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LTE and WiFi: Experiences with Quality and Consumption

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Abstract

Numerous reports over the past few years have noted that wireless data consumption continues to increase at incredible rates. Such growth rates tend to be felt most acutely in the cellular space where smartphones and tablets continue to increase in capability and popularity. Unfortunately, there exists limited public data with regards to fine-grained user performance, particularly with regards to the transition between 3G and LTE and the interplay between 3G, LTE, and WiFi. The focus of this paper is to offer insight into these particular transition points as gleaned from nearly two hundred well-instrumented smartphone users. Specifically, we note the considerable impact that the quality of smartphone WiFi plays in addition to noting that consumption across WiFi and cellular tends to stay remarkably consistent once sufficient cellular speeds are achieved. We conclude our paper with a variety of research and data challenges that we pose to the wireless networking community.

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Keywords: Measurement, Mobility, WiFi, LTE, 3G

1. Introduction

In the past few years, cellular and wireless data consumption have experienced breathtaking growth. With device capabilities continuing to grow in terms of processing power, pixel density, screen size, and application diversity, demand is unlikely to abate any time in the near future. Furthermore, new demands via the Internet of Things (IoT) loom heavily on the horizon driving wireless service providers to embrace multi-tiered strategies to meet increasing demand. The aptly dubbed *data tsunami* represents considerable technical and policy challenges that have attracted considerable research efforts from the wireless community.

From the myriad of technologies available, *WiFi offloading* has emerged as one of the centerpieces of service provider strategy. Two critical efforts in this space are beginning to gain traction including ANDSF (Access Network Discovery and Selection Function)[1] and Hotspot 2.0[2]. ANDSF provides awareness and policy to mobile devices while Hotspot 2.0 streamlines joining WiFi by providing automatic login and additional access point interrogation mechanisms. In short, ANDSF tells the device whom to trust while Hotspot 2.0 provides the mechanisms to join those trusted networks without user intervention. Though tremendously complex with regards to their implementation and integration into existing networks, progress continues in terms of pilot deployments and development.

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The focus of this paper though is not on how to discover or how to join WiFi but rather on the analysis of what actually happens with WiFi in practice, namely *how does user data consumption change between cellular and WiFi* and *to what extent do design decisions at the device impact that consumption*? While several studies have explored the impact of WiFi offloading[3,4], there exists limited public data studying offloading with much of the existing network literature focusing on peak performance rather than observed data consumption. In this paper, we leverage our NetSense smartphone study of nearly two hundred students over a period of two and a half years to conduct an in-depth study of WiFi performance in practice. Through the use of a fine-grained user-level agent, we are able to observe actual user WiFi and cellular performance. Most notably, the monitoring period includes a handset refresh affording the opportunity to study usage changes across changing wireless technologies (3G vs. LTE) and device design (Nexus S vs. Galaxy S4 / HTC ONE). Hence, the key contributions of our work are as follows:

- *Analyze the transitional impact of WiFi design quality:* We observe the impact of transitioning from low quality WiFi at the mobile device (Nexus S) to significantly improved WiFi with newer handset models, all the while with the campus WiFi infrastructure relatively unchanged. In contrast to our prior work[4] which noted potential roadblocks for WiFi, we find in this work that device design plays a tremendous role in WiFi offloading with new handsets delivering an order of magnitude more consumption versus the Nexus S bringing performance back in line and even beyond prior results[3]. The potential impact of low-quality WiFi in the handset could have significant implications for bargain or low-cost cellular providers (ex. MVNOs) aiming to reduce handset costs.
- *Analyze the transitional impact of 3G vs. LTE:* We observe the impact of transitioning to LTE-capable handsets with our study cohort. We believe our work is the first work to observe such transitions. Most critically, we compare and contrast the respective 'burn rates' for data between cellular only and mixed cellular / WiFi environments. We find that users tend not to dramatically adjust their consumption habits in the pure cellular environment with sufficient network speeds (LTE). Moreover, we find that downlink versus uplink ratios tended to stay similar across both mixed and pure cellular environments (roughly 4:1).

The remainder of our paper is organized as follows. In Section 2, we compare and discuss several pieces of related work to our own paper. Next, in Section 3, we discuss the NetSense study dataset and key characteristics of the dataset as related to this paper. Section 4 presents the key findings of the paper related to transitioning between 3G, LTE, and better WiFi support. Finally, Section 5 offers several concluding remarks and open data collection / research challenges.

2. Related Work

With regards to related work, we examine two distinct categories of work: *smartphone data gathering efforts* and *WiFi optimization*. In the first case, we compare / contrast versus other on-going data collection efforts. In the second case, we explore various works examining WiFi offloading both from a performance perspective as well as larger system-level optimizations.

To start, the notion of high quality, fine-grained usage data is an extremely challenging topic for the community. Although wireless service providers possess significant bodies of performance data, challenges with respect to user privacy and competitive advantage prevent wholesale sharing of information. Hence, researchers are left to either collaborate with wireless service providers directly[5] or deploy their own studies[6]. Our own NetSense study was one of the first large scale studies[6,7,8,9] in part having been inspired from a data collection perspective heavily by the work of the MIT Reality Mining group[10]. While our study was just beginning, other studies have also stood up including the PhoneLab system (500 users)[7], LiveLabs[8], the Nokia Data Challenge, and more recently even larger scale efforts (1k users) with the Copenhagen Networks study[9]. As noted by our experience as well as by others in the space, data gathering on such larger scales are typically quite time consuming and expensive though invaluable for the purposes of effective comparisons and contrast versus industry-centric efforts.

The notion of WiFi offloading performance has received only limited attention, in part due to the relative dearth of publicly available data. One of the earliest studies[3] characterized the potential for WiFi offloading at roughly 65% of the total consumed bandwidth with significant battery savings as well if communications could be delayed. Similar energy savings were also observed in the work in[11]. The works in[12] and[13] both focused on enhancing existing 3G infrastructure with WiFi. Our own results in[4] cast serious doubts on the broader applicability of WiFi showing cases where cellular consumption can often exceed WiFi. Furthermore, poor WiFi design can also be a significant factor for increased battery drain as evidenced by[14]. In particular, we dive deeper in this work showing that handset design choices dominate and were the likely culprit fpr the reduced WiFi offloading of our prior work.

Other works have looked more broadly at using WiFi in conjunction with cellular[15] rather than as a replacement. Alternatively, there have been several studies exploring publicly[16] and privately[17] gathered available WiFi / cellular performance tests. Notably, such analytic efforts tend to focus on mobile network performance rather than actual device consumption of the users. Finally, the emergence of the *802.11hew* working group has noted the need for refinement of WiFi in ultra-dense environments, particularly those of sporting events for improved performance.

3. NetSense Dataset

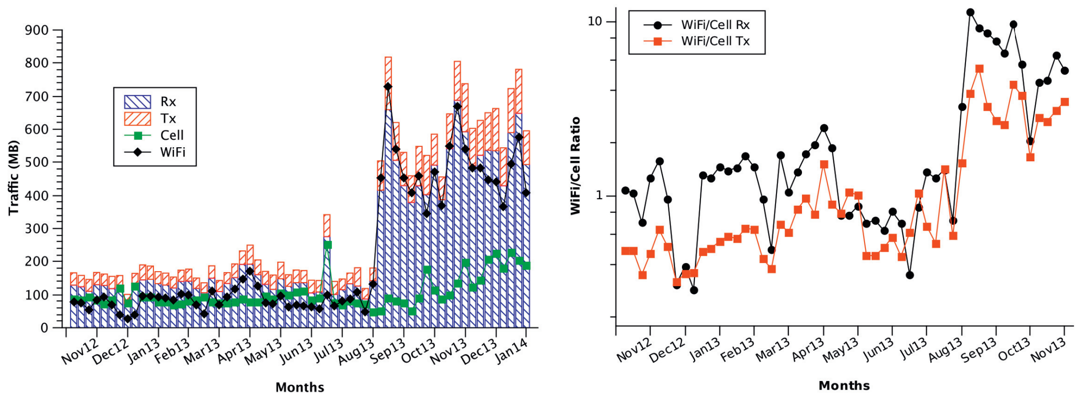
As noted earlier, the data for this paper is drawn from the NetSense smartphone study. The study consists of nearly two hundred smartphone users drawn from undergraduate students at the University of Notre Dame and has been running for well over two and a half years. In the Fall of 2011, incoming freshmen were offered the opportunity to join the study with the twin goals of studying social interactions as well as the interplay of social interactions and pervasive wireless. Students were provided with a free phone (Google Nexus S[1]) and free data plan in exchange for complete monitoring rights for all smartphone activities and communications. Cellular service was provided through Sprint which included unlimited texting, unlimited mobile-to-mobile calling, and unlimited data. Notably, actual message content was not logged but rather only metadata regarding the communications (ex. to, from, length) and the smartphone environment at the time. All data collection was fully approved with the appropriate Institutional Review Board (IRB) and full participant consent was gained prior to study participation. A comprehensive review of the study mechanics can be found in our prior work[6].

In the Fall of 2013, students were given the option to upgrade their phone (at a cost to themselves) and would continue to receive a free cellular plan through May of 2015 (graduation). Students could elect to purchase either a Galaxy S4, a Galaxy S3, or a HTC ONE. A limited pool of free phones were offered for those in need of financial aid including the HTC EVO and LG Optimus. The minimum requirement for a handset refresh was that the phone must continue to be an Android phone and the phone must support LTE. Through attrition (primarily due to study abroad and acquisition of an iPhone), the steady state of the study participants dropped down to roughly one hundred twenty augmented by twenty new enrollees in October of 2013.

Data on the phones was recorded by a user-level agent developed as part of the study. Data was recorded primarily via periodic polling (current wireless consumption, application consumption, wireleless state) with triggers are used as appropriate for data that was of increased time sensitivty (ex. screen on, wireless roam). At periodic intervals, data was securely sent to the central study servers (see[6] for more details). The initial instantiation of the agent was a custom APK (Android application package file) while a Play STore app was distributed in late fall / early spring of 2013 / 2014. For the purposes of this paper, there are several key attributes that should be noted:

- *Handsets:* All handsets were running Android (Ice Cream Sandwich+). The Nexus S ran a slightly modified build of Cyanogenmod adapted to enable permanent Bluetooth discoverability. The second phase of the study (post Fall 2013) relied on the stock Android carrier build for each device. All study participants were expected to use the device as their primary device.
- *WiFi Support:* All handsets in the study from the initial launch in Fall of 2011 were fully 802.11n capable. The majority of campus upgrades to 802.11n for the student cohort were completed in the 2011-2012 academic year timeframe. All participants had their phones configured upon receipt to support campus WiFi (ND-Secure, ND-Guest) with connectivity monitored to ensure that students were indeed campus WiFi capable.
- *Cellular:* The Nexus S had EVDO (3G) / WiMAX (4G) support while all models in the second phase had full LTE support. Cellular service on campus was provided via a DAS (Distributed Antenna System) that supported

[1] Although the Nexus S supported WiMAX, WiMAX was not available locally.



(a) (b)

Fig. 1. Traffic consumption (a) Longitudinal perspective; (b) Ratio perspective

only 3G (EVDO, 1X). Off-campus towers provided green space LTE (March 2013+). Students traveling outside of campus (home, local municipality) would also likely receive LTE coverage.

- *Wireless state:* Wireless roaming events were recorded via triggered callbacks. Data consumption for cellular and WiFi was recorded once per minute (Tx, Rx). WiFi discovery was conducted every three minutes with all WiFi APs reported by the Android API including Station ID, MAC address, and RSSI.
- *Phone state:* Additional pieces of phone state were recorded including location, proximity of other users (via Bluetooth), available storage, and screen state (on / off).

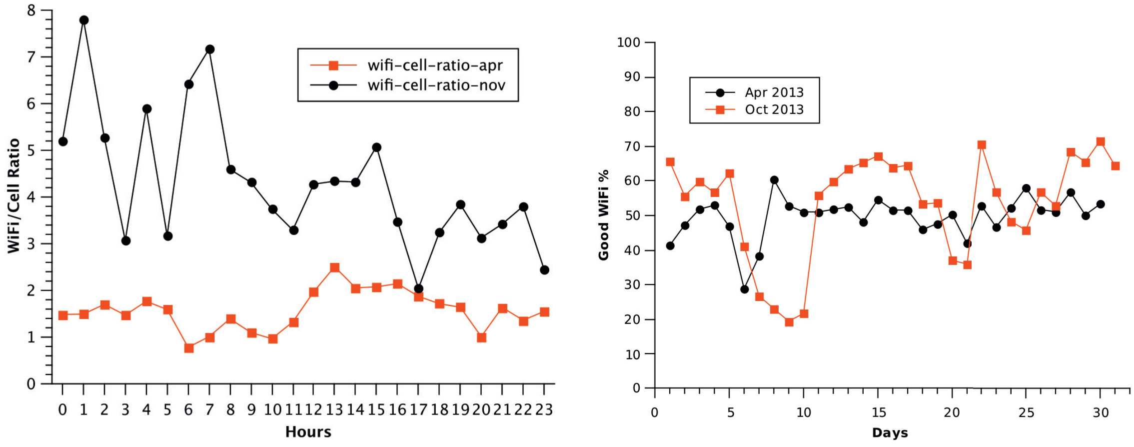
4. Data Analysis

For the purposes of our analysis, we focus on two key aspects: (1) the longitudinal performance of WiFi, handset usage, and data consumption; and (2) a deeper analysis of pure cellular versus mixed WiFi / cellular across 3G and 4G environments.

4.1. Longitudinal Performance: Device Usage

We begin by first exploring the data consumption between the downlink and uplink directions and the cellular and WiFi adapters. Figure 1(a) plots average weekly traffic consumption over nearly the entirety of the NetSense study from October 2012 onwards. We note that September 2012 is excluded to account for the study cohort learning their new phones. Figure 1(b) plots the ratio of WiFi versus cellular on a logarithmic scale for both downlink (Rx) and uplink (Tx) where a score of 1 indicates that WiFi and cellular consumption is equal, a score of less than 1 indicates that cellular dominates, and a score greater than 1 indicates that WiFi dominates. The most intriguing part of the graph (as observed by our work in[4]) is that for the bulk of the time period, the WiFi / cellular ratio tends to be on other order of either a slight favoring for WiFi or at times, directly favoring cellular despite pervasive campus WiFi (802.11n). At the time, there seemed to be consistent patterns amongst several popular smartphone models (Nexus S, HTC Incredible, Galaxy S2) that pointed to a 3-5 dBM signal penalty compared to laptops and tablets. The net result was that in a well-tuned campus environment, there emerged numerous ‘black holes’ with respect to coverage where either the device would cling to previously associated WiFi or simply fall back to cellular.

In contrast, consider the step function that occurred in the Fall of 2013 when the various devices were refreshed from the Nexus S (which received numerous complaints regarding WiFi performance via on-line reviews) to a newer series of smartphones (Samsung Galaxy S4, HTC ONE). The results are nothing short of dramatic. Whereas the ratios tended to hover in the one to less than one range for the Nexus S, the ratios immediately jumped to roughly a 10x ratio, exceeding the vast majority of gains predicted by[3,13]. Critically, the campus WiFi infrastructure itself had



(a) (b)

Fig. 2. Traffic consumption (a) Di-urnal perspective for two months for WiFi versus cellular; (b) Percentage of 'Good' WiFi

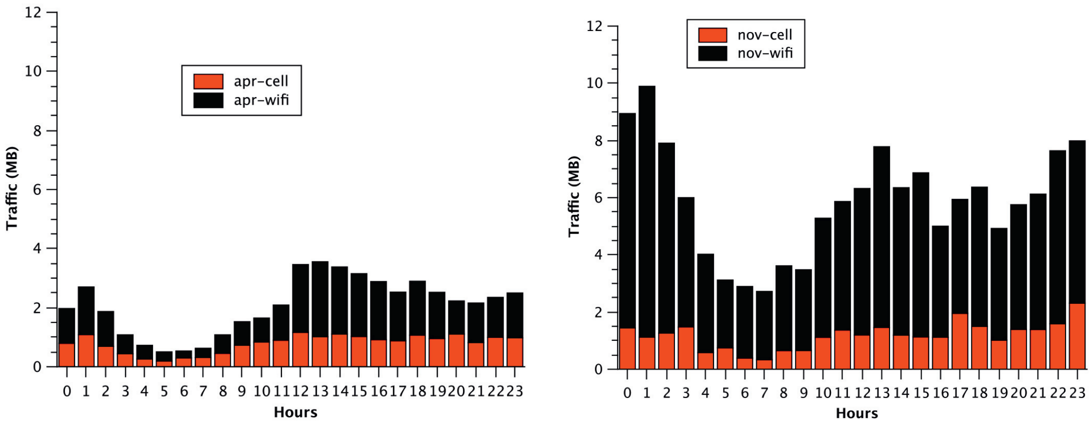
changed little with many of the 802.11n deployments having completed for the study cohort regions in the 2012-2013 academic year. Note that device energy levels were also monitored and noted to have little impact on the consumption ratio.

Figure 2 continues by exploring the effects on the ratio across two months (April 2013 with the Nexus S, November 2013 with the new handsets). First, Figure 2(a) explores the diurnal effects on the ratio across the two months. While the diurnal ratio hides the actual total volume of the hour (ex. limited traffic is seen in the AM hours from 2-6 AM), the key observation is the notable shfit up in the graph with regards to the ratio. Interestingly, Figure 2(b) complicates the analysis by plotting the daily percentage of 'Good' WiFi where Good WiFi is defined as the best WiFi being better than -80 dBm. In the graph, a value of 65% denotes that a 'Good' WiFi signal was seen during 65% of the observation periods across all nodes in aggregate. The dip in the graph for October 2013 represents fall break. While the new handset has an improved percentage of WiFi, the improvement is not nearly dramatic enough to explain the 10x growth, suggesting that uplink quality likely plays a key role.

Next, Figure 3 continues by comparing and contrasting the diurnal consumption for cellular and WiFi between April 2013 and November 2013. Notably, cellular consumption stays remarkably similar (not terribly unexpected due to the in-building DAS only supporting 3G) while only WiFi enjoys significant growth. The growth is fairly consistent across the entire day with the largest growths occuring during the early morning hours (12-2 AM, 0-2).

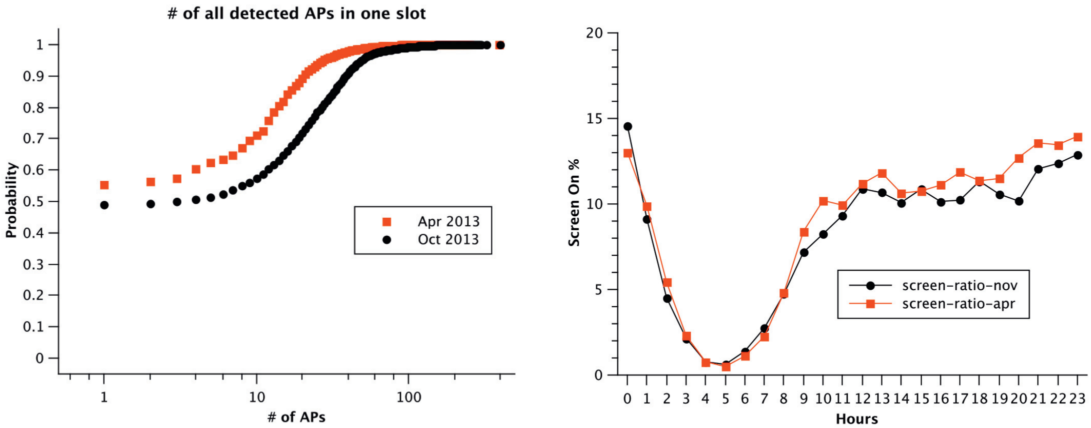
We continue further by exploring the extent to which WiFi quality plays a role. Figure 4 captures the number of detected APs as well as the actual screen usage on the device. Two interesting properties emerge from these two graphs. In the first graph, Figure 4, the number of detected APs for the two months is plotted as an ECDF. Notably, the curve shifts rightwards for October 2013 (despite fall break) indicating that on average, a significantly higher number of APs were detected compared to April of 2013 despite the actual campus deployment largely being unchanged. Furthermore, we note that in 4(b), the actual screen usage of the devices varied little between April of 2013 and November of 2013, in fact even dropping slightly during November of 2013. Hence, it appears that the actual usage periods appeared to slightly decrease while growing significantly in consumption or at a minimum, the installed applications increased their consumption (ex. background applications).

The key takeaway from this analysis is that the quality of the WiFi in the handset could play a tremendous role in the ability of a device to successfully embrace WiFi offloading. For carriers offering lower quality handsets which offer reduced quality WiFi as a mechanism for meeting cost savings (ex. prepaid plans), the cost savings of poor WiFi on the handset may be offset by increased cellular data consumption. Furthermore, the heterogeneity of devices in terms of WiFi performance may also place serious strains with regards to load balancing and roaming under a fully functional Hotspot 2.0 deployment.



(a) (b)

Fig. 3. Diurnal comparison of consumption for WiFi and cellular for (a) April 2013 (Nexus S - 3G/802.11n); (b) Nov 2013 (Mixed devices - LTE/802.11n).



(a) (b)

Fig. 4. Considerations for other external factors including (a) ECDF when Android system state considers WiFi as connected; (b) Diurnal screen usage patterns (April vs. Nov 2013).

4.2. Mixed Cellular WiFi versus Pure Cellular

Table 1 presents a detailed and nuanced view of the consumption of users across four time periods, April 2013 (Nexus S), November 2013 (minimal break - new handsets), December 2013 (last week), and January 2014 (mixed on / off campus). For the purposes of the analysis, each day is split into 288 five minute blocks whereby usage is categorized into one of three categories: (1) mixed WiFi / cellular (WiFi > 0), (2) pure cellular (WiFi = 0), (3) powered off. Hence, the first line for each of the categories represents that number of slots (on average) that a device would be in a particular state. Notably, the newer handsets tended to be used more (less likely to be powered off) due to improved / newer batteries though not excessively. Each value in terms of data consumption represents the average per-device consumption across a five minute block, ex. an average device in November of 2013 consumed 346.23 kB per five minute block in terms of WiFi downloads. Devices considered in the table must have been present in both the April 2013 and Fall 2013 timeframe to be considered, hence the difference versus earlier aggregate numbers across

Table 1. Consumption per time block comparison - WiFi/3G (Spring 2013) vs. WiFi/LTE (Fall 2014)

Connected With	**Field**	**Apr 2013**	**Nov 2013**	**Dec 2013**[2]	**Jan 2014**
Mixed WiFi / Cel	Num Slots	170	180	186	173
Mixed WiFi / Cell	WiFi Rx (KB/slot)	191.54	346.23	318.64	431.29
Mixed WiFi / Cell	WiFi Tx (KB/slot)	38.17	75.64	78.34	103.32
Mixed WiFi / Cell	Cell Rx (KB/slot)	28.32	44.42	77.12	82.52
Mixed WiFi / Cell	Cell Rx (KB/slot)	9.60	13.18	15.33	16.52
Cell (LTE+3G) Only	Num Slots	26	36	42	32
Cell (LTE+3G) Only	Cell Rx (KB/slot)	84.14	303.53	358.01	382.76
Cell (LTE+3G) Only	Cell Tx (KB/slot)	27.54	53.89	91.04	104.38
Power Off	Num Slots	92	68	60	83

the cohort. The December 2013 and January timeframes were selected to have increased opportunities for pure LTE instances due to travel home for winter break.

There are several interesting observations from the table. First, the average cellular consumption in the mixed regime doubled from April to November 2013 even under mixed WiFi / cellular regimes. Note that we considered any WiFi traffic to be indicative of the presence of WiFi, hence a time slot with WiFi present only 5% of the time was treated equally to a time slot with WiFi present 100% of the time. Critically, the most interesting aspect is that pure cellular consumption with LTE saw similar consumption as when on high-speed WiFi (802.11n). This finding is quite intriguing as it implies that with the faster speeds afforded by LTE and unlimited data (as offered by our provider), users tended to mimic their same behavior on the smartphone as the users consumed on WiFi (346.23 kB vs. 303.53 kB). Looking forward towards 802.11ac or improved LTE, questions might emerge to the extent that such capacity would be embraced by individual users but rather would be more important in the aggregate.

Finally, the other intriguing observation is that the ratio of uplink versus downlink traffic tends to center around 1:4 where roughly 1 unit of uplink is needed versus 4 units of downlink. For systems such as TDD LTE or considerations for pure downlink systems, the ratios might offer some insight for general system performance. Large scale events (ex. sporting events) may modify the ratio but the ratio of 4x seems to stay remarkably consistent across both adapters and environments.

5. Conclusions

In conclusion, we presented one of the first studies to explore the transition effects between WiFi quality changes and 3G versus 4G availability. We noted several key takeaways that included: (1) concern for inexpensive handsets and WiFi quality, (2) consumption of LTE versus WiFi is approaching parity, and (3) a rough ratio of downlink versus uplink of 4x. Most notably, while our work is one of the first to offer public insight into the transition, there are numerous research and data gathering opportunities for other researchers to explore that include:

- *Unaffiliated UEs and WiFi:* While we noted the phenomenon of poor quality UEs (user elements) and their inability to see / stay connected with WiFi, are there spillover effects of aggressive WiFi offloading in ultra-dense venues? Particularly, given that most UEs are heavily prompted to probe for WiFi availability through all WiFi channels, what happens in larger scales when the UEs are unable to join? What performance penalty do UEs scanning for WiFi have on already affiliated / joined UEs?
- *Rapid WiFi quality characterization:* Although we can do a fairly reasonable job of capturing when a device is connected to WiFi, how do we rapidly capture the actual performance of the WiFi AP? Certainly, Hotspot 2.0 offers mechanisms to query APs via ANQP but how can we rapidly assess performance without overwhelming the network with assessment? Are techniques like iPerf and Speedtest.net[16] appropriate for rapid WiFi characterization, looking towards the adoption of Multipath TCP (MP-TCP)?

- *Load Balancing in Practice:* One of the difficult challenges with smartphones is how to instrument the whole of the wireless environment. Load balancing has been touted as a key feature with Hotspot 2.0. To what extent will load balancing truly help UEs in practice? Will it end up being a decision between APs with loads of 0.87, 0.85, and 0.84 or will there truly be variety in choices (ex. 0.8, 0.2, 0.5 observed loads to choose from)?
- *D2D and On-Ramping WiFi:* To what extent should device-to-device communications (the *-Direct family including WiFi-Direct, LTE-Direct) be used to help extend the range of WiFi? Could D2D[18] offset the use of poor quality WiFi or would such devices with poor quality WiFi be unlikely to support D2D in the first place?
- *Increasing the pool of wireless datasets:* Wireless data gathering tends to remain quite expensive, both in terms of the effort required to maintain the collection infrastructure as well as the expense in attracting user participation. A key question and challenge is to ask, how much data is enough to gather for the purposes of analysis? Is longitudinal data essential and how big of a user population is required for data gathering[7,9]? To what extent should researchers independently gather data and to what extent should there be convergence with regards to data gathering frameworks and / or methods?

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References

1. 3GPP TS23.402, v8.8.0 (2009-12): Architecture enhancements for non-3GPP accesses. 2012;URL: http://www.3gpp.org/ftp/Specs/html-info/23402.htm.
2. Cellular-wi-fi integration. Tech. Rep.; InterDigital; 2012.
3. Lee, K., Lee, J., Yi, Y., Rhee, I., Chong, S.. Mobile data offloading: How much can wifi deliver? In: *Proceedings of CoNEXT*; Co-NEXT '10. New York, NY, USA: ACM. ISBN 978-1-4503-0448-1; 2010, p. 26:1–26:12. URL: http://doi.acm.org/10.1145/1921168.1921203. doi:10.1145/1921168.1921203.
4. Liu, S., Striegel, A.. Casting doubts on the viability of WiFi offloading. In: *Proc. of CellNet*. Helsinki, Finland; 2012, p. 25–30.
5. Finamore, A., Mellia, M., Gilani, Z., Papagiannaki, K., Erramilli, V., Grunenberger, Y.. Is there a case for mobile phone content pre-staging? In: *Proceedings of the Ninth ACM Conference on Emerging Networking Experiments and Technologies*; CoNEXT '13. New York, NY, USA: ACM. ISBN 978-1-4503-2101-3; 2013, p. 321–326.
6. Striegel, A., Liu, S., Meng, L., Poellabauer, C., Hachen, D., Lizardo, O.. Lessons Learned from the Netsense Smartphone Study. In: *Proceedings of the 5th ACM Workshop on HotPlanet*. Hong Kong, China: ACM; 2013, p. 51–56.
7. Nandugudi, A., Maiti, A., Ki, T., Bulut, F., Demirbas, M., Kosar, T., et al. Phonelab: A large programmable smartphone testbed. In: *Proceedings of First International Workshop on Sensing and Big Data Mining*; SENSEMINE'13. New York, NY, USA: ACM. ISBN 978-1-4503-2430-4; 2013, p. 4:1–4:6.
8. Shepard, C., Rahmati, A., Tossell, C., Zhong, L., Kortum, P.. Livelab: measuring wireless networks and smartphone users in the field. *ACM SIGMETRICS Performance Evaluation Review* 2011;**38**(3):15–20.
9. Stopczynski, A., Sekara, V., Sapiezynski, P., Cuttone, A., Madsen, M.M., Larsen, J.E., et al. Measuring large-scale social networks with high resolution. Tech. Rep.; 2014. URL: http://arxiv.org/abs/1401.7233.
10. Nathan Eagle, A.P., Lazer, D.. Inferring social network structure using mobile phone data. *Proc of the National Academy of Sciences (PNAS)* 2009;**106**(36):15274–15278.
11. Ding, A.Y., Hui, P., Kojo, M., Tarkoma, S.. Enabling energy-aware mobile data offloading for smartphones through vertical collaboration. In: *Proc. of CoNEXT Student Workshop*. Nice, France; 2012, p. 27–28.
12. Balasubramanian, A., Mahajan, R., Venkataramani, A.. Augmenting mobile 3G using WiFi. In: *Proc. of MobiSys'10*. San Francisco, CA, USA; 2012, p. 209–222.
13. Dimatteo, S., Hui, P., Han, B., Li, V.. Cellular traffic offloading through WiFi networks. In: *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*. 2011, p. 192–201. doi:10.1109/MASS.2011.26.
14. Ding, N., Wagner, D., Chen, X., Pathak, A., Hu, Y.C., Rice, A.. Characterizing and modeling the impact of wireless signal strength on smartphone battery drain. *SIGMETRICS Perform Eval Rev* 2013;**41**(1):29–40. URL: http://doi.acm.org/10.1145/2494232.2466586. doi:10.1145/2494232.2466586.
15. Schmidt, P.S., Merz, R., Feldman, A.. A first look at multi-access connectivity for mobile networking. In: *Proc. of CSWS'12*. Nice, France; 2012, p. 9–14.
16. Sommers, J., Barford, P.. Cell vs. WiFi: On the performance of metro area mobile connections. In: *Proceedings of the 2012 ACM Conference on Internet Measurement Conference*; IMC '12. New York, NY, USA: ACM. ISBN 978-1-4503-1705-4; 2012, p. 301–314. URL: http://doi.acm.org/10.1145/2398776.2398808. doi:10.1145/2398776.2398808.
17. Nikravesh, A., Choffnes, D.R., Katz-Bassett, E., Mao, Z.M., Welsh, M.. Mobile network performance from user devices: A longitudinal, multidimensional analysis. In: *Proc. of PAM'14*. Los Angeles, CA, USA; 2014, p. 12–22.
18. Asadi, A., Wang, Q., Mancuso, V.. A survey on device-to-device communication in cellular networks. *Communications Surveys Tutorials, IEEE* 2014;doi:10.1109/COMST.2014.2319555.