A Four-Year Retrospective of Mobile Access Bandwidth Evolution: The Inspiring, the Frustrating, and the Fluctuating

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***Abstract*—Recent advances in mobile technologies (like WiFi 6 and 5G) do not seem to deliver the promised access bandwidth. To effectively characterize mobile access bandwidth in the wild, we work with a major commercial mobile bandwidth testing app to conduct a long-term (2020-2023) and large-scale (involving 4.76M users) measurement study in China, based on coarse-grained general statistics and fine-grained sampling diagnostics. Our study presents distinct facts as to WiFi, 5G, and 4G: in the past few years, the average WiFi download bandwidth exhibits a considerable rise (by 119.7%), the average 5G download bandwidth constantly decreases (by a total of 20.2%) despite the enormous infrastructure investments, while the average 4G download bandwidth first declines (by 22.1%) and then increases (by 22.5%). The situations of upload bandwidths are generally similar to those of download bandwidths, except that 5G upload bandwidths manifest *N*-shaped (↗↘↗) fluctuations. Our cross-layer and cross-technology analysis reveals a variety of impact factors as well as their complicated interplay as the root causes, such as the bottlenecks in underlying infrastructure (e.g., communication devices and wired Internet access), the traffic offloading from one access technology to another, the influence of the COVID-19 pandemic, and the side effects of aggressively migrating radio resources from 4G to 5G. With the longitudinal, holistic picture of today's mobile access bandwidth, we finally provide multifold practical implications on closing the technology gaps.**

***Index Terms*—Mobile network, WiFi network, 4G/5G network, access bandwidth, bandwidth testing, network performance analysis.**

I. Introduction

Mobile access technologies have made significant progress in recent years—WiFi 6 and 5G, the latest WiFi and cellular technologies, support up to 9.6 Gbps and 20 Gbps download bandwidths respectively. Those exciting new technologies are the key enabler for various emerging applications such as Metaverse, autonomous vehicles, and 3D Ultra-HD videos. Despite the aggressive deployment of WiFi 6 and 5G, reports from large-scale bandwidth testing services (BTSes) reveal that as of early 2023, the median WiFi download bandwidth is only 202 Mbps in the US and 216 Mbps in China, while the median 5G download bandwidth merely reaches 131 Mbps in the US and 278 Mbps in China [1]. Apparently, the promises of new wireless technologies are significantly under delivered in real-world deployments.

Understanding the root causes of undesirable wireless performance in the wild is a first step towards improving the state of the art. However, it is hampered by the high complexity of wireless protocol stacks, the wide spectrum of the mobile ecosystem, and a lack of large-scale measurements. For example, existing studies on commercial 5G performance are based on controlled experiments at limited scales [2], [3], [4]. While some major BTSes do report the landscape of mobile Internet performance, their data are limited by (mostly) web-based tools which are incapable of capturing rich and detailed diagnostic data.

Cross-Layer & Cross-Technology Measurement: To fill the critical gap, we take a unique opportunity to work with a major Android BTS app named UUSpeedTest [5] (BTS-APP for short), which has 17M users (mostly located in China) and serves ∼0.2M test requests per day. Its bandwidth testing uses the standard "probing by flooding" approach [6] also used by almost all the commercial BTSes today (e.g., Speedtest [7] and SpeedOf [8])—upon a test request, BTS-APP first downloads (uploads) large files from a nearby server for ten seconds, and then samples the throughput statistics over time to estimate the access bandwidth.

To gain deep insights into the undesirable access bandwidth, BTS-APP faces a fundamental challenge—the coarse-grained data collected prevent it from pinpointing the root causes, which customers (and researchers like us) are eager to learn. Concretely, for each test BTS-APP records the average access bandwidth (i.e., the final test result), average end-to-end latency, packet loss rate, and network jitter. However, these general

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statistics are only useful for benchmarking the client-side overall network performance and environment.

In order to address the limitation, we enhance the client of BTS-APP by continuously collecting important PHY- and MAC-layer data through standard Android APIs during a bandwidth test. Our enhancement is implemented as a lightweight plugin for BTS-APP without requiring any additional privileges, making it easy to deploy. Under informed user consent and a proper IRB (Investigational Review Board), over a total of eight months consisting of two separate periods (08/01–11/30, 2021 and 02/15–06/15, 2023), 4.76M customers opted in to use the enhanced BTS-APP, performing 48.7M bandwidth tests. The tests cover all the four major ISPs in China, 6.27M WiFi APs (WiFi 4/5/6), and 2.68M cellular (4G/5G) base stations (BSes).

Data Analysis: Combining the above fine-grained dataset with BTS-APP's coarse-grained dataset collected on 4.76M users during 2020–2023, our analysis yields several major findings. In particular, we note very different facts with regard to WiFi, 5G, and 4G. In the past few years, the average WiFi download bandwidth exhibits a considerable rise (by 119.7%) from 132 Mbps to 290 Mbps, the average 5G download bandwidth constantly decreases (by a total of 20.2%) from 343 Mbps to 274 Mbps despite the ISPs' enormous infrastructure investments, while the average 4G download bandwidth first declines (by 22.1%) from 68 Mbps to 53 Mbps and then increases (by 22.5%) from 53 Mbps to 65 Mbps. In this paper, we reveal the root causes of such inspiring, frustrating, and fluctuating results from cross-layer and cross-technology perspectives.

For WiFi 4/5/6, their average download bandwidths have increased by 17.2% (58 Mbps → 68 Mbps), 20.9% (201 Mbps → 243 Mbps), and 46.9% (322 Mbps → 473 Mbps) respectively, which look remarkably lower than the overall increase (119.7%). This is mostly attributed to the proliferation of WiFi 6 access points (APs), whose market share has surged from 10.5% to 42.7% . As for WiFi 6, we are also interested in the non-negligible 46.9% bandwidth increase. We comprehensively investigate recent advances in WiFi 6 technologies, but do not observe significant innovations widely adopted by commercial WiFi 6 APs, except the 3.3% adoption of *dual WiFi acceleration*[1]. Hence, the 46.9% increase should largely stem from the upstream, i.e., the enhancement of wired access bandwidth. In recent years, stimulated by the (advertised) "ultra-high" access bandwidth of 5G, many ISPs have been upgrading their fixed broadband services. Moreover, to ensure that the upgraded services can be fully delivered to WiFi users, they typically bundle WiFi 6 APs with high-bandwidth service plans [10].

With regard to 5G, although the number of its BSes has increased by 317% (0.77M → 3.21M) from 2020 to 2023, we are surprised to observe a continuous decrease (343 Mbps → 274 Mbps) in its average download bandwidth. Deeper analysis indicates that due to the vigorous propaganda of 5G, even more users (160M → 754M, increasing by 371%) have subscribed/switched to 5G access, draining the service capacity of 5G network infrastructure. Worse still, as for the two low-frequency bands (N1 and N28) "refarmed" from 4G [11], the average 5G download bandwidth is as low as 95 Mbps and 87 Mbps respectively, because of their thin ($\leq$60 MHz) spectrum. In addition, a strong received signal strength (RSS) level does not necessarily translate into high 5G bandwidth: the average download bandwidth (302 Mbps) under level-5 RSS is even lower than that (324 Mbps) under level-4 RSS. We find that excellent-RSS tests are more likely to be performed in crowded urban areas where complex multipath interference incurred by buildings [12], load balancing issues caused by heavy population [13], and poor handover problems due to dense 5G gNodeBs [14] all become prominent.

As to 4G, the average download bandwidth fluctuated over the past three years. Our preliminary work [15] reveals a sharp decrease (22.1%) of 4G download bandwidth from 2020 to 2021, mainly because of the high-bandwidth LTE spectrum (Bands 1, 28, and 41) being aggressively re-farmed for 5G use. Interestingly, from 2021 to 2023 the average 4G download bandwidth has gradually recovered for three reasons. First, the aforementioned influx of users to 5G has led to a substantial (27%) reduction of 4G users, thus largely alleviating the service pressure on 4G infrastructure. Second, ISPs have deployed 0.13M more LTE BSes from 2021 to 2023 to further enhance the LTE network performance. Third, due to some eNodeBs' adopting LTE-Advanced technologies (such as carrier aggregation and enhanced MIMO), in 1.6% tests the download bandwidth even exceeds 300 Mbps.

The situations of mobile upload bandwidths are generally similar to those of download bandwidths, except that 5G upload bandwidths do not constantly decrease from 2020 to 2023, but manifest *N*-shaped (↗↘↗) fluctuations. On average, 5G upload bandwidth increased by 38.3% (26.1 Mbps → 36.1 Mbps) from 01/2020 to 01/2021, with the widespread infrastructure deployment in China; after that, it experienced an obvious (62.9%) decline (36.1 Mbps → 13.4 Mbps) from 01/2021 to 06/2022, due to the surge of high-demand scenarios like telework and live streaming during the COVID-19 pandemic; finally (since early 2023), it has quickly recovered due to the abolishment of COVID-19 quarantine and ISPs' continuous investments in 5G BSes.

Implications: Our analysis depicts a longitudinal, holistic picture of today's mobile access bandwidth. In particular, it quantitatively reveals several key impact factors (including communication devices, technical innovations, wired Internet access, radio resource migration, ambient conditions, and user workload versus service capacity), as well as the complicated interplay among them, as the root causes of the above diverse, oftentimes counter-intuitive findings.

Mobile users usually resort to novel communication devices (that enable new access technologies) for high access bandwidths. In practice, however, if the devices do not come with appropriate infrastructure support, the resulting bandwidths might well be far below expectation, e.g., when WiFi 6 APs are subject to slow wired Internet access or 5G phones are connecting via inferior radio-frequency bands. Besides, users typically take

[1] Dual WiFi acceleration [9] enables a user device to simultaneously connect to two WiFi APs in different bands. However, it exhibits poor real-world performance (decreasing the access bandwidth by 17.9%) due to insufficient support from APs and mobile OSes/apps (see Section IV-B).

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the signal strength as a major indicator of access bandwidth, while ignore the crucial impact of ambient conditions and radio interference in wireless communications. In a nutshell, users should be better informed and educated to understand the *actual* performance and bottlenecks of new technologies.

Mobile ISPs' aggressively (and perhaps imprudently) migrating radio resources from 4G to 5G has generated obvious side effect. Although spectrum refarming is inevitable as cellular technology evolves, the current LTE spectrum resources are severely fragmented. This makes contiguous high-bandwidth spectrum available for refarming rather scarce, leading to unexpectedly low 5G bandwidths as exhibited in our data. Consequently, our results advocate more effective band defragmentation and refarming strategies.

Last but not the least, our study illustrates a clear time lag between the surge of 5G users and the deployment of 5G BSes. Thus, the service capacity of 5G infrastructure can hardly match the user workload, incurring excessive cross-user contentions and making 5G bandwidths mostly unsatisfactory. On the other hand, we note that the gradual reduction of 4G users has been relieving the pressure on the mature 4G infrastructure. Given that the vanilla Android system blindly prioritizes 5G access over 4G [16], we suggest 5G phone vendors and/or BSes to conduct cross-technology load balancing between 5G and 4G, especially when a user device is confronted with a nearby competent 4G BS and an overburdened 5G BS. Furthermore, since 4G and 5G will coexist for a very long time, we also suggest ISPs to strengthen existing LTE infrastructure in a cost-effective manner, such as widening the LTE-Advanced deployment.

Roadmap: The remainder of this paper is organized as follows. Section II reviews related work on bandwidth testing approaches and mobile bandwidth measurements. Section III describes our data collection methodology. Our key findings are presented in Section IV, including general statistics as well as a detailed exploration of different access technologies. Section V discusses the generalizability of our findings to other regions and feasible optimization strategies. Finally, Section VI concludes the paper by summarizing our main contributions and outlining directions for future research.

Code and Data Release: The code and data involved in this study are publicly available at https://MobileBandwidthEvolution.github.io/.

II. Related Work

This section reviews existing bandwidth testing approaches and measurement studies on mobile access bandwidths. We also compare them to our approach and study results.

Bandwidth Testing Approaches: Almost all commercial BTSes, such as SpeedTest [7], XFinity [17], and SpeedOf [8], take a "probing by flooding" approach to fully saturate the access bandwidth. In spite of its accuracy, this approach may consume considerable (metered) bandwidth when applied to mobile networks. In the literature, there are also much less invasive approaches, such as IGI [18], TOPP [19], and pathChirp [20], that use strategically crafted packets to probe the bandwidth. However, they are known to suffer from high measurement errors in particular over high-speed wireless links [6], [21]. Recently, some BTSes such as FAST [22] and FastBTS [6] take a more balanced strategy that reduces the probing traffic while maintaining high accuracy.

All the above bandwidth testing approaches only capture coarse-grained data like bandwidth results and latencies during a test. In comparison, the enhanced version of BTS-APP leverages the cross-layer and cross-technology measurement to passively and selectively collect PHY- and MAC-layer information, so as to help diagnose the root causes of undesirable mobile access bandwidths.

Mobile Bandwidth Measurements: Leveraging the above-described bandwidth testing approaches, in the past 15 years, the research community have conducted a plethora of studies to understand realistic cellular and WiFi bandwidths through either field measurements or crowdsourcing. For example, Huang et al. perform crowdsourced measurements of 3G [23] and 4G LTE [24], [25] bandwidths in various application scenarios. Sommers et al. compare the cellular and WiFi bandwidth from different aspects in metro areas [26]. More recently, as 5G makes its debut, Narayanan et al. measure 5G bandwidth through controlled experiments and drive tests [3], [4]; a similar characterization is performed by Xu et al. [2].

Some other studies focus on mobile bandwidth in particular contexts such as multipath [27], high-speed train [28], [29], mobile virtual operators [30], cellular upload [31], and crowded events [32], to name a few. Complementing academic publications, the industry have also published whitepapers and reports on mobile bandwidths [33]. In a broader scope, there is a number of work on estimating mobile bandwidth [6], [25], [34], incorporating bandwidth-awareness into application design [35], [36], [37], and saving mobile bandwidth on metered links [38], [39], [40].

By contrast, our study features a much larger scale, a special cross-layer (covering PHY-, MAC-, NET-, CTL- and APP-layers) and cross-technology (covering WiFi 4/5/6 and 4G/5G) perspective, and a variety of new insights.

III. Study Methodology

This section first presents the bandwidth test logic and server deployment of BTS-APP, and then describes the lightweight plugin we build for collecting in-depth network information in the wild.

System Architecture of BTS-APP: The bandwidth test logic and server deployment of BTS-APP are quite similar to those of Speedtest, a state-of-the-art BTS system that owns the largest user scale (around 15M user requests served per day) and server pool (more than 18,000 test servers deployed across the globe as of July 2023) [7]. Some additional adaptations made by the development team to fit the specific workload of BTS-APP are presented as follows.

Upon a test request, BTS-APP first measures the PING latency from the user client to a subset of its deployed test servers, so as to find a nearby server with the lowest latency. Then, during the actual bandwidth testing process, it continuously downloads large files from the selected server via HTTP connections to probe the

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access bandwidth for 10 seconds, and acquires a bandwidth sample every 50 milliseconds in the meantime (therefore generating a total of 200 samples). Here the probing duration (10 seconds) is shorter than that of Speedtest (15 seconds) because almost all of BTS-APP's user requests come from Mainland China (meaning shorter RTTs for data transmission).

In order to ensure that the user-side access bandwidth is fully saturated, BTS-APP progressively sets up new HTTP connections to other nearby test servers, if the latest bandwidth sample reaches a predefined threshold (i.e., 25 Mbps, 35 Mbps, and so on, resembling the design of Speedtest).

To produce the test result, BTS-APP first partitions the collected bandwidth samples into 20 groups, each containing 10 samples. Then, to address the noises caused by TCP slow start and network dynamics, it discards 5 groups (of samples) with the lowest average bandwidth and 2 groups with the highest. The remaining groups' average bandwidth is used as the final result. All the empirical parameters used in this stage conform to those of Speedtest [7], whose robustness has been extensively evaluated in the real world.

BTS-APP's current infrastructure consists of 352 test servers distributed across Mainland China, whose bandwidths range from 1 Gbps to 10 Gbps.

In particular, 62 of the test servers are directly provided by ISPs through commercial negotiations, which are close to the Internet backbone networks (more specifically, the IXPs) and thus are especially high-speed.

In each test, 5 (out of the 352) geographically nearby (determined by the IP addresses) servers are PINGed to find the nearest server; in contrast, 10 out of the 16,190 servers are PINGed in Speedtest. This seemingly "degraded" configuration is acceptable in practice, as it can well handle the present workload of BTS-APP (serving ~0.2M user requests per day generally issued from Mainland China) without harming the test accuracy.

Fine-Grained Data Collection: Despite being able to provide reliable and accurate bandwidth testing service in the past eight years or so, BTS-APP cannot give an in-depth analysis of its test results, making it hard to understand the root causes of undesirable access bandwidths (which the customers and researchers like us are eager to learn). This is because although BTS-APP is an Android app, the implementation of its bandwidth test logic is mostly web-based (similar to other BTSes introduced in Section I). Consequently, as shown in the upper part of Table I, BTS-APP can only record some general statistics such as user identifier, network type (e.g., WiFi 6 or 5G), average access bandwidth, average end-to-end latency, network jitter, and packet loss rate, yet cannot capture critical underlying network information (such as frequency band and signal strength) for in-depth performance analysis and troubleshooting.

To address the shortcoming, in the preliminary work [15] we implemented an enhancement plugin for BTS-APP to enable cross-layer and cross-technology data collection, i.e., to capture fine-grained measurement and diagnostic data during each bandwidth test. In particular, to let the plugin run smoothly on heterogeneous mobile devices at scale, we need to make it *lightweight* and *privacy-preserving*.

TABLE I
DETAILED INFORMATION CAPTURED DURING EACH BANDWIDTH TEST BY BTS-APP, OUR IMPLEMENTED ENHANCEMENT PLUGIN FOR CROSS-LAYER AND CROSS-TECHNOLOGY MEASUREMENT IN 2021, AND THE UPGRADED VERSION OF OUR PLUGIN IN 2023

Tool	Collected Data
BTS-APP	UserID NetworkType Bandwidth Latency Jitter LossRate
Our Plugin (2021)	DeviceBrand DeviceModel OSVersion ISP Province/City ASU dBm TimingAdvance CellIdentity SignalLevel CellBand CellBandwidth MCC MNC Earfcn Nrarfcn Rsrp SsRsrp Rssnr SsSinr WiFiRssi BandFrequency HiddenSSID WiFiStandard RxLinkSpeed TxLinkSpeed MaxSupportRxLinkSpeed MaxSupportTxLinkSpeed
Our Plugin (2023)	IsNrAvailable IsEndcAvailable IsDualWiFi

For the former, we passively monitor critical PHY- and MAC-layer information using generic Android APIs. For the latter, we carefully avoid any data collection that would require additional privileges the original app does not possess with regard to diverse radio access technologies (RATs), so as to minimize users' privacy concerns. The detailed information collected is listed in the middle part of Table I. The plugin is implemented as a Java class, and during bandwidth testing, BTS-APP periodically (every second) invokes methods from this class to collect data.

With respect to cellular networks, we collect both static and dynamic properties. First, we record hardware and network configurations of the user device, such as device brand/model, OS version, coarse-grained location, mobile country/network code (`MCC/MNC`, retrieved using `getNetworkOperator()` from `TelephonyManager`), and radio-frequency channel number (`Earfcn`, obtained via `getEarfcn()` from `CellIdentityLte` for 4G and `Nrarfcn`, obtained via `getNrarfcn()` from `CellIdentityNr` for 5G). Meanwhile, we continuously gather dynamic properties like received signal strength (`Rsrp` for 4G and `SsRsrp` for 5G, respectively retrieved using `getLteRsrp()` and `getNrSignalStrength()` from `SignalStrength`) and signal-to-noise ratio (`Rssnr` for 4G and `SsSinr` for 5G, respectively retrieved using `getLteRssnr()` and `getNrRssnr()` from `SignalStrength`). Furthermore, we are concerned with the information of the connected base station (BS), such as BS ID (`CellIdentity`, obtained via `getCellIdentity()` from `CellIdentity`), frequency band, channel number, and channel bandwidth.

Regarding WiFi networks, we are interested in the connected WiFi AP's attributes and capabilities, such as WiFi standard, radio frequency band (`BandFrequency`, retrieved using `getFrequency()`), MAC-layer link capacity (`MaxSupportRxLinkSpeed`, and `MaxSupportTxLinkSpeed`, retrieved using `getMaxSupportedRxLinkSpeedMbps()` and `getMaxSupportedTxLinkSpeedMbps()`, respectively), current transmit link speed (`RxLinkSpeed` and `TxLinkSpeed`, both retrieved using `getLinkSpeed()`), signal strength (`WiFiRssi`, retrived using `getRssi()`), and local network status (e.g., states of the other WiFi APs that are

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detected at the moment). All the retrieval methods mentioned above are from the `WifiInfo` class.

Further, to deeply understand the evolution of mobile access bandwidth over the past three years, in early 2023 we upgraded our plugin by capturing new diagnostic information for 5G and WiFi networks. As listed in the lower part of Table I, for 5G networks we capture the fields of `isNrAvailable` and `isEndcAvailable` in the `DataSpecificRegistrationInfo` class to jointly judge whether the 5G network is in NR-SA (New Radio - Standalone) mode or NR-NSA (New Radio - Non-Standalone) mode. The `isNrAbailable` field indicates whether the device is connected to a 5G NR network, while the `isEndcAvailable` field indicates whether E-UTRAN New Radio - Dual Connectivity (EN-DC), i.e., dual connectivity between 4G and 5G, is enabled. Thus, if `isNrAbailable` is true and `isEndcAvailable` is false, the 5G network is operating in NR-SA mode. Conversely, if both fields are true, the 5G network is functioning in NR-NSA mode.

Given that *dual WiFi acceleration* [9] has been adopted in some WiFi networks, to capture this feature, we scan all the WiFi connections managed by `ConnectivityManager`, and set the `isDualWiFi` field as true when there exist multiple active WiFi connections.

The upgraded plugin is small in size: 1.2K lines of code and 114KB of binary, and can be dynamically loaded by BTS-APP at runtime. During a bandwidth test, the plugin carries out data collection every second, incurring negligible ($\leq$2%) CPU and ($\leq$1 MB) memory overheads on an Android phone. After the bandwidth test, the result and the collected data are uploaded via WiFi (whenever possible) to our data server for subsequent detailed analysis.

Analysis Pipeline: We analyze the collected data in multiple steps. First, we conduct a macro-level analysis on the collected data, calculating key metrics such as average bandwidth and signal strength for different access technologies. By grouping the data annually and making a longitudinal comparison, we reveal the trends and fluctuations in WiFi, 4G, and 5G bandwidths over the past few years. Then, through cross-sectional comparison, we examine the disparities in WiFi, 4G, and 5G bandwidths across different cities, highlighting significant variations between major cities and smaller cities, as well as between urban and rural areas within the same city. Additionally, we examine how variables such as user device configuration, OS version, ISP investment, PRB allocation strategy and user mobility correlate with bandwidth.

Furthermore, to gain a deeper understanding of the various factors affecting bandwidth, we conduct a cross-layer analysis, combining PHY- and MAC-layer data with actual measured bandwidth data, including 1) frequency band, signal strength, and user load on WiFi bandwidth, 2) spectrum refarming, signal strength, and base station density on 5G bandwidth, and 3) frequency range, channel bandwidth, and user traffic migration on 4G bandwidth.

Crowdsourcing and Ethical Considerations: Thanks to BTS-APP's development team, we managed to deploy the plugin on a large part of BTS-APP's users (the remainder choose to opt out).

Hence, we perform in-depth crowdsourced measurements over a total of eight months consisting of two separate periods (08/01–11/30 in 2021 and 02/15–06/15 in 2023), collecting detailed diagnostic data from as many as 48.7M access bandwidth tests performed by 4.76M users. None of our measurements violate BTS-APP's user agreements. The users involved in this study opted in with informed user consent, and the analysis is conducted under a well-established IRB. During the study, no personally identifiable information was collected, and we have no way of linking the data with users' actual identities.

IV. Measurement Findings

In this section, we first present the general statistics (Section IV-A) from our measurement. Then, we zoom in on the respective bandwidth characteristics of WiFi (Section IV-B), 5G (Section IV-C), and 4G (Section IV-D) in terms of both technical and non-technical factors. Our analyses focus on download bandwidth since it is more important for most users; on the other side, we also describe in brief the situation of upload bandwidth in Section IV-E.

A. General Statistics

During our eight-month measurement, 4,763,936 user devices conducted 48,721,398 access bandwidth tests in total, 99.98% of which are located in China, involving four mobile ISPs, 2,679,018 BSes, and 6,270,577 WiFi APs. More specifically, during the former four months (08/01–11/30 in 2021) we recorded the results of 21,051 3G tests, 1,632,616 4G tests, 905,471 5G tests, and 21,077,214 WiFi tests; during the latter four months (02/15–06/15 in 2023), we gathered 18,984 3G tests, 2,354,939 4G tests, 3,744,894 5G tests, and 18,966,229 WiFi tests. Along with each test result, we also captured the cross-layer, in-situ network information as discussed in Section III. In addition, to enable the longitudinal analysis, we refer to BTS-APP's coarse-grained (and larger-scale) measurement reports in recent years when necessary.

Temporal Variation: As the commercial prosperity of WiFi 6 and 5G commenced in late 2019, mobile access bandwidth was expected to grow constantly in the subsequent years (2020 to 2023) in response to the increasing deployment of WiFi 6 APs and 5G BSes. Within our expectation, the average WiFi bandwidth exhibits a significant increase (119.7%) from 2020 to 2023, given that the market share of WiFi 6 APs has surged from 11.5% to 42.7% . Nevertheless, as illustrated in Fig. 1, the average 5G bandwidth continuously decreases by a total of 20.2% (343 Mbps $\rightarrow$ 274 Mbps) from 2020 to 2023. More surprisingly, the average 4G bandwidth first declines by 22.1% (68 Mbps $\rightarrow$ 53 Mbps) from 2020 to 2021, and then gradually increases by 22.5% (53 Mbps $\rightarrow$ 65 Mbps) in the next two years.

Furthermore, we closely examine the bandwidth variation with regard to the same user group (that belong to the same ISP in the same city), including those China Unicom, China Mobile, and China Telecom users in Beijing, Shanghai, Guangzhou, and Shenzhen. Not surprisingly, we observe 10% –36% declines in average 5G bandwidths for the same user group; as to 4G, the

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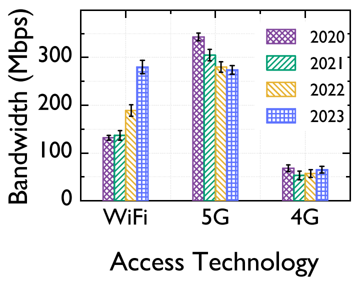

Fig. 1. Average WiFi, 5G, and 4G bandwidth over time.

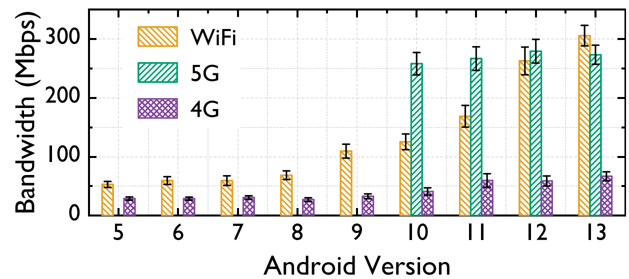

Fig. 2. Average WiFi, 5G, and 4G bandwidth for different versions of Android OSes.

average bandwidths first decrease by 12% –31% from 2020 to 2021, and then increase by 9% -34% from 2021 to 2023.

The above findings reveal that in real-world deployment, the advance in wireless technologies is far from being fully exploited. In particular for cellular access, the QoS for the majority of users (i.e., 4G users) is in fact damaged despite the well expected improvement of the "average overall" QoS. This, in our opinion, is unknown and hardly acceptable to 4G users, and thus may hurt users' confidence and do harm to the mobile ecosystem. Worse still, even 5G users who are prioritized are experiencing deteriorated QoS. We will investigate the undesirable situations later from cross-technology and cross-layer perspectives.

Spatial Disparity: We further examine the bandwidth variation across different cities in China during the two measurement periods, including 21 mega cities, 51 medium cities, and 254 small cities. In general, we observe noticeable difference among the access bandwidths of 4G (28–119 Mbps in 2021 versus 17–142 Mbps in 2023), 5G (113–428 Mbps in 2021 versus 54–421 Mbps in 2023), and WiFi (83–256 Mbps in 2021 versus 109–572 Mbps in 2023) with regard to these cities. A mega city (such as Guangzhou) does not necessarily possess relatively high 4G, 5G, and WiFi bandwidths (55 Mbps, 301 Mbps, and 136 Mbps in 2021, versus 47 Mbps, 236 Mbps, and 227 Mbps in 2023) even with dense infrastructure deployment, probably due to the severe network resource contention among plenty of users.

Besides, 41% cities are subject to unbalanced development of 4G and 5G networks; for example, in 2021 Shanghai has higher 5G bandwidth (337 Mbps) as compared to the national average (305 Mbps), while its 4G bandwidth (48 Mbps) is 9% lower than the national average. Similar situations are also observed in 2023. In a same city, on average, the 4G and 5G access bandwidth in urban areas is 24% and 33% higher than that in rural areas, respectively, mostly owing to distinct densities of infrastructure deployment. This is generally consistent with Zreikat and Mathew's study [41] which highlights that 5G network performance differs significantly between urban and suburban areas, particularly in terms of signal transmission and coverage. Although urban areas, with their dense high-rise buildings, may lead to signal obstruction and attenuation, suburban areas face challenges as well, due to more complex terrains and longer signal propagation paths.

User-side Hardware and Software: We also study the impact of user-side hardware and software (i.e., the Android system that actually manages the wireless data connectivity) on the access bandwidth. To ensure temporal consistency in the data, we focus our analysis on data from the year 2023. By selecting the most recent year, we also ensure that our analysis include the latest software versions during the measurement (Android 13 was released in August 2022 [42]). In our dataset, there are 196 mobile phone vendors and 2,407 device models whose hardware configurations vary from low-end to high-end. At first glance, it appears that mobile access bandwidth is in general positively correlated with the superiority of hardware. Closer examination, however, indicates that this is merely a common illusion caused by missing a key factor at play—software that bridges the hardware and mobile access networks.

Fig. 2 lists the average WiFi, 5G and 4G bandwidth for different Android versions, illustrating that it might well be the Android version that essentially determines the access bandwidth (in a statistical sense). This is quite understandable in principle, given the considerable improvements made in the cellular/WiFi management modules by higher-version Android systems. In contrast, when a low-end device model and a high-end device model are equipped with the same Android version, usually we do not observe obvious difference in mobile access bandwidth between them—the standard deviation for the same access technology is smaller than 26 Mbps. Consequently, the fact that higher-end mobile phones often (but do not necessarily) possess higher access bandwidths is only because they have more up-to-date hardware that is more often used for running higher-version OSes.

ISP-side Infrastructure Investment: Our study involves all the four major ISPs in China: China Mobile, China Unicom, China Telecom, and China Broadcast Network, who provide both cellular and fixed broadband services for Internet users. They are referred to as ISP-1, ISP-2, ISP-3, and ISP-4 henceforth. Fig. 3 presents their average WiFi, 5G and 4G bandwidths. As shown, while their average 4G bandwidths are quite similar (probably owing to their wide deployment of mature and similar 4G infrastructure), there is noticeable difference among their average 5G bandwidths. In particular, as a newly-founded ISP that focuses on 5G, ISP-4 bears obviously lower 5G bandwidth, since its 5G service is based on a special low-bandwidth 700 MHz band originally designated for 4G and radio broadcast services. In other words, ISP-4 is trading bandwidth for low-cost deployment. We also note that ISP-3 outperforms the other three ISPs in both 5G and WiFi bandwidths. The former is because

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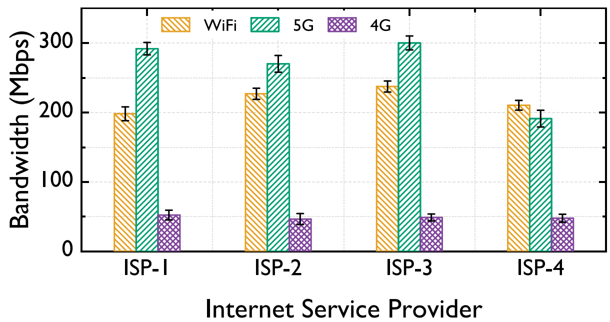

Fig. 3. Avg. WiFi, 5G, and 4G bandwidth for different ISPs.

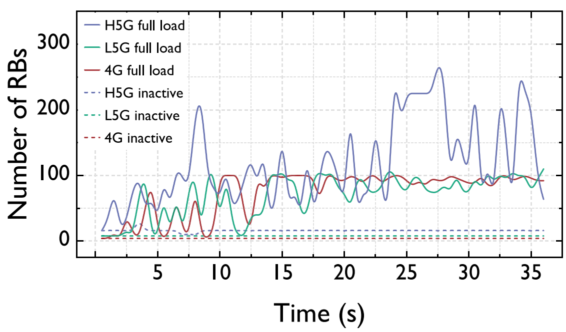

Fig. 4. # of allocated RBs for high-bandwidth 5G (H5G), low-bandwidth 5G (L5G), and 4G under different loads.

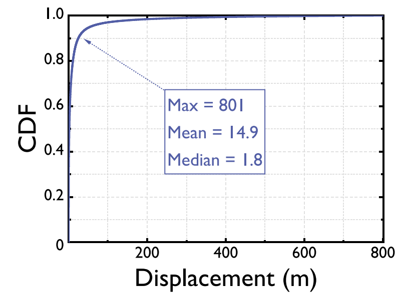

Fig. 5. Distribution for user mobility during bandwidth tests.

ISP-3 deploys 5G mostly on an advantageous frequency range of a dedicated 3 GHz band (detailed in Section IV-C). The latter is due to ISP-3's heavier investment in its fixed broadband infrastructure (detailed in Section IV-B).

Physical Resource Block (PRB) Allocation Strategy: In 4G and 5G, a PRB is a fundamental unit of resource allocation in the time-frequency grid, usually consisting of 180kHz of bandwidth over a time slot of 0.5 ms [43]. The strategy for allocating PRBs is closely related to the available bandwidth, as it determines how much of the frequency spectrum is utilized for data transmission.

Typically, there is no direct way to figure out the PRB allocation strategy (which is rather low-level information during data communication). One possible approach is to infer different allocation strategies by observing the changes in the number of resource blocks (RBs). However, collecting RB data on a large scale is still challenging as it requires modem-level access, so we perform it through benchmark experiments using the Qualcomm QXDM tool [44] (with certificate support from the Xiaomi phone manufacturer [45]). Specifically, we measure the changes in the number of RBs on mobile devices under both *inactive* (with minimal bandwidth demand) and *full bandwidth load* (achieved through flooding) conditions in high-bandwidth 5G ($\sim$800 Mbps), low-bandwidth 5G ($\sim$60 Mbps), and 4G ($\sim$60 Mbps) environments.

We observe from Fig. 4 that in all the concerned network environments, the number of allocated RBs remains stable when a mobile device is inactive, i.e., consistently holding at a fixed value (16 in high-bandwidth 5G, 8 in low-bandwidth 5G, and 4 in 4G environments). The differences in these fixed values can be attributed to that in 5G networks, base stations usually tend to allocate more RBs to user devices, so as to ensure a rapid response during high-demand periods. Meanwhile, we note that the default values in higher-bandwidth environments are obviously higher than those in lower-bandwidth environments.

When a mobile device is under full bandwidth load, by comparing the situations in low-bandwidth 5G and 4G environments (we suppose that the bandwidth loads in the two environments are similar), we find that the number of allocated 5G RBs fluctuates more (with a 26.3% higher coefficient of variation) than that in 4G, reflecting more adaptation in 5G's PRB allocation strategy.fig In comparison to the case of low-bandwidth 5G, the coefficient of variation for the number of RBs under full load in high-bandwidth 5G is as high as 41.1% , indicating an even more aggressive PRB allocation strategy. Generally, we summarize the PRB allocation strategies of 4G, low-band 5G, and high-band 5G as being *conservative on-demand* (relatively stable, only changing when there is increased demand), *constrained adaptive* (having greater fluctuations, but still within a limited range), and *aggressive dynamic* (showing significant fluctuations, with a wide range of PRB quantities), respectively.

Mobility of User Devices: Would a moving user device suffer from inferior 4G/5G access bandwidth? This is a question oftentimes asked by both network professionals and nonprofessionals. To explore the relationship between the moving status of user devices and their access bandwidths, we collect a whole week (06/17-06/24 in 2024) of data, which include fine-grained location information during users' bandwidth tests. Note that the data are only collected from those users with informed consent, who fully understand that it would be used solely for academic research. The distribution of user device mobility is shown in Fig. 5, from which we can see that the majority (70%) of user devices have a displacement of less than 3 meters. In all the tests, we do not observe an essential correlation between upload/download bandwidths and moving distances; that is to say, a moving user device usually would not bear a lower 4G/5G access bandwidth than a stationary one.

B. WiFi Access Bandwidth

As a widely-deployed mobile access technology, WiFi mainly works in home and enterprise environments. In this part, we dig into the access bandwidth of WiFi across its 4th, 5th, and 6th generations of technical standards.

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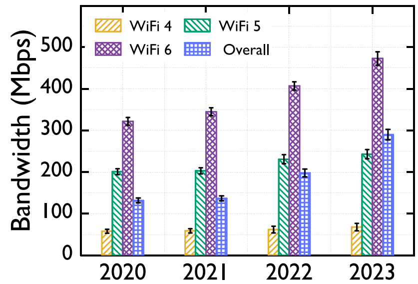

Fig. 6. Avg. bandwidths of WiFi 4/5/6 and the overall situation.

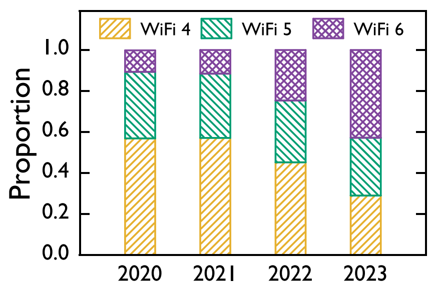

Fig. 7. Market shares of WiFi 4/5/6 from 2020 to 2023.

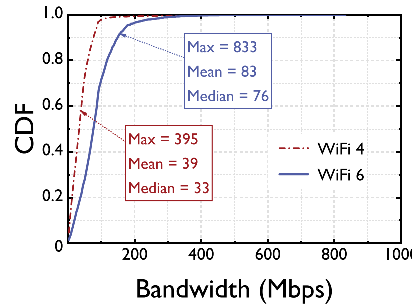

Fig. 8. WiFi bandwidth distribution on the 2.4 GHz band.

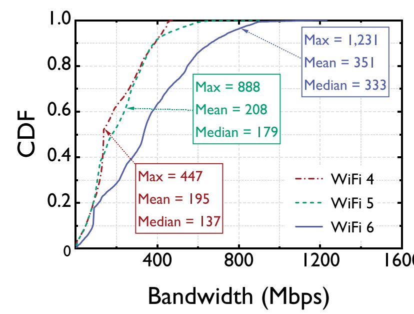

Fig. 9. WiFi bandwidth distribution on the 5 GHz band.

Fig. 6 depicts the evolution of average bandwidth for WiFi 4/5/6 from 2020 to 2023, and Fig. 7 illustrates how their corresponding market shares change. As shown, the overall WiFi bandwidth increased by 119.7% (132 Mbps $\rightarrow$ 290 Mbps), while the average monthly expenditure of fixed broadband remained almost unchanged (35.7 RMB/household $\rightarrow$ 35.8 RMB/household) [46] [47], indicating a reduction of approximately 55.6% in the price per Mbps (0.27 RMB/Mbps $\rightarrow$ 0.12 RMB/Mbps).

Over the four years, average bandwidths of WiFi 4/5/6 have increased by 17.2% (58 Mbps $\rightarrow$ 68 Mbps), 20.9% (201 Mbps $\rightarrow$ 243 Mbps), and 46.9% (322 Mbps $\rightarrow$ 473 Mbps) respectively, which are however remarkably lower than the overall increase (119.7% , 132 Mbps $\rightarrow$ 290 Mbps). This is mostly attributed to the increasing deployment of WiFi 6 access points (APs) over the past few years. As indicated in Fig. 7, the market share of WiFi 6 has surged from 10.5% to 42.7% from 2021 to 2023. By contrast, the market share of WiFi 4 has decreased from 57.0% to 29.1% , and the market share of WiFi 5 has reduced from 32.4% to 28.2% .

Besides, we pay close attention to the access bandwidths of WiFi 4/5/6 on different frequency bands. Given that WiFi 5 only uses the 5 GHz band, we look at the 2.4 GHz and 5 GHz bands separately (see Figs. 8 and 9). We are surprised to find that the average bandwidths of WiFi 4 and WiFi 5 are in fact fairly close over the 5 GHz band—195 Mbps versus 208 Mbps. This suggests that the overall bandwidth improvement from WiFi 4 to WiFi 5 is mostly because WiFi 4 users are also using the 2.4 GHz band, rather than benefiting from the technical advances introduced in WiFi 5, such as beamforming and downlink multi-user MIMO.

As for WiFi 6, we notice that it manifests the highest average bandwidths on both bands, and it achieves 46.9% increase in overall bandwidth over the past few years. To understand this, we comprehensively investigate recent advances in WiFi 6 technologies. However, we do not observe significant innovations widely adopted by commercial WiFi 6 APs, except the 3.3% adoption of *dual WiFi acceleration*. Dual WiFi acceleration enables a user device to connect to two WiFi APs in different frequency bands (i.e., 2.4 GHz and 5 GHz) at the same time, in order to increase the access bandwidth and improve the network stability. Unfortunately and surprisingly, in practice we observe that this technique exhibits poor real-world performance—it decreases the average bandwidth by 17.9% .

Deeper analysis indicates that the unexpected performance degradation is likely induced by insufficient support from WiFi APs, mobile OSes, and mobile apps.

In particular, many existing WiFi AP devices are not designed with the capability of supporting dual WiFi connections. Even if the hardware is capable, some AP firmware lacks the optimization for dual WiFi connectivity, leading to uneven resource allocation or interference between frequency bands [48]. For mobile OSes, if they fail to efficiently manage multiple WiFi connections, there may be unnecessary resource contention between frequency bands. Plus, if the network selection algorithm within the OS is not intelligent enough, it might choose suboptimal frequency bands for connections [49]. For mobile apps, they need to be specifically designed to support dual WiFi acceleration in order to fully leverage the benefits of dual WiFi. However, most mobile applications are designed to use only a single network connection [48]. Hence, WiFi 6's 46.9% increase

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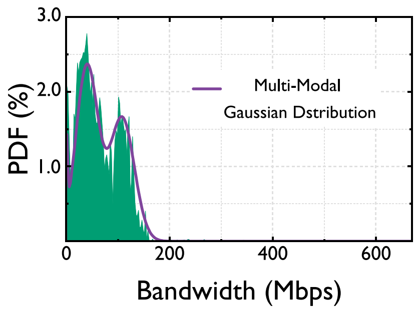

Fig. 10. Probability distribution for WiFi 4 bandwidths in our study.

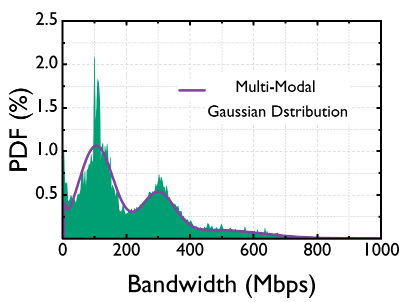

Fig. 11. Probability distribution for WiFi 5 bandwidths.

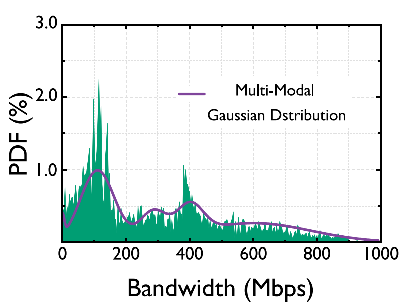

Fig. 12. Probability distribution for WiFi 6 bandwidths.

in overall bandwidth should largely stem from the upstream, i.e., the enhancement of wired access bandwidth.

Furthermore, we delve deeper into the bandwidth distribution of WiFi 4/5/6. We notice that for each generation, WiFi bandwidths tend to cluster around certain 100× values. As shown in Figs. 10, 11, and 12, WiFi 4 bandwidths tend to cluster around 50 Mbps and 100 Mbps, WiFi 5 bandwidths tend to cluster around 100 Mbps, 300 Mbps, and 500 Mbps, while WiFi 6 bandwidths tend to cluster around 100 Mbps, 300 Mbps, 400 Mbps, and 600 Mbps. Interestingly, we find that the above values, which are typically 100× Mbps, well match the promised bandwidths of ISPs' typical fixed broadband plans [50], [51], [52]. As a matter of fact, they generally reflect the distribution of WiFi users' purchased fixed broadband plans. Based on this heuristic, the fixed broadband plans of ISPs, and other public reports on the bandwidth distribution of fixed broadband in China [53], [54], we can now roughly infer that ∼64% of the WiFi users are still using ≤200-Mbps fixed "broadband" Internet access. Consequently, the technical advantages of WiFi 5 are in fact largely offset by the tardy evolution of wired Internet access.

On the other hand, for WiFi 6 there are fewer (∼39%) users using the ≤200-Mbps fixed broadband. By analyzing their coarse-grained location information, we find that WiFi 6 users are more likely to live in urban areas where wired broadband infrastructure evolves more quickly. In particular, we notice that for an ISP (ISP-3) that has made heavy investments in its fixed broadband infrastructure, the corresponding WiFi access bandwidth is also the highest among the studied four ISPs. This observation conforms with our inference that the increase of WiFi 6 access bandwidth is basically derived from the enhancement of wired access bandwidth. Nevertheless, the average bandwidth of WiFi 6 is still far below its advertised capability, leading to significant under-utilization of WiFi 6's superiority.

C. 5G Access Bandwidth

As the state-of-the-art cellular technology, 5G can offer up to 20Gbps access bandwidth along with ultra-low latency (e.g., 5 ms) and ultra-high service capacity (e.g., 1M devices per square kilometer). Over the past four years, ISPs have made enormous investments on 5G's infrastructure and commercial promotion. In particular, the number of 5G base stations has increased by 317% (0.77M → 3.21M) from 2020 to 2023. Moreover, even part of 4G's infrastructure (radio spectrum) has been refarmed for 5G use (detailed in Section IV-D).

Nevertheless, the average 5G bandwidth in 2023 is 274 Mbps, 20.2% lower than that in 2020 (i.e., 343 Mbps according to BTS-APP's measurement reports). Deeper analysis indicates a likely explanation to this unexpected and undesired situation—due to the vigorous propaganda of 5G, even more users (160M → 754M, increasing by 371%) have subscribed/switched to 5G access, draining the service capacity of 5G network infrastructure. To further understand the continuous decrease of 5G access bandwidth from 2020 to 2023, we next examine in depth some key factors that lead to the dilemma, regarding spectrum refarming, diurnal pattern, and received signal strength.

Spectrum Refarming: As shown in Table II, five bands are used by the four ISPs for 5G deployment in China, dubbed N1, N28, N41, N78 and N79 according to 3GPP's specifications [55]. All these bands are sub-6 GHz and three of them (N1, N28 and N41) are in fact refarmed from the three LTE bands (Band 1, Band 28 and Band 41) respectively (detailed in Section IV-D). N78 and N79, on the other hand, are dedicated to 5G usage, among which N78 is the core band that provides most of 5G's service capacity[2] while N79 is still under test deployment. There are only eight N79-related tests in our measurement, so we will exclude N79 from our analysis to avoid bias. We list the average access bandwidth of each 5G band in Fig. 13, and the number of access bandwidth tests conducted on each band in Fig. 15.

As shown, there exists a significant discrepancy among the average bandwidths of the three refarmed bands. Specifically, the

[2] ISP-3 uses lower-frequency spectrum in N78, offering wider coverage while not sacrificing bandwidth, so it has higher signal strength and bandwidth.

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TABLE II
THE FIVE 5G BANDS INVOLVED IN OUR STUDY, ORDERED BY THEIR DOWNLINK SPECTRUM

5G Band	Downlink Spectrum	Max Channel Bandwidth	ISPs
N28	758 – 803 MHz	20 MHz	China Broadcast Network (ISP-4)
N1	2110 – 2170 MHz	20 MHz	China Unicom (ISP-2), China Telecom (ISP-3)
N41	2496 – 2690 MHz	100 MHz	China Mobile (ISP-1)
N78	3300 - 3800 MHz	100 MHz	China Unicom (ISP-2), China Telecom (ISP-3)
N79	4400 – 5000 MHz	100 MHz	China Mobile (ISP-1), China Broadcast Network (ISP-4)

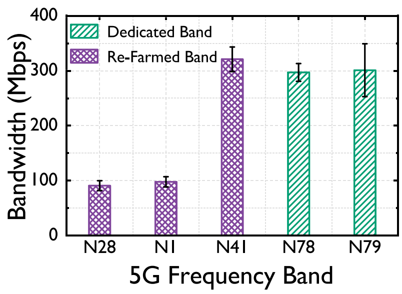

Fig. 13. Average bandwidth of each 5G band.

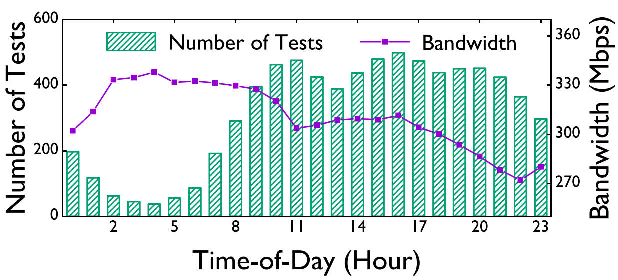

Fig. 14. Number of 5G tests and average 5G bandwidth in different times of a typical day.

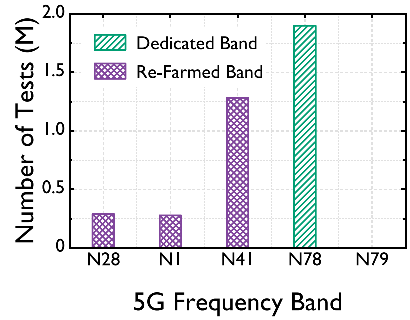

Fig. 15. Number of bandwidth tests conducted on each 5G band.

average 5G bandwidth on N41 is 321 Mbps, which is even higher that of 5G's core band N78 (297 Mbps). In contrast, the results on the other two refarmed bands (N1 and N28) are much lower, i.e., 98 Mbps and 91 Mbps. A deeper investigation clears the mystery—a 100-MHz contiguous spectrum (2515–2615 MHz) from Band 41 has been refarmed into N41, which is quite wide to support relatively high bandwidth. Additionally, this mid-frequency band experiences less path loss and provides better signal quality compared to the higher-frequency N78 band (3.4–3.9 GHz) [56]. In contrast, the refarmed contiguous spectrum from Band 1 and Band 28 is rather thin (i.e., 60 MHz and 45 MHz), leading to undesirable bandwidth. Thus, we conclude that refarming is a major contributor to the decline of 5G's average access bandwidth.

Diurnal Pattern: We also examine the number of 5G tests and the average 5G access bandwidth at different times of the days during our measurement period (Aug. to Nov. 2021). Fig. 14 demonstrates the data collected in a typical day. We observe that in most cases, the average 5G bandwidth is negatively correlated with the number of tests. This is because more bandwidth tests performed usually indicate that more users are sharing the access network, leading to heavier workloads and resource contention on the BSes.

Nevertheless, we find that the average bandwidth hits the bottom (276 Mbps) between 21:00 and 23:00, during which the number of tests is as small as 362 per hour. In contrast, even with 25% more tests performed per hour from 15:00 to 17:00, the average bandwidth in that time period is 10% higher (308 Mbps). Deeper investigations show that the above phenomenon stems from the sleeping strategy of 5G BSes, in which ISPs selectively turn off the active antenna processing units of 5G BSes from 21:00 to 9:00 to reduce energy consumption [57], [58], [59]. Notably, we observe that despite the sleeping strategy, the average bandwidth in fact reaches the peak (334 Mbps) between 3:00 and 5:00, since very few people are using the network during this period (46 tests per hour).

In comparison, for 4G networks, we find that the average bandwidth at different times of the days is in general positively correlated with the number of tests conducted by users. This is because an LTE BS consumes much less energy and thus does not adopt the sleeping strategy of 5G BSes. Note that similar phenomena are also observed from the data we collect from Feb. to Jun. 2023.

Received Signal Strength (RSS): In common sense, an excellent RSS usually implies a higher SNR, hence a higher access bandwidth [60]. While our data show that RSS and SNR are indeed positively correlated (Fig. 16), a counter-intuitive finding is that RSS and 5G access bandwidth are not. Fig. 17 clearly depicts that as RSS rises from level-1 to level-4, the average 5G bandwidth monotonously grows from 157 Mbps to 304 Mbps. However, when RSS becomes excellent (level 5), the average 5G bandwidth sharply drops below that with level-3 and level-4 RSS. The situation is similar when we examine the median 5G bandwidth.

To understand the above, we notice that the excellent-RSS 5G bandwidth tests are mostly performed in crowded urban areas, where 5G BSes in close proximity tend to yield consistently

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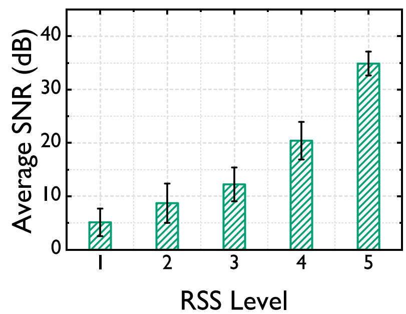

Fig. 16. Correlation between 5G RSS level and avg. SNR.

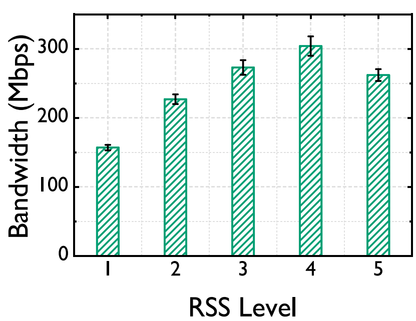

Fig. 17. Correlation between 5G RSS level and bandwidth.

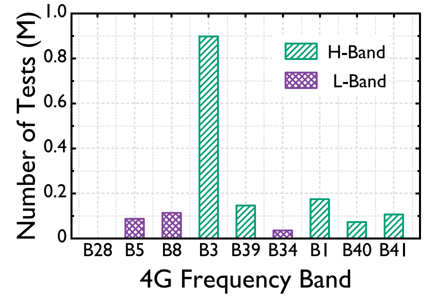

Fig. 18. Number of bandwidth tests on each LTE band in 2023.

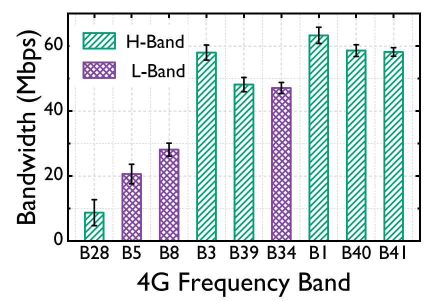

Fig. 19. Average bandwidth of each LTE band in 2021.

low bandwidth. Heavy population in such areas often requires dense deployment of 5G BSes (termed gNodeBs) [4]. Although this can provide higher signal strength, improper gNodeB placement and antenna configurations can easily lead to cross-region coverage [61], i.e., overlaps of different gNodeBs' signal coverage, which can aggravate the already complex multi-path and co-channel interference [62], [63] in urban areas with dense buildings, as well as the various load balancing issues and poor handover problems [14], [64], [65]. This may especially be the case given that current 5G technology and deployment are rather immature. In comparison, we do not observe such a phenomenon on 4G access, given its much more mature, well-provisioned infrastructure deployed for 10+ years.

D. 4G (LTE) Access Bandwidth

As illustrated in Fig. 1, the average bandwidth of 4G access has been fluctuating over the past four years. Specifically, in our preliminary work [15], we observe a sharp decrease (22.1%) of 4G bandwidth from 2020 (68 Mbps) to 2021 (53 Mbps). Interestingly, from 2021 to 2023 the average 4G bandwidth has gradually recovered from 53 Mbps to 65 Mbps. While in the top 1.6% of tests the bandwidth exceeds 300 Mbps, in nearly a quarter (24.1%) of tests the result is below 10 Mbps. In this part we explain the above phenomena by delving into the radio characteristics of LTE, the migration of radio resources from LTE to 5G, and the deployment of the novel LTE-Advanced technology.

Radio Characteristics: Frequency range (a.k.a, spectrum) and channel bandwidth are among the key radio characteristics that determine the performance of cellular access. Each LTE band is unique in the two characteristics. In theory, lower-frequency bands have less signal propagation loss, and thus can bring better radio coverage and signal-to-noise ratio (SNR). On the other hand, channel bandwidth has a more direct impact on the access bandwidth—the limit of access bandwidth linearly grows as the maximum channel bandwidth increases, as dictated by the Shannon-Hartley theorem [60]. Given the above theoretical radio features of different bands, we are particularly interested in their actual impact on the access bandwidth.

We have captured all the nine LTE bands used in China, referred to as Band 1, 3, 5, 8, 28, 34, 39, 40 and 41 following 3GPP's definition [66]. Table III lists each band's downlink spectrum (recall that our study concentrates on the download bandwidths of mobile devices), maximum supported channel bandwidth, and corresponding ISP(s)—note that one band can be multiplexed by multiple ISPs. According to 3GPP's LTE specifications [66], the channel bandwidth should reach 20 MHz to realize the theoretical bandwidth limit of 4G access, so we denote the bands that support the 20MHz channel bandwidth as *high-bandwidth* bands (H-Bands for short), and the others as *low-bandwidth* bands (L-Bands for short).

Fig. 19 lists the average access bandwidths of the nine LTE bands in 2021. Note that Band 28, which is assigned to the 5G-first ISP-4, was only used in two LTE bandwidth tests (see Fig. 20) so its result is highly biased here. Not surprisingly, H-Bands (except Band 28) yield higher access bandwidths than L-Bands. However, the average bandwidth of Band 39 is as low as 48.2 Mbps, even close to that (47.1 Mbps) of Band 34 which is an L-Band. This is because Band 39 is dedicated to serving rural areas where LTE BSes are sparsely deployed [67]. In comparison, Band 40 is used for penetrating indoor environments where LTE BSes are usually densely deployed, and thus offers

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TABLE III
THE NINE LTE BANDS INVOLVED IN OUR STUDY, ORDERED BY THEIR DOWNLINK SPECTRUM

LTE Band	Downlink Spectrum	Max Channel Bandwidth	ISPs
Band 28	758 – 803 MHz	20 MHz	China Broadcast Network (ISP-4)
Band 5	869 – 894 MHz	10 MHz	China Telecom (ISP-3)
Band 8	925 – 960 MHz	10 MHz	China Mobile (ISP-1), China Unicom (ISP-2)
Band 3	1805 - 1880 MHz	20 MHz	ISP-1, ISP-2, ISP-3
Band 39	1880 – 1920 MHz	20 MHz	China Mobile (ISP-1)
Band 34	2010 - 2025 MHz	15 MHz	China Mobile (ISP-1)
Band 1	2110 - 2170 MHz	20 MHz	China Unicom (ISP-2), China Telecom (ISP-3)
Band 40	2300 - 2400 MHz	20 MHz	China Mobile (ISP-1)
Band 41	2496 – 2690 MHz	20 MHz	China Mobile (ISP-1)

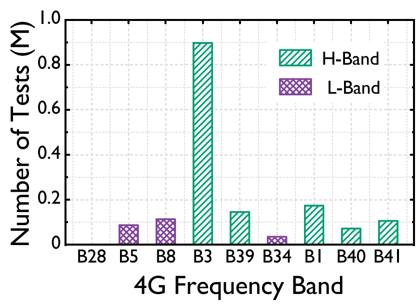

Fig. 20. Number of bandwidth tests on each LTE band in 2021.

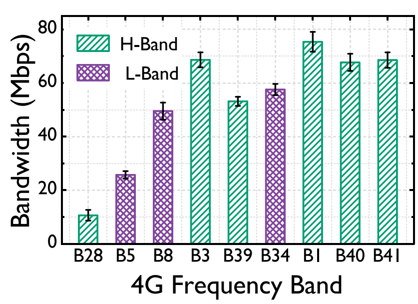

Fig. 21. Average bandwidth of each LTE band in 2023.

better signal strength—an average of -88dBm for Band 40 versus -94dBm for Band 39. These special purposes explain the low correlation between spectrum and access bandwidth for certain bands as shown in Fig. 19.

As illustrated in Fig. 21 (comparing with Fig. 19), the average bandwidth in each LTE band in 2023 has increased by 10% to 76% respectively compared with that in 2021. By investigating public reports and whitepapers [68], [69], [70], we find that the influx of users to 5G (as introduced in Section IV-C) has led to a substantial (27%) reduction of 4G users, which in some sense, is also reflected in the ratio of number of 4G/5G bandwidth tests performed by BTS-APP in 2021 and 2023 (i.e., 1 : 0.55 to 1 : 1.59). Besides, ISPs have deployed 0.13M more LTE BSes from 2021 to 2023 to improve the LTE network capacity. As a result, both the alleviation of LTE service pressure and the enhancement of LTE network infrastructure together lead to the gradual recovery of 4G access bandwidth in the past two years.

Radio Resource Migration: Since H-Bands are superior to L-Bands in terms of access bandwidth, most mobile users should be served by H-Bands, which are reflected on Figs. 20 and 18, where the majority (85.6% and 86.9%) of LTE bandwidth tests are conducted on H-Bands in 2021 and 2023 respectively. In particular, Band 3 alone serves 55% and 59% tests in 2021 and 2023 respectively. More specifically, for all the three ISPs (ISP-1, ISP-2 and ISP-3) that deploy LTE on Band 3, the percentage of Band-3 LTE bandwidth tests is the highest among their used bands, i.e., 31% , 63% and 76% in 2021, and 34% , 59% and 75% in 2023.

We attribute this skewed workload distribution to the recent migration of radio resources from other LTE H-Bands to 5G. In early 2021, a large portion of LTE H-Band spectrum was "refarmed" for 5G usage [11]; the affected bands include Band 1, Band 28, and Band 41, which in together occupy 58.2% of the entire H-Band spectrum. Such an aggressive migration constitutes an important cause of the sharp decrease in LTE access bandwidth from 2020 to 2021 (as mentioned in Section IV-A). In detail, the average bandwidths of the refarmed Band 1 (63 Mbps) and Band 41 (58 Mbps) have fallen below the average LTE bandwidth in 2020 (68 Mbps).

LTE-Advanced Deployment: As mentioned in the beginning of this part, although the average LTE bandwidth is rather low (65 Mbps in 2023), we do observe that in 1.6% LTE bandwidth tests the result is higher than 300 Mbps, averaging at 419 Mbps and peaking at 891 Mbps. A closer examination reveals that the majority of these tests are performed alongside urban main roads, where ISPs deploy the LTE-Advanced [71] technology for the nearby LTE BSes (termed eNodeBs) to deal with the large traffic volume.

LTE-Advanced makes significant improvements on conventional LTE bandwidth (which can only reach 150 Mbps) through a suite of innovations such as carrier aggregation, multi-antenna technology, enhanced MIMO and mobility. Carrier aggregation allows LTE-Advanced to extend the channel bandwidth by combining multiple carriers. For instance, LTE-A supports the aggregation of up to five carriers, each with a channel bandwidth of up to 20MHz, resulting in a total bandwidth of up to 100MHz. In this setting, the theoretical peak downlink data rate can reach 1.5 Gbs, while the peak uplink data rate can reach 500 Mbs.

Multi-antenna technology, particularly the support for eight-layer DL Spatial Multiplexing, has been enhanced in LTE-Advanced. By transmitting multiple independent data streams simultaneously over the same frequency resources,

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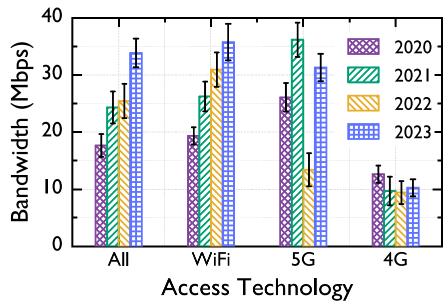

Fig. 22. Avg. WiFi, 5G, 4G upload bandwidth over time.

it significantly improves the spectral efficiency and data transmission rates. In a Multi-User MIMO system, a base station can simultaneously transmit data to multiple user devices using multiple antennas. LTE-Advanced also supports dynamic switching between Single-User and Multi-User MIMO modes, allowing it to flexibly adjust the transmission mode based on network conditions and user demands [71]. As a result, LTE-Advanced can achieve up to 2Gbps bandwidth, comparable to the bandwidth of today's commercial 5G. More importantly, LTE-Advanced is technically mature, easy-to-deploy, and cost-effective.

E. Upload Bandwidth

Recent years have witnessed the increasing importance of upload access bandwidth to common users, especially in the context of telework and self-media. Fig. 22 shows the evolution of upload bandwidth from 2020 to 2023 for WiFi, 5G, and 4G in China. The overall situation is encouraging, with a total improvement of 91.7% over the four years (17.7 Mbps $\rightarrow$ 33.8 Mbps). The major contribution comes from WiFi, with continuous annual increases of 35.8% , 17.9% , and 15.5% (19.3 Mbps $\rightarrow$ 26.2 Mbps $\rightarrow$ 30.9 Mbps $\rightarrow$ 35.7 Mbps). Similar to the case of download bandwidth, this substantial increase is owing to the widespread adoption of WiFi 6 and its growing market share.

On the other hand, 5G upload bandwidth has experienced obvious fluctuations over the four years, exhibiting an *N*-shaped ($\nearrow\searrow\nearrow$) trend. Concretely,fig it grew by 38.3% from 2020 to 2021 (26.1 Mbps $\rightarrow$ 36.1 Mbps), a period that corresponded with the widespread adoption of 5G infrastructure, where more access points and enhanced network capacities effectively supported the growth. However, from 2021 to 2022, it sharply declined by 62.9% (36.1 Mbps $\rightarrow$ 13.4 Mbps). During this period, governments' conservative policies in response to COVID-19 led to a significant shift of offline activities, such as education and office, to online platforms, resulting in a surge of users in scenarios like online meeting and UHD (ultra high-definition) live streaming. The high concentration of upload bandwidth-intensive applications put tremendous pressure on the 5G network, ultimately causing the overall bandwidth decline.

Good news is that with the abolishment of pandemic restrictions in early 2023, the pressure on 5G upload bandwidth was quickly relieved. Additionally, ISPs' continuous investments in 5G BSes further contributed to the rapid recovery of upload bandwidth, resulting in a 133.4% increase (13.4 Mbps $\rightarrow$ 31.3 Mbps). By the end of 2023, the total number of 5G BSes had reached 3.3 million, representing a year-on-year growth of 46.1% . On average, there were 24 5G BSes per 10,000 people, exhibiting an increase of 7.6% compared to the previous year [72].

Similar to the case of 4G download bandwidth, 4G upload bandwidth experienced a decrease (23% , 12.6 Mbps $\rightarrow$ 9.7 Mbps) from 2020 to 2021, which was also due to radio resource refarming. As a result, 4G upload bandwidth remained depressed from 2021 to 2022 (9.7 Mbps and 9.4 Mbps, respectively), until it began to show slight improvement in 2023 (10.2 Mbps) with the support of LTE-Advanced and more 4G base stations deployed.

V. Discussion

This section discusses the generalizability of our findings to other regions, and feasible optimization techniques available for improving 4G/5G bandwidth.

A. Generalizability to Other Regions

Although our study focuses on the situation of China, there is considerable evidence suggesting that our findings are applicable to other regions as well.

As an example, the UAE, which ranked first globally in mobile broadband speed in 2024 [1], has illustrated how spectrum refarming has been effectively implemented. According to the 2024 5G white paper by Etisalat by e& [73], the largest telecom provider in the UAE, the country has gradually reallocated existing spectrum resources since 2022, enabling a smooth transition of 2G/3G/4G frequency bands to support 5G and even 5G-Advanced. As a result, the UAE's 5G median download speed increased by over 11.5% from Q1-Q2 2023 to Q1-Q2 2024 (672 Mbps $\rightarrow$ 750 Mbps) [74]. In contrast, the median download speeds of South Korea's two major operators, SK Telecom and LG U+, declined from Q1 to Q2 2023 by 17.1% (194 Mbps $\rightarrow$ 161 Mbps) and 4.6% (99 Mbps $\rightarrow$ 94 Mbps), respectively [75]. This decline was primarily due to the decision made by the Ministry of Science and ICT (MSIT) at the end of 2022 to impose penalties for non-compliance with the 2018 5G spectrum allocation requirements [76]. Specifically, SK Telecom's 28 GHz spectrum license duration was reduced by 10% , and LG U+ lost its 28 GHz spectrum allocation entirely for failing to meet the minimum obligations. In both examples above, the impact of spectrum allocation on the overall download bandwidth aligns with our findings.

Like the situation in China, we can also infer the access bandwidth changes in a region based on the variation in the amount of usage. From 2022 to 2023, the number of 5G subscribers in India increased over tenfold (12 million $\rightarrow$ 131 million) and continues to rise, with projections reaching 575 million by 2026 [77]. Meanwhile, the surge in usage pressure led to a consistent decline of 7.7% in India's 5G download bandwidth over the four quarters of 2023 (304 Mbps $\rightarrow$ 301 Mbps $\rightarrow$ 291 Mbps $\rightarrow$ 280 Mbpsn) [78]. Similarly, according to the Mobile Matters report [79] [80] published by Ofcom (the U.K.'s regulator for communication services), the proportion of 5G connections in the cellular network increased by more than 3.5 times, rising

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from less than 0.5% in 2023 to 19.6% in 2024. Given this surge, it is imperative for the government and telecom operators to take proactive measures to ensure the service quality of 5G.

B. Feasible Optimizaions

With the increasing demand for mobile access bandwidth posed by emerging data-intensive applications, addressing the declining or fluctuating trend in 4G/5G bandwidth becomes crucial. While new hardware solutions are essential, the inherent delays in deployment make it necessary to explore practically feasible software-based interventions for more immediate improvements.

Virtualization-based Optimization: Virtualization offers a transformative methodology to enhance mobile network efficiency by decoupling hardware functionalities from software ones [81] [82]. CoreKube [83] demonstrates a cloud-native approach to virtualizing mobile core functions, offering dynamic scaling and resilience by decoupling core network state/processing, as validated through its integration with OpenAirInterface (OAI) [84]. This approach is further refined by CloudRIC [85], which optimizes the processing efficiency of 5G virtual Radio Access Network (vRAN) by pooling heterogeneous computing resources across Distributed Units (DUs), achieving energy savings and cost efficiency while maintaining very high (99.999%) reliability under real-world workloads.

In addition, Nuberu [86] introduces a reliable vRAN solution with a novel pipeline architecture for DUs, maintaining the vast majority (95% +) of theoretical spectrum efficiency even under severe computing fluctuations. Concordia [87] pushes the boundaries of vRAN efficiency by reclaiming most (70% +) of idle CPU cycles for general-purpose workloads, while meeting almost all (99.999%) of vRAN processing deadlines. Moreover, vPIFO [88] introduces a virtualized packet scheduler that supports hierarchical scheduling in high-speed networks, demonstrating efficiency and scalability with up to 128 Push-In First-Out (PIFO) instances at 400Gbps on FPGA.

Intelligent Resource Allocation: Better allocation strategies for mobile network resources are also worth investigating [89]. A deep reinforcement learning-based control framework [90] for multi-slice RANs is proposed to dynamically optimize the Physical Resource Block (PRB) allocation, showing improvements in resource utilization and Service-Level-Agreement (SLA) violations across 19 enhanced eNodeBs. Janus [91] offers a programmable framework for real-time PRB allocation in 5G vRANs, allowing precise control at the MAC scheduler level. Complementing these solutions, TinyRIC [92], a real-time control platform for Open Radio Access Network (O-RAN) base stations, utilizes its Flexus service to enable dynamic PRB allocation and efficient user scheduling, achieving as low as 50 μs of round-trip time for scheduling decisions.

On the latency reduction front, the Latency Reduction Protocol (LRP) [93] successfully reduces median LTE uplink latency by up to 7.4 times by proactively managing uplink resource allocation, as evidenced across five mobile carriers. Additionally, the Programmable Calendar Queues (PCQs) [94] offer dynamic prioritization and resource allocation in high-speed networks to improve fairness and delay guarantees. PCQs have been implemented on programmable switch hardware, supporting throughput rates of up to 400Gbps and achieving nanosecond-level packet scheduling accuracy.

Leveraging Advanced Techniques: The community have been exploring advanced techniques, such as carrier aggregation (CA) and network slicing, to enhance the access bandwidth of mobile networks. A detailed study of CA in 5G networks [95] demonstrates that aggregating multiple component carriers remarkably elevates data rates, achieving up to 4.1Gbps in real-world scenarios; it also introduces Prism5G, a CA-aware deep learning framework, to increase the throughput prediction accuracy by over 14% . Similarly, a comparative study of mid-band 5G deployments in the U.S. [96] highlights how reliance on CA significantly improves throughput, often surpassing 1Gbps.

In terms of network slicing, Fronthaul Slicing Architecture (FSA) [97] stands out as a pioneering solution for the 5G fronthaul, enabling multipoint-to-multipoint routing and packet prioritization; it supports up to 80Gbps of fronthaul traffic while reducing latency-sensitive traffic completion by four times. Additionally, Zipper [98] introduces a real-time RAN slicing system that dynamically allocates PRBs, supporting up to 200 apps and 70 slices on a 100 MHz 5G channel, reducing SLA violations by nine times. Mambas [99] enhances network slicing in mmWave networks through analog multi-user beamforming, achieving 1.92-3.86$\times$ increase in sum rates compared to existing methods.

VI. Conclusion

As 5G and WiFi 6 flourish over the past four years (2020–2023), this paper presents a timely study on the status quo, evolution, and optimization opportunities of mobile download/upload access bandwidth. Our study is featured by its cross-layer and cross-technology measurement at scale in the wild, which is enabled by our collaboration with a major mobile bandwidth testing app that serves around 0.2M user requests per day. Based on the fine-grained data we collected from 48.7M bandwidth tests, we discover critical yet diverse performance gaps between the advertised mobile access bandwidth and what is actually delivered in the wild. For the first time, we reveal the root causes of these gaps by jointly considering the impact of user devices, ISP infrastructure investment, radio resource allocation and migration, and recent advances in cellular technology, with potential solutions to filling these gaps.

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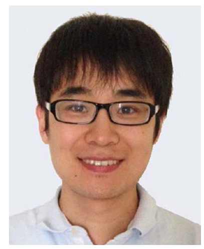

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