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A Look into the Performance of mmWave 5G, 3G, 4G/LTE using PC Application, iPerf3 and DASH

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ABSTRACT

With the fast-paced growth and expansion of cellular networks, the high bandwidth mmWave 5G is intensely sought after by businesses, medical centers and civilians. However, this relatively new network has already encountered various obstacles, such as instability, weakness and inconsistency. The nature of mmWave 5G consists of high frequency resulting in shorter wavelengths. This causes the current issues with upper layer management, which is seen with various applications such as video streaming. My research focuses on the performance and user quality of mmWave 5G, 3G, and 4G/LTE (4th Generation **L**ong **T**erm **E**volution, which is standard wireless data transmission today) with PC application. While 5G and other cellular networks have been studied with mobile based applications, my research uses PC applications to see how PCs work with various networks. To analyze the performance of these cellular networks, I used iPerf3, a network tool, and DASH, a video streaming software. With iPerf3, I was able to understand the network via a client and server side that the test provided. With DASH, I was able to further my knowledge around the networks with new data around user experience (UE). I also analyzed how mmWaves react to different variables, such as signal blockage, and how that affects the user experience and overall performance. My findings reveal critical insights to how mmWaves perform with PCs by measuring various metrics to get Quality of Experience (QoE) and on user experience of mmWaves.

Introduction

The cellular network industry is expanding, especially with its newest innovation, 5G. In each cellular network, there is a spectrum of bandwidths, and each starts at a higher bandwidth than the preceding one. Inside the 5G New Radio (NR) specifications, which is a bandwidth spectrum, cellular carriers are competing with each other to be at the forefront of mmWave technology [1]. This mmWave 5G is a specific bandwidth of 5G that is known to have very low latency and high speed due to its high frequency. As a result, it is in high demand with a growing number of cities gaining access to it. However, the mmWaves have short wavelengths, which poses many problems in upper-layer network management [2]. Upper-layer network management consists of the presentation and application of the network [3].

- One critical issue of mmWave application is the spotty coverage. While mmWaves are emitted from access points, due to the nature of mmWaves, the coverage from the access point is very small resulting in many gaps. This issue is further exacerbated by the growing trend of carrier services transitioning into NR Stand Alone (SA) networks. Many carrier services have begun to offer SA 5G which creates issues when 5G connection is lost. However, the implementation of LTE/5G integration is also problematic due to different cores of the different networks [4]. Furthermore, due to the spotty coverage, mmWave 5G is not ideal for suburban or rural areas: densely packed areas are the most ideal because then mmWaves can be accessed by the most amount of people [1].

- Another issue is weakness. Not only are mmWaves very weak, especially in certain conditions such as rain, buildings are also obstacles to mmWaves because mmWaves are not able to penetrate through buildings and walls, which also contributes to their instability [5]. The overall weakness of the signal makes mmWave 5G unstable, which causes the issues in upper-layer network management. Prior works have reported that mmWave 5G is quite inconsistent, due to its instability, leaving certain analysis tests with poor results [2].

My research focuses on performance analysis using PC applications over mmWave 5G and comparing those to 3G and 4G/LTE. The main issue with cellular network applications on PCs is that the specific access points that phones have to connect to cellular networks is not present in PCs. To combat this, I used various tools to create a hotspot to simulate a cellular connection in PCs. I then ran a speed test on the Ookla server, a network server used to test the speed and performance of a network connection [6], to get the latency for various locations around the world. Using those latencies, I choose 4 values to use in later experiments to simulate various distances between the server and client side. I then use a network test, using the network tool iPerf3, to analyze various conditions surrounding how mmWave 5G works. Finally, I run video streaming experiments to calculate Quality of Experience (QoE) to understand the user experience of mmWave 5G.

Methods

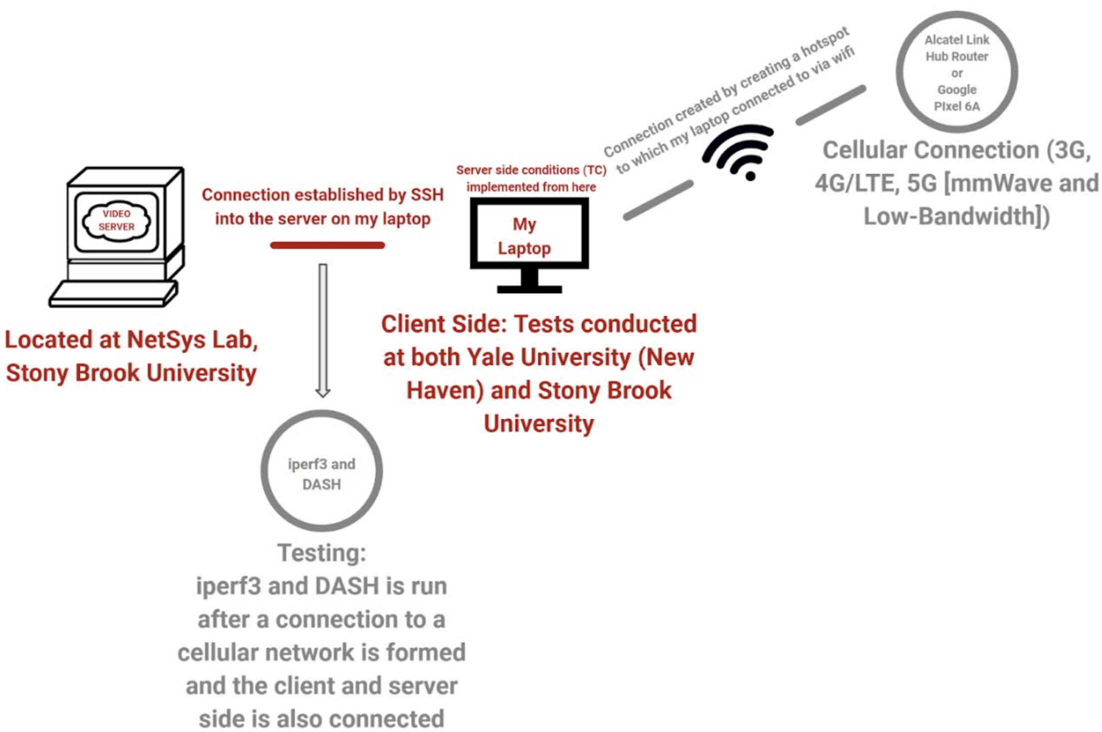

Figure 1. Experimental Setup

In order to test the performance and gather data on user experience over mmWave 5G as well as other cellular networks, I ran experiments on two different tools: one on DASH video streaming and the other on iPerf3 (Figure 1). Before conducting experiments on the two network tools, I first ran speed tests with Ookla and set the server connection to be in various cities around the world, to get an estimate on the latency from the base server (Stony Brook) to various parts of the world. With these tests, I extracted various quantities: ping (latency), goodput, downlink, and uplink (Figure 2). These metrics are useful because we are able to get Quality of Experience (QoE) from them: latency is the delay in data being sent over a network [7]; goodput is the number of MegaBytes of useful data delivered per second [8]; downlink is the downwards direction of information being delivered (a signal from satellite to a ground station), while uplink would be the upwards direction (a signal from a ground station to a satellite) [9].

Server Location	Latency (ping)	Download (Mbps)	Upload (Mbps)	Goodput
4G/LTE				
Ashburn, VA	31 ms	44.09	32	5.51125
Seattle, WA	99 ms	48.13	33.33	6.01625
Seoul, South Korea	214 ms	39.57	27.64	4.94625
New Delhi, India	249 ms	33.4	31.82	4.175
Cayenne, French Guiana	89 ms	40.74	26.19	5.0925
Paris, France	99 ms	37.89	32.4	4.73625
San Francisco, CA	119 ms	42.98	30.41	5.3725
3G				
Ashburn, VA	75 ms	13.95	1.07	1.74375
Seattle, WA	129 ms	12.72	0.95	1.59
Seoul, South Korea	248 ms	11.07	0.93	1.38375
New Delhi, India	322 ms	11.6	1.12	1.45
Cayenne, French Guiana	117 ms	11.26	0.96	1.4075
Paris, France	124 ms	11.07	1.05	1.38375
San Francisco, CA	139 ms	11.53	18.05	1.44125

Figure 2. Ookla speed test results

Using the range of latencies from these speed tests, I picked four values of latency within: 30ms, 70ms, 90ms, and 120ms (Figure 3). With these four values, I created a simulated lag to represent distance between the server and client, using traffic control (TC) for the three different cellular networks on the PC for both iPerf3 and DASH. TC in networking is used to manage or control network traffic by a network scheduler [10]. I first used TC in iPerf3, which is a network tool that provides active measurements of the maximum achievable bandwidth on IP networks [11]; in this case, the network scheduler would be the server side because it controls the packets (data) sent. For 3G and 4G/LTE, I used the Alcatel Link Hub to create a hotspot to which I connected my computer to simulate a cellular connection. After establishing this cellular connection, I connect the client side (my laptop) to the server side using the IP address of the server side. After connecting and setting up each side, I set TC values to 30ms, 70ms, 90ms, and 120ms. With each TC value, I ran multiple iPerf3 tests for each cellular network to get values for loss rate, retransmits (packets that had to be resent), goodput, and more.

Parameters for Testing	Latency added	Bandwidth restrictions	Test length
DASH	30ms, 70ms, 90ms, 120ms	3mbps	59 sec
iPerf3	30ms, 70ms, 90ms, 120ms	N/A	10 sec
WiFi	30ms, 70ms, 90ms, 120ms	8mbps, 25mbps	N/A

Figure 3. Testing Parameters

Following the tests with 4G/LTE and 3G, I began testing with low bandwidth 5G and mmWave 5G. To test with 5G, I used a Google Pixel to create a mobile hotspot with a Verizon Unlimited Data Plan. However, due to the lack of mmWave 5G in Stony Brook, the mmWave 5G and low bandwidth 5G tests took place at Yale University in New Haven, CT. On the Pixel, the connection of mmWave 5G and low bandwidth 5G is differentiated by the marking of “UW” next to 5G, along with the confirmation that the Pixel is connected to a NR network with high frequency (Figure 4). For these tests, the same metrics were measured, however, various new tests were added. After running iPerf3 tests, I then experimented with the strength and nature of the mmWaves. I ran the same tests with different conditions, making the previous tests without conditions my control group: I varied the location of the Pixel— putting it in my pocket, a paper bag, and more— to see the effects of adding obstacles to the path of the mmWaves.

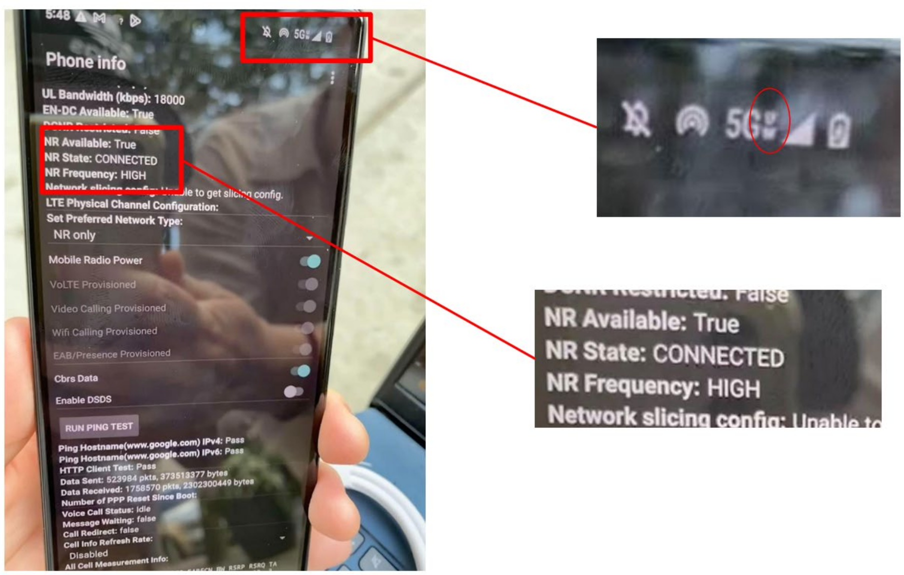

Figure 4. Established mmWave connection

After completing tests with iPerf3, I then ran DASH video streaming sessions, with the client side being my laptop, and the server being in Stony Brook, NY. The experimental setup of this was similar to the iPerf3 testing. In order to set DASH up, I downloaded a DASH video onto the video server in multiple qualities: 1000 kbps, 2000 kbps, 4000 kbps, and 6000 kbps (equivalent to 360p, 480p. 720p, and 1080p respectively). These video files were placed into the server side, where it would send packets of pixels and data to the client side, my PC, when the code for video streaming was run, which would then stream the video in a new Chrome browser. For DASH testing, the Pixel was used to create a hotspot. However, when creating a 3G hotspot, the video streaming tests would not run because the packet sizes were too large to send over without a low-quality network. To combat this issue, I set a cap on the maximum bandwidth to be 3 Mbps: 3G network has a bandwidth of 3 Mbps. Then, during the video streaming tests, I also put TC on the server side. I then ran the code, which connected the client side (my PC) to the server (NetSys Lab) and opened a video streaming tab, and recorded data on stall rate and mean quality rate.

Results

The key takeaways from my experiments are:

- The trends in goodput and latency with iPerf3
- Trends with the different metrics with latency for video streaming
- The factors that affect mmWave stability

In my experiments, there was an inconsistent trend increasing latency and goodput and loss rate, as seen in Figure 5. However, to fully assess the trend, I have to look at multiple metrics. For example, there is an overall decrease in loss rate for 3G results. However, there was also an overall decrease in bytes sent, meaning that there were fewer bytes to lose, which could explain the lower loss rate despite the greater latency. Another trend can also be seen with latency and goodput: there was an overall increase in goodput for 3G. As I tested with higher bandwidth connections, these trends were also apparent in some and not in others. In LTE testing, there was an overall decrease in loss rate and goodput. However, for 5G (low bandwidth and mmWave), there was an overall increase in goodput and an overall decrease in loss rate (Figures 6 and 7). Comparatively, there were large differences in goodput between 3G and LTE and mmWave for iPerf3 tests: while mmWave and LTE had similar goodputs, 3G had a significantly smaller goodput, as seen in Figure 6. However, in iPerf3 mmWave tests, goodput values remained similar to or even higher than those LTE while total bytes sent was on average lower than LTE. What this means is that mmWave is more efficient at delivering information and LTE has more loss, therefore their goodput is lower. This is seen in Figure 5 where LTE has greater amounts of bytes sent but similar goodput values and a higher average loss rate. For video streaming, there is a much more consistent trend with stall rate and latency. For 3G, 4G/LTE, and mmWave 5G, there was an increase in stall rate with each increasing latency. Furthermore, the stall rate values range was smaller with each higher bandwidth cellular connection.

name	total packets lost	loss rate	min rtt (sec)	max rtt(sec)	mean rtt(sec)	seconds total	bytes total	bits per sec total	bits/sec mean	bits/sec median	retransmits mean	retransmits median	goodput (MB/sec)
30 ms 3G	0	0.2311558	0.294101	1.626865	0.738387	10.000538	2,209,696	1,767,661.70	1,767,720.98	1,843,014.34	0	0	0.151029
70 ms 3G	0	0.2326186	0.283572	1.63549	0.756125	10.000672	2,136,132	1,708,790.77	1,708,895.77	1,614,818.64	0	0	0.146188
90 ms 3G	0	0.1730263	0.262994	1.587578	0.713996	10.001034	2,109,760	1,687,633.50	1,687,675.35	1,465,321.48	0	0	0.155654
120 ms 3G	13	0.1284722	0.301785	0.873116	0.587649	10.000677	1,598,976	1,279,094.21	1,279,066.93	1,454,185.89	1.3	0	0.141802
30 ms LTE	0	0.0786974	0.063866	0.399737	0.202568	10.000323	39,993,208	31,993,533.01	31,994,243.24	35,666,709.40	0	0	3.979889
70 ms LTE	0	0.0512129	0.076184	0.452778	0.220148	10.000627	22,142,764	17,713,100.59	17,713,432.83	19,542,317.84	0	0	2.22559
90 ms LTE	0	0.0725088	0.060409	0.404312	0.220069	10.000177	28,304,992	22,643,592.81	22,644,029.19	24,426,880.05	0	0	2.793565
120 ms LTE	0	0.0359026	0.061762	0.474438	0.24669	10.000254	35,203,264	28,161,895.89	28,162,506.12	31,022,867.95	0	0	3.605004
30 ms 5G	0	0.0618152	0.06551	0.625807	0.275911	10.000418	23,484,192	18,786,568.32	18,786,922.88	20,560,394.49	0	0	2.302699
70 ms 5G	0	0.0559839	0.200573	0.977859	0.516103	10.000731	22,298,400	17,837,416.08	17,838,273.19	18,822,875.09	0	0	2.095596
90 ms 5G	0	0.0644027	0.061843	0.529695	0.250637	10.000541	20,340,032	16,271,145.33	16,272,488.99	14,861,380.80	0	0	2.02549
120 ms 5G	0	0.0151738	0.155187	0.568091	0.33171	10.000537	32,396,896	25,916,125.10	25,916,735.79	25,513,160.99	0	0	3.359817
30 ms 5G mmWave	0	0.0567305	0.065529	0.404809	0.175734	10.00035	28,820,640	23,055,705.05	23,056,619.98	21,877,041.97	0	0	2.864532
70 ms 5G mmWave	0	0.0816526	0.053474	0.287471	0.171004	10.000228	26,871,296	21,496,546.68	21,497,121.89	20,064,148.16	0	0	2.648237
90 ms 5G mmWave	0	0.0556523	0.055148	0.36182	0.212092	10.000506	31,942,336	25,552,575.84	25,553,250.02	27,488,260.71	0	0	3.226581
120 ms 5G mmWave	0	0.0260952	0.048436	0.484547	0.230447	10.000213	38,552,960	30,841,711.07	30,842,039.84	31,458,648.92	0	0	4.02336
30 ms WiFi	0	2.83E-05	0.078747	0.102981	0.086227	10.000454	320,580,992	256,453,150.63	256,453,422.14	256,891,136.27	0	0	35.33925
70 ms WiFi	0	3.77E-05	0.043231	0.095776	0.085773	10.00026	326,351,564	261,074,463.26	261,074,670.56	262,131,031.89	0	0	35.96337
90 ms WiFi	4	0.0051305	0.004409	0.020171	0.011647	10.000165	290,039,034	232,027,398.75	232,028,989.77	249,550,412.02	0.4	0	32.02057
120 ms WiFi	855	0.0045656	0.01742	0.031495	0.02389	10.000124	311,781,210	249,421,875.17	249,423,020.83	255,456,662.46	85.5	0	34.35895

Figure 5. iPerf3 Test Results for 3G, 4G/LTE, WiFi, and 5G (low bandwidth and mmWave)

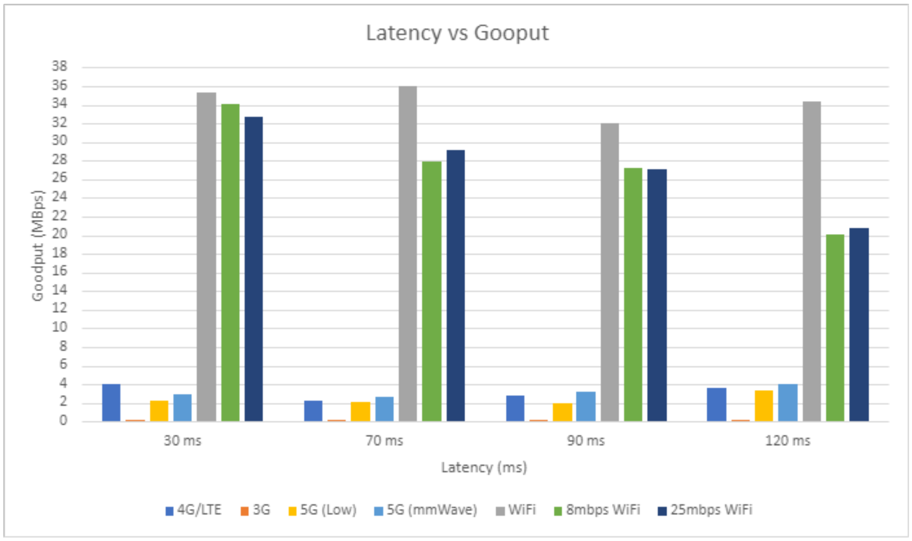

Figure 6. Latency vs. Goodput

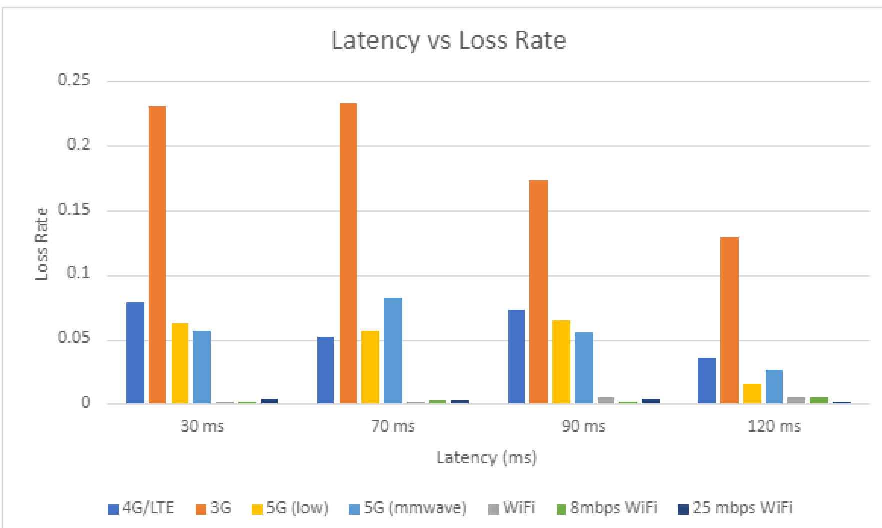

Figure 7. Latency vs. Loss Rate

Results for 3G and 4G/LTE: iPerf3

For iPerf3 3G testing, the average mean round trip time (rtt)— the amount of time it takes for a data packet to be sent to a destination and a confirmation to be sent back [12]— for the four latency values was 0.699 sec, as seen in Figure 8. Meanwhile, the average mean rtt for LTE was 0.222 sec. The 3G average mean rtt is nearly triple compared to LTE. Furthermore, as roundtrip decreases by 68%, as cellular connection goes from LTE to 3G, goodput is increased by 2019%. This trend of increasing mean rtt leading to decreased goodput, or vice versa, can also be seen in consecutive latencies. For example, in LTE connection from 70 ms to 90 ms, if we go from mean rtt 0.2201 sec to 0.2200 sec, a seemingly slight decrease, the goodput increases by 25%. However, this trend is also not seen in consecutive latencies. For instance, from 90 ms to 120 ms in LTE connection, mean rtt increases from 0.2200 sec to 0.2466 sec, but goodput also increases by 29%. Furthermore, the relationship between mean rtt and goodput cannot be evaluated based on only these two values: various other metrics such as loss rate and total bytes sent must be taken into consideration, which is why QoE is evaluated with a variety of metrics.

Averages	loss rate	mean rtt (sec)	bytes total	goodput (MB/sec)
3G	0.19132	0.6990393	2,013,641	0.148668122
4G/LTE	0.05958	0.2223688	31,411,057	3.151012026
5G	0.04934	0.3435903	24,629,880	2.445900287
mmWave	0.05503	0.1973193	31,546,808	3.190677695
WiFi	2.44E-03	0.0518843	312,188,200	34.42053493

Figure 8. Averages of values from iPerf3 tests

Results for 3G and 4G/LTE: DASH Video Streaming

For DASH video streaming, values and tests are different from iPerf3 because it provides us information about user experience: using video streaming allows me to see how the user interacts with the video, how the video is perceived and more, which further allows me to calculate QoE [13]. Additionally, DASH is unique from iPerf3 because of its software: DASH uses an adaptive bitrate algorithm (ABR) which allows video streaming to adjust to the network based on network predictions [14]. Using DASH has created more consistent results as seen in Figure 9. The stall rates consistently increase as latency increases for each cellular connection and the range of stall rates increase as bandwidth decreases: stall rate range for 3G is about 0.156, while the stall rate range for mmWave 5G is about 0.013 (this increasing trend is illustrated in Figure 10). However, the mean quality rates (Figure 11) are not as consistent, but that is also based on the network predictions. For example, the mean quality rates (where 3 is the highest quality achievable- 6000 kbps) trend for LTE is that mean quality level remains the same for 30 ms, 70 ms, 90 ms and then drops for 120 ms to 2.125 ms. Meanwhile, for 3G, at 30 ms, the mean quality level is 2.6 and then it drops to 1.9 for 70 ms, and then goes back up to 2.6 for 90 ms, and then drops to 1.53 for 120 ms. The main takeaway from these tests is that video streaming allows us to get more consistent results and can be more useful for applications because it is user experience based and uses ABR.

name	total playback (ms)	video duration (ms)	stall rate	mean quality level	bytes sent
30 ms 3G	60,033	59,466.666	0.009523554	2.6	45,197,785
70 ms 3G	60,484	59,466.666	0.017107635	1.904761905	41,739,739
90 ms 3G	60,698	59,466.666	0.020706289	2.6	45,197,785
120 ms 3G	69,349	59,466.666	0.166182748	1.533333333	42,112,023
30 ms LTE	59,447	59,466.666	-0.000330706	2.6	45,197,785
70 ms LTE	59,441	59,466.666	-0.000431603	2.6	45,197,785
90 ms LTE	59,858	59,466.666	0.006580729	2.6	45,197,785
120 ms LTE	60,280	59,466.666	0.013677141	2.125	50,902,592
30 ms mmWave	59,431	59,466.666	-0.000599765	2.6	45,197,785
70 ms mmWave	59,434	59,466.666	-0.000549316	2.6	45,197,785
90 ms mmWave	60,007	59,466.666	0.009086334	2.125	50,902,592
120 ms mmWave	60,290	59,466.666	0.013845303	2.6	45,197,785

Figure 9. DASH results for 3G, 4G/LTE, and mmWave 5G

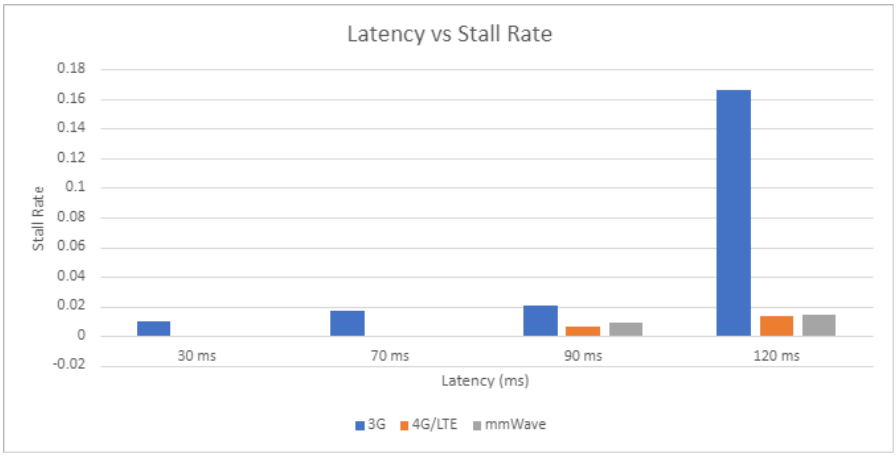

Figure 10. Latency vs Stall Rate

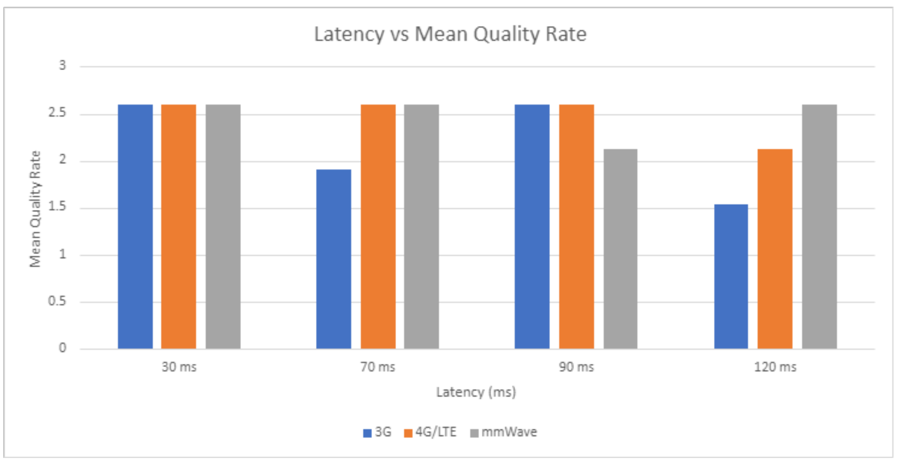

Figure 11. Latency vs Mean Quality Rate

Results for mmWave testing

For mmWave iPerf3 testing, average mean rtt was 0.197 sec, which is much faster than 3G and LTE. Furthermore, on average, mmWave loss rates were less than that of 3G and LTE. Furthermore, mmWave, on average, had a greater goodput and sent fewer bytes total. This means that mmWave is not only faster but also efficient as well. When experimenting with obstacles to mmWaves, various variables had effects on the performance of mmWaves. For example, there was a considerable difference in loss rate for when the Pixel (mmWave receiver and 5G hotspot) was placed in the front pocket as opposed to the back pocket of pants (Figure 12). Additionally, the tin box had blocked out many mmWaves resulting in the highest loss rates. The DASH test was even unable to be completed for the 120 ms test. For goodput, the location of the Pixel also had a significant impact, where the greater blockage resulted in the lesser amount of goodput (Figure 13).

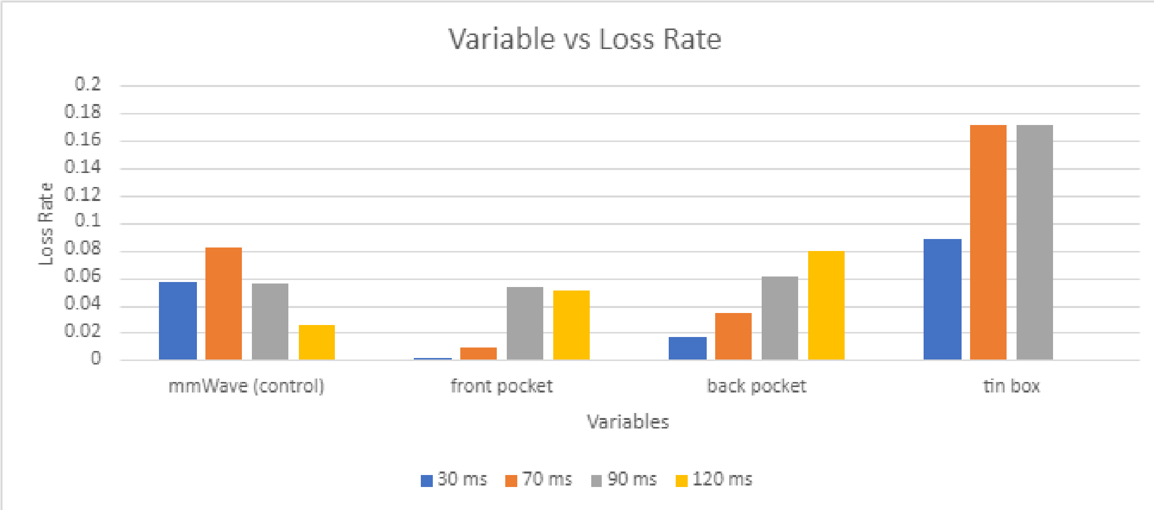

Figure 12. Variable vs. Loss Rate

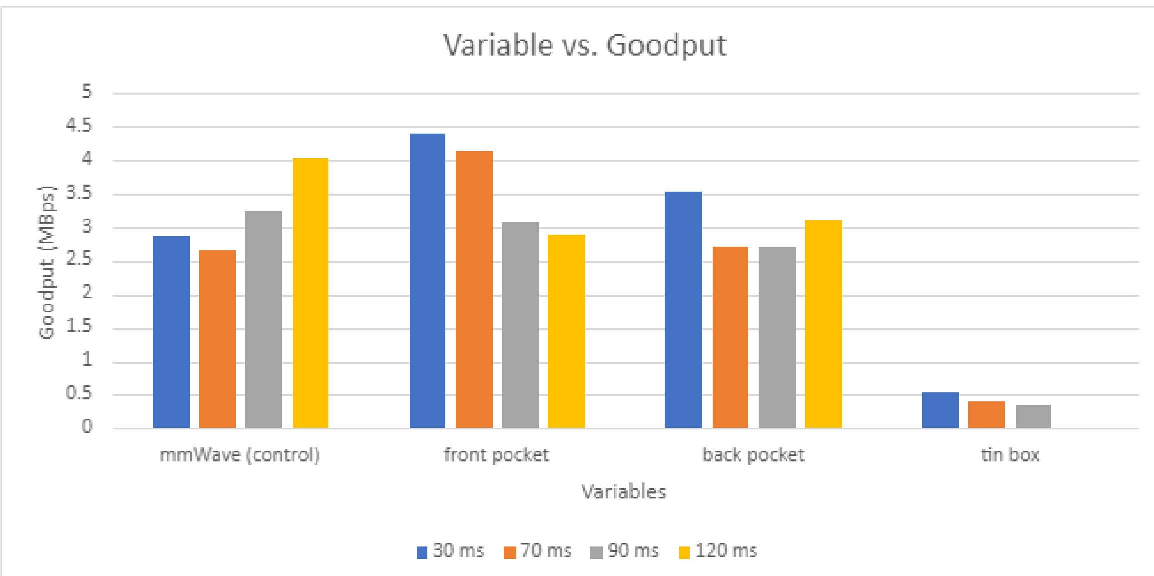

Figure 13. Variable vs. Goodput

For DASH video streaming, stall rates were similar to those of LTE, but also significantly less than those of 3G. Furthermore, mean quality levels were also very similar to LTE. For mmWaves, DASH video streaming results show that the network condition is rather stable and exceptional because of its low stall rates and high mean quality levels. When changing the location of the Pixel, however, there was no great effect on stall rates and mean quality rates (Figure 14). The key takeaways from these experiments is that DASH ABR helps significantly with the results and user experience of video streaming. Furthermore, mmWave 5G is significantly faster and more efficient with PC based applications.

name	total playback (ms)	video duration (ms)	stall rate	mean quality level	bytes sent
30 ms mmWave	59,436	59,466.666	-0.000515684	2.6	45,197,785
70 ms mmWave	59,437	59,466.666	-0.000498868	2.6	45,197,785
90 ms mmWave	59,436	59,466.666	-0.000515684	2.6	45,197,785
120 ms mmWave	59,432	59,466.666	-0.000582948	2.6	45,197,785
30 ms mmWave front pocket	59,431	59,466.666	-0.000599765	2.6	45,197,785
70 ms mmWave front pocket	59,437	59,466.666	-0.000498868	2.6	45,197,785
90 ms mmWave front pocket	59,437	59,466.666	-0.000498868	2.6	45,197,785
120 ms mmWave front pocket	59,433	59,466.666	-0.000566132	2.6	45,197,785
30 ms mmWave back pocket	59,436	59,466.666	-0.000515684	2.6	45,197,785
70 ms mmWave back pocket	59,435	59,466.666	-0.0005325	2.6	45,197,785
90 ms mmWave back pocket	59,435	59,466.666	-0.0005325	2.6	45,197,785
120 ms mmWave back pocket	59,437	59,466.666	-0.000498868	2.6	45,197,785

Figure 14. DASH video streaming results variables

Discussion and Conclusion

Overall, mmWave 5G shows very efficient and fast network performance, but also shows signs of instability and inconsistency. These experiments showcased various aspects of not only mmWave 5G but also 3G and 4G/LTE. These results have reaffirmed the stability of LTE but also showed how slow it is in comparison to mmWave 5G. These experiments have also shown results that DASH video streaming is rather helpful for PC based video streaming, compared to mobile based, as seen in “A Variegated Look at 5G in the Wild: Performance, Power, and QoE Implications” [2]. My results show the sensitivity of mmWaves to various obstacles and how different applications react to it. Furthermore, my results show how the metrics need to be analyzed together not separately to properly determine how different cellular networks work.

For future experimentation, I would rerun the iPerf3 tests I previously performed with the same parameters but add an additional parameter which sets the number of packets sent. This way the total bytes would be more similar across all networks making the analysis easier. Furthermore, I would also only use the Pixel for iPerf3 testing in the future because the Alcatel router seemed to be inconsistent with either creating an LTE hotspot or 3G hotspot. Finally, for DASH 3G video streaming tests, I would also use a 3G hotspot in future testing and then lower the maximum quality to get a true 3G hotspot, instead of creating a simulated 3G connection by limiting bandwidth on LTE.

This research is ongoing, and I will be further studying the relationship between signal strength of mmWaves, QoE, and other various metrics. I will also be continuing my research on DASH video streaming with various walking tests to see further applications of mmWaves and see how it reacts when the signal receiver is moving and if line of sight (a line where an observer has an unobstructed view to the cellular tower [15]) is no longer available.

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