

[3] "Devices with LTE-A Support," https://en.wikipedia.org/wiki/List_of_devices_with_LTE_Advanced/.

[4] "iPerf," https://iperf.fr/.

[5] "OpenSignal: 3G and 4G LTE Cell Coverage Map," https://opensignal.com/.
[6] "Netmanias. SK Telecom Strategy," http://www.netmanias.com/en/post/blog/10035/5g-iot-lte-sk-telecom-samsung/sk-telecom-s-strategies-for-next-generation-network-evolution/.
[7] J. Sommers and P. Barford, "Cell vs. wifi: on the performance of metro area mobile connections," in *Proceedings of the 2012 ACM conference on Internet measurement conference*. ACM, 2012, pp. 301–314.
[8] J. Hyun, Y. Won, J.-H. Yoo, and J. W.-K. Hong, "Measurement and analysis of application-level crowd-sourced lte and lte-a networks," in *NetSoft Conference and Workshops (NetSoft), 2016 IEEE*. IEEE, 2016, pp. 269–276.
[9] A. Nikravesh, D. R. Choffnes, E. Katz-Bassett, Z. M. Mao, and M. Welsh, "Mobile network performance from user devices: A longitudinal, multidimensional analysis," in *International Conference on Passive and Active Network Measurement*. Springer, 2014, pp. 12–22.
[10] A. Gember, A. Akella, J. Pang, A. Varshavsky, and R. Caceres, "Obtaining in-context measurements of cellular network performance," in *Proceedings of the 2012 ACM conference on Internet measurement conference*. ACM, 2012, pp. 287–300.
[11] "Korea Telecom, Big Data Center," http://www.kt.com/eng/.
[12] "Netmanias. SK Telecom Market Stagnation," http://www.netmanias.com/en/?m=view&id=blog&no=10974/.
[13] A. Farshad, M. K. Marina, and F. Garcia, "Urban wifi characterization via mobile crowdsensing," in *2014 IEEE Network Operations and Management Symposium (NOMS)*. IEEE, 2014, pp. 1–9.
[14] J. Erman and K. K. Ramakrishnan, "Understanding the super-sized traffic of the super bowl," in *Proceedings of the 2013 conference on Internet measurement conference*. ACM, 2013, pp. 353–360.
[15] M. Z. Shafiq, L. Ji, A. X. Liu, J. Pang, S. Venkataraman, and J. Wang, "A first look at cellular network performance during crowded events," in *ACM SIGMETRICS Performance Evaluation Review*, vol. 41. ACM, 2013, pp. 17–28.
[16] A. Frömmgen, J. Heuschkel, P. Jahnke, F. Cuozzo, I. Schweizer, P. Eugster, M. Mühlhäuser, and A. Buchmann, "Crowdsourcing measurements of mobile network performance and mobility during a large scale event," in *International Conference on Passive and Active Network Measurement*. Springer, 2016, pp. 70–82.
[17] Y. Xu, Z. Wang, W. K. Leong, and B. Leong, "An end-to-end measurement study of modern cellular data networks," in *International Conference on Passive and Active Network Measurement*. Springer, 2014, pp. 34–45.
[18] S. Sundaresan, N. Feamster, and R. Teixeira, "Measuring the performance of user traffic in home wireless networks," in *International Conference on Passive and Active Network Measurement*. Springer, 2015, pp. 305–317.
[19] K. Fukuda, H. Asai, and K. Nagami, "Tracking the evolution and diversity in network usage of smartphones," in *Proceedings of the 2015 ACM conference on Internet measurement conference*. ACM, 2015, pp. 253–266.
[20] "NTT DoCoMo. Speedtest results (in Japanese)," https://www.nttdocomo.co.jp/support/area/effective_speed/.
[21] "KDDI AU. Speedtest results (in Japanese)," https://www.au.com/mobile/area/effective-speed/.
[22] "Softbank. Speedtest results (in Japanese)," http://www.softbank.jp/mobile/network/explanation/speed-survey/.