Impact of Device Thermal Performance on 5G mmWave Communication Systems

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Abstract—5G millimeter wave (mmWave) cellular networks have been deployed by carriers mostly in dense urban areas of the US, and have been reported to deliver a throughput of around 1 - 2 Gbps per device. These throughput numbers are captured via speed-testing applications which run for only a few seconds at a time and are not indicative of the sustained throughput obtained while downloading a large volume of data that can take several minutes to complete. In this paper we report the first detailed measurements in three cities, Miami, Chicago, and San Francisco that study the impact of skin temperature, as measured by the device, on the throughput that the device is able to sustain over many minutes. We report results from experiments conducted on deployed 5G mmWave networks that show the effect of thermal throttling on a 5G mmWave communication link when a large file download is initiated that saturates the link, i.e., the device is connected to 4 mmWave downlink channels each 100 MHz wide. We observe a gradual increase of skin temperature within 1 – 2 minutes which correlates to a decrease in the data rate due to the number of aggregated mmWave channels reducing from 4 to 1 before finally switching to 4G LTE. Finally, we identify messaging in the Radio Resource Control (RRC) layer confirming that the reduction in throughput was due to throttling due to the skin temperature rise and further demonstrate that cooling the device restores throughput performance. These results are extremely important since they indicate that the Gbps throughput that can be delivered by a 5G mmWave connection link when a large file download is initiated that saturates the link, i.e., the device is connected to 4 mmWave downlink channels each 100 MHz wide is connected to 4 mmWave downlink channels each 100 MHz wide.

I. INTRODUCTION

5G New Radio (5G NR) cellular networks are being rapidly deployed around the world in low (< 1 GHz), mid (1 – 6 GHz), and high (> 24 GHz) bands. Of these, the high, or mmWave bands, are being deployed predominantly in dense urban areas in the US while the low and mid-bands, including the C-Band (3.7 - 3.98 GHz) are witnessing deployments that can provide wider coverage in suburban and rural areas due to the favorable propagation characteristics. It is anticipated that the extremely high throughput and low latency that will be possible with 5G mmWave will support applications such as vehicular networks, virtual reality and increased user density [1] with better Quality of Service (QoS) than the other bands. Recent measurements on deployed 5G mmWave networks in major US cities demonstrate that indeed 5G mmWave can deliver extremely high throughput in the range of 1 - 2 Gbps [2], [3], [4]. These high throughputs are enabled by aggregating up to 8 100 MHz mmWave channels, depending on network and device capabilities.

However there are still a number of challenges associated with guaranteeing QoS in 5G mmWave: beam-tracking, beam management, building blockage and rain attenuation, to name a few, and there are many research efforts underway to address these challenges [5], [6]. In this paper we address a question that has received less attention by the research community: what is the sustained throughput, over several minutes, that can be delivered by a 5G mmWave connection? Most reported speed-test measurements use commonly used speedtest apps such as Ookla [7] or the FCC Speedtest [8], where the test runs for only 5 - 10 secs and is not indicative of the average throughput when an application is running over several minutes at the high throughput. We postulate that high-throughput data transfer over several minutes using multiple mmWave channels will cause device heating with a resultant increase in the skin temperature that will then trigger throttling of the throughput until the device cools to acceptable levels. We present results from detailed experiments conducted with consumer 5G smartphones operating over deployed 5G mmWave networks to demonstrate that indeed this phenomenon occurs repeatedly when the ambient temperatures are high enough to deter the cooling of the device. We demonstrate that as the skin temperature measured by the device increases, the number of mmWave channels being aggregated drops from 4 to 1 followed by handover to 4G LTE, with the throughput dropping at each step. When the device is artificially cooled...
by placing on a ice-pack, or when the ambient temperature is low enough (e.g. on a Chicago winter day) to enable rapid cooling, there is no drop in throughput, even over several minutes. Furthermore, we identify explicit message exchanges in the Radio Resource Control (RRC) layer between the user equipment (UE) and the base-station (BS) that confirm that the reason for handing over to 4G LTE is thermal and not network congestion or other considerations.

The paper is organized as follows. Section II provides a brief background on 5G NR operation and existing measurement results on deployed networks, Section III describes the measurement tools and methodology used in the experiments, Section IV presents the measurements and analyses of the experiments, and finally Section V concludes the paper.

II. RELATED WORK

Recent literature \cite{2}, \cite{3} has demonstrated the feasibility of achieving very high throughput with consumer smartphones over commercially deployed 5G mmWave cellular networks, in spite of the well-known limitations of mmWave propagation due to beam tracking, beam management, mobility management and building blockage. Advanced techniques, based on machine learning and artificial intelligence, have been proposed for addressing these limitations, for example in \cite{5}, \cite{6}. Most recently, \cite{7} presents detailed measurements of 5G mmWave deployments by two major commercial 5G operators in the US in two diverse environments: an open field with a baseball park and a downtown urban canyon region, using smartphone-based tools that collect measurements across several layers (PHY and MAC) including beam-specific metrics like signal strength, beam switch times, and throughput per beam. The measurement-driven propagation analysis demonstrated the performance difference due to terrain, frequency of operation, antenna pattern, etc. However, the relationship between device temperature and sustained 5G mmWave throughput was not explored. The experimental results presented in this paper seek to address the gap in the literature on effect of device thermal management on end-user throughput on 5G mmWave networks.

In particular, we seek to demonstrate that indeed the drop in throughput is due to thermal. According to the 3GPP standard \cite{8}, an UE can provide information to the BS about its thermal state via the RRC CONNECTED message field. Upon receiving such a message from the UE, the BS will respond by temporarily reducing the number of aggregated data streams, in both component carriers and MIMO layers, in both downlink and uplink transmissions until the thermal warning messages are no longer received. This reduction in component carriers (e.g. reduction from 4 to 1 mmWave channels) will lead to a reduction in throughput until the skin temperature drops to below a pre-specified threshold.

III. MEASUREMENT TOOLS AND METHODOLOGY

In order to demonstrate the effect of device skin temperature on sustained throughput over 5G mmWave, the following requirements need to be met:

- A sustained download of a high-bandwidth data stream over ~15 minutes while connected to a 5G mmWave BS,
- A method of measuring temperature while the download is occurring, and
- A method of extracting RRC messaging between the UE and the BS while the download is occurring.

In this section, the tools and methodology used in this paper to satisfy the above requirements are described.

Table I summarizes the parameters of the experiments conducted in two locations in Chicago, one location in Miami and one location in San Francisco. Data was collected in all 3 locations over September - October 2021, as well as in Chicago in January 2022 for comparison of performance as ambient temperatures cooled. All the experiments were conducted using the same UE model and network: Google Pixel 5, running Android 11 equipped with a Verizon SIM.
card with an unlimited data plan[7]. Fig. 1 shows the specific measurement locations in Chicago, Miami and San Francisco, while Table II shows detailed information of each location. The Verizon 5G mmWave network at each of the locations utilizes the 28 GHz n261 frequency band.

Downlink throughput saturation is achieved using a combination of two methods:

- **Background Download (BG DL)** using HTTP download of a 10 GB dataset file [9].
- **FCC Speed Test (FCC ST)** app: the 5 sec downlink throughput test is run repeatedly to ensure that the link stays saturated continuously.

Thermal throttling was observed using either one of the above methods, but combining both methods ensures that the link is fully saturated. The Miami measurements used only the BG DL traffic, while BG DL + FCC ST was used in the Chicago and San Francisco measurements. Due to this minor difference in methodology, there are two separate throughput measurements: PHY level throughput collected by Network Signal Guru (NSG), described below, and APP level throughput collected by FCC ST.

Using all the measurements reported in this paper, we verified that, as expected, the APP throughput is always proportionally lower than the PHY throughput. APP throughput values are easier to extract from FCC ST than PHY throughput from NSG (requiring manual data input). Thus, these different types of throughput measurements are carefully separated and only the same type of throughput values are compared whenever needed in our analysis.

The following Android apps were used to extract the information needed for the experiments during the download:

- **SigCap** [4], an Android app developed at the University of Chicago which collects Global Positioning System (GPS), time and location information along with signal and network parameters (e.g., 4G and 5G RSRP, RSRQ, RSSI, PCI, 4G frequency, etc) through Android APIs that extract this information directly from the modem chip and hence is compliant to relevant standards. Instantaneous skin, CPU and GPU temperature measurements from the APIs were added to SigCap for the results reported in this paper [10].
- **Network Signal Guru (NSG)** [4], a commercial app that utilizes the phone’s root capability to provide more extensive information (compared to the Android APIs) about the transmission such as operating frequency, number of carrier components, bandwidth, PHY throughput, and RRC messaging.

The above tools and methodologies were used to collect measurements systematically in the locations described above.

### IV. Experimental Results

In this section, we demonstrate the impact of 5G mmWave transmission on the device temperature, and the resulting effect on UE throughput under various operating conditions that impact the UE temperature (e.g., phone cover and ambient temperature).

#### A. Impact of 5G mmWave on UE Temperature

5G mmWave throughput and UE temperature Vs. time

In order to demonstrate the effect of 5G mmWave on device temperature we conducted numerous measurements using the tools and methodologies described in the previous section. We performed a total of 32 measurement runs over all locations, where each measurement run starts with a cool phone. Fig. 2 shows a representative measurement at Location 1 in Chicago (taken on Oct 9, 2021) using the combined BG DL + FCC ST method. The PHY data rate and number of mmWave channels are manually transcribed from NSG, while the temperature data is collected from SigCap, both at 5 second intervals and synchronized using timestamps from both apps. The figure only shows the PHY throughput when the FCC ST is running.

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[7] Subscribed Verizon plan indicates a throttling after 50 GBytes for 4G and 5G low/mid-band data, and no throttling for 5G mmWave data. [https://m.qrun.com/en/product.html](https://m.qrun.com/en/product.html)
Cumulative distribution function

Temperature (°C)

Skin - NR 4 Ch. to 1 Ch.
Skin - NR 1 Ch. to LTE
Skin - NR 4 Ch. only
CPU - NR 4 Ch. to 1 Ch.
CPU - NR 1 Ch. to LTE
CPU - NR 4 Ch. only

20  30  40  50  60  70  80
0.2  0.4  0.6  0.8  1

Fig. 3: CDF of CPU and skin temperature when number of NR channels changed, and when NR channel is 4.

(at ~20 seconds interval) in order to display the conditions when the downlink to the UE is fully loaded.

Fig. 2a shows a PHY data rate of almost 2 Gbps was achieved soon after the experiment was started at the 200 seconds mark, which is the result of aggregating 4 mmWave channels as shown in Fig. 2b. The rate increase is accompanied by a temperature rise on all three temperature measurements: skin, CPU and GPU. At the 300 s mark, the number of aggregated mmWave channels reduces to 1 and the resultant throughput is reduced significantly. At this point, the CPU and GPU temperatures are reduced slightly, but the skin temperature does not reduce sufficiently to restore the throughput to the levels seen at the beginning of the experiment. The download was completed at 800 s.

Analysis of skin temperature effect on throughput. We observe two events: first, when the number of 5G mmWave channels is reduced from 4 to 1 (i.e., 300 s on Fig. 2a), and second, when the device is handed over to the LTE network (500 s). At both events, we recorded a “Secondary Cell Group Failure” signalling packet in the NSG log, which shows compliance to the 3GPP standard [3]. Moreover, using the Android Temperature API [10], we obtained the static temperature threshold values: 96° C for CPU and GPU, and 43° C for Skin. Fig. 3 shows the skin and CPU temperature distribution of all our data from all locations for the following cases: (i) the temperature when 4 mmWave channels are being aggregated, (ii) the temperature just after the switch from 4 mmWave channels to 1 mmWave channel, and (ii) the temperature just after the switch from 5G mmWave to LTE. We omit GPU temperature since we observe that the CPU and GPU temperatures are similar. The figure clearly shows that throttling to 1 mmWave channel happens mostly at skin temperature of 43° C, while throttling down to LTE happens mostly at skin temperature of 45° C. On the other hand, the data clearly shows that CPU temperature does not exhibit any correlation with the events since the CPU temperature threshold is never crossed. Hence, we infer that the skin temperature is the trigger that causes the throughput degradation. However, the skin temperature measurements are not exact, i.e., there is some delay between the threshold being breached and the event to prevent a rapid oscillation between network states. However, we can still observe an on-off pattern in Fig. 2 between the 500 to 770 s mark, which shows that there is a feedback loop between the mmWave/LTE usage and skin temperature.

Fig. 4 displays all 5G mmWave measurements collected at Chicago and San Francisco, using both BG DL and FCC ST to saturate the downlink transfer. It demonstrates clearly that higher skin temperature correlates to lower 5G mmWave throughput, with the lower throughputs recorded mostly in summer (Sep-Oct) and the higher throughputs recorded in Chicago in winter (Jan).

B. Thermal performance as a function of ambient conditions

Effect of ambient temperature over seasons and location. Fig. 5 shows the mmWave throughput versus time, where the time axis has been normalized i.e., 0 s is the timestamp of the first data point. Fig. 5a shows the comparison of APP throughput between summer (Sep-Oct) and winter (Jan) in Chicago. These measurements are from Location 1 and 2, using the combination of FCC ST and BG DL. It is clear from the figure that in the warmer months, when the ambient temperature was ~24° C, there is a degradation of throughput after 200 s, while no such degradation is observed in the winter months when the ambient temperature was ~−10° C.

Fig. 5b shows the comparison of measurements in Chicago, Miami, and San Francisco collected in summer. Since the data in Miami was captured using BG DL traffic only, PHY throughput from NSG is used in this analysis. The throughput in Miami data degrades faster (at ~60 s) than Chicago and San Francisco, which can be explained by the climate difference between these cities and the time of experiment. The Miami data was taken with ambient temperature of ~31° C, while Chicago and San Francisco data was taken with ambient temperature of ~24° C and ~15° C, respectively.

Effect of external cooling and phone cover. In order to further confirm that increasing UE temperature is the cause of reduced 5G mmWave throughput, the following experiment was conducted in Miami in summer. Measurements were taken with the phone either held in the hand or placed on an ice-
V. CONCLUSIONS AND FUTURE WORK

We presented the first detailed measurements demonstrating the dramatic impact of device skin temperature on 5G mmWave throughput. The experiments were conducted in three different cities under various ambient conditions, with all results indicating that 5G mmWave sustained throughput is limited due to the rising skin temperature of the UE. First, we demonstrate a 3-step throughput profile which starts with a high rate above 1 Gbps due to utilizing 4 carrier components to a 5G mmWave network in its full potential.

Second, we investigate the impact of using a phone protective case on extending the 5G mmWave throughput. Three runs were conducted to measure the achievable throughput using a phone with a standard commercially-available case and three additional runs were conducted for the same phone without the covering, both type of experiments were ran in Miami. Fig. 7a shows the achievable PHY throughput for all six runs. Without phone cover, the phone can sustain a higher 5G mmWave throughput of ~1 Gbps using 4 carrier components, for up to 60 s. On the other hand, with the cover, the phone can only sustain the higher rate up to 30 s.

The lower throughput performance of covered phone can be explained by Fig. 7b which shows the corresponding skin temperature over all six runs. The covered phone’s temperature passes the 43°C threshold starting from 20 s, compared to the uncovered phone from 40 s. In other words, the covered phone has higher skin temperature due to its limited heat dissipation introduced by the phone cover. However, this phone cover experiments were conducted with the limitation of one specific phone case in a specific climate, thus further experiments with more variables are needed. Still, we demonstrated that the ability of faster heat dissipation allows for longer utilization of the 5G mmWave network in its full potential.

https://www.spigen.com/products/pixel-5-case-tough-armor
before finally falling back to the baseline 4G/LTE system as the device skin temperature increases. Second, we have shown that this 3-step profile repeats once the skin temperature reduces and the test is restarted. Finally, we have shown that the duration of sustained 5G mmWave throughput can be significantly increased by not using a phone covering or by using improved cooling mechanisms (e.g., an ice-pack for proof of concept purposes). These results also indicate that device skin temperature should be considered in scheduling and resource allocation algorithms so that the user does not experience a fluctuating throughput and the device does not heat up beyond the limits of skin temperature. Our future work in this area will focus on using tools such as Accuver XCAL that allows detailed analysis of all management messaging between the device and the base-station as well as using infra-red imaging to more accurately identify the source of the observed temperature rise. The authors have provided public access to their data at [https://bitbucket.org/kyuucr/thermal-paper-data](https://bitbucket.org/kyuucr/thermal-paper-data).

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