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Performance Analysis of Mobile Broadband Networks With 5G Trends and Beyond: Urban Areas Scope in Malaysia

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ABSTRACT The performance of Mobile Broadband (MBB) services of Fourth Generation (4G) and Third Generation (3G) mobile networks over urban morphology is studied in Malaysia based on experimental measurements of drive test data. The aim of this study is to provide a roadmap for service providers to establish a realistic plan for future Fifth Generation (5G) networks. This work is a continuation of our previous work for the scope of rural areas in Malaysia. The MBB measurement data have been gathered through drive tests conducted in the urban areas of four states throughout Malaysia (namely, Klang Valley/Selangor, Johor, Sarawak and Sabah) to characterise and analyse MBB performances. The gathered data are from the cities, highways and federal roads of the chosen states, and encompasses three main Mobile Network Operators (MNOs). Data has been collected in a time span of 2 months, from January to February, using the Samsung Galaxy S6 smartphone handsets. Four MBB Key Performance Indicators (KPIs) are considered in this study (coverage, latency, satisfaction and speed) for two MBB services (web browsing and video streaming). The measurement data for characterising the performance of each MBB service has been collected using a dedicated smartphone handset. YouTube videos with 720p and 1080p resolutions have been sequentially streamed to assess the performance of MBB video-streaming services. Three distinct websites (Google, Instagram and mStar) have been accessed to evaluate the performance of MBB web-browsing services. The experimental methodology of this study integrates several diversified elements including four different urban states, four distinct KPIs, three main MNOs, two MBB services and two radio networks (4G and 3G), which are both accessible by the smartphones when available to mimic real-world scenarios. The results of this study reveal that the performance of 4G radio networks is generally superior to that of 3G. For instance, 4G networks achieved a vMOS score of more than 3 for both MBB video-streaming and web-browsing services, while 3G networks scored less than 3 across all four study areas. The analysed experimental results confirmed that compared to 3G networks, 4G technology presents an enhancement factor of up to 1.6 and 4.2 in download speed when streaming a video and browsing a web page, respectively. The study outcomes can contribute to the efficient planning of non-standalone (NSA) 5G networks in Malaysia where 5G networks will be aided by existing 4G infrastructures. Analysing the 4G coverage performance is the first step towards deciding the deployment rate of NSA 5G in Malaysia.

INDEX TERMS Mobile broadband, urban areas, Malaysia, 3G and 4G networks, plans for 5G technology in Malaysia.

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I. INTRODUCTION

Several entities across the globe are continuously tracking and forecasting the global MBB data traffic to analyse its growth trends, which is crucial for MBB service providers [1], [2]. For instance, the Cisco Visual Networking Index (VNI) Global Mobile Data Traffic Forecast Update released in February 2019 had reported informative figures that reflect the dynamic effect of networking applications on global networks [3]. This report stated that the monthly global MBB traffic touched the figure of 11.5 Exabyte at the end of 2017, which is a growth rate of 71% with respect to the 6.7 Exabyte recorded at the end of 2016. During the past five years (from 2012 to 2017), the mobile data traffic grew 17-fold. In 2017, 72% of mobile traffic was generated from the MBB services of 4G networks. The global mobile User Equipment (UE) and communication reached 8.6 billion in 2017, which was an increase from the 7.9 billion recorded in 2016. During 2017, smartphones represented 51% and 88% of the total number of mobile devices and total traffic, respectively [3]. Regarding MBB forecasting, informative projection figures for years 2017 to 2022 have been presented by the VNI report. A global MBB data traffic increase of 7-fold is anticipated. The report also revealed that by 2022, there will be 1.5 mobile devices per capita. 4G will be 54% of connections and 71% of total traffic, while 5G will be 3.4% of connections and 11.8% of total traffic [3]. The report further stated that mobile data traffic and number of mobile devices will continue to increase tremendously in coming years. It further mentions that the number of smart devices will continue in conjunction with upgraded mobile generations whenever available. The upgraded 5G mobile generation expected to be implemented by 2020 will include additional challenges in terms of increased data traffic as a result of more video-like steaming. Therefore, measuring the gap between forecasted mobile data traffic and performance with the actual MBB data traffic and performance is highly necessary. This will help service providers recognise performance shortage so as to provide remedial solutions to rectify potential degradation and offer continuous customer satisfaction.

If the measurement analysis of actual MBB performance is available to potential consumers, this will help them make informed decisions regarding the choices of MNOs. Other factors affecting consumer preferences of MNOs are present, such as retail price and available coverage. However, the actual MBB performance reflected in specific performance metrics, such as Hypertext Transfer Protocol (HTTP) download/upload speed, web browsing speed, latency [4], [5], etc., are known to be the determinant factors in the selection of MNOs [6]. In fact, the MBB performance of consumer mobile devices is influenced by various aspects including the distance from base stations, physical obstacles, urban/rural morphology, interference levels and network congestion. Therefore, it is significant to measure and assess the performance and satisfaction of existing MBB service providers from the consumer's perspective. The study of MBB data traffic in a region or country can help in estimating the population dynamics [7] as well as provide useful insight concerning human mobility laws [8], natural disaster recovery [9], urban growth forecasting [10], [11] and social graphs extracted from MBB data analysis [12]. The literature does provide several studies and reviews of MBB data measurements and analyses for various fields such as social networks, mobility, geography, security or business applications [13]–[15]. In [15], MBB datasets were proven to be effective in supporting or even replacing the classical sources of obtaining timely demographic data, such as surveys, which are often limited by factors of cost, real-time data extraction and scalability. Generally, studies on MBB performance analysis can be divided into three categories. The first is social analysis which examines the correlations between MBB data traffic and various social features. The second is mobility analysis which employs MBB data traffic to extract mobility information. The third is network analysis which is more technical in nature as it investigates the dynamics of MBB traffic demands to be accommodated and the actual MBB performance [15]. The current research study falls under the third category.

The use of MBB data traffic can be explored from the perspective of either the service provider or the mobile user. From the service provider's perspective, the MBB data traffic of many users within the same coverage area can be aggregated and analysed to extract patterns relating to temporal, spatiotemporal or special dynamics. For instance, research has shown that MBB traffic at the level of service providers has a tendency of following specific temporal patterns. Mobile networks are usually highly loaded during weekdays compared to weekends [16]–[20]. When incorporating the geographical area with temporal dynamics to form spatiotemporal dynamics, studies revealed that there is geographical heterogeneity of MBB data traffic, especially for a smaller temporal scale of hours, as shown in [17], [19], [21], [22]. The unique dynamics and analysis of MBB data traffic can be characterised when special events occur, such as global exhibitions, FIFA World Cup, Christmas, etc. From the mobile user's perspective, MBB traffic can be characterised to analyse the consistency or variability of per-user MBB traffic over time and space. In [23], [24] for instance, it was found that the average voice call duration per user has a peak at around one minute. In [25], it was proven that 80% of mobile data consumers in Mexico City are active for not more than 4 hours. Such analyses of consumer-level dynamics help differentiate activity distributions over time as well as distinguish user categories in terms of calling durations or internet browsing frequency.

The performance of MBB networks has been extensively studied from various aspects and contexts throughout the literature [26]–[31]. Several measurements and data processing applications, software packages and platforms with various measurement data types have been used for distinct MBB performance metrics. Among others, mobile applications for MBB performance measurements include PRTG Network Monitor from PAESSLER [32], HAKOMetar [33], Speedtest from Ookla [34], Datum from Spirent [35], TEMS Pocket from ASCOM [36], Nemo Handy from KEYSIGHT [37], QualiPoc from Rohde & Schwarz [38] and OpenSignal [39].

MBB data processing applications and monitoring platforms have also been used, such as Nemo Outdoor [37] and MONROE in Europe [28]. Others apply custom performance measurement tools that better fit their research aims [40], [41]. The MBB data measurement can be conducted in indoor environments [42], [43], within university campuses [44]–[47], along roads [48], [49], in different locations of the same city [41], [50], in several cities [6], [51], in different countries [52] or at specific large-scale events [53]. To preserve the privacy of the measurement analysis outcomes, the names of MBB service operators may be coded to conceal their identities [44], while others choose to surprisingly declare the findings of operators' measurement results, as in [45], [46], or as by Ofcom in the United Kingdom (UK) [6]. Most of these studies had focused on 3G/4G or 4G services only as received by consumers' 3G/4G-capable smartphones or any other UE. The measured data referred to MBB performance metrics such as the Reference Signal Received Power (RSRP)/received signal strength [44]–[46], [48], [49], [53], downlink/uplink data rate [6], [40], [42], [50], [52], [53], latency/Round Trip Time (RTT) [6], [40], [42], [45], [51], etc. Some works categorised the measurement datasets as either during the weekdays or weekends [49], [50], while others classified datasets during peak or off-peak hours [45], [51]. Most studies in the literature revealed that Long-Term Evolution (LTE)/4G networks provide better services than those of Universal Mobile Telecommunications System (UMTS)/3G networks, with only marginal differences from the target figures as set by 3GPP. In [6] for example, the 4G download speeds were more than double that of 3G. In [45], the RTT was found to be almost similar to the 3GPP target of less than 20 ms.

Continuous studies are deemed necessary to identify more informative and robust frameworks for the data measurement of MBB performance. Various factors must be considered such as the national MBB operators' networks, MBB performance metrics, measurement data types, 3G/4G/5G technologies, software and hardware-based measurement applications and platforms, spatial dynamics, temporal dynamics, activity-based dynamics, consumer mobility or stationery, indoor or outdoor environments, urban or rural morphologies, etc. It is crucial to determine the gap between consumer expectations as promised by radio regulators/operators and the actual MBB performance. This gap is very much dependent on the geographical location where the MBB performance is measured due to various aspects, such as physical impairments and channel conditions.

The aim of this study is to understand the performance of MBB services experienced by actual users in the urban morphology of Malaysia. Drive tests and data collection from five different morphologies (dense urban, urban, suburban, rural and indoor areas) have been accomplished. However, this paper only focuses on the urban morphology, while the other papers highlight the remaining morphologies. The methodology used in this paper is the same as that used in our previous papers [26], [54], but with one substantial difference: the scope of this study only focuses on the urban areas throughout Malaysia, while the previous study had focused on rural areas. The study outcomes will enable MBB service providers and radio regulators to establish plans for sustainable MBB services in Malaysia. The findings can also serve as a benchmark for other countries considering that MBB traffic is forecasted to exponentially increase in coming years. An overview is presented on the performance variability of MNOs across specific areas where data measurements have been conducted. The advantages of the deployed 4G networks in comparison to 3G are also highlighted. This helps in developing new aspects regarding the benefits of 5G and beyond networks once established. Our research assesses the performance of MBB services in Malaysia while considering the major national MNOs and their performances. The evaluation was accomplished throughout two months (January and February). Our team of researchers from Universiti Teknologi Malaysia (UTM) measured the performance of MBB services of 4G and 3G networks across four different states with urban morphology. The MBB data of web browsing and video streaming services were captured using Samsung Galaxy S6 smartphones. The performance of the MBB video-streaming service was tested with low (720p) and high (1080p) resolution videos. The performance of MBB web browsing services was also examined while accessing three different webpages: google, Instagram and mStar. The practical scenario where mobile users are unable to lock their smartphones to a particular 4G or 3G technology has been emulated. During January and February, the work encompassed the areas of four states with urban morphology: Klang Valley/Selangor, Johor, Sabah and Sarawak. The MBB measurement data for 4G and 3G networks of 3 MNOs have been collected during car test drives using similar sets of Samsung Galaxy S6 devices. The types of collected data focused on four key performance metrics: coverage, latency, satisfaction and speed.

In this research, the factors excluded due to limited datasets are the following: (i) the analysis of MBB services received at devices other than smartphones; (ii) the mobile voice and messaging services; (iii) the analysis of publicly available Wi-Fi services and (iv) the analysis of 2G networks.

The rest of this paper is organised as follows: Section II presents the system model and the related methodology used in this study. Sections III and IV outline the Key Performance Indicators (KPIs), the results of testing, the comparisons of MBB performances across different MNOs as well as the key findings of the study outcomes. Section V highlights the research limitations and future directions, and Section VI presents the conclusion of this study.

II. METHODOLOGY AND SYSTEM MODEL

A comprehensive review of the performance of 3G vs 4G networks is provided. To the best of our knowledge, no similar study that covers several urban cities in Malaysia is present. Two different mobile applications with twelve KPIs have been considered based on real measurements, drive tests and scenarios. This paper examines the performance of currently deployed 3G and 4G networks. The aim is to assess network performances based on various KPIs and the different applications utilised. This will contribute to the development of 5G networks in Malaysia, especially in areas that still face issues regarding coverage latency and data speed rate. It will encourage operators to enhance coverage, data rates and overall network performance in places struggling with bad reception. The regions that require further improvement can be successfully pinpointed during the deployment of 5G networks.

This section presents the research methodology used for collecting data and conducting this study, including the hardware and software employed, the tested geographical areas, the test processes, quality control aspects, MBB services and MNO networks of radio technologies. This methodology has been applied to various morphologies such as the rural areas of Malaysia, as presented in our previous works [26], [54]. However, the morphology type and testing areas in this research are entirely different. The results, discussions, findings and concluding remarks of this paper are far more distinctive.

In this test approach, the metrics related to user experience of MBB service applications have been measured. The methodology has been designed to obtain statistically genuine datasets that characterise each MNO fairly and transparently. The following considerations are as follows:

- The environmental and channel conditions for each MNO have been made similar by the concurrent collection of measurement data.
- User experiences have been made independent of the advancement of MNO networks and the advancement of users' smartphones with the use of identical smartphones.
- Undue contention was avoided by testing networks in parallel and ensuring that no concurrent tests were running on the same network.

Two applications from Huawei Technology have been applied for MBB data collection: MBB explorer and Speedvideo for web-browsing and video-streaming services, respectively. The use of these two applications is justified as follows:

- The actual data of MBB services, as experienced by users, can be collected using these two applications.
- They require no alternations or modifications of the smartphone software.
- The use of the two applications is very practical as it requires minimal interaction between the tester and the device. This is because testing activities can be periodically scheduled in cycles.
- Both applications have been employed in similar works in neighbouring countries of the South East Asia region, including Singapore and Thailand. This will enable us to benchmark our findings with those of nearby countries in future research.

The KPIs of web-browsing services measured by the MBB explorer application are:

- Cellular signal strength (dBm)
- Total Service Attempt (Count) and Average Page Display Success Ratio
- Average Page Download Throughput (kbps)
- Average Page Response Latency (ms)
- Average Page Display Latency (ms)
- Average of Ping RTT Delay (ms)

The KPIs of video-streaming services measured by the Speedvideo application are:

A. Cellular signal strength (dBm)
B. Total Service Attempt (Count) and Average Initial Buffering Success Ratio
C. Average Mobile vMOS Score (Scale 1 to 5; Worst = 1, Best = 5)
D. Average Video Total Download Rate (kbps)
E. Average Initial Buffering Latency (User perceived delay) (ms)
F. Average Ping RTT Delay (ms)
G. Average Total Rebuffering Latency (ms)

A. OUR TEST PROCESS

For the experimental test of web-browsing MBB services, each use cycle of the MBB explorer application includes the access of 3 different websites: Google, Instagram and mStar which have been classified as light-, medium- and heavy-sized websites, respectively. Figure 1 presents the testing methodology. Google is classified as light-sized since the testing application only accesses the homepage of the search engine. Instagram is categorised as medium-sized because it is a photo-sharing based website. mStar, which is a popular news website in Malaysia, is classified as heavy-sized since it includes texts, photos and videos.

For the experimental testing of video-streaming MBB services using the Speedvideo application, each testing cycle included YouTube video streaming of low-resolution (720p) and high-resolution (1080p). The MBB explorer can be set to run for 100 testing cycles, while Speedvideo can be set to run for any number of cycles as defined by the user.

B. QUALITY CONTROL

The MBB data collected by the two measurement applications was stored in a database for further processing. To ensure that the collected data is successfully stored, a pre-test exercise consisting of a 10-minute drive test was conducted, and the stored data was checked. The successful storing of the last MBB data measurements was also verified using the time stamps. This quality control exercise ensures that no loss of data or wasted efforts will occur during the MBB data collection.

C. TEST TYPES

In this research, the MBB data was collected through drive tests. This outdoor data collection is implemented using drive tests in cities, inter-city roads and highways. The car speed within the city and inter-city roads was set to 60 km/hour, while for highways, the speed was set to 80 km/hour.

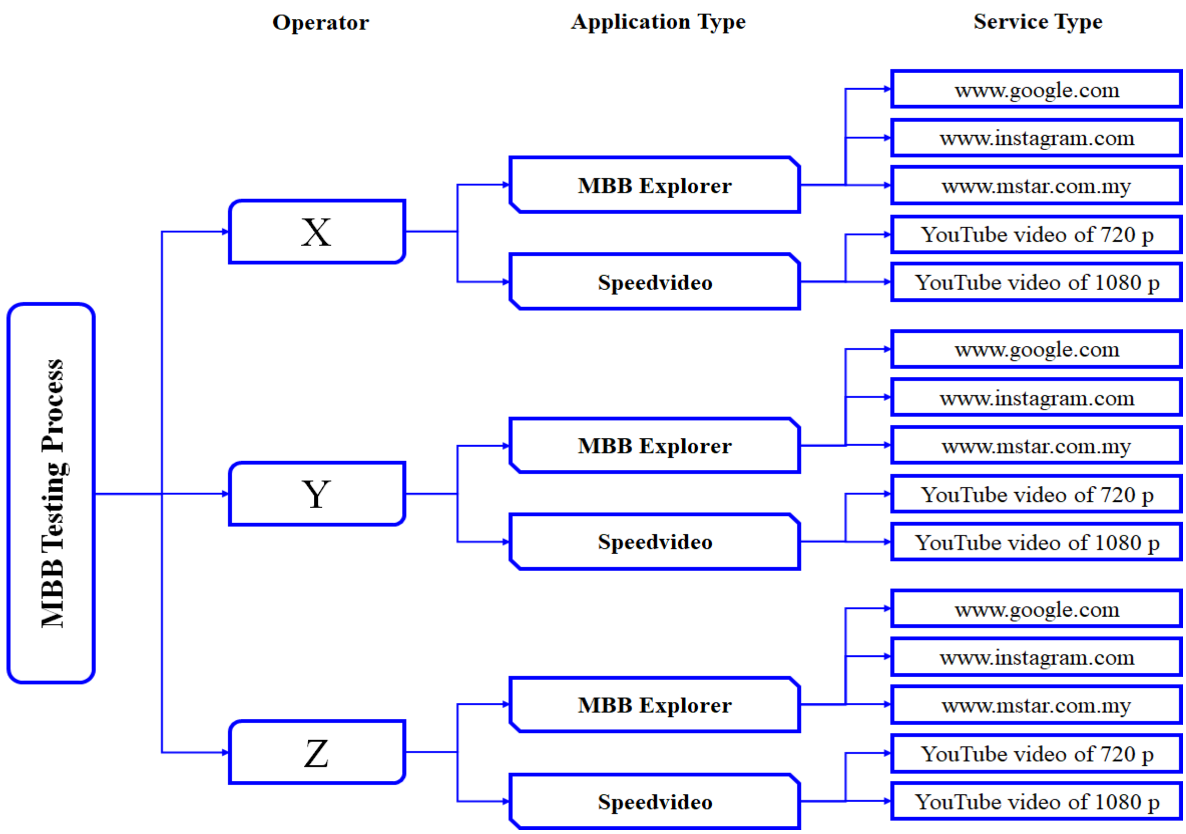


FIGURE 1. Structure of the test process employed with operators, applications and service types.

D. MNO SIM CARDS

Since solely comparing the performance of three MNOs in Malaysia is not the purpose of this study, these MNOs were coded as X, Y and Z, as illustrated in Figure 1. For each MNO, two different sim cards were purchased from official sales representatives. One was allocated to test the web-browsing MBB service, while the other was assigned to assess the video-streaming MBB service. A subscription was made to the pre-paid packages of these three MNOs.

E. TESTED LOCATIONS

The MBB test was conducted in four states of Malaysia throughout January and February. The states are Klang Valley/Selangor, Johor, Sabah and Sarawak. Two teams of researchers were assigned to conduct these intensive measurements during the scheduled periods. One team was responsible for the areas of Klang Valley/Selangor and Johor, while the other team was assigned to Sabah and Sarawak. To analyse the urban morphologies, 13 drive test areas have been organised throughout the four states. Table 1 presents the areas of the drive tests.

The GPS route measurement records of all four locations are illustrated from Figures 2 to 5. The GPS route record was captured using the GPS Trip Recorder android application that was installed on a different mobile phone. The phone with the GPS Trip Recorder recorded the route taken during the measurement, while the Samsung Galaxy 6 measured the MBB test parameters.

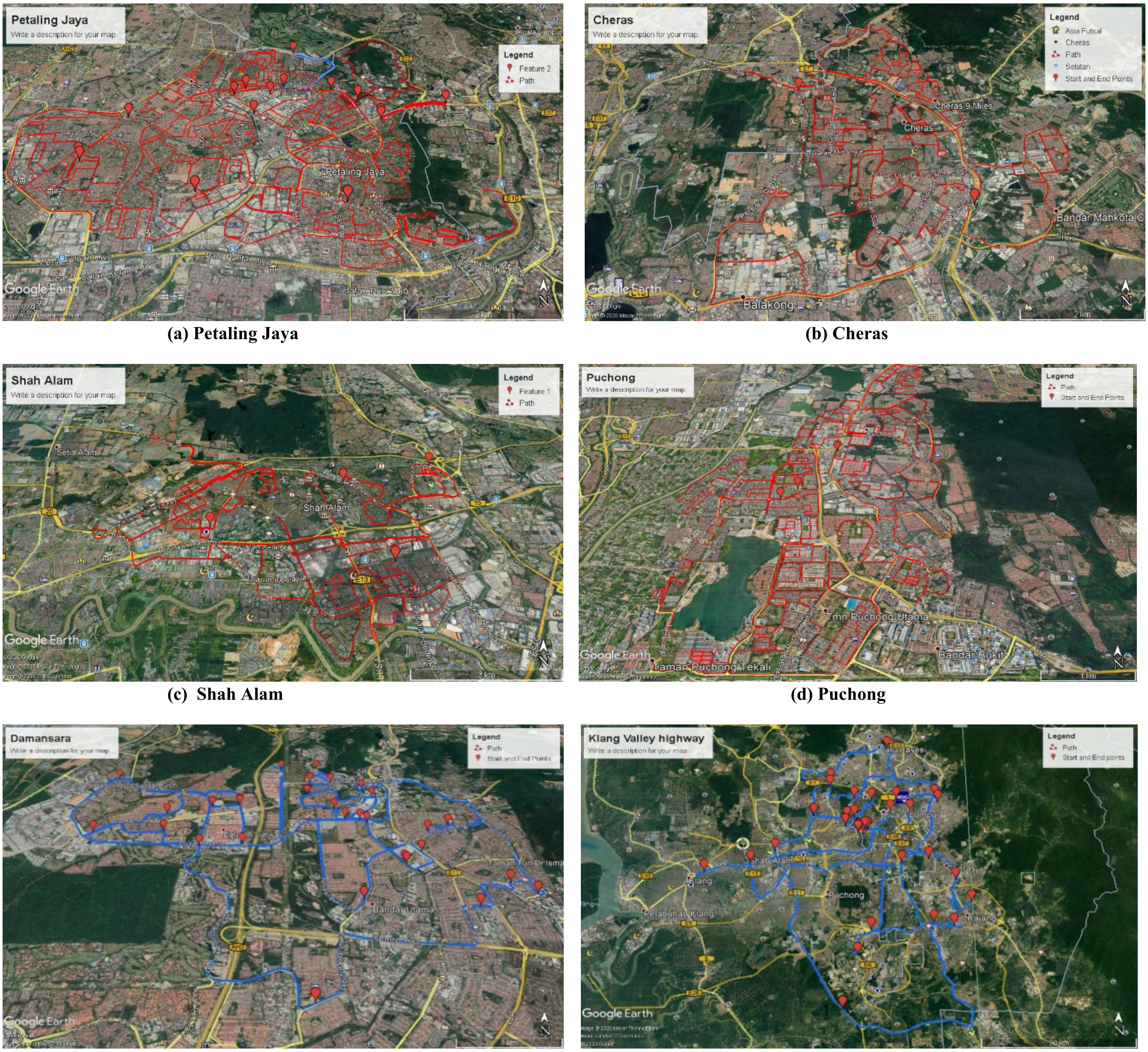
TABLE 1. Tested areas with urban morphologies.

KV and Selangor	Johor	Sarawak	Sabah
1. Petaling Jaya	1. Johor Bahru	1 Kuching	1 Kota Kinabalu
2. Cheras	2. Skudai	2 Miri	
3. Shah Alam	3. Pasir Gudang		
4. Puchong	4. Taman Johor Jaya		
5. Damansara			
6. Klang Valley highway			

III. KEY PERFORMANCE INDICATORS

The metrics related to user experience when utilising MBB services have been calculated. The methodology is designed to obtain statistically genuine datasets that characterise each MNO fairly and transparently. Therefore, the following elements have been considered:

- The environmental and channel conditions for each MNO have been made similar by the concurrent collection of measurement data.
- The users' experiences have been made independent of the advancement of MNO networks and the



(a) Petaling Jaya (b) Cheras

(c) Shah Alam (d) Puchong

(e) Damansara (f) Klang Valley highway

FIGURE 2. GPS route measurements recorded at urban areas of Klang Valley State, Malaysia.

advancement of users' smartphones with the use of identical smartphones.

- Undue contention was avoided by simultaneously testing networks and ensuring that no concurrent tests were run on the same network.

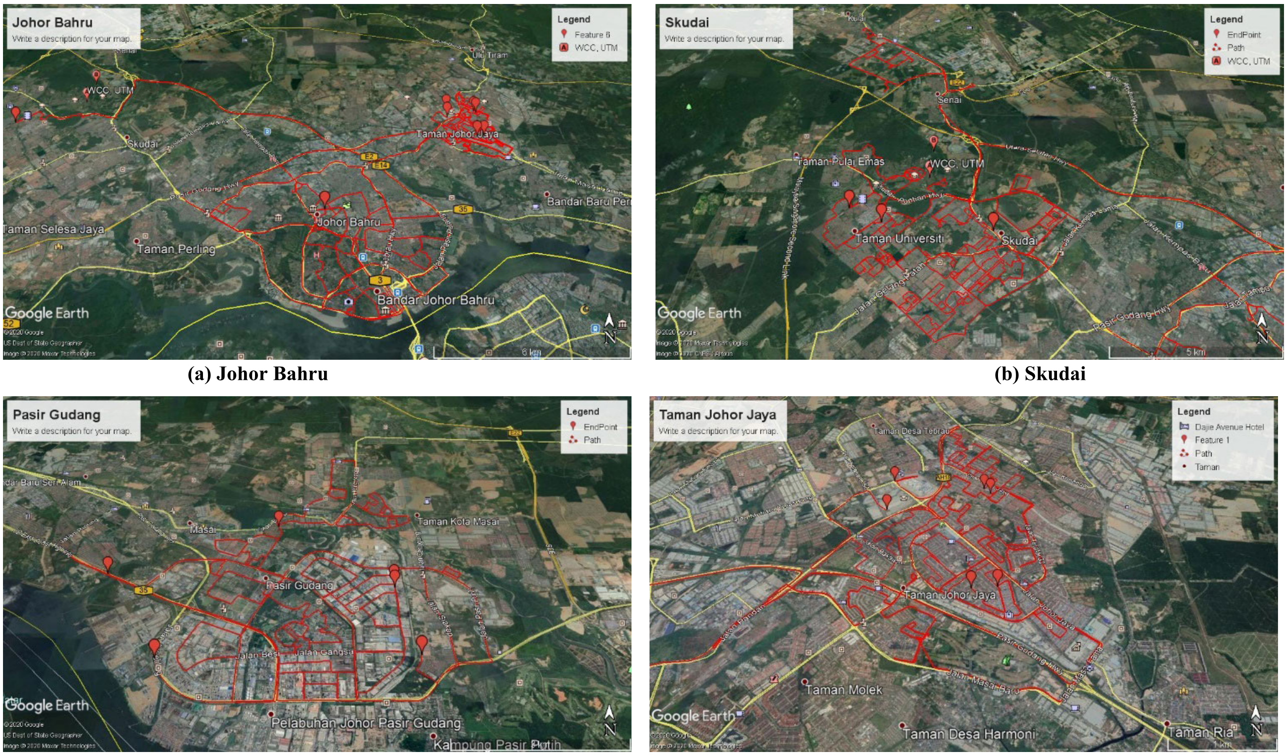
Two applications from Huawei Technology have been used for MBB data collection in this research: the MBB explorer for web-browsing and Speedvideo for video-streaming services. The use of these two applications is justified as follows:

A. The actual data of MBB services, as experienced by users, can be collected using these two applications.
B. They require no alternations or modifications of the smartphone software.
C. The use of these two applications is very practical as it requires minimal interaction between the tester and the device. This is because testing activities can be periodically scheduled in cycles.
D. Both applications have been employed in similar works in neighbouring countries of the South East Asia region, including Singapore and Thailand. This will enable us to benchmark our findings with those of nearby countries in future research.

A. KPIs OF WEB-BROWSING SERVICES

The KPIs of web-browsing services measured by the MBB explorer application are:

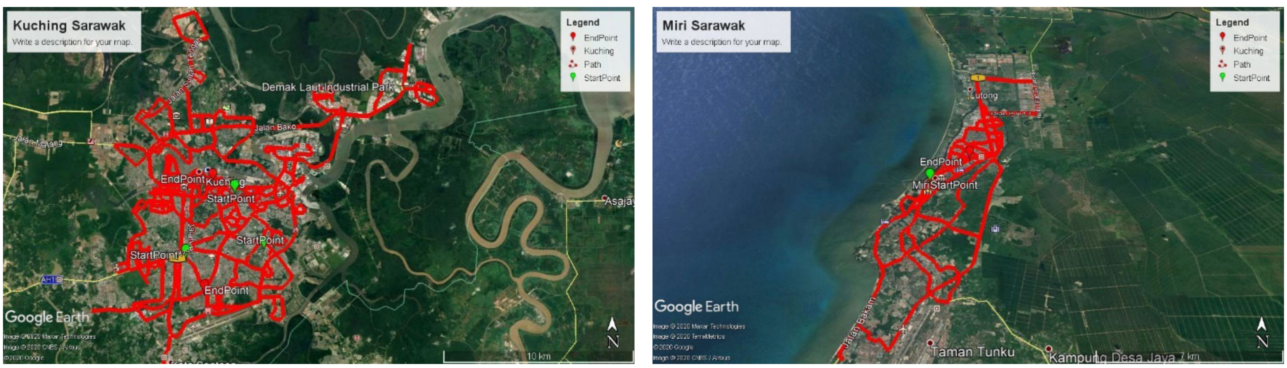
1). Cellular signal strength (dBm)



(a) Johor Bahru (b) Skudai

(c) Pasir Gudang (d) Taman Johor Jaya

FIGURE 3. GPS route measurements recorded at urban areas of Johor Bahru State, Malaysia.



(a) Kuching (b) Miri

FIGURE 4. GPS route measurements recorded at urban areas of Sarawak State, Malaysia.

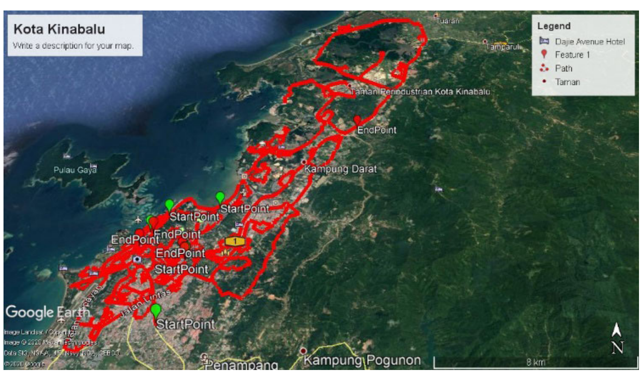


FIGURE 5. Probability Density Function (PDF) of the cellular signal strength of 4G technology web browsing for urban morphologies.

2). Total Service Attempt (Count) and Average Page Display Success Ratio
3). Average Page Download Throughput (kbps)
4). Average Page Response Latency (ms)
5). Average Page Display Latency (ms)
6). Average of Ping RTT Delay (ms)

B. KPIS OF VIDEO-STREAMING

The KPIs of video-streaming services measured by the Speedvideo application are:

1). Cellular Signal Strength (dBm)
2). Total Service Attempt (Count) and Average Initial Buffering Success Ratio

3). Average Mobile vMOS Score (Scale 1 to 5; Worst = 1; Best = 5)
4). Average Video Total Download Rate (kbps)
5). Average Initial Buffering Latency (User perceived delay) (ms)
6). Average Ping RTT Delay (ms)
7). Average Total Rebuffering Latency (ms)

This research measured the performance of MBB services using four Key Performance Indicators (KPI) that are relevant to the quality of user experiences. Various KPIs have been applied to measure web and video MBB services. In relation to user experiences, these KPIs were clustered into four main indicators: coverage, latency, satisfaction and speed. They are further described in the following subsections:

C. COVERAGE

The coverage area of a specific MNO is determined by the received signal strength at the end user. The higher the received signal strength, the better the user's experience.

D. LATENCY

Latency determines how responsive a network is since it refers to the delay of communicating data between two nodes existing in different platforms and applications. When loading a webpage from a user's device, the loading speed or browsing speed is determined by the network latency. The same applies when streaming a video. Good latency performance enhances user experience while accessing MBB services.

E. SATISFACTION

The network performance of MBB services is measured by the satisfaction of users while accessing a website or downloading a video. User satisfaction is numerically quantified by the number of successful attempts to access the network. Several factors play crucial roles in determining the performance of video services, such as the stalling and buffering times while streaming.

F. SPEED

The MBB services for browsing a website or streaming a video are influenced by the download rate or throughput of transferring data from the cloud to the user's device. After switching to 4G, several studies have stated that browsing websites is the most common exercise of end users.

IV. MBB PERFORMANCE MEASUREMENT RESULTS

The results presented in this paper are based on the time and areas at which the experimental data of MBB services have been collected. To ensure that the collected data is genuine, we performed tests to measure the performance of the same MNO at the same location using two different smartphones. The brand, model and settings of the smartphones used are all identical with no modifications. Several checks have been made to ensure that the collected data are not somehow biased.

The collected MBB data from the four states have been gathered from either 4G or 3G networks. Due to the limited presence of 2G networks in the testing areas, the data of 2G networks was excluded. The following sections present the obtained MBB data and discuss the results acquired. The first part of the results focuses on MNO performance in terms of web-browsing MBB services, while the second part focuses on MNO performance for video-streaming services.

A. WEB BROWSING EXPERIENCES

This section presents the results of the web browsing experiences that have been measured by the MBB explorer app. The following subsection presents the overall results from the KPIs of web browsing services, such as: (1) cellular signal strength, (2) total service attempt (count) and average page display success ratio, (3) average page download throughput, (4) average page response latency, (5) average page display latency and (6) average of ping RTT delay.

1) NETWORK SIGNAL COVERAGE FOR WEB

The network signal coverage is represented by the cellular signal strength. The distributions of the cellular signal strength for web services are presented in Figures 6 and 7 for 4G and 3G networks, respectively. The Y-axis represents the number of web access cycles, while the X-axis represents the cellular signal strength of web services. The number of web access - cycles is the count of cycles that the MBB explorer application is accessing the web pages of Google, Instagram and mStar. Browsing one of these webpages is counted as one web access cycle.

The results in Figure 6 indicate that the received signal power of 4G networks ranges between −120 dBm and −50 dBm in all four states. However, most of the recorded signal power values ranged between −105 dBm and −75 dBm. On the other hand, the results in Figure 7 reveal that the received signal power of 3G networks ranges between −110 dBm and −55 dBm in all four states. However, most of the recorded signal powers are between −90 dBm and −75 dBm.

The number of recorded access cycles to 4G networks is more than 3G networks. This could be due to two main reasons: the coverage provided by the 4G network is better than the 3G network, and the resources provided by 4G are more available than those of 3G in the four states considered.

Benchmarking the measured cellular signal strength (CSS) data with the –100 dBm threshold of the cell edge CSS for 4G networks [55]–[57], we found that at least 80% of the measured 4G RSL for the worst performance MNO X in Klang Valley are equal or stronger than –100 dBm. As for other MNOs and test areas, 80% of the measured CSS are stronger than −100 dBm. The best 4G coverage is achieved by MNO Z in Sarawak, where 80% of the 4G RSL are equal to or stronger

TABLE 2. Summary of the minimum value of CSS levels for 3G and 4G technologies with 80% coverage in tested areas found to be stronger than or equal to the presented minimum cellular signal strength values.

MNO	NETWORK TYPE	AREA			
		KLANG VALLEY	JOHOR	SABAH	SARAWAK
X	4G	-100 dBm	-97 dBm	-93 dBm	-91 dBm
	3G	-100 dBm	-89 dBm	-89 dBm	-85 dBm
Y	4G	-98 dBm	-98 dBm	-96 dBm	-94 dBm
	3G	-89 dBm	-93 dBm	-95 dBm	-91 dBm
Z	4G	-95 dBm	-96 dBm	-91 dBm	-90 dBm
	3G	-91 dBm	-91 dBm	-99 dBm	-91 dBm

Note: The highest mean dBm level is the best

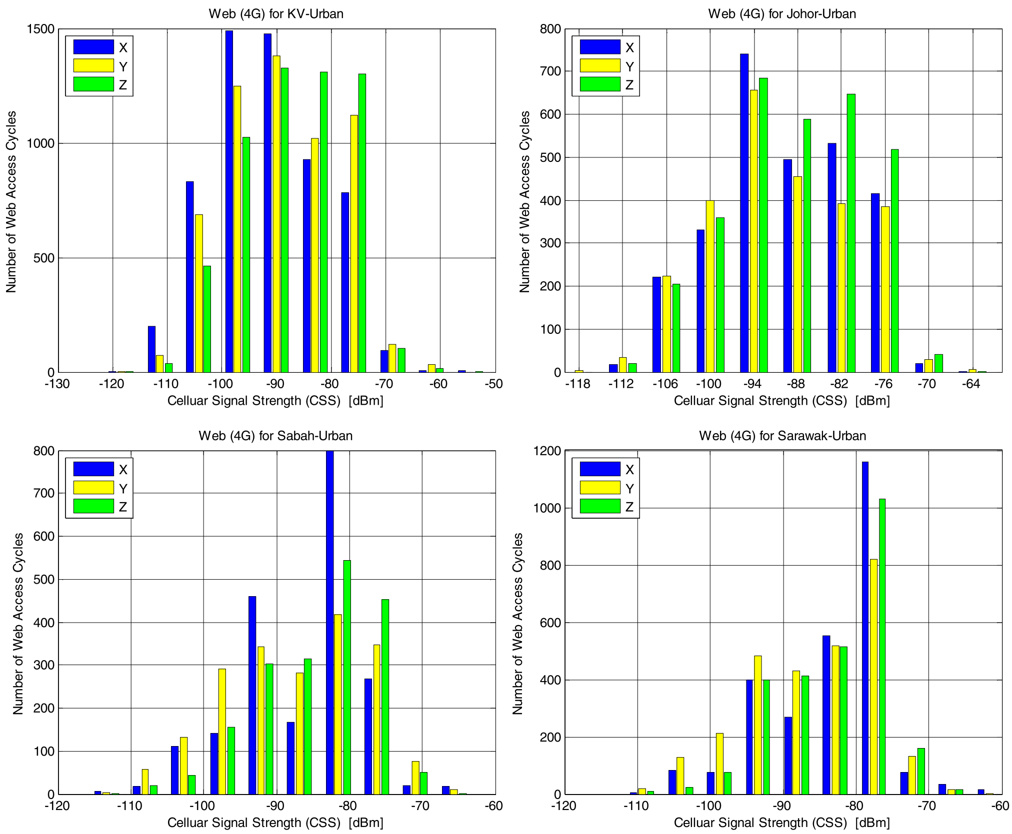


FIGURE 6. PDF of the cellular signal strength of 3G technology web browsing for urban morphologies.

than –90 dBm. Table 2 summarises the minimum values of CSS levels for 3G and 4G technologies where 80% of the coverage in the tested areas are stronger than or equal to the presented minimum cellular signal strength values. The outcomes are separately presented for each operator. The results indicate that some operators offer better services than others, but the differences are insignificant. The most substantial conclusion to be drawn from these results is that 4G networks provide better coverage compared to 3G networks. This is because the deployment of 4G networks in the considered urban areas is relatively higher than the deployment of 3G networks. This signifies that 4G has become the dominant network in the studied areas.

2) NETWORK SATISFACTION FOR WEB

This section presents the total number of web access attempts and the overall page display success ratio. The total number of web access attempts is the overall number of counted cycles for browsing websites. Heading towards the maximum total number of web access attempts indicates good mobile connection for the specified serving network. The overall page display success ratio is the ratio of the number of pages displayed successfully to the total number of mobile web access attempts. The total web access attempts should not necessarily be the same for 3G and 4G networks, it is more dependent on the network availability and to which network the mobile is connected.

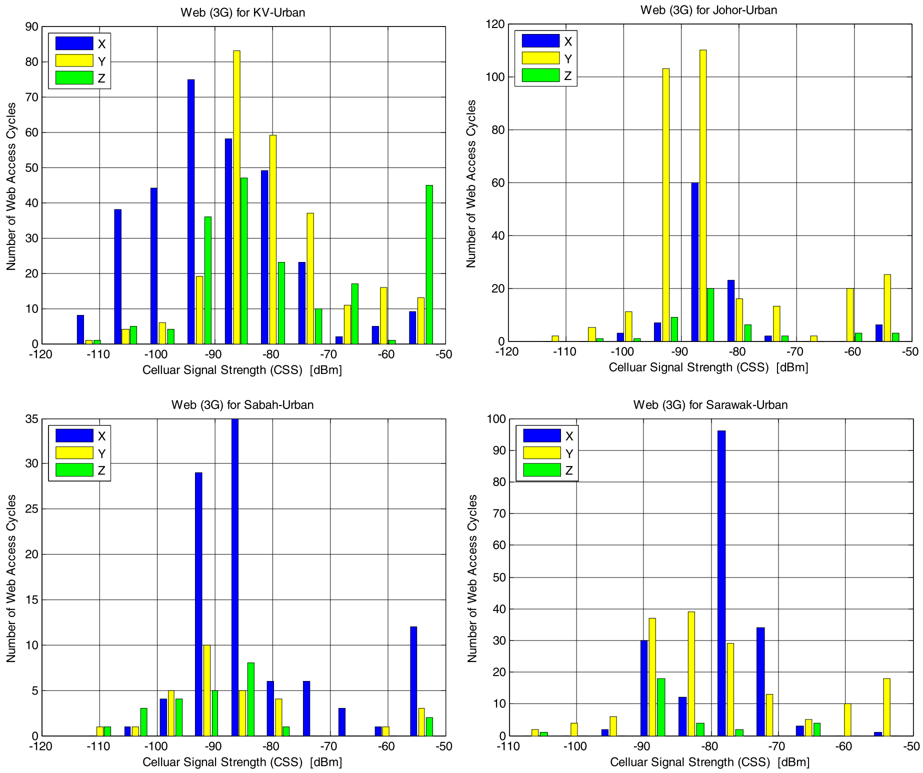


FIGURE 7. GPS route measurements recorded at urban areas of Sabah State, Malaysia.

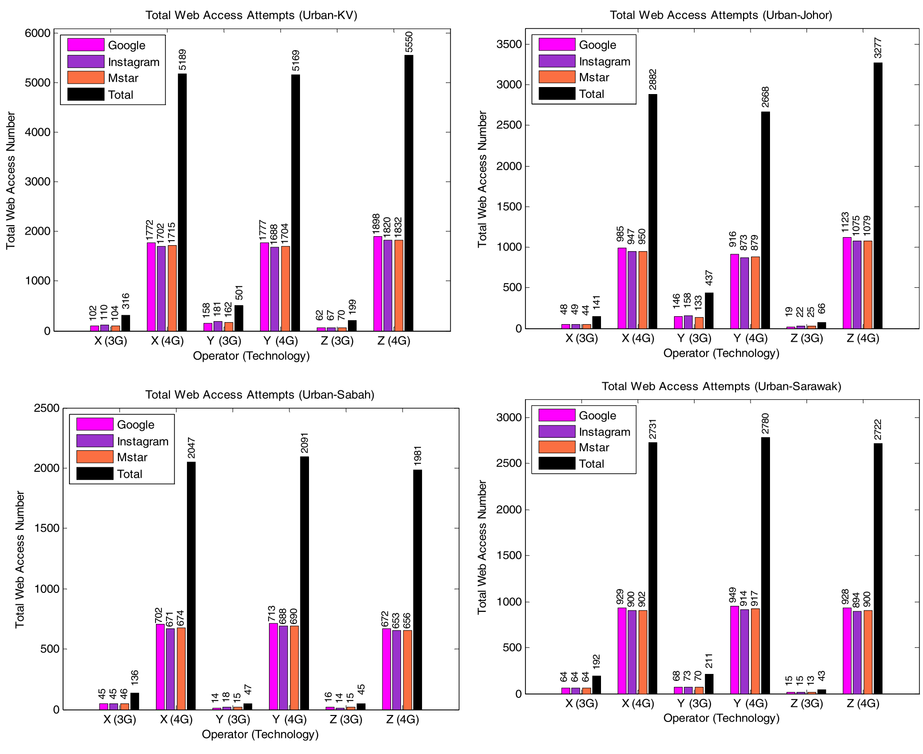


FIGURE 8. The total web access attempts classified based on network, MNOs and locations.

Figure 8 presents the total number of attempts for accessing web services using the selected smartphones during the drive test experiments. The results reveal that 4G technologies are prominently utilised to access the internet for web services with 94.1%, 93.2%, 96.4% and 94.8% for Klang Valley, Johor, Sabah and Sarawak, respectively. Figure 8 also confirms that among the three webpages, the performance of accessing Google is better for all locations when using 4G

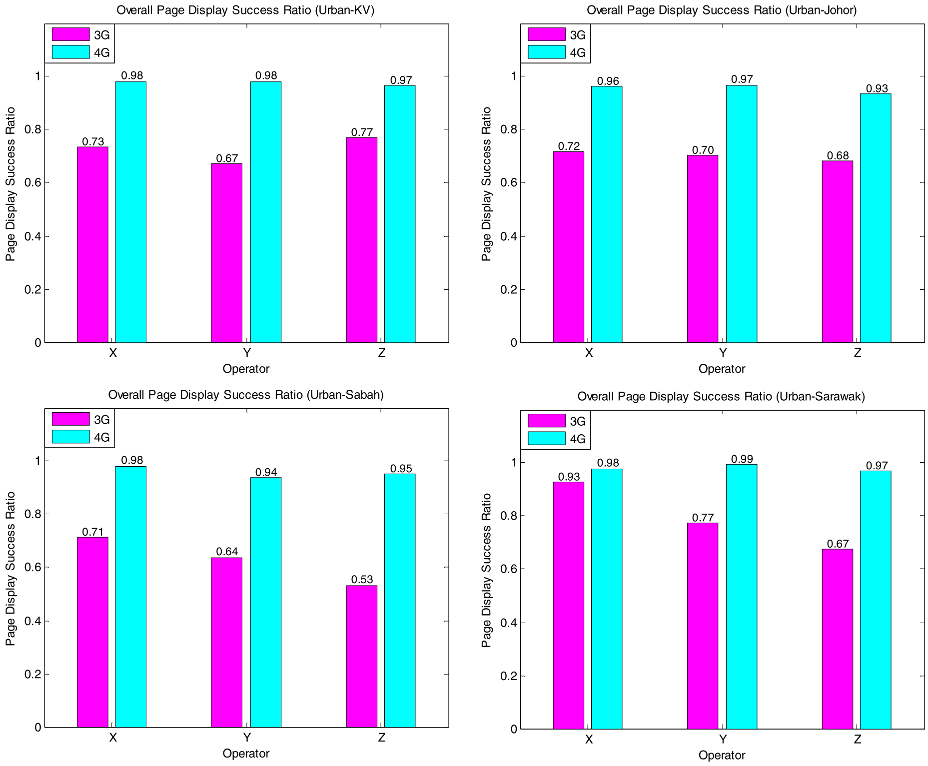


FIGURE 9. The overall page display success ratio for urban morphologies of each state.

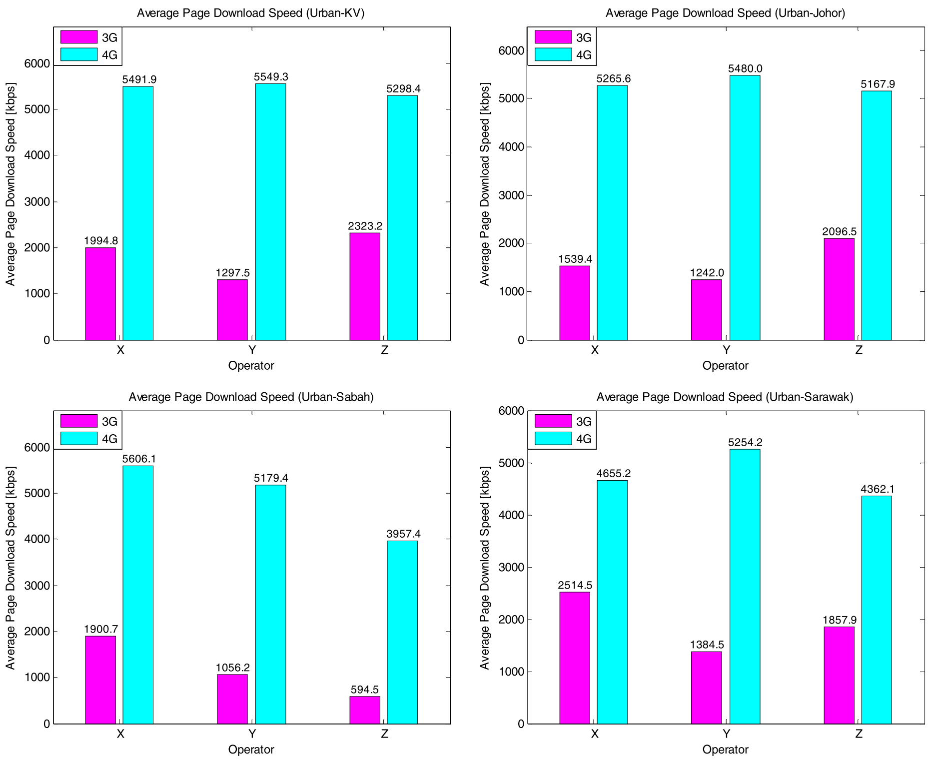


FIGURE 10. The average page download speed categorised according to network and test locations.

technology. It is clear that the performance of 3G networks is insufficient for accessing webpages at the selected urban areas throughout Malaysia.

Figure 9 presents the results of the overall page display success ratios for each 3G/4G technology and MNO. The page display success ratio is the ratio of the successful display

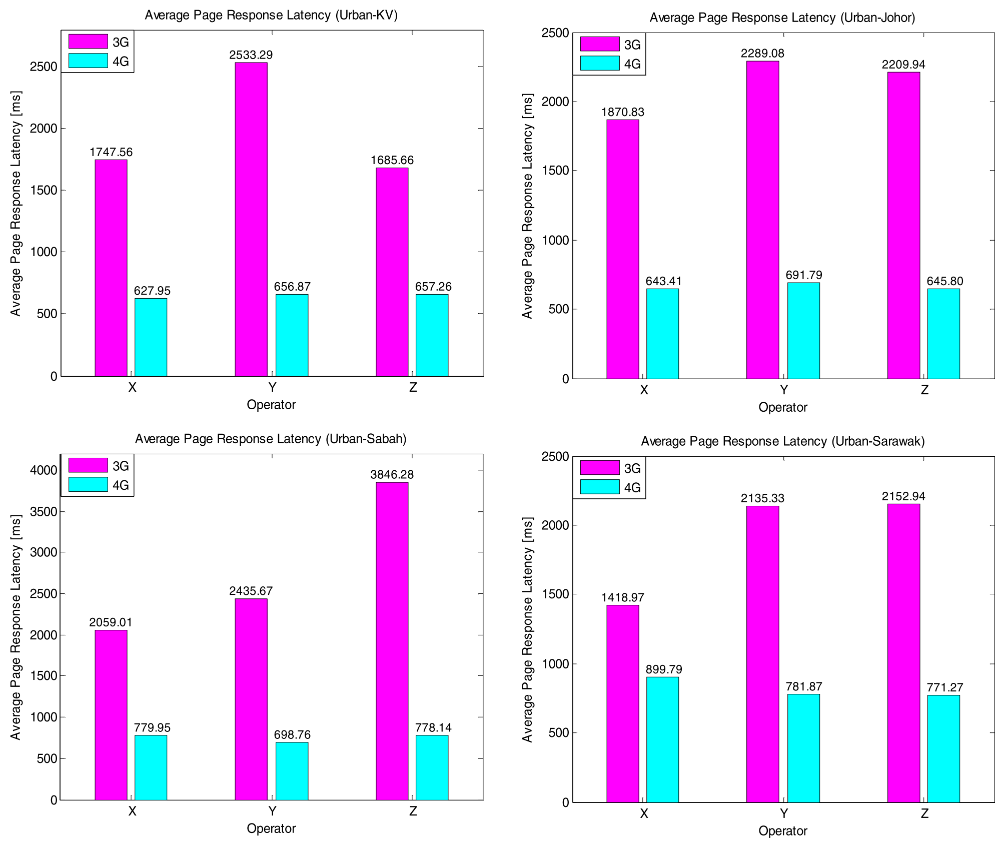


FIGURE 11. **The average of web page response latency for urban morphology.**

of web pages throughout the total number of web access attempts. The two figures highlight the success scenario and implicitly indicate the ratio of failed attempts as well. The failed attempts ratio is the decreased ratio from the success ratio. If the success ratio is 0.98% and the failed attempts ratio is 0.02%, this is a good indication that the network's Quality of Service (QoS) is satisfactory. The experimental results signify that the network performance of 4G using this metric is far better than 3G for the types of MNOs considered in this study. This is expected due to the distinctive features of 4G technology in terms of throughput and latency, as shown in the following sections.

3) NETWORK DOWNLOAD SPEED FOR WEB

In Figure 10, the experimental results of the average page download throughputs of web services are presented for all states, networks and MNOs. Based on these results, the state of Sabah appears to have the highest web browsing speed using 4G as compared to 3G. Overall, the 4G web download speed improves by 2.5, 2.9, 3.2 and 4.2 times in contrast to the web download speed of 3G in Sarawak, Klang Valley, Johor and Sabah, respectively. These outcomes indicate that the practical download speed is lower than the theoretical LTE download speed. The obtained practical download speed does not exceed 5.7 Mbps, while the maximum theoretical LTE for mobile users is 100 Mbps. The total cell load traffic is the main factor for obtaining this practical result. The increase of users in the cell will lead to a linear reduction in the number of resources within the cell.

4) NETWORK LATENCY FOR WEB

This section presents the results derived from three types of network latencies. The first network latency is known as the average/mean webpage response latency, the second is the average webpage display latency and the third is the average of webpage ping average RTT. The different types of latencies are presented in Figures 11, 12 and 13, respectively, and discussed in the following paragraphs.

Figure 11 displays the average webpage response latency for the urban morphology of four different states of Malaysia. Throughout all states examined in this study, the average webpage response latency over all MNOs for 4G scored 647.4 ms, 660.3 ms, 752.28 ms and 817.64 ms for Klang Valley, Johor, Sabah and Sarawak, respectively, while they were found to be quite longer with 1988.8 ms, 2123.3 ms, 2780.32 ms and 1902.4 ms for 3G, respectively. The total average of webpage response latency across all tested regions is 719.405 ms for the 4G network and 2198.705 ms for the 3G network. The results indicate that the 4G network offers lower latency than the 3G network in these areas.

Figure 12 presents the average webpage display latency of all 3G and 4G operators across the testing areas. The results

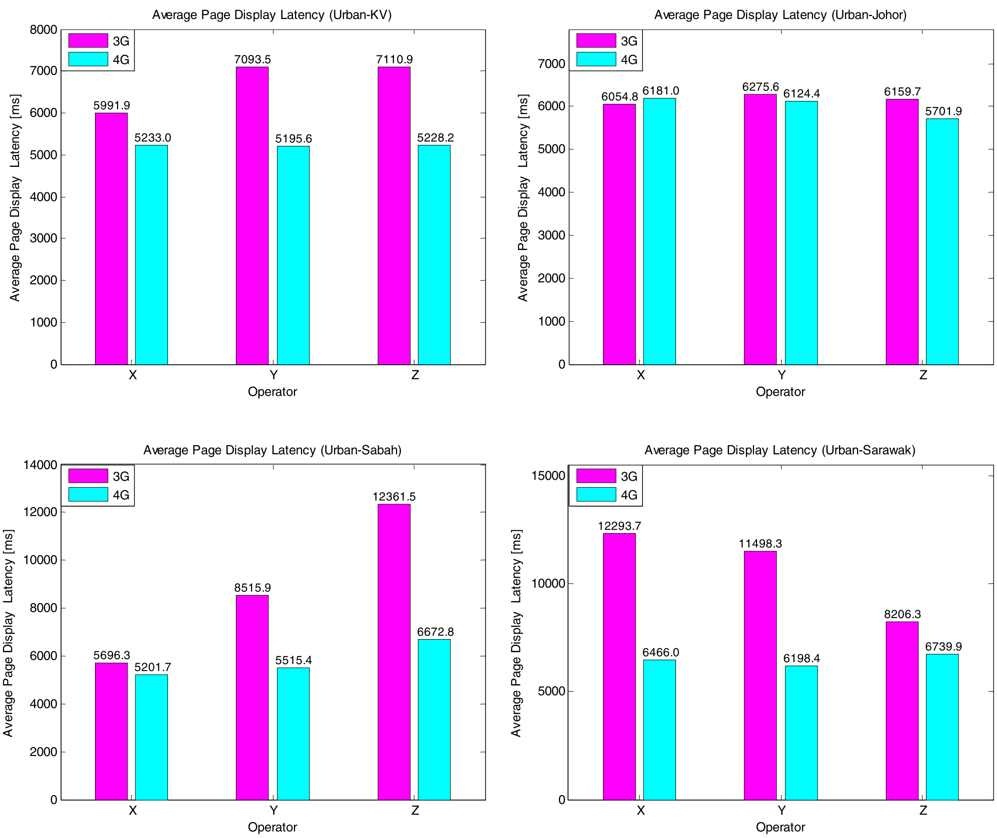


FIGURE 12. **The average of web page display latency for urban morphology.**

reveal that 4G networks are superior to 3G networks since the former provides lower average webpage display latency, except in the case of operator X in Johor. Alternatively, the 3G network of operator X achieved much lower latency compared to the other operators for all testing areas, except for Sarawak.

Throughout all states examined in this study, the average webpage display latency for 4G scored 5218.9 ms, 6002.3 ms, 5796.6 ms and 6468.1 ms for Klang Valley, Johor, Sabah and Sarawak, respectively, while they were found to once again be longer with 6732.1 ms, 6163.4 ms, 8857.9 ms and 10666.1 ms for 3G, respectively.

Figure 13 displays the average ping average RTT latency for all testing areas. This figure refers to the delay of a 2-way journey of a packet between the source and the destination. This performance metric estimates the latency based on a ping. According to results, the 4G networks exhibited lower average of webpage ping average RTT than 3G networks. Throughout all testing areas and taking the average performance of all networks of MNOs considered in this study, the webpage ping latencies over 4G were found to be 48.9 ms, 57.8 ms, 80.8 ms, and 75.0 ms, while they were longer for 3G with 99.8 ms, 97.3 ms, 195.7 ms and 108.7 ms for Klang Valley, Johor, Sabah and Sarawak, respectively. The total average RTT latencies over 4G for operators X, Y and Z are 71.08 ms, 59.05 ms and 62.18 ms, respectively.

It can be seen that the average latency of the page response, page display and RTT for all 4G operators is almost at the same latency levels for each testing area compared to those of 3G. This finding is justified since all operators in these areas have similar infrastructures of 4G networks, leading to low latency for page responses. The 4G networks exhibit superior and consistent performance across all testing areas in comparison to 3G.

5) SUMMARY OF WEB SERVICE RESULTS

Table 3 provides a brief summary of web service results for the urban morphology. The outcomes are classified according to various MNOs. The presented results in the first, second and third sub-tables are for the three different operators X, Y and Z, respectively. In each sub-table, the results for six different KPIs and for four different states are presented. Table 3 provides a clear comparison between 3G and 4G networks. Firstly, the measurement results have been vertically compared across different operators for the same KPIs, state and technology using the green and yellow cells, as per the legend of the table.

For 3G, operator Z exhibited better overall performance for web services in Klang Valley as compared to the other two operators, Y and X. The 3G performance of operator X is the best in 3 states, namely, Sabah, Johor and Sarawak. The overall 3G performance of operator Y is inferior compared to

TABLE 3. Summary of web services for urban morphology classified according to MNOs.

LEGEND:

(green)	The best value among the 3 operators for the same state, technology and KPI	**Bold blue font colour**	The best value for 3G technology among the 4 states for the same operator and KPI
(yellow)	The same value achieved by two or more operators for the same state, technology and KPI	**Bold red font colour**	The best value for 4G Technology among the 4 states for the same operator and KPI

Morphology: Urban	Operator X				MBB service WEB			
KPI	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Overall page Display Success Ratio [Higher is better]	0.73	**0.98**	0.72	0.96	0.71	**0.98**	**0.93**	**0.98**
Average Page Response Latency (ms) [Lower is better]	1747.6	**627.9**	1870.8	643.4	2059	780	**1419**	899.8
Average Page Display Latency (ms) [Lower is better]	5991.9	5233	6054.8	6181	**5696.3**	**5201.7**	12293.7	6446
Average Page Download speed (kbps) [Higher is better]	1994.8	5491.9	1593.4	5265.6	1900.7	**5606.1**	**2514.5**	4655.2
Average Ping Average RTT (MS) [Lower is better]	**84.1**	**51**	99.8	56.9	134.2	86.8	106	89.5
Average Cellular Signal Strength (dBm) [Higher is better]	-95	-92	-83.7	-89.1	-85.7	**-81.6**	**-78.4**	-83.3

Morphology: Urban	Operator: Y				MBB service WEB			
	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Overall page Display Success Ratio [Higher is better]	0.67	0.98	0.7	0.97	0.64	0.94	**0.77**	**0.99**
Average Page Response Latency (ms) [Lower is better]	2533.3	**656.9**	2289.1	691.8	2435.7	698.8	**2135.3**	781.9
Average Page Display Latency (ms) [Lower is better]	7093.5	**5195.6**	6275.6	6124.4	8515.9	5515.4	**1498.3**	6198.4
Average Page Download speed (kbps) [Higher is better]	1297.5	**5549.3**	1242	5480	1056.2	5179.4	**1384.5**	5254.2
Average Ping Average RTT (ms) [Lower is better]	131.6	**47.7**	133.7	54.4	199.4	67.8	**129.3**	66.3
Average Cellular Signal Strength (dBm) [Higher is better]	-79	-89	-83.7	-89.9	-84.8	-87.2	**-78.9**	**-85.8**

Morphology: Urban	Operator: Z				MBB service WEB			
	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Overall page Display Success Ratio [Higher is better]	**0.77**	**0.97**	0.68	0.93	0.53	0.95	0.67	**0.97**
Average Page Response Latency (ms) [Lower is better]	**1685.7**	657.3	2210	**645.8**	3846.3	778.1	2152.9	771.3
Average Page Display Latency (ms) [Lower is better]	7110.9	**5228.2**	**6159.7**	5710	12361.5	6672.8	8206.3	6739.9
Average Page Download speed (kbps) [Higher is better]	**2323.2**	**5898.4**	2096.5	5167.9	594.5	3957.4	1857.9	4362.1
Average Ping Average RTT (MS) [Lower is better]	83.6	48	**58.4**	**44.1**	253.7	87.7	90.8	68.9
Average Cellular Signal Strength (dBm) [Higher is better]	**-79**	-89	-82	-88.2	-86.5	-84.9	-79.6	**-83.2**

the other operators. In contrast, the 4G performance of operator Y is superior compared to the performances of the other operators in Klang Valley and Sarawak. This indicates that the management of operator Y prioritises the performance of its 4G over its 3G network. Operator Z exhibited better overall performance in Johor, while operator X is better in Sabah. Overall, operator X has shown better performance for both 3G and 4G technologies in comparison with the other operators.

Secondly, the measurement results have been horizontally compared across different states for the same operators, KPIs and technology using the bold blue and red font colours, as per the legend of the table. For 3G web services, operator

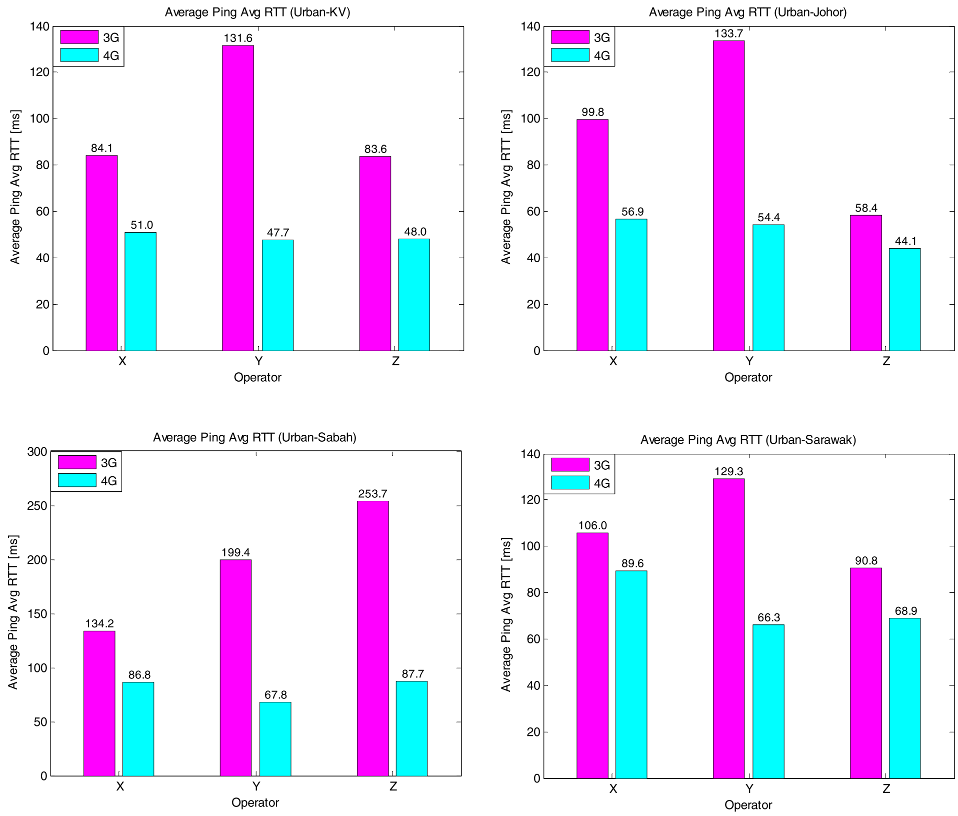


FIGURE 13. **The average of web ping average RTT for urban morphology of each test area categorised by MNOs.**

X displayed better performance in Sarawak than in other states. For 4G web services, operator X performed better in Sabah than in the other three states. For operator Y, the 3G performance is best in Sarawak, while its 4G performance is best in Klang Valley. The 3G and 4G performances of web services for operator Z are both better in Klang Valley than their counterparts in all other states. For operator Z, the second-best performance of 3G and 4G web services have been observed in Johor.

Overall, the performance of 4G services is better than 3G services for the three network operators throughout all four states and under all KPIs, except for the average cellular signal strength. This indicates that the coverage areas of 4G networks must be extended to provide better signal strength for web services. Overall, there is no absolute winner among the three service providers across all KPIs, networks and states.

The presented results of the sub-tables signify that 4G networks achieve remarkable performance compared to 3G networks for all testing areas.

B. VIDEO STREAMING EXPERIENCE

This section presents the findings of the video streaming experience measured by the Speedvideo application. The KPI results for video streaming services measured by the Speedvideo application are also discussed in this section, including: (1) the cellular signal strength, (2) the total service attempt (count) and average initial buffering success ratio, (3) the average mobile vMOS score, (4) the average video total download rate, (5) the average initial buffering latency (user perceived delay), (6) the average of average ping RTT delay and (7) the average total re-buffering latency.

1) NETWORK SIGNAL COVERAGE FOR VIDEO

This section highlights the signal coverage of networks based on the video streaming experience. The network signal coverage is represented in terms of cellular signal strength. Figures 14 and 15 with Table 4 show the cellular signal strength distributions of 4G and 3G networks for video services, respectively. For the 4G technology, the presented results in Figure 14 indicates that the network operator Z presented better performance compared to operators X and Y for all locations except for Sabah. For the 3G technology, the network operator Y exhibited better performance for all four sites. Comparing the results of Figures 14 and 15, the network signal coverage for 4G technology is better than 3G technology for all three operators at Johor, Sabah, Sarawak and Klang Valley. Due to the dense urbanity of Klang Valley, the highest 4G coverage is around 99%. The number of video cycles is also different for 4G networks compared to 3G. This is because the deployment of both networks in the tested area is not the same. The user connects to a specific network and handover between cells is automatically performed based on network availability in that particular region.

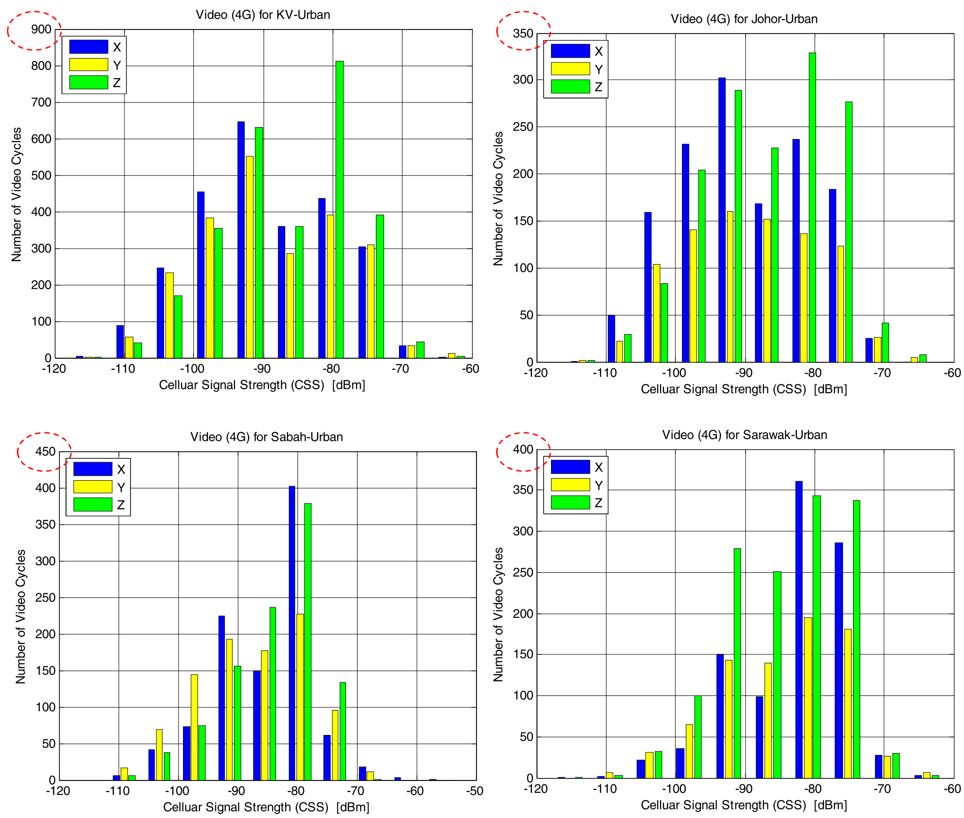


FIGURE 14. PDF of the cellular signal strength of 4G technology video streaming for urban morphologies.

TABLE 4. Summary of the minimum value of CSS levels for 3G and 4G technologies where 80% of coverage in tested areas are stronger than or equal to the presented minimum cellular signal strength values [Higher dBm is better].

MNO	NETWORK TYPE	AREA			
		KLANG VALLEY	JOHOR	SABAH	SARAWAK
X	4G	-97 dBm	-98 dBm	-92 dBm	-90 dBm
	3G	-99 dBm	-85 dBm	-91 dBm	-85 dBm
Y	4G	-97 dBm	-97 dBm	-95 dBm	-93 dBm
	3G	-89 dBm	-89 dBm	-91 dBm	-87 dBm
Z	4G	-95 dBm	-95 dBm	-91 dBm	-91 dBm
	3G	-89 dBm	-85 dBm	-91 dBm	-85 dBm

Although real measurement data demonstrates the superior performance of 4G networks, 3G networks are also very important since they offer complementary support to 4G networks. 3G networks act as a bridge between major 4G coverage areas, providing backbone coverage in areas with less population density.

The results in Figure 14 show that the received signal power of 4G networks ranges between −115 dBm and −65 dBm in all four states. However, most of the recorded signal power is distributed between −105 dBm and −70 dBm. The results in Figure 15 reveal that the received signal power of 3G networks ranges between −115 dBm and −30 dBm in all four states. However, most of the recorded signal power is distributed between −100 dBm and −65 dBm. In addition to the received signal power, the number of recorded access cycles to 4G networks is double that of 3G networks. If we compare the number of access cycles for 4G networks, we see that Klang Valley scored the highest from the other areas. If we compare the number of access cycles for 3G networks, Johor scored the highest from the other three sites.

2) NETWORK SATISFACTION FOR VIDEO

This section presents the total video access attempts and overall video access ratio for urban morphologies throughout the four states considered in this study. The total number of video access attempts is the entire number of counted cycles attempts for watching videos streams. The overall

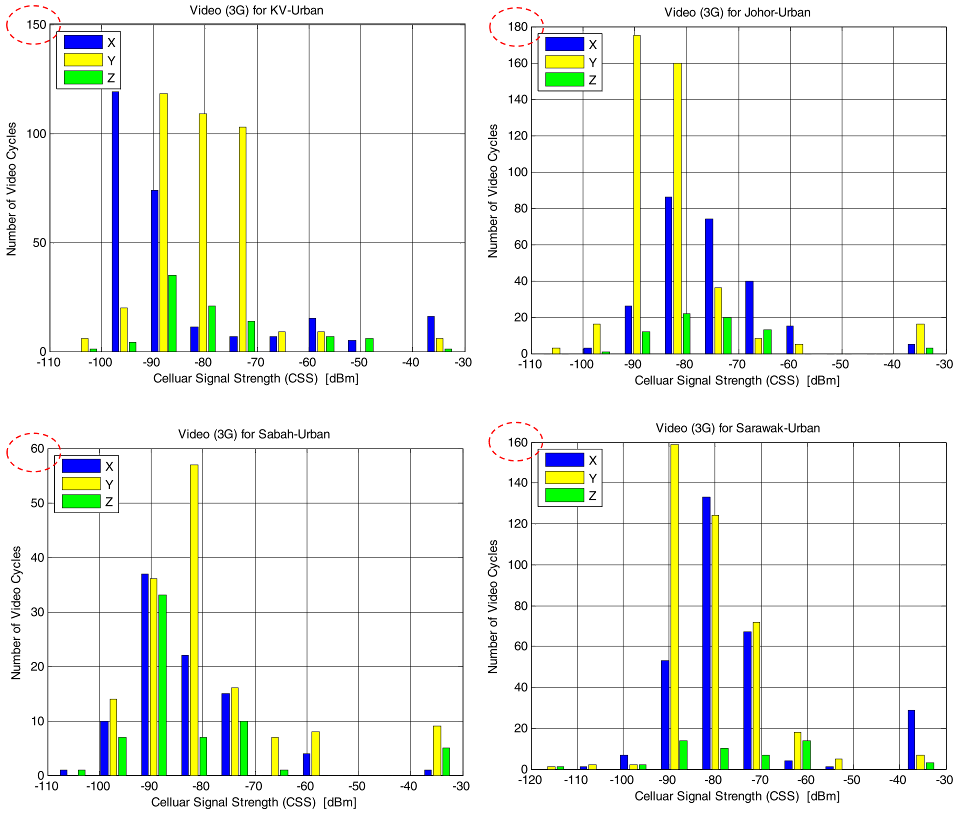


FIGURE 15. **PDF of the cellular signal strength of 3G technology video streaming for urban morphologies.**

video access ratio is the ratio of the overall videos watched successfully to the total mobile video access attempts. This KPI resembles the general page display success ratio of web-page browsing.

Figure 16 presents the number of attempts for accessing video service using the Samsung Galaxy S6 during the experimental drive tests. Our video streaming attempt reveals that the smartphones access the internet via 4G technology for video services with 90.3%, 82.3%, 90% and 79.7% for Klang Valley, Johor, Sabah and Sarawak, respectively. These results indicate that the number of attempts of 4G networks is more than the attempts of 3G networks. This may be due to the wide deployment and resource availability of 4G networks.

Figure 17 displays the overall video access ratio for urban morphologies in each state. The video access ratio ranges between zero and one (0, 1). When the ratio increases to one, the overall video access ratio is higher, and the failure ratio is lower. The results in Figure 17 reveal that the overall video access ratios for 3G networks in all locations and across all operators range between 0.85 and 0.986, while those of 4G networks range between 0.998 and 1. The outcomes prove that 4G networks have better video access ratios than 3G networks across all cites and MNOs considered in this work.

3) AVERAGE MOBILE VMOS SCORE

The vMOS metric, developed by HUAWEI, is another KPI applied in this study to measure video quality. This KPI is a good indicator for demonstrating video performance. Figure 18 displays the vMOS scores of network performances for all categorised MNOs based on technology. The results are separately presented for each testing state. For the urban morphology, 4G networks have higher vMOS scores for all three MNOs compared to 3G networks. 4G networks have a vMOS score of more than 3.39, while 3G networks have scores ranging between 1.43 to 2.79. This is justified by the better and wider coverage provided by 4G networks; thus, more resources are available compared to 3G networks.

4) NETWORK DOWNLOAD SPEED FOR VIDEO

Each mobile technology has different download speeds for the mobile internet. The download speed refers to the data rate that can be transferred from the source to the mobile device. The transmitted data can be a web page, a video or an application. In our measurement campaign, video services have been considered to measure the download speeds of 3G and 4G operators in four different regions. Figure 19 displays the average total of the video download rate for all 4 testing sites. The average total for 4G video download rate is about 1.29, 1.34, 1.14 and 1.24 times faster than the rate provided by 3G for Klang Valley, Johor, Sabah and Sarawak, respectively. Faster download rates entail shorter waiting time for downloading a content from the internet. 4G technology provides higher video streaming quality without buffering or interruptions compared to 3G technology. In some cases,

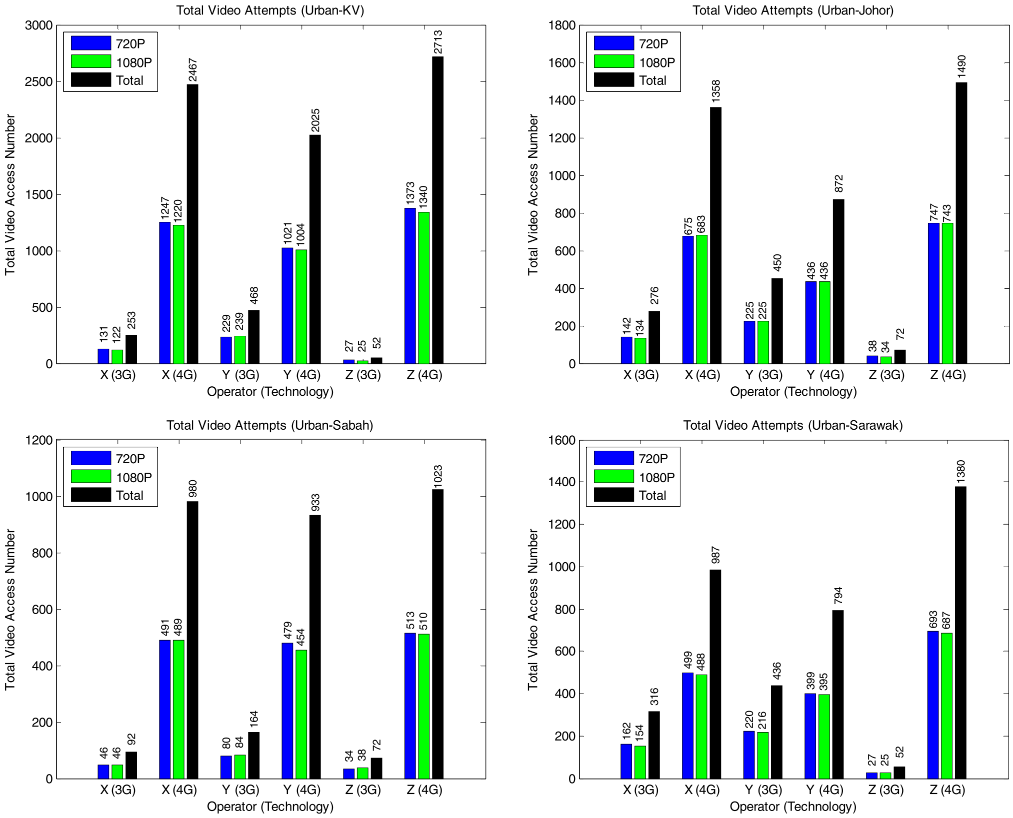


FIGURE 16. **The total video access attempts classified based on network, MNOs and locations.**

4G technology does not perform adequately due to imperfect coverage or site congestion, as shown in Figure 19 (e.g., operator Y in Sabah).

This is also related to the latency concept discussed in the previous section which affects internet responsiveness. The average download speeds for 4G operators X, Y and Z throughout all four testing sites are 1.86 Mbps, 1.94 Mbps and 1.83 Mbps, respectively. For 3G operators, they are 1.48 Mbps, 1.53 Mbps, and 1.49 Mbps, respectively. The overall results have shown a slight improvement in download speeds achieved by 4G operators. The download speed does not affect the amount of data consumed by the mobile user since the download video size is the same size. Thus, some video service providers, such as Netflix and YouTube, adjust the video quality in accordance with the type of serving technology (3G/4G). For instance, the video quality of standard definition and high definition is adjusted based on 3G and 4G connections, respectively. This leads to an increase in the amount of consumed data as the mobile user moves to a faster internet connection.

5) NETWORK LATENCY FOR VIDEO

The network latency is yet another important indicator that affects user experiences. The network latency refers to the response delay of an initial server when a mobile user begins to download some contents from the internet. The content begins to download once the server responds. The network latency generally refers to the initial buffering latency, initial End-To-End (E2E) RTT-Ping server latency and re-buffering latency. These three latency types are discussed accordingly. The average of the initial video buffering latency is presented in Figure 20. The average of the initial video E2E RTT-Ping server latency is presented in Figure 21, while the average of the total video re-buffering latency is presented in Figure 22.

Figure 20 displays the average of the initial video buffering latency for different operators and testing regions. Significant performance enhancements have been observed in the average initial buffering latencies for 4G compared to 3G for all three MNOs considered in this study. This has also been observed after acquiring the average latency performance of all three networks. The average latencies for 4G are 1314.5 ms, 1481.4 ms, 1631.4 ms and 1545.6 ms for Klang Valley, Johor, Sabah and Sarawak, respectively; while they are 8974.4 ms, 9213.1 ms, 9466.5 ms and 7046.8 ms for 3G, respectively. The lowest network latency was recorded in Klang Valley across all 4G operators compared to all other regions. The highest and lowest network latencies in 3G technology were recorded in Johor and Sabah, respectively, for operator X. This proves that 3G technology has a long response delay compared to 4G. High network latency causes interruptions when downloading videos, thus affecting user experience. Several applications that support and require real-time connections are also affected, such as gaming

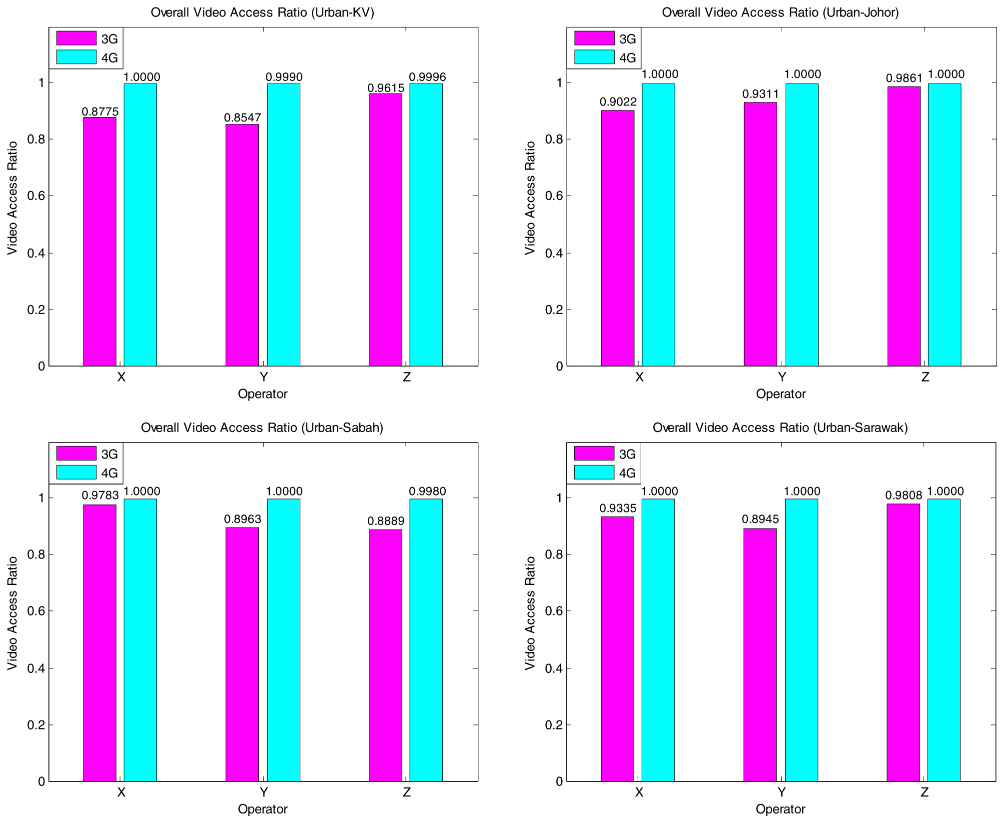


FIGURE 17. **The overall video access ratio for urban morphologies of each state.**

applications and video calling. The total average of video response latency across all testing regions for 4G operators X, Y, and Z are 1,500 ms, 1,393 ms and 1,662 ms, respectively, while they are 9,426.9 ms, 8,882 ms and 7,708.7 ms for 3G operators, respectively.

On average, operator Y has the lowest latency on the 4G network, while operator Z has the lowest latency on the 3G network. The 4G network has 82% better latency than the 3G network. When a long duration is needed for sending data to a specific destination across a network, this indicates that the network connection has high latency which results in decreased bandwidth (as well as throughput). Therefore, not much data can be sent. Although the bandwidth will not always be affected by the latency and may only last a few seconds, it can develop into a continuous problem.

For latency-sensitive applications, such as gaming or self-control vehicles, the concern will always be the latency of the network. Consider the case of self-driving cars where an autonomous/adaptive decision must be made to avoid a crash in real-time. Network latency between the self-driving car and the cloud may result in a severely negative outcome.

Figure 21 displays the average of the initial video E2E RTT-Ping server latency for each test region over three different operators. 4G networks have lower average video E2E RTT-Ping server latencies than 3G networks. By taking the average performance of all networks, the latencies of 4G are 44.6 ms, 56.8 ms, 65.35 ms and 67.3 ms, while the latencies of 3G are 441.3 ms, 480.7 ms, 524.7 ms and 326.6 ms for Klang Valley, Johor, Sabah and Sarawak, respectively. The lowest network latency across all 4G operators was recorded in Klang Valley. Alternatively, the highest E2E RTT-Ping server latency was recorded for all 3G operators across all test regions. The increased RTT is due to the long timeframe required by the server to respond to a given request. Thus, all 3G operators in all testing regions have demonstrated inferior network performances in terms of E2E RTT latency (between 123-974 ms), while 4G networks scored remarkable performances with low E2E RTT latency (between 33-94 ms).

The E2E RTT latency is affected by several factors including the propagation, processing, queuing and encoding delays. The reason why the RTT latency in 3G networks is greater than that of 4G networks is essentially due to 3G's circuit switched architecture. It is massively complex with multi-layer design, numerous nodes and parallel strands. Thus, the 2-way time taken for a packet to travel from the source to the destination and back will be longer.

Figure 22 displays the video re-buffering latency for all testing regions. Two areas have been tested in west Malaysia: Klang Valley and Johor. In Klang Valley, the results indicate that the 4G networks for operators X, Y and Z reduce

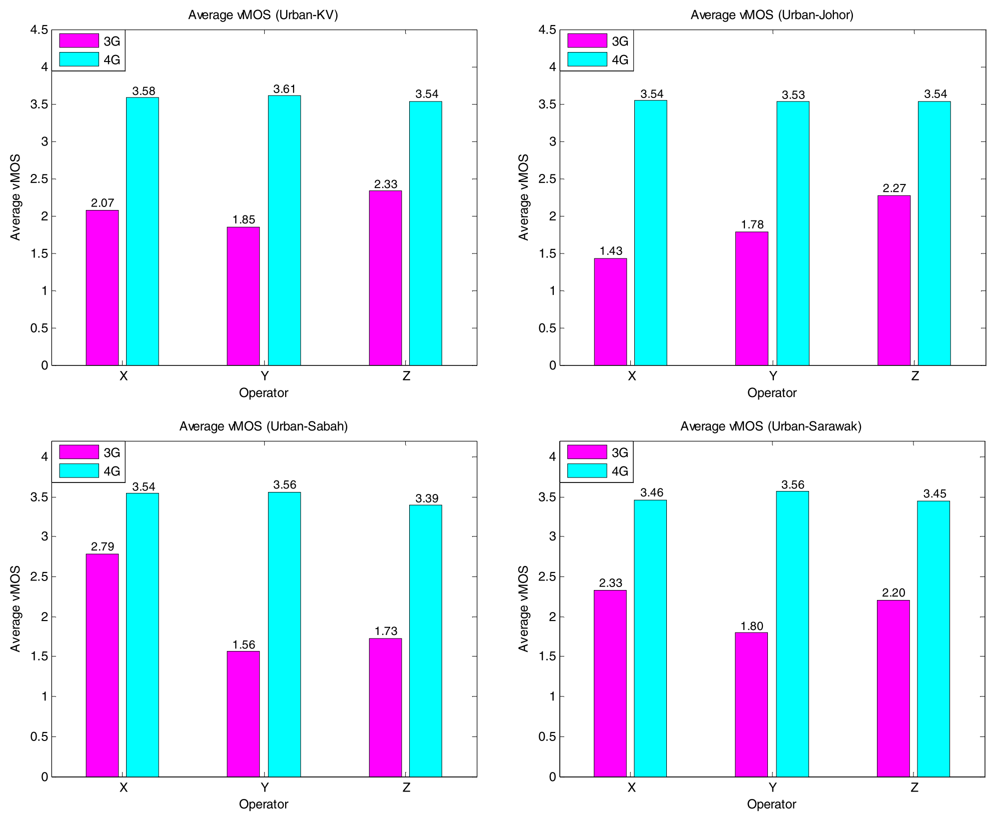


FIGURE 18. The vMOS score for urban morphologies.

the average total re-buffering latency by 88.9%, 64.7% and 79.8%, respectively, compared to 3G networks. Operator X scored significantly lower re-buffering latency over all 3G and 4G networks, while operator Y recorded the highest re-buffering latency compared to the other operators. In Johor, the 4G networks for operators X, Y and Z reduce the average total re-buffering latency by 77.8%, 81.4%, 73.1%, respectively, compared to 3G networks. The 3G networks of operator Z reduce the re-buffering latency by 54.3% and 32.3% compared to operators X and Y, respectively. The high transmission speeds (downlink and uplink) lead to high spectrum efficiency, more flexibility and lower packet latency.

Two areas have been tested in east Malaysia: Sabah and Sarawak. The presented results show that operator Y provides the highest re-buffering latency compared to the other operators in the same testing areas. In Sabah, the performances of 3G and 4G are relatively the same in terms of re-buffering latency for operator X compared to the other operators. All 4G operators have achieved a low re-buffering latency in the area of Sabah compared to operators in the area of Sarawak.

Figure 22 depicts the total average of video re-buffering latency for all testing regions. The real-time results prove that 4G networks achieve lower total average of re-buffering latency compared to 3G networks. Across all testing areas, the average latency of 4G networks for Klang Valley, Johor, Sabah and Sarawak are 2374.4 ms, 2794.0 ms, 2775.8 ms and 3485.5 ms, respectively; while for 3G, they are 10138.5 ms, 12645.9 ms, 14579.8 ms and 13001.9 ms, respectively. The re-buffering latency leads to degraded network performance since the system bandwidth would be insufficient to satisfy the download speeds. As previously mentioned, operators automatically adjust the quality of video resolution based on the transmission link conditions and re-buffering latency records.

6) NETWORK LATENCY FOR VIDEO

Table 5 presents a summary of performance measurement results of video services in the urban morphology for the coded MNOs (X, Y and Z). The presented results include eight distinct KPIs, four different states and two networks (3G and 4G).

Firstly, the measurement results have been vertically compared across different operators for the same KPIs, states and networks using the green and yellow cells, as per the legend shown in the table. For 3G, operator X exhibited better overall performance for video services in Sabah compared to the other two operators, Y and Z. The 3G performance of operator Y is inferior to all other operators, while the 3G performance of operator Z is the best in 3 states: Klang Valley, Johor and Sarawak. Alternatively, the 4G performance of operator Y is superior to the performances of the other operators in Klang Valley, Sabah and Sarawak. This indicates that the

TABLE 5. Summary of video services for the urban morphology classified according to MNOs.

LEGEND:

(green)	The best value among the 3 operators for the same state, technology and KPI	**Bold blue font colour**	The best value for the 3G technology among the 4 states for the same operator and KPI
(yellow)	The same value achieved by two or more operators for the same state, technology and KPI	**Bold red font colour**	The best value for the 4G technology among the 4 states for the same operator and KPI

Morphology: Urban	Operator: X				MBB service: VIDEO			
	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Initial Buffering Success Ratio [Higher is better]	0.8775	1	0.9	1	0.98	1	0.93	1
Average vMOS Score [Range =1 to 5] [Higher is better]	2.07	3.58	1.43	3.54	2.79	3.54	2.33	3.46
Average Video Total Download Rate [kbps] [Higher is better]	1376.8	1865.3	1310.4	1812.6	1570.6	1895.4	1672.6	1864.6
Average Video Maximum Download Rate [kbps] [Higher is better]	6269.2	20177.3	5338.2	16273.9	7321.8	21613.6	7570.8	18010.3
Average Initial Buffering Latency [ms] [Lower is better]	11715.8	1341.4	14316.2	1465.4	3822.9	1476.9	7853	1714.1
Average Video E2E RTT Ping [ms] [Lower is better]	728	51.2	823.2	59.2	190.4	46.5	493.3	65.5
Average Total Re-buffering Latency [ms] [Lower is better]	10853	1203.7	17797.5	3953.4	5694.9	4450.5	12641.3	5186.4
Average Cellular Signal Strength[dBm] [Higher is better]	-89	-90	-75.8	-89.7	-84	-84.9	-74.9	-82.6

Morphology: Urban	Operator: Y				MBB service: VIDEO			
	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Initial Buffering Success Ratio [Higher is better]	0.8547	0.9990	0.93	1	0.9	1	0.9	1
Average vMOS Score [Range =1 to 5] [Higher is better]	1.85	3.61	1.78	3.53	1.56	3.56	1.8	3.56
Average Video Total Download Rate [kbps] [Higher is better]	1370.7	1864.2	1286.3	1870.5	2127.7	2153.2	1346.4	1869.7
Average Video Maximum Download Rate [kbps] [Higher is better]	5358.9	20303.5	4404.3	19122.8	4976.9	17366.5	5157.5	19108.3
Average Initial Buffering Latency [ms] [Lower is better]	9795.6	1201.6	7569.6	1527.9	9951.3	1439.1	8212.9	1405.2
Average Video E2E RTT Ping [ms] [Lower is better]	472.8	33.3	15.8	59	409.6	55.2	249.3	55.4
Average Total Re-buffering Latency [ms] [Lower is better]	13066.7	4609.3	12007.9	2238.2	20372.5	1278.3	17299.3	3254.7
Average Cellular Signal Strength[dBm] [Higher is better]	-80	-87	-82.5	-88.9	-79.9	-87.3	-78.5	-84.7

Morphology: Urban	Operator: Z				MBB service: VIDEO			
	KV		JOHOR		SABAH		SARAWAK	
	3G	4G	3G	4G	3G	4G	3G	4G
Initial Buffering Success Ratio [Higher is better]	0.9615	0.9996	0.99	1	0.89	1	0.98	1
Average vMOS Score [Range =1 to 5] [Higher is better]	2.33	3.54	2.27	3.54	1.73	3.39	2.2	3.45
Average Video Total Download Rate [kbps] [Higher is better]	1577.9	1862.3	1525.1	1845.5	1395.2	1766.7	1481.5	1858.9
Average Video Maximum Download Rate [kbps] [Higher is better]	7309.5	18302.9	6635.2	17017.8	5614.6	13017.8	5834.8	15094.7
Average Initial Buffering Latency [ms] [Lower is better]	5411.9	1400.4	5723.4	1450.9	14625.2	1978.3	5074.5	1817.6
Average Video E2E RTT Ping [ms] [Lower is better]	123	49.3	303	52.3	974.1	94.3	237.1	81
Average Total Re-buffering Latency [ms] [Lower is better]	6495.8	1310.2	8132.5	2190.4	17672	2598.8	9065	2015.5
Average Cellular Signal Strength[dBm] [Higher is better]	-80	-87	-76.8	-87.2	-82.3	-84.1	-74.9	-84.5

management of operator Y prioritises the performance of its 4G network over its 3G. Operator Z displayed better overall performance in Johor than in other areas.

Secondly, the measurement results have been horizontally compared across different states for the same operators, KPIs and networks using the bold blue and red font colours, as per the legend shown in the table. For 3G video services, operator X exhibited better performance in Sabah than in other states, while the 3G performance in Sarawak came second. The performance of video services for the same operator X is

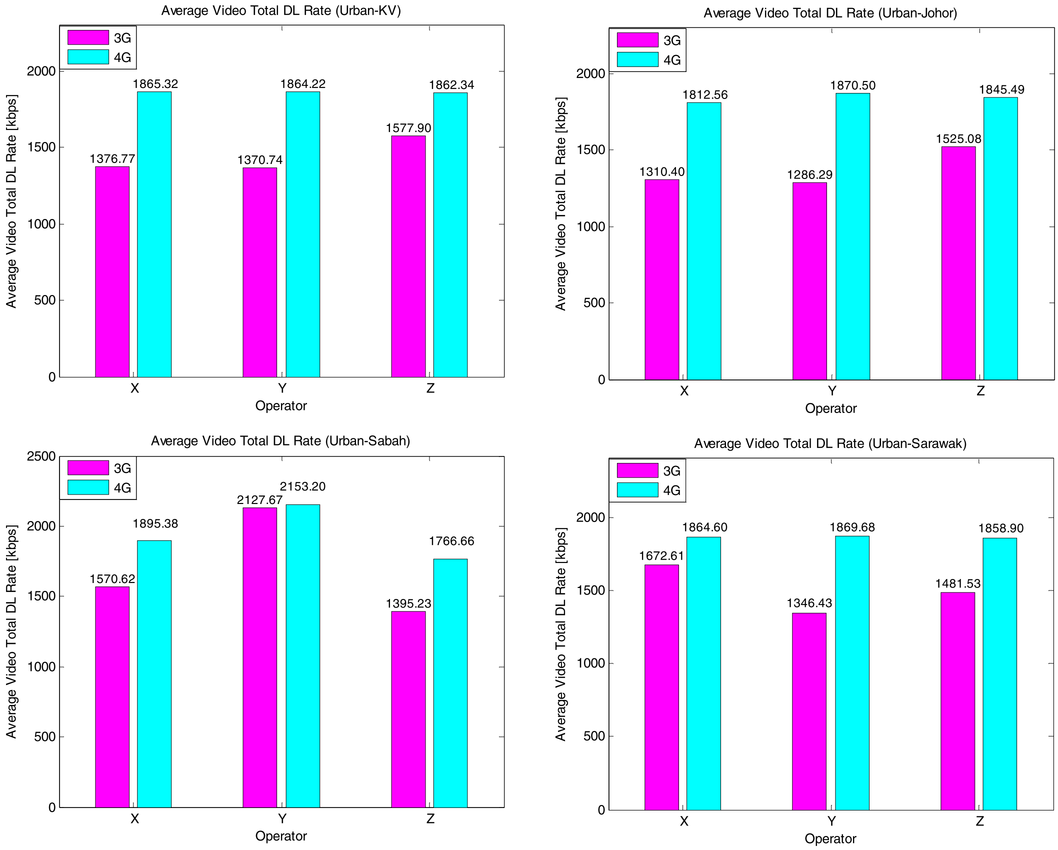


FIGURE 19. The total average video download rate categorised according to technology and test areas.

comparable in Klang Valley and Sabah and it is better than in the other two states. For operator Y, its 3G performance is the best in Johor, while its 4G performance is the best in Klang Valley. The **3G and 4G performances of video services for operator Z are both better in Klang Valley than their counterparts in all other states.**

Overall, the performance of 4G networks is better than 3G networks for all three service providers, all 4 states and across all KPIs, except for the average cellular signal strength. Service providers should be informed that the coverage areas of 4G networks must be extended to provide better signal strength. It can be concluded that no absolute winner exists from the three service provides across all KPIs, networks and states.

V. KEY FINDINGS

In this research, the performance of MBB services has been measured using four metrics relevant to the quality of user experience. The four main metrics are coverage, latency, satisfaction and speed. Coverage is measured by the cellular signal strength when the smartphone streams a video or browses a web. This is obviously the main factor contributing to consumer experience when accessing the two services. Latency determines the responsiveness of a network since it refers to the delay of communicating data between two nodes existing in different platforms and applications. For video services, user satisfaction is a comprehensive user experience indicator (e.g., vMOS) of mobile video services (on a scale of 1 to 5), signifying the network transmission inflicted upon video playing. Generally, the rate of successful web browsing and video streaming provides a level of user satisfaction. Speed refers to the download rate which quantifies the throughput of communicating data from the cloud to user devices. These metrics reflect the main attractions of 4G technology in comparison to 3G. The key findings of this research are summarised as follows:

A. SUPERIOR PERFORMANCE OF 4G COMPARED TO 3G

The experimental measurements and data analysis revealed that the performance of 4G networks is far better than that of 3G networks across all testing areas, MNOs and KPIs. This was expected, however, the facts are now associated with figures that allow researchers, regulators and decision-makers identify the performance of MBB service providers from an independent third party.

B. COVERAGE

The experimental measurements accomplished in this study revealed that the three MNOs have no significant difference in terms of received signal strength. This was proven when the same 3G and 4G technology were examined across all networks of different MNOs.

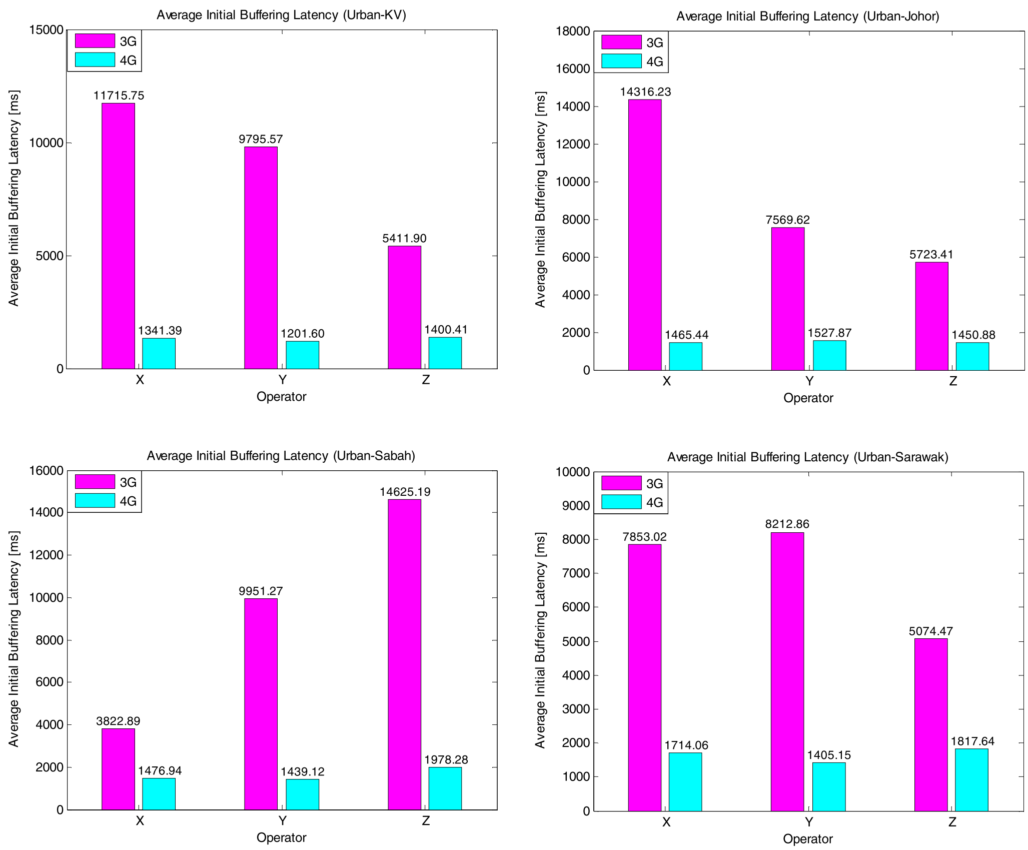


FIGURE 20. **The initial average of video buffering latency for urban morphology of each test area categorised by MNOs.**

C. LATENCY

The 4G technology achieved a minimum web ping average RTT latency of 42.4 ms, while 3G achieved a minimum of 69.9 ms. In terms of the average E2E RTT-ping server latency, 4G reached as low as 33.27 ms, while 3G achieved a minimum of 122.98 ms.

D. SATISFACTION

In this study, the vMOS indicator was used to provide a comprehensive measure of video services on a scale of 1 to 5 (the higher the better). The results of the outdoor tests revealed that user satisfaction gauged by vMOS presented a score higher than 3 for 4G technology across all MNOs, while it was less than 3 for the 3G technology for both web and video services.

E. SPEED

The experimental measurements and analyses revealed that 4G technology provides enhanced download speed by a factor of 4.2 and 1.6 for web browsing and video streaming, respectively, in comparison to 3G.

VI. RESEARCH LIMITATIONS AND FUTURE TRENDS

This study presented relevant data on the performance of MBB services for browsing websites and streaming videos. The performance of making voice calls or sending short message service (SMS) did not fall within the scope of this study. The highlighted limitations are as follows:

- The study did not consider other factors that may contribute to the experience of end users while utilising MBB services; for instance: data packages, prices, tariff, policies, privacy, billing, etc.
- The performance of MBB services is largely dependent on network availability as observed by the smartphones of end users. Network availability is influenced by several factors, such as the distance from the base station. The current research did not assess the network availability of a given MNO. For instance, when a device connects to a 4G network, this does not mean that the 3G network is unavailable. The applied methodology did not include instructing the device to connect to a specific technology during the drive tests.
- The performance of MBB services is influenced by the number of users in the vicinity that are simultaneously accessing the network. Thus, the spatial-temporal consideration of the number of users accessing the service is yet another factor that can be examined in future research.
- This study was limited to four states and did not represent performance for all morphologies of Malaysia.
- The urban area of Klang Valley has more 4G coverage than 3G compared to the urban areas of other states.

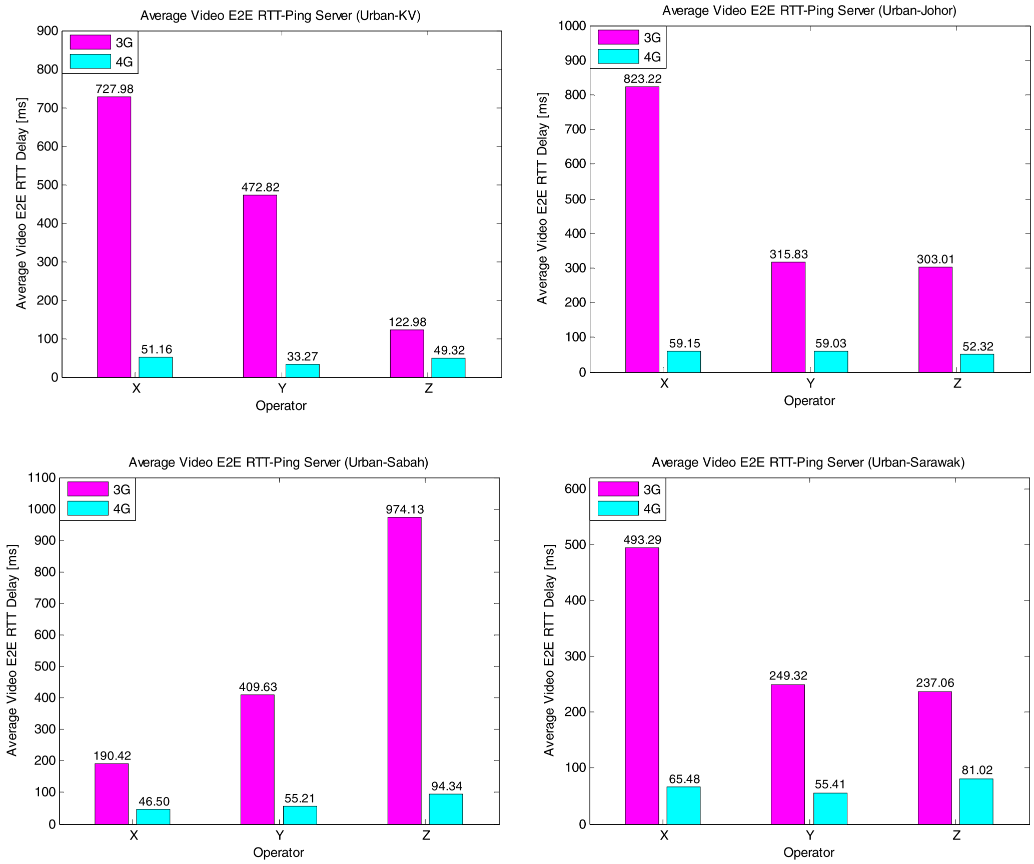


FIGURE 21. **The initial average of video E2E RTT-Ping server latency for urban morphology of each test area categorised by MNOs.**

Operators may need to balance their investments for upcoming 5G systems between states, especially for the capital cities of each state.

- Longer drive tests are needed. The tests should cover larger areas to obtain complete measurements. This approach can be time consuming.
- During the drive tests, the measurement logs should be downloaded from measurement devices and uploaded for processing. The amount of data needed is exceedingly high.
- The drive test solution is costly since the rent of vehicles, maintenance and fuel costs must all be considered.
- Using the measured dataset obtained from the present study, the signal strength, download speed, latency, etc., can be predicted in real-time. This will help increase the reliability of future 5G networks.
- The problems of passive interference due to rain and other channel impairments caused by tall buildings [58]–[60] or trees should be examined for the improved implementation of 5G networks with better link performance.
- This study can be extended to include the performance of MBB services while accessing various combinations of photo and video-based website contents, web-browsing and video-streaming test applications, MBB services and KPIs across diversified urban regions of the study area.
- This research can be further extended to investigate handover issues in urban areas over heterogeneous networks. This will become more significant in future ultra-dense networks as the number of small base stations increases and network specifications become more complex. Considerable increase of mobility management issues is expected [61]–[64].
- With 5G networks, the average latency is around 1 ms. It should be noted that it takes 10 ms for an image to be captured by the human eye and processed by the brain. In real-time critical applications, such as remote surgery, low latency becomes increasingly essential. It is believed that the latency performance is the key enabler for advancing 5G and beyond technology. Analysing the latency of 5G networks based on drive test data will be required in future. The reliability of this new technology should be determined so as to support real-time critical applications.
- Once 5G technology is widely deployed in Malaysia, the current study can be extended to include the performance of 5G MBB service providers to recognise

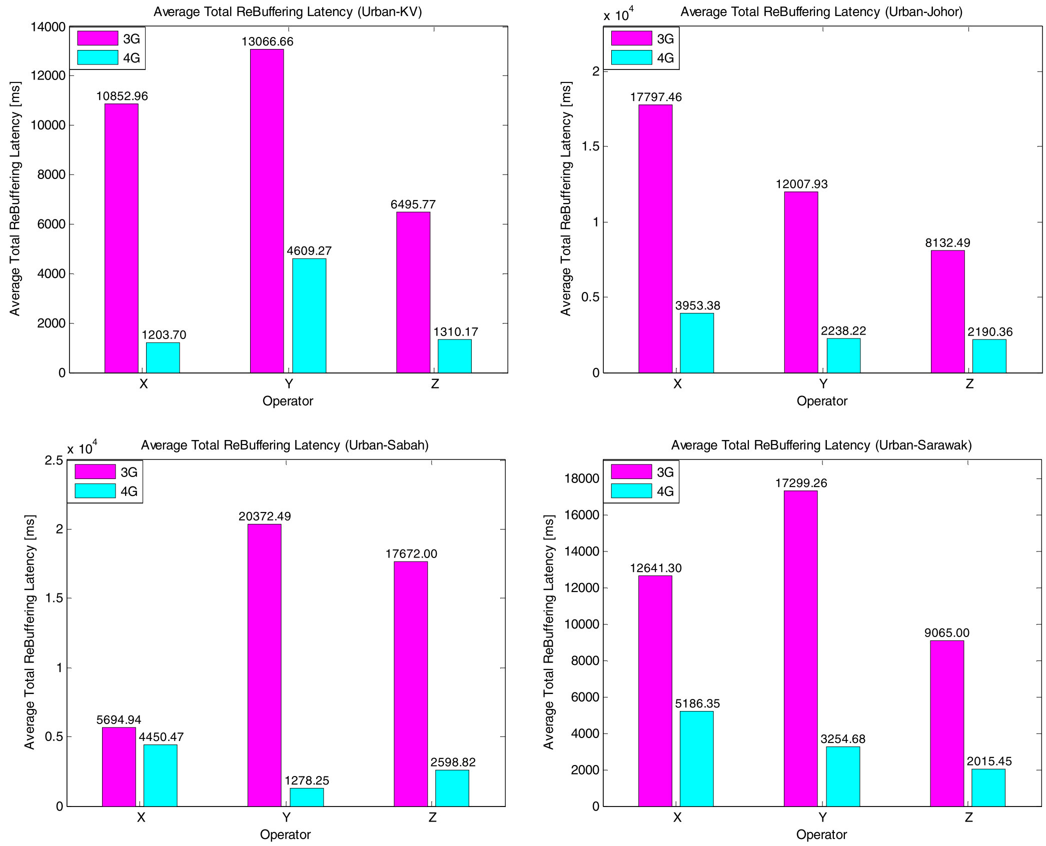


FIGURE 22. The total average of video re-buffering latency for urban morphology of each test area categorised by MNOs.

its superiority in comparison to older MBB generations. This will be beneficial since 5G implementation is based on millimetre-wave bands characterised by high path loss and small cell size support [58]–[60], [65].

VII. CONCLUSION

In this work, the measurement results of 4G and 3G mobile network performances for the urban morphology in Malaysia have been presented. Their performances were investigated using four performance metrics: coverage, latency, satisfaction and speed for two types of MBB services, web browsing and video streaming. The current study compared 4G and 3G networks, including the performance of each MNO at four different sites: Klang Valley, Johor, Sarawak and Sabah. The outcomes revealed that, on average, 4G networks perform much better than 3G networks for all selected regions. The most significant conclusion to be drawn from these results is that 4G networks provide better coverage, lower latency, greater user satisfaction and higher speed as compared to 3G networks. 4G networks are deployed more than 3G networks in the urban areas considered. This indicates that 4G has become the dominant network in the tested regions. These results are consistent for all mobile operators. This study will enable the upgrade of existing MBB services for urban areas throughout Malaysia so as to meet increasing traffic demands of 5G technology.

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