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Comparative analysis of 5G network performance at Thailand's premier shopping centers

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ABSTRACT

This paper evaluates 5G network performance across three well-known shopping malls in Bangkok: Icon Siam, Siam Paragon, and CentralWorld. The study focuses on assessing key quality of service (QoS) metrics, consisting of download (DL) speed, upload (UL) speed, and latency. Measurements were taken in various zones within each mall; including high, ground, and outdoor areas through field tests using two different mobile network operators (MNO-1 and MNO-2). The findings indicate noticeable differences in performance, with Icon Siam recording the highest average DL speed of 273.6 Mbps (MNO-1) and the outdoor zone at Siam Paragon having the lowest at 11.2 Mbps (MNO-2). While MNO-1 provided more stable UL speeds, MNO-2 showed greater variability. Latency results also highlighted MNO-1's stronger network efficiency, often staying below 20 ms, apart from a slight increase in outdoor areas. Statistical analyses, using ANOVA and t-Test, revealed significant disparities in QoS parameters depending on location and MNO, with outdoor areas often underperforming. These results underline the importance of in-building distributed antenna systems (IB-DAS) and improved infrastructure for boosting 5G performance. Furthermore, this study offers insights that can be useful to improve network quality in high-traffic locations.

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1. INTRODUCTION

Thailand's capital, Bangkok, is a popular tourist destination. Digital technologies are increasingly being integrated into "digital tourism" to improve visitor experiences [1]. The program provides features such as reserving accommodation and information about relevant attractions nearby. Thailand's economy has benefited greatly from the rise in foreign travel. With an estimated 35.5 million foreign visitors as of January 16, 2025, Thailand saw a 26.3% increase in foreign visitors compared to 2023 [2]. Additionally, the country has emerged as a popular location for digital nomads due to its affordability, rich culture, and robust digital infrastructure, which includes dependable high-speed internet as a crucial component supporting their work-from-anywhere lifestyle as remote working becomes increasingly common [3]. In a similar vein, Thailand's strong connectivity is advantageous to contemporary travelers. The caliber of Thailand's 5G infrastructure, guarantees seamless operation of digital services to satisfy the needs of both tech-savvy tourists and digital nomads.

5G consists of three key service categories, specifically enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC), and massive machine type communication (mMTC). This enables 5G to support a huge number of connected devices simultaneously, making it an essential component of smart city infrastructures, including devices and sensors [4], [5]. Specifically, mMTC enables 5G to support a massive number of connected devices simultaneously, making it an essential component of smart city infrastructures. This capability allows 5G to power a wide range of applications, including smart homes, smart factories, and smart cities. It is particularly vital for large buildings with high concentrations of mobile users and devices, such as crowded shopping malls or large-scale buildings, where reliable connectivity is crucial. To evaluate and analyze the quality of service (QoS) provided by 5G mobile networks in large-scale buildings, specifically in Bangkok's premier shopping malls, this study employed stationary-mode field testing to measure latency as well as download (DL) and upload (UL) speeds. The key findings of this study can help mobile network operators (MNOs) improve their QoS in large building environments.

This article is an extended version of [6], enhanced with comprehensive analysis and additional data gathered from two more iconic shopping malls in Bangkok. Following this section, the background and the methodology are described in sections 2 and 3, respectively. The results, analysis, and discussion are then presented in sections 4–6, respectively. Finally, the conclusion and future work directions are outlined in section 7.

2. BACKGROUND

2.1. Recent 5G status in Thiland

As stated in [6], with the high theoretical performance of 5G technology, such as, ultra-low latency of 1 ms and peak data rate of 20 Gbps maximum, 5G services were implemented in many countries worldwide. In Thailand, 5G service was officially launched in Q1/2020 by one of the major MNOs. As mentioned in [7], Bangkok was among the top 20 capital cities globally for 5G DL speed in 2021, while Thailand's fixed broadband DL speed was ranked sixth in the Speedtest Global Index in 2023. During its early stage of 5G, there were three major MNOs, which were AIS, TrueMove H, and DTAC. In 2024, AIS claimed that its 5G wireless network covered 95% of total Thai population [8]. Meanwhile, TrueMove H and DTAC also expanded their networks but face challenges related to QoS and coverage consistency. The merger of True Corporation and DTAC which took place during Q4/2021-Q1/2023 was the largest telcom business merger in Southeast Asia, based on combined enterprise value. This merger formed True Corporation, surpassing AIS to become Thailand's leading MNO [9]. Despite regulatory approval, the merger faced criticism for potential monopolistic practices, unfair competition, regulation and control by the National Broadcasting and Telecommunication Commission (NBTC), and consumer concerns over rising costs and reduced service quality [9].

2.2. Quality of service parameters

According to Srimuk *et al.* [6], a number of QoS metrics, including DL and UL speeds or data rates, are crucial for evaluating 5G network performance. These indicators are easy for average users to understand: DL speed typically surpasses UL speed, and higher speeds indicate better performance. They demonstrate how well the network can handle bandwidth-demanding tasks like streaming videos and sending big files. Latency, sometimes referred to as "delay" or "ping," is another crucial QoS metric [6]. It calculates how long it takes data to move between two points. For mission-critical (e.g., remote surgery) and real-time applications (e.g., voice over internet protocol (VoIP) [10]), this value is especially crucial. As stated in [6], it can be deduced that technology developments not only reduce latency but also increase DL and UL speeds.

2.3. In-building distributed antenna systems

Providing indoor network coverage to all important areas of the building is essential, as it allows businesses to continue their operations without interruption. Therefore, integrating multiple networks and studying methods to implement indoor coverage systems that support multi-services, low cost, low power consumption, and multi-network integration are necessary to support connectivity from IoT devices [11]. A general indoor distributed antenna system (DAS) network is illustrated in Figure 1 [12]. To further enhance indoor mobile signal quality, DAS is often combined with in-building coverage (IBC) solutions, commonly referred to as in-building distributed antenna systems (IB-DAS). These systems are particularly useful in locations where outdoor signals struggle to penetrate, such as basements, elevators, underground parking, and small hallways [13]. IB-DASs are intended to increase data rates, lessen interference, and offer dependable coverage in areas where signal strength is typically low [13]. In addition to the BS node, there are two sets of nodes: the first set consists of distributed antennas, and the second set consists of optional locations, referred to as intermediate nodes, for installing power devices [14]. Antennas, coaxial cables, couplers, and splitters are used by an IB-DAS to transmit outdoor signals into a building [15]. It is perfect for urban structures that need robust indoor connectivity since it connects signals both within and across floors, minimizing dead zones and signal travel distance [15].

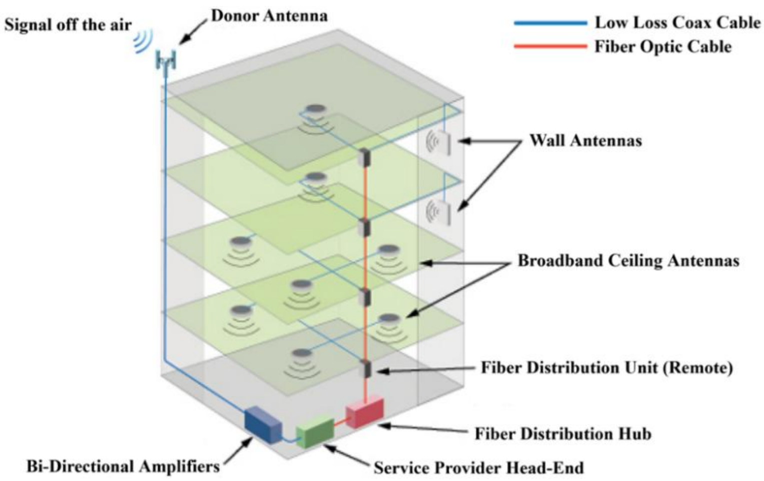


Figure 1. Overview on a typical indoor DAS network, adopted from [12]

2.4. Related works

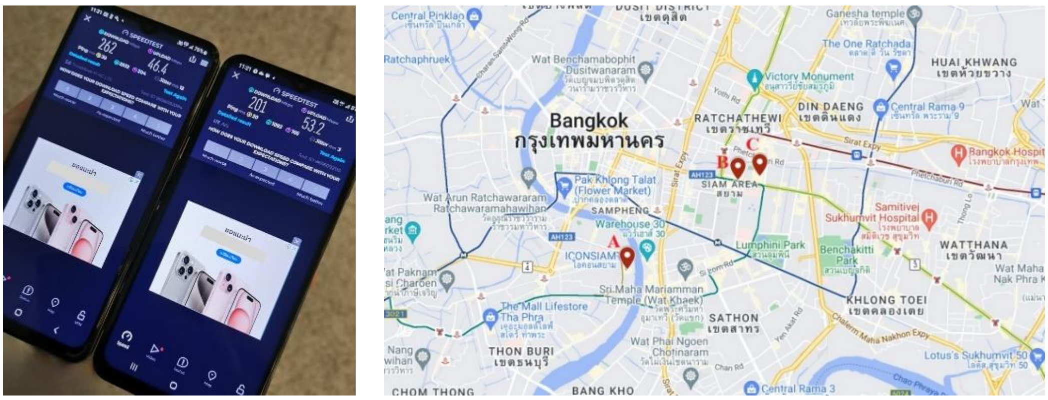
There have been a number of intriguing prior studies on DASs and IBC solutions. For IB-DAS network planning, a tree-encoded evolutionary algorithm (TMOEA) was first introduced in [15]. It outperformed four other algorithms that were benchmarked in that study while achieving reduced construction costs. The results demonstrated higher performance in two situations, enhancing coverage and lowering computing costs, even though a multi-objective genetic algorithm with Bayesian optimization for effective antenna placement in complicated indoor 5G environments was suggested in [13]. Regarding the medium-sized installations, the study with LTE or 4G in [16] revealed that the passive component of a hybrid-DAS performed 7.3% better than the active section in file transfer protocol uplink (FTP DL) throughput, but FTP UL throughputs were almost the same. A 4×4 multiple input multiple output (MIMO) indoor 5G network utilizing radio-over-fiber (RoF) technology and a DAS was shown in [17]. With delay enhancements of just a few hundred nanoseconds, it was able to attain a total throughput of roughly 4 Gbps. Finally, different small cell base station (SBS) architectures for dynamic spectrum sharing were introduced in [18] to address indoor solutions. It was discovered that while transceiver quantity had minimal impact on spectral efficiency, channel parameters and spectrum bands did.

Several earlier studies were found with reference to 5G QoS criteria. The current study using drive tests was conducted in the same city [19]. It evaluated 5G network performance provided by three MNOs. The findings highlight 5G's improvements over 4G, emphasizing the need for enhanced base station deployment and ongoing network optimization. In addition, a study emphasizing latency, signal-to-noise ratio (SNR), and throughput was conducted in Ibra, Oman [20], which evaluated indoor performance metrics of mobile broadband networks. It compared MNOs, highlights performance disparities, and offers insights for network optimization. Another study [21] analyzed 5G network performance in Muscat, Oman, across indoor and outdoor environments using data from three MNOs. The results revealed 4G dominance indoors and suboptimal 5G outdoor performance, highlighting the need for enhanced 5G base station deployment and continuous monitoring to improve QoS. In Thailand, the current study, which was carried out in Bangkok using drive testing with the G-NetTrack Pro application, discovered that the latencies offered by True and DTAC were roughly 26 ms and 38 ms, respectively, for outdoor scenarios [7]. The average indoor DL and UL rates from AIS were around 300.5 Mbps and 41.6 Mbps, respectively, as shown in [22]. Its average DL and UL rates outside, however, were 40.6 and 80.5 Mbps, respectively. The high uplink bandwidth demand from video content makers at tourist areas presents challenges for 5G implementation in Thailand, as seen in [23]. It was discovered that one major MNO's outside UL rate in the Grand Palace was 66.2 Mbps, whereas another MNO's UL rate at the same spot was 30.4 Mbps. However, one large MNO offered an outside DL rate of 268.2 Mbps at the Grand Palace, while another MNO offered 166.5 Mbps. Last but not least, t-Test analysis and field testing conducted in a major Bangkok hospital demonstrate that height has a substantial impact on 5G performance, with lower altitudes producing faster DL speeds [24]. However, it was discovered that one MNO's DL and UL rates at the interior ground level were 324.2 Mbps and 60.6 Mbps, respectively, while the latency was 19.0 ms.

Many studies have been conducted on 5G indoor networks. For example, Sheikh *et al.* [25] conducted a study on the performance analysis of ultra dense network (UDN) and DAS in an office building at 3.5 GHz, 28 GHz, and 60 GHz using 3D simulations. The results showed that basic solutions cannot provide consistent service quality at high frequencies, and indoor dedicated networks such as UDN or DAS are necessary. Similarly, Alade and Ahmed [26], along with Alade and Wang [27], conducted a study on the performance comparison of SBS and DAS in a multi-story building, analyzing signal distribution, inter-floor interference, and factors such as co-occurrence, signal loss, and co-channel interference. The results showed that the placement of equipment has different effects on throughput. Some research has tried to address indoor signal challenges. For instance, one study proposed a high-performance RAU-based mmWave-over-fiber DAS system, which enhances coverage and data speed, measuring wireless data rates of up to 24 Gbps in NLOS and 48 Gbps with a distributed MIMO technique [28]. The results demonstrated the system's capability to support reliable high-speed wireless communication for next-generation networks. Another study introduced a conceptual framework called iGeoStat, combining stochastic indoor environment modeling with physical propagation simulation to reflect indoor variations and simulate signal propagation based on material properties. The framework achieved much wider signal coverage [29]. Additionally, another research study proposed a bi-directional polarized transmit array antenna for indoor 5G communication at 28 GHz, enabling multi-zone coverage with comprehensive signal power distribution [30]. The findings suggest its potential for millimeter-level frequency applications. From the thorough survey above, it shows that while research has been done for both indoor and outdoor settings, no study has yet been done within a large shopping center. Thus, defining the QoS characteristics of such business spaces is the primary contribution of this study.

3. METHOD

This study was conducted in a stationary mode, similar to [22]-[24]. For the field tests, it used two 5G smartphones, as shown in Figure 2(a), with the same characteristics as those used in [22], [24]. Two distinct MNOs (henceforth referred to as MNO-1 and MNO-2) offered them limitless service packages. The "Speedtest" program, which has been widely used in earlier research, was another crucial instrument utilized in this work for testing and data collection [22]-[24]. After the tools were ready, field tests were carried out over a few days in January 2024 at Icon Siam, Siam Paragon, and CentralWorld, three of Bangkok's best retail centers (see their locations in Figure 2(b)). Each shopping center was split into three areas for the field tests: the high level, the G level, and the outside space.



(a) (b)

Figure 2. Tools and test areas; (a) two 5G smartphones used this study and (b) three locations of shopping malls under the fields tests, A-C, which are Icon Siam, Siam Paragon, and CentralWorld, respectively

In particular, the fifth, sixth, and seventh floors at Siam Paragon, Icon Siam, and CentralWorld, respectively, were defined as the top levels. The pier zone at Icon Siam, the fountain area at Siam Paragon, and CentralWorld Square in front of CentralWorld were among the outdoor spaces. Nine areas in all were used to conduct the field tests, and each area had 36 tests conducted for each MNO, covering the whole region. There are 648 records of gathered raw data in total. The overall processes of this study can be shown in Figure 3. The resulting QoS parameters comprising DL and UL speeds, as well as latency are presented in section 4.

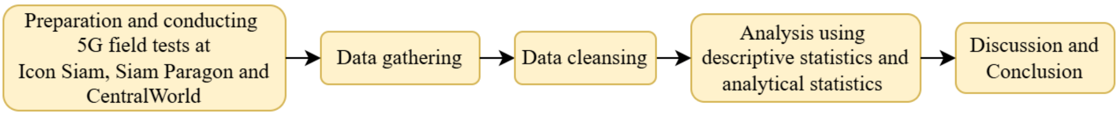


Figure 3. The overview on the processes in this study

4. RESULTS

After gathering raw data from each area in the premier shopping centers, outliers were discarded from the dataset. These outliers included the highest DL speeds of 801.8 Mbps and 780.2 Mbps from MNO-1 and MNO-2, respectively, the highest UL rates of 96.0 Mbps and 83.8 Mbps from MNO-2 and MNO-1, respectively, and the lowest values measured from each location (see Table 1 for examples). The validated data were then presented, as shown in Figures 4–6. As illustrated in Figure 4, the average DL speed at Icon Siam is the highest, reaching 273.6 Mbps, while the speeds at Siam Paragon and CentralWorld are 246.3 Mbps and 231.8 Mbps, respectively, as provided by MNO-1. From MNO-2, the average DL speeds are 206.2 Mbps and 141.7 Mbps at Icon Siam and CentralWorld, respectively, whereas it is only 27.5 Mbps at Siam Paragon.

Table 1. The highest and the lowest results measured from the three shopping malls in Bangkok

Results	DL rate		UL rate		Latency	
	MNO-1	MNO-2	MNO-1	MNO-2	MNO-1	MNO-2
Highest	801.8 Mbps @ 5th Floor, Siam Paragon	780.2 Mbps @ 1st Floor, CentralWorld	83.8 Mbps @ G Floor, Siam Paragon	96.0 Mbps @ 7th Floor, CentralWorld	79 ms @ G Floor, Icon Siam	126 ms @ 7th Floor, CentralWorld
Lowest	6.6 Mbps @ 5th Floor, Siam Paragon	1.1 Mbps @ G Floor, Siam Paragon	0.2 Mbps @ 5th Floor, Siam Paragon	0.9 Mbps @ G Floor, Siam Paragon	12 ms @ several locations	13 ms @ several locations

Focusing on specific areas, as shown in Figure 4, the highest average DL speed is 468.0 Mbps at the G level of CentralWorld, provided by MNO-1. The DL speeds at the G level of Siam Paragon and Icon Siam are 421.4 Mbps and 339.0 Mbps, provided by MNO-1 and MNO-2, respectively. Moreover, overall, it can be observed that MNO-1 provides better DL speeds than MNO-2, while the DL speeds in outdoor areas are lower than those in indoor areas of the shopping malls. Notably, the DL speed at the outdoor area of Siam Paragon is particularly low, measuring only 11.2 Mbps.

For UL speeds, surprisingly, the speed provided by MNO-1 at the outdoor area of Icon Siam is higher than the speed provided by the same MNO at the G and H levels of the same shopping mall. As presented in Figure 5, it is evident that the UL speeds are significantly lower than the DL speeds. The highest UL speed is 67.0 Mbps, provided by MNO-2 at the G level of Icon Siam, while the second and third highest speeds are 58.9 Mbps, provided by MNO-1 at the G level of CentralWorld, and 51.9 Mbps, provided by MNO-2 at the H level of Icon Siam, respectively. On the other hand, the lowest UL speeds are found at the G level and outdoor area of Siam Paragon, measuring 8.5 Mbps and 11.5 Mbps, respectively, provided by MNO-2. Furthermore, overall, UL speeds provided by MNO-1 are more stable than those provided by MNO-2, which tend to fluctuate significantly. Finally, the average UL speeds at Icon Siam appear to be the highest, as the combined average UL speed of 49.3 Mbps from MNO-2 and 38.7 Mbps from MNO-1 exceeds the combined average UL speeds at CentralWorld.

For latencies, as shown in Figure 6, it can be observed that, in most cases, the latency values measured at every area from MNO-1 are less than 20 ms, except at the out-door areas of CentralWorld and Icon Siam, where the laten-cy values are 23.6 ms, which is the worst, and 22.9 ms, respectively. The best latency value for MNO-1 is 13.8 ms, measured at the G level of CentralWorld. From MNO-2, the latency values are generally between 20–30 ms, except for two extremes: 16.9 ms at the H level of Siam Paragon, which is the lowest, and 34.1 ms at the outdoor area of Si-am Paragon, which is the highest.

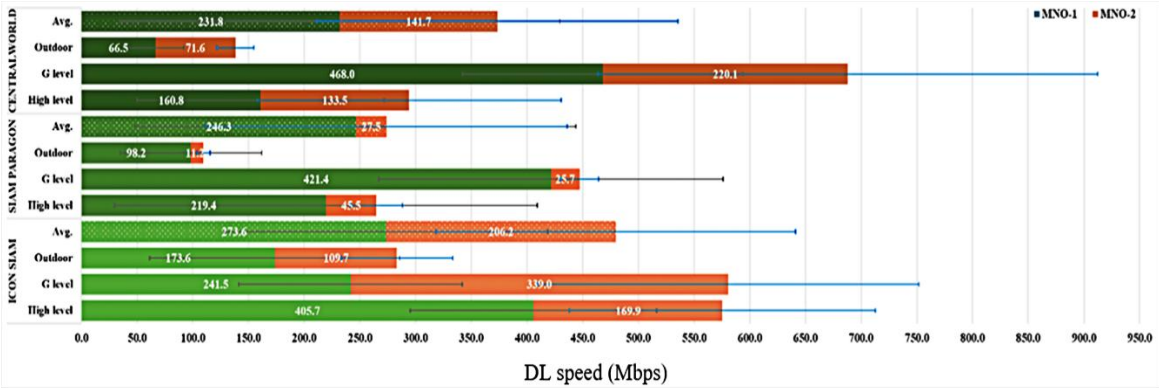


Figure 4. DL speeds from two MNOs at three zones of the shopping mall

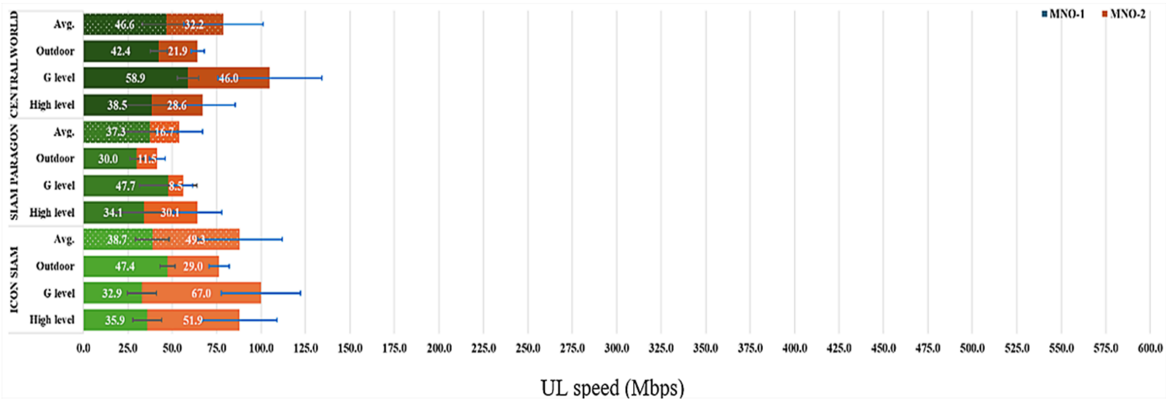


Figure 5. UL speeds from two MNOs at three zones of the shopping mall

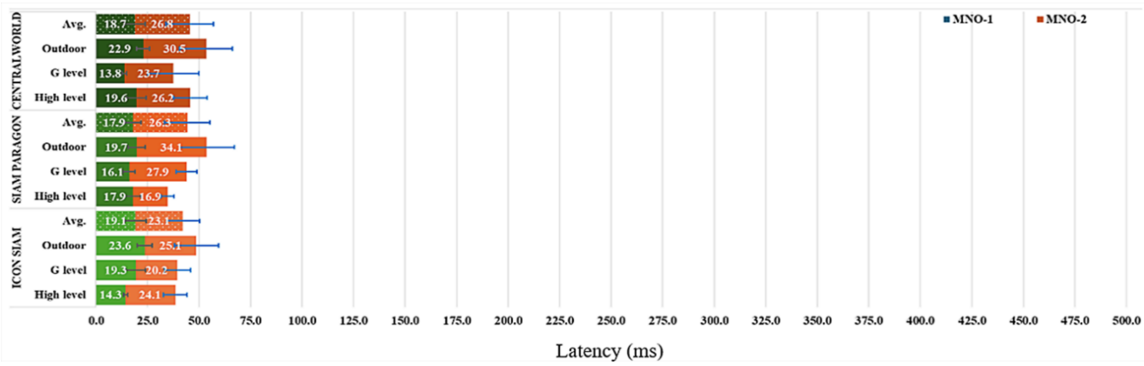


Figure 6. Latencies from two MNOs at three zones of the shopping mall

5. ANALYSIS

From the previous section, it can be observed that there are differences among areas in the three shopping malls. However, to ensure accuracy, statistical techniques such as ANOVA and t-Tests, as used in [22]-[24], were applied and described, while '*' in every table means the p-value is less than 0.05 with 95% confidence interval. As presented in Table 2 (in Appendix), the hypotheses H1–H6, associated with comparing the overall QoS parameter performance provided by MNO-1 and MNO-2 under each condition, were tested using ANOVA. The p-values for H1 and H5 are 0.293 and 0.244, respectively, which are significantly higher than 0.05. Therefore, it is confirmed that there is no difference in the overall DL speeds provided by MNO-1 across all shopping malls, which is consistent with the overall latency values. On the other hand, for the DL speeds from MNO-2, UL speeds, and latency values, the analysis of hypotheses H2, H3–H4, and H6 confirms that there are significant differences, as the p-values are less than 0.05.

In addition to the six hypotheses discussed earlier, several other hypotheses, as presented in Tables 2–11, were also analyzed and described. For the high levels of the shopping malls, the p-values of 0.149 and 0.306 for H10 and H13, respectively, indicate no significant differences in DL speeds between Siam Paragon and CentralWorld provided by MNO-1, or between Icon Siam and CentralWorld provided by MNO-2. Similarly, the p-values of 0.480, 0.594, 0.424, and 0.298 for H15, H16, H17, and H18, respectively, confirm no significant differences in UL speeds among the high levels of the three shopping malls or between any pair of malls provided by MNO-1. Likewise, the p-value of 0.720 for H22 indicates no significant difference in UL speeds between Siam Paragon and CentralWorld provided by MNO-2 (see Table 2). At the G level, the p-value of 0.205 for H34 also shows no significant difference in DL speeds between Siam Paragon and CentralWorld provided by MNO-1.

Table 3. Analyzed results comparing each parameter among three zones provided by MNO-1 at Icon Siam

Hypothesis		*p*-value
H79	The DL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H80	The DL speeds between the high level and the G level are the same or different	<0.001*
H81	The DL speeds between the high level and the outdoor are the same or different	<0.001*
H82	The DL speeds between the G level and the outdoor are the same or different	0.017*
H83	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H84	The UL speeds between the high level and the G level are the same or different	0.152
H85	The UL speeds between the high level and the outdoor are the same or different	<0.001*
H86	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H87	The latencies among the high level, the G level and the outdoor are the same or different	<0.001*
H88	The latencies between the high level and the G level are the same or different	<0.001*
H89	The latencies between the high level and the outdoor are the same or different	<0.001*
H90	The latencies between the G level and the outdoor are the same or different	<0.001*

Table 4. Analyzed results comparing each parameter among three zones provided by MNO-2 at Icon Siam

Hypothesis		*p*-value
H91	The DL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H92	The DL speeds between the high level and the G level are the same or different	<0.001*
H93	The DL speeds between the high level and the outdoor are the same or different	0.028*
H94	The DL speeds between the G level and the outdoor are the same or different	<0.001*
H95	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H96	The UL speeds between the high level and the G level are the same or different	0.009*
H97	The UL speeds between the high level and the outdoor are the same or different	<0.001*
H98	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H99	The latencies among the high level, the G level and the outdoor are the same or different	0.041*
H100	The latencies between the high level and the G level are the same or different	0.013*
H101	The latencies between the high level and the outdoor are the same or different	0.651
H102	The latencies between the G level and the outdoor are the same or different	0.033*

Table 5. Analyzed results comparing each parameter between MNO-1 and MNO-2 in each zone at Icon Siam

Hypothesis		*p*-value
H103	The overall DL speeds provided by MNO-1 and MNO-2 are the same or different	0.004*
H104	The DL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H105	The DL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	0.009*
H106	The DL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	0.006*
H107	The overall UL speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H108	The UL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H109	The UL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H110	The UL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	<0.001*
H111	The overall latencies speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H112	The latencies speeds at the high level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H113	The latencies speeds at the G level provided by MNO-1 and MNO-2 are the same or different	0.551
H114	The latencies speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	0.458

Latency values across different levels were also tested. The p-values of 0.149, 0.250, 0.166, 0.163, 0.429, 0.082, and 0.287 for H26, H29, H53, H54, H73, H77, and H78, respectively, indicate no significant differences in latency between the high, G, and outdoor levels across the shopping malls (Siam Paragon, Icon Siam, and CentralWorld) for both MNO-1 and MNO-2 (see Table 2). At Icon Siam, the p-values of 0.152, 0.651, 0.551, and 0.458 for H84, H101, H113, and H114, respectively, show no significant differences in UL speeds between the high and G levels, or in latencies between the high level and outdoor areas or the G level and outdoor areas, for both MNO-1 and MNO-2 (see Tables 3-5). Similarly, at Siam Paragon, the p-values of 0.208, 0.325, and 0.258 for H121, H144, and H148 confirm no significant differences in UL speeds or latency values between the high level, outdoor areas, and between MNO-1 and MNO-2 (see Tables 6 and 8). At CentralWorld, the p-values of 0.184, 0.101, 0.076, 0.051, 0.071, 0.367, 0.127, and 0.373 for H157, H161, H164, H169, H171, H172, H173, and H178, respectively, indicate no significant differences in UL speeds, DL speeds, or latencies across the high level, G level, and outdoor areas or between the two operators (see Tables 9-11). While some p-values (e.g., H164, H169, and H171) are close to the 0.05 threshold, they remain above it, confirming no statistically significant differences.

Finally, for the remaining hypotheses, significant differences were observed, suggesting that some measured parameters vary under specific conditions. These differences highlight variations in performance influenced by factors such as location, network provider, or the level within the shopping malls. Such findings provide insight into the nuances of 5G network performance in complex environments.

Table 6. Analyzed results comparing each parameter among three zones provided by MNO-1 at Siam Paragon

	Hypothesis	*p*-value
H115	The DL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H116	The DL speeds between the high level and the G level are the same or different	<0.001*
H117	The DL speeds between the high level and the outdoor are the same or different	0.002*
H118	The DL speeds between the G level and the outdoor are the same or different	<0.001*
H119	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H120	The UL speeds between the high level and the G level are the same or different	0.002*
H121	The UL speeds between the high level and the outdoor are the same or different	0.208
H122	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H123	The latencies among the high level, the G level and the outdoor are the same or different	<0.001*
H124	The latencies between the high level and the G level are the same or different	<0.001*
H125	The latencies between the high level and the outdoor are the same or different	<0.001*
H126	The latencies between the G level and the outdoor are the same or different	<0.001*

Table 7. Analyzed results comparing each parameter among three zones provided by MNO-2 at Siam Paragon

	Hypothesis	*p*-value
H127	The DL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H128	The DL speeds between the high level and the G level are the same or different	<0.001*
H129	The DL speeds between the high level and the outdoor are the same or different	<0.001*
H130	The DL speeds between the G level and the outdoor are the same or different	<0.001*
H131	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H132	The UL speeds between the high level and the G level are the same or different	0.009*
H133	The UL speeds between the high level and the outdoor are the same or different	<0.001*
H134	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H135	The latencies among the high level, the G level and the outdoor are the same or different	<0.001*
H136	The latencies between the high level and the G level are the same or different	<0.001*
H137	The latencies between the high level and the outdoor are the same or different	<0.001*
H138	The latencies between the G level and the outdoor are the same or different	0.020*

Table 8. Analyzed results comparing each parameter between MNO-1 and MNO-2 in each zone at Siam Paragon

	Hypothesis	*p*-value
H139	The overall DL speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H140	The DL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H141	The DL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H142	The DL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	<0.001*
H143	The overall UL speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H144	The UL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	0.325
H145	The UL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H146	The UL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	<0.001*
H147	The overall latencies speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H148	The latencies speeds at the high level provided by MNO-1 and MNO-2 are the same or different	0.258
H149	The latencies speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H150	The latencies speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	<0.001*

Table 9. Analyzed results comparing each parameter among three zones provided by MNO-1 at CentralWorld

	Hypothesis	*p*-value
H151	The DL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H152	The DL speeds between the high level and the G level are the same or different	<0.001*
H153	The DL speeds between the high level and the outdoor are the same or different	<0.001*
H154	The DL speeds between the G level and the outdoor are the same or different	<0.001*
H155	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H156	The UL speeds between the high level and the G level are the same or different	<0.001*
H157	The UL speeds between the high level and the outdoor are the same or different	0.184
H158	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H159	The latencies among the high level, the G level and the outdoor are the same or different	<0.001*
H160	The latencies between the high level and the G level are the same or different	<0.001*
H161	The latencies between the high level and the outdoor are the same or different	0.101
H162	The latencies between the G level and the outdoor are the same or different	<0.001*

Table 10. Analyzed results comparing each parameter among three zones provided by MNO-2 at CentralWorld

	Hypothesis	*p*-value
H163	The DL speeds among the high level, the G level and the outdoor are the same or different	0.001*
H164	The DL speeds between the high level and the G level are the same or different	0.076
H165	The DL speeds between the high level and the outdoor are the same or different	0.017*
H166	The DL speeds between the G level and the outdoor are the same or different	<0.001*
H167	The UL speeds among the high level, the G level and the outdoor are the same or different	<0.001*
H168	The UL speeds between the high level and the G level are the same or different	0.008*
H169	The UL speeds between the high level and the outdoor are the same or different	0.051
H170	The UL speeds between the G level and the outdoor are the same or different	<0.001*
H171	The latencies among the high level, the G level and the outdoor are the same or different	0.071
H172	The latencies between the high level and the G level are the same or different	0.367
H173	The latencies between the high level and the outdoor are the same or different	0.127
H174	The latencies between the G level and the outdoor are the same or different	0.043*

Table 11. Analyzed results comparing each parameter between MNO-1 and MNO-2 in each zone at CentralWorld

	Hypothesis	*p*-value
H175	The overall DL speeds provided by MNO-1 and MNO-2 are the same or different	0.001*
H176	The DL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	0.398
H177	The DL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H178	The DL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	0.373
H179	The overall UL speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H180	The UL speeds at the high level provided by MNO-1 and MNO-2 are the same or different	0.028*
H181	The UL speeds at the G level provided by MNO-1 and MNO-2 are the same or different	0.021*
H182	The UL speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	<0.001*
H183	The overall latencies speeds provided by MNO-1 and MNO-2 are the same or different	<0.001*
H184	The latencies speeds at the high level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H185	The latencies speeds at the G level provided by MNO-1 and MNO-2 are the same or different	<0.001*
H186	The latencies speeds at the outdoor provided by MNO-1 and MNO-2 are the same or different	0.003*

6. DISCUSSION

This study advances beyond [6] by incorporating two additional locations and conducting more comprehensive analyses. Moreover, it differs from [23], which focused solely on 5G performance in outdoor environments, and [24], which primarily examined indoor environments. While similar to [22], which studied 5G performance in both indoor and outdoor environments, that work focused on a high-rise building within a public hospital. In contrast, this study expands to a broader context with more comprehensive analyses. In addition, this study differs from [21], which used the G-Net track pro application as the primary tool for testing and gathering data, particularly signal strength data. This study also differs from [19], [20], which utilized drive tests and included SNR measurements, respectively.

The findings of this study emphasize the variability in 5G network performance across different areas within Bangkok's top shopping malls, highlighting distinctions in QoS parameters such as DL and UL speeds, as well as latency values. The results indicate that MNO-1 generally outperforms MNO-2 in DL speeds, particularly in indoor zones, with Icon Siam registering the highest average DL speed of 273.6 Mbps. The contrast in DL speeds between shopping malls underscores the impact of location and infrastructure on network performance. Notably, outdoor areas consistently exhibit significantly lower DL speeds, with the outdoor zone of Siam Paragon recording only 11.2 Mbps provided by MNO-2, which could be attributed to weaker signal propagation and the absence of optimized infrastructure or very high traffic of data since this shopping mall is lacated in the one of the most busiest urban area in Bangkok. For UL speeds, they demonstrate significant disparities between indoor and outdoor zones. Surprisingly, the outdoor area of Icon

Siam shows higher UL speeds for MNO-1 compared to its indoor counterparts. However, the UL speeds provided by MNO-2 exhibit considerable fluctuations, which might reflect variations in network optimization or load management strategies. The stability of MNO-1's UL speeds suggests superior network optimization and consistency in providing reliable service. Additionaly, Latency analysis reveals that MNO-1 consistently delivers lower latency values, often below 20 ms, except in outdoor areas where latency slightly increases. In contrast, MNO-2's latency values vary significantly, ranging from 16.9 ms to 34.1 ms. These findings highlight the critical role of infrastructure in minimizing latency, particularly for applications requiring real-time responsiveness.

Statistical analyses further corroborate these observations. ANOVA and t-Tests confirm significant differences in QoS parameters across zones and MNOs under various conditions. While many hypotheses indicated no significant differences, others revealed notable variations, particularly in outdoor areas, where network performance was generally suboptimal. Finally, the study underscores the importance of IB-DAS and infrastructure enhancements to address signal propagation issues and optimize 5G performance. The results also highlight the need for network providers to prioritize consistency across different areas, particularly in outdoor and high-demand zones, to ensure equitable user experiences.

7. CONCLUSION

This study provides valuable insights into 5G network performance in Bangkok's top shopping malls, focusing on QoS parameters across different zones and MNOs. It reveals significant variability in DL and UL speeds, as well as latency values, which are influenced by location, infrastructure, and provider strategies. MNO-1 consistently outperformed MNO-2 in stability and overall performance, particularly in indoor areas. The results highlight the challenges of providing consistent 5G connectivity in complex urban environments, emphasizing the need for enhanced infrastructure, such as IB-DAS, to mitigate signal propagation issues. Outdoor areas remain a significant concern, with noticeably lower performance compared to indoor zones, underscoring the need for targeted improvements.

Future work could expand this analysis to include other metropolitan areas and explore the impact of user density and network load on QoS parameters. This research contributes to the understanding of 5G network optimization and serves as a reference for stakeholders aiming to enhance connectivity in high-demand locations.

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C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
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Fo	: **Fo**rmal analysis	E	: Writing - Review & **E**diting		

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICAL APPROVAL

This study conducts a comparative analysis of 5G network performance in prominent shopping malls across Thailand. Data were collected through field testing using two 5G-enabled smartphones. In conclusion, this research does not involve human subjects and is therefore not classified as human research.

DATA AVAILABILITY

The data that support the findings of this study are available from the first author, [TD], or the corresponding author, [PP], upon reasonable request.

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APPENDIX

Table 2. Analyzed results comparing each parameter provided by MNO-1 and MNO-2 in each condition

	Hypothesis	*p*-value
H1	The overall DL speeds provided by MNO-1 at 3 shopping malls are the same or different	0.293
H2	The overall DL speeds provided by MNO-2 at 3 shopping malls are the same or different	<0.001*
H3	The overall UL speeds provided by MNO-1 at 3 shopping malls are the same or different	<0.001*
H4	The overall UL speeds provided by MNO-2 at 3 shopping malls are the same or different	<0.001*
H5	The overall latency values provided by MNO-1 at 3 shopping malls are the same or different	0.244
H6	The overall latency values provided by MNO-2 at 3 shopping malls are the same or different	0.036*
H7	The DL speeds among the high level, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H8	The DL speeds between the high level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H9	The DL speeds between the high level, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H10	The DL speeds between the high level, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.149
H11	The DL speeds among the high level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H12	The DL speeds between the high level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H13	The DL speeds between the high level, at Icon Siam and Central World provided by MNO-2 are the same or different	0.306
H14	The DL speeds between the high level, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H15	The UL speeds among the high level, at 3 shopping malls provided by MNO-1 are the same or different	0.480
H16	The UL speeds between the high level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	0.594
H17	The UL speeds between the high level, at Icon Siam and Central World provided by MNO-1 are the same or different	0.424
H18	The UL speeds between the high level, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.298
H19	The UL speeds among the high level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H20	The UL speeds between the high level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H21	The UL speeds between the high level, at Icon Siam and Central World provided by MNO-2 are the same or different	<0.001*

Table 2. Analyzed results comparing each parameter provided by MNO-1 and MNO-2 in each condition (*continued*)

	Hypothesis	*p*-value
H22	The UL speeds between the high level, at Siam Paragon and Central World provided by MNO-2 are the same or different	0.720
H23	The latency values among the high level, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H24	The latency values between the high level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H25	The latency values between the high level, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H26	The latency values between the high level, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.149
H27	The latency values among the high level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H28	The latency values between the high level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H29	The latency values between the high level, at Icon Siam and Central World provided by MNO-2 are the same or different	0.250
H30	The latency values between the high level, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H31	The DL speeds among the G level, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H32	The DL speeds between the G level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H33	The DL speeds between the G level, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H34	The DL speeds between the G level, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.205
H35	The DL speeds among the G level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H36	The DL speeds between the G level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H37	Average DL speeds between the G level, at Icon Siam and Central World provided by MNO-2 are the same or different	0.025*
H38	Average DL speeds between the G level, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H39	Average UL speeds among the G level, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H40	Average UL speeds between the G level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H41	Average UL speeds between the G level, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H42	Average UL speeds between the G level, at Siam Paragon and Central World provided by MNO-1 are the same or different	<0.001*
H43	Average UL speeds among the G level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H44	Average UL speeds between the G level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H45	Average UL speeds between the G level, at Icon Siam and Central World provided by MNO-2 are the same or different	0.003*
H46	Average UL speeds between the G level, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H47	The latency values among the G level, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H48	Average latency values between the G level, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H49	The latency values between the G level, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H50	The latency values between the G level, at Siam Paragon and Central World provided by MNO-1 are the same or different	<0.001*
H51	The latency values among the G level, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H52	The latency values between the G level, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H53	The latency values between the G level, at Icon Siam and Central World provided by MNO-2 are the same or different	0.166
H54	The latency values between the G level, at Siam Paragon and Central World provided by MNO-2 are the same or different	0.163
H55	The DL speeds among the outdoor, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H56	The DL speeds between the outdoor, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H57	The DL speeds between the outdoor, at Icon Siam and Central World provided by MNO-1 are the same or different	0.002*
H58	The DL speeds between the outdoor, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.013*
H59	The DL speeds among the outdoor, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H60	The DL speeds between the outdoor, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H61	The DL speeds between the outdoor, at Icon Siam and Central World provided by MNO-2 are the same or different	<0.001*
H62	The DL speeds between the outdoor, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H63	The UL speeds among the outdoor, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H64	The UL speeds between the outdoor, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*

Table 2. Analyzed results comparing each parameter provided by MNO-1 and MNO-2 in each condition (*continued*)

	Hypothesis	*p*-value
H65	The UL speeds between the outdoor, at Icon Siam and Central World provided by MNO-1 are the same or different	<0.001*
H66	The UL speeds between the outdoor, at Siam Paragon and Central World provided by MNO-1 are the same or different	<0.001*
H67	The UL speeds among the outdoor, at 3 shopping malls provided by MNO-2 are the same or different	<0.001*
H68	The UL speeds between the outdoor, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	<0.001*
H69	The UL speeds between the outdoor, at Icon Siam and Central World provided by MNO-2 are the same or different	<0.001*
H70	The UL speeds between the outdoor, at Siam Paragon and Central World provided by MNO-2 are the same or different	<0.001*
H71	The latency values among the outdoor, at 3 shopping malls provided by MNO-1 are the same or different	<0.001*
H72	The latency values between the outdoor, at Icon Siam and Siam Paragon provided by MNO-1 are the same or different	<0.001*
H73	The latency values between the outdoor, at Icon Siam and Central World provided by MNO-1 are the same or different	0.429
H74	The latency values between the outdoor, at Siam Paragon and Central World provided by MNO-1 are the same or different	0.002*
H75	The latency values among the outdoor, at 3 shopping malls provided by MNO-2 are the same or different	0.020*
H76	The latency values between the outdoor, at Icon Siam and Siam Paragon provided by MNO-2 are the same or different	0.005*
H77	The latency values between the outdoor, at Icon Siam and Central World provided by MNO-2 are the same or different	0.082
H78	The latency values between the outdoor, at Siam Paragon and Central World provided by MNO-2 are the same or different	0.287

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