Analyzing 5G performance: investigating altitude-induced variations

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ABSTRACT

Since the launch of fifth generation (5G) services in Thailand in 2020, there have been continuous improvements in 5G coverage. Currently, 5G coverage extends to most areas throughout the country. However, coverage issues persist not only in rural areas but also in high-rise buildings in urban areas. Consequently, a study was conducted within such buildings. This paper assesses the performance of 5G at different altitude test points. The chosen location for the field tests was a high-rise building within a crowded public hospital, which receives numerous patients every weekday, in the major urban area of Bangkok. Two smartphones from the same manufacturer, both supporting 5G technology and equipped with the Speedtest application, were employed as tools for this study. Tests were carried out on the third and twenty-fourth floors of the high-rise building for data collection. The primary finding of this study reveals that download speeds exhibited a significant decrease with increasing altitude of the test points, as evidenced by statistical analysis (p-values<0.001). This implies an issue with altitude-induced variations, indicating a need for the improvement of indoor 5G coverage in high-rise buildings.

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1. INTRODUCTION

After the fifth generation (5G) spectrum auction in 2020 and the 5G systems rollout by mobile network operators (MNOs), most of Thailand is currently covered by 5G [1]. It has been predicted that there will be a rise in the number of 5G mobile subscribers from 0.45 million in 2020 to nine million in 2023 and 14 million in 2025 [2]. One of the factors contributing to the increase in 5G mobile customers is the rapidly increasing data usage of consumers. Thai customers' monthly data consumption climbed from 25 GB in 2021 to about 33 GB in 2022 [3]. Furthermore, it is predicted to reach approximately 80 GB per month in 2025 [3].

As is well known, distributing signals across a large coverage area is a significant challenge for 5G mobile network providers in Thailand, quality of service (QoS) is a particular concern. While 5G-QoS research projects were carried out in Thailand and other nations [4]-[7], it should be noted that the studies examined 5G performance or QoS, but there were not any research projects that compared 5G quality across various test points at different altitudes or investigated the effects of various altitudes. Therefore, this study was carried out to close this research gap. To go beyond earlier studies that concentrated on 5G, particularly in Thailand (e.g., [7]), this study was carried out at Rajvithi Hospital, a very busy public hospital that serves approximately 6,000 outpatients each day in the Dasamindradhiraj building, which is the tallest building with a 25-story structure, see Figure 1, MNOs will be able to use the findings to improve 5G-QoS in these healthcare facilities.

Figure 1. The selected 25-story building in the major urban area in Bangkok for this study

According to 5G, the number of people who use mobile internet is continuously increasing due to the development and spread of wireless communications at present. Especially the International Mobile Telecommunications-2020 (IMT-2020) or the 5G mobile technologies will be widely adopted and extensively utilized worldwide by 2025 [8]. These communication technologies have become the most significant part of everyone's life [9]. 5G networks can be used by industries and consumers in many purposes, especially in wireless devices. When compared to 4G, 5G offered substantially greater connectivity, lower latency, higher data speeds, and increased capacity, which revolutionized mobile network communications [10]. 5G technology serves as the fundamental infrastructure for emerging services and exceptional services, including high spectral efficiency, flexibility, quick convergence, uncompromised security, and high data rates. [11]. Thus, 5G networks can support a wider range of technologies and applications, including the internet of things, device-to-device and machine-to-machine communications, telehealth, telemedicine, and telesurgery. 5G technologies offer fast data transfer speeds and low latency, enabling the creation of novel automation and applications in the physical and social environment [12]. The development of 5G technology brings significant changes in various sectors, such as increased productivity, efficiency, and innovation, but also raises security and privacy concerns that need to be addressed [13].

However, one of the most classic issues for mobile communications is QoS. It refers to different types of priority for many purposes by the requirements and ensures a particular level of data transmission performance [14]. QoS is normally impacted by a variety of performance metrics, including delay [14]. QoS in a network is the ability of the network to provide good or appropriate services to the user with efficiently. Particularly, QoS is crucial for real-time services and applications (e.g., voice over internet protocol (VoIP), video telephony and online gaming) [15]-[17]. QoS is associated with network performance level. Therefore, QoS metrics are used to manage telecommunication services' usability, reliability, and performance [18]. Several QoS parameters can be used to measure the quality of mobile or telecommunication networks (e.g., loss, delay, and jitter) [5], [7], [10], [19]. However, in this paper, only four QoS parameters are focused on, each can be described as follows [7], [10], [20], [21]:

- Download (DL): this term refers to the process of receiving data from a remote server or another device and saving it to a user's device. For instance, when a movie is downloaded from a streaming service, the movie file is transferred from the service's servers to the device for viewing.
- Upload (UL): this means sending data from a user's device to a remote server or device. For example, when photos are uploaded to a server of a social media platform, the image files are sent to the platform's server for storage and sharing. In general, the DL rate is higher than UL.

- Latency which is also known as ping or delay. it measures how quickly the terminal or device receives a response after sending a request over the connection. In real-time applications where time is critical, a low latency indicates a more responsive connection. Especially, in the theory of 5G, a latency of <1 ms is required for ultrareliable and low-latency communications (uRLLC).
- Jitter: this is a variation in the delay or latency time of sequential packets that is usually caused by congestion in communication networks. It is a vital QoS metric that substantially affects the end-to-end experience of real-time applications or services and users' perceptions.

In addition, according to some previous works, most of the altitude studies focused on high-altitude platforms (HAPs). For example, an analysis of the 5G massive multiple-input multiple-output (MIMO) systems with triangular lattice arrays for HAPs stations showed that a triangular lattice array offered a higher performance when compared to square one, making it useful for the 5G massive MIMO paradigm [22]. A study utilizing an unmanned aerial vehicle (UAV) service for smart cities is presented in [23], which found that the QoS result from a 5G network is more sensitive to altitude changes than a 4G network. There are some other similar studies in [24]-[27] but they focus on improvements to coverage, QoS, and related issues. A study of 5G service deployment via the HAPS system was conducted and presented that appropriate or higher elevation angles of ground users provided higher performance [28]. However, there are also a few studies associated with antenna performance and propagation [29]-[31], while other studies were associated with femtocells for indoor coverage [32], [33]. In addition, there are a few studies based on long-term evolution (LTE) with indoor design, implementation, and/or deployment [34], [35], whereas ray-tracing simulation for 5G coverage in indoor hotspots was conducted and presented in [36]. Also, there was a study associated with the electromagnetic field effects of 5G antennas over school and hospital buildings, but it did not focus on QoS or high-rise buildings [37]. No previous work has focused on a comparison of low and high altitudes based on a high-rise building, such as Rajvithi Hospital. Thus, there is space and opportunity for this study to conduct 5G field tests and analysis. The findings about the impact of different altitudes might be useful for 5G-QoS improvement in high-rise buildings.

This article was extended from [10]. It has been organized into four main sections. This section is the introduction, including background information and significance, an overview of 5G systems, and related works. The next section is section 2, which presents the methodology. Next, section 3 presents the results and the analysis. In section 4, it presents the discussion. In the final section, section 5, the conclusion are described, highlighting the major finding that download speeds tend to decrease as the altitude of the test points increases.

2. METHOD

This study used stationary tests to focus on the DL and UL speeds, latency, and jitter of the 5G networks from two MNOs, hereafter called Operator-A and Operator-B [4]. The tools used for the measurements were two 5G smartphones, the same brand and model that contain the central processing unit (CPU) called Snapdragon 695 5G/Octa-core, and the memory of 128GM/8GB RAM, while its operating system is Android 13. Furthermore, the Speedtest application by Ookla (version 5.2.1) is the same application used in [38].

The data were collected during one day in the last week of October and one day in the first week of November 2023, at the Rajvithi Hospital's tallest building (indoors only), which stands at a height of 105 meters from the ground to its pinnacle. For comparison between the results measured from the ground, the middle, and the high stories of the building, the ground and the second floors were represented as low altitude, while the 12th and 13th floors were represented as middle altitude, and the 23rd and 24th floors were represented as high altitude. The middle altitude is about 45–50 meters, approximately from ground level, while the high altitude is about 90–95 meters.

The raw data were gathered from each floor at least 24 times per operator. Therefore, there were at least 48 records of data gathered from each level. Then the data were pre-processed by eliminating outliers and uncompleted records. Overall, there were about 44 records per parameter per altitude for creating the graphic results before an analysis was conducted. After the processes as shown in Figure 2, the results and analysis are presented in section 3.

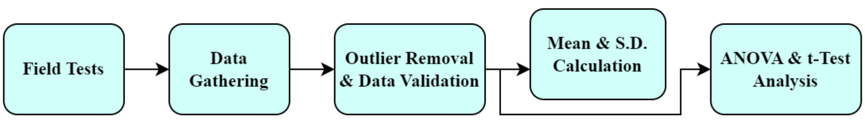

Figure 2. The processes for obtaining the results

3. RESULTS AND ANALYSIS

3.1. Results from the field tests

After conducting the field tests in the 25-story building at Rajvithi Hospital, the results from the low, middle, and high altitudes were analyzed and presented as shown in Figure 3. Overall, (a) one can see that the average download speeds from testing at the low altitude (about 268-298 Mbps provided by two operators in the test) are greater than the average download speeds at the middle and high altitudes (the average speeds are in the range of about 100–180 Mbps), whereas the average download speeds at the high altitude (about 106–141 Mbps) are less than those at the middle and low altitudes. When comparing the average download speeds provided by Operator-A and Operator-B, one can see that at low altitude, Operator-A showed a higher average speed than Operator-B (Figure 3). However, the average upload speeds at each level, as shown in Figure 4, provided by each operator are almost the same, while the average upload speeds from Operator-A (about 50–55 Mbps) are slightly higher than those from Operator-B (about 36–39 Mbps).

For latency at a low altitude level, see Figure 5, Operator-B provided better average latency (about 18 ms) than the average latency provided by Operator-A (about 26 ms), while the average latency values from both MNOs are almost the same at the middle and the high altitudes (19–22 ms, approximately). However, it is surprising that at low altitudes, Operator-A provides the worst latency when compared to the middle and high altitudes. Nevertheless, as the average jitter values shown in Figure 6, every condition shows an average jitter value of less than 10 ms, except for the value at the middle altitude provided by Operator-B which shows about 13 ms at the middle altitude. Furthermore, one can see that several scenarios show different results when the two MNOs are compared or the three different altitudes on the high-rise building; therefore, analytical techniques were applied in this study to test the hypotheses. Further details are presented in the next section.

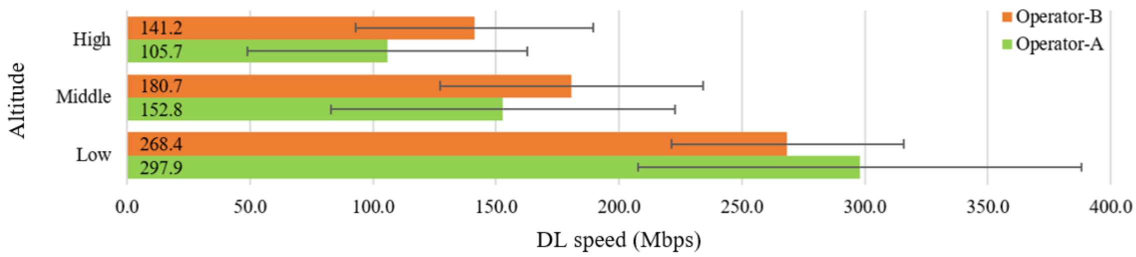

Figure 3. The results of DL speeds

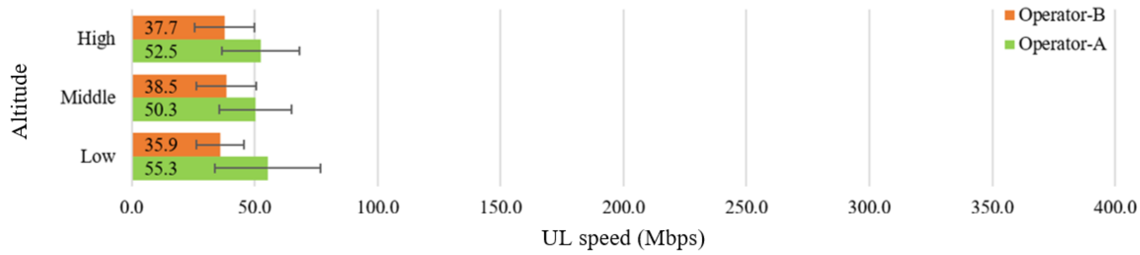

Figure 4. The results of UL speeds

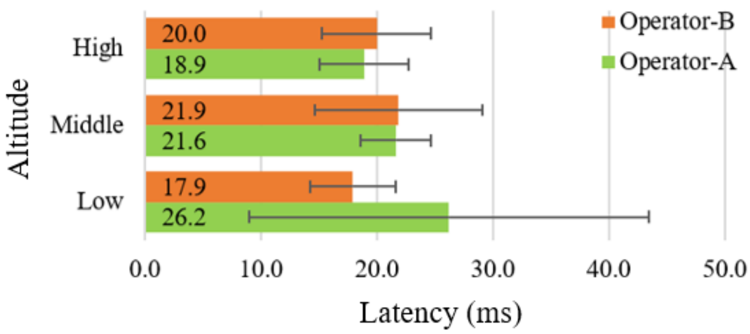

Figure 5. The results of the latency values

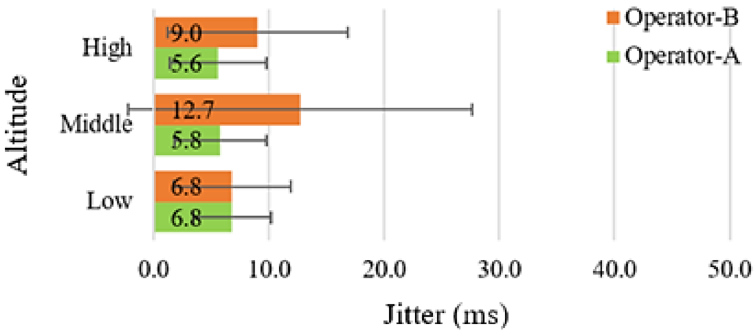

Figure 6. The results of the jitter values

3.2. Analysis

The first is a comparison of the QoS results, consisting of DL, UL, latency, and jitter, at the low (L), middle (M), and high (H) altitudes of the building, for each MNOs using analysis of variance (ANOVA) to compare the means of two or more groups of a dependent variable. Using this method to test the hypotheses, the variations within each sample are compared to the variance between samples. When the differences between the variances are greater than the means of several samples, they are not equal. However, if there is no discernible difference in the means of the samples, then they are equal [39], [40]. Moreover, the analysis in this study also makes use of the t-Test method known as the two-sample t-Test or unpaired t-Test, to find out if there is a significant difference between the means of two independent groups [41]. The analytical hypothesis test assumes that the variances of the two groups are equal, and that the data is normally distributed [41]. About the second perspective, a comparison between the QoS results at each level provided by the two MNOs, was analyzed by using the same technique.

The first steps of the analysis used ANOVA. The following hypotheses (H1–H8) were investigated, and then the results of the hypotheses test are presented in Table 1.

– H1: the average DL speeds at the L, M, and H altitudes provided by Operator-A are the same or not.
– H2: the average DL speeds at the L, M, and H altitudes provided by Operator-B are the same or not.
– H3: the average UL speeds at the L, M, and H altitudes provided by Operator-A are the same or not.
– H4: the average UL speeds at the L, M, and H altitudes provided by Operator-B are the same or not.
– H5: the average latency values at the L, M, and H altitudes provided by Operator-A are the same or not.
– H6: the average latency values at the L, M, and H altitudes provided by Operator-B are the same or not.
– H7: the average jitter values at the L, M, and H altitudes provided by Operator-A are the same or not.
– H8: the average jitter values at the L, M, and H altitudes provided by Operator-B are the same or not.

Table 1. ANOVA results at 3 levels with each MNOs

Hypothesis	p-values	Remarks
H1	<0.001*	Significant (DL@L≠M≠H; Operator-A)
H2	<0.001*	Significant (DL@L≠M≠H; Operator-B)
H3	0.403	Insignificant (UL@L=M=H; Operator-A)
H4	0.560	Insignificant (UL@L=M=H; Operator-B)
H5	0.013*	Significant (Latency@L≠M≠H; Operator-A)
H6	0.004*	Significant (Latency@L≠M≠H; Operator-B)
H7	0.284	Insignificant (Jitter@L=M=H; Operator-A)
H8	0.029*	Significant (Jitter@L=M=H; Operator-B)

Remark: the '*' is p-value<0.05, which means significant with 95% confidence.

Table 1 shows the ANOVA results or p-values for the five hypotheses, including H1, H2, H5, H6, and H8, are less than 0.05. This means that there is at least one pair of the data at different altitudes of the building that has significant differences. The post-hoc t-Tests were then conducted with ten hypotheses, H9–H18. Then, the results are presented in Table 2. However, it is noted that the post-hoc t-Tests for L and H altitudes were not conducted because those QoS parameters were obviously different.

– H9: the average DL speeds at the L and M altitudes provided by Operator-A are the same or not.
– H10: the average DL speeds at M and H altitudes provided by Operator-A are the same or not.
– H11: the average DL speeds at the L and M altitudes provided by Operator-B are the same or not.
– H12: the average DL speeds at M and H altitudes provided by Operator-B are the same or not.

– H13: the average latency values at the L and M altitudes provided by Operator-A are the same or not.
– H14: the average latency values at M and H altitudes provided by Operator-A are the same or not.
– H15: the average latency values at the L and M altitudes provided by Operator-B are the same or not.
– H16: the average latency values at M and H altitudes provided by Operator-B are the same or not.
– H17: the average jitter values at the L and M altitudes provided by Operator-B are the same or not.
– H18: the average jitter values at M and H altitudes provided by Operator-B are the same or not.

Table 2. Post-hoc t-Tests after the ANOVA analysis

Hypothesis	p-values	Remarks
H9	<0.001*	Significant (DL@L≠M; Operator-A)
H10	<0.001*	Significant (DL@M≠H; Operator-A)
H11	<0.001*	Significant (DL@L≠M; Operator-B)
H12	<0.001*	Significant (DL@M≠H; Operator-B)
H13	0.230	Insignificant (Latency@L=M; Operator-A)
H14	<0.001*	Significant (Latency@M≠H; Operator-A)
H15	0.002*	Significant (Latency@L≠M; Operator-B)
H16	0.151	Insignificant (Latency@M=H; Operator-B)
H17	0.016*	Significant (Jitter@L≠M; Operator-B)
H18	0.158	Insignificant (Jitter@M=H; Operator-B)

Remark: the '*' is p-value<0.05, which means significant with 95% confidence.

Furthermore, to investigate if the 5G-QoS results obtained from the two MNOs at the same altitude level were the same or different, an additional analysis using t-Tests was also conducted to test the hypotheses in H19–H30. The results are shown in Table 3.
– H19: the average DL speeds at the L altitude provided by Operator-A and Operator-B are the same or not.
– H20: the average DL speeds at the M altitude provided by Operator-A and Operator-B are the same or not.
– H21: the average DL speeds at the H altitude provided by Operator-A and Operator-B are the same or not.
– H22: the average UL speeds at the L altitude provided by Operator-A and Operator-B are the same or not.
– H23: the average UL speeds at the M altitude provided by Operator-A and Operator-B are the same or not.
– H24: the average UL speeds at the H altitude provided by Operator-A and Operator-B are the same or not.
– H25: the average latency values at the L altitude provided by Operator-A and Operator-B are the same or not.
– H26: the average latency values at the M altitude provided by Operator-A and Operator-B are the same or not.
– H27: the average latency values at the H altitude provided by Operator-A and Operator-B are the same or not.
– H28: the average jitter values at the L altitude provided by Operator-A and Operator-B are the same or not.
– H29: the average jitter values at the M altitude provided by Operator-A and Operator-B are the same or not.
– H30: the average jitter values at the H altitude provided by Operator-A and Operator-B are the same or not.

One can see p-values from the hypotheses in Tables 1–3; some of them are higher than 0.05, whereas some of them are lower than 0.05. Therefore, additional discussion is required. Thus, all the results obtained from the analysis in this section are discussed and described in section 4, which is the last section that includes the conclusion.

Table 3. t-Test results from a comparison of the two MNOs

Hypothesis	p-values	Remarks
H19	0.058	Insignificant (DL@L from Operator-A=Operator-B)
H20	0.039	Significant (DL@M from Operator-A≠Operator-B)
H21	0.002	Significant (DL@H from Operator-A≠Operator-B)
H22	<0.001*	Significant (UL@L from Operator-A≠Operator-B)
H23	<0.001*	Significant (UL@M from Operator-A≠Operator-B)
H24	<0.001*	Significant (UL@H from Operator-A≠Operator-B)
H25	0.002*	Significant (Latency@L from Operator-A≠Operator-B)
H26	0.833	Insignificant (Latency@M from Operator-A=Operator-B)
H27	0.239	Insignificant (Latency@H from Operator-A=Operator-B)
H28	0.983	Insignificant (Jitter@L from Operator-A=Operator-B)
H29	0.004*	Significant (Jitter@M from Operator-A≠Operator-B)
H30	0.014*	Significant (Jitter@H from Operator-A≠Operator-B)

Remark: the '*' is p-value<0.05, which means significant with 95% confidence.

4. DISCUSSION

Unlike [25], [28] based on LTE, and [21] that used simulation for 5G indoor coverage, this study conducted realistic field tests based on 5G technology within the building with a high density of mobile phone equipment. Furthermore, this study is unlike [7], which conducted the studies within the BTS Skytrain station areas in Bangkok, which are classified as low altitude only. Although this article has been extended from [10], there are several issues presented in this article that advance beyond the previous version, including the additional tests at the middle level of the building and the additional study and analysis with jitter.

Figures 3–6 show that the average download speeds on the ground floor were the best when compared with the other altitudes, while other QoS parameters require additional statistical analysis for more confidence. Furthermore, one can see that in some scenarios, the standard deviations are wide, which means that the mobile networks may have an instability issue. The results of the statistical analysis of the data, as shown in Figures 3–6, are presented in Tables 1–3. However, this section focuses firstly on the results in Tables 1 and 2, where many issues need to be discussed, as follows:

- H1 confirms that the average download speeds provided by Operator-A at the low altitude (the first and the second floors) of the building are significantly better (p-value<0.001) than the middle altitude (the 12th and 13th floors) and the high altitude (23rd and 24th floors). This result is also consistent with the result from H2. This means that both MNOs provide better download speeds at the low altitude of the building than at the middle and high altitudes. Therefore, the MNOs may utilize this evidence to improve 5G-QoS in high-rise buildings.
- H3 confirms that the average upload speeds provided by Operator-A at the low altitude (the first and the second floors) of the building are not significantly different from the speeds at the middle and the high altitude (p-value<0.403). This result is consistent with H4 for Operator-B, which has the p-value of 0.506. This means that both MNOs provide the same upload speeds at all three altitudes, which is different from the download speeds.
- H5 confirms that the average latency values at the low, middle and high altitudes provided by Operator-A are significantly different (p-value=0.013). This is consistent with the result associated with H6 for Operator-B (p-value=0.004).
- H7 shows that the average jitter values at the three altitudes of the building for Operator-A are not significantly different (p-value=0.284), which is different from the results for H8 associated with Operator-B which shows a significant difference between the jitter values for the three altitudes of the building (p-value=0.029).
- H9 and H10 confirm that there are significant differences between the average download speeds at the low and the middle altitudes provided by Operator-A (p-value<0.001), and between the download speeds at the middle and high altitudes provided by the same MNOs. These p-values are consistent with the results for Operator-B from H11 and H12.
- H13 (p-value 0.23) shows that there is no significant difference between the average latency values at the low and the middle altitudes of the building provided by Operator-A but this is inconsistent with the results for the same operator from H14 (p-value<0.001) which showed that there are significant differences between the latency values at the middle and high altitudes.
- Unlike H13 and H14, the p-values from H15 and H16 are 0.002 and 0.151, respectively. This means that there are significant differences between the latency values at the low and middle altitudes of the building for Operator-B, whereas there is no significant difference between the middle and the high altitudes of the building.
- With regard to jitter, only the results referring to Operator-B were considered using post-hoc t-Tests since there is no significant difference between the three altitudes for Operator-A. H17 shows significant differences between the jitter values at the low and middle altitudes (p-value=0.015), whereas there is no significant difference between the jitter values at the middle and high altitudes in H18 (p-value=0.158).

In addition, a comparison was made between the 5G-QoS parameters provided by Operator-A and Operator-B. Thus, the additional issues associated with the results in Table 3 are considered. Then, each issue can be discussed as follows:

- The hypothesis test result for H19 shows that there is no significant difference between the average download speeds for Operator-A and Operator-B at the low altitude of the building (p-value=0.058). On the other hand, the results for H20 and H21 show that Operator-B provides significantly different better average download speeds than Operator-A at the middle and high altitudes (p-values are 0.039 and 0.002, respectively).
- According to hypotheses H22-H24, the average upload speeds provided by Operator-A are significantly better at all three altitudes of the building than the upload speeds provided by Operator-B (p-values<0.001).

- Hypothesis H25 shows that the average latency value at the low altitude of the building provided by Operator-B is significantly higher than the latency value for Operator-A (p-value=0.002). Nevertheless, there is no significant difference between the average latency values for both MNOs at the middle and high altitudes of the building (p-values from H26-H27 are 0.833 and 0.239, respectively).
- Lastly, the hypothesis test result for H28 confirms that the average jitter values at the low altitude of the building from both MNOs are the same statistically (p-value=0.983). By contrast, the results from the hypothesis tests for H29-H30 show that the average jitter values from Operator-A and Operator-B at the middle and high altitudes of the building are not the same. Operator-A provides significantly different better average jitter values than Operator-B (p-values are 0.004 and 0.014, respectively.

5. CONCLUSION

This study conducted within a high-rise building situated in one of Bangkok's major hospitals, located in the capital city of Thailand, demonstrates the varying impact of different altitudes on the quality of 5G service, specifically concerning download speeds. The higher the altitude the lower the download speed. However, in practice, several factors may impact QoS (e.g., location and alignment of the antennae and interference). Furthermore, the data in this study were gathered on a few weekdays. Users' perspectives on the use of mobile phones could be affected by those of others, population density, and the time of data collection. Thus, a future study should consider testing at the weekends, putting more emphasis on minimizing other conflicting factors, conducting an in-depth investigation, and providing greater indoor coverage of this particular building and other tall towers (e.g., condominiums where mobile users usually have internet service and voice quality issues). Moreover, other QoS parameters referring to signal quality (e.g., signal-to-noise ratio (SNR), reference signal received power (RSRP), and reference signal received quality (RSRQ)) have not been considered in this paper, therefore, these parameters can be gathered and analyzed for further study and analysis in future work.

In conclusion, the data gathered from field tests in a crowded hospital in urban Bangkok using a popular mobile application and analysis using One-way ANOVA and a t-Test showed that different altitudes or altitude variations impact 5G performance significantly (p-values<0.05). In particular, the lower altitude of 5G mobile devices tends to obtain better download speeds than the higher altitudes, whereas different altitudes do not appear to impact upload speeds significantly. Therefore, operators who provide mobile network services can apply the findings from this study as the evidence for their network improvement, particularly by enhancing QoS for high-rise buildings. However, this study was conducted in a hospital area only; future work can be conducted in other areas or places, including high-rise condominiums. Additionally, other cases in other countries may also benefit from the methodology described in this study.

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REFERENCES

[1] C. Srinuan and P. Srinuan, "Determining spectrum caps and service efficiency: A case study of mobile operators in Thailand," *Telecommunications Policy*, vol. 45, no. 10, p. 102225, Nov. 2021, doi: 10.1016/j.telpol.2021.102225.

[2] Statista, Forecast number of 5G subscriptions in Thailand from 2020 to 2025. (in Thai) [Online]. Available: https://www.statista.com/statistics/1131751/thailand-forecast-for-5g-adoption/. (Accessed 12 Seb. 2024)

[3] Bangkokpost, Thai demand for 5G subscriptions surges. (in Thai) [Online]. Available: https://www.bangkokpost.com/business/2419401/thai-demand-for-5g-subscriptions-surges. (Accessed 12 Seb. 2024)

[4] F. D. Putra and Widyasmoro, "Quality of service analysis of 5G telkomsel network technology," in *Proceedings - 2022 2nd International Conference on Electronic and Electrical Engineering and Intelligent System, ICE3IS 2022*, IEEE, Nov. 2022, pp. 231–236, doi: 10.1109/ICE3IS56585.2022.10010232.

[5] Widyasmoro, I. Surahmat, T. K. Hariadi, and F. Dwi Putra, "Comparative performance analysis of 4g and 5g cellular network technology in indonesia: case study in the city of Jakarta," in *Proceedings - 2022 2nd International Conference on Electronic and Electrical Engineering and Intelligent System, ICE3IS 2022*, IEEE, Nov. 2022, pp. 158–163, doi: 10.1109/ICE3IS56585.2022.10010105.

[6] N. K. M. Madi, M. M. Nasralla, and Z. M. Hanapi, "Delay-based resource allocation with fairness guarantee and minimal loss for eMBB in 5G heterogeneous networks," *IEEE Access*, vol. 10, pp. 75619–75636, 2022, doi: 10.1109/ACCESS.2022.3192450.

[7] T. Daengsi, P. Sriamorntrakul, S. Chatchalermpun, and K. Phanrattanachai, "Revisiting 5G quality of service in Bangkok metropolitan region: BTS Skytrain station areas," *Bulletin of Electrical Engineering and Informatics*, vol. 13, no. 4, pp. 2555–2565, Aug. 2024, doi: 10.11591/eei.v13i4.7337.

[8] P. Akkaraekthalin, "5G mobile communications and antennas," *The Journal of King Mongkut's University of Technology North Bangkok*, vol. 31, no. 2, pp. 175–178, 2021, doi: 10.14416/j.kmutnb.2021.01.002.

[9] M. S. Rana and M. M. R. Smieee, "Design and analysis of microstrip patch antenna for 5G wireless communication systems,"

Bulletin of Electrical Engineering and Informatics, vol. 11, no. 6, pp. 3329–3337, Dec. 2022, doi: 10.11591/eei.v11i6.3955.
[10] S. Chatchalermpun, T. Daengsi, P. Pornpongtechavanich, K. Phanrattanachai, P. Sriamorntrakul, and C. Chukusol, "Impacts of different altitudes on 5G performance: a case study of a public hospital in Central Bangkok," *8th International Conference on Recent Advances and Innovations in Engineering: Empowering Computing, Analytics, and Engineering Through Digital Innovation, ICRAIE 2023*, 2023, doi: 10.1109/ICRAIE59459.2023.10468096.
[11] Y. O. Imam-Fulani *et al.*, "5G frequency standardization, technologies, channel models, and network deployment: advances, challenges, and future directions," *Sustainability (Switzerland)*, vol. 15, no. 6, p. 5173, Mar. 2023, doi: 10.3390/su15065173.
[12] P. Sun, *Evolution to 5.5G and 6G and Key Applications*. Unleashing the Power of 5GtoB in Industries, 2021, doi: 10.1007/978-981-16-5082-6_18.
[13] I. Elan Maulani and C. Amalia Johansyah, "The development of 5G technology and its implications for the industry," *Devotion : Journal of Research and Community Service*, vol. 4, no. 2, pp. 631–635, Feb. 2023, doi: 10.36418/devotion.v4i2.416.
[14] S. F. Jabbar, N. S. Mohsin, J. F. Tawfeq, P. S. Josephng, and A. L. Khalaf, "A novel data offloading scheme for QoS optimization in 5G based internet of medical things," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 5, pp. 3124–3133, Oct. 2023, doi: 10.11591/eei.v12i5.5069.
[15] T. Daengsi, N. Khitmoh, and P. Wuttidittachotti, "VoIP quality measurement: subjective VoIP quality estimation model for G.711 and G.729 based on native Thai users," *Multimedia Systems*, vol. 22, no. 5, pp. 575–586, Oct. 2016, doi: 10.1007/s00530-015-0468-3.
[16] P. Pornpongtechavanich and T. Daengsi, "Video telephony - quality of experience: a simple QoE model to assess video calls using subjective approach," *Multimedia Tools and Applications*, vol. 78, no. 22, pp. 31987–32006, Nov. 2019, doi: 10.1007/s11042-019-07928-z.
[17] P. Pornpongtechavanich, P. Wuttidittachotti, and T. Daengsi, "QoE modeling for audiovisual associated with MOBA game using subjective approach," *Multimedia Tools and Applications*, vol. 81, no. 26, pp. 37763–37779, 2022, doi: 10.1007/s11042-022-12807-1.
[18] Z. Shakir, A. Al-Thaedan, R. Alsabah, M. Salah, A. Alsabbagh, and J. Zec, "Performance analysis for a suitable propagation model in outdoor with 2.5 GHz band," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 3, pp. 1478–1485, Jun. 2023, doi: 10.11591/eei.v12i3.5006.
[19] M. T. Sultan and H. El Sayed, "QoE-aware analysis and management of multimedia services in 5G and beyond heterogeneous networks," *IEEE Access*, vol. 11, pp. 77679–77688, 2023, doi: 10.1109/ACCESS.2023.3298556.
[20] K. Hammad, A. Moubayed, A. Shami, and S. Primak, "Analytical approximation of packet delay jitter in simple queues," *IEEE Wireless Communications Letters*, vol. 5, no. 6, pp. 564–567, Dec. 2016, doi: 10.1109/LWC.2016.2601609.
[21] A. A. El-Saleh, M. A. Al Jahdhami, A. Alhammadi, Z. A. Shamsan, I. Shayea, and W. H. Hassan, "Measurements and analyses of 4G/5G mobile broadband networks: an overview and a case Study," *Wireless Communications and Mobile Computing*, pp. 1–24, Apr. 2023, doi: 10.1155/2023/6205689.
[22] F. A. Dicandia and S. Genovesi, "Spectral efficiency improvement of 5G massive MIMO systems for high-altitude platform stations by using triangular lattice arrays," *Sensors*, vol. 21, no. 9, p. 3202, May 2021, doi: 10.3390/s21093202.
[23] S. Horsmanheimo *et al.*, "5G communication QoS measurements for smart city UAV services," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*, IEEE, Mar. 2022, pp. 1–5, doi: 10.23919/EuCAP53622.2022.9769210.
[24] J. Jayaraman, V. R. Balu, S. Bregni, D. Scazzoli, and M. Magarini, "Rooftop relay nodes to enhance URLLC in UAV-Assisted cellular networks," in *IEEE International Conference on Communications*, IEEE, May 2022, pp. 733–738, doi: 10.1109/ICC45855.2022.9839057.
[25] B. Galkin, J. Kibilda, and L. A. Dasilva, "Coverage analysis for low-altitude UAV networks in urban environments," in *Proceedings - IEEE Global Communications Conference, GLOBECOM*, IEEE, Dec. 2017, pp. 1–6, doi: 10.1109/GLOCOM.2017.8254658.
[26] C. You, Z. Kang, Y. Zeng, and R. Zhang, "Enabling smart reflection in integrated air-ground wireless network: IRS meets UAV," *IEEE Wireless Communications*, vol. 28, no. 6, pp. 138–144, Dec. 2021, doi: 10.1109/MWC.001.2100148.
[27] A. K. Patel and R. D. Joshi, "Area coverage analysis of low altitude UAV Bases station using statistical channel model," in *2022 International Conference on Signal and Information Processing, IConSIP 2022*, IEEE, Aug. 2022, pp. 1–6, doi: 10.1109/ICoNSIP49665.2022.10007493.
[28] A. A. Abu-Arabia, Iskandar, and R. Hakimi, "Performance of 5G services deployed via HAPS system," in *TSSA 2019 - 13th International Conference on Telecommunication Systems, Services, and Applications, Proceedings*, IEEE, Oct. 2019, pp. 168–172, doi: 10.1109/TSSA48701.2019.8985496.
[29] X. Liu, Z. Zhao, M. Wei, H. Guan, and H. Yang, "Performance analysis of micro site with tilted antenna in a realistic high rise building scenario," in *IEEE Vehicular Technology Conference*, IEEE, Sep. 2014, pp. 1–5, doi: 10.1109/VTCFall.2014.6966116.
[30] M. A. Erol, S. S. Seker, F. Kunter, and A. Y. Citkaya, "Optimized indoor propagation model for office environment at GSM frequencies," in *Proceedings of the 2015 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications, IEEE APWC 2015*, IEEE, Sep. 2015, pp. 1284–1287, doi: 10.1109/APWC.2015.7300206.
[31] S. S. Al-Bawri *et al.*, "Multilayer base station antenna at 3.5 GHz for Future 5G Indoor Systems," in *2019 1st International Conference of Intelligent Computing and Engineering: Toward Intelligent Solutions for Developing and Empowering our Societies, ICOICE 2019*, IEEE, Dec. 2019, pp. 1–4, doi: 10.1109/ICOICE48418.2019.9035137.
[32] K. T. Cho, J. Kim, G. Jeon, B. H. Ryu, and N. Park, "Femtocell power control by discrimination of indoor and outdoor users," in *Wireless Telecommunications Symposium*, IEEE, Apr. 2011, pp. 1–6, doi: 10.1109/WTS.2011.5960834.
[33] O. M. Amine and Z. Sylia, "Femtocell placement in an indoor building using NSGA II," in *2017 5th International Conference on Electrical Engineering - Boumerdes, ICEE-B 2017*, IEEE, Oct. 2017, pp. 1–7, doi: 10.1109/ICEE-B.2017.8192181.
[34] T. Yang, Z. Ouyang, J. Liu, and T. H. Luan, "Design of TD-LTE based signal indoor distribution system," in *IEEE Vehicular Technology Conference*, IEEE, Sep. 2017, pp. 1–7, doi: 10.1109/VTCFall.2017.8288330.
[35] P. T. Mahida, S. Shahrestani, and H. Cheung, "Indoor positioning framework for visually impaired people using Internet of Things," in *Proceedings of the International Conference on Sensing Technology, ICST*, IEEE, Dec. 2019, pp. 1–6, doi: 10.1109/ICST46873.2019.9047704.
[36] X. Guo *et al.*, "Ray-tracing based 5G coverage analysis and capacity evaluation in an indoor hotspot scenario," in *2022 IEEE 5th International Conference on Electronic Information and Communication Technology, ICEICT 2022*, IEEE, Aug. 2022, pp. 464–469, doi: 10.1109/ICEICT55736.2022.9908635.
[37] L. Chiaraviglio *et al.*, "How much exposure from 5G towers is radiated over children, teenagers, schools and hospitals?," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1592–1614, 2022, doi: 10.1109/OJCOMS.2022.3208938.
[38] L. Ding, Y. Tian, T. Liu, Z. Wei, and X. Zhang, "Understanding commercial 5G and its implications to (Multipath) TCP," *Computer Networks*, vol. 198, p. 108401, Oct. 2021, doi: 10.1016/j.comnet.2021.108401.
[39] Z. M. Altukhi and N. F. Aljohani, "Using descriptive analysis to find patterns and trends: a case of car accidents in Washington D.C.," *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 5, pp. 257–264, 2023, doi:

10.14569/IJACSA.2023.0140527.
[40] A. Kusyanti, R. Primananda, and K. J. Saputro, "Lizard cipher for IoT security on constrained devices," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 11, pp. 507–511, 2019, doi: 10.14569/IJACSA.2019.0101169.
[41] G. S. Fuhnwi, V. Adedoyin, and J. O. Agbaje, "An empirical internet protocol network intrusion detection using isolation forest and one-class support vector machines," *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 8, 2023, doi: 10.14569/IJACSA.2023.0140801.

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